Effect of Residual Stresses in Roll Forming Process of Metal Sheets

By

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Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Deakin University
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List of Publications

Journal papers


Conference papers


Abstract

Roll forming is a continuous process in which a flat strip is shaped to the desired profile by sequential bending in a series of roll stands. Bending is the dominant deformation mode in roll forming. Sheet materials used in this process are generally temper rolled, roller- or tension- leveled. These processes introduce residual stresses into the material, and recent studies have shown that those affect the material behavior close to the yield in a bend test. Thus, residual stresses introduced during prior steel processing operations may affect the roll forming process. Effect of residual stresses in a roll forming process is unknown and a uniform material data delivered from tensile test is usually used for roll forming simulation.

This thesis investigates the effect of pre-existing residual stresses in the incoming material on final shape in a roll forming process, through a combination of theoretical, numerical, and experimental techniques. A lack of detailed information with regard to the pre-processing conditions for the incoming material is the major concern for using an analytical approach to predict residual stress in metal strip. On the other hand the experimental methods available for measuring residual stress are time consuming, expensive and not applicable to test residual stress in incoming material on a day to day basis. Therefore the aim of this thesis is introducing a new technique for estimating residual stress in roll forming strip and using that information in roll forming simulation.

Finite element analysis and experimental verification was utilized to achieve a reliable model for roll forming simulation with the capability of including a residual stress profile through the material thickness. It was found that solid-shell element can be used in bending and roll forming simulation of a simple V-section with reliable model accuracy. This element type has arbitrary numbers of integration points through the thickness that can be used to
implement the pre-existing residual stress information. Using solid-shell element can also save CPU time significantly compared to the analysis uses multilayers of solid elements.

A thickness reduction rolling process was used to introduce some residual stresses into a stress relieved material. It was shown that the thickness reduction leads to the introduction of tensile residual stress at the material surface, and compressive residual stress in the mid-plane center of the sheet. Experimental and numerical studies explored that residual stress in the material due to a thickness reduction rolling process will change the final shape in a V-section roll forming process. It was shown that using tensile test is not sufficient enough to capture the shape defects in a roll forming process if a residual stress profile exists in the material. Including the residual stress information in finite element simulation led to improved model accuracy compared to a simple model that uses uniform material data delivered from a tensile test.

A novel bend tester was developed which enables the analysis of material properties close to the yield, to clearly observe the effect of residual stresses in the material, and relevant to the roll forming process. Furthermore, the effect of initial residual stresses on the material response close to yield in the tensile and in the developed bend test was compared numerically. Both tensile and bend test simulations showed early yielding in the material due to pre-existing residual stresses while the bend test offers advantages to obtain material data for roll forming and for capturing the effect of residual stresses.

An inverse routine was developed that, combined with experimental bend test data, allows the determination of the residual stress profile of incoming material. Experimental measurement of residual stresses were applied to verify the developed inverse routine. It was shown that the developed inverse routine combined with experimental bend test data allows to determine residual stress in incoming steel strip with high accuracy.
Finally, the application of the inverse routine was shown for a simple roll forming case. Material data delivered from the inverse routine that takes into account a pre-existing residual stress profile in the material was successfully applied in a roll forming simulation. It was also shown that effect of residual stresses on final product in a roll forming process are more significant when a high strength steel material is formed to a profile with large bending radius to thickness ratio.
Nomenclature

Some symbols appear more than once, their specific meaning follows from their context.

Commonly used notations

\[ a \] Length variable in bend tester
\[ a \] Variable to define a residual stress profile
\[ a \] Lattice constant
\[ b \] Bending arm length
\[ b \] Variable to define a residual stress profile
\[ b' \] Effective bending arm length
\[ c \] Length variable in the clip–on gauge
\[ c \] Variable to define a residual stress profile
\[ c(z_i) \] Correction in stress
\[ d \] Interplanar spacing between in the atomic lattice
\[ d_n \] Interplanar spacing of the strained material
\[ d_0 \] Interplanar spacing of the unstrained material
\[ d_{ik} \] The \( k \)th discrete variable for the \( i \)th variable
\[ dx \] The increment size
\[ f(\mathbf{x}) \] Objective function
\[ g_i(\mathbf{x}) \] Constrains in the optimization process
\[ h \] Thickness of the strip
\[ h_1 \] Bow height
\[ h_2 \] Bow height
\[ i \] Increment number
\[ i_1 \] The unit vector
\[ l \] The initial distance between two selected nodes
\[ l_f \] Common length of fibres
\[ l_p \] Plastic part of length of a fibre
\[ l_0 \] Longitudinal distance between two bending arms
\[ m \] The gradient of the \( d \) versus \( \sin^2 \psi \) curve in XRD
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>Total number of constraints in optimization process</td>
</tr>
<tr>
<td>$m$</td>
<td>Material parameter</td>
</tr>
<tr>
<td>$n$</td>
<td>Order of reflection (an integer)</td>
</tr>
<tr>
<td>$n$</td>
<td>Material parameter</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of variables in the optimization process</td>
</tr>
<tr>
<td>$n_d$</td>
<td>Number of discrete design variables</td>
</tr>
<tr>
<td>$p$</td>
<td>Number of equality constraints in the optimization process</td>
</tr>
<tr>
<td>$q_i$</td>
<td>Number of available discrete variables for the $i$th variable</td>
</tr>
<tr>
<td>$r$</td>
<td>Atomic radius</td>
</tr>
<tr>
<td>$r$</td>
<td>Residuals vector</td>
</tr>
<tr>
<td>$r_{roll}$</td>
<td>Roll radius</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Bending inner radius</td>
</tr>
<tr>
<td>$r_{i1}$</td>
<td>Bending radius in loading</td>
</tr>
<tr>
<td>$r_{i2}$</td>
<td>Bending radius after springback</td>
</tr>
<tr>
<td>$s$</td>
<td>Direction</td>
</tr>
<tr>
<td>$t$</td>
<td>Material thickness</td>
</tr>
<tr>
<td>$x$</td>
<td>Optimization variables</td>
</tr>
<tr>
<td>$y$</td>
<td>Distance from the mid-surface</td>
</tr>
<tr>
<td>$y$</td>
<td>Obtained curve in each increment</td>
</tr>
<tr>
<td>$y'$</td>
<td>Target curve</td>
</tr>
<tr>
<td>$z$</td>
<td>Normalised strip thickness</td>
</tr>
<tr>
<td>$z_1$</td>
<td>The distance from the bottom of the sample to the uncovered depth (new thickness after the layer removal in each step)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$A$</td>
<td>Material parameter</td>
</tr>
<tr>
<td>$A$</td>
<td>Hardening thermodynamical forces</td>
</tr>
<tr>
<td>$D$</td>
<td>Length in the shouldered sample</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Set of the discrete variables for the $i$th variable</td>
</tr>
<tr>
<td>$E$</td>
<td>Elastic modulus</td>
</tr>
<tr>
<td>$E$</td>
<td>Set of equality constrains</td>
</tr>
<tr>
<td>$E'$</td>
<td>Elastic modulus in plane strain</td>
</tr>
<tr>
<td>$F$</td>
<td>Force in the bend test</td>
</tr>
<tr>
<td>$F$</td>
<td>Total force in the tensile test</td>
</tr>
<tr>
<td>$F^p$</td>
<td>Plastic part of the deformation gradient</td>
</tr>
</tbody>
</table>
G  Roll gap
G'  Theoretical end of the grip
G''  Effective end of the grip
H  Original thickness of the sample
H  Material parameter
I  Set of inequality constrains
\( J_2(\cdot) \)  Second invariant of the deviatoric part of stress
L  Bending length
L'  Distance between the ends of the grips
L''  Effective gauge length
M  Bending moment
M  Mass
M  Number of iterations in the simplex method
N  Number of increments
N  Flow vector
R  Bending radius
R  Radius of fillet in the shouldered sample
R_0  Loading radius
R_{P0.2}  Yield stress
R_m  Ultimate tensile strength
S  Plane strain flow stress
S  Feasible set in the optimization process
V_{\text{line}}  Roll forming line speed
W  Sample width

\( \alpha \)  Bending angle
\( \alpha_1 \)  Bending angle in loading
\( \alpha_2 \)  Bending angle after springback
\( \beta \)  Back-stress tensor
\( \dot{\gamma} \)  Plastic multiplier
\( \delta \)  Length variable in the clip-on gauge
\( \varepsilon_{\text{bend}} \)  Bending strain
\( \varepsilon_{\text{ult}} \)  Ultimate tensile strain
\( \varepsilon \)  True strain
\( \varepsilon^e \)  Elastic strain

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\( \varepsilon^p \) Plastic strain
\( \varepsilon_0 \) Material parameter
\( \bar{\varepsilon} \) Equivalent strain
\( \bar{\varepsilon}^p \) Accumulated plastic strain
\( \varepsilon_{eng} \) Engineering strain
\( \varepsilon_s \) Material parameter
\( \dot{\varepsilon}^p \) Plastic strain rate
\( \theta \) Initial angle between arms in bend tester
\( \theta \) Bending angle
\( \theta \) Reflection angle in XRD
\( \theta' \) Unloading angle
\( \theta' \) Effective initial angle between arms
\( \lambda \) Wavelength of X-ray
\( \mu \) Friction coefficient
\( \nu \) Poisson's ratio
\( \sigma_x \) Longitudinal stress
\( \sigma_y \) Transverse stress
\( \sigma_1 \) Principal stress
\( \sigma_{11} \) Longitudinal stress
\( \sigma_2 \) Principal stress
\( \sigma(z_1) \) Corrected (true) stress at depth \( z_1 \)
\( \sigma_m(z_1) \) Measured stress at depth \( z_1 \)
\( \sigma_m(H) \) True surface stress
\( \sigma_m(H) \) Successive derivative with respect to \( z \) at the surface
\( \sigma_{yo} \) Initial yield stress
\( \sigma_y \) Yield stress
\( \sigma \) True stress
\( \sigma_{eng} \) Engineering stress
\( \sigma_{bend} \) Bending stress
\( \sigma_Y \) Material parameter
\( \sigma_s \) Material parameter
\( \tau \) Shear stress
\( \tau_y \) Shear yield stress
\( \psi \) Surface tilt angle
\( \omega_{\text{roll}} \) Rolls rotational speed

\( \Delta l \) Displacements of two selected nodes

\( \Delta \theta \) Springback angle

\( \Delta \) Displacement of upper arm in bend tester

\( \Delta \theta \) Specimen bend angle during bend test

\( \Delta \left( \frac{1}{R} \right) \) changing in the curvature due to springback

\( \Phi \) Angle between selected direction and principal direction 1

\( \Phi \) Yield function

\( \left( \frac{1}{R} \right) \) Bending curvature

\( \left( \frac{1}{R} \right)_0 \) Bending curvature before springback

\( (h \ k \ l) \) miller indices of lattice planes

\( \|T\| \) \( \|T\| \equiv \sqrt{T:T} \)

\( T:T \) Double constrain of tensors (internal product of second-order tensors)

**Abbreviations**

2D Two dimensional

3D Three dimensional

AHSS Advanced High Strength Steels

ANS Assumed Natural Strain

DP780 Dual Phase 780 steel

EAS Enhanced Assumed Strain

FEA Finite Element Analysis

GT Game Theory-based optimization

GA Genetic Algorithms

HSS High Strength Steels

MDO Multidisciplinary Design Optimization

OPS Oxide Polishing Suspensions

PSO Particle Swarm Optimization

RESS Reduced integration Enhanced strain Solid-Shell element

RI Reduced Integration
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>RMS</td>
<td>Root-Mean Square</td>
</tr>
<tr>
<td>SA</td>
<td>Simulated Annealing</td>
</tr>
<tr>
<td>SHS</td>
<td>Square Hollow Section</td>
</tr>
<tr>
<td>SI</td>
<td>Swarm Intelligence</td>
</tr>
<tr>
<td>SRI</td>
<td>Selective Reduced Integration</td>
</tr>
<tr>
<td>UHSS</td>
<td>Ultra-High Strength Steels</td>
</tr>
<tr>
<td>XRD</td>
<td>X-Ray Diffraction</td>
</tr>
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Chapter 1

Introduction

1.1 Motivation

Cold forming of long, uniform sections is principally performed by roll forming or press-brake forming. In brake forming, the deformation of the panel is performed in one step, while roll forming is a continuous process to form a metal strip along straight, longitudinal, and parallel bend lines with multiple pairs of controlled rolls without changing the material thickness (Figure 1.1).

The roll forming industry uses 8% of the world-wide production of steel [1]. Roll forming allows the forming of complex profile shapes from materials that
have limited formability and the compensation of springback can be achieved by simple methods. For this reason the process is increasingly used in the automotive industry for the forming of Advanced High Strength Steels (AHSS) for structural and crash components. It is suggested that the application of AHSS will increase from 68 kg/vehicle in 2009 to 204 kg/vehicle in 2020 to reduce the weight of vehicle body structure by 25% [2]. Each 10% reduction in the weight of automobiles reduces the fuel consumption by 6-8% which leads to less $CO_2$ emission to the environment [3].

Due to the high part quality and tolerance requirements of the automotive industry, Finite Element Analysis (FEA) has been increasingly applied in roll forming process design. Although FEA is a standard tool for simulating metal forming, only limited information exists with regard to the accuracy of numerical models of the roll forming process.

Bending is the major deformation mode in a roll forming process. Compared to a conventional brake forming operation in which bending is uniform along the length of the strip, Figure 1.2.a, and the material outside the bend does not deform, in roll forming each element of the material has a forming path during the roll forming process, Figure 1.2.b. This forming path leads to shear and longitudinal strain and it may progress to forming defects such as edge wave and longitudinal curvature [4, 5]. During the roll forming process the material in the bending zone is in compression (point A in Figure 1.2.b) while the material outside of the bending area is in tension (point B in Figure 1.2.b).

The shape defects in roll forming are often due to very small plastic strains at the flange in the longitudinal direction. Moreover, some shape defects in a roll forming process are due to variation of small longitudinal strains across the strip width (variation of strain from point A to point B in Figure 1.2.b). For this reason the material behaviour close to yield is important.
Figure 1.2 Comparison between brake forming and roll forming a) In a brake forming operation the deformation in uniform b) in a roll forming process the material deformation path changes along the length.

Roll forming materials are generally temper rolled (skin passed), or tension or roller levelled to eliminate ageing effects and to produce a smooth surface finish. These processes introduce residual stresses into the material, and previous studies [6, 7] have shown that those stresses affect the material behaviour close to yield.

So early yielding in the material at the flange due to residual stresses in steel processing might have an important effect on deformation in this region, and subsequent part quality in a roll forming process.

The effect of residual stresses therefore needs to be accounted for in roll forming simulations to achieve model accuracy; however, roll forming simulations generally involve a large number of elements because the long strip needs to be discretized. The number of elements used through the thickness is therefore limited and this precludes the detailed consideration of residual stresses in the numerical analysis of the roll forming process. In addition, residual stress information is needed in the incoming material for a roll forming process. If the exact pre-processing conditions (i.e. coiling and uncoiling) of the strip are known, the initial residual stresses can be determined analytically [8, 9], however, these parameters are usually unknown in industrial roll forming applications. Conversely, the experimental
measurement of residual stresses is expensive, difficult, time consuming and of limited accuracy.

To consider of the effect of residual stress in roll forming simulations a reliable and efficient method to determine residual stresses in metal strip needs to be developed and this information included and understood in an efficient numerical model.

1.2 Thesis objectives

As stated, the objective of this thesis is to determine residual stresses in sheet metal given no knowledge of pre-processing conditions, which will provide an approach to greater understand the effect of residual stresses in roll forming. The sub-tasks of this thesis are:

- To identify an element formulation that leads to suitable model accuracy in roll forming simulations and allows the implementation of an initial residual stress profile (Chapter 3);
- To investigate the effect of residual stresses on shape defects commonly observed in the roll forming process (Chapter 4);
- To introduce a novel bend test device by which residual stresses can be observed in sheet material, and to compare the effect of residual stresses on the material behaviour in the tensile and the developed bend test (Chapter 5);
- To develop and verify an inverse routine based on experimental bend test data that predicts the residual stresses in the material input for simulation of roll forming (Chapter 6);
- To show the application of the inverse routine in roll forming industry (Chapter 7).

A schematic of the thesis objectives is shown in Figure 1.3. A pure bend test will be performed on the incoming material for roll forming to obtain moment–curvature data. The moment–curvature diagram of the material will
be applied as the target curve in an inverse analysis using finite element and optimization method to predict residual stresses through the material thickness and material parameters for finite element simulation. The information obtained from the inverse routine will be implemented in the roll forming simulation to improve model accuracy and show the effect of residual stresses on final product quality.

**Figure 1.3** Schematic of thesis objectives.
1.3 Thesis outline

This section will outline the structure of the thesis and will explain how the above objectives will be achieved.

Chapter 2 – Literature review: A brief introduction of the roll forming process; the major deformation modes and the shape defects commonly observed in the process will be given. Steel pre-processing techniques such as skin passing, roller and tension levelling will be discussed and their effect on residual stresses in roll forming materials reviewed. After this, previous studies on the effect of residual stress on the material behaviour in bending and the roll forming process will be discussed. In the final part of this chapter various analytical approaches and experimental techniques to predict and measure residual stresses in the material will be reviewed; the major focus will be on finding a reliable approach to obtain residual stresses in the incoming material for a roll forming process.

Chapter 3 – Bending and roll forming models to identify an appropriate element type: The characteristics of different element types which can be used for sheet metal forming simulations will be reviewed in the first part of this chapter to select the proper element type for this thesis. A sensitivity study will be performed to identify the best possible model arrangement, material model, and element type for the numerical simulation of pure bending and the roll forming process. Major focus will be on the identification of an element type that allows the consideration of a residual stress profile through the material thickness and combines good model accuracy with acceptable calculation time. Experimental bending and roll forming trials will be performed to verify the numerical results and to quantify model accuracy. This chapter will determine whether sufficient model accuracy combined with reduced calculation time can be achieved for bending and roll forming models by using a recently developed solid-shell element type.
Chapter 4 – *Effect of residual stress on a roll forming process*: A thickness reduction rolling process will be used to introduce residual stresses into a metal strip. The initial and thickness reduced material will then be used in the experimental roll forming process to identify the effect of residual stress on the final shape. Numerical simulation of the roll forming process will be performed for the fundamental analysis of the effect of residual stress on the material behaviour in roll forming. The FEA results will be compared to the experimental data for validation. Additionally it will be shown if using material data delivered from a tensile test is sufficient enough to capture the shape defects in a roll forming process when a residual stress profile exists in the material.

Chapter 5 – *Bend test to observe a residual stress profile in sheet material*: A review on previous studies focusing on identifying material properties via the bend test will be presented. It will be shown that a new bend test arrangement needs to be developed to enable the analysis of material properties close to the yield, to clearly observed the effect of residual stresses in the material, and relevant to the roll forming process. The new bend test device will be developed and its performance will be examined experimentally. Furthermore, the effect of initial residual stresses on the material response close to yield in the tensile and in the developed bend test will be compared numerically. The numerical analysis will show if residual stresses introduced by a thickness reduction rolling process lead to material softening in tensile and bend tests and whether the developed bend test indicates the presence of residual stresses more clearly.

Chapter 6 – *Development of an inverse routine to predict residual stress in sheet materials*: An inverse routine will be developed that, combined with experimental bend test data, allows the determination of the residual stress profile of incoming material. First, a background will be provided where the necessary components of an inverse routine of this type are outlined: material
model, and search techniques/optimization methods. Then, a review of similar inverse models for extracting material data using a bend test will be presented. The developed bend tester of Chapter 5 will be used to obtain material data for the inverse routine in this thesis. Experimental measurement of residual stresses through the thickness of the material will be performed in the last part of this chapter to verify the inverse routine. This chapter will show whether it is possible to estimate the residual stress profile in metal strip using an inverse model combined with experimental pure bend test data.

**Chapter 7 – Application of the inverse routine in roll forming industry:** This chapter will show the application of the inverse routine for a simple roll forming case. The influence of material properties and cross sectional geometry on the severity of the effect of a residual stress profile in the material on final product in a roll forming process will be also discussed.

**Chapter 8 – Conclusions and recommendations:** Discussion summarises the main conclusions of this thesis, and the authors’ recommendations for future work in this field will be presented.
Chapter 2

Literature Review

2.1 The scope of the literature review

Chapter 1 defined the scope of this thesis. It was highlighted that there is a significant need to predict residual stresses in the material, and have an optimum strategy in finite element simulation to explore the effect of residual stresses in the roll forming process. This chapter will present a critical review of the literature relevant to the defined scope and identify where the gap in the field of research exists.

A large amount of research has been conducted on the topic of roll forming. Hence, an exclusive review of the all available literature is not possible, nor it is necessary. Therefore, this chapter will focus specifically on simulation of a roll forming process including the effect of pre-existing residual stresses in the material with the following research fields:

- *Roll forming and its typical shape defects* (Section 2.2): this section will give a brief introduction on the roll forming process. The major deformation modes and shape defects commonly observed in this process will be reviewed.
- *Steel pre-processing, resulting residual stresses, and their effect on material behaviour* (Section 2.3): the source of common shape deviations in steel production line, temper rolling and levelling processes which are usually used to eliminate those defects and
produce a flat strip will be discussed. Definition of residual stresses and residual stresses in the material due to temper rolling or levelling will be further explored. Last part of this section will discuss about the effect of residual stresses on bending or a roll forming process. This section will show that there is a gap in this area of knowledge and that the effect of residual stresses in the material on a roll forming process has not been investigated by other researchers.

- **Obtaining residual stress information of incoming sheet** (Section 2.4): to investigate the effect of residual stresses in the material on a roll forming process, the residual stress information is needed. Most researchers have used experimental or analytical methods to obtain that information in the material. Various techniques to measure or predict residual stresses in the material will be reviewed.

### 2.2 Roll forming and its typical shape defects

Cold forming of long, uniform sections is principally performed by roll forming or press-brake forming. In brake forming, the deformation of panel is performed in one step, while roll forming is a continuous process to form sheet metal strip along straight, longitudinal, and parallel bend lines with multiple pairs of controlled rolls without changing the material thickness at room temperature (Figure 2.1).

![Figure 2.1 Continues bending in a roll forming process [10].](image)
Although roll forming was already used in the early 1900s, it was widely applied in the industry after the Second World War when the labor content of many products was significantly reduced due to the high efficiency of the roll forming process. In the 1950s and 1960s, other operations like inline welding, and pre-punching were incorporated into the roll forming production lines, while in the late 1970s and 1980s computer aided roll design systems were introduced to the roll forming process. In 1990s, programmable controllers and computers were added allowing the control of the roll forming production line. Roll forming is still growing in the twenty first century, where the material tolerances have become tighter while the demand for manufacturing flexibility has increased [11].

Roll forming is increasingly applied to manufacture structural components from High Strength Steels (HSS) and Ultra-High Strength Steels (UHSS) [12]. The higher strength to weight ratio is the main advantage of using HSS and UHSS in industry [13]. The yield strength and tensile strength of HSS are 210-550 MPa and 270-700 MPa respectively, while for UHSS the yield strength is greater than 550 MPa and the tensile strength is more than 700 MPa [14]. Achieving the required dimensional accuracy is the main difficulty of using these materials. Springback (elastic recovery after forming), bow (curving in the vertical direction), camber (curving in the horizontal direction), flare (change in the cross section at the cut ends of a roll formed product), twist, corner buckling, edge waving, edge cracking and splitting are common shape defects in the roll forming of HSS and UHSS. All these shape defects are often not visible until the strip is totally unloaded [15]. Bow, twist and camber in the roll forming are shown in Figure 2.2, while Figure 2.3 shows the flare defect.
The main types of deformation in roll forming are elongation and bending in the transversal and longitudinal directions, as well as shear across the strip and through the strip’s thickness [4]. Transversal bending is the desirable deformation type, while the others are typically the redundant deformations that lead to the main shape defects found in this process.

Longitudinal strain, bow, springback, and end flare will be investigated in this thesis to explore shape defects in roll forming. These effects will be now further explained.

### 2.2.1 Longitudinal strain

In roll forming, the material at the flange moves more than the material at the web of the sheet (Figure 1.2.b). This movement differential causes longitudinal...
and shear strain during the process. Longitudinal and shear strain development in the roll forming process and the relationship between them was presented in [5]. It was shown that it is theoretically possible to have just shear strain or longitudinal strain in a roll forming process, but the deformation in practice is a combination of these two strains. If the longitudinal strain of the sheet edge exceeds the yield limit of the material, defects like bow, camber and edge waviness may occur. Ideally longitudinal strain should remain in the elastic region during the process to avoid major shape defects in the part. When the strip first contacts the rolls, the peak longitudinal strain in cross section will occur and by increasing the roll diameter, the peak longitudinal strain will decrease [16]. Han et al. [17, 18] showed that peak longitudinal membrane strain of the deformed strip is a function of the material thickness, material yield, and bend angle. In particular, the peak longitudinal membrane strain increases when the material thickness increases, or the bend angle is increased between forming stations, or the yield of the sheet material is increased. However, there is some debate over the role of a material yield strength with regard to the peak longitudinal membrane strain. It was shown in [19] that the peak longitudinal membrane strain decreases in a material with higher yield strength. Thus, shape defects in a roll forming process due to peak longitudinal strain depend on various material and process parameters and a close investigation of longitudinal edge strain is needed to estimate the likelihood of shape defects.

2.2.2 Longitudinal bow

Longitudinal bow is a shape defect where there is a vertical curvature error along the length of the final product (see Figure 2.2). Longitudinal bow is caused by non-uniform transversal distribution of the longitudinal membrane strain (see Figure 2.4). This non-uniformity is a fundamental characteristic deformation of the strip in a roll forming process and cannot be avoided when a flat strip is roll formed to a cross section with a critical height and width.
The magnitude of longitudinal strain and its transversal distribution can be reduced by an appropriate strategy in the roll forming process design. The proper number of passes should be used in the roll forming process. When the number of passes is too few, then the amount of transversal bending caused by each pair of rolls can become excessive. This leads to more non-uniformity in distribution of longitudinal strain in the transversal direction. If too many passes are used, then the production costs will increase significantly. Designing the optimum number of passes for a roll forming process is critical, where the shape defects are minimised and the production cost is also reduced. The roll profiles and the position of the rolls should be also modified to reduce the longitudinal bow by decreasing the magnitude and non-uniformity of the longitudinal membrane strain.

Figure 2.4 Relationship between transversal distribution of longitudinal strain and longitudinal bow [11].
2.2 Roll forming and its typical shape defects

2.2.3 Springback

Springback is an important shape defect in a roll forming process. It is the elastic recovery of the material that changes the final cross sectional geometry of a roll formed profile after the part is released of the tooling. The amount of springback is dependent on various material and process parameters. The springback angle will increase with the yield and tensile strength of the material, with decreasing Young's Modulus and increasing forming radius to thickness ratio $R/t$ ($\text{Radius/thickness}$) and roll gap [11]. The influence of different bending parameters (e.g. bending radius, sheet thickness, yield strength, and Young's modulus) on springback during the roll forming process of high and ultra-high strength steels was investigated in [20]. Formulas from other researchers that estimate the springback angle in roll forming were presented. These formulas can be used for analytical prediction of springback in the roll forming process to validate the numerical simulation. It was shown that the Biswas formula gave the most realistic prediction of springback angle for the roll forming process [20].

2.2.4 End Flare

End flare is the change in the cross sectional geometry at the ends (front and rear) of a roll formed part compared to any other sections along its length. End flare of a roll formed product can be toward or away from the centerline of the section, where the flanges move at the open ends of the part. If lower strength materials are used in roll forming of shallow sections with pre-cut strips, then usually the front end is “flared-in” and the tail end is “flared-out”. However, deep sections or high strength materials usually flare out at both ends. The flare is usually higher when pre-cut strips are roll formed [11].

When a roll formed product is cut-off to two pieces after forming, the entry and exist cross sections of each piece are usually flared due to springback of the material (see Figure 2.5). Springback is mainly caused by the residual
shear stress at the edges of the formed section. When the formed section is cut-off, the release of residual shear stress leads to end flare in both pieces [11].

![Figure 2.5 Flare of cut-off ends [11].](image)

The effect of various components of stress in the formed section on end flare for a roll forming process was investigated in [21]; and it was shown that the flare for a roll formed section after cutting is due to the release of the bending and twisting moments at the end of the strip. A large flare at the end of the deformed sheet was due to release of residual shear stress in the longitudinal direction and in-plane shear stress at the edge. End flare after cutting the end of the roll formed section was explored, but the flare for the formed section before cutting was not shown.

The deformation modes and the source of common shape defects in a roll forming process were reviewed in this section. From each of the sections on defects it can be seen that material behaviour plays a strong part in the level of the defect. Moreover, the yield strength and the stress state of the material have definite effects on the final part quality. However, it does beg the question of how the final roll formed part is affected by the stress state and material properties of the material coming into the roll forming process. These incoming material properties will be hence explored in the next section.
2.3 Steel pre-processing, resulting residual stresses, and their effect on material behaviour

2.3.1 Shape deviations in as-received strips

Incoming material to a roll forming process might have some shape deviations from the steel mill production line. This deviation will need to be eliminated before the sheet can be used in the roll forming line. Either the shape deviations in the strip, or the processes that have been used in industry to eliminate the deviations, will change the material properties of virgin material. Common shape deviations in the strip and the methods to remove them will be reviewed in this section.

Local changes in the rolling plastic deformation across the width or thickness of the strip can lead to shape deviations. Moreover, when the residual stress in the material exceeds the critical buckling limit, shape deviations (waves) will happen [15]. These deviations exist in the material before it is used in the roll forming process, and the deviations are typically due to: heating or cooling in the steel mill production line; rolling of the steel; or coiling and uncoiling operations.

The strip deviations can be classified into strip flatness and strip straightness deviations. Waviness, bow shaped faults, and a non-uniform strip thickness profile are flatness deviations, while strip camber is the straightness deviation.

Strip waviness is the most common shape deviation in cold rolling and can be described via the two measurable parameters as wave height and wave length as shown in Figure 2.6.
In some cases of the edge waviness tensile and compressive strains through the strip thickness in the direction of rolling leads to opposite longitudinal residual stresses at the top and bottom side of the strip. The magnitude of these stresses is constant in the cross strip direction. This shape deviation can be removed by a simple bending process.

Existing Curve lines in the strip is another type of the waviness, which is due to plastic stretching of the longitudinal fibres that varies in intensity along the cross strip direction (Figure 2.7). The amount of this fibre stretching remains constant over the strip thickness. An uneven distribution of the residual stresses in longitudinal and transverse directions will be observed as a result of this waviness. This shape deviation cannot be eliminated by a simple bending process and the strip must be subjected to local plastic stretching across the strip width; this is done so that the shortest strip fibres will be plastically elongated to at least the length of the longer fibres [15].
Bow shape deviations can be classified as strip curvature across the strip length ("length bow" or "coil set"), strip curvature across the strip width ("cross bow"), and torsion about the longitudinal strip axis ("twist"). Coil set and cross bow are symmetrical buckling shape defects while twist (which is torsion of the strip in longitudinal direction) is asymmetric (see Figure 2.8).

Figure 2.8 Types of bow shape defects [15].

When the plastic stretching varies through the strip thickness in longitudinal direction, bow defects will arise. If the strip is in tension, then non-uniform stresses will be observed in the top and the bottom side of the strip in longitudinal direction. These stresses are constant across the strip width. When the longitudinal tension is removed, the strip will curve in longitudinal direction due to residual stresses and the shape defect known as "coil set" will be observed (Figure 2.9).
Figure 2.9 Stress distribution through the thickness of the strip due to “coil set” shape defect.

When the longitudinally curved strip is laid out in a flat plane, compressive and tensile stresses will occur in the cross strip direction, and the resulting bending moment leads to the strip buckling in cross strip direction which is called “cross bow” (see Figure 2.8).

Bow shape defects can be eliminated by plastic bending without superimposing tension [15].

Finally, a non-uniform strip thickness profile may occur in the hot rolling of the strip before the cold rolling operations in the steel mill production line. Variation of the strip thickness in the cross strip direction can lead to camber of the strip in the rolling process. Camber occurs if the thickness of the strip increases or decreases at uniform rate across the strip width during the rolling process. Non-uniform stretching of the strip fibres across the strip width is required to remove camber [15].

Various methods (i.e. temper rolling or levelling) are usually used in industry to eliminate the initial shape defects in the strip before it is used in a roll forming process; it also produces a flat strip with improved surface quality. Temper rolling (skin passing) and levelling will be summarised in the next section and the effect of these processes on material behaviour will be explored.
2.3.2 Temper rolling (skin passing) and levelling

Temper rolling is the final step in the production of cold rolled steels, and it is usually applied after the annealing process to eliminate upper and lower yield stress behaviour, yield elongation, improve sheet flatness, and to obtain a specific surface texture [22] (see Figure 2.10). In temper rolling there is a reduction in thickness by 0.5% to 3% [23-25], the material deformation is highly localised and there is a considerable springback in the strip. The contact length between the rolls and the sheet is large compared to the thickness in this process. Severe inhomogeneous deformation develops in the temper rolling process as a result of dry friction conditions and rough roll surfaces, which lead to high friction between the metal sheet and the rolls [26]. For steels without upper and lower yield stress behaviour a temper rolling or skin passing operation can be used to improve surface roughness.

![Temper rolling process](image)

**Figure 2.10** Temper rolling process.

To improve the flatness of the strip, levelling methods can also be used to stretch the strip fibres plastically to a uniform length over the strip width and equalize the strip length differences to eliminate centre or edge waviness. Roller levelling, stretch levelling, and tension levelling are commonly used for this [27]. The metal sheet is bent in alternate directions in a roller levelling operation to correct the flatness defects and make the internal stresses in the material uniform (see Figure 2.11).
In stretch levelling a tensile load is applied to the strip to produce plastic deformation, while in tension levelling a combination of longitudinal tension and bending are applied to the strip to produce plastic deformation.

The quantity of stress to achieve the identical amount of stretching is lower in the tension levelling process and there is a lower risk for material fracture. But, more inhomogeneous stresses will be observed after tension levelling due to bending stresses in the material [15]. The Stretch and tension levelling processes are shown in Figure 2.12.

A straightening capacity model was presented in [28]. Material properties and the initial shape of the incoming sheet affects the straightening capacity. It was shown that the straightening capacity is larger for a material with a higher elastic modulus, while high speed straightening and wider sheets decrease this capacity.
Severe inhomogeneous deformation occurs in the material due to temper rolling and tension levelling processes. This changes the state of residual stresses in the material [29, 30]. Residual stresses will influence the material properties of the sheet, for instance the initial yielding of the metal strip will be suppressed due to the variation of the residual stresses through the thickness [31, 32]. This change in the material properties may influence the final shape in a subsequent roll forming process. Thus, residual stresses in the material due to temper rolling or levelling will be reviewed in the following sections in more detail.

### 2.3.3 Definition of residual stress

It has been discussed in the previous section that the shape deviations introduced into the strip or the processes that are applied to eliminate those deviations often introduce residual stresses into the material. This section will present the definition of residual stress in the material.

Residual stresses are those stresses that remain in the material after the part has been removed from the constraints of the manufacturing process. The origin of residual stresses in the material can be due to many factors such as: phase transformation; differences in the cooling rate; or change in the plastic flow in the material. Residual stresses can be classified to three groups [33]

- **Macro residual stresses (type I)** - that exist in the material on the scale larger than the grain size of the material;
- **Micro residual stresses (type II)** - that vary on the scale of an individual grain;
- **Micro residual stresses (type III)** - that exist within a grain, especially due to the presence of dislocations or other crystalline defects.

Some examples of the residual stresses are shown in Figure 2.13. The residual stresses arise from misfits between different phases within a material or
different regions of a material [34]. In each case of residual stress in this figure, the process is shown on the left, the misfit in the center, and the resulting residual stress pattern on the right. The Macro residual stresses, type I, are important for the material properties of sheet, and their effect on roll forming will be discussed later in this thesis.

![Figure 2.13](image) Different types of macro and micro residual stresses [34].

Residual stress in the material can be divided to two components as flexural (bending) and membrane residual stresses (Figure 2.14).

![Figure 2.14](image) Definition of flexural and membrane residual stresses [35].

Early yielding at the surfaces of cold-rolled steel members is due to dominant flexural (bending) residual stresses through the thickness. The magnitude of flexural residual stresses are more than the membrane residual stresses in cold-formed sections, but the membrane residual stresses are more prevalent in roll-formed sections compared to the press-braked ones [35].
2.3.4 Residual stresses due to temper rolling and levelling

Both temper rolling (skin passing) and levelling processes will change the state of residual stresses in the material. Variation of residual stresses in the strip due to temper rolling and levelling will be reviewed in this section.

First considering skin passing, a rolling operation is used in the low strain skin passing process, which leads to heavy deformation (compression) at the surfaces and less deformation in the mild-thickness of the strip. A compressive residual stress at the strip surface in a low strain skin passing process was observed using experimental measurement in [29, 31, 36], while Hundy et al. [29] discussed that it only occurs under certain conditions of forming and in some cases a tensile residual stress may be observed at the strip surface due to a low strain skin passing process. Material properties of the strip, dimension of the rolls, and friction between the rolls and the strip could affect the surface residual stress.

At higher strains, the presence of crossing Lüders bands from the top and bottom surfaces causes more work in the middle of the strip (between the top and bottom surfaces) compared to the surfaces. Thus, tensile stress will be observed at the surface and compression at the mid-plane. Residual stresses through the thickness of a mild steel strip, thickness of 1.27 mm, due to a light rolling process, were measured experimentally in [29]. Skin passing is a light rolling process and the measurement from [29] may represent the residual stress profile after skin passing of a metal sheet. The through thickness distribution of residual stresses due to a 6% thickness reduction is shown in Figure 2.15. This figure shows that tensile residual stress exists at the strip surface while the mid-plane undergoes a compressive residual stress. It was explored in [29, 31, 36] that an increase in the level of thickness reduction in the skin passing process leads to a higher tensile residual stress at the surface of the strip, while Hundy et al. [29] also discussed that surface residual stress
may decrease as the thickness reduction increases. They presented similar studies in which residual stress at the surface decreased with an increase in the thickness reduction level. The residual stress at surface, therefore, depends on the rolling conditions and the strip material properties.

Figure 2.15 Residual stress distribution for a 6% thickness reduced mild steel. The total level of extension is considerably higher than a typical skin passing process [29]. Distribution of residual stresses through the thickness of material after a skin passing process was predicted using a numerical model in [6, 7]. Stainless steel and aluminum strips were modelled and the residual stresses were recorded after one or two-step thickness reduction rolling operations. The residual stresses were lower in the material after a two-step skin passing operation compared to the one with the same level of thickness reduction in one step. Only numerical results were shown for the variation of residual stress through the thickness, and the paper did not provide any experimental verification. It was shown that even a very low strain skin passing operation, 0.5% thickness reduction, led to tensile residual stress at the strip surface. This is in contrast with the experimental data in the literature for residual stress measurement after a low strain skin passing process [29, 31, 36]. The discrepancy in the surface residual stress after a low strain skin passing operation could be due to using different materials or various rolling conditions, but this is yet to be investigated.
Now let us consider a tension levelling process. Residual stresses due to tension levelling of recovery annealed steels were measured in [31]. In a tension levelling operation, bending strains lead to higher strain values at the strip surface (plastic deformation) compared to the mid-plane (elastic deformation). Compressive residual stresses are observed at the surface, while tensile residual stresses occur at the mid-plane. Thus the main difference between tension levelling and skin passing is that the mid-plane is in tension rather than compression, while the surfaces are in compression rather than tension. In both cases, the residual stress profile is symmetric about the strip mid-plane.

The purpose of tension levelling is again to eliminate the non-uniform elongation of the strip across the width and thus eliminate the existing residual stresses due to shape defects. An analytical model was presented in [30] to predict residual stresses at the surfaces of a sheet after tension levelling. It was hypothesised that tension levelling reduces the residual stresses in the material if an initial stress distribution exists at the sheet surface. It was previously discussed that the experimental measurements of [31] showed that the maximum residual stress using tension levelling occurred at the strip mid-thickness, and an increase in the tension leveller extension (more plastic deformation in the material) led to higher tensile residual stress in the recovery annealed steel. Although tension levelling reduces the magnitude of residual stresses at the strip surface in a sheet that has some residual stresses due to shape defects [30], to the author’s knowledge, the distribution of residual stresses through the thickness of the sheet has not been fully determined. That is, it has not been investigated how the residual stress at the mid-thickness plane of the sheet changes due to tension levelling. The following questions are still open with regard to tension levelling. Does a tension levelling process also reduce the magnitude of
residual stress in mid-thickness? Or does it depend on the distribution of residual stresses in the sheet before tension levelling?

Let us now consider a roller levelling process. Roller levelling reduces the magnitude of residual stresses in the metal sheet [37-39]. Residual stresses through the thickness and in width direction of the sheet due to a roller levelling process were predicted using a mechanics model in [39]. A comparison between various initial residual stresses in the sheet and the output residual stress after roller levelling showed that residual stresses were reduced significantly due to the roller levelling process. Experimental results from the literature were used to verify the model.

A finite element model was presented in [40] to predict the distribution of residual stresses through the thickness of the strip after a roller levelling operation. Experimental measurement of residual stresses was also applied to verify the numerical results. Figure 2.16 shows the experimentally measured residual stresses through the thickness of the strip before and after a roller levelling process, along with the residual stress distribution from the finite element simulation. The yield stress of the material was $368 \text{ Mpa}$.

![Figure 2.16](image)

Figure 2.16 Experimental and numerical distribution of the residual stresses through the thickness of the strip due to a roller levelling process [40].
It is shown in Figure 2.16 that a roller levelling operation reduces the magnitude of residual stresses in the material. However, one cannot see a considerable reduction in the residual stress (especially in the maximum tensile residual stress). Another study on finite element simulation of a roller levelling process showed that levelling can lead to the introduction of residual stresses in a sheet that did not have any initial residual stress [41]. Experimental verification was not explored, but it begs the question whether a levelling operation should only be used when there is a considerable amount of residual stresses in the material? Additionally to that does the roller levelling process reduce residual stress in incoming material sufficiently to eliminate the effect on final shape in roll formed sections?

It was discussed in this section that a skin passing operation leads to a complex strain distribution in the metal sheet, which in turn creates a residual stress profile through the material thickness. The variation of residual stresses through the thickness depends on various conditions, such as: the amount of thickness reduction, rolling condition, and material properties. Tensile residual stress is usually observed at the surface of the sheet due to skin passing and the magnitude of residual stress rises with an increase in the thickness reduction level, however contrary results have been observed for certain conditions. Although levelling is designed to reduce the magnitude of residual stresses in the material, to the author’s knowledge it appears to be an open problem regarding the amount of residual stress reduction this process provides.

There are many parameters (such as material properties, rolling conditions, level of plastic deformation, and the magnitude of existing residual stresses in the material due to shape defects) that can affect the state of residual stresses after skin passing or levelling of the material. **Thus, it is clear that effects of pre-processing operations on the residual stress state must be understood.**
The next question is what effect does residual stress have on forming? Bending is the major deformation mode in roll forming, so the effect of residual stresses on bending and roll forming will be reviewed in the next few sections.

### 2.3.5 Effect of residual stresses in bending

Bending is a process that creates a strain gradient through the thickness of the bent sheet or plate. This strain gradient ensures that the largest strains are on the outer surfaces. This implies that bending may be very sensitive to variations in the state of material from the outer surface to the mid-core of the sheet or plate. *Duncan* suggested that to observe the effect of residual stresses in a bend test, the device should be able to clearly capture the material behaviour in elastic-plastic transition [42]. There are two bending devices that were especially designed to capture material behaviour close to yield for roll forming applications [42, 43]. The first one was designed by *Duncan et al.* [42]. Although using the introduced device made it possible to capture the material properties close to yield, the effect of residual stresses in the material was not investigated.

*Scott* [31] used the bend tester of [42] to show the effect of residual stresses in bending of high strength recovery annealed steels. Skin passing and tension levelling were used to introduce residual stresses in the material and then the strips were analysed using the bend test. It was shown that both skin passing and tension levelling processes reduce the bending yield strength of the material. The experimental arrangement of the bending device only allowed bending of very thin strips, thus *Weiss et al.* [43] introduced a new bend tester that was able to bend thicker materials for roll forming applications. Using the developed bend tester of [43], the effect of residual stresses due to skin passing on the material behaviour of stainless steel strips in a pure bend test was explored in [7]. It was shown that the residual stress profile has a significant effect on the elastic bending limit. Residual stresses in the material
reduced the elastic bending limit, which is in agreement with [31], and a two-step skin passing operation had higher elastic bending limit compared to the one step skin passing process. It should be noted that only the moment-curvature curves from 2D plane stress numerical simulations were shown. The experimental verification of these results was not investigated.

The same bending operation of [7] was used in [38] to show the effect of roller levelling and skin passing on bending response of aged steel strips. It was determined that the bend test can clearly detect a reduction in the yield strength of skin passed strips compared to a tensile test. The authors concluded that residual stresses in the material due to skin passing were the reason for observing various yield transition points in the experimental bend test. However, the change of the residual stress profile through the thickness was not validated experimentally.

The most comprehensive study on the effect of residual stresses in the material using a bend test was performed by Weiss et al. [6]. The effect of residual stresses in the material due to skin passing on tensile and bending behaviour of aluminium was explored. Moment-curvature data was recorded in the bend test using skin passed and non-skin passed strips. Material softening and a reduction in the offset yield stress in the bend test were detected, which is in agreement with the observation from previous studies in [7, 31, 38]. The normalised through the thickness residual stress profiles due to the skin passing operation, obtained from numerical simulation, and the related experimental moment–curvature diagrams in the bend test for various thickness reduction levels are shown in Figure 2.17.
The authors concluded from the Figure 2.17 that residual stresses in the material suppress the yield strength in the bend test. Only finite element results were provided for residual stress profiles through the material thickness and experimental verification was not shown. When a strip undergoes a skin passing process, plastic deformation occurs in the material that changes the yield strength of the strip in the bend test due to strain hardening. Since residual stresses are always accompanied with strain hardening in a cold forming operation, the combined effect of residual stress and plastic deformation should be considered in FEA to take into account the effect of skin passing on bending. Although it was discussed in [6, 7, 31, 38] that early yielding in the bend test of skin passed strips was due to the existence of residual stresses in the material, decoupling the effect of residual stress on the yield strength from the effect of strain hardening due to the skin passing operation was not investigated. To the author’s knowledge, it is not clear whether changes in moment–curvature curves after various levels of skin passing (seen in Figure 2.17.b) are only due to residual stresses, or the effect of other parameters, such as accumulated plastic strain. Moreover, it was not identified how the variation of residual stresses through the thickness changes the slope of elastic-plastic transition in the moment–curvature curves. Is it possible to observe the same results by reducing the yield strength in the material model in FEA? Or is a residual stress profile needed to capture
the exact slope of transition from elastic to plastic region for skin passed strips?

A good agreement was presented between the moment–curvature curves predicted by FEA and the experimental result for the initial annealed material in [6], but a considerable discrepancy was detected between the FEA and experimental moment–curvature data for the skin passed strips. It was shown that the FEA results always over-predicted the moment resistance close to the elastic-plastic transition. A simple 2D plane stress model was used in numerical simulation, while the material deformation is plane strain in a skin passing process. Additionally, it was not investigated whether the bend test was actually plane stress and using a 3D material model may improve the accuracy of the obtained results. Both the FEA and experimental results showed early yielding in the bend test of skin passed strips, but the FEA predictions are far from the experimental results. Furthermore, a systematic approach was not applied to emphasise the effect of residual stresses from other parameters in the material.

Therefore, it is obvious that the following questions must be answered:

- **Does the existence of residual stress in the material only change the yield transition point in a bend test or it does also affect the material behaviour at higher strain values?**
- **What is the effect of residual stresses in a bend test without the influence of other material/process parameters?** That is, can the residual stress effect be uncoupled from other effects?
- **How can a material model in FEA be created to capture the bending response of skin passed strips in the experiment?**

Material deformation at the flange in a roll forming process is close to the yield point and any changes in material behaviour in the elastic-plastic transition
may vary the final shape in roll forming. Particularly because the yield point has a strong influence on the springback, bow and camber. This will be further explored in the next section.

### 2.3.6 Effect of residual stresses in roll forming

In a roll forming process the amount of strain in the areas far from the bending zone, point $B$ in Figure 2.18, is low (generally around 1% [5]), and a high amount of strain (20% [44]) exists in the bending zones, point $A$ in Figure 2.18. The shape defects in roll forming are often due to very small plastic strains at the flange in the longitudinal direction. Figure 2.18 shows that the variation of the longitudinal strain at the edge in a roll forming process is close to elastic limit of the material. Moreover, some shape defects in a roll forming process are due to variation of small longitudinal strains across the strip width. For this reason the material behaviour close to yield is important.

![Figure 2.18](image) Variation of the longitudinal strain at the edge of the strip in a roll forming process.

The previous section showed that residual stress in the material changes the material behaviour close to yield in a bend test. Roll forming is an incremental bending operation, so early yielding at the flange due to residual stresses may
have a significant effect on flange based-defects in the roll formed parts, such as bow. The effect of residual stresses therefore needs to be properly understood. Given the effect of residual stresses in a bend test, the authors of [6] concluded that a difference in the skin passing regime of two identical steel grades will lead to differing defect levels in the roll forming process. Even though the two materials have the same composition and overall thickness with the same general tensile properties.

Coiling-uncoiling and flattening of the metal sheet before roll forming introduces some residual stresses into the material. An analytical approach was presented in [45] to investigate the effect of coiling-uncoiling on the final residual stress distribution through the thickness of a roll formed section. An elastic-perfect plastic material model was considered and the strain hardening was neglected. Plane strain behaviour was assumed during coiling-uncoiling and cross sectional roll forming while considering a 3D material model may change the obtained results. The radial location of the sheet in the coil must be known to apply this approach for residual stress prediction, but this parameter is not always recognised in an incoming material for a roll forming process. Moreover, experimental verification was not shown to evaluate the relationship between the coil radius and the residual stresses though the thickness of the sheet.

Oil canning (pocket wave) and edge ripple are two kinds of shape defects in a roll forming process that can develop at extremely low plastic strains [31, 46, 47]. These defects are due to strain localisation at certain points of the strip width (Figure 2.19). There are many parameters in a roll forming process that can create strain localisation in the material leading to oil canning or edge ripple. Existence of initial residual stresses in the material is one of those parameters that should be considered in a roll forming process. Scott [31] related the observation of oil canning in a roll forming process to initial residual stresses in the material, but Hira et al. [47] showed that oil canning
will happen in a cold roll forming process when the ratio of width to thickness of web is bigger than 300. To the author's knowledge, it is not recognised that if residual stresses in the material are the only reason for the observation of oil canning or a combined effect of various parameters in a roll forming process, such as the material behaviour, cross sectional geometry, flower design, or the distance between stations.

![Figure 2.19](image)

**Figure 2.19** Shape defects at low plastic strains (a) oil canning (b) edge ripple [31].

The effect of mechanical properties, chemical compositions and the levelling process of steel sheets on oil canning was investigated in [47]. It was shown that a decrease in the elastic limit of the high carbon steels due to levelling leads to an increase in the magnitude of oil canning in the experiment. Neither an analytical nor a numerical model was presented to clearly understand the effect of residual stresses due to levelling on oil canning. Levelling is usually used to decrease residual stresses in the material [30, 39], and a reduction in residual stresses in the material would lead to an increase in the elastic limit [38]. However, the theory developed in [23, 34] is in contradiction to the experimental results from [42]. To the author's knowledge, it has not been identified whether the magnitude of oil canning after the levelling of the sheet increases only in the high carbon steels (that show ageing)? Or whether
levelled sheets without ageing also see increases in the magnitude of oil canning?

A summary of various studies on the effect of low level of plastic strain in roll forming on oil canning was presented in [31]. It was concluded that the small plastic behaviour of the material should be included in the investigation of material properties for a roll forming process. A discussion was presented based on the BHP steel internal research report that showed an increase in peak tensile residual stress through the thickness of the sheet due to tension levelling. This led to higher oil canning and edge ripple severity in roll forming. Moreover, this observation is in agreement with the results of [47] that showed levelling leads to an increase in the magnitude of oil canning. However, neither a numerical nor an experimental investigation was performed to decouple the effect of residual stresses on final product quality from other parameters in the roll forming process. In contrast, it was also pointed out in [31] that experimental work in Germany showed that a decrease in the thickness reduction level in a skin passing process increased the elastic limit of recrystallised steel, and through that reduced oil canning. However, these experimental results did not investigate the residual stresses in the sheet.

The Effect of tensile flow properties, grain size, and manufacturing conditions on the magnitude of oil canning in roll forming of commercially pure titanium sheets was also investigated experimentally in [46]. Thin strips, thickness of 0.3 to 0.8 mm, were used in the experiments. It was shown that grain size is the most correlative parameter to oil canning. A sharp yield drop, due to strain ageing, in the stress–strain curve of the fine-grained titanium sheets led to the prevention of oil canning. It was suggested that the skin passing operation removes the sharp yield drop in the material, and this increases the magnitude of oil canning significantly. The increase in the magnitude of oil canning due to the removal of the sharp yield drop after skin passing is in agreement with the
observations made in [47]. Those showed that eliminating the ageing effect of high carbon steels due to levelling increases the level of oil canning. It was further hypothesized that a decrease in the elastic limit of the material, or the decrease in the ratio of the elastic limit to the 0.2% proof strength, increases the magnitude of oil canning. However, to the author’s knowledge, it is not recognized how the observation of oil canning will be changed if a sharp yield drop does not exist in the stress-strain curve of the material before skin passing.

Now the effect of the roll forming process itself on the residual stress state of the sheet material will be discussed. A roll forming process changes the state of residual stress in the material. Some researchers studied the variation of residual stresses in the final product after roll forming [48, 49]. A finite element simulation of a roll forming process was carried out using COPRA-FEA in [48] to show the variation of residual stresses in a roll formed section. Only FEA results were shown and the residual stresses in the material before roll forming were not included in numerical simulation. It must have been assumed that the incoming sheet was residual stress free.

A Roll forming simulation of an upright section (a typical rack section) was performed using COPRA-FEA in [49] and the obtained residual elastic and plastic strains were applied as an initial condition to analyse the load capacity of a column with an upright cross section. Although only residual stresses due to roll forming were considered in the FEA, the FEA model predicted the load capacity of the column with a reasonable accuracy. However, the incoming material may have had some material imperfections, and these potential defects should also have been included in the FEA model. For instance a residual stress profile may have existed through the thickness of the sheet before roll forming and including this information may change the stress and the strain distribution in the roll-formed product. Thus, the material imperfections in the sheet prior to roll forming were neglected in [49].
In summary of this section, although the initial residual stress profile causes a change in the material behaviour close to yield, based on author’s knowledge, it is not known in detail what effect initial residual stress profiles have on the final roll formed product. Furthermore, how can this be decoupled from the manufacturing conditions or the process parameters.

Therefore, the following questions must be addressed:

- **How can the effect of initial residual stresses in the material be deeply investigated independent from other parameters in a roll forming process?**
- **What is the effect of initial residual stress in the incoming material on final roll formed product geometry?**

Finite element simulation combined with experimental verification will be used in this thesis to address above questions. The development of a reliable numerical model of a roll forming process is the first step to understand the effect of residual stresses. This will be discussed in the next sub-section.

### 2.3.6.1 Numerical investigation of the effect of residual stresses in roll forming

A reliable roll forming model is necessary to understand the effect of an initial residual stress. In the past various software programs have been applied by other researchers to simulate a roll forming process and experimental validation has been used to verify the FEA results. Previous finite element studies to simulate a roll forming process are briefly reviewed in Appendix A.

Most of the previous researchers in roll forming used solid or shell elements to simulate the sheet, and only some of them validated their work with experimental data. The aim of most previous studies in finite element simulation of a roll forming process was deeper understanding of the material deformation during roll forming, and achieving a reliable mode configuration that can represent the complex stress
and strain state in this process. This knowledge from using FEA can be applied to optimise the design process and prevent unexpected defects [19, 50-72]. The Effect of main process parameters such as roll gap, line velocity, material properties, and inter distance of the rolls on the final product of the roll forming process was investigated by [73-84]. Other researchers used FEA to simulate a roll forming process and investigate the post-forming properties on the final product behaviour. For instance the load capacity of a column formed by roll forming was explored in [48, 49].

To show the reliability of a roll forming model, some researchers only used experimental data found in the literature to validate their simulations [48, 56, 61, 63, 75, 76]. Others applied only one or two output results for validation [51, 53, 54, 59, 60, 65]. Roll forming is a complex forming operation, and to insure that the numerical model is reliable, a detailed output, such as the longitudinal strain on the flange, and a large geometry output, such as springback or bow should be investigated.

The aim of the investigation on previous finite element studies in this thesis is to explore whether previous models included the effect of pre-existing residual stresses in a roll forming simulation. Secondly, how reliable is such a model that does include residual stresses. Based on the author’s knowledge from reviewing the literature, none of the previous studies investigated the effect of a residual stress on a roll forming process. This begs the question what should be considered when developing a finite element simulation of roll forming that also accounts for residual stress.

Section 2.3.4 showed that the initial residual stress in a sheet due to steel mill processing varies through the thickness, and there is a nonlinear residual stress profile through the thickness of the sheet. Thus, a numerical roll forming model should have the capability of changing residual stresses through the thickness to explore the effect of pre-existing residual stresses on final shape in roll forming.
Solid elements were used by many researchers to discretize the sheet. The advantage of using solid elements is that no kinematic relations in rotational degree of freedom are needed, and a three dimensional stress-strain state can be obtained automatically with a three dimensional material model. However, when solid elements are used in simulation of shell like structures, locking in the element is a serious issue as a result of bending. Furthermore, it is not possible to include the variation of residual stresses through the material thickness by using only one [48-50, 54, 57, 64, 68, 73, 76-78, 80, 83] or two [66] solid elements in the thickness direction. Four layers of solid elements were used in [55] to simulate the sheet, and the sheet was modelled using three layers of solid elements in [65, 67]. Although using multilayers of elements through the thickness can make it possible to include a residual stress profile in the sheet, the effect of residual stresses has not been investigated. Moreover, using only three or four layers of elements may not be sufficient to capture the nonlinear variation of residual stresses through the material thickness and using many elements through the thickness will increase the calculation time in numerical simulation.

Shell elements have been used commonly for simulation of shell like structures to reduce calculation time. Shell element with multiple integration points through the thickness were applied to simulate the sheet in a roll forming model in [19, 52, 58, 61, 69, 70, 74, 79, 81, 84]. Those models may have the potential of implementing a residual stress profile in the model using various integration points through the material thickness, but currently this has not been investigated.

To use the advantage of both shell and solid elements in a sheet metal forming simulations, much effort has been made to develop solid-shell elements. Solid-shell elements have the 3D structure of a solid element, but locking is prevented in a solid-shell element by applying various remedies such as penalty scaling, local and global constrain reduction, and local enhanced methods (this will be discussed more in Chapter 3). Solid-shell elements were
used in [62, 63, 72] to simulate the sheet in a roll forming model. Then again, the effect of residual stresses were not investigated in those studies. The particular advantages and disadvantages of various element types will be discussed in detail in Chapter 3 when an appropriate element type will be selected for the numerical simulation of a roll forming process for this thesis.

It is clear that to numerically show the effect of residual stresses in a roll forming process, the question below must be answered:

- **What is an appropriate element type to simulate the sheet in numerical modelling of a roll forming process with the capability of including an initial residual stress profile in the material?**

Development of a reliable roll forming model with the capability of including a pre-existing residual stress profile in the material will be presented in Chapter 3. However, detailed information with regard to the residual stress profile is needed to include the effect of residual stress in a roll forming model. Available methods to acquire the residual stress information will be reviewed in the next section.

### 2.4 Obtaining residual stress information of incoming sheet

Analytical and finite element approaches can be used to obtain the residual stress profile. Therefore, the next sub-section will present a literature review on the previous analytical and finite element methods that have been used by other researchers to predict residual stresses in the cold-formed sections. The aim is to explore whether a similar approach can be used in this thesis.

#### 2.4.1 Analytical and finite element approaches to predict residual stresses in the material

The manufacturing process has a significant effect on structural behaviour and strength of cold-formed sections. So, to predict residual stresses in cold formed members, their manufacturing process should be directly modeled.
Section 2.3 already outlined the effect of steel processing on residual stress in produced steel strip.

First, the residual stress profile through the thickness of sheet that has been coiled and uncoiled will be reviewed. The residual stress in carbon steels due to the coiling and uncoiling process before cold forming the steel sheet into a section was predicted analytically in [8]. The coiling-uncoiling process was modeled as an elastic-plastic plane strain pure bending problem; and the von Mises yield criteria combined with the Prandtl-Reuss flow rule were used to model the material behavior. It was shown that the residual stress due to coiling-uncoiling is dependent on two parameters: the yield stress of the material; and the coil diameter to sheet thickness ratio. Finite element analysis was also used to validate the obtained analytical results. 24 layers of 2D plane strain elements were applied in Abaqus to capture the through-thickness profile of stress in a sheet of 2 mm thickness. Both the analytical and the finite element results showed that the profile of the through-thickness residual stress is non-linear, and that the residual stress is sensitive to the coiling curvature and the steel yield stress.

A finite element method to predict residual stresses in press-braked thin wall sections was presented in [9]. It was shown that maximum residual stress in press-braked sections will occur in the corner region away from surface and that its value can be far higher than those at the surfaces. The longitudinal and transverse residual stresses along with the equivalent plastic strain due to coiling-uncoiling were calculated by analytical methods and used as initial conditions for the press-braking analysis to predict the final residual stresses. It was shown that in press-braked sections the coiling diameter does not have any effect on the final press-braked part’s residual stress in the corner regions, but that the initial residual stress due to uncoiling did remain in the flat areas of the formed part.
The method which was presented in [8, 9] for the prediction of residual stress in carbon steel sheets was based on material isotropy and elastic-perfectly plastic material behaviour and cannot be used for stainless steel materials with anisotropy and strain hardening behaviour. An analytical method to predict the residual stress and co-existing equivalent plastic strain in press-braked stainless steel sections was presented in [85, 86]. The coiling, uncoiling and flattening was modelled as a pure inelastic bending process. Hill’s anisotropic yield criterion with isotropic hardening was used to consider anisotropy and nonlinear stress-strain behaviour in the material.

The final stress and strain fields from a cold forming process are needed as an initial configuration for the non-linear finite element modelling of a subsequent forming step. The analytical solutions to predict residual stresses and equivalent plastic strains in carbon and stainless steel sections [8, 9, 85, 86] were implemented to an advanced finite element simulation to explore the effect of cold-working on column behaviour in [87]. The equivalent plastic strain represents the strain hardening effect due to cold work, and this has a positive effect on the load capacity of final product. Whereas the residual stresses usually have a negative effect on the load capacity. Two user subroutines were implemented in Abaqus to predict the residual stresses and equivalent plastic strains. The finite element model used shell elements with 17 integration points through the thickness.

In the research work reviewed above the analytical methods to predict residual stress in cold-formed members were applied to press-braked sections. Residual stress and effective plastic strain due to a roll forming process were predicted in [45]. The flat and corner surface strain measurements of some roll-formed specimens were also used to evaluate the accuracy of the prediction method. Two manufacturing processes - sheet coiling-uncoiling-flattening and cross sectional roll forming - were considered as the sources of through-thickness residual stresses in the corners and flat
2.4 Obtaining residual stress information of incoming sheet areas. The through-thickness longitudinal residual stress distribution due to coiling, uncoiling, and flattening is shown in Figure 2.20.a, while Figure 2.20.b shows the nonlinear through-thickness residual stress distribution due to cold-forming of a metal sheet.

![Figure 2.20](image)

**Figure 2.20** a) longitudinal residual stress distribution due to coiling, uncoiling, and flattening of a steel sheet  
 b) nonlinear through-thickness residual stress distribution due to cold-forming of a metal sheet [45].

It was shown in [45] that both longitudinal and transverse residual stresses will occur in coiling-uncoiling and cross sectional roll forming processes.

Now, we shall move the discussion onto modelling residual stresses in levelling and temper rolling. Finite element simulation was used in [88] to show the distribution of residual stresses at the surface of the strip due to tension levelling. It was determined that the distribution of stresses across the width is uneven and a 3D analysis should be used instead of implementing a 2D simulation model. Shell elements were used to simulate the sheet in the 3D
simulation, however, the distribution of residual stresses through the thickness of the sheet was not investigated. An analytical model [30] and finite element simulation [27, 30] were also applied by other researchers to predict the evolution of residual stress at the surface of the sheet due to a tension levelling operation.

A finite element simulation of roller levelling process was developed in [40] to predict residual stresses through the thickness of the sheet. Contact treatment between the sheet and the rolls as well as springback were considered using an elastic-plastic large deformation model. The results of a case study in [40] to capture the distribution of residual stresses in the sheet due to a roller levelling operation was previously shown in Section 2.3.4 (Figure 2.16).

The Effect of the material hardening model on the explanation of the final residual stresses in the material after the roller levelling process was investigated in [41]. It was shown that a pure isotropic hardening material model predicts higher residual stresses in the material after the levelling process compared to a combined hardening material model. This result appears logical as the bending and unbending that occurs during the roller levelling process, and would lead to reduced final stress levels when using combined hardening. Nevertheless, verification of the numerical results was not performed.

Various analytical approaches to determine the distribution of residual stresses through the thickness of a sheet due to a rolling process were presented in [89]. The typical rolling process applies a heavy thickness reduction, while temper rolling or skin passing applies a very low thickness reduction. A simplified approach was also presented to predict the longitudinal residual stresses after a low thickness reduction rolling. The distribution of residual stresses through the thickness of sheet material for a low thickness reduction in the rolling process, 8%, was shown. Although this
amount of thickness reduction is still higher than a typical skin passing process, the distribution of residual stresses through the thickness are in agreement with the residual stress pattern after a skin passing operation that was discussed in Section 2.3.4. The longitudinal residual stress can be obtained from:

\[ \sigma_{11} = \frac{E}{1 - \nu^2} \frac{(l_f - l_p)}{l_p}, \]  

(2.1)

where

\[ l_f = \frac{h}{2 \int_0^1 \frac{1}{l_p} dx}, \]  

(2.2)

and

\[ l_p = \sqrt{F_p^T F_p i_1 . i_1}. \]  

(2.3)

In the above equations \( \sigma_{11} \) is the longitudinal residual stress, \( E \) the elastic modulus, \( \nu \) the Poisson’s ratio, \( l_f \) the common length of fibres, \( l_p \) the plastic part of length of a fibre, \( h \) thickness of the strip, \( F_p \) the plastic part of the deformation gradient, and \( i_1 \) is the unit vector.

Thus, the analytical equations of [89] can be used if the residual stress information due to temper rolling of a sheet is needed. However, there is a serious concern when using an analytical or a finite element method for the prediction of residual stresses in the material: detailed information about the source of residual stress must be known, and this information is not usually available for the incoming material in a roll forming process.

Therefore, the following question must be answered:

- **Given no knowledge of pre-processing conditions, how can residual stress information be obtained for incoming steel material?**
The Measurement of residual stresses in the material can be used to answer the above question. Standard methods to measure residual stresses in the material will be reviewed in the next section.

### 2.4.2 Residual stress measurement

The residual stress prediction in structures were limited for many years because of the lack of numerical methods and powerful computers to solve the detailed equations. Using modern computers and advanced analytical methods have solved these problems, but the pre-processing data by which residual stresses were generated is not usually available, that is one of the reasons that the prediction of residual stresses in the material is still problematic.

In most experimental studies to measure the residual stress in a material, only residual surface stresses were measured due to the small plate thickness of the sample material, and the variation of residual stress was considered linear across the thickness. Residual stress measurements performed on thicker plate however show that the residual stress profile varies across the thickness in a complex manner [90, 91], and a nonlinear through thickness residual stress will be observed as a result of springback after plastic deformation of the metal sheet.

Residual stress measurement has been widely used to consider the effect of residual stresses in the design process of final product, tooling, and machineries in various industries. Most of the previous researchers did post forming measurements of residual stress in final products, while the some others measured residual stresses in the incoming material (this will be further discussed in Section 2.4.2.3). Many destructive and non-destructive methods to measure residual stress were presented in [33]. These methods will be briefly reviewed in the next sub-section.
2.4 Obtaining residual stress information of incoming sheet

2.4.2.1 Destructive methods

The most common destructive techniques to measure residual stresses in metal sheet are the:

- Hole-drilling method;
- Ring core technique;
- Bending deflection method; and
- Sectioning method.

In the hole drilling method a small hole (1-4 mm in diameter) is drilled and the resulting surface strains in the material around the outside of the hole measured. The same approach is used in the ring core method by drilling a ring hole with 5-150 mm diameter. Advances in the measurement and analytical equations of the hole drilling method for residual stress measurement were reviewed in [92].

The Bending deflection and sectioning (curvature and layer removal) techniques can also be applied to measure residual stresses in samples with a simple geometry. The curvature in the layer that has been removed is related to the residual stresses and mechanical properties of the material. The residual stresses in each layer can be obtained by curvature measurement of that layer [33].

The sectioning method is based on the fact that internal stresses are relieved when cutting the sample into many strips with smaller cross sections. This method is considered the most accurate if it is applied on samples that only have residual stresses in longitudinal direction. Longitudinal stresses can be obtained by slitting longitudinal strips from the specimen and measuring their change in length [93].
The destructive methods are usually time consuming, expensive and with limited accuracy. So, non-destructive techniques have been increasingly used in recent years. The next section will review those methods.

### 2.4.2.2 Non-destructive methods

Non-destructive methods to measure residual stresses in the material are based on the relationship between the physical and crystallographic parameters in the material. The most common non-destructive methods to measure residual stresses in the material are:

- **X-ray, synchrotron, and neutron diffraction methods**: diffraction methods are based on determining the elastic deformation, which changes the interplanar spacing of the material from the stress free value.
- **Magnetic methods**: are based on the interaction between magnetization and elastic strain in ferromagnetic materials.
- **Ultrasonic techniques**: are based on the variation of ultrasonic wave propagation in the materials due to the change in mechanical stresses.

X-ray diffraction (XRD) is the most common non-destructive method to measure residual stresses in a material. The XRD method for residual stress measurement has been proposed by Lester and Aborn in 1925 and was compared to the other mechanical methods by Sachs and Weerts in 1930 [94]. This method is based on the fact that residual stresses in the crystalline material change their interplanar spacing. The XRD method can be used to measure residual stresses at the surface of the material, but the internal residual stress levels can only be obtain by a combination of XRD and layer-removal. The layer removal technique for residual stress measurement was explained in [95].
A review on using X-ray to measure residual stresses in the material was presented in [96]. The limitation of the sample geometry is a disadvantage of using XRD method. The geometry has to be such that the X-ray is still deflected to the detector after hitting the measurement area without hitting any barriers. Some limitations of laboratory based X-ray technique have been overcome by the rapid development of third generation synchrotron sources. High intensity and high culmination of the beam and fast data recording rates for samples with various thicknesses from millimetre to micron size are some advantages of using synchrotron beams [97].

The neutron diffraction method is based on elastic deformation within a polycrystalline material that changes their stress-free conditions. The high penetration depth is the major advantage of this method compared to X-ray diffraction. While X-ray is limited to depths of 5 μm the depth measurable in neutron diffraction techniques is 50 mm [97, 98]. Using neutron diffraction technique to measure residual stresses in the material was summarized in [97].

In the using ultrasonic wave technique waves are launched by a transmitting transducer, and these waves propagate through the region of the material and are detected by a receiving transducer. The propagation of ultrasonic waves in the material will be changed due to the residual stress variation [99]. Some advantages of using the ultrasonic technique compared to X-ray diffraction include: a deeper layer can be measured; it is quick to setup and easy to use; it is portable, inexpensive and free from radiation risk. Residual stress only leads to a small change in wave propagation which is why the ultrasonic equipment needs to have a very high resolution, be reliable and computerized to provide a trustworthy measurement.

There are some other non-destructive techniques to measure residual stresses. These techniques are dependent on the influence of stress on
conductivity (eddy currents) [100], or Raman excitations [101]. These methods have some limitations as poor spatial resolution and very low penetration depths and are not commonly used.

### 2.4.2.3 Deciding on an appropriate technique to measure residual stress

A schematic indicative of approximate capabilities of various destructive and non-destructive techniques to measure residual stress in sheet material are shown in Figure 2.21. The destructive techniques are shaded gray. It is shown in this figure that the achievable depth for residual stress measurement and spatial resolution depends the technique chosen.

![Figure 2.21 Schematic of approximate capabilities of various techniques to measure residual stresses. The destructive techniques are shaded gray [98].](image)

The various methods used for residual stress measurement and recent advances in this field were reviewed in [102]. The advantages and disadvantages of using each method for residual stress measurement are shown in Table 2.1.
### Table 2.1: A comparison between various residual stress measurement techniques [102].

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray diffraction</td>
<td>Ductile</td>
<td>Lab-based systems</td>
</tr>
<tr>
<td></td>
<td>Generally available</td>
<td>Small components</td>
</tr>
<tr>
<td></td>
<td>Wide range of materials</td>
<td>Only basic measurements</td>
</tr>
<tr>
<td></td>
<td>Hand-held systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macro and Micro RS</td>
<td></td>
</tr>
<tr>
<td>Hole Drilling</td>
<td>Fast</td>
<td>Interpretation of data</td>
</tr>
<tr>
<td></td>
<td>Easy use</td>
<td>Semi destructive</td>
</tr>
<tr>
<td></td>
<td>Generally available</td>
<td>Limited strain sensitivity and resolution</td>
</tr>
<tr>
<td></td>
<td>Hand-held</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wide range of materials</td>
<td></td>
</tr>
<tr>
<td>Neutron Diffraction</td>
<td>Macro and Micro RS</td>
<td>Only specialist facility</td>
</tr>
<tr>
<td></td>
<td>Optimal penetration and resolution</td>
<td>Lab-based system</td>
</tr>
<tr>
<td></td>
<td>3D maps</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Generally available</td>
<td>Limited resolution</td>
</tr>
<tr>
<td></td>
<td>Very quick</td>
<td>Bulk measurements over whole volume</td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hand-held</td>
<td></td>
</tr>
<tr>
<td>Sectioning</td>
<td>Wide range of material</td>
<td>Destructive</td>
</tr>
<tr>
<td></td>
<td>Economy and speed</td>
<td>Interpretation of data</td>
</tr>
<tr>
<td></td>
<td>Hand-held</td>
<td>Limited strain resolution</td>
</tr>
<tr>
<td>Deep hole drilling</td>
<td>Deep interior stresses measurement</td>
<td>Interpretation of data</td>
</tr>
<tr>
<td></td>
<td>Thick section components</td>
<td>Semi destructive</td>
</tr>
<tr>
<td></td>
<td>Wide range of material</td>
<td>Limited strain sensitivity and resolution</td>
</tr>
<tr>
<td>Synchrotron</td>
<td>Improved penetration and resolution of X-rays</td>
<td>Only specialist facility</td>
</tr>
<tr>
<td></td>
<td>Depth profiling</td>
<td>Lab-based systems</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macro and micro RS</td>
<td></td>
</tr>
</tbody>
</table>

Above table shows that selecting an appropriate method for residual stress measurement depends on various parameters, such as: the required accuracy, sample specifications, and the equipment availability. In this thesis the applicable method should be able to measure residual stresses through the thickness of thin sheets over a thickness ranging from 1 to 2 mm as commonly used in roll forming. Some of the previous studies to measure residual stresses due to cold-forming will be reviewed below.
The curvature and layer removal (bending deflection) technique was used in [29, 31, 40] to measure residual stresses through the thickness of material. Hundy et al. [29] investigated the effect of skin passing on the variation of the residual stresses through the thickness of mild steel strips, while the effect of skin passing and tension levelling on the distribution of residual stresses in the high strength recovery annealed steel was investigated in [31]. Furthermore, Park et al. [40] showed the distribution of residual stresses in a strip due to a roller levelling process. The obtained results of [29, 31, 40] have shown the variation of residual stresses in the material, this has been previously discussed in Section 2.3.4. Although residual stresses through the thickness of a strip can be acquired by applying the curvature method, measuring is difficult and has limited accuracy, especially when thin layers have to be removed.

The sectioning technique has been used by some researchers to measure residual stresses in a material [90, 91, 103-105]. Weng et al. [103] measured residual stresses at the surface of cold formed steel members. They also measured residual stresses through the thickness of a severely cold bent high strength steel plates, with a thickness of 25.4 mm, in [91]. Residual stresses at the surface of structural stainless steel sections were analysed in [104], and Spoorenberg et al. [105] measured residual stresses at the surfaces of cold bent I-sections. Furthermore, residual stress through the thickness of a Square Hollow Section (SHS) column, with a thickness of 6.3 mm, was measured in [90].

The destructive methods to measure residual stresses in the material have limited accuracy, and it is very difficult to measure residual stresses through the thickness of thin strips (which are usually used in roll forming). X-ray diffraction (XRD) is the most common non-destructive method to measure residual stresses [33], and it has been widely used for the measurement of residual stresses in metal sheets [106-111]. With this technique only residual
stresses at the surface of the strip can be analysed but a through thickness residual stress profile can be obtained by combining XRD with the layer removal technique.

Some researchers used XRD to measure residual stresses only at the surface of the strips [27, 111]. Residual stresses due to a heavy cold-rolling process of 304 stainless steel plates (thickness reduction was from 34% to 196%) were measured in [111], while Morris et al. [27] measured residual stresses in the medium and low carbon steels due to a tension levelling operation.

Other researchers used XRD and the layer removal technique to obtain the residual stress profile through the thickness of a material [112-117]. Residual stresses in cold-rolled stainless steel hollow sections were measured in [112], while Tong et al. [113] measured residual stresses in thick-walled (thickness of 10 mm and 16 mm) square hollow sections. The measurement of residual stresses in a roll-formed square hollow section, with a thickness of 10 mm, was performed in [114], while Chinnaraj et al. [115, 116] measured residual stresses in the cold formed truck frame rail structures with a thickness of 6 mm. Additionally, residual stresses through the thickness of an Aluminum strip, with a thickness of 2 mm, due to an equal channel angular rolling operation were measured in [117].

The above studies show that reasonable accuracy can be achieved if XRD is combined with the layer removal technique to measure residual stresses through the thickness of material. However, the experimental measurement is difficult, expensive, and time consuming. This begs the question that whether there is a reliable approach that does not have the limitations of experimental techniques to obtain the variation of residual stresses through the thickness of a metal sheet.
2.4.3 A new approach to predict residual stresses in the material

Analytical and experimental methods to obtain residual stress information in the material have been reviewed and the difficulties of applying those approaches were discussed. A lack of detailed information with regard to the pre-processing conditions for the incoming material is the major concern for using an analytical approach to predict residual stress in metal strip. On the other hand the experimental methods available for measuring residual stress are time consuming, expensive and not applicable to test residual stress in incoming material on a day to day basis. Therefore new technique for estimating residual stress in roll forming strip is required.

2.5 Summary

Section 2.2 gave a brief introduction to the roll forming process and the common shape defects observed in this process were reviewed. It was shown in this section that the longitudinal strain at the flange has an important effect on final shape defects in roll forming. If the longitudinal strain exceeds the yield limit of the material, shape deviations such as bow, camber, and edge waviness do occur.

Section 2.3 reviewed the temper rolling, and levelling as steel pre-processing techniques that are usually applied in the industry to produce a flat sheet with improved surface quality for roll forming production lines. It was shown that those processes can introduce or change residual stress in the material that is generally nonlinear over the material thickness. Previous studies have shown that residual stresses in the material can change the material behaviour close to yield in a bend test. Roll forming is an incremental bending operation and therefore changes in the material behaviour close to yield may affect the final shape of a roll formed profile. Nevertheless currently there is no systematic understanding of the effect of residual stress on the material behaviour in the roll forming process. There are two major concerns to numerically investigate
the effect of residual stresses in roll forming: First, a reliable roll forming model setup is required that allows to include an initial residual stress profile in a roll forming simulation. This model setup should be accurate and robust and computationally efficient. Furthermore, there is a lack of knowledge about the pre-existing residual stress profile in a sheet, and this is the second reason that the effect of residual stresses has not been considered in a roll forming process in the literature. Thus, exploring the effect of residual stress profiles on a bend test and the final shape defects in a roll forming process will be the main focus of this thesis.

Section 2.4 reviewed various approaches to obtain residual stress information from a material. It was shown that analytical, or experimental techniques have been widely used by other researchers to get that information. A lack of detailed information with regard to the pre-processing conditions of the incoming material is the most important concern when using an analytical approach to predict residual stresses in the incoming material. On the other hand experimental methods used to measure residual stress are time consuming and expensive. This led to the suggestion that a new approach should be developed in this thesis to predict residual stress that is fast, inexpensive and reliable.

As a result of this review of the literature, the following research questions have been identified:

- Does the existence of residual stress in the material only change the yield transition point in a bend test or it does also affect the material behaviour at higher strain values?
- What is the effect of residual stresses in a bend test without the influence of other material/process parameters? That is, can the residual stress effect be uncoupled from other effects?
• How can a material model in FEA be created to capture the bending response of skin passed strips in the experiment?
• How can the effect of initial residual stresses in the material be deeply investigated independent from other parameters in a roll forming process?
• What is the effect of initial residual stress in the incoming material on final roll formed product geometry?
• What is an appropriate element type to simulate the sheet in numerical modelling of a roll forming process with the capability of including an initial residual stress profile in the material?
• Given no knowledge of pre-processing conditions, how can residual stress information be obtained for incoming steel material?

The following chapters of this thesis aim to answer the above research questions, using a combination of numerical, theoretical, and experimental approaches.
Chapter 3

Bending and Roll Forming Models to Identify an Appropriate Element Type

3.1 Introduction

In the previous chapter the problem of residual stresses in roll forming was revealed. However, bending is the major deformation mode in a roll forming process. So, before selecting an appropriate element type for roll forming simulations, the accuracy of the forming behaviour of this element should be examined with a numerical simulation of a bend test. An optimized model is needed to investigate the effect of residual stresses in the finite element simulation of bending type forming processes. To account for residual stress in a roll forming simulation is not trivial. Although Finite Element Analysis (FEA) is a standard tool for metal forming simulations, it is only now being increasingly used for the analysis of the roll forming process. This is because of the excessive computational time due to the long strip length and the multiple numbers of stands that have to be modeled [50, 83].

Typically a single solid element is used through the thickness of the sheet for roll forming simulations [76, 80]. The residual stresses in the material vary in intensity through the thickness and therefore, it is not possible to input that information as initial condition with one solid element through the material
thickness. However, using more than one solid element through the thickness is not computationally affordable. Thus, selecting an appropriate element type for the numerical simulation of bending and roll forming processes with the capability of changing the residual stresses through the material thickness is the first step to achieve a reliable model.

This chapter will show that a solid-shell element provides benefits with regard to forming behaviour and computational time, it also enables residual stresses to be included in a simulation. An in depth study using of solid-shell element for roll forming simulation is presented.

3.2 Various element types in sheet metal forming simulations

Previous works on finite element simulation of a roll forming process were reviewed in Chapter 2, Section 2.3.6.1, to explore the possible configuration in the current thesis for a roll forming simulation. To save the extensive computational time, which is due to long strip length in roll forming model, the appropriate element type should have the capability of implementing the residual stress profile through the thickness using only one layer of elements. Thus, the characteristics of different element types which can be used for sheet metal forming simulations will be reviewed in this section to select the proper element type for this thesis.

A sheet metal forming process consists of geometrical and material nonlinearity in simulation and the validation of results is dependent on several parameters such as the constitutive material model, element type and computational methods. Shell elements have been used commonly for simulation of shell like structures to save the calculation time. The plane stress state is being usually used for shell elements while three dimensional constitutive laws are required for accurate material modelling in sheet metal forming. Complicated material model as a result of plane stress condition,
difficulties in connection with solid elements, and handling the rotational
degree of freedom are some difficulties in using shell elements.

In contrast, when eight-node hexahedral (solid) elements are used in
simulation of shell like structures, locking in the element is a serious issue as
a result of bending which leads thickness to length ratio to zero. Low
computational efficiency especially in bending problems, and using multilayer
solid elements in thickness direction, are two other disadvantages of using
solid elements. The main source of obtaining poor results in using solid
elements for simulation of shell like structures is over estimation of stiffness
matrix due to locking in the element [118]. The advantages of using solid
element are that no kinematic relations in rotational degree of freedom are
needed and a three dimensional stress–strain state can be obtained
automatically with a three dimensional material model.

To use the advantage of both shell and solid elements in sheet metal forming
simulations, many efforts have been performed to develop solid-shell
elements, which avoid thickness, volumetric, and shear locking in the element.
Despite having the 3D structure of solid elements, solid-shell elements are like
typical shell elements in which the rotational degree of freedom is omitted.
Solid-shell elements can be used for double side contact condition problems
and evaluation of stress and strain fields through the thickness.

Furthermore, it is not possible to implement the variation of residual stresses
in thickness direction by using only one solid element through the thickness.
However, using more than one solid element in thickness direction is not
computationally affordable. So, shell or solid-shell elements with arbitrary
number of integration points can be used in this thesis to simulate a roll
forming process with the potential of changing the residual stresses through
the thickness of the metal sheet. The next section will review the advantages
and disadvantages of using shell or solid-shell elements for application in this thesis.

### 3.2.1 Shell or solid-shell elements for roll forming simulation

Longitudinal and shear strains are important in a roll forming operation and the selected element type for a roll forming simulation should be able to capture this parameters and shape defects such as bow, twist, and springback. Application of shell and solid-shell elements with the capability of changing residual stresses at arbitrary integration points through the material thickness in sheet metal forming simulations will be reviewed in this section. Different methods that have been used by other researchers to improve the accuracy of these element types in numerical simulations will be explored to select the suitable element type in this thesis.

The degenerated shell element which was introduced by Ahmed [119] has been widely used in sheet metal forming simulations. When this element cannot take the pure bending mode, the membrane and shear locking might happen. Locking will occur in the element when the total number of independent strain fields in calculation of stiffness matrix of element is more than the dimension of global equations. Many techniques like selective and reduced integration, assumed strain, and hybrid stress method have been used to overcome the membrane and shear locking problems. Hybrid stabilization method was used in [120] to prevent membrane locking in an explicit hybrid lagrangian 9-node shell element. Hybrid stress, and assumed natural strain methods were used in [121-123] to prevent membrane and shear locking in the element.

Although the accuracy of shell elements has been improved for sheet metal forming simulations using the above methods, difficult procedure for convergence update due to rotational degree of freedom, not having physical nodes in both sides for double side contact problems and natural calculation
of thickness variations, and a necessity for plane stress assumption in constitutive material model are some difficulties when shell elements are used in roll forming simulation.

Solid-shell element is the second choice for a roll forming simulation. Solid-shell elements have a number of advantages over conventional shell elements:

- Convergence in the element is simpler due to the absence of rotational degrees of freedom at the nodes.
- The 3D stress state for constitutive laws can be applied without the assumption of plane-stress in the material.
- Automatic consideration for double side contact problems and natural calculation of thickness variations due to existing physical nodes.
- Complex stress states can occur when using shell elements in simulations of complicated roll forming processes, which makes convergence of the simulations more difficult because of the existence of the rotational degree of freedom in the element. Using solid-shell elements can overcome this problem.

However, by diminishing the thickness of element, shear and membrane locking may happen in a solid-shell element which leads to too stiff element formulation. Shear locking due to tendency of thickness to length ratio to zero in bending situation, volumetric locking as a result of incompressible deformation type in plasticity, and thickness locking due to insufficient update of strain field in thickness direction are different modes of locking in a sheet metal forming simulation using solid-shell elements. Various remedies such as penalty scaling, local and global constrain reduction, and local enhanced methods have been used by different researchers to overcome these problems. Reduced Integration (RI), Selective Reduced Integration (SRI), hybrid stress, and hybrid strain are some examples of local reduction methods.
while Enhanced Assumed Strain (EAS) and Assumed Natural Strain (ANS) are some examples of global constrain reduction methods.

The number of independent strain fields reduces at global level in global constraint reduction methods by selecting the tangential components of strains in element boundary. In local enhancement methods, some of the strain fields can be eliminated by supplementation of assumed displacement with incompatible modes.

Various approaches such as hybrid formulation, EAS, ANS, RI, and SRI have been applied by many researchers to improve the efficiency of solid-shell elements for sheet metal forming simulations [124-135]. Numerical simulation of several processes such as S-rail, cylindrical cup drawing deformation [63, 124, 125], deep drawing [132, 136], and a U-channel roll forming [63] verified the accuracy of solid-shell elements for sheet metal forming application.

The EAS method has been widely used to prevent locking in solid-shell elements. The problem of EAS method is its low computational performance which increases the CPU time. For instance up to 30 enhanced variables are needed in some 3D analyses leading to hardly treatable stiffness matrix. A new solid-shell element which has the accuracy and locking free properties of fully integrated EAS elements, with a good efficiency in CPU time was presented in [118]. This new eight-node Reduced integration-Enhanced strain-Solid-Shell element (RESS) has the capability of using arbitrary number of integration points through the thickness. The developed solid-shell element of [118] was extended to use in large deformation elasto-plastic thin shell structures [137]. This element was validated for simulation of large deformation with contact and elasto-plastic material behaviour problems such as springback, hydroforming, and drawing [132]. Figure 3.1 shows a schematic of this solid-shell element.
The above solid-shell element has been recently implemented in MSC-Marc software [138], so this element type can be used as the first trial for simulation of a roll forming process. This element not only has locking free properties, but it also has reduced integration for efficiency in computational time.

Therefore, the nominated element type in this thesis will be a solid-shell element with arbitrary number of integration points through the thickness. This will allow the application of an initial residual stress gradient through the sheet.

Before using the solid-shell element in the numerical simulation of a roll forming process, the accuracy of models with one solid-shell element through the material thickness for bending type processes needs to be verified. The accuracy of the selected solid-shell element [118, 132, 137] that has been implemented in MSC-Marc finite element software [138] will be investigated using the experimental results and the models with multiple layers of solid elements for verification.

3.3 Bend test

3.3.1 Introduction

The accuracy and efficiency of using one layer of solid-shell elements to simulate a bend test is investigated in this section by a sensitivity analysis using the MSC-Marc finite element software. The bend tester used has been previously introduced in [43]. The simulation results obtained using one solid-
shell element to simulate the strip in a three dimensional (3D) bending process are compared to the results obtained with multiple layers of solid elements and experimental data.

3.3.2 Bend test arrangement

The bend test arrangement of [43] consists of two bending arms that are attached to an Instron tensile testing machine. The bending test-piece is gripped between plates at the ends of the arms and bending of the sample occurs through the movement of the upper arm. The schematic of bend test arrangement is shown in Figure 3.2.

![Figure 3.2 Schematic of bend test arrangement [43].](image)

A schematic drawing of the bend progression during the bend test is shown in Figure 3.3. Parameters \(a\), \(b\), and the angle \(\theta\) in the current bend test arrangement are 215 mm, 265.2 mm, and 35.8° respectively.
The moment–curvature diagram of the material can be obtained from the above bending arrangement using the equations shown below.

Before bending, the initial distance between two arms is

\[ l_0 = L + 2b \sin \theta, \quad (3.1) \]

where \( L \) is the bending length, \( l_0 \) is the longitudinal distance between two arms, and \( b \) and \( \theta \) are the bending arm length and initial angle respectively. In the bend test of this thesis a bend length of \( L = 50 \, \text{mm} \) was used.

After a displacement of \( \Delta \), the bend angle is \( 2\Delta \theta \), where

\[ l_0 + \Delta = L + 2b \sin(\theta + \Delta \theta), \quad (3.2) \]

\( \Delta \theta \) can be calculated from the above equation.

The bending moment at each end of the sample is

\[ M = F \cdot b \cdot \cos(\theta + \Delta \theta), \quad (3.3) \]

where \( F \) is the force which is recorded by a load-cell during the test.
In the experimental test procedure, a clip on gauge (LVDT device) was used to obtain a more accurate determination of the radius of curvature. Figure 3.4 shows a schematic of the device.

![Figure 3.4 Schematic of LVDT device.](image)

Recording $\delta$ and $c$ which are shown in the above figure, the curvature ($\frac{1}{R}$) can be obtained as

$$
\delta = R - \sqrt{R^2 - c^2} \Rightarrow \frac{1}{R} = \frac{2\delta}{c^2 + \delta^2}.
$$

(3.4)

The above equations will be used in the upcoming bend tests and simulations to obtain the moment–curvature diagram from the force and displacement data.

### 3.3.3 Bending test-piece specifications

Bend test and simulation based on the discussed arrangement in the previous section are needed to show the accuracy of solid-shell element. Previous studies have shown that the initial material conditions such as pre-existing residual stresses have effect on moment–curvature diagram in a bend test [6]. So, bending results of a commercial fully annealed Aluminum were used to validate the finite element simulation with the experimental data. The residual
stresses through the sheet are really low in this material due to annealing, and
the material does not age like many steel grades. An Aluminum strip with
bending length, width, and thickness of 50 mm, 20 mm, and 2.92 mm
respectively was used. The total length of the Aluminum sample was 170 mm
(60 mm of the strip was clamped by the arms at each side).

### 3.3.3.1 Experimental tensile test to get material data for FEA

The tensile tests were performed in a 30 kN Instron machine in accordance
with Australian Standard AS 1391 – 1991; specimens were oriented along the
extrusion direction. A non-contact extensometer with a gauge length of 50 mm
was used and the cross-head speed was 2 mm/min. A total of 3 or 4 tests were
performed for each condition and averaged. Yield was determined at the onset
of non-linearity. True stress–true strain curve of the Aluminum obtained from
the tensile test is shown in Figure 3.5.

![Figure 3.5](image)

**Figure 3.5** Aluminum true stress–true strain curve obtained from the tensile test.

The yield stress of the Aluminium was found to be 101 MPa, and the Young's
Modulus was 70 GPa. The Poisson's ratio was set to 0.33 [139, 140] for FEA.
The true stress–effective plastic strain curve which was used in FEA is given
in Figure 3.6. An isotropic hardening material model was considered in all bending simulations.

![True Stress vs Effective Plastic Strain](image)

**Figure 3.6** Aluminum true stress–effective plastic strain curve.

### 3.3.4 Bending simulation

The bending arms were represented as rigid contact bodies (four surfaces to model each arm) and a glue contact was used between the bottom elements of the strip and the related arm (see Figure 3.7). A control node was defined at the middle of the two lowest nodes of each arm and the boundary conditions were assigned to the control nodes. Figure 3.7 shows the finite element model of the 3D bending analysis with solid elements. The right arm was fixed in $Y$ and $Z$ direction and given a displacement of 80 mm in $X$ direction while the left arm was fixed in $X$, $Y$, and $Z$ directions. Both arms can rotate about the $Y$ axis.
A sensitivity analysis was performed to show the accuracy of solid-shell element and various solid elements available in MSC-Marc to predict the moment-curvature diagram in FEA. 3D solid reduced integration structural element (element type 117), 3D solid reduced integration with 20 nodes (element type 57), full integration solid element (element type 7), and solid-shell element (element type 185) [138] were applied to simulate the bending test-piece.

The mesh density in the models with solid elements is the same, but only one layer of elements was used in the models with solid-shell element and the number of integration points varied.

In the models using solid elements a convergence study was performed changing the number of elements in three directions (Table 3.1) and determining the response in maximum von Mises stress in the sample. Maximum von Mises stress in the models using reduced integration solid element (element type 117) is shown in Figure 3.8.
Table 3.1 Various model configurations in the convergence test.

<table>
<thead>
<tr>
<th>Element type</th>
<th>Number of elements in ( X ) direction</th>
<th>Number of elements in ( Y ) direction</th>
<th>Number of elements in ( Z ) direction (number of layers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>38</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Solid</td>
<td>64</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Solid</td>
<td>64</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Solid</td>
<td>64</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>Solid</td>
<td>64</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Solid</td>
<td>64</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Solid-shell</td>
<td>28</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 3.8 Convergence test in the models with different number of reduced integration solid elements through the thickness.

The study showed that in the models use various types of solid elements above 10 elements through the material thickness the maximum von Mises stress converges. In the final 3D model therefore 10 elements through the material thickness are used combined with a reduced element density in specimen length direction towards the two ends of the bending test-piece, which are not deforming, to save calculation time (Figure 3.9). The total number of elements in the model is 12800 and the aspect ratio is lower than 0.5.
To calculate the moment-curvature data using Equations (3.3), and (3.4), the reaction force at the control node of the right arm and the displacement of the two nodes on the surface of the bending test-piece (in the same position as the clip on gauge in the experimental trials) were recorded. The distance between these two nodes at the strip surface is 14 mm (Figure 3.9) which refers to \(2c\) with regard to the clip on gauge in Figure 3.4.

**Figure 3.9** Selected nodes at the surface of the bending test-piece with solid elements to calculate the bending curvature.

The moment-curvature response predicted by the 3D bending analysis using solid elements is compared to the experimental results in Figure 3.10. As can be seen in the figure that acceptable model accuracy is achieved using solid reduced integration 8 nodes or 20 nodes elements. However, some discrepancies exist between the numerical results and experimental data that need further investigation.

One layer of solid-shell elements was used in the next trial to simulate the bending test-piece. The number of elements in three directions is shown in Table 3.1 and mesh density of the bending test-piece using solid-shell elements is compared to the models using solid elements in Figure 3.11.
Figure 3.10 Moment curvature diagram determined experimentally and with the 3D FEA model using 10 solid elements through the material thickness.

Figure 3.11 Mesh density of bending test-piece in the models a) using solid elements and b) using solid-shell elements.

The solid-shell element has the capability of using an arbitrary number of integration points through the thickness. The maximum von Mises response of the model using solid-shell elements was analysed for various quantities of integration points through the material thickness to determine the convergence point for one layer of solid-shell elements in thickness direction. Convergence was observed for 9 integration points through the thickness and in the rest bending simulations of this thesis 11 integration points will be used through the thickness of each element to ensure sufficient model accuracy. The effect of the number of integration points used through the element
thickness on the moment-curvature diagram is shown in Figure 3.12; only two model arrangements are compared to the experimental data to allow comparison. It is clear that the number of integration points through the element thickness has a vital effect on model accuracy and that a good agreement between the experimental and the numerical results can be achieved by using 11 integration points through the material thickness.

![Figure 3.12](image)

**Figure 3.12** Effect of the number of integration points through the thickness on model accuracy in the bend test using solid-shell elements.

A comparison between the moment–curvature results obtained using various element types is shown in Figure 3.13. It becomes clear that the model accuracy achieved with one layer of solid-shell element combined with 11 integration points is comparable to that achieved with 10 layers of solid element through the material thickness (the results of using solid-shell elements are very close to the results of the model using 20 nodes reduced integration solid elements).
The CPU time in the various simulations are compared in Table 3.2. The processor and installed memory (RAM) of the used system are a Xeon(R) CPU E31280@3.50GHz, and 16 GB respectively. It can be seen that the use of solid-shell elements leads to a significant reduction in CPU time.

<table>
<thead>
<tr>
<th>Element type</th>
<th>CPU time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>117 (reduced int-solid)</td>
<td>551</td>
</tr>
<tr>
<td>57 (reduced int-solid 20 nodes)</td>
<td>3729</td>
</tr>
<tr>
<td>7 (full int-solid)</td>
<td>903</td>
</tr>
<tr>
<td>185 (solid-shell)</td>
<td>11</td>
</tr>
</tbody>
</table>

It can be concluded that one layer of solid-shell elements with 11 integration points through the thickness can be applied to accurately simulate the deformation of a metal strip in a pure bend test while leading to significant savings in required CPU time compared to solid element models that give similar model accuracy.

Springback after release of the formed sample is also an important issue in the simulation of bending type processes. This section showed the capability of potential elements candidate for bending simulations and it was discussed.
that the reduced integration solid element model (element type 117) with 10 layers of elements through the material thickness and solid-shell element model (element type 185) with one layer of elements and 11 integration points in thickness direction deliver acceptable model accuracy in bending. Therefore these model set ups will be investigated with regard to their capability to predict springback accurately.

### 3.3.5 Springback analysis in bending

Springback is due to the release of residual stresses in the work piece after forming. The magnitude of springback is depended on the ratio between the residual stress and the Young’s modulus [141]. Choosing a reliable material model is important to predict the springback in the FEA. The previous analyses showed the efficiency of solid-shell elements to predict material behaviour in simple bending. In this section the accuracy of this element type for accurately predicting springback will be investigated. For model validation the numerical results of the model with 10 layers of reduced integration solid elements in Table 3.1, an analytical model, and experimental data were used. The Isotropic hardening material model was considered in all simulations.

The introduced bend tester from the previous section (Figure 3.2) was used for springback prediction. To simulate springback, one additional load-case was added to the initial model of the bend test described in Section 3.3.4. Therefore there are two load-cases in springback analysis: the first one has the same boundary conditions as used for the previous numerical analysis of the bend test (loading stage); while in the second load-case (springback) the same boundary conditions of loading stage were considered for the left arm (see Figure 3.7) while the right arm was fixed in Y and Z direction so that it could rotate about Y axis and move in X direction to allow springback in the bending test-piece.
After performing the springback analysis, the springback ratio was calculated as

\[
Springback \ ratio = \frac{\Delta \left( \frac{1}{R} \right)}{\left( \frac{1}{R} \right)_0},
\]  

(3.5)

where \( \left( \frac{1}{R} \right)_0 \) is the bending curvature before springback, and \( \Delta \left( \frac{1}{R} \right) \) is changing in the curvature due to springback.

It has been stated previously that the number of layers has effect on bend test and former studies [142] have shown the number of layers should also have effect on springback prediction. Bending strain will be calculated in the current bending arrangement to further explore the effect of number of layers in FEA.

The bending strain in a bend test is

\[
\varepsilon_{\text{bend}} = \frac{y}{R},
\]  

(3.6)

where \( y \) is the distance from the mid-surface and \( R \) is the bending radius in the bending test-piece. The maximum bending strain which happens at the surface of the strip is 1\% in the current bend test. This value indicates the bending curvature is not big enough, so there is not enough plastic strain in the formed material to show the effect of number of layers in springback prediction.

It has also been mentioned in [142] that to use solid elements in springback analysis the ratio of \( R/t \) should be lower than 5 or 6, \( t \) is the material thickness. This ratio is 41.8 in the current bend test. So, it confirms the idea that to see the effect of number of solid elements through the thickness in springback analysis the sample should be bent to higher curvatures.
The final mesh density in the bending models using 10 layers of reduced integration solid element in Table 3.1 (element type 117), and the solid-shell element model (element type 185) with one layer of elements and 11 integration points through the material thickness were used for springback analysis. The moment–curvature diagrams of 3D springback analysis using these two model configurations are shown in Figure 3.14. The smoothed curve of experimental data (compared to the experimental data in the bend test) is shown here for better comparison.

![Moment curvature diagram in 3D springback analysis and the experimental data.](image)

**Figure 3.14** Moment curvature diagram in 3D springback analysis and the experimental data.

The above figure shows that the moment–curvature data of the model using solid-shell elements is close to the experimental results. The springback ratio in the models with solid and solid-shell elements was -0.24, and -0.26 respectively while this ratio was -0.27 in the experiment.

An analytical solution [143] has also been used to calculate the springback ratio in the present bend test.
Springback ratio \( = \frac{\Delta \left( \frac{1}{R} \right)}{\left( \frac{1}{R} \right)_0} = -3 \frac{S}{E'} t' \), \( (3.7) \)

\[ E' = \frac{E}{1 - v^2}, \] \( (3.8) \)

where \( S, E', R_0, t, E, \) and \( v \) are the plane strain flow stress, elastic modulus in plane strain, loading radius, sheet thickness, elastic modulus, and Poisson’s ratio respectively.

In the current bend test the springback ratio from the above analytical solution was -0.3.

A comparison between the springback ratios from two various model configurations, analytical result and the experimental data is shown in Table 3.3.

<table>
<thead>
<tr>
<th>Table 3.3 Springback ratio in the current bending arrangement.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEA_Solid</td>
</tr>
<tr>
<td>Springback ratio</td>
</tr>
</tbody>
</table>

It can be concluded that solid-shell element is accurate enough to predict the springback angle in the present bend test.

3.3.6 Summary

The solid-shell element was trialled for its applicability to simulate bending, because this type of element can enable the inclusion of residual stress profile through the thickness of the sheet. A 3D Bending and springback analyses were performed using MSC-Marc and the model results compared to experimental test data. The numerical results show that reasonable model accuracy can be achieved using only one solid-shell element through the material thickness. The model accuracy obtained using one solid-shell element
with 11 integration points through the material thickness is comparable to that observed with 10 layers of solid elements but results in significant savings in CPU calculation time. This suggests that solid-shell elements can be used in the future investigations of this thesis to simulate simple bending operations with reliable model accuracy.

In the upcoming section the solid-shell element will be investigated with regard to its capability to be applied in the numerical analysis of roll forming applications.

### 3.4 Roll forming trial

#### 3.4.1 Introduction

The previous section has shown that one layer of solid-shell elements through the material thickness leads to sufficient model accuracy in simple bending simulations. The accuracy and efficiency of this solid-shell element will now be investigated to simulate a V-section roll forming process.

Roll forming is used widely to form AHSS materials. Formability and springback are two major concerns in the roll forming of AHSS materials because of high material strength which leads to the development of high residual stresses during forming. An advanced high strength steel material (dual phase DP780 steel) will be therefore used in the roll forming process of present section. Numerical results of using one layer of solid-shell elements and multiple layers of solid elements to simulate the metal strip will be compared to the experimental data for validation.

#### 3.4.2 Roll forming of a V-section

The roll forming process has been developed with COPRA-RF [144] using the constant length forming method. Forming of a 15 mm radius V-section was designed using a sequence of five forming stations. Both top and bottom rolls were driven at a strip speed of 22.5 mm/sec, the distance between the stations
was 305 \textit{mm}, and the pre-cut strip (2000 \textit{mm} length) was fed in over a feeder without the use of any lubrication.

The flower diagram for the process and the experimental arrangement are shown in Figure 3.15 and Figure 3.16 respectively while Figure 3.17 shows a schematic of V-section roll forming process.

To compare the numerical results and the experimental data, edge strain, longitudinal bow, and springback angle were recorded experimentally and numerically. The different methods used to determine these parameters will be explained in the next sections.

![Figure 3.15 Flower design of the roll forming process.](image1)

![Figure 3.16 Experimental arrangement of V-section roll forming process.](image2)
3.4 Roll forming trial

3.4.3 Edge strain measurement

The edge strain was measured using a single element TML strain gauges with 120Ω gauge resistance [145] (Figure 3.18). The longitudinal strain was recorded in the middle of strip at a 2 mm distance from the strip edge (Figure 3.19).
Typical longitudinal edge strain measurement in a roll forming process with 5 forming stations is shown in Figure 3.20. It is shown in this figure that the maximum longitudinal edge strain happens in the material when the strip passes each forming station. Small plastic edge strain exists during the forming process and material deformation at the strip edge is close to the yield limit. Small values of plastic strains in this area lead to the common shape defects, such as bow, in the final product of roll forming operation.
3.4 Roll forming trial

To validate the numerical simulations, the amount of longitudinal bow was also measured experimentally. The bow curvature was determined by drawing a line between the start and the end point of the formed strip; and the height of regular spaced points from the drawn line to the bottom of the section in longitudinal direction was measured (see Figure 3.21).

An EXAscan high resolution 3D scanner [146] was used to scan the formed section and measure the bow curvature over the length of the part (Figure 3.22.a). After scanning the outer surface of the formed section in the experiment, the Geomagic Qualify software [147] was used to compare the scanned geometry of the sample to the reference geometry without any shape defects (Figure 3.22.b).

**Figure 3.20** Typical longitudinal edge strain measurement in a roll forming process.

**3.4.4 Bow measurement**

To validate the numerical simulations, the amount of longitudinal bow was also measured experimentally. The bow curvature was determined by drawing a line between the start and the end point of the formed strip; and the height of regular spaced points from the drawn line to the bottom of the section in longitudinal direction was measured (see Figure 3.21).

An EXAscan high resolution 3D scanner [146] was used to scan the formed section and measure the bow curvature over the length of the part (Figure 3.22.a). After scanning the outer surface of the formed section in the experiment, the Geomagic Qualify software [147] was used to compare the scanned geometry of the sample to the reference geometry without any shape defects (Figure 3.22.b).

**Figure 3.21** Definition of longitudinal bow.
Figure 3.22 Bow measurement using a 3D scanner a) the scanning process b) a comparison between the scanned geometry and the reference one.

3D alignment was applied to create the best fit between the scanned shaped to the reference geometry for comparison and then a section cut with the $Y-Z$ plane at the middle of the V-section was used to capture the bow height. The $Y$ deviation of various points along $Z$ axis was recorded as the longitudinal bow (Figure 3.23.a).

An example contour plot of the bow height is shown in Figure 3.23.b. A scale of 10 was used in the contour plot for better visualization of the bow shape in this figure.

Figure 3.23 Bow measurement of the V-section a) fitting the scanned geometry to the reference one and using the $Y-Z$ plane for the section cut b) a contour of $Y$ deviation of various points along $Z$ axis.

3.4.5 Springback measurement

The angle $\theta'$ between the two section walls was measured after release (Figure 3.24). These measurements were taken using an angle gauge at 5 locations 350 mm apart and 300 mm away from the front and the back edge
of the formed section to exclude the effect of end flare. Forming angle under the load is $80^\circ$ so the change in angle $\Delta \theta = \theta' - \theta = \theta' - 80^\circ$ was taken as the measure for springback.

![Springback diagram](image)

**Figure 3.24** Springback measurement.

### 3.4.6 Material data for FEA

DP780 strips with a thickness of 2 mm were used in a standard tensile test similar to the Section 3.3.3.1 to get material data for FEA. 0.2% offset approach was applied to determine the yield point (see Figure 3.25); the yield stress is 579 MPa, and the Young’s Modulus is 197 GPa. The Poisson’s ratio was set to 0.3 [139, 140] for FEA. The true stress–effective plastic strain curve obtained from the standard tensile test is given in Figure 3.26. An isotropic hardening material model was considered in all roll forming simulations.
3.4.7 Roll forming simulation

There are two types of models developed for this thesis:

*Roll forming model without friction* - in which the sheet is fixed and the rolls are moved along the strip without any friction between the sheet and the rolls.
Roll forming model with friction - the sheet is moved by the friction between the rotating rolls.

The numerical simulations were performed using an MSC-Marc solver. The models were based on some simulations initially developed in COPRA-FEA.

It was shown in the bending analysis, Section 3.3.4, that using one layer of solid-shell element delivers acceptable model accuracy. The capability of this element type in roll forming simulation will be examined. Full integration solid element has been applied by other researchers [50, 57, 78, 80] to simulate the roll forming process and this element type is being used in COPRA-FEA for roll forming simulation. So, both solid-shell and full integration solid elements were used in this section to discretize the strip. Symmetry was considered along the mid-plane of the strip, and the rolls were modelled as rigid bodies. In the case of the solid-shell element model (Element type 185 [138]), only one element with 7 integration points through the thickness was used while the model with solid elements (Element type 7 [138]) was developed using three elements through the material thickness. It is recognised that solid-shell results may not be converged with 7 integration points, as 9 were necessary in the bending simulation. However, this was done to provide an equivalent number of integration points through the thickness, as each solid element of MSC-Marc has two integration points in the thickness direction. The solid-shell and the solid elements were used in both model arrangements with and without friction.

The mesh configurations are the same in the models with solid-shell elements (with and without friction) and the total number of elements is 9450, while there are 28350 elements in the both solid element models (with and without friction).

The finite element models without friction is shown in Figure 3.27. As for the boundary conditions, in the model without friction, the strip is fixed and the
rolls move in Z direction without any rotation to shape the strip. The friction between the sheet and the rolls is zero. Six nodes at the front of the strip near the mild-plane are fixed in Z direction (Z – lock boundary condition) and three nodes at the strip end are fixed in Y direction (Y – lock boundary condition) to prevent the strip movement during the roll forming. X – lock boundary condition refers to all nodes at mid-plane of the strip that cannot move in X direction to consider symmetry in the model.

Figure 3.27 Roll forming finite element model without Friction.

In contrast, in the models with friction (Figure 3.28), the strip is pulled in Z direction in the first step to initiate contact between the strip and the rolls, then the strip moves as a result of the contact between it and the rotating upper and lower rolls. The rolls rotate at $\omega_{\text{roll}} = 0.321 \text{ rad/s}$ to give the speed of $V_{\text{line}} = 22.5 \text{ mm/s}$ to the roll forming line as the experimental arrangement. The strip has only a $X – \text{lock}$ boundary condition, which refers to all nodes at mid-plane of the strip that cannot move in X direction to consider symmetry in the model. Additionally the Feeder was included in the numerical model, but a frictionless contact was assumed between the surface of the sheet and the feeder. The friction coefficient between the rolls and the strip was chosen to be 0.2 for the first trial, similar to [75, 76].
A node to segment contact control was used in both the model with friction and the frictionless model. Also, the model including friction used an additional bilinear Coulomb contact model.

![Feeder](image1)

**Figure 3.28** Roll forming finite element model with Friction.

### 3.4.8 Results and discussion

This section will compare longitudinal edge strain, longitudinal bow, and the springback angle across the various model types. The results will be compared to experimental data for validation (three trials were done in the experiment to insure the repeatability of the obtained data). The longitudinal edge strain data was close in all three trials (see Figure 3.29) and one of them (trial 3) was considered for validation while maximum and minimum tolerance will be given for the measured bow curvature and springback angle in the experiment.
Figure 3.29 Strain measurement in the three experimental trials.

In the numerical simulation the edge strain was measured during the forming operation by recording the history plot of the node at the same position that the strain gauge was attached to the metal strip in the experiment (see Figure 3.18, and Figure 3.19). The measurement of longitudinal bow and springback angle were carried out when the roll forming simulation finished and the strip was shaped to the V-section. To be sure that the strip is fully unloaded, the total simulation time was more than the time which was needed for roll forming process. It means that there was enough time for the springback of the strip in finite element simulation when it passed the rolls. The longitudinal bow and springback angle were measured by recording the path plot of the strip nodes at similar positions to the experiment (see Figure 3.21, and Figure 3.24).

3.4.8.1 Effect of element type

Finite element simulation without friction

The edge strains in the models without friction using three solid elements or one solid-shell element with 7 integration points through the material
thickness are shown in Figure 3.30, while the bow results are shown in Figure 3.31.

**Figure 3.30** Edge strain measurement in the models without friction with one solid-shell element and three solid elements through the thickness, the residual longitudinal (edge) strain can be seen from length 2500mm onwards.

**Figure 3.31** Bow measurement for the models without friction with one solid-shell element and three solid elements through the thickness.

The results from both models are very similar with regard to the longitudinal peak strains and the residual longitudinal strain. The residual longitudinal
strain is higher in both models compare to the experiment, but both models under-predict the experimental bow. The maximum bow height is lower in the model using solid elements compare to the model with solid-shell elements.

The springback angle in the models without friction using three solid elements or one solid-shell element with 7 integration points through the material thickness is shown in Table 3.4. It is shown in this table that the springback angle in the model using solid-shell elements is higher and closer to the experimental data, but both models under-predict the springback angle.

**Table 3.4** Springback measurement for the models without friction using one solid-shell element or three solid elements through the material thickness.

<table>
<thead>
<tr>
<th>Friction</th>
<th>Solid</th>
<th>Solid-shell</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Springback $\Delta \theta$</td>
<td>6.5</td>
<td>7.7</td>
<td>11.3 ± 0.5</td>
</tr>
</tbody>
</table>

**Finite element simulation with friction**

The edge strains in the models with friction using three solid elements or one solid-shell element with 7 integration points through the material thickness are shown in Figure 3.32, while the bow results are shown in Figure 3.33.
3.4 Roll forming trial

Figure 3.32 Edge strain measurement in the models with friction with one solid-shell element and three solid elements through the thickness, the residual longitudinal (edge) strain can be seen from length 2500mm onwards.

Figure 3.33 Bow measurement for the models with friction with one solid-shell element and three solid elements through the thickness.

The results show that the longitudinal peak strain and the residual strain in the model using solid-shell elements is higher compared to the solid element model. The solid-shell element model over-predicts the maximum bow height while the model with solid elements under-predicts this experimental result,
while the maximum bow height in the model using solid elements is closer to the experiment.

The springback angle in the models with friction using three solid elements or one solid-shell element with 7 integration points through the material thickness is presented in Table 3.5. It is shown in this table that the springback angle in the model using solid-shell elements is higher and closer to the experimental data but both models under-predict the springback angle. A comparison between this table and Table 3.4 shows that including the effect of friction has only a minor effect on the amount of springback predicted by both the solid and the solid-shell element models.

Table 3.5 Springback measurement for the models with friction using one solid-shell element or three solid elements through the material thickness.

<table>
<thead>
<tr>
<th>Friction</th>
<th>Solid</th>
<th>Solid-shell</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Springback $\Delta\theta^{\circ}$</td>
<td>6.6</td>
<td>7.7</td>
<td>11.3 ± 0.5</td>
</tr>
</tbody>
</table>

The above results indicate that the longitudinal edge strain in FEA is close to the experiment and there is a reasonable model accuracy in longitudinal strain prediction using solid or solid-shell elements. The discrepancies in bow and springback angle prediction in FEA need more investigations.

The residual longitudinal edge strain is the strain that remains in the edge of the part after it leaves the roll former. The residual longitudinal edge strain for the models with friction is higher than the model without friction, see Figure 3.30, Figure 3.32. The maximum bow height in the models with friction is also significantly higher than that predicted by the frictionless models, see Figure 3.31, Figure 3.33. If the effect of friction is included in the model, the simulations provide a better agreement between the numerical and the experimental results to predict the bow. In contrast, the frictionless models under-predict the bow in the V-channel. Thus, the results suggest that
improved accuracy with regard to bow can be achieved if the effect of friction is included in the model.

Although the maximum bow height in the model with friction using solid elements is closer to the experimental data, solid-shell element model with friction predicts more accurate springback angle. So, obtained results of using three layers of solid element or one layer of solid-shell element have close model accuracy.

The CPU time in the models with friction using three layers of solid element of one layer of solid-shell element with 7 integration points through the thickness are compared in Table 3.6. The processor and installed memory (RAM) of the used system are a Xeon(R) CPU E31280@3.50GHz, and 16 GB respectively.

<table>
<thead>
<tr>
<th>Element type</th>
<th>Friction</th>
<th>Number of elements through the thickness</th>
<th>Total number of elements</th>
<th>CPU time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid-shell</td>
<td>✓</td>
<td>1</td>
<td>9450</td>
<td>28868</td>
</tr>
<tr>
<td>Solid</td>
<td>✓</td>
<td>3</td>
<td>28350</td>
<td>151172</td>
</tr>
</tbody>
</table>

It is shown in the above table that the use of solid-shell elements leads to a significant reduction in CPU time. So, applying this element type in finite element simulation of a roll forming process to capture the effect of pre-existing residual stresses in the material is more reasonable compare to using a model with multilayers of solid elements. The finite element simulation of solid-shell element with friction will be considered in the upcoming simulations of this chapter to investigate the possible reasons of discrepancies between FEA and the experimental data.
3.4.8.2 Effect of number of integration points in the model with solid-shell element

It was shown in the previous section that there are still some discrepancies in the obtained results using solid-shell element compare to the experimental data in roll forming simulation. The number of integration points through the material thickness is one of the parameters that might have effect on shape defect observation in FEA. Seven integration points were used through the thickness of solid-shell element in the previous simulations. To show the effect of number of integration points through the thickness on finite element simulation results, the roll forming simulation was repeated with the same arrangement for solid-shell element model with friction and only increasing the number of integration points to eleven. The edge strain and bow predicted in the models using one layer of solid-shell element with eleven or seven integration points through the thickness are compared to the experimental data in Figure 3.34 and Figure 3.35 respectively.

![Figure 3.34](image)

Figure 3.34 Edge strain measurement in the models using one solid-shell element with 7 or 11 integration points through the thickness, the residual longitudinal (edge) strain can be seen from length 2500mm onwards.
The above figures show a slight decrease in the maximum longitudinal edge strain and the residual longitudinal strain due to increasing the number of integration points in the solid-shell element model with friction. The maximum bow height in the model using eleven integration points is also lower than the model with seven integration points in thickness direction and closer to the experimental data.

The springback angle prediction in the solid-shell element models with friction using eleven or seven integration points through the material thickness are shown in Table 3.7. This table shows a slight increase in the springback angle prediction using eleven integration points through the thickness.

Table 3.7 Springback angle in the models using one solid-shell element with 7 or 11 integration points through the thickness.

<table>
<thead>
<tr>
<th></th>
<th>Solid-shell_7 integration points</th>
<th>Solid-shell_11 integration points</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Springback $\Delta \theta$ ($^\circ$)</td>
<td>7.7</td>
<td>7.9</td>
<td>11.3 ± 0.5</td>
</tr>
</tbody>
</table>
It can be concluded that closer results to the experimental data was achieved by increasing the number of integration points through the material thickness in FEA, but there are still some discrepancies especially in springback prediction.

To explore if better model accuracy can be achieved by further increase of the number of integration points through the material thickness, another trial was performed with fifteen integration points in thickness direction of the solid-shell element model with friction. This change did not have any effect on FEA results and the results were similar to the model with eleven integration points through the material thickness. So the model is converged using eleven integration points in thickness direction and this number of integration points will be applied through the thickness in all upcoming simulations of this thesis with solid-shell elements.

### 3.4.8.3 Changing the friction coefficient

Section 3.4.8.1 suggested that improved accuracy can be achieved in numerical simulation of present V-section if the effect of friction is included in the model. To check the effect of friction in the finite element simulations that use the solid-shell element with eleven integration points through the thickness, two more simulations were performed and the value of the friction coefficient varied.

The edge strains for the solid-shell element models using various friction coefficients are shown in Figure 3.36, while Figure 3.37 shows the bow results.
The results show that the longitudinal peak strain and the residual strain reduce with decreasing the friction coefficient in the model. The maximum bow height in the model with lower friction coefficient is also lower than the other models. The model with friction coefficient of 0.15 provides highest model accuracy to predict longitudinal edge strain and bow. However, the
actual effect of friction on bow is low; for instance the difference is less than $5\, mm$ when changing the friction coefficient from 0.2 to 0.1.

The springback angle in the above models with different friction coefficients is shown in Table 3.8. This table shows that changing the springback angle was only $0.1^\circ$ between various model arrangements that confirms the friction does not have a considerable effect on springback prediction. Though, more investigations are still needed to determine the exact effect of friction on the final shape in the roll forming process.

<table>
<thead>
<tr>
<th>Friction coefficient (μ)</th>
<th>Solid-shell</th>
<th>Solid-shell</th>
<th>Solid-shell</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>7.9</td>
<td>7.9</td>
<td>8</td>
<td>$11.3 \pm 0.5$</td>
</tr>
</tbody>
</table>

The above results showed that solid-shell elements with eleven integration points through the thickness provide better model accuracy in bow prediction when the friction coefficient of 0.15 is used in finite element simulation but the springback prediction is still far from the experimental data. The next section of this chapter will concentrate on springback angle in the current roll forming arrangement to explore the reason of discrepancies between FEA and experiment for springback prediction.

### 3.4.8.4 Springback investigation in the present roll forming process

It was shown that there are some discrepancies between the springback prediction in FEA and experimental results in the present roll forming process. It was also proven that including friction does not have a considerable effect on springback prediction in FEA. Considering the fact that finite element simulation of roll forming process without friction is faster than the model with friction, four more configurations were considered in FEA of frictionless
models to show the effect of mesh density and element type on springback angle prediction precisely.

Shell elements are usually used for springback prediction in nonlinear analyses; furthermore the current roll forming process is not a complicated one which suggests using shell elements to predict the springback angle. So, thin-shell element (Element type 139 [138]) and thick-shell element (Element type 75 [138]) which are available in MSC-Marc were used for simulation of the strip. Mesh density in the models with shell element is shown in Figure 3.38.

![Figure 3.38](image)

*Figure 3.38* Metal sheet mesh density in the roll forming models with shell element.

In the third configuration (configuration III) more elements were used in the width direction of the model with solid-shell element (Figure 3.39).

Finally in the fourth configuration (configuration IV), by using three solid elements through the thickness, finer mesh was used in the remaining dimensions of the sheet while aspect ratio was less than 0.5. Mesh refinement was also used in this configuration for a length of 350 mm (more than the distance between two stations) at the middle section of the strip in longitudinal direction to measure the springback angle (Figure 3.40).
Figure 3.39 Mesh refinement in the model with solid-shell elements (a) initial configuration (b) configuration III.

Figure 3.40 Mesh refinement in the model with solid elements (a) initial configuration (b) configuration IV (c) finer mesh zone in longitudinal direction of the strip in configuration IV.
Analytical methods were also used by many researchers to predict the springback angle in a simple roll forming process. An analytical method will be used in this section to predict the springback angle in the current roll forming process and compare the results to the four new configurations that were discussed above.

Most of the analytical approaches are based on the springback in a bending process [142]. Various formulas from other researchers to estimate the springback angle in a roll forming process were presented in [20] and the results were compared. It was shown in this study that the Biswas formula [148] presented the more realistic prediction of springback angle in roll forming of high strength steels. So, this formula will be used in this section to calculate the bending radius after springback analytically and then this value will be applied in the equation of [149] to obtain springback angle.

Springback variables of the formed section are shown in Figure 3.41 in which index 1, and 2 describe the part geometry in loading and after unloading condition. Bending inner radius ($r_i$), sheet material thickness ($t$), and bending angle ($\alpha$) are the important parameters to predict the springback angle analytically.

![Figure 3.41 Springback variables in the analytical solution.](image)
The inner bending radios after springback can be calculated as below.

\[
    r_{i2} = \frac{r_{i1} + 0.5t}{(1 - \frac{V}{E})\left\{1 - 1.5\frac{r_{i1} + 0.5t}{r_{mF}} + 0.5\left(\frac{r_{i1} + 0.5t}{r_{mF}}\right)^3\right\}} - 0.5t, \quad (3.9)
\]

where

\[
    r_{mF} = \frac{Et}{2R_{P0.2}} \quad \text{and} \quad V = \frac{R_m - R_{P0.2}}{\varepsilon_{gl} - 0.002}. \quad (3.10)
\]

In the above formula, \(E\) is Young's Modulus, \(R_{P0.2}\) is yield stress, \(R_m\) is ultimate tensile strength, \(\varepsilon_{gl}\) is ultimate tensile strain, \(t\) is the sheet material thickness, \(r_{i1}\) is bending radius in loading, \(\alpha_1\) is bending angle in loading, \(r_{i2}\) is bending radius after springback, and \(\alpha_2\) is bending angle after springback.

The calculated bending radius after springback from the above equation can be used in the below formula to obtain the springback angle.

\[
    \alpha_2 = \alpha_1 \left(\frac{r_{i1} + 0.5t}{r_{i2} + 0.5t}\right), \quad (3.11)
\]

\[
    \text{Springback angle} = 2 \times (\alpha_1 - \alpha_2). \quad (3.12)
\]

The above parameters in the present roll forming trial are shown in Table 3.9.

**Table 3.9** Parameters to calculate springback angle analytically in the present V-section roll forming.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E) (GPa)</td>
<td>197</td>
</tr>
<tr>
<td>(R_{P0.2}) (MPa)</td>
<td>575</td>
</tr>
<tr>
<td>(R_m) (MPa)</td>
<td>954</td>
</tr>
<tr>
<td>(\varepsilon_{gl})</td>
<td>0.106</td>
</tr>
<tr>
<td>(t) (mm)</td>
<td>2</td>
</tr>
<tr>
<td>(r_{i1}) (mm)</td>
<td>15</td>
</tr>
<tr>
<td>(\alpha_1) (mm)</td>
<td>50</td>
</tr>
</tbody>
</table>

The springback angle predicted using different mesh configurations or the above analytical approach are shown in Table 3.10.
Comparing the results of above table to Table 3.4 and Table 3.7 shows that refining the mesh density has a minor effect on springback angle prediction in the models with solid and solid-shell elements which confirmed the initial mesh density in accurate enough to predict the springback angle. The springback angle in the models using thin-shell or thick-shell elements are almost the same and similar to the model using solid-shell element which shows that solid-shell element can predict the springback angle in the present roll forming process correctly and using shell elements will not change the springback angle prediction in FEA.

Analytical prediction of springback angle is slightly higher than the FEA results using shell or solid-shell elements. The above analytical equations refer to springback angle prediction in a bend test while FEA shows the springback angle in the roll forming. Previous studies [150] showed that springback angle in the bending is more than the springback angle in roll forming for a similar cross section, which can explain why the springback prediction in the analytical method is slightly higher than FEA results. The springback angle is the experiment is still higher than FEA or analytical prediction results.

The above investigation on springback angle prediction in FEA and analytical approach suggests that there might be some other parameters in the experiment which increase the springback angle and those parameters were not taken into account in the current roll forming model.

Roll gap (distance between upper and lower rolls) is one of the most important parameters which can affect the springback angle in the roll forming. The roll

**Table 3.10** Springback prediction for different configurations in FEA and the analytical approach.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Thin-shell</th>
<th>Thick-shell</th>
<th>III</th>
<th>IV</th>
<th>Analytical</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Springback $\Delta \theta^\circ$</td>
<td>8.2</td>
<td>8.1</td>
<td>8.2</td>
<td>6.9</td>
<td>8.7</td>
<td>11.3 ± 0.5</td>
</tr>
</tbody>
</table>
gap is directly depends on shaft deflation in the roll forming process and
deflection of the shafts increases the roll gap which leads to higher springback
angle [64]. Therefore, shaft deflection will be measured in the experimental
arrangement and shaft deflection compensation will be considered in the next
section to make the FEA arrangement closer to the reality.

3.4.8.5 Shaft deflection compensation

A schematic of the industrial roll former which was used for the experimental
trials is shown in Figure 3.42. The ideal roll gap in various stations,
$G_1, G_2, G_3, G_4, G_5$ in Figure 3.42, is the same as material thickness which is 2
$mm$ in the present roll forming line.

![Figure 3.42](image)

Measuring the roll gap in various stations during the experimental trials in the
loading condition showed that the gap increases in the roll forming operation
due to shaft deflection. The actual roll gap during the forming process in each
station was more than the designed gap in the unloading condition (more than
2 $mm$ in the present roll forming line).

The roll gap was exactly 2 $mm$ in FEA and this difference might be one reason
for the discrepancies between experimental and FEA results. To make the
finite element simulation closer to the reality, the shaft deflection
compensation approach was used. The experiments were repeated considering the deflection of the shafts in various stations. It means the roll gap in each station in unloading condition decreased by the same value of the roll gap increase due to shaft deflection so that the operating roll gap in various stations during the roll forming experiments was 2 mm.

A comparison between the finite element simulation results using two different friction coefficients with solid-shell element (the models of Section 3.4.8.3) and the experimental data considering shaft deflection for edge strain and bow measurement are shown in Figure 3.43 and Figure 3.44 respectively. The results show that the longitudinal peak strain and the residual strain in the model with friction coefficient of 0.1 is lower than the model with friction coefficient of 0.15 and the longitudinal strain results of the model with friction coefficient of 0.1 are closer to experimental data (especially for residual longitudinal strain). The maximum bow height in the model with friction coefficient of 0.1 is also lower than that predicted by the numerical model using friction coefficient of 0.15.
Figure 3.43 Edge strain measurement in the models with one solid-shell element through the thickness with various friction coefficients and considering shaft deflection compensation in the experiment, the residual longitudinal (edge) strain can be seen from length 2500mm onwards.

Figure 3.44 Bow measurement for the models with one solid-shell element through the thickness with various friction coefficients and considering shaft deflection compensation in the experiment. A comparison between Figure 3.44 and Figure 3.37 shows that the maximum bow height in the experiment reduces if the shaft deflection compensation is considered. Considering the shaft deflection compensation, the model with
friction coefficient of 0.1 provides the highest model accuracy to predict bow and longitudinal strain.

The springback angle prediction is shown in Table 3.11. This table shows that shaft deflection has a vital effect on springback angle and the springback angle in FEA is now very close to the experiment. Increase of the roll gap in the experimental arrangement due to the shaft deflection leads to more springback in final product. Springback angle reduced by considering the shaft deflection compensation in this thesis (the springback angle was $11.3^\circ$ without the shaft deflection compensation).

<table>
<thead>
<tr>
<th>Friction coefficient ($\mu$)</th>
<th>Solid-shell</th>
<th>Solid-shell</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>0.1</td>
<td>$8.8 \pm 0.5$</td>
<td>$8.8 \pm 0.5$</td>
</tr>
</tbody>
</table>

Table 3.11 Springback angle in the models using one solid-shell element through the thickness and considering shaft deflection compensation in the experiment.

Edge strain, bow and springback prediction results considering the shaft deflection in the experiments indicate that shaft deflection compensation will decrease the discrepancy between FEA and experiment for edge strain, bow, and springback prediction. A reasonable accuracy was achieved to predict those parameters using solid-shell element in numerical simulation with 11 integration points through the thickness and friction coefficient of 0.1 in the model.

3.4.9 Summary

One solid element through the thickness for the simulation of a roll formed strip has been typically used by many researchers. However, it is not possible to implement a residual stress profile through the thickness by using one solid element in thickness direction. Using one layer of solid-shell elements in the model is an alternative way in which the residual stresses can vary at each integration point of this element. Multiple layers of solid elements can be also
used to simulate the strip and vary the initial residual stresses through the thickness, however this is computationally expensive. This chapter showed that a solid-shell element provides benefits with regard to forming behaviour and computational time, it also enables residual stresses to be included in a simulation. An in depth study using solid-shell elements for roll forming simulation was presented.

It was found that for the simple case of roll forming a V-section with a large profile radius, including friction in the finite element simulation led to higher permanent residual longitudinal strain in the strip edge and to higher bow. This thesis shows that considering friction does not have a significant effect on springback prediction in FEA and the predicted springback angle is higher and closer to experimental results in the models (for both the friction and frictionless cases) that use solid-shell element compare to the models use solid element.

The accuracy of roll forming models was improved if the effect of friction is included compared to using a frictionless contact condition. The obtained results of using three layers of solid elements or one layer of solid-shell elements had similar model accuracy, while the use of solid-shell elements led to a significant reduction in CPU time. So, applying solid-shell element in finite element simulation of a roll forming process to capture the effect of pre-existing residual stresses in the material is more practical compare to use of a model with multiple layers of solid element.

Increasing the number of integration points through the thickness in the model use solid-shell element can improve the model accuracy and eleven integration points were used in the final model arrangement of this thesis.

The results from the current simulations on a simple V-channel roll forming process also showed that mesh density has effect on springback prediction (especially in the model with multiple layers of solid element). The springback
angle prediction in the models use shell element was similar to the models use solid-shell element. So solid-shell element is an appropriate element type to capture the shape defects in the present V-section roll forming process with large profile radius.

Shaft deflection in the experiment had a crucial effect on the shape defects especially the springback angle in the roll forming of a V-section channel. Shaft deflection compensation showed that deflection of the shafts increases the roll gap and leads to higher springback angle in the experiment.

In conclusion, the above numerical and experimental results show solid-shell element with an arbitrary number of integration points through the thickness leads to acceptable simulation accuracy in the current roll forming arrangement and may therefore be used in roll forming simulations that need to take into account a pre-existing residual stress profile in the metal strip. Nevertheless this thesis was performed on the very simplified case of roll forming a V-section with a large profile radius and is therefore not necessarily representative of complex roll forming applications. Further work is needed to prove the functionality of solid-shell element for the numerical simulation of industrial roll forming processes.
Chapter 4

Effect of Residual Stress on a Roll Forming Process

4.1 Introduction

Temper rolling is heavily used in steel processing to eliminate ageing and waviness [15], and previous studies have shown that the process introduces permanent residual stresses through the material thickness [29]. A thickness reduction rolling process available at Deakin that leads to material deformation similar to an industrial temper rolling operation will be used in this chapter to introduce residual stresses into a metal strip. The initial and thickness reduced material will then be used in the experimental V-section roll forming set-up previously introduced in Chapter 3 (Section 3.4.2) to identify the effect of residual stress on the final shape. It has been shown in the previous chapter that a solid-shell element can be used to simulate bending and the roll forming processes with acceptable model accuracy. The numerical model of the V-section roll forming process introduced in Section 3.4.7 will be applied in this section for the fundamental analysis of the effect of residual stress on the material behaviour in roll forming. To the author’s knowledge this is the first time the effect of pre-existing residual stress on final part shape in a roll forming process has been investigated. The FEA results will be compared to the experimental data for validation. It will be shown that using material data delivered from tensile test is not sufficient enough to capture the
shape defects in a roll forming process if a residual stress profile exists in the material. Therefore, including the residual stress information leads to improved model accuracy in roll forming simulation.

The commercial software package MSC-Marc (which is an implicit solver) will be used in all finite element simulations within this chapter. Three different numerical models will be applied.

1. **Combined Model:** In this model the thickness reduction rolling and the roll forming process will be simulated in a single 3D analysis. In this way the incoming material used in the roll forming simulation has the full stress–strain history from the thickness reduction model. This model is expected to give the highest model accuracy and can be considered as a reference model.

2. **Tensile Model:** In a practical roll forming simulation, material input based on the conventional tensile test is usually applied to define the material model in FEA and the 0.2% yield offset approach is often used to determine material yield. In this model the tensile testing of the roll forming material before and after thickness reduction is numerically modeled and the 0.2% method used to determine yield and to generate material input data. The thickness reduction rolling and tensile steps are in a single 3D analysis. The generated data set is then applied to numerically analyse the roll forming process. This represents the approach currently used in the industry, and a comparison with the combined model will show if the reduced model leads to sufficient model accuracy if residual stress exists in the material.

3. **Initial Condition Model:** A 3D simulation of the steel processing methods applied such as the temper rolling is time consuming and generally detailed information about the pre-processing condition is not available. An inverse routine will be introduced in Chapter 6 that will estimate the pre-existing residual stress profiles in incoming steel
4.2 Effect of residual stresses in roll forming

Above three model configurations are compared in Table 4.1.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Material data for roll forming simulation</th>
<th>How to include the effect of thickness reduction in roll forming model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined Model</td>
<td>Tensile test of stress relieved material</td>
<td>Material has full stress–strain history from the thickness reduction step</td>
</tr>
<tr>
<td>Tensile Model</td>
<td>Tensile simulation of thickness reduced material</td>
<td>Only tensile data of thickness reduced material is used</td>
</tr>
<tr>
<td>Initial Condition Model</td>
<td>Tensile test of stress relieved material</td>
<td>Residual stress information after thickness reduction rolling will be used as an initial condition</td>
</tr>
</tbody>
</table>

4.2.1 Stress relief annealing, thickness reduction rolling, and roll forming experiments

DP780 strips with a thickness of 2 mm were used in the experimental part of this chapter. The length and width of the strips were 1000 mm and 75 mm respectively. The incoming material was heat-treated at 300°C for 40 minutes in a Binder fan forced oven [151] (Figure 4.1.a) followed by air cooling to eliminate any pre-existing residual stresses (Figure 4.1.b). The oven allowed for 6 samples to be heat treated at the same time with an air flow to all sample surfaces leading to a uniform stress relief annealing.
Thickness reduction rolling, with rolls being 200 mm in diameter and a roll speed of $\omega_{\text{roll}} = 3.456 \, \text{rad/s}$, was used in the experiment to introduce a residual stress profile into the stress relieved material. Thickness reductions of approximately 0.5\%, 1.5\%, and 2.5\% were performed in the thickness reduction rolling process using a thin layer of oil lubricant to achieve a uniform thickness reduction in the samples (Figure 4.2.a).

Roll forming trials of thickness reduced and non-thickness reduced material were performed to determine the effect of the level of thickness reduction and through that residual stress on part shape and quality (Figure 4.2.b). The experimental roll forming process set-up is similar to that introduced in Section 3.4.
4.2 Effect of residual stresses in roll forming

Figure 4.2 Experimental procedure to compare the final shape defects in the thickness reduced and non-thickness reduced strips a) thickness reduction rolling process of stress relieved material b) roll forming trial of a thickness reduced sample.

4.2.2 Experimental procedure to get material data for FEA

Standard tensile tests similar to Section 3.3.3.1 were performed to obtain the input material properties of the stress relieved DP780 strips for FEA. A total of 3 tests were performed and one of the repeatable results was used. The yield stress is determined using the 0.2% offset approach (see Figure 4.3).

Figure 4.3 True stress–true strain curve of the stress relieved DP780 steel obtained from the tensile test.
The yield stress is $665\, MPa$, and the Young's Modulus is $203\, GPa$. The Poisson’s ratio was set to 0.3 [139, 140] for FEA. The true stress–effective plastic strain curve obtained from the standard tensile test is given in Figure 4.4. A small ageing region can be seen, which is due to the stress relieving process. A finite element simulation of the roll forming process using material input with and without the ageing region showed no considerable effect on the final result; so all numerical simulations were performed using the full curve of Figure 4.4 to represent the strain hardening behaviour of the material. An Isotropic hardening material model was applied for all the numerical simulations.

![Figure 4.4](image)

**Figure 4.4** True stress–effective plastic strain curve of the stress relieved DP780 steel.

### 4.2.3 Thickness reduction rolling simulation

The thickness reduction rolling process of the Section 4.2.1 was modelled in the FEA. The boundary conditions of this model are shown in Figure 4.5. Two solid-shell elements (Element type 185 [138]) with 11 integration points (as this number gave converged results in Chapter 3) through the material thickness were used for simulating the strip. The rolls are modeled as rigid bodies and frictionless contact was assumed.
4.2 Effect of residual stresses in roll forming

**Figure 4.5** Boundary conditions in the thickness reduction rolling model.

The roll geometry is the same as in the experimental trial explained in Section 4.2.1 but only half of the strip is modelled in the $X$ direction to save calculation time. So, the length, width, and thickness of the strip are 1000 mm, 37.5 mm, and 2 mm respectively. All nodes in the mid-surface of the metal strip are fixed in $Y$ direction, while the nodes at the mid-surface of the strip front plane are fixed in $Z$ direction to prevent the strip from moving. The two rigid rolls (diameter of 200 mm) are moved over the strip in $Z$ direction with a the speed of $V_{\text{roll}} = 345.6$ mm/s and rotate at $\omega_{\text{roll}} = 3.456$ rad/s. This keeps the slip between the rolls and the strip at zero following

$$\omega_{\text{roll}} = V_{\text{roll}}/r_{\text{roll}},$$ \hspace{1cm} (4.1)

with the roll radius $r_{\text{roll}}$.

The amount of cold work introduced into the steel during steel making can be quantified using residual stresses and accumulated plastic strain [87]. The accumulated plastic strain represents the strain hardening effect due to cold work. In most numerical modelling of cold formed sections the effect of residual stress has been considered without the consideration of accumulated plastic strain in the material [90, 152, 153]. Since residual stresses are always
accompanied with strain hardening, the combined effect of residual stress and accumulated plastic strain should be considered in the FEA to take into account the effect of a cold work operation such as thickness reduction rolling. The effect of cold work on column behaviour was examined in [87] by combining the influence of residual stress and accumulated plastic strain in the numerical simulation. It was shown that residual stress usually has a negative effect on the strength of a steel column while the effect of accumulated plastic strains is mostly positive. The strength of a steel column can enhance or diminish due to the combined effect of residual stresses and accumulated plastic strains.

Therefore, for numerical investigation of this thesis, the residual stresses and accumulated plastic strains in the material will be recorded after thickness reduction rolling to represent the amount of cold work. This information can be used in the Initial Condition Model to represent the effect of thickness reduction rolling on the material behaviour of the incoming strip in the roll forming simulation.

The residual stress and the accumulated plastic strain were recorded at various integration points through the thickness at the middle of the strip in longitudinal and width direction when the thickness reduction rolling simulation finished. Figure 4.6.a shows the path through which that information was recorded. A section view of the strip is shown in this figure. The strip that was modelled is fully rectangular (1000 mm × 37.5 mm) but for better visualization some elements of the strip are deleted in this figure.

Nodes A and B are located on the bottom and top surfaces respectively and residual stresses, and accumulated plastic strains were recorded in various integration points over path AB. Each element has 11 integration points through the thickness and there are two elements in thickness direction of the
strip, so data was recorded in 22 integration points as a function of the normalised strip thickness (see Figure 4.6.b).

4.2.4 Combined Model: thickness reduction rolling-roll forming simulation in a single 3D model

This numerical analysis has two steps; the thickness reduction rolling process is simulated in the first step (this step has been explained in the previous section), and the roll forming step (step two), which has the same boundary conditions as the V-section roll forming model with friction introduced in
Chapter 3 (Section 3.4.7). Both the thickness reduction rolling step and the roll forming step are simulated in a single 3D analysis and the roll forming step starts when the thickness reduction rolling step finishes (see Figure 4.7).

The rigid rolls pass the fixed strip in the thickness reduction rolling step and when this step finishes, the strip is fed into the forming rolls for roll forming simulation. So the strip has the full stress and strain history from the thickness reduction rolling step at the first increment of the roll forming step. The roll forming simulation of the material without thickness reduction does not have the first step and the strip is just roll formed. The friction coefficient between the strip and the rigid rolls in the roll forming process is 0.2 while this coefficient is 0 in the thickness reduction rolling step.
4.2 Effect of residual stresses in roll forming

4.2.5 Analysis of shape defects

The longitudinal bow, springback angle and end flare were compared in the roll forming process using non-thickness reduced material and the materials that were thickness reduction rolled. An EXAscan high resolution 3D scanner [146] was used to scan the formed sections and measure the bow curvature over the length of the part (same procedure as used in Section 3.4.4), while an angle gauge was used in the experiment to measure the springback and the end flare in the formed sections.

The definition of longitudinal bow, and springback were explained in detail in Chapter 3. End flare is defined in this chapter as the difference between the angles of the formed section measured 10 mm inwards from the front of the strip and the angle determined at the middle of the strip (see Figure 4.8). End flare was determined at the end of the roll forming process when the strip was fully unloaded.

![Figure 4.8: End flare measurement.](image)

4.2.6 Variation of longitudinal strain and residual stress across the width

To further understand the relationship between the thickness reduction and the maximum bow height in the formed sections, the final longitudinal strain was numerically determined in the centre of the section across the width of the strip (Nodes $M_1$ to $M_9$ in Figure 4.9).
The relationship between the thickness reduction and the end flare in the formed sections was explored by recording the residual stresses in the product at the end of roll forming process. The final longitudinal stress was determined across the width of the strips at the section points where the end flare was measured, i.e., from 10 mm away from the front edge (Nodes $F_1$ to $F_9$ in Figure 4.9).

![Figure 4.9 Nodes across the width of the strip a) node $M_1$ to node $M_9$ in which the final longitudinal strain was recorded b) node $F_1$ to node $F_9$ in which the final stress was recorded.](image)

**4.2.7 Results and discussion**

**4.2.7.1 Residual stress and accumulated plastic strain in the strip after the thickness reduction rolling process**

The residual stress profiles through the thickness after thickness reduction rolling can be seen in Figure 4.10. It is shown in this figure that thickness reduction rolling leads tensile residual stress at the material surface, and compressive residual stress in the center for all thickness reduction levels. The residual stress profiles are symmetric over the sheet thickness and in qualitative agreement with results presented previously for the temper rolling
of steel [6, 29, 36, 89] for similar thickness reduction levels as analysed in this section.

**Figure 4.10** Residual stress profile through the material thickness for various thickness reduction levels.

The stress variation through the thickness of the strip during the thickness reduction rolling process is shown in Figure 4.11. It is shown in this figure that when the strip is passing the rolls (loading condition) the surface of the strip undergoes compressive stress while the centre is under tension. When the strip passes the rolls, elastic recovery takes place through the thickness of the material leading to tensile stress in surface and compressive stress in the centre. The final residual stress through the thickness of the strip is a combination of the loading stress and the elastic recovery. This figure shows that the final residual stress is tensile in the surface and compressive in the centre of the strip.
It was shown in [36] that thickness reductions above 0.5% generally lead to tensile residual stress in the surface and compressive stress in the middle of the strip and that the surface residual stress increases with thickness reduction level. The FEA results of the current study indicate the same trend but the surface residual stress after a 1.5% thickness reduction is slightly higher compared to that observed with a thickness reduction of 2.5%. It is also shown in Figure 4.10 that the residual stress in the centre of the strip increases with thickness reduction which is in an agreement with [29] for the temper rolling of mild steel with 1.27 mm thickness on a 254mm×254mm rolling mill using dry rolls.

When there are not any external forces on the material, the internal stresses have to be balanced. It can be seen in Figure 4.10 that the integral of the residual stresses over the normalised thickness of the material is approximately zero at various thickness reduction levels. This means

$$\int_0^1 \sigma_z dy \approx 0,$$

where $y$ is the normalised thickness.

The accumulated plastic strain through the strip thickness is shown for various thickness reduction levels in Figure 4.12.
4.2 Effect of residual stresses in roll forming

Figure 4.12 Accumulated plastic strain profile through the material thickness for different thickness reduction levels.

The above figure shows an increasing thickness reduction level leads to higher plastic strains and accumulated plastic strains. It can be seen in this figure that the accumulated plastic strain in the center of the strip is more than this value at the surface for each thickness reduction level.

4.2.7.2 The effect of thickness reduction rolling on final shape in roll forming

This section will compare the effect of thickness reduction rolling on the final part shape and shape defects for the roll forming of a V-section profile. The maximum bow height, springback and end flare were determined for the Combined Model and compared to the experimental results.

Figure 4.13 shows that the maximum bow height decreases with increasing thickness reduction levels in both the FEA and the experimental results. For instance, a 2.5\% thickness reduction in the experiment decreases the maximum bow height by 22.7\% compared to the initial non-thickness reduced condition. It also becomes obvious that there are some discrepancies between the FEA and the experimental results and this will be addressed later.
Figure 4.13 Comparison between the maximum bow height predicted by the Combined Model and the experimental results.

The longitudinal strain variation across the width of the strip, see Figure 4.9, for various thickness reduction levels is shown in Figure 4.14.a, while Figure 4.14.b shows the difference between longitudinal strain at the edge (node $M_0$) and the middle of the strips (node $M_1$).

Figure 4.14 shows that for the non-thickness reduced material, longitudinal strain at node $M_1$ (symmetry line) is compressive while at node $M_0$ (edge) it is tension. In contrast to that the final longitudinal strain at the edge and at the symmetry line is tensile for all the thickness reductions.
It was previously shown in Figure 4.10 that thickness reduction rolling leads to tensile residual stress at the strip surface. This initial tensile stress adds additional tensile strain to the surface of the material after the roll forming simulation (see Figure 4.14.a). Higher permanent tensile strain exists at the edge of thickness reduced material compared to the material without
thickness reduction and the final strain along the symmetry line is also tensile in the thickness reduced material, while the non-thickness reduced one had compressive permanent strain along the symmetry line. Final residual stress due to thickness reduction rolling at the surface of the material with 1.5% thickness reduction is higher than the other thickness reduced samples. This can explain why a greater tensile permanent strain is observed across the width of this strip after the roll forming process.

It is also shown in Figure 4.14.b that thickness reduction rolling reduces the difference between the final longitudinal strain at the edge and the middle of the strip. This may be due to the increase in the yield strength of the material after thickness reduction rolling or the observation of residual stresses in the thickness reduced materials (this will be addressed later).

A comparison between Figure 4.13 and Figure 4.14.b shows as the final longitudinal strain variation across the strip width increases, there is an increase in the difference between longitudinal strain at the edge and the symmetry line. This increasing difference in the longitudinal strain also correlates with higher maximum bow height. The non-thickness reduced material has the most difference and the maximum bow height is higher in this model compared to the other samples, while this difference is lowest for 2.5% thickness reduced sample and the bow height is also at a minimum.

It was explored in [11] that longitudinal bow in a roll formed section is due to the non-uniform distribution of the membrane strain across the cross section of the product. Figure 4.15 shows how the magnitude and direction of bow follows the variation in distribution pattern of the longitudinal strain. When the flange of the strip undergoes a tensile longitudinal strain and compressive longitudinal strain exists in the web downwards bow will be observed (Figure 4.15.a) while a uniform distribution of longitudinal strain leads to a straight section (Figure 4.15.b).
4.2 Effect of residual stresses in roll forming

The springback angles determined for the various thickness reduction levels are shown in Figure 4.16. Both the FEA and the experimental results show that the final springback angle increases with increasing thickness reduction rolling level. For instance, a thickness reduction of 2.5% increases the springback angle by 11% in the experiment compared to the initial material.

It was shown in [11] that the springback angle in a roll forming process increases with the yield strength of the material. Thickness reduction rolling introduces plastic deformation in the material and this leads to an increased yield stress and through that increased springback. There is a slight decrease in the springback angle for the 0.5% thickness reduction in the FEA compared to the non-thickness reduced condition; this may be due to early yielding. The level of plastic deformation for this thickness reduction level is low and the effect of residual stresses is dominant. Residual stresses in the material diminish the yield strength of the material [6] and a decrease in yield strength may have led to the slight reduction of the springback angle after 0.5% thickness reduction rolling. There are some discrepancies between the FEA
and experimental, but overall the trend of springback angle variation with thickness reduction level is comparable.

**Figure 4.16** Comparison between the springback angle prediction of Combined Model to the experimental results.

The comparison of end flare between the FEA and experimental results is shown in Figure 4.17.

**Figure 4.17** Comparison between the end flare prediction of Combined Model to the experimental results.
Both, the FEA and the experiment show that the front of the formed section closes due to flaring in (negative value for end flare) and that the overall level of end flare increases with thickness reduction. For example the experimental end flare increases by 20.5% after a thickness reduction of 2.5% in the material. There is a good agreement for end flare between the FEA and the experimental results.

The variation of the final longitudinal stress across the width of the strip, nodes \( F_1 \) to \( F_5 \) in Figure 4.9, for various thickness reduction levels is shown in Figure 4.18. It becomes clear that across the width the variation of the longitudinal stress is higher in the thickness reduced samples compared to the strip without thickness reduction. A comparison between Figure 4.17 and Figure 4.18 shows the greater the variation of longitudinal stress across the width of the formed section, the greater is the final end flare in the product.

![Figure 4.18 Variation of final longitudinal stress across the width for various thickness reduction levels.](image)

It was shown in [11, 154] that residual stresses in a roll forming process make themselves apparent with greater variation at the ends of the part. Residual
stresses at the ends of the part leads to end flare, which is in agreement with the obtained results of this thesis.

It can be concluded that the maximum bow height decreases with increasing thickness reduction level, while springback and end flare increase. Both the FEA and the experiments show the same trend for the effect of thickness reduction on the final shape defects, so the FEA results are accurate enough to capture the effect of thickness reduction rolling on the final shape in the roll forming simulation. There are some discrepancies between the FEA and the experimental results, especially with regard to the maximum bow high and the prediction of springback. Some possible explanations for these discrepancies are given below.

- The DP780 steel was heat-treated at 300°C in the stress relieving process. This temperature was chosen so that the internal phases of the material do not change. Therefore, the material is not fully stress relieved and there may still be some residual stresses in the material that might affect the final results.

- A simple isotropic hardening material model was used in the FEA. It was shown in [155] that the elastic modulus of the DP780 steel changes when the material undergoes plastic deformation and this affects final shape in the V-section roll forming process. The material in the thickness reduction rolling is compressed and released. So, using a more complicated material model such as a combined material hardening model or including the evolution of elastic modulus with plastic deformation in the material may improve the accuracy of the results.

- Chapter 3 showed that shaft deflection in the industrial roll former which was used for the roll forming experiments can change the final product quality. Although shaft deflection compensation was
considered in the experiments, it may still have some effects on final shape.

4.3 A simplified model

4.3.1 The Tensile Model: Using the tensile material data of thickness reduced samples to simulate the roll forming process

The tensile testing of the roll forming material before and after thickness reduction is numerically modeled and the 0.2\% method used to determine material yield and to generate material input data for a roll forming simulation. A schematic diagram of this approach is shown in Figure 4.19. Various thickness reduction levels will be simulated, the tensile simulation of thickness reduced material will then be applied to determine the material data for the numerical simulation of the roll forming process. This will show if material data based on the conventional tensile test is sufficient to accurately predict shape defects in the roll forming of sheet material show a pre-existing residual stress through the material thickness.

![Figure 4.19](image)

*Figure 4.19* Schematic diagram of the Tensile Model a) thickness reduction rolling b) tensile analysis c) roll forming simulation.

The finite element simulation of the standard tensile test was performed using the sample geometry shown in Figure 4.20 which is equivalent that used for the experimental tensile trials performed in Section 4.2.2.
Both the thickness reduction rolling and the tensile steps were simulated in a single 3D analysis. The tensile step starts when the thickness reduction step finishes. The strip in the thickness reduction step therefore needs to have the same geometry and mesh density of the strip used for the analysis of the tensile test (two solid-shell elements with 11 integration points were used through the thickness of the strip).

The boundary conditions in the thickness reduction rolling model are the same as used in Section 4.2.3. In the tensile test, the nodes on the surface of the lower clamped region are fully fixed while an external force is applied to the nodes on the surface of the upper clamped region (see Figure 4.21).

Figure 4.20 Geometry of the sample in the standard tensile test.

Figure 4.21 Finite element simulation of the tensile test.
4.3 A simplified model

The external load will increase from 0 to 600N on each node during the tensile test. There are 39 nodes in the top surface so the total force increases from 0 to 23400N. The tensile properties of the material were investigated in the same way as it would be done in an experimental tensile test. The displacement of the two nodes which are shown in Figure 4.21 were recorded to determine the tensile strain. The true stress-true strain data in the tensile simulation can then be calculated as below.

\[ \varepsilon_{\text{eng}} = \frac{\Delta l}{l}, \]  
\[ \sigma_{\text{eng}} = \frac{F}{A}, \]  
\[ \varepsilon = \ln(1 + \varepsilon_{\text{eng}}), \]  
\[ \sigma = \sigma_{\text{eng}}(1 + \varepsilon_{\text{eng}}), \]

where \( \Delta l, l, \varepsilon_{\text{eng}}, F, A, \sigma_{\text{eng}}, \varepsilon, \) and \( \sigma \) are the displacements of two selected nodes, the initial distance between two selected nodes, the engineering strain, the total force recorded on the top surface, the area of the top surface, the engineering stress, the true strain, and the true stress respectively.

The true stress-true strain material data of the thickness reduced strips obtained from the tensile simulation, similar to Section 4.2.2, are then used in the numerical simulation of the V-section roll forming trial.

The element type, mesh density and boundary conditions of the roll forming simulation used in this section are the same as used for the roll forming analysis in the Combined Model of Section 4.2.4. Therefore the material in the roll forming process has the same element type, mesh density, and boundary conditions as used in the Combined Model. However, instead of including the full stress-strain history from the thickness reduction process, as it was done
for the Combined Model, in the Tensile Model only material input based on the artificial tensile test data generated for the three different thickness reduction levels will be used for the roll forming simulation.

### 4.3.2 The Initial Condition Model: Using the residual stress and accumulated plastic strain due to thickness reduction rolling as an initial condition to simulate the roll forming process

The roll forming model that was used in this section is the same as the roll forming models of Sections 4.2.4, and 4.3.1. Material properties (DP780 steel without thickness reduction), element type, mesh density, boundary conditions, and geometry of the strips are the same as those used in the two previous models. However, in contrast to the previous two models the residual stresses and accumulated plastic strains determined in Section 4.2.7.1 (see Figure 4.10, and Figure 4.12) were used as initial material condition in roll forming simulation to include the effect of thickness reduction rolling (see Figure 4.22).

![Figure 4.22 Using residual stresses and accumulated plastic strains due to thickness reduction rolling as an initial condition in the roll forming process.](image)

*UINSTR* and *INITPL* user subroutines [156] were applied in the numerical simulation to change the residual stress and accumulated plastic strain in all integration points of all solid-shell elements representing the strip. The user
subroutines read the coordinate of each integration point in $Y$ direction from the roll forming model in the first step of the analysis and then apply the residual stress and accumulated plastic strain data based on the position of that integration point through the material thickness. After all elements have been provided with the residual stress and accumulated plastic strain information that represents the amount thickness reduction before roll forming, the roll forming simulation is started.

### 4.3.3 Results and discussion

#### 4.3.3.1 Material data from the numerical tensile test

The true stress-true strain diagrams of the thickness reduced samples obtained from the tensile simulation are compared to that of the non-thickness reduced material in Figure 4.23.

![Stress–strain diagrams for the non-thickness reduced and the thickness reduced materials (0.2% offset approach is shown).](image)

**Figure 4.23** Stress–strain diagrams for the non-thickness reduced and the thickness reduced materials (0.2% offset approach is shown).

The obtained Young's Modulus and the yield transition point for non-thickness reduced and the thickness reduced materials using the 0.2% offset approach is given in Table 4.2. This shows that the yield stress increases with thickness reduction while the Young's modulus remains constant.
Table 4.2 Yield transition point of the non-thickness reduced and thickness reduced materials in the tensile test using the 0.2% offset approach.

<table>
<thead>
<tr>
<th>Thickness reduction level (%)</th>
<th>0</th>
<th>0.5</th>
<th>1.5</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress (MPa)</td>
<td>670</td>
<td>714</td>
<td>795</td>
<td>866</td>
</tr>
<tr>
<td>Young's Modulus (GPa)</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
</tr>
</tbody>
</table>

The above data in combination with the true stress–effective plastic strain curve (see Figure 4.24) is used to define the material properties for the roll forming simulation.

Figure 4.24 True stress–effective plastic strain diagrams for the non-thickness reduced and the thickness reduced materials.

4.3.3.2 Roll forming simulation results

The experimental validation, Section 4.2.7.2, showed that the Combined Model is sufficiently accurate to capture the effect of residual stress on the shape defects in a roll forming process. Therefore only a comparison between the numerical results of the Tensile Model and the results of Initial Condition Model with the Combined Model will be performed in this section.
The results for maximum bow height are shown in Figure 4.25. All approaches predict a reduction in the maximum bow height with increasing thickness reduction.

![Figure 4.25](image)

**Figure 4.25** Maximum bow height in three model configurations for various thickness reduction levels.

To further understand the effect of residual stress on bow, final longitudinal strain was recorded across the width as previously performed in Section 4.2.7.2 (see Figure 4.9).

The longitudinal strain variation across the width of the strip for various thickness reduction levels, and the difference between longitudinal strain at the edge (node $M_0$) and the middle of the strips (node $M_1$) are shown in Figure 4.26, and Figure 4.27 for the Tensile Model and the Initial Condition Model respectively.
Figure 4.26 A comparison between various thickness reduction levels in the Tensile Model for a) longitudinal strain across the width of the strip b) difference between longitudinal strain at the edge and the middle of the strip ($\varepsilon_{M_0} - \varepsilon_{M_1}$).
A comparison between various thickness reduction levels in the Initial Condition Model for a) longitudinal strain across the width of the strip b) difference between longitudinal strain at the edge and the middle of the strip ($E_{M_0} - E_{M_1}$).

Figure 4.27 A comparison between Figure 4.14, Figure 4.26, and Figure 4.27 shows that the difference between longitudinal strain at the edge and the middle of the strip decreases with increasing thickness reduction level in all three model configurations. The maximum bow height also decreases with thickness reduction which confirms the theory that a higher longitudinal strain variation
across the strip width leads to higher maximum longitudinal bow height in the sample.

A decrease in the longitudinal strain variation across the width in the Tensile Model shows that increasing the yield strength of the material due to thickness reduction rolling is the main reason of the decrease in the strain variation. The permanent longitudinal strain across the width in the Initial Condition Model is close to the Combined Model, which confirms the effect of initial tensile residual stress at the surface on permanent longitudinal strain after roll forming (it was discussed in Section 4.2.7.2). If the Tensile Model is used, the permanent longitudinal strain across the width in the thickness reduced samples stays close to the material without thickness reduction (final strain is compressive at the symmetry line and tensile at the flange edge for all strips in Figure 4.26). Thus the higher permanent longitudinal strain across the width of the thickness reduced samples (due to existence of initial tensile residual stress at the strip surface) will further decrease the maximum bow height in the Combined Model and the Initial Condition Model.

It can be concluded that the final bow height in the formed section is a combination of the effect of the magnitude of permanent longitudinal strain at the strip surface and the longitudinal strain variation across the width of the strip. The higher is the permanent longitudinal strain at the surface or the less is the variation of longitudinal strain across the width, the lower is the maximum bow height. The permanent longitudinal strain at the surface and the strain variation across the width in the Initial Condition Model are closer to the Combined Model compared to the results of Tensile Model. This can explain why the bow height prediction is more accurate in the Initial Condition Model.

Only longitudinal residual stresses were considered in the Initial Condition Model while the material in roll forming simulation using a Combined Model
also has normal and shear residual stresses in other directions that can lead the small discrepancy between the results of Combined Model and Initial Condition Model for bow prediction in Figure 4.25.

The springback angle predictions for the various model configurations is shown in Figure 4.28. The results achieved with all three models are similar. For the thickness reduction level of 0.5% springback is slightly lower in the Combined and Initial Condition Models compared to the Tensile Model. This again could be the result of a slight decrease in material yield strength due to the effect of residual stress. It can be concluded from this figure that the springback angle variation in the present roll forming process is mainly due to a change in yield strength of the material which can be captured by conventional tensile input and that including residual stress information will not significantly affect the springback angle prediction.

![Figure 4.28 Springback angle in three model configurations for various thickness reduction levels.](image)

The end flare prediction are compared in Figure 4.29. It is shown in this figure that good accuracy can be achieved using the Initial Condition Model in the
case of 0.5% thickness reduction but there are some discrepancies for other thickness reduction levels and this needs more investigation.

Figure 4.29 shows that end flare reduces by increasing the strength of material in the Tensile Model. Closer results to the Combined Model was achieved by using the Initial Condition Model.

The variation of the longitudinal stress in the front of the strip across the strip width as previously analysed in Section 4.2.7.2 (nodes $F_1$ to $F_9$ in Figure 4.9), is shown in Figure 4.30 for the Tensile Model and the Initial Condition Model.
4.3 A simplified model

A comparison between Figure 4.18, Figure 4.29, and Figure 4.30 shows that across the width variation of longitudinal stress in the Initial Condition Model is closer to the Combined Model compared to the Tensile Model. Initial residual stress at the surface of thickness reduced material changes the final longitudinal stress variation after a roll forming process if the Combined Model or Initial Condition Model are used. Whereas the across the width

**Figure 4.30** Variation of longitudinal stress across the width for various thickness reduction levels a) Tensile Model b) Initial Condition Model.
variation of longitudinal stress in the thickness reduced samples is similar to the material without thickness reduction in the Tensile Model.

The decrease in the end flare with increasing thickness reduction level in the Tensile Model shows that end flare decreases with increasing the yield strength of the material. However, a big discrepancy was shown in the case of 2.5% thickness reduction between the results of Tensile Model and the Combined Model. If the Tensile Model is used, then the final end flare in the 2.5% thickness reduced material is less than that measured for the material without thickness reduction; while in the Combined Model the material with 2.5% thickness reduction shows more end flare compared to the non-thickness reduced condition. The final longitudinal stress variation across the width of the strip due to thickness reduction is higher in the Combined Model compared to the Tensile Model. The Tensile Model shows similar longitudinal stress variation across the width for thickness reduced and non-thickness reduced samples. This proves the idea that more variation of longitudinal stress in the front of the strip increases the end flare. This observation can clarify why the end flare of the 2.5% thickness reduced material is more than the material without thickness reduction in the Combined Model, and is less than the end flare of the material without thickness reduction in the Tensile Model.

The end flare in the strip is a combination of the effect of an increasing strength of material due to the plastic deformation in the thickness reduction rolling process and the across the width variation of residual stress at the front of the strip. Increasing the strength of material due to plastic deformation reduces the end flare (the obtained results of Tensile Model show that), while the end flare increases due to the increase of across the width variation of residual stresses at the front of the strip.
It can be concluded that using residual stress information as an initial condition improves the accuracy of the finite element simulation in the prediction of end flare compared to applying conventional tensile test data. Only the longitudinal residual stresses were considered in the Initial Condition Model, while the material in roll forming simulation using a Combined Model also has normal and shear residual stresses in other directions that change the variation of final stress in various directions at the front of the strip after roll forming process.

The residual stresses in other directions can lead to more end flare in the roll forming process and this could be the reason for the discrepancies between the FEA predictions of the Initial Condition Model and the Combined Model. The across the width variation of shear stress $\tau_{yz}$ at the front of the strip in the Combined Model is compared to the Initial Condition model in Figure 4.31 as an example. This figure shows more variation across the width of the strip for various thickness reduction levels in the Combined Model compared to the Initial Condition Model.

The effect of various stress components at the front-end of the strip on end flare of the roll formed section was investigated in [21] and it was shown that the flare in a roll formed section after the cutting is due to the release of bending and twisting residual stresses at the front-end. Thus, it can be suggested that more variation of bending and twisting residual stresses at the front-end of the strip leads to higher end flare in the Combined Model compared to the Initial Condition Model in the results of current chapter.
Figure 4.31 Across the width variation of shear stress $\tau_{yz}$ for various thickness reduction levels a) Combined Model b) Initial Condition Model.

The difference in results between the Tensile and the Initial Condition model and the Combined Model are summarised in Table 4.3. The table suggests that especially for the prediction of bow and end flare, the Initial Condition Model delivers higher model accuracy compared to the Tensile Model.
4.4 Summary

<table>
<thead>
<tr>
<th>Table 4.3 Differences in the results between the Tensile, the Initial Condition and the Combined Model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Tensile Model</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Initial Condition Model</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The CPU time for various thickness reduction levels in the Combined Model is compared to the Initial Condition Model in Table 4.4. The processor and installed memory (RAM) of the used system are a Xeon(R) CPU E31280@3.50GHz, and 16 GB respectively. It can be seen that the use of a model with an Initial Condition leads to a reduction in CPU time.

<table>
<thead>
<tr>
<th>Table 4.4 CPU time determined in the Combined Model and the Initial Condition Model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness reduction level</td>
</tr>
<tr>
<td>CPU time (sec) in the Combined Model</td>
</tr>
<tr>
<td>CPU time (sec) the Initial Condition Model</td>
</tr>
</tbody>
</table>

4.4 Summary

Using solid-shell element with an arbitrary numbers of integration points through the thickness made it possible to simulate thickness reduction rolling and roll forming in a single 3D analysis with a reasonable computational time. Various integration points in the thickness direction of solid-shell element can be also used to change residual stresses through the thickness in a roll forming simulation to apply an initial condition in the sheet. According to the author’s knowledge, this was the first time the effect of pre-existing residual stress on final part shape in a roll forming process was investigated in-depth with regard to the literature on roll forming. It was shown that the thickness reduction leads to the introduction of tensile residual stress at the material
surface, and compressive residual stress in the mid-plane center of the sheet. The accumulated plastic strain in the center of the material after the thickness reduction rolling process is more than that in the surface. The combined effect of residual stress and accumulated plastic strain needs be used to quantify the amount of cold work in the material.

Thickness reduction rolling will increase the final springback angle and end flare in the roll forming of a V-section while the maximum bow height decreases due to the thickness reduction operation.

Thickness reduction rolling reduces the difference between the final longitudinal strain at the edge and the middle of the strip. Non-thickness reduced material has the highest strain difference and maximum bow height is also higher compared to the thickness reduced materials. In general bow height increases with variation of final longitudinal strain across the width of the strip. The magnitude of permanent longitudinal strain at the surface of the strip also changes the bow height. Existence of tensile residual stresses at the surface of the strip due to thickness reduction rolling increases the permanent longitudinal strain at the strip surface after the roll forming process. The higher is permanent longitudinal strain at the strip surface, the lower is maximum bow height. More accuracy in the results can be achieved by including the residual stress information compared to the model using only tensile test data.

The springback angle variation in the roll forming process is mainly due to change in material strength due to plastic deformation during thickness reduction rolling. This can be captured by a conventional tensile test and including the effect of residual stress in the FEA did not significantly affect the springback angle prediction.

The final end flare in the strip is a combination of the effect of an increasing material strength due to plastic deformation in the thickness reduction rolling
process and the variation of residual stresses at the front of the strip. Increasing the strength of the material due to plastic deformation reduces the end flare, while end flare increases with increasing the variation of longitudinal residual stress at the front of the strip. Including the residual stress information increased the accuracy of roll forming model to predict the end flare compared to the model which uses only tensile data.

It can be concluded that using tensile test is not sufficient enough to capture the shape defects in a roll forming process if a residual stress profile exists in the material. Including the residual stress and accumulated plastic strain information as an initial condition leads to improved model accuracy.

If the residual stress information is available for the incoming material in the roll forming process, modelling accuracy can be improved by including that information in finite element analysis. An inverse routine will be developed in Chapter 6 to obtain the residual stress information in the incoming material in a fast and simple way.
Chapter 5

Bend Test to Observe a Residual Stress Profile in Sheet Material

5.1 Introduction

The previous chapter revealed that the accuracy of numerical simulation of a roll forming process can be improved by taking into account the effect of pre-existing residual stress in the material. The tensile test is widely used in the roll forming industry to identify material parameters. However, the variation of material properties through the thickness due to the presence of residual stress cannot be accurately determined by the conventional tensile test, which involves the uniform loading over the cross-sectional area. In contrast to that in a bend test, the load varies through the thickness and this allows the observation of the non-uniform material properties in the thickness direction. In addition, the major deformation mode in roll forming is transverse bending, which is why material data from a bend test may be more relevant for roll forming applications than that determined using the conventional tensile test.

A review on previous studies focusing on identifying material properties via the bend test will be presented in this chapter. It will be shown that a new bend test arrangement needs to be developed to enable the analysis of material properties close to the yield, to clearly observe the effect of residual stresses in the material, and relevant to the roll forming process. The new
bend test device will be developed and its performance will be examined experimentally in this chapter.

The last part of this chapter will compare numerically the effect of initial residual stresses on the material response in the tensile and in the developed bend test. A detailed comparison between the effect of residual stresses on elastic-plastic transition in a bend and a tensile test is performed, to the author's knowledge, for the first time with regard to the literature. It will be shown that the bend test offers advantages for capturing the effect of residual stresses.

### 5.2 Analysing material parameters via the bend test

Buckling of the sheet in compression makes a tension–compression test difficult to get material hardening parameters. Bending and reverse bending has been used as an alternative way to determine the material hardening properties during strain reversal. However, the output from a bend test is a moment–curvature diagram, and this does not allow the generation of a tensile stress–strain curve or tension–compression material data directly from bend test; for this generally an inverse approach is needed.

Most of previous studies to get material data from a bend test focused on bending and reverse bending of the strips to define the material hardening parameters and material behaviour. The close to yield behaviour was not explored in any depth, which is important for roll forming applications [141, 157-159].

Three point and four point bend tests are standard test set-ups for obtaining mechanical bend properties from sheet material. The three-point bend test has been widely used by other researchers to obtain material data [141, 157, 158] and a special bending–unbending devices were developed by other researchers to define material properties based on a bend test [42, 43, 159-165]. The arrangement of these bending devices are shown in Figure 5.1.
5.2 Analysing material parameters via the bend test

A summary of previous bend test arrangements to obtain material data is shown in Table 5.1. The maximum strain that was shown in various studies, material thickness that was used in the test or the appropriate range of material thickness that can be used, and the bending type are summarised in this table.
Table 5.1 Previous studies to obtain material data using a bend test.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Maximum strain (%)</th>
<th>Material thickness (mm)</th>
<th>Figure of bend test arrangement</th>
<th>Bending Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eggertsen [141, 157]</td>
<td>6</td>
<td>0.7 – 1.46</td>
<td>5.1.a</td>
<td>Three point bend</td>
</tr>
<tr>
<td>Zhao [158]</td>
<td>4</td>
<td>1.2 – 1.4</td>
<td>5.1.a</td>
<td>Three point bend</td>
</tr>
<tr>
<td>Doig [159]</td>
<td>10</td>
<td>1</td>
<td>5.1.b</td>
<td>Bend over a radius</td>
</tr>
<tr>
<td>Duncan [42, 160]</td>
<td>–</td>
<td>0.67</td>
<td>5.1.c</td>
<td>Pure bend</td>
</tr>
<tr>
<td>Weiss [43, 165]</td>
<td>1</td>
<td>2 – 5.6</td>
<td>5.1.d</td>
<td>Pure bend</td>
</tr>
<tr>
<td>Yoshida [161, 162]</td>
<td>3</td>
<td>0.42 – 1.75</td>
<td>5.1.e</td>
<td>Pure bend</td>
</tr>
<tr>
<td>Brunet [163], Carbonniere [164]</td>
<td>10</td>
<td>0.5 – 2</td>
<td>5.1.f</td>
<td>Pure bend</td>
</tr>
</tbody>
</table>

Using a three point bending reverse test to develop material hardening models for accurate springback prediction was investigated in [141, 158] and the material hardening parameters compared to those acquired from a tension-compression in [157]. The main objective of this study was to generate the first few loops of sheet metal response in loading-reverse loading and represent the phenomena such as Bauschinger effect, and permanent softening in an advanced material model. The study showed that the test setup allows to realise outside fibre strains up to 6% but the material behaviour close to yield was not clearly analysed.

The INPRO bend test device was used by Doig et al. to define Advanced High Strength Steels (AHSS) material hardening parameters, and then to compare the springback prediction results (using INPRO bending data) to the simulation results using material data from tension-compression tests [159]. It was shown that using the bend test data an improved prediction of springback can be achieved compared to a model that uses tension-compression test data. The elastic modulus from the bend test was less than that determined in the tensile test and this was related to the elastic deflection of the bending machine. This suggests that the setup will not deliver precise
material properties close to yield. The additional problem with this approach is the large amount of contact that occurs around the bending die, it is unknown how much effect this will have on the resulting measured material properties.

A cyclic bend test was developed by Yoshida to define the parameters of a constitutive material model [161, 162]. This test set-up was able to remove the contact issue that may affect the material parameter estimation. However, it was shown that the maximum acquired curvature in the cyclic bend test was not high enough to introduce appropriate plastic strain to the strip and identify material hardening parameters. However, the aim of developed bend tester was identification of material hardening parameters such as the Bauschinger effect and material behaviour close to yield was not clearly analysed. Using a step-motor to rotate one end of the test-piece and side rails for free movement of the other end (see Figure 5.1.e) make the arrangement of the bend tester complex. Strain gauges are also required to be bonded on both surfaces of each specimen to determine the bending curvature.

It was explored in [163] that the constitutive behaviour of sheet metals subjected to complex loading paths can be modelled accurately using a bend test. Material hardening parameters from bend test were used to simulate a simple shear test in [164]. It was shown that the delivered material parameters from bend test were not able to precisely represent the material behaviour in the shear test for the low strain range, below the equivalent plastic strain of 0.1. Although, the authors’ suggested that this discrepancy was due to different saturated values to define a material model in the bending or shear test, it is not clear whether the bending device is accurate enough to detect material behaviour close to yield.

Above studies focused on high strain bending to develop material kinematic hardening parameters. The material behaviour close to yield was not the
major focus and some studies have actually shown low accuracy at low strains [158, 159, 161-164]. There has been some research work investigating the close to yield region in bending.

A bend test arrangement to obtain material properties for roll forming was introduced by Duncan et al. [42, 160] (see Figure 5.1.c); this bend tester allowed the bending of thin strip with a maximum 1 mm thickness. The objective was to bend the strip with a pure moment at the onset of plastic deformation in the outer fibres of the sample. Calculating the limit of elastic behaviour and hence determining the yield stress of material was the main focus of this work.

A new bending device was developed by Weiss et al. [43, 165] to bend thicker materials (see Figure 5.1.d). This bend tester, which is available at Deakin University, was used in Chapter 3 to show the applicability of the solid-shell element for bending dominated forming. The main focus of this bending arrangement is to capture the material behaviour close to yield and it was shown in Section 3.3.5 that the maximum achievable strain using this set-up is limited to 1 % strain for material thicknesses in the range between 2 and 5.6 mm. The experimental arrangement and limitation of using a clip-on gauge (curvature gauge) to capture the curvature does not allow bending of the strips to high curvatures which limits the maximum outer fibre strain achievable. Thin materials are usually used in the roll forming industry and bending of thin strips to higher strain values is needed in this thesis to obtain material data from a bend test for roll forming simulation. Thus, the design of a new bend tester is needed in this thesis. The bend test arrangement introduced should have the specifications given below:

- The bend tester will be used to obtain material properties for roll forming application, so it should be able to explore material behaviour close to yield and for strip thicknesses ranging from 1–2 mm. The
device should also allow to achieve outside fibre strains that are relevant to roll forming.

- The main idea is focusing on industrial use of the bend tester to obtain material data for roll forming application. So, the developed bend tester should be simple, inexpensive, and easy to use.

The development of a new bend tester will be presented in the next section.

5.3 New bend tester development

5.3.1 Design of the new bend tester

The new bend tester will be designed and its performance investigated experimentally in this section. It was discussed in the previous section that the material properties close to the yield can be observed using the bending device of [43, 165], but the maximum strain that can be established is limited. So the new bend tester can have the same concept to show material behaviour in elastic–plastic transition but the angle between bending arms should be lower to allow bending of the thin strips to higher strain values.

A schematic drawing of the bend tester developed with short bending arms and the experimental arrangement are shown in Figure 5.2. The bend tester is attached to the standard tensile machine by replacing the conventional tensile grips with the fabricated bending arms. Counterbalance weights are attached to the arms so that the centre of gravity is close to the vertical axis of the machine. The bending test-piece is gripped between plates at the ends of the arms and bending of the sample occurs through the movement of the upper arm. Variables $a$, $b$, and the angle $\theta$ in the current bend test arrangement are 100 mm, 103.66 mm, and 15.27° respectively, and the bending gauge length (L in Figure 5.2.a) is 40 mm in the first trial. The part drawings of this new bend tester are presented in Appendix B.
There are two approaches to determine the moment–curvature data from the new bend test device.

The first applies a clip–on gauge (curvature gauge) in which the curvature is measured by recording the displacement of the middle point of the bending test-piece. This method has been used in combination with the available bend tester at Deakin to analyse material properties in Chapter 3 (see Figure 3.4). A comparison between experimental moment–curvature data generated for the bending of DP780 steel using the current bend tester at Deakin (old bend tester) and the device newly developed in this chapter (new bend tester) is shown in Figure 5.3 for the same sample length \( L = 40\, mm \) tested; the clip–on gauge was used in both cases to record the moment–curvature data. The figure shows that higher curvatures are achievable by using the new bend tester while the accuracy of capturing material behaviour close to yield remains the same.
5.3 New bend tester development

Figure 5.3 A comparison between the moment–curvature data in the bending of DP780 steel using the old and the new bend tester.

Applying the clip–on gauge in the experiment is time consuming and prevents the testing of shorter sample lengths. This restricts the maximum outer surface strains achievable in the test. Therefore performing bend tests without a clip–on gauge is the preferred option.

The second approach to determine moment–curvature data from the new bend test device uses the load–displacement data (cross-head displacement) recorded during the test. The moment–curvature diagram can be determined by applying the analytical equations shown below:

After a displacement of $\Delta$, the bend angle is $2\Delta \theta$ (see Figure 5.4), where

$$I_0 + \Delta = L + 2b \sin(\theta + \Delta \theta),$$  \hspace{1cm} (5.1)

$\Delta \theta$ can be calculated from the above equation.

The bending curvature $\left(\frac{1}{R}\right)$ is
The bending moment at each end of the sample can be obtained as below

\[ M = F \cdot b \cdot \cos(\theta + \Delta \theta), \]  \hspace{1cm} (5.3)

where \( F \) is the force recorded during the bend test and \( M \) is bending moment.

![Figure 5.4 Schematic of the bend test progression.](image)

The next section will investigate if, for the new bend test arrangement and the bend test data generated on the basis of load–cross head displacement data, the obtained results are comparable to the data generated by performing bend test with a clip–on gauge.

### 5.3.2 A comparison between two approaches to determine moment–curvature data in the bend test

DP780 steel with 2 \( mm \) thickness was used in the experiments. The width of the test samples was 20 \( mm \) and the bending gauge length was 40 \( mm \). A comparison between the moment–curvature results determined by using the clip–on gauge and the cross-head displacement data is shown in Figure 5.5.
The above figure shows that in the experimental test there is a discrepancy between the moment curvature graph generated by using the clip–on gauge data and that determined on the basis of cross-head displacement data. This difference can be clearly observed in the elastic region. The Young’s modulus of the material can also be obtained from the elastic part of the moment–curvature data. For the elastic bending case, the outer fibre bending stress ($\sigma_{bend}$) and bending strain ($\varepsilon_{bend}$) can be determined as below [143]:

$$\sigma_{bend} = \frac{6M}{t^2},$$  \hspace{1cm} (5.4)

$$\varepsilon_{bend} = \frac{t}{2R},$$  \hspace{1cm} (5.5)

$$E = \frac{\sigma_{bend}}{\varepsilon_{bend}},$$  \hspace{1cm} (5.6)
where $M$ is bending moment, $t$ is material thickness, $\frac{1}{R}$ is the bending curvature, and $E$ is Young’s modulus. (Note that, as mentioned, the above relations are only valid in within the elastic strain range.)

The experimental data using the clip-on gauge gives $E \approx 203 \text{ GPa}$ which is close to the value determined in the tensile test in Chapter 3 ($197 \text{ GPa}$) and generally in accord with previous studies that used a tensile test for Young’s modulus determination [166].

If the cross-head data is used, the resulting Young’s modulus is $E \approx 175 \text{ GPa}$, which is too low.

To better understand the reason for the cross-head displacement approach providing a low Young’s modulus, a finite element simulation of the developed bend tester was created (see Figure 5.6). The two methods same as experimental trials are implemented in FEA to obtain the moment–curvature data from bend test. The results are then compared between the numerical simulation and the experimental set-up. The bending arms are modelled as rigid bodies and both arms can rotate around the $Z$ axis, while a bending moment is introduced by movement of the upper arm in a $Y$ direction. A “glue contact” is applied to represent the clamping of the strip to the bending arms.

**Figure 5.6** Finite element model of the bending process.
The same material model used for the simulation in Chapter 3 (Section 3.4.6) was applied to simulate the bending test-piece. Displacement of the upper arm in the $Y$ direction is recorded in cross-head displacement approach, while the clip–on gauge method uses the displacement of the nodes at the surface of bending test-piece (similar to Section 3.3.4) to obtain the curvature data. A comparison between the numerical results using the two approaches of the moment–curvature analysis is shown in Figure 5.7.

![Figure 5.7](image)

**Figure 5.7** Comparison between two approaches to record moment–curvature data in numerical simulation of the bend test.

The moment–curvature data shows that in the numerical simulation of the process both conditions lead to the same results, especially in a region close to material yield. Again the Young's modulus was calculated for both approaches. Both methods lead to the same value for the Young's modulus $E \approx 197 \, GPa$ and this is the value that was specified in the material model.

In the numerical model very similar moment–curvature results were achieved with both methods and this suggests that the discrepancy in moment curvature data between the clip–on gauge and the cross-head displacement are due to elastic deflections in the experimental set-up. Those do not appear
in the numerical model where the bending arms are rigid and the conditions are “ideal’, that is, there is no movement between the connections and the bearings, or between the material and the clamping device. Using a clip-on gauge that records the material deformation on the bending sample avoids this problem similar to an extensometer used in the tensile test. However, as discussed above, the clip-on gauge limits the minimum testable gauge length, and through that the maximum bending strain achievable. Thus a different solution would be desirable. In the next section a shouldered specimen shape with an effective gauge length will be introduced. This promises to lead to accurate moment-curvature measurements without applying a clip-on gauge.

5.3.3 Analytical equations for the bending of a shouldered sample

Previous section showed that elastic deflection in the experimental arrangements leads to inappropriate moment-curvature data when using the cross-head displacement approach. A shouldered sample is usually used in a conventional tensile test and the elastic deflection in the experimental arrangement is corrected by using an extensometer. When a shouldered sample is used in the tensile test, the effective (equivalent) gauge length can be obtained analytically if the extensometer data is not available. This section will try to apply a similar method in the bend test. A shouldered sample will be used to correct the bend test data without using a clip-on gauge.

The introduced shouldered sample for bend test in shown in Figure 5.8. Two gauge lengths were used in the shouldered sample ($D = 40\text{mm}$ and $D = 50\text{mm}$ in Figure 5.8) that were close to the gauge length of the rectangular bending test-piece used in the previous section, $L = 40\text{mm}$. Radius of the fillet in the shouldered sample was considered as $R = 8\text{mm}$ to maintain the $\frac{D}{R}$ ratio similar to the standard tensile test-piece.
5.3 New bend tester development

Figure 5.8 Shoulder sample for the bending test.

The actual gauge length is different from the distance between the ends of the grips in the shouldered sample because of the existence of some material in the shouldered part. Analytical equations to obtain the effective gauge length in the bend test will be presented in this section. The clip–on gauge data will be used for verification of the bending data with a shouldered sample and it will be shown whether it is possible to record the same bending data using a clip–on gauge and cross-head displacement approaches.

A schematic of the original arrangement of the bend tester is shown in Figure 5.9.a while Figure 5.9.b shows a new configuration to consider the effective gauge length in the bending progression. Here it is assumed that the effective end of the grip, G', is at some distance away from the actual end of the grip and that the starting dimensions are b' and θ'.

A routine is developed below to calculate the curvature based on the new dimensions b' and θ' and to find values for b' and θ' that give a fit between the moment–curvature curve determined by using a clip–on gauge with that generated on the basis of cross-head displacement data.
Variable $a$ is constant, so

$$bc\cos\theta = b'\cos\theta'.$$  \hspace{1cm} (5.7)

The distance between the effective end of the grip, $G'$, to the end of the arm in which the load is applied is also constant, so

$$b \sin \theta + GG' = b' \sin \theta'.$$ \hspace{1cm} (5.8)

From Equation (5.7):

$$b' = \frac{b \cos \theta}{\cos \theta'}.$$ \hspace{1cm} (5.9)

Substituting Equation (5.9) into (5.8):

$$\frac{b \cos \theta}{\cos \theta'} \sin \theta' = b \sin \theta + GG',$$ \hspace{1cm} (5.10)

$$b \cos \theta \tan \theta' = b \sin \theta + GG',$$ \hspace{1cm} (5.11)
\[
\tan \theta' = \frac{b \sin \theta + GG'}{b \cos \theta},
\]
(5.12)

\[
\theta' = \tan^{-1} \frac{b \sin \theta + GG'}{b \cos \theta}.
\]
(5.13)

The effective gauge length, \(L'\), is

\[
L' = L - 2GG'.
\]
(5.14)

\(L\), and \(L'\) are the distance between the ends of the grips, and the effective gauge length in the shouldered specimen respectively (see Figure 5.9).

The effective gauge length that can deliver a fit between the moment–curvature results of the clip–on gauge and the cross-head displacement data in a shouldered sample can be obtained as below.

A curve fitting approach will be used to minimise the discrepancy between the moment–curvature results of the clip–on gauge and the cross-head displacement methods. The value of \(GG'\) in Equation (5.13) will be updated by the curve fitting method and then the new values of \(\theta'\), \(L'\), and \(b'\) from Equations (5.13), (5.14), and (5.9) will be used in Equations (5.2), (5.3), and (3.4) to calculate the moment–curvature data in both approaches. (It should be noted that a similar method is used in conventional tensile testing to obtain an equivalent gauge length when the test is performed with a shouldered test-piece and without an extensometer.)

5.3.4 Experimental trials of bend test with a shouldered sample

Experimental bending trials were performed with both shouldered samples shapes shown in Figure 5.8 and the cross-head displacement and the clip–on gauge approaches applied to analyse curvature for the moment–curvature diagram. Curve fitting method was used to obtain the effective bend length, \(L'\), giving a fit between both moment–curvature curved. The bending
arrangement is shown in Figure 5.10. DP780 steel with 2 \text{mm} thickness was used for all tests.

Figure 5.10 Bending arrangement with a shouldered sample.

Three experimental trials were performed with $D = 50 \text{mm}$ in Figure 5.8 in the shouldered bending sample. A comparison between the moment-curvature results using the cross-head displacement data and the clip-on gauge data in trial one is shown in Figure 5.11. It can be seen that the results of using cross-head displacement data are very close to the results using a clip-on gauge if the effective bending length method is used in the experiment. The Young's modulus was calculated for both approaches. Both approaches lead to the same value for the Young's modulus $E \approx 201 \text{GPa}$ which is similar to the value reported in other work for DP780 steel and close to the tensile data. Similar accuracy was achieved in the other two trials.
5.3 New bend tester development

Figure 5.11 Comparison between moment–curvature results using cross head displacement or clip-on gauge data in the shouldered specimen with D=50 mm, first trial.

The distance between the ends of the grips and the effective bending length from Equation (5.14) which can fit the moment–curvature data are shown in Table 5.2. It is shown in this table that the average effective bending length is 1.9 mm greater than the distance between the end of the grips and this means that theoretically each of the top and bottom grip points moves 0.95 mm.

Table 5.2 Effective bending length which can fit the moment–curvature data in various shouldered samples with D=50 mm.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>trial1</th>
<th>trial2</th>
<th>trial3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between grips (mm)</td>
<td>69</td>
<td>68.1</td>
<td>70.8</td>
</tr>
<tr>
<td>Effective bending length (mm)</td>
<td>71</td>
<td>70.7</td>
<td>71.8</td>
</tr>
</tbody>
</table>

Three more trials were done experimentally by changing the $D$ to 40 mm in the shouldered bending samples (see Figure 5.8). A comparison between the moment–curvature results using the cross-head displacement data or the clip-on gauge data in trial one is shown in Figure 5.12. This figure shows that again good correlation can be achieved by using the effective bending length method in combination with the shouldered sample with $D = 40$ mm; the
results based on the cross-head displacement data are very close to those generated with the clip-on gauge. Again the Young’s modulus was calculated and it was \( E \approx 200 \, GPa \). Similar accuracy was observed in two other trials.

![Figure 5.12](image)

**Figure 5.12** Comparison between moment–curvature results using cross head displacement or clip-on gauge data in the shouldered specimen with \( D=40 \, mm \), first trial.

The distance between the two ends of the grips and the effective bending length for different samples which can fit the data are shown in Table 5.3. It is shown in this table that if \( D = 40 \, mm \) in the shouldered sample, the distance between the end of the grips and the effective bending length are very similar. This suggests that a shouldered bending sample with \( D = 40 \, mm \) in combination with cross-head displacement data can be applied to determine the bending curvature for the moment–curvature diagram.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>trial1</th>
<th>trial2</th>
<th>trial3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between grips (mm)</td>
<td>57.2</td>
<td>57.4</td>
<td>57.5</td>
</tr>
<tr>
<td>Effective bending length (mm)</td>
<td>57.2</td>
<td>57.4</td>
<td>57.5</td>
</tr>
</tbody>
</table>

**Table 5.3** Effective bending length which can fit the moment–curvature data in various shouldered samples with \( D=40 \, mm \).
5.3.5 Summary

A new bend test set-up was developed that allows the bending of thin strip to high bending strains while maintaining high measurement accuracy at low forming strains and close to material yield.

The comparison of experimental and numerical results has shown that the deflection of the tooling leads to inaccuracies in the elastic range if cross-head displacement data is used for moment–curvature analysis. One solution to correct the results is the use of shouldered specimens.

The experimental results showed that a shouldered specimen with the geometry of Figure 5.13 can be applied in the bend test to use the cross-head displacement data for calculation of the curvature in the moment–curvature curve with reasonable accuracy without using a clip-on gauge. The distance between two ends of the shoulders (58 mm) should be considered as the bending gauge length.

![Shouldered sample final geometry for the bend test.](image)

Cutting a shouldered specimen is time consuming and with a bending gauge length of 40 mm it is possible to use the clip-on gauge provided the limitation on maximum strain is acceptable. The purpose of the work detailed above is to show how higher strain tests can be performed. Equation (5.2) shows that reducing the sample length \( L \) increases the achievable bending curvature \( \frac{1}{R} \).
So a shouldered sample with shorter gauge length can be applied in the experiment using the effective bending length method to achieve higher strain values. The work in the following sections, the interest is to explore bending behaviour near the elastic plastic transition, so the clip-on gauge approach using a parallel specimen will be used.

5.4 Effect of residual stress in tensile and bending deformation

5.4.1 Observation of the effect of residual stress in a bend test

A new bend test device was developed in the previous section. This bend tester will be applied together with an inverse approach to obtain an indication of the initial residual stress profile in the material. Before describing the application of the bend tester in the inverse routine, the advantages of the bend test developed for exploring the effect of residual stresses in the material compared with information derived from a tensile test will be discussed. Numerical simulation of the thickness reduction rolling process that was used in Chapter 4 will be applied to introduce some residual stresses into the material. This will be followed by a numerical analysis of the tensile and the bend test for the material before and after thickness reduction rolling. This will illustrate the effect of residual stress on the material behaviour close to yield in tensile and bending dominated deformation. It will be shown that the bend tester developed above is better suited to capture the effect of residual stress for incoming material.

5.4.2 Finite element model

A numerical simulation of the thickness reduction rolling process will be first performed in this section to introduce some initial residual stress into the DP780 strip. This will then be followed by the numerical analysis of the material behaviour in tensile and bending deformation to examine the effect of residual stress on the material behaviour close to yield. A single 3D analysis will be used with two separate steps for the thickness reduction rolling and
the tensile or bending step. In this way the strip used in the tensile or bending step has the full stress–strain history from the previous thickness reduction operation. The boundary conditions and roll geometry in the thickness reduction step are the same as those introduced in Chapter 4 (Section 4.2.3). Tensile sample geometry shown in Figure 4.20 was used in thickness reduction–tensile analysis while a rectangle strip geometry of 60mm*20mm was applied in the thickness reduction–bending analysis (see Figure 5.14).

The tensile or bending step will start when the thickness reduction step finishes. A schematic drawing of the numerical methods is shown in Figure 5.15. The tensile model is the same as introduced in Section 4.3.1 while the bending model was previously explained in Section 5.3.2.

**Figure 5.14** Sample geometry in the thickness reduction step a) thickness reduction for the upcoming tensile analysis b) thickness reduction for the upcoming bending analysis.
5.4.3 Results and discussion

This section will capture the effect of thickness reduction rolling on the stress–strain diagrams in the tensile test, and moment–curvature along with bending stress–bending strain diagrams in the bend test.

5.4.3.1 Effect of residual stresses in a tensile simulation

The tensile material behaviour of thickness reduced strips was shown in Chapter 4 (Section 4.3.1) to obtain material data for roll forming simulation. The effect of thickness reduction on the tensile material behaviour close to yield will be investigated in the present section. The true stress–true strain diagrams of the thickness reduced samples obtained from the tensile
simulation are compared to that of the non-thickness reduced material in Figure 5.16. It can be seen that the yield stress of the material in tension rises with increasing thickness reduction level. However, there is an area of early yielding that is not captured by the 0.2% offset usually used in a tensile test.

![Stress-strain diagrams for the non-thickness reduced and the thickness reduced materials](image)

**Figure 5.16** Stress–strain diagrams for the non-thickness reduced and the thickness reduced materials (0.2% offset approach was used).

To investigate the early yielding, a smaller offset of 0.02% has also been used [6]. The true stress–true strain diagram of the thickness reduced samples are compared to that of the non-thickness reduced material in Figure 5.17 for a lower range of true strain.
Chapter 5 Bend Test to Observe a Residual Stress Profile in Sheet Material

Figure 5.17 Stress–strain diagrams for the non-thickness reduced and the thickness reduced materials (0.02% offset approach was used).

The obtained Young’s Modulus and yield transition point for non-thickness reduced and thickness reduced materials using the 0.2% or 0.02% offset approaches are given in Table 5.4. The 0.2% offset approach shows that the yield stress increases with thickness reduction. If the 0.02% offset approach is used, the 0.5% and 1.5% thickness reduction lead to a reduction in yield stress by 24.7% and 7.4% respectively while the yield stress increases by 8.7% after a thickness reduction of 2.5%. The Young’s Modulus stays constant in all cases.

Table 5.4 Yield transition point and Young’s Modulus for non-thickness reduced and thickness reduced materials in the tensile test using 0.2% or 0.02% offset approach.

<table>
<thead>
<tr>
<th>Thickness reduction level (%)</th>
<th>0</th>
<th>0.5</th>
<th>1.5</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% offset</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>670</td>
<td>714</td>
<td>795</td>
<td>866</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
</tr>
<tr>
<td>0.02% offset</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>664</td>
<td>500</td>
<td>615</td>
<td>722</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
</tr>
</tbody>
</table>

It is shown in the above table that 0.2% offset approach misses the early yielding in the material due to thickness reduction rolling and applying the 0.02% offset approach is the better approach to analyse the effect of residual stress on the material behaviour at yield.
5.4.3.2 Effect of residual stresses in a bending simulation

Three different thickness reduction levels as 0.5%, 1.5%, and 2.5% thickness reduction were simulated and the moment-curvature diagrams of the thickness reduced samples were compared to that of the non-thickness reduced strip in Figure 5.18. It can be seen that in all cases, the slope of the curves in the elastic region is similar while the bending moment near yield reduces with thickness reduction. Similar observations were made in [6].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{moment_curvature_diagram.png}
\caption{Moment-curvature diagrams for the non-thickness reduced and the thickness reduced materials.}
\end{figure}

For a better comparison between the tensile and bend test data, the bending stress-bending strain diagrams were obtained (see Equations (5.4), and (5.5)).

The bending stress-bending strain diagrams of the thickness reduced material are compared to that of the non-thickness reduced material in Figure 5.19.
The onset of transition from the elastic part to the plastic deformation in the bending stress–bending strain diagram is taken as “bending yield stress”. The equations used to determine bending stress–bending strain curve are only valid for the elastic range, so the 0.2% approach cannot be used to capture the bending yield stress. Using the 0.02% offset approach delivers reasonable results in the tensile test, so this method will also be used to capture the bending yield stress. To investigate if the 0.02% offset is representative for the onset of yielding in the bend test, the obtained data will be compared to the correlation factor method which should represent the ideal case.

0.02% offset approach- a line is constructed parallel to the elastic curve that is offset by 0.02% bending strain in the outer fibre. The intersection of this line with the bending stress curve will be determined as “bending yield stress” (see Figure 5.20).

**Figure 5.19** Bending stress–bending strain diagrams for the non-thickness reduced and the thickness reduced materials.
Figure 5.20 0.02% offset approach to determine the “bending yield stress”.

Correlation factor method: the correlation coefficient between the bending stress–bending strain data and the fitted elastic portion will be determined as a function of bending strain. The stress at which this curve deviates from linearity represents the “bending yield stress” (see Figure 5.21).

Figure 5.21 Correlation factor method to determine the “bending yield stress”.
The bending yield transition point for non-thickness reduced and thickness reduced materials using both offset and correlation approaches are given in Table 5.5.

<table>
<thead>
<tr>
<th>Thickness reduction level (%)</th>
<th>0</th>
<th>0.5</th>
<th>1.5</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending yield stress using offset approach ((\text{MPa}))</td>
<td>820</td>
<td>502</td>
<td>650</td>
<td>795</td>
</tr>
<tr>
<td>Bending yield stress using correlation coefficient method ((\text{MPa}))</td>
<td>810</td>
<td>498</td>
<td>645</td>
<td>790</td>
</tr>
</tbody>
</table>

It can be seen in the above table that the obtained results using both offset and correlation methods are very similar. In the further part of this section results obtained with the 0.02% offset method will be used.

### 5.4.3.3 Comparison between the effect of residual stresses in tensile and bending simulations

The numerical results show early yielding in the material due to pre-existing residual stresses as a result of the thickness reduction rolling process. Residual stresses through the thickness of the strip due to thickness reduction rolling have been previously shown in Chapter 4 (Figure 4.11). Early yielding in the material can be detected if the 0.02% offset approach is used. Comparison of results between the tensile and the bend test simulations (Figure 5.17 and Figure 5.20) shows that the trend of yield stress reduction in the tensile test is the same as found for the bend test. The change of the yield stress with thickness reduction rolling level is shown in Figure 5.22 for both the tensile and the bend test using the 0.02% offset for yield stress determination.

A 0.5% thickness reduction reduces the yield transition point in both the tensile and the bend test. The strain hardening in the material as a result of further thickness reduction increases the yield point transition in both the
5.4 Effect of residual stress in tensile and bending deformation

tensile and the bend test. The stress of this transition point is below the non-thickness reduced material in both the tensile and the bend test for 1.5% thickness reduction. Looking at 2.5% thickness reduction results shows that the transition stress of this sample is above the non-thickness reduced material in the tensile and below the stress of non-thickness reduced material in the bend test.

It can be concluded that the observation of material softening close to yield is clearer in a bend test compared to the tensile test. For instance the bend test shows 39% reduction in the bending yield point stress as a result of 0.5% thickness reduction while the tensile test predicts only 25% reduction in the yield point compared to the material that had not been rolled.

![Figure 5.22](image)

**Figure 5.22** Variation of the yield transition point in the tensile and bending simulation (using the 0.02% offset) as a function of the level of thickness reduction.

A schematic of the stress distributions through the thickness of the strip in a tensile or bend test is shown in Figure 5.23. This figure shows that stress distribution is uniform through the thickness of the strip in the tensile test, while in the bend test the material deformation is more at the strip surface and a non-uniform stress distribution exists through the thickness of the strip.
This explains why a bend test is more sensitive to the pre-existing residual stresses in the material compared to a tensile test. The bend test that has been developed can be used in the inverse approach to clearly detect the effect of residual stresses and obtain the residual stress profile through the thickness of the incoming material for roll forming process. Furthermore, roll forming is a bending deformation and material data delivered from a bend test are more relevant for roll forming simulation compared to tensile material data.

Figure 5.23 A schematic of the stress distribution through the thickness of the strip in a tensile and a bend test.

5.4.4 Summary

A comparison between the material behaviour close to yield in a tensile or bend test due to pre-existing residual stresses in the strip was made. Both tensile and bend test simulations show early yielding in the material due to pre-existing residual stresses. Early yielding in the material can be detected reliably if a 0.02% instead of the common 0.2% offset approach is used. The benefits of using a bend test instead of using a tensile test to obtain material data for roll forming simulation are as below.
Roll forming is an incremental bending deformation so material properties from a bend test are more relevant compared with those from a tensile test.

Incoming material for a roll forming process has usually some residual stresses due to steel processing or uncoiling. The effect of those residual stresses can be clearly detected in the bend test.

The above comparisons are made on the basis of simulation. It would be hoped that experimental evidence could be provided in future.

5.5 Chapter summary

A novel bend test arrangement was developed and its performance was verified experimentally in this chapter. Using this bend tester enables the analysis of material properties close to the yield, to clearly observe the effect of residual stresses in the material, and relevant to the roll forming process.

Then, the effect of initial residual stresses on the material response in the tensile and in the developed bend test were compared numerically. A detailed comparison between the effect of residual stresses on elastic–plastic transition in a bend and a tensile test was performed, to the author’s knowledge, for the first time with regard to the literature. It was shown that the bend test offers advantages for capturing the effect of residual stresses.

An inverse approach will be developed in the next chapter to predict residual stress information through the thickness of material based on bend test data provided by the developed bend tester of this chapter. This material data delivered from the inverse routine will then be used for numerical simulation of a roll forming process.
Chapter 6

Development of an Inverse Routine to Predict Residual Stress in Sheet Materials

6.1 Introduction

A new bend tester was developed in previous chapter and it was shown that the effect of residual stresses in the material can be observed using a pure bend test. The main goal of the present chapter is to develop an inverse routine that, combined with experimental bend test data, allows the determination of the residual stress profile of incoming material. In this chapter not only has a residual stress profile for as-received material been determined for roll forming applications, but also an in-depth understanding of the effects this residual stress profile has on the bending type deformation.

Thickness reduction rolling, as introduced in Chapter 4, will be applied to introduce residual through thickness stress into stress relieved steel sheet. The thickness reduced strips will be bent using the bend tester developed in Chapter 5 to determine the moment–curvature response. Using a developed inverse routine the experimental bend test data will be applied to predict the residual stress profile in the material. This profile will be validated against an experimentally determined residual stress profile.
X-ray diffraction (XRD) with layer removal will be used to analyse residual stress through the thickness of the thickness reduced materials and to verify the results of the inverse approach. This will show that the developed inverse routine combined with experimental bend test data allows to determine residual stress in incoming steel strip with high accuracy.

To develop an inverse routine for determination of a residual stress profile from as-received sheet material, the below steps will be presented in this chapter:

- First, a background will be provided where the necessary components of an inverse routine of this type are outlined: material model, and search techniques/optimization methods.
- Then, a review of similar inverse models for extracting material data using a bend test will be presented. This section will provide various material models and optimization techniques that have been used by other researchers in an inverse analysis.
- An appropriate material for development of an inverse routine will be chosen in the next step.
- After selecting the material, an in-depth understanding of the effect of a residual stress profile and the associate plastic strain in the material form a cold forming process on the material bending response will be provided. The aim of this section is to emphasise the effect of residual stress from the effect of strain hardening in the material due to plastic deformation and layout the concept of inverse routine.
- Possible methodologies for an inverse routine to be applied in this thesis will be presented in the next step.
- Finally, there will be a presentation of the inverse model developed for the application of predicting a residual stress profile through the thickness of sheet materials.
Material models are critical to inverse modelling material properties. If the particular behaviour cannot be demonstrated by the material model, then the parameter values extracted from the inverse model will have no use and lead to spurious FEA results. This section will review the basics of modelling materials, and the general models that are available to inverse modelling.

### 6.2.1 Strain decomposition

An idealised stress-strain behaviour obtained from a tensile test is shown in Figure 6.1. Plasticity commences at uniaxial stress $\sigma_y$ and strain hardening will be observed in the material after this point. Strain hardening is a phenomenon exhibited by most metals and alloys whereby the strength of the material increases by plastic deformation.

![Figure 6.1 Decomposition of the strain to elastic and plastic parts](image)

If the load is reversed at strain $\varepsilon$, the material would show a linearly decreasing stress with strain such that the gradient of this part in the stress-strain curve would again be the Young's modulus, $E$, shown in Figure 6.1. Once a zero stress is achieved, the remaining strain in the material is plastic (permanent) strain, $\varepsilon^p$, while $\varepsilon^e$ is the elastic (reversible) strain. It can be seen that the total strain, $\varepsilon$, is the sum of the two:
\[ \varepsilon = \varepsilon^e + \varepsilon^p. \]  

(6.1)

This is called the classical additive decomposition of the strain which is one of the fundamental hypotheses in the small strain theory of plasticity. The constitutive law to achieve the stress at a strain of \( \varepsilon \) can be expressed as

\[ \sigma = E\varepsilon^e = E(\varepsilon - \varepsilon^p). \]  

(6.2)

### 6.2.2 Idealization of the strain hardening behaviour

Real material behaviour in the plastic region is very complex. A perfect plastic, and a linear strain hardening models in a uniaxial tensile test were shown in Figure 6.1. However, the strain hardening is not linear in most metals. Many empirical equations have been suggested in order to represent the actual stress–strain curve of a material, especially the hardening part in the stress–strain curve. Most common equations to represent the nonlinear strain hardening behaviour in the stress–strain curve are

\[ \sigma = \sigma_Y + HE^n \]  

(6.3) 

\[ \sigma = \sigma_Y \tanh \left( \frac{E\varepsilon}{\sigma_Y} \right) \]  

(Prager 1938)  

(6.4)

\[ \sigma = HE^n \]  

(Holloman 1944)  

(6.5)

\[ \sigma = H(\varepsilon_s + \varepsilon)^n \]  

(Swift 1947)  

(6.6)

\[ \sigma = \sigma_Y + (\sigma_s - \sigma_Y)\{1 - \exp(-n\varepsilon)\} \]  

(Voce 1948)  

(6.7)

\[ \varepsilon = \frac{\sigma}{E} + H\left(\frac{\sigma^e}{E}\right)^n, \]  

(Ramberg and Osgood 1943)  

(6.8)

in all of the above cases the \( \sigma \) and \( \varepsilon \) are true stress and true strain respectively. Additionally, \( \sigma_Y, H, n, E, \varepsilon_s, \) and \( \sigma_s \) are material parameters and must be determined experimentally [168].
6.2.3 Yield criteria

The elastic limit of a material can be clarified using the yield function $\Phi$. It shows whether the material is in the elastic limit or the deformation is elastoplastic. In a one-dimensional particular case the yield function can be defined as

$$\Phi(\sigma, \sigma_y) = |\sigma| - \sigma_y,$$  \hspace{1cm} (6.9)

where $|\sigma|$ is the absolute value of stress in the material, and $\sigma_y$ is the uniaxial yield stress. The elastic domain is the set of stresses $\sigma$ that satisfy

$$|\sigma| < \sigma_y.$$  \hspace{1cm} (6.10)

It should be noted that, at any stage, the stress level $\sigma$ is below the current yield stress $\sigma_y$. Thus, the plastically admissible stresses lie either in the elastic domain or on the yield surface boundary. For the stress levels within the elastic limit, only elastic strain exists in the material, whereas on the elastic-plastic boundary (yield stress), either plastic loading or elastic unloading takes place in the material. Therefore, the yield criterion can be represented as

$$\Phi(\sigma, \sigma_y) \leq 0,$$  \hspace{1cm} (6.11)

If $\Phi(\sigma, \sigma_y) < 0 \Rightarrow \dot{\varepsilon}^p = 0$,

If $\Phi(\sigma, \sigma_y) = 0 \Rightarrow \dot{\varepsilon}^p = 0$ for elastic unloading,

If $\Phi(\sigma, \sigma_y) = 0 \Rightarrow \dot{\varepsilon}^p \neq 0$ for plastic loading.

Note that $\dot{\varepsilon}^p$ is plastic strain rate (time derivative of the plastic strain) in the above equations.
The concept of yield stress in uniaxial state can be extended to a three-dimensional case. A plastic flow may occur in the material only when

$$\Phi(\sigma, A) = 0,$$  \hspace{1cm} (6.13)

where the scalar yield function, $\Phi$, is now a function of stress tensor and a set $A$ of hardening thermodynamical forces. The set of plastically admissible stresses can be defined as

$$\sigma | \Phi(\sigma, A) \leq 0.$$  \hspace{1cm} (6.14)

A general form of the yield criterion was discussed. Additionally, some of the most common classical yield criteria used in engineering practice will be presented below.

*Tresca* suggested the first yield criterion for the metals under a combined state of stress in 1868. He assumed that the plastic yielding will occur in the material when the maximum shear stress reaches a critical value. *von Mises* proposed a yield criterion for plastic yielding in metals in 1913. According to his criterion, plastic yielding begins when the $J_2$ stress deviator invariant reaches a critical value. The von Mises yield criterion can be represented as

$$\Phi(\sigma) = \sqrt{J_2(s(\sigma))} - \tau_y,$$  \hspace{1cm} (6.15)

where $J_2(s(\sigma))$ is the second invariant of deviatoric stress $s(\sigma)$, and $\tau_y$ is the shear yield stress.

*Tresca*, and *von Mises* yield criteria are based on elastoplastic isotropy. More advanced yield criteria such as *Hill*, *Hoffman*, and *Barlat-Lian* can be found in [169].
6.2.4 Plastic flow rule, loading/unloading conditions

When the plastic yielding begins in the material, the direction of the flow can be determined by the plastic flow rule. In a one-dimensional case, upon plastic loading, the plastic strain rate $\dot{\varepsilon}^p$ is positive under tension and negative under compression. Thus the plastic flow rule for a uniaxial model can be represented as

$$\dot{\varepsilon}^p = \dot{\gamma} \text{sign}(\sigma),$$  \hspace{1cm}(6.16)$$

where sign is the signum function, and $\dot{\gamma}$ is the plastic multiplier - it is always non-negative, $\dot{\gamma} \geq 0$.

Considering the plastically admissible stresses phenomena in the yield function, Equation (6.11), and the fact that plastic multiplier is a non-negative property, the consistency condition can be expressed as

$$\dot{\gamma} \Phi = 0.$$  \hspace{1cm}(6.17)$$

Therefore, loading/unloading conditions of the elastoplastic model can be defined as

$$\Phi \leq 0, \hspace{0.5cm} \dot{\gamma} \geq 0, \hspace{0.5cm} \dot{\gamma} \Phi = 0.$$  \hspace{1cm}(6.18)$$

The plastic flow rule in a three-dimensional case can be represented as

$$\dot{\varepsilon}^p = \dot{\gamma} \mathbf{N},$$  \hspace{1cm}(6.19)$$

where the tensor $\mathbf{N} = \mathbf{N}(\sigma, \mathbf{A})$ is termed the flow vector.

The Prandtl-Reuss plasticity law is the flow rule obtained by considering the von Mises yield function, Equation (6.15), as the flow potential. The corresponding flow vector is
\[ N \equiv \frac{\partial \Phi}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[ \sqrt{3f_2(s)} \right] = \frac{3}{2} \frac{s}{\|s\|}, \quad (6.20) \]

and the flow rule results is

\[ \dot{\varepsilon}_p = \dot{\gamma} \frac{3}{2} \frac{s}{\|s\|}. \quad (6.21) \]

### 6.2.5 Isotropic Hardening

A uniaxial stress–strain curve with nonlinear hardening along with a schematic representation of initial and subsequent yield surfaces is shown in Figure 6.2. In an isotropic hardening material model that is shown in this figure, the initial yield surface expands uniformly in all directions in the stress space. If the loading is in the \( \sigma_2 \) direction, then the load point moves in the \( \sigma_2 \) direction from zero to the initial yield at \( \sigma_y \). The Consistency condition, which means the load point should remain on the yield surface during plastic deformation in time independent materials, requires the yield surface expands as \( \sigma_2 \) increases when hardening takes place in the material. The amount of this expansion is a function of accumulated plastic strain.

![Figure 6.2 Loading with isotropic hardening a) the yield surface b) the corresponding stress-strain curve [167].](image-url)
Reverse loading of a material which hardens isotropically is shown in Figure 6.3. At strain of $\varepsilon_i$ which is load point (1) in this figure, the load is reversed and the material behaves elastically until load point (2), which is on the expanded yield surface. If the material is reverse loaded more, it will go to the plastic deformation. This figure shows that reverse yield load is equal in magnitude (and opposite in sign) when using the isotropic hardening model.

![Figure 6.3 Reversed loading with isotropic hardening](image)

For a multiaxial plasticity model with a von Mises yield surface, isotropic hardening corresponds to the increase in the radius of the von Mises cylinder in principal stress space. The von Mises accumulated plastic strain can be defined as

$$\bar{\varepsilon}^P \equiv \int_0^t \sqrt{\frac{2}{3}} \bar{\varepsilon}^P : \bar{\varepsilon}^P \, dt = \int_0^t \sqrt{\frac{2}{3}} \| \bar{\varepsilon}^P \| \, dt . \quad (6.22)$$

Therefore, a von Mises isotropic strain hardening model is defined as a function of the accumulated plastic strain:

$$\sigma_y = \sigma_y (\bar{\varepsilon}^P) . \quad (6.23)$$
6.2.6 Kinematic hardening

For most metals the (absolute) stress–strain curve in a simple monotonic tension test is equal to the (absolute) stress–strain curve in a simple monotonic compression test [170]. However, if a specimen of material is loaded in tension or compression to the plastic region, then the load is reversed to yield point, it has been observed that yield stress in reverse loading is significantly less than the initial yield stress in the first direction. This phenomenon is called the Bauschinger effect. Thus, Isotropic hardening is a reasonable assumption in the case of loading in one direction, but for the case of reverse loading it cannot predict the actual material behaviour.

Bauschinger effect has been observed in a single crystal and polycrystalline metals and it can be explained by the anisotropy of the dislocation fields due to previous loading [168]. The microscopic residual stresses which remain in the individual crystals after loading are the main reason of observation of low yield stress in reverse direction [171].

In a kinematic hardening model, that approximates the Bauschinger effect, the yield surface translates rather than expanding, as shown in Figure 6.4. The kinematic hardening model assumes that the yield stress reduction in the reverse direction is equal to the stress increment by which the specimen is loaded beyond the yield stress in original direction [168]. It is shown in Figure 6.4 that if the material is loaded to initial yield point (point (1)), then the load is reversed until point (2) - which is the yield point in the reverse loading, the elastic region due to kinematic hardening is much smaller than that for isotropic hardening. It is shown in this figure that the initial yield point is translated by $|\beta|$ in the kinematic hardening model. The amount of $\beta$ is the kinematic hardening variable and is called back-stress.
The von Mises yield surface for a kinematically hardening model is given by

\[ \Phi(\sigma, \beta) = \sqrt{3J_2(\eta(\sigma, \beta))} - \sigma_y , \]

where

\[ (\eta(\sigma, \beta)) \equiv s(\sigma) - \beta \]

is the relative stress tensor, defined as the difference between the stress deviator and the symmetric deviatoric back-stress tensor \( \beta \). Thus, the relative stress is deviatoric. The constant \( \sigma_y \) in Equation (6.24) defines the radius of the yield surface. When \( \beta = 0 \), then \( \eta = \beta \) and the yield surface defined by \( \Phi \) is the isotropic von Mises yield surface with uniaxial yield stress \( \sigma_y \).

### 6.2.6.1 Combined isotropic and kinematic hardening

In cyclic plasticity, the kinematic hardening appears the dominant in each individual cycle, but it has been observed that isotropic hardening occurs after a large number of cycles so that the peak tension and compression stresses increase from one cycle to the next. So, neither isotropic nor kinematic hardening models can predict completely a real material hardening behaviour.
Experiments also show a change in the yield surface can happen after the initial yield which may include both expansion and translation. This behaviour can be modelled by a combination of isotropic and kinematic hardening models.

Armstrong-Fredrick and Chaboche are two common combined hardening models [172, 173]. These models were extended to capture the permanent softening, kinematic and kinematic-isotropic modification of the bound surface by Geng-Wagoner [174] and Yoshida-Uemori [175]. Chun [176] modified the isotropic part of Chaboche model to better capture the Bauschinger effect. Chung [177] introduced a combined hardening law for springback prediction in automotive sheet metal forming processes by modification of the Chaboche hardening model. Zang [178] modified the Chung theory to capture the permanent softening with Bauschinger effect and transient behaviour for springback prediction.

More information about material hardening models can be found in [169, 173].

6.3 Function fitting / Optimisation techniques / Search algorithms

The previous section described the laws to enable the evolution of stress given increments of strain. Next a function is needed to estimate the initial residual stress state in the as-received material. A curve fitting approach will be used in this thesis to predict residual stresses in the material. The predicted residual stress profile will be obtained through an optimization process. A comprehensive review on all available methods is not possible, but this section will briefly review the basics of function fitting, search algorithms and optimization methods.
6.3 Function fitting / Optimisation techniques / Search algorithms

6.3.1 Function fitting

The goal of function fitting is to choose values for the parameters of a function that can best describe a set of data. Suppose that there are \( n \) observations of a system, where each observation is made up of a dependent variable \( y \) measured for a given independent variable \( x \).

\[
(x_1, y_1), (x_2, y_2), (x_3, y_3), \ldots, (x_n, y_n) .
\] (6.26)

The first step in construction of mathematical model that can represent a physical process is to plot the above data points and postulate a function form \( f(x) \) to represent the general trend in the data. Some simple functions commonly used to fit the data are:

- straight line: \( f(x) = ax + b \) (6.27)
- parabola: \( f(x) = ax^2 + bx + c \) (6.28)
- polynomial: \( f(x) = a_m x^m + a_{m-1} x^{m-1} + \cdots + a_2 x^2 + a_1 x + a_0 \) (includes the previous two cases)
- exponential: \( f(x) = c \exp(ax) \) (6.30)
- Gaussian, e.g. \( f(x) = c \exp(-bx^2) \) (6.31)
- sine or cosine, e.g. \( f(x) = a \cos(bx) + c \) , (6.32)

where the coefficients \( a, b, c \) etc. are adjustable parameters in the formula of \( f(x) \).

It is obvious that the \( f(x) \) cannot fit the data perfectly. The aim is to change the parameters of the function \( f(x) \) to minimise the fitting error, which is the distance between the observed dependent data values \( y_i \) and the estimated \( y \)-values on the fitted curve \( f(x_i) \). The residuals are defined to be the difference between the two values at each observation:

\[
r_i = y_i - f(x_i) \quad \text{for } i = 1, 2, \ldots, n .
\] (6.33)
The residuals can be collected into a vector, \( r \), and the aim of the function fitting exercise is to minimise the norm or magnitude of this vector. Three standard methods for error measurement are:

- **Average error**
  
  \[
  E_1(f) = \frac{1}{n} \| r \|_1 = \frac{1}{n} \sum_{i=1}^{n} |r_i| = \sum_{i=1}^{n} |y_i - f(x_i)|. \tag{6.34}
  \]

- **Root mean square error**
  
  \[
  E_2(f) = \frac{1}{\sqrt{n}} \| r \|_2 = \left( \frac{1}{n} \sum_{i=1}^{n} |r_i|^2 \right)^{1/2} = \frac{1}{n} \sum_{i=1}^{n} (y_i - f(x_i))^2. \tag{6.35}
  \]

- **Maximum error**
  
  \[
  E_{\infty}(F) = \| r \|_{\infty} = \max_{i = 1, 2, \ldots, n} |r_i| = \max_{i = 1, 2, \ldots, n} |y_i - f(x_i)|. \tag{6.36}
  \]

If the parameters of \( f \) are chosen in order to minimise the root mean square error, then the process is called *least squares fitting*.

Minimizing the root mean square error \( \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - f(x_i))^2} \) is equivalent to minimizing

\[
\| r \|_2^2 = \sum_{i=1}^{n} (y_i - f(x_i))^2. \tag{6.37}
\]

### 6.3.2 Optimization techniques

Optimization is a mature field that has been conducted over about 60 years [179] as a methodology of making something as fully perfect, functional or
6.3 Function fitting / Optimisation techniques / Search algorithms

effective as possible [180]. A true optimization process is to find the absolute best situation under a given set of circumstances, while practical optimization has focused on finding an improved situation rather than a true global optimum.

Converting an optimization problem to a mathematical formulation is a critical step in the process of using an optimization approach to solve a problem. If the formulation of the optimization approach is improper, unacceptable results will be achieved. Any optimization problem has three basic components:

- **Optimization variables**, also called design variables, denoted as vector \( \mathbf{x} \).
- **Objective function**, also called cost function, denoted as \( f(\mathbf{x}) \).
- **Constraints** expressed as equalities or inequalities denoted as \( g_i(\mathbf{x}) \).

The variables for a problem can be continuous or discrete. Considering continuous or discrete variables in the model leads to solving the optimization problems as below.

### 6.3.2.1 Optimization models: continuous variables

Any continuous variables optimization problem can be transcribed into a standard nonlinear programming (NPL) model defined as minimization of an objective function subject to the equality and inequality constraints form as problem \( \mathbf{P} \).

**Problem P** [179]: find the optimization variable vector \( \mathbf{x} \) to minimise an objective function \( f(\mathbf{x}) \) subject to equality and inequality constraints as:

\[
\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad (6.38)
\]
where \( n \) is the number of variables, \( p \) is the number of equality constraints, and \( m \) is the total number of constraints. The feasible set, or the constraint set, for the problem is defined as recording all points that satisfy the constraints of Equations (6.39), and (6.40). The feasible set is denoted as \( S \):

\[
S = \{ x | g_j(x) = 0, \ j = 1 \ \text{to} \ p; \ g_j(x) \leq 0, \ j = p + 1 \ \text{to} \ m \}. \quad (6.41)
\]

Thus the problem \( P \) can be written as

\[
\text{minimize } f(x) \\
x \in S
\]

6.3.2.2 Optimization methods: mixed variables

In many practical applications, discrete variables exist in the problem formations. For instance: the thickness of a sheet must be selected from the available dimensions form the steel producer; number of bolts must be integer; and material properties must be selected from the existing materials.

A mixed continues-discrete variable optimization problem can be defined as problem \( MP \) as

**Problem \( MP \) [179]:** a general mixed variables nonlinear optimization problem is defined by modifying problem \( P \) to minimize cost function \( f(x) \) subject to the constraints of Equations (6.39), and (6.40) with the additional requirement that each discrete variable must be selected from the specified set:

\[
x_i \in D_i, \ D_i = (d_{i1}, d_{i2}, \ldots, d_{iq_i}); \ i = 1 \ \text{to} \ n_d. \quad (6.43)
\]
6.3 Function fitting / Optimisation techniques / Search algorithms

Where $n_d$ is the number of discrete design variables, $D_i$ is the set of the discrete variables for the $i$th variable, $q_i$ is the number of available discrete variables for the $i$th variable, and $d_{ik}$ is the $k$th discrete variable for the $i$th variable.

Note that the computational time in an optimization problem with discrete variables is considerably higher compared to the continuous variable problems.

### 6.3.3 Search algorithms

An optimisation consists of an objective function and a search algorithm that tries to find the region of the design space that minimizes the objective function. Optimization search algorithms can be classified into two main categories as deterministic and stochastic methods [181, 182]. A brief review on various available approaches in those categories will be presented below. Most of the information of this part takes cue from [182].

#### 6.3.3.1 Deterministic optimization

Deterministic optimization, or mathematical programming, is a classical optimization method in mathematic in which a rigid mathematical algorithm is followed and no random elements appear in the process of optimization. A Gradient-based optimization is one category of deterministic optimization methods which relies on the computation of the gradient of the objective function.

A deterministic optimization method can be constrained or unconstrained. A constrained optimization refers to the optimization algorithm in which the input variables are constrained.
(i) **Unconstrained optimization**

An unconstrained optimization algorithm generally starts from a point \( x^{(1)} \) and generates a sequence of points \( \{ x^{(n)} \} \) in the design space converging to the solution \( x^{(*)} \) as

\[
x(\alpha) = x' + \alpha s, \quad \forall \alpha \in \mathbb{R},
\]

where \( x' \) is a point in the design space and \( s \) is a direction [182].

Common methods for unconstrained optimization will be defined below.

**(i-1) Simplex method**

The first simplex method for nonlinear optimization was introduced by *Spendley* in 1962. A simplex is a geometrical figure enclosed within \( k + 1 \) vertices in an \( k \)-dimensional space. The simplex is called to be regular if the edges connecting the vertices all have the same length.

The *Spendley* simplex method starts from a set of \( k + 1 \) samples locating a regular simplex in the design space. The values of the objective functions at the vertices of the simplex are computed and compared. Then the vertex in which the value of the objective function is the largest is reflected through the centroid of the other \( k \) vertices to form a new simplex and the process is repeated. If the reflected vertex still has the highest value of the objective function, the vertex which has the second highest value will be reflected. When a certain vertex \( x_i \) has been in the simplex for more than \( M \) number of iterations, the simplex becomes smaller by replacing all the other \( x_i \) vertices. Each new vertex is set at half of the distance along the edge connecting the old vertex \( x_i \) to vertex \( x_j \). The value of \( M \) suggested by *Spendley* is

\[
M = 1.65k + 0.05k^2.
\]
Nedler and Mead proposed a modified simplex method in 1965. Irregular simplexes can be used in their method and different mechanisms (reflection, contraction, expansion, and shrinkage) were suggested to move the simplex around.

**(i-2) Newton’s method**

Newton’s method is the most famous classic optimisation algorithm. In this method a quadratic model of the objective function is obtained from a shortened Taylor series expansion

\[
f(x^n + \delta) \approx q^{(n)}(\delta) = f^{(n)} + g^{(n)r} \delta + \frac{1}{2} \delta^T G^{(n)} \delta. \quad (6.46)
\]

Then \(x^{(n+1)} = x^{(n)} + \delta^{(n)}\) is chosen where \(\delta^{(n)}\) minimises the \(q^{(n)}(\delta)\). The method requires the first and second derivatives of the objective function to be computed and it is well defined if \(G^{(n)}\) is positive definite.

**(i-3) Quasi-Newton methods**

Only first derivatives of the objective function need to be computed by finite differences in the Quasi-Newton methods.

**(i-4) Levenberg-Marquardt methods**

Levenberg-Marquardt are restricted step methods that were introduced for solving nonlinear least-squares curve fitting problems. Levenberg-Marquardt methods are the modified version of the Newton’s method to increase the stability. However, similar to the Newton’s method, second derivatives of the objective function need to be computed.

**(ii) Constrained optimization**

The structure of a generic constrained optimization problem is
minimize \quad f(x) \quad x \in \mathbb{R}^k,

subject to \quad g_i(x) = 0 \quad i \in E

\quad g_i(x) \geq 0 \quad i \in I, \tag{6.47}

where \( f(x) \) is the objective function, \( g_i(x) \) are constrained functions, \( E \) is the set of equality constrains, and \( I \) is the set of inequality constrains. Some commonly used methods for the constrained optimization are: Elimination methods; Lagrangian methods; Active set methods; and Penalty and barrier function methods. More information about these methods can be found in [182].

### 6.3.3.2 Stochastic optimization

Stochastic optimization refers to the optimization algorithms in which there is a presence of randomness in the search procedure.

Most of the stochastic optimization methods are population-based in which a set of initial samples evolves (or move) up to the convergence. The rules of evolution which always have some randomness depends on the natural model of the algorithm. Population-based algorithms are also named as Swarm Intelligence (SI) when they mimic the collective behaviour of self-organized natural systems. Usually the collective behaviour is taken from animals: flocking, hunting, swarming, feeding, and etc. Compared to the deterministic optimization methods, the stochastic methods are less mathematically complicated, while they have a much slower convergence to the optimum solution due to existence of randomness in the search procedure.

The stochastic methods are capable to have a comprehensive investigation of the design space and allow the global optimization to be performed without sticking with local minima. The ability to overcome the local minima in the
objective function improves the possibility of finding the global minimum and it is called the *robustness* of the method.

The stochastic optimization methods are commonly single objective, however they can be easily implemented to account for multi-objective problems. The implementation of multi-objective problems is fundamentally impossible for the deterministic optimization methods due to the way they work.

**(I) Multi-objective optimization**

A single objective optimization process is quite straightforward. For instance the mass \( M = f_1(x) \) or the maximum stress \( \sigma_{max} = f_2(x) \) of a mechanical system needs to be minimized. While, in a multi-objective optimization problem there are more than one objective in the process of optimization. For instance the aim is to minimize both mass \( M \) and maximum stress \( \sigma_{max} \) of a mechanical system at once.

The aim of a multi-objective function is to keep the two or more objective functions separated. It is logical that if a configuration \( x^* \) minimises \( M \), it probably cannot also minimises the \( \sigma_{max} \). Thus, the result will not be a single optimum for the problem.

A different definition of optimality is needed, so the concept of *Pareto optimality* is usually used. It is considered that \( f(x) = (f_1(x), ..., f_l(x))^T \) is the vector collecting the values of \( l \) objective functions at the point \( x = (x_1, ..., x_k)^T \) in the design space. Because of the conflicting objectives, there is not a single solution for \( x^* \) that would be optimal for all the objectives \( f_i(x), i = 1, ..., l \) simultaneously. However, some objective vectors can be better than the others. In those solutions, none of the components can be improved without deteriorating at least one of the other components. Therefore, a point \( x^* \) in the design space is Pareto optimal if the vector of the objective function \( f(x^*) \) is *non-dominated*. A vector \( f(x_1) \) dominates vector \( f(x_2) \) if and only if
\[ f_i(x_1) \leq f_i(x_2) \quad \forall i, \] and at least a \( j \) exists for which \( f_j(x_1) < f_j(x_2) \). The \textit{Pareto frontier} is given by the set of objective functions whose vectors \( \{ f(x) \} \) are non-dominated. The set of optimum solutions is represented by the corresponding values of the input variables \( \{ x \} \) in the design space.

The number of performed simulations in a multi-objective problem is more than a deterministic single objective optimization process. However, a multi-objective technique is a powerful approach that may save time over running a series of single objective optimisations.

\section*{(II) Methods for Multi-threading Stochastic Optimisation}

Traditional deterministic optimization methods commonly start from a single point in the design space. Assuming that there is a convex nature to the objective function, then the search algorithm would eventually find the global optimum. However, if the objective function has some local minima, that is places in the objective function in which have zero gradient of the objective function, but are not the global optimum. Secondly, if the objective function has an element of randomness, then in these two cases a multi-threaded approach is necessary. A multi-threaded approach starts with a set of samples in the design space, and this set of samples evolve through the search iterations. The set of samples is called a \textit{population} and each sample of the population is called an \textit{individual}. The size of population, that is the number of individuals in the population, is kept constant through all the iterations. Stochastic optimization algorithms can be classified into various families. Some common classifications are presented in the following.

\subsection*{(II-1) Simulated Annealing (SA)}

The annealing heat treatment process of steel is emulated in SA method. Annealing is a technique in metallurgy which involves heating and controlled cooling of the material to increase the size of its crystals and reduce their
defects. The annealing process starts with a high temperature, then the metal is slowly cooled that increases the chance of forming a configuration in which the atoms are ordered in a crystal lattice. SA optimization starts from evaluating the value of the objective function at an initial random point in the design space. A law will be introduced to define how the temperature parameter decreases over the successive function evaluations. The notation of slow cooling the temperature decreases the probability of accepting worse solutions as the optimization algorithm explores the design space.

**(II-2) Particle swarm optimization (PSO)**

The social behaviour of birds flocking is emulated in PSO method. The aim of this technique is to sweep the design space by letting the solutions fly through the design space by following the current optimum individual. It is said that this method mimics the behaviour of a flock of birds looking for food (that is looking for the optimum location in the design space) and following the leader of the flock that is the bird which has found where the food is. Each individual is a bird in the design space and each iteration is the movement of the birds in the design space to find the global best location by the swarm through the local best location found so far by a bird.

**(II-3) Game theory-based optimization (GT)**

The evolution of a game in which different players try to fulfil their own objectives is emulated in GT method. This method was developed for the purpose of multi-objective optimization. \( l \) players are participating in the game to minimize the \( l \) objective functions, thus one objective function is assigned to each player. The aim of the players is to minimize the given objective function. The input variables are subdivided between the players. At each turn of the game, for instance, the player will carry out a few Nedler and Mead simplex iterations on the design subspace of the input variables that have been allocated to him with the aim of minimising his objective function.
The strategy of each player is influenced by the other players, thus an equilibrium is met at the end as a compromise between the objectives. Changing the rules of the game which is applying a different subdivision of the input variables would lead to finding a different equilibrium.

\textbf{(II-4) Genetic algorithms (GA)}

This method tries to emulate the evolution of species, where a population of genes evolve towards the optimum. The poor performing genes are removed, and the high performing genes are crossed together to form better genes. Finally the genes have a small random mutation added to enable them to search more of the design space (and avoid local minima).

\textbf{6.3.3.3 Selecting an appropriate search algorithm}

The main advantages of the stochastic optimization methods are possibility to handle a multi-objective problem, and the capability of overcoming local minima. A comprehensive investigation of the design space is performed due to the presence of randomization and considering the multi-threaded sample populations. However, number of required iterations are higher in a stochastic optimization method compared to a deterministic algorithm. The random mutations of the sample population can mean that the search algorithm can take a long time to find a minimum.

The \textit{HEEDS MDO} [183] software tool will be used in the optimization process of this thesis. A parameter optimization study is performed in \textit{HEEDS MDO} to achieve an optimized design by iteratively changing the values of tagged variables and extracting the response for each design candidate. Project variables and responses are created globally for the entire project, and it is specified that how they will be used in design evaluations. New design candidates are generated based on the mathematical search algorithms. For each design, new values will be selected for the variables based on the
variables definition. As the search progresses, HEEDS MDO uses intelligent methods to choose the values based on the results of previous design. It evaluates each new design against the best design it has found so far and the data from each new best design is written to the output file [180].

Combining an optimization technique with finite element simulation has found its application in industry in the recent decade due to using fast and powerful computers and the development of new optimization methods. An increasing demand in the metal forming industry is optimizing the material properties and geometry of the components to satisfy the design objectives, while reducing the design time and cost. One of the most comprehensive applications of the combined FEA-optimization technique is automotive industry in which using high strength steel materials would lead to weight reduction of vehicles.

**6.4 Previous studies to obtain material data in an inverse modelling using a bend test**

It was shown in Section 6.2 that a plasticity material model consists of different parameters such as yield condition, and the material hardening law. Buckling of the sheet in compression makes a tension-compression test difficult to get material hardening parameters. Chapter 5 showed that bending and reverse bending has been used as an alternative way to determine the material hardening properties during strain reversal. However, the output from a bend test is a moment–curvature diagram, and this does not allow the generation of a tensile stress–strain curve directly from bend test. This means an inverse approach is needed to determine the tensile stress–strain curve from a model of the bend test, given an experimental moment–curvature diagram from the actual test. A finite element simulation is usually used to simulate the bend test, and an optimization procedure is applied to update the material parameters in the finite element simulation to achieve the best fit between the numerical results and experimental data of the bend test.
A summary of various studies in which an inverse approach was applied to identify material parameters through a bend test is shown in Table 6.1. Detailed information about the bending arrangement and the purpose of those studies was previously discussed in Chapter 5 (Section 5.2).

Table 6.1 Previous studies to obtain material data in an inverse modelling using a bend test.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material model</th>
<th>Optimization technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eggertsen [141]</td>
<td>Armstrong-Frederick, Geng-Wagoner, and Yoshida-Uemori to define material hardening; Hill, Barlat-Lian, and Banabic/Aretz to define yield criterion</td>
<td>Response surface method using LS-OPT software tool</td>
</tr>
<tr>
<td>Eggertsen [157]</td>
<td>Armstrong-Frederick, and a modified version of the Yoshida-Uemori to define material hardening</td>
<td>Response surface method using LS-OPT software tool</td>
</tr>
<tr>
<td>Zhao [158]</td>
<td>Chaboche material hardening model</td>
<td>Micro-genetic algorithm technique</td>
</tr>
<tr>
<td>Doig [159]</td>
<td>Chaboche material hardening model combined with Hill anisotropy yield criterion</td>
<td>Genetic algorithm technique in software IMA; and LS-OPT software tool</td>
</tr>
<tr>
<td>Weiss [165]</td>
<td>Power law material model with isotropic hardening</td>
<td>Nelder-Mead Simplex optimization technique</td>
</tr>
<tr>
<td>Yoshida [161]</td>
<td>Chaboche-Rousselier material hardening model</td>
<td>Based on an iterative multipoint approximation concept</td>
</tr>
<tr>
<td>Yoshida [162]</td>
<td>Chaboche-Rousselier, and Prager, material hardening models</td>
<td>Based on an iterative multipoint approximation concept</td>
</tr>
<tr>
<td>Brunet [163]</td>
<td>Chaboche material hardening model combined with Hill anisotropy yield criterion</td>
<td>A specific optimization technique using sequential quadratic programming algorithm</td>
</tr>
<tr>
<td>Carbonniere [164]</td>
<td>Ziegler nonlinear kinematic hardening model combined with Hill anisotropy yield criterion</td>
<td>Numerical optimization based on a dichotomy method</td>
</tr>
</tbody>
</table>

The above table shows that a bend test combined with various material models has been used by other researchers to identify material parameters. Different optimization techniques have been applied to identify the material parameters that can represent the experimental data. Selecting an appropriate
material model in the bend test depends on the characteristics of the bend device and the actual deformation of the material during the test. For instance an isotropic material model is sufficient only if monotonic bending happens during the test, and there is no strain reversal. While a combined hardening material model is necessary to represent the material behaviour in a cyclical bend test. The existence of many variables in the material model makes the optimization process difficult to represent a unique set of results. Thus, the first step to identify the material parameters in an inverse approach is selecting a relevant material model that can represent the actual deformation of the material in the experiment.

Material modelling, optimization techniques, and previous studies to identify material data using an inverse process have been reviewed. It is clear that an appropriate strategy should be used in this chapter to identify residual stresses in a material through a bend test. Identification of an appropriate strategy in this thesis and the development of the inverse routine for prediction of residual stresses will be presented in the following sections.

6.5 Selecting the appropriate material for developing the inverse approach

Reiterating the purpose of this chapter, a thickness reduction rolling process will be used in this chapter to add some residual stress profiles into a stress relieved material and an inverse approach will be applied using the bending behaviour of thickness reduced material to predict residual stress profile through the thickness of the strip.

The tensile test results of Chapter 4 showed that strain ageing will be observed in DP780 steel during stress relieving. Strain ageing is a material softening effect that can only be modelled using detailed strain rate effects (lüders bands). This approach would also introduce additional degrees of freedom into the inverse model (upper and lower yield points), which would under-
constrain the inverse analysis. Therefore, there would be more unknown parameters to estimate, yet there is only the same available known data. This would lead to non-unique solutions. Thus, the aim became first to develop an inverse approach that would work on a simpler material. An extra low carbon stainless steel, 304L stainless steel, was selected as it does not experience strain ageing.

6.5.1 Stress relieving process

The chemical composition of the 304L stainless steel, with material thickness of 2 mm, in weight percentage (wt %) is shown in Table 6.2.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(wt %)</td>
<td>0.016</td>
<td>0.63</td>
<td>1.16</td>
<td>0.030</td>
<td>0.003</td>
<td>8.06</td>
<td>18.14</td>
<td>0.052</td>
</tr>
</tbody>
</table>

The as received material was stress relieved at 700°C in a muffle furnace for 1 hour followed by air cooling to insure that it was fully stress free (without any initial residual stress).

An optical microscope, Olympus high resolution DP70, was used to capture the microstructure of the material. The microstructure of stress relieved stainless steel is shown in Figure 6.5. Villela’s reagent (1 g picric acid, 5 ml hydrochloric acid, and 95 ml ethanol) was used as etchant. This stainless steel consists of one single austenite phase.
6.5 Selecting the appropriate material for developing the inverse approach

Figure 6.5 Microstructure of the 304L stainless steel.

A comparison between the tensile test data of the as-received and stress-relieved materials is shown in Figure 6.6 for a low range of true strain to visualise material behaviour close to the elastic-plastic transition. The figure shows that there is no strain ageing effect and this makes the alloy suitable for residual stress prediction in an inverse approach based on bend test data.

Figure 6.6 Tensile test results of as-received, and stress-relieved 304L stainless steel.

6.5.2 Thickness reduction rolling process

A thickness reduction rolling process, same as Section 4.2.1, was performed to introduce a residual stress profile into the stress-relieved material. Strips were cut to the same geometry of the samples in the bending simulation in
Chapter 5, Section 5.4.2. The thickness, length and width of strips were 2 \text{mm}, 60 \text{mm}, and 20 \text{mm} respectively.

Thickness reductions of 0.5\%, 1\%, and 2.3\% were performed in the thickness reduction rolling process. Note that the aim was to achieve a thickness reduction that was the same as the three performed levels in Chapter 4 (0.5\%, 1.5\%, and 2.5\%). However, the set-up of the process was difficult to make exact to the previous reduction set due to variables such as: the material initial thickness, and the rolling condition. Nevertheless, the measurement was performed precisely to calculate the level of thickness reduction and the obtained levels are close to those in Chapter 4.

6.5.3 Material model and material data for FEA

A material model is needed in this chapter for the inverse analysis, instead of introducing the stress–strain data directly into the finite element simulation.

A review on material modelling to define material parameters for FEA was presented in Section 6.2. An appropriate material model needs to be used to represent the obtained material data from the tensile test. The material model will be used in the bending analysis to predict residual stresses in the material through and inverse approach. Thus, the selected material model should be able to represent the actual deformation in the experimental bend test, while it is necessary that there are not too many parameters in the material model to prevent under-constraining of the optimization process.

Identification of material behaviour close to yield is important for roll forming simulation and the aim of this chapter is to predict the residual stress profile in the material based on the effect of residual stresses on material behaviour close to yield. Therefore, bending of the strips in one direction, just loading, will be applied and there is no strain reversal in the bend test. Thus, using an isotropic hardening material model is sufficient.
The constitutive law and the power law isotropic hardening material models will be used in all simulations of the present chapter, see Equations (6.48), and (6.49). *Von Mises* yield criterion will be applied in simulations.

\[
\sigma = E\varepsilon^e
\]  
(6.48) 

\[
\sigma_y = A(\varepsilon_0 + \bar{\varepsilon})^m
\]  
(6.49) 

In the above equations \(\sigma\) is the stress, \(E\) the elastic modulus, \(\varepsilon^e\) the elastic strain, \(\sigma_y\) the yield stress, \(\bar{\varepsilon}\) the equivalent strain, while \(A\), \(\varepsilon_0\), and \(m\) are material parameters. In the proposed material model for this chapter, the \(\varepsilon_0\) parameter is set by the initial yield point, \(\sigma_{y_0}\), where there is zero equivalent strain by combining the constitutive law and power law as

\[
\sigma_{y_0} = A(\varepsilon_0)^m = E\varepsilon_0 \Rightarrow \varepsilon_0 = \frac{1-m}{\sqrt{E}}. 
\]  
(6.50) 

Standard tensile tests as those performed in Section 3.3.3.1 were applied to obtain the input material properties of the stress relieved 304L stainless steel. A total of 3 tests were performed and one of the repeatable results was used. A curve fitting method was used to obtain the above material parameters for the 304L stainless steel (see Table 6.3). Only the experimental tensile test data up to 3% stain was used for the curve fitting approach; the data will be applied in the bend test which is restricted to a maximum outside fibre strain of 2%. Note that \(\sigma_{y_0}\) is reported as a material parameter since the value of \(\sigma_{y_0}\) is more practical compared to \(\varepsilon_0\). However, in the material model of this chapter

\[
\varepsilon_0 = \frac{\sigma_{y_0}}{E}. 
\]  
(6.51)
Table 6.3 Material parameters of the stress relieved 304L stainless steel restricted to 3% tensile strain.

<table>
<thead>
<tr>
<th>Material data</th>
<th>$E$ (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$A$ (MPa)</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>196</td>
<td>259.1</td>
<td>666.2</td>
<td>0.142</td>
</tr>
</tbody>
</table>

A comparison between the experimental stress – strain data and the results of using the above material parameters is shown in Figure 6.7. It is shown that power law model can fit the experimental data with reasonable accuracy. The Poisson's ratio was set to 0.3 [139, 140] for FEA.

![Figure 6.7](image_url) Comparison between the experimental data and the results of power-law model, restricted to 3% tensile strain, for stress relieved 304L stainless steel.

The thickness reduced materials were also used in the tensile test to obtain the material properties for FEA. A curve fitting method was applied to acquire the power law material parameters for the thickness reduced stainless steel strips, see Table 6.4. Same as the tensile test of non-thickness reduced material, only the tensile test data up to 3% strain were used in the curve fitting method.
Table 6.4 Material parameters of thickness reduced 304L stainless steel from a tensile test restricted to 3% strain.

<table>
<thead>
<tr>
<th>Thickness reduction</th>
<th>$E$ (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$A$ (MPa)</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 %</td>
<td>196</td>
<td>295.5</td>
<td>684.1</td>
<td>0.129</td>
</tr>
<tr>
<td>1.0 %</td>
<td>196</td>
<td>301.6</td>
<td>721.8</td>
<td>0.135</td>
</tr>
<tr>
<td>2.3 %</td>
<td>196</td>
<td>358.3</td>
<td>758.1</td>
<td>0.119</td>
</tr>
</tbody>
</table>

The above table shows that yield stress of the material increases in a tensile test due to the thickness reduction rolling process. Numerical simulations of Chapter 5, Section 5.4.3, have previously shown this, while it was proven by experimental tensile test in this section.

6.6 Effect of a residual stress profile and the associate plastic deformation on bending

The material model for modelling 304L stainless steel has been chosen, and hence it is necessary to compare the bending simulation results of the material with and without a residual stress profile to the experimental data. Effect of residual stresses on a bending simulation were shown in Chapter 5, however experimental verification was not performed. The main goal of this section is to intensely understand the effect of a residual stress profile and the associate plastic deformation in the material. This understanding will layout the inverse routine methodology to determine a residual stress profile in a metal sheet.

The related numerical simulations of this chapter were performed using an MSC-Marc solver.

6.6.1 Accuracy of a bending simulation using tensile data to define the material model

The finite element simulation of the bend test which was performed in Chapter 5 (Section 5.4.2), will be used in this section. Strip geometry, element type, and mesh density are the same, however instead of using the stress –
strain data to define material behaviour, the introduced material model of Section 6.5.3 is used.

A comparison between the moment-curvature data of a non-thickness reduced (stress relieved) material in the experiment to the finite element simulation results of using tensile data of stress relieved material to simulate the bend test (data of Table 6.3) is shown in Figure 6.8.

![Figure 6.8](image)

**Figure 6.8** Comparison between the bending moment–curvature data of non-thickness reduced material from experiment to the numerical results using tensile test material data for the simulation of the bend test.

It is shown in the above figure that if material data from a tensile test is used to numerically model the bend test of the stress relieved material, the numerical simulation can predict the yield transition point with very good accuracy, while there are some discrepancies between the experimental and numerical results at higher bending curvatures. This suggests that the material hardening parameters from a standard tensile test may be slightly different to those from a pure bend test. However, the tensile input data allows to predict the yield transition point in the bend test correctly if there is no residual stress in the material.
Finite element simulation of the bend test was also performed using the material parameters of Table 6.4 to simulate the bending behaviour of thickness reduced strips using tensile data. A comparison between the numerical and experimental results of bending of thickness reduced materials is shown in Figure 6.9.

**Figure 6.9** Comparison between the bending responses of thickness reduced materials in finite element simulation using tensile test material data to the experimental results. The above figure shows that numerical simulation of the bend test using tensile material data for FEA cannot detect the early yielding in the material. The yield transition point in the numerical simulation increases with further thickness reduction due to the increasing yield stress from the tensile test, while experimental bending results shows that early yielding will be observed in the material if thickness reduced materials are used in the bend test.

It was proven in Figure 6.8 that for a stress relieved material the tensile data can predict correct yield transition point in the bending simulation (yield transition point is the same in the tensile and bend test), while the bending
results of the thickness reduced materials showed that the tensile material data is not sufficient to capture the early yielding in the bend test.

The material is plastically deformed during the thickness reduction rolling process and therefore the discrepancies shown in Figure 6.9 can be due to the combined effect of plastic deformation and residual stress. Finite element simulation will be used in the next sub-section to separate the effect of a residual stress profile from the effect of associate plastic deformation in the material.

6.6.2 In-depth understanding of the effect of a residual stress profile on bending

Finite element simulation of the thickness reduction rolling process will be used in this section to observe a residual stress profile through the thickness of material due to various levels of thickness reduction. The boundary conditions and roll geometry are the same as those introduced in Chapter 4 (Section 4.2.3), while the strip geometry, element type, mesh density, and material model are the same as the bending simulation of stress relieved material in Section 6.6.1. The friction coefficient between the rolls and the strip is 0.2.

Residual stress profiles through the normalised material thickness due to various levels of thickness reduction rolling are shown in Figure 6.10.

All thickness reduction levels led to the introduction of tensile residual stress at the sheet surface, compressive residual stress exists in the center of the samples with 0.5%, and 1.0% thickness reduction while this value is almost zero for the material with 2.3% thickness reduction. The residual stress profiles are symmetric over the sheet thickness and are in a good agreement with the results presented previously in Chapter 4, Section 4.2.7.1, and for a
temper rolling process that applied a setup similar to the thickness reduction rolling of this thesis [29, 31].

![Figure 6.10](image)

Figure 6.10 Residual stress profiles through the normalised material thickness for various thickness reduction rolling levels in the numerical simulation.

To show that the reduction in yield stress with thickness reduction rolling in the experimental bend test is due to residual stresses, the residual stress profiles shown in Figure 6.10 were introduced in the un-deformed (non-thickness reduced) strip by applying the UINST subroutine [156]. This material with initial residual stresses was then used for the modeling of the bend test.

Figure 6.11 shows the effect of the residual stress profiles on the moment-curvature diagram. It can be seen that the yield transition point is significantly reduced after thickness reduction rolling to 0.5 and 1% while it remains at a similar level compared to the initial condition after thickness reduction rolling to 2.3%. The yield transition point is lower in the thickness reduced material with 0.5% thickness reduction due to more residual stresses through the material thickness.
Comparing the results of Figure 6.9 and Figure 6.11 suggests that the increase in the bending moment at higher curvatures, observed for the thickness reduced samples in the experiment can be related to strain hardening. While Figure 6.9 (effect of strain hardening due to plastic deformation in thickness reduction rolling excluded) does not show any increase in bending moment level with thickness reduction rolling, a clear increase in bending moment with increasing thickness reduction can be seen in experimental data of Figure 6.9 at higher curvatures.

The finite element simulation of the thickness reduction rolling-bending analysis in a combined model which was presented in Chapter 5 (Section 5.4.2), will be used to include the effect of strain hardening in material bending response in FEA. Thus, the material in the bending analysis has full stress–strain history form the previous thickness reduction rolling step and it will represent the combined effect of residual stress profile and the associate plastic strain. The boundary conditions and roll geometry are the same as those introduced in Chapter 5, while the strip geometry, element type, mesh
density, and material model are the same as the bending simulation of stress relieved material in Section 6.6.1. The friction coefficient between the rolls and the strip is 0.2.

The moment–curvature diagrams of the thickness reduced material predicted by the combined model are compared to those of the non-thickness reduced material in Figure 6.12.

![Graph showing moment-curvature](image)

**Figure 6.12** Numerical moment–curvature diagrams for the non-thickness reduced and the thickness reduced materials from a combined thickness reduction rolling-bending model.

It becomes clear that the combined model also shows the early yielding in the material, while a clear increase in the bending moment is shown with increasing the thickness reduction level similar to the experimental data. A comparison between the results of the combined model to the experimental data is shown in Figure 6.13.
The above figure shows that both numerical results and experimental data detect early yielding in the material due to existence of residual stresses, while bending moment increases at higher curvatures due to the strain hardening effect as a result of existence of plastic strain in the material after thickness reduction rolling. Although numerical simulation clarified the effect of a residual stress profile and the associate plastic deformation in the bend test, there are some discrepancies between the results of combined model and the experimental data in Figure 6.13. Some possible reasons for the observed discrepancy are:

- Two solid-shell elements were used through the thickness of the strip in numerical simulation. Although Chapter 3 shows that this element type can detect the bending response of material with reasonable accuracy, more elements may be needed through the thickness for the thickness reduction rolling analysis.
- Advanced material phenomena such as the evolution of elastic modulus with plastic deformation [185-188] was not considered and an
isotropic hardening material model was used in FEA. However, using more advanced material models would improve the accuracy of the obtained results.

Acquiring the in-depth knowledge about the effect of a residual stress profile and the associate plastic strain in the material on the material bending response helps the development of the inverse routine in the following sections.

### 6.7 Methodology of the inverse routine

The previous section showed that existence of a residual stress profile in the material leads to early yielding in a bend test. It was also explored that residual stresses due to cold forming, a thickness reduction rolling in this thesis, are always accompanied with plastic strain and a combined effect of those parameters needs to be considered to represent the material behaviour in the bend test. An inverse approach will be developed in this thesis to predict residual stresses in the material based on experimental bending response of thickness reduced materials. The inverse approach will consider the experimental moment–curvature data of a thickness reduced material as a target graph and then changes the initial residual stresses in the material to obtain the best fit between FEA results and the experimental target graph. Therefore, in addition to changing initial residual stresses in the material, it is necessary for the inverse routine to modify the parameters of the material model to detect the strain hardening behaviour of the material due to existence of plastic strain after a thickness reduction rolling process.

Modifying the material model parameters in an inverse approach begs this question whether early yielding of the material in bending can be detected only by reducing the initial yield strength of the material, \( \sigma_y^0 \) in Equation (6.50), in FEA. The goal of this chapter is prediction of residual stresses in the material, however it is not clear if existence of a residual stress profile is
necessary to detect the elastic-plastic transition in the bend test of a thickness reduced material or this phenomena can be simply observed by suppressing the initial yield strength in the material model.

Consequently, there are two possible approaches in the inverse routine as below to obtain material data for numerical simulation which can fit the experimental bending response of a thickness reduced material.

1. *Inverse routine excluding initial residual stress*: The inverse optimization approach will change the coefficients of power law isotropic hardening material model \((A, \varepsilon_0, \text{ and } m\) in Equation (6.49)) in the bending simulation of thickness reduced material to deliver the best fit between the numerical results and the target experimental moment–curvature data of a thickness reduced material. There is not any pre-existing residual stress profiles in the material using this approach.

2. *Inverse routine including initial residual stress*: In the second methodology, initial residual stresses will be considered in the material in numerical simulation of the bend test. The inverse approach will change the coefficients of power law isotropic hardening material model \((A, \varepsilon_0, \text{ and } m\) in Equation (6.49)) and the initial residual stresses through the thickness of the material to deliver the best fit between the numerical results and the target experimental moment–curvature data of a thickness reduced material.

### 6.7.1 Mathematical representation of a residual stress profile

A mathematical representation of the residual stress profile is needed for development of the inverse routine. Residual stress profiles due to the thickness reduction rolling process, see Figure 6.10, and the results of similar studies [6, 29, 31] suggests that the residual stresses that are due to steel processing can be presented by a polynomial. A second degree polynomial will
be used in this thesis to present the residual stresses through the material thickness as

\[ \sigma_{Residual}(x) = ax^2 + bx + c, \]  

(6.52)

where \( x \) is the coordinate from the center of the sheet in thickness direction, and there are three variables \((a, b, c)\) to define a residual stress profile. The stresses will be calculated separately from above function for positive and negative values of \( x \).

### 6.8 Development of the inverse routine

An optimization technique was applied to develop the inverse routine in this thesis. The experimental moment–curvature diagram of the thickness reduced material is the target curve for the optimization method. The Coefficients of power law isotropic hardening material model \((A, \varepsilon_0, \text{ and } m \text{ in Equation (6.49)})\) are the project variables in the inverse routine if initial residual stresses are neglected. While there are six project variables in the optimization procedure including an initial residual stress profile as: \(a, b, c\) in Equation (6.52) to represent the residual stress profile; and \(A, \varepsilon_0, \text{ and } m\) in Equation (6.49) to define the material model.

The project variables to define an initial residual stress profile, \(a, b, c\) in Equation (6.52), are introduced into the numerical simulation using an UINSTR user subroutine. The initial residual stresses in the integration points of solid-shell elements and coefficients of power law isotropic hardening material models (project variables) are changed in the bending simulation to approximate the moment–curvature diagram (project response).

The HEEDS MDO optimization software package [183] is used for the optimization process. A parameter optimization technique is used in HEEDS
MDO using SHERA search algorithm, more information about the optimization process was presented in Section 6.3.

The root-mean square (RMS) curve fitting method, see Section 6.3.1, is applied to deliver the best fit between the numerical moment–curvature results and the experimental data. The RMS value can be represented as

$$ RMS = \sqrt{\left( \frac{1}{N} \sum_{i=1}^{N} (y - y')^2 \right)} $$  \hspace{1cm} (6.53)

where $N$ is the number of increments, $y$ is the obtain curve in each increment, $y'$ is the target curve, and $dx$ is the increment size for $i$. The smaller the value of RMS the closer is the match between the two curves and a better prediction exists. Thus, the aim of the optimization process is to minimize the RMS value by updating the project variables (material parameters and the initial residual stress profile) and comparing the project response (moment–curvature data in each bending simulation) to the target curve (experimental moment–curvature data).

A flowchart summarizing the inverse routine for obtaining the material parameters and the residual stress profile is shown in Figure 6.14, while Figure 6.15 shows a schematic of the inverse routine.

The experimental moment–curvature data which is the target graph in the optimization process and the calculated elastic modulus from bend test are the input for the inverse method in HEEDS MDO. The parameters $a$, $b$, $c$ to define an initial residual stress at each integration point of the solid-shell elements and power law material parameters $(A, E_0, m)$ are project variables. A user subroutine is used to define the initial residual stresses at each integration point of solid-shell elements. Simulation of the bend test will be run in MSC-Marc while the RMS method applied to determine the difference between the
predicted and the target curves. The optimization search algorithm, SHERPA, will then update the project variables to minimise the RMS value. This loop will continue till the maximum evaluation is reached. The project variables that provide the best fit will be identified by the HEEDS MDO.

The inverse routine excluding residual stresses in the material uses the same approach in which there are only three project variables as $A$, $C_0$, and $m$.

---

**Figure 6.14** Flowchart of the inverse method to predict material model and residual stresses in the material.
6.8.1 Application of the inverse routine to predict residual stresses through the thickness of 304L stainless steel

Figure 6.9, and Figure 6.10 showed that experimental moment–curvature data of the materials with 0.5% and 1% thickness reduction and the obtained residual stress profiles in FEA are similar. Thus, the inverse approach of the current section will concentrate on two thickness reduction levels as 1% and 2.3%.

6.8.1.1 Obtaining the elastic modulus from the experimental data

In addition to the experimental moment–curvature data which is the target curve in the optimization process, elastic modulus of the thickness reduced sample is also needed as an input parameter for the inverse routine, see Figure 6.15. The relation between moment and curvature in the elastic part of the bend test can be presented as

\[
\sigma_y = A(\varepsilon_0 + \varepsilon)^m
\]
\[ M = \frac{1}{12} WE \left(\frac{1}{R}\right) t^3, \]  

(6.54)

where \( M \) is the bending moment, \( W \) is sample width, \( E \) is elastic modulus, \( \frac{1}{R} \) is bending curvature, and \( t \) is the material thickness.

The Elastic modulus \( (E) \) is the only unknown variable in the experimental bend test using the above equation. A curve fitting approach was used to obtain the elastic modulus from the experimental bending data of thickness reduced materials in the elastic part (experimental data of Figure 6.9). The obtained elastic modulus was used as the project input to simulate the bend test in the optimization process.

The obtained results from bending data showed a reduction in the elastic modulus, from 196 GPa in the non-thickness reduced material to 160 GPa and 159 Gpa in the materials with 1% and 2.3% thickness reduction respectively. Previous studies [185-188] have shown that the elastic modulus of cold rolled plate reduces with plastic deformation which is in agreement with the results of this thesis.

### 6.8.1.2 Investigating the accuracy of the two proposed inverse methodologies

This section will show whether both of the introduced inverse approaches in Section 6.7 are able to precisely capture the slope of elastic-plastic transition in the bend test or not.

Detecting the material behaviour close to yield, the elastic-plastic transition slope, is important for the optimization process of this section. Thus, a lower plastic strain range of moment–curvature data (Bending curvature up to 6.3 m^{-1} in experimental results of Figure 6.9) was considered as the target graph in the first trial to minimize the effect of strain hardening in the optimization
process. The inverse routine was run separately for each case of 1.0%, and 2.3% thickness reduction, the same optimization parameters were used and just the input data, target curve and elastic modulus, was different. The project variables from the optimization method that can deliver the best fit in various model configurations and the related RMS value are shown in Table 6.5. Note that instead of material parameter $\varepsilon_0$, the initial yield stress, $\sigma_{y_0}$, is shown in this table since $\sigma_{y_0}$ is more practical. The relation between these two parameters was previously presented in Equation (6.51).

**Table 6.5** Project variables from optimization method to capture early yielding in the bend test and the related RMS value.

<table>
<thead>
<tr>
<th>Inverse model</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>$\sigma_{y_0}$ (MPa)</th>
<th>$A$ (MPa)</th>
<th>m</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%-excluding residual stresses</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>184.3</td>
<td>2760.79</td>
<td>0.4</td>
<td>0.145</td>
</tr>
<tr>
<td>2.3%-excluding residual stresses</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>187.5</td>
<td>2782.02</td>
<td>0.4</td>
<td>0.185</td>
</tr>
<tr>
<td>1%-including residual stresses</td>
<td>0</td>
<td>-720</td>
<td>185.5</td>
<td>205</td>
<td>1992.95</td>
<td>0.341</td>
<td>0.064</td>
</tr>
<tr>
<td>2.3%-including residual stresses</td>
<td>-310</td>
<td>-560</td>
<td>174.7</td>
<td>194.5</td>
<td>2843.88</td>
<td>0.4</td>
<td>0.081</td>
</tr>
</tbody>
</table>

The achieved moment–curvature data in finite element simulation of bend test for 1% and 2.3% thickness reduction using the project variables from the above table are compared to the experimental results in Figure 6.16.
Table 6.5 shows that the RMS value of the models excluding initial residual stresses in the material are higher than those in the models including residual stresses. It is also shown in Figure 6.16 that the discrepancy between numerical and experimental data is also higher in FEA if initial residual stress
is excluded from the model. Therefore, it is clear that the accurate transition between elastic to plastic region in the bend test cannot be detected by only suppressing the yield strength of material through an optimization process to capture early yielding. Applying a residual stress profile in the numerical simulation is necessary to precisely detect the slope of transition from elastic to plastic region in the moment–curvature diagram of a thickness reduced material.

It can be concluded that the correct inverse approach of this thesis has initial residual stresses in the material in the bend test and there are six project variables in the optimization procedure as: $a$, $b$, $c$, $A$, $E_0$, and $m$.

6.8.1.3 Final approach to predict residual stresses through the thickness

The experimental moment–curvature data of the thickness reduced stainless steel (Figure 6.9) were used as the target graph in the final inverse method to predict the material model and initial residual stresses through the thickness of the material. The inverse routine was run separately for each case of 1.0%, and 2.3% thickness reduction, the same optimization parameters were used and just the input data, target curve and elastic modulus, was different. The project variables in the inverse approach that can deliver the best fit to the experimental results and the related RMS value are shown in Table 6.6. This results show that thickness reduction rolling reduces the initial yield stress of the material in the bend test compared to the non-thickness reduced material (259.1 MPa). The initial yield stress of the material in the bend test reduces by 11.4%, and 20.9% due to 1.0%, and 2.3% thickness reduction respectively.
Table 6.6 Project variables from inverse analysis of 304L stainless steel and the related RMS value to define material model and residual stresses.

<table>
<thead>
<tr>
<th>Thickness reduction level</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$\sigma_y$ (MPa)</th>
<th>$A$ (MPa)</th>
<th>$m$</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>-170</td>
<td>-540</td>
<td>142.3</td>
<td>229.5</td>
<td>1255.8</td>
<td>0.260</td>
<td>0.11</td>
</tr>
<tr>
<td>2.3%</td>
<td>-880</td>
<td>-80</td>
<td>101.8</td>
<td>205</td>
<td>2264.2</td>
<td>0.361</td>
<td>0.13</td>
</tr>
</tbody>
</table>

The predicted residual stress profiles from the inverse approach (by applying the variables $a$, $b$, and $c$ in Table 6.6 to the Equation (6.52)) are shown in Figure 6.17.

![Figure 6.17 Predicted residual stress profiles from the inverse routine for 1.0% and 2.3% thickness reduction in the thickness reduction rolling process.](image)

The above figure shows that tensile residual stresses exists at the surface of the material due to the thickness reduction rolling process while centre of the material undergoes compressive residual stresses. A similar observation was presented in Chapter 4, Section 4.2.7.1. Maximum compressive and tensile residual stresses in the material due to 1.0% thickness reduction are more than these values in the material with 2.3% thickness reduction in the thickness reduction rolling operation. Finite element simulation and experimental measurement using X-ray diffraction (XRD) with layer removal
technique will be presented in the following sections to verify the residual stress profiles obtained from the inverse routine.

### 6.9 Finite element simulation to verify the results of inverse routine

The simulated thickness reduction rolling process of Section 6.6 is same as the thickness reduction rolling process in the inverse approach. Thus, the obtained residual stress profiles from 3D simulation of thickness reduction rolling process are comparable to the results of inverse routine. A comparison between the residual stress profiles from the inverse routine (Figure 6.17) to the residual stress profiles from 3D analysis of the thickness reduction rolling process (Figure 6.10) is shown in Figure 6.18. It is shown in this figure that there are some discrepancies between the FEA results and the results of inverse routine.

Two solid-shell elements were used through the material thickness in 3D rolling analysis and the metal strip was fixed while the rolls were moved to reduce the thickness of the material. Using solid-shell element for roll forming and bending simulations was verified in Chapter 3, while more elements through the thickness may be needed to simulate the thickness reduction rolling process accurately. 3D simulation of thickness reduction rolling process using many elements through the thickness is time consuming, thus a 2D simulation of the same thickness reduction rolling operation with a boundary condition same as the experimental arrangement, see Section 4.2.1, was carried out to compare the results. The rolls are rotating and the metal strip is moved through the rigid rolls as a result of friction between the rolls and the strip (see Figure 6.19). The friction coefficient was considered as 0.2 and 20 plane strain reduced integration elements (Element type 115 [138]) were used through the thickness of metal strip. Material parameters of stress relieved stainless steel, Table 6.3, were used.
6.9 Finite element simulation to verify the results of inverse routine

Figure 6.18 Comparison between the residual stress profiles from 3D finite element simulation of the thickness reduction rolling process to the results of inverse routine a) 1% thickness reduction and b) 2.3% thickness reduction.

A contour of longitudinal residual stresses through the thickness of material after 1% the thickness reduction rolling process is shown in Figure 6.19, while Figure 6.20 shows a comparison between the residual stress profiles due to thickness reduction rolling process in 2D analysis and the obtained residual stress profiles from the inverse approach. In 2D numerical simulation residual
stresses were recorded through the thickness of the strip at the strip middle along its length.

Figure 6.19 2D simulation of the thickness reduction rolling operation and the longitudinal residual stresses after 1% thickness reduction rolling process.

Figure 6.20 shows that there is a good agreement between the residual stress profiles from the inverse approach to the results of 2D simulation and the trend is similar. More discrepancies in 3D finite element simulation can be due to the below reasons.

- Only two solid-shell elements were used through the thickness of the material in 3D finite element simulation. Although each of the solid-shell elements has 11 integration points in thickness direction and it was previously proven in Chapter 3 that this element type has acceptable accuracy in bending and roll forming simulation, more elements through the thickness may be needed for a precise residual stress prediction in the thickness reduction rolling process.
- In 3D analysis of the thickness reduction rolling process the metal sheet is fixed and the rolls are rotating and moving to reduce the thickness (this boundary condition was chosen due to the existence of
subsequent bending or roll forming simulation), while in 2D simulation of the thickness reduction rolling process the boundary conditions are same as the experimental arrangement and the metal sheet is moved through the rolls as a result of friction. The boundary conditions in 2D analysis are closer to the reality.

![Graph](image-url)

**Figure 6.20** Comparison between the residual stress profiles from 2D finite element simulation of the thickness reduction rolling process to the results of inverse approach a) 1% thickness reduction and b) 2.3% thickness reduction.
It can be concluded that both finite element simulation and the inverse approach predict similar results for the residual stress profile through the thickness of stainless steel due to a thickness reduction rolling process. Experimental verification will be explored in the next section.

6.10 X-ray diffraction to measure residual stresses in the material

An inverse routine was developed in the previous section to predict residual stresses in the material. Experimental verification is needed before using the acquired data from inverse approach in roll forming simulation. Literature review of this thesis (Chapter 2) suggested that the X-ray diffraction (XRD) with layer removal technique can be used to measure residual stresses through the thickness of the material. The equipment is also available at Deakin University. Thus, XRD with layer removal technique will be applied to measure residual stresses through the thickness of a thickness reduced stainless steel strip.

First, some principles of X-ray diffraction will be presented. Then the basics of strain and stress measurement using XRD will be explained. XRD residual stress measurement in practice will be presented in the next step and finally, XRD with layer removal will be performed to measure residual stresses through the thickness of a thickness reduced 304L stainless steel strip.

6.10.1 Principles of X-ray Diffraction

The main precaution for residual stress measurement using XRD is that the material needs to be crystalline or semi-crystalline.

When a monochromatic X-ray beam irradiates a solid material, it will be scattered by the atoms of the material. In a perfect crystalline material, the atoms are packed regularly in three dimensional periodic lattices. The distance between the crystallographic planes is perfectly defined for each material in the given environment. The scattered X-ray waves can interference
6.10 X-ray diffraction to measure residual stresses in the material

similar to the visible light diffraction by an optical pattern due to the regular
distribution of atoms. When an X-ray beam irradiates the surface of a
crystalline material, it is scattered only if it meets the lattice panels orientated
to fulfill the Bragg’s law as (see Figure 6.21)

\[ n\lambda = 2dsin\theta , \]  

(6.55)

where \( n \) (an integer) is order of reflection, \( \lambda \) is wavelength of X-ray, \( d \) is the
interplanar spacing between in the atomic lattice, and \( \theta \) is the reflection angle.

![Figure 6.21 X-ray diffraction principle.](image)

So, the information about lattice planes can be obtained from the position of
the diffraction peaks and the d-spacing that they represent.

Diffractometry is one of the practical XRD techniques. In this method a fix
wavelength of \( \lambda \) is used by choosing a monochromatic X-ray target while the
specimen rotates to vary the angle of incidence (\( \theta \)). Figure 6.22 shows the XRD
technique in practice. The entire set of reflection can be achieved by rotating
the specimen and the detector. Whenever the incident beam goes through an
angle that satisfies the Bragg’s law, an intensity peak will appear. The
projection angle of the beam that goes to the detector (2\( \theta \)) is recorded and the
intensity is plotted as a function of 2\( \theta \) in XRD reports.
6.10.2 Residual stress and strain

The diffraction pattern of a crystalline material under uniform or non-uniform strain is shown in Figure 6.23.

A part of unstrained grain is shown in Figure 6.23.a on the left and the diffraction line from these planes is shown on the right. It is shown in this figure that the unstrained material has a constant spacing of $d_0$.

When a polycrystalline material is deformed elastically in such a way that the strain is uniform in a large distance, the lattice plane spacing will change from its stress free value to a value that corresponds to the magnitude of the applied stress. This new spacing is constant from one grain to another for any individual set of planes. This uniform strain causes a shift of the diffraction line to the new $2\theta$ position in the XRD report. If the plane undergoes a tensile
strain, their spacing become larger than \( d_0 \) and the corresponding diffraction line shifts towards lower angles but the shape of the peak remain constant compared to the unstrained material (Figure 6.23.b). This line shift is the basic for using the XRD method to measure macro-stresses in the material.

In contrast, if the material is deformed plastically, the lattice planes distorted so that the spacing of any particular sets of planes varies from one grain to another. This non-uniform macro strain causes a broadening in the corresponding diffraction line. In fact, both kinds of uniform and non-uniform strains are observed in a plastic deformed material and the diffraction line is both shifted and broadened. If the grain is bent and the strain is not uniform (Figure 6.23.c), on the top side (tension) the plane spacing is more than \( d_0 \) while on the bottom side (compression) the plane spacing is less than \( d_0 \) and somewhere in between it equals \( d_0 \). We can consider this grain to be composed of a number of small regions in each of which the plane spacing is constant but different form the neighbor region. This region causes various sharp diffraction lines which are shown on the right of Figure 6.23.c with the dotted lines. The summation of these curves is the broadened diffraction line which is shown by the full curve and is the only one that can be observed experimentally [189].

The line shift due to uniform strain in the material will be explored in this chapter. The strain can be calculated from the shift in the diffraction pattern, knowing the strain, we can calculate the stress in the material. Therefore the stress is not measured directly in the XRD method and similar to other approaches for stress measurement, the strain is measured and the stress will be obtained by calculation or calibration. Various methods of stress measurement differ depending on the strain gauges used and the strain in XRD method is obtained by recording the spacing of lattice planes.
The XRD measurement is over an area of the surface of the sample and the number of grains and crystals that contribute in the measurement depends on the geometry and grain size. The XRD measurement is near the surface but the X-ray beam penetrates some distance into the material which depends on the X-ray anode, sample, and incident angle. The penetration of X-ray in most materials is in the range of $5 - 50\mu m$ [190]. Thus, the strain measurement is the average of strain a few microns under the surface of the sample.

**6.10.3 XRD residual stress measurement in practice**

It has been shown that there is a clear relationship between the diffraction pattern and the inter plane spacing of the material. The change of inter plane spacing in the strained material compared to the material which is free from strain will cause a shift in the diffraction pattern. By the precise measurement of this shift, the inter plane spacing and thus the strain in the material can be calculated. So the relationship between the inter plane spacing and the strain needs to be established.

A schematic of diffraction planes and stress distribution at the surface of the sample is shown in Figure 6.24. The measurement is within the surface of the sample, so it can be assumed that $\sigma_z = 0$. The $\varepsilon_z$ is not zero and can be calculated as

$$
\varepsilon_z = \frac{d_n - d_0}{d_0},
$$

(6.56)

where $d_n$ and $d_0$ are the inter plane spacing of the strained and unstrained material. The value for $d_n$ can be obtained by measuring the peak position of $2\theta$ and solving the Bragg’s law (Equation (6.55)) for $d_n$. So if we know the value for $d_0$, the strain can be obtained using Equation (6.56).
6.10 X-ray diffraction to measure residual stresses in the material

Figure 6.24 A schematic of diffraction planes and stress distribution at the surface of the sample.

By tilting the specimen within the diffractometer, measurements can be made in the planes at angle $\psi$ and the strain in this direction can be calculated as

$$\varepsilon_{\phi \psi} = \frac{d_{\phi \psi} - d_0}{d_0}. \quad (6.57)$$

Planes parallel to the surface of the material and planes at an angle $\Phi \psi$ to the surface are shown in Figure 6.24. By tilting the specimen the planes with angle to the surface which satisfy the Bragg's law will contribute in the diffraction pattern and various $d_{\phi \psi}$ will be recorded. Obtaining the strain from the above equations, the stress can be calculated as below.

It has been assumed that a plane stress state exists in the surface of the material ($\sigma_z = 0$) and the stress is biaxial, so the relationship between the strain components is

$$\varepsilon_z = \varepsilon_\phi = -\nu(\varepsilon_x + \varepsilon_y) = \frac{-\nu}{E} (\sigma_x + \sigma_y) = \frac{-\nu}{E} (\sigma_1 + \sigma_2), \quad (6.58)$$

where $\sigma_x$ and $\sigma_y$ are longitudinal and transverse stress respectively, $\sigma_1$ and $\sigma_2$ are principal stresses, and $\nu$ is the Poisson's ratio. Combining the Equations (6.57) and (6.58):
The above equation is a general case in which by knowing the value of \( d_0 \), the sum of principal stresses can be obtained. We now want to measure the single stress \( \sigma_\phi \) in some direction at the surface of the material, direction \( OB \) in Figure 6.24, where \( OB \) makes an angle \( \Phi \) to the principal direction 1.

The elasticity theory for an isotropic solid shows that the strain along line \( OA \) at angle \( \psi \) to the surface normal and angle \( \Phi \) to the principal direction 1 is

\[
\varepsilon_{\phi\psi} = \frac{1 + \nu}{E} (\sigma_1 \cos^2 \Phi + \sigma_2 \sin^2 \Phi) \sin^2 \psi - \frac{\nu}{E} (\sigma_1 + \sigma_2). \tag{6.60}
\]

To measure \( \sigma_\phi \) it can be assumed that \( \Phi = 0 \) (\( \sigma_\phi \) is one of the principal stresses). Combining Equations (6.56), (6.59), and (6.60), it can be obtained that

\[
\varepsilon_\psi - \varepsilon_z = \frac{1 + \nu}{E} \sigma_\phi \sin^2 \psi, \tag{6.61}
\]

\[
\frac{d_\psi - d_0}{d_0} - \frac{d_n - d_0}{d_0} = \frac{1 + \nu}{E} \sigma_\phi \sin^2 \psi, \tag{6.62}
\]

\[
\frac{d_\psi - d_n}{d_0} = \frac{1 + \nu}{E} \sigma_\phi \sin^2 \psi. \tag{6.63}
\]

If \( d_0 \) is replaced by \( d_n \) with very small error then

\[
\sigma_\phi = \frac{E}{(1 + \nu) \sin^2 \psi} \left( \frac{d_\psi - d_n}{d_n} \right). \tag{6.64}
\]

Therefore, the stress in any chosen direction can be calculated from the interplane spacing.
The $\sin^2 \psi$ method is the most common technique which is used for stress calculation. A number of XRD measurements are done at different $\psi$ tilt. The inter plane spacing is calculated from the Bragg’s law and is plotted versus the $\sin^2 \psi$ in a curve similar to Figure 6.25.

![Figure 6.25 Example of d versus $\sin^2 \psi$ plot.](image)

Assuming the zero stress at $d = d_n$, where $d_n$ is the plane in which $\sin^2 \psi = 0$, the stress can be obtained by calculating the gradient of the $d$ versus $\sin^2 \psi$ in the above figure as

$$
\sigma_\Phi = \frac{E}{(1 + v)} m, \quad (6.65)
$$

where $m$ is the gradient of the $d$ versus $\sin^2 \psi$ curve.

The above equation is the basis for the stress determination by X-ray diffraction when $\varepsilon_{13} = \varepsilon_{23} = 0$ (see Figure 6.24). More complex solutions can be found in [189-192].

A schematic of the XRD procedure for residual stress measurement is shown in Figure 6.26.
A fix wavelength of $\lambda$ is used by choosing a monochromatic X-ray target while the specimen rotates to vary the angle of incidence. An entire set of reflection will be recorded by rotating the specimen and the detector (changing $2\theta$). The appropriate peak in the diffraction pattern will then be used for residual stress measurement. This peak should be clear and needs to have a high value of $2\theta$ angle. Using the $\sin^2 \psi$ method, a fine scan will be performed around this peak and the specimen will rotate to different $\psi$ tilts. By recording the inter plane spacing for various tilted angles, the residual stress can be calculated from Equation (6.65).

### 6.10.4 Residual stress measurement of 304L stainless steel sheet

#### 6.10.4.1 XRD of the surface of non-thickness reduced material

The complete diffraction pattern of the surface of the sample is needed in the $\sin^2 \psi$ technique to determine the appropriate peak position for the residual stress measurement. To remove the oxide layer at the surface produced by the stress relief annealing treatment, diamond polishing was applied continuously with 6 $\mu$m, 3 $\mu$m, and 1 $\mu$m diamonds. After that the Oxide Polishing Suspensions (OPS) technique was applied for 5 minutes. Electro-polishing was then used to remove 50 $\mu$m of material from the surface.
Lacomit varnish was used to mask the irrelevant surfaces of the sample and to bring only the surface of interest in contact with the electrolyte (solution) in the electro-polishing process. The solution was 8% perchloric acid in acetic acid and the voltage applied was 21V (see Figure 6.27). The sample is connected to the positive terminal of DC power supply and serves as the anode. The negative terminal is connected to the conductive beaker (cathode). When current is applied, the electrolyte acts as a conductor and the metal ions on the surface of the anode are oxidised and dissolved in the electrolyte. While the ions are drawn toward the cathode, a reaction occurs at the cathode which normally produces hydrogen.

![Figure 6.27 A schematic of the electro-polishing process.](image)

The XRD tests were performed with a PANalytical’s X’Pert Powder machine [193] (Figure 6.28) using a Cu target radiation with wavelength of $\lambda_{K\alpha} = 1.5406$ Å and an irradiated area of 5×5 mm on the sample surface.
Figure 6.28 Standard optics setup of the PANalytical’s X’Pert Powder machine. The full surface scan involved a range of diffraction angle $\theta$ from $20^\circ$ to $145^\circ$ with a step size of $0.05^\circ$ and 2 sec diffraction time per step leading to the diffraction pattern shown in Figure 6.29. The voltage and current of the XRD machine were 40 kV and 30 mA respectively.

Figure 6.29 Surface diffraction pattern of the non-thickness reduced sample. The crystal structure and miller indices of lattice planes $(h k l)$ that create the peak in the XRD test can be determined as below.
In a cubic crystal with lattice constant $a$, the spacing $d_{hkl}$ between adjacent lattice planes is

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}. \quad (6.66)$$

We also now from the Bragg's law (first order of Bragg's law is used) that

$$\lambda = 2d\sin\theta. \quad (6.67)$$

Combining the above equations leads to

$$\frac{\lambda^2}{4a^2} = \frac{\sin^2 \theta}{h^2 + k^2 + l^2} = \text{constant}. \quad (6.68)$$

The value of $\lambda$ is constant for each monochromic target used in the XRD test and so is the lattice parameter ($a$) suggesting that Equation (6.68) is constant.

The $2\theta$ angle of each peak can be recorded from the diffraction pattern and the miller indices can be calculated as below (see Table 6.7).

- Start with $2\theta$ and generate a set of $\sin^2 \theta$ values.
- Normalise the $\sin^2 \theta$ by dividing to the first value.
- Clear fractions from the normalised column (the normalised values were multiplied by 3 to clear fractions).
- Now the $(h\ k\ l)$ value can be chosen so that the $h^2 + k^2 + l^2$ can generate the sequence of clear fraction column.

The value of $\frac{\sin^2 \theta}{h^2+k^2+l^2}$ is also calculated for each plane and as mentioned above, this value is constant for all peaks.
Table 6.7 304L stainless steel XRD peak analysis.

<table>
<thead>
<tr>
<th>$2\theta$ (Degree)</th>
<th>$\sin^2 \theta$</th>
<th>Normalised Clear fraction $(h^2 + k^2 + l^2)$</th>
<th>Miller indices $(h k l)$</th>
<th>$\sin^2 \theta$ $(h^2 + k^2 + l^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.70</td>
<td>0.1385</td>
<td>1.00</td>
<td>3</td>
<td>1 1 1</td>
</tr>
<tr>
<td>50.88</td>
<td>0.1845</td>
<td>1.33</td>
<td>4</td>
<td>2 0 0</td>
</tr>
<tr>
<td>74.78</td>
<td>0.3687</td>
<td>2.66</td>
<td>8</td>
<td>2 2 0</td>
</tr>
<tr>
<td>90.70</td>
<td>0.5061</td>
<td>3.65</td>
<td>11</td>
<td>3 1 1</td>
</tr>
<tr>
<td>96.07</td>
<td>0.5529</td>
<td>3.99</td>
<td>12</td>
<td>2 2 2</td>
</tr>
<tr>
<td>118.18</td>
<td>0.7361</td>
<td>5.31</td>
<td>16</td>
<td>4 0 0</td>
</tr>
<tr>
<td>138.46</td>
<td>0.8742</td>
<td>6.31</td>
<td>19</td>
<td>3 3 1</td>
</tr>
</tbody>
</table>

It can be seen from the above table that the miller indices $(h k l)$ of each plane are all odd or all even which is the selection rule for the Bragg's reflection from a Face Centered Cubic (FCC) crystal structure [194].

In a FCC crystal structure we have,

$$ a = \frac{4r}{\sqrt{2}} \quad (6.69) $$

in which $(a)$ is the lattice constant and $(r)$ is the atomic radius.

So the atomic radius of the 304L stainless steel can be calculated from the above equation which is 0.127 $nm$ and in agreement with the atomic radius of iron [195].

Miller indices of the peak diffraction planes in the X-ray diffraction of non-thickness reduced stainless steel are shown in Figure 6.29. The $(4 0 0)$ plane was chosen for residual stress measurement in this thesis.

6.10.4.2 Residual stress measurement of the thickness reduced material

A thickness reduction rolling process same as Section 6.5.2 was applied to introduce residual stresses in the stress-relieved material. The $\sin^2 \psi$
technique was used to measure the residual stresses at the surface of the sample and the layer removal method was applied to obtain the stress variation through the thickness.

The diffraction angle $\theta$ ranged from $117^\circ$ to $119.5^\circ$ (see Figure 6.29) on an irradiated area of $5\times5\,mm$, the step size was 0.02 sec, and the diffraction time for each step was 25 sec to ensure optimum intensity. A positive $\psi$ tilt was chosen to change the angular position of the diffraction peak from $0^\circ$ to $50^\circ$ in 12 equal steps.

The biaxial plane stress state ($\sigma_3 = 0$) was chosen for residual stress measurement using the $\sin^2\psi$ method and the modified lorentzian fitting technique was applied to define the position of the diffraction peak in each $\psi$ tilted angle. Figure 6.30 shows the diffraction pattern for the 1% thickness reduced sample at various $\psi$ tilted angles.

![Figure 6.30](image.png)

Figure 6.30 Diffraction pattern for various $\psi$ tilted angle at the surface of the sample with 1% thickness reduction in the thickness reduction rolling process.

The inter plane spacing $d$ vs $\sin^2\psi$ plot, and the longitudinal stress measurement ($\sigma_x$) at the surface of this sample are shown in Figure 6.31. It is
shown that the stress is $144.4 \pm 15.1$ MPa at the surface of the 1% thickness reduced sample.

![Stress Measurement Graph](image)

**Figure 6.31** Residual stress measurement of the sample with 1% thickness reduction in the thickness reduction rolling process.

Material deformation due to thickness reduction rolling process in this thesis is similar to a temper rolling operation and previous studies showed that the residual stress profile is symmetric over the strip thickness in temper rolling (skin passing) [6, 29, 31]. Thus, the layer removal approach was only applied to one half of the material thickness and 5 stress values were recorded over this range.

In the technique applied for layer removal, first 75% of the surface material was removed using grinding paper. After this 6 $\mu$m, 3 $\mu$m, and 1 $\mu$m diamond polishing was applied followed by the Oxide Polishing Suspensions (OPS) method for 5 minutes. The material was then electro-polished to remove about 50 $\mu$m of the material and prepare the surface for the XRD stress measurement.

It is necessary to remove thin layers of the material in order to determine the residual stress variation through the thickness of the sample. However, the
residual stresses are self-equilibrated within the sample and if some material is removed the specimen will find a new equilibrium state for stress distribution and geometrical deformation.

Thus the change of the stress distribution due to layer removal will affect the stress measurement in the XRD method. The true (corrected) stress-depth profile can be obtained from the measured stress-depth profile after the surface layer has been removed. The relation between the measured stress and the true stress is related to the stress distribution, the geometrical shape of the sample and the shape of the removed layer. There is not a general solution for this problem but there are some equations for common cases such as a flat or a cylindrical samples in [94, 191].

It is assumed that the residual stress in a flat surface with a uniform thickness depends on the distance from the measurement point to one of the flat surfaces of the plate (except the area near the edges). In a flat sample the corrected (true) stress $\sigma(z_1)$ at depth $z_1$ can be calculated from the integration of the measured stress after layer removal over the removed layer as

$$
\sigma(z_1) = \sigma_m(z_1) + 2 \int_{z_1}^{H} \frac{\sigma_m(z)}{z} \, dz - 6z_1 \int_{z_1}^{H} \frac{\sigma_m(z)}{z^2} \, dz .
$$

(6.70)

where $\sigma_m(z_1)$ is the measured stress at depth $z_1$, $H$ is the original thickness of the sample and $z_1$ is the distance from the bottom of the sample to the uncovered depth (new thickness after the layer removal in each step). It is assumed that the biaxial stress condition exists at the surface of the flat sample and $\sigma_z = 0$ (see Figure 6.32).
The correction in stress $c(z_1)$ is the difference between the true and the measured stress and is given by

$$c(z_1) = \sigma(z_1) - \sigma_m(z_1) = 2 \int_{z_1}^{H} \frac{\sigma_m(z)}{z} \, dz - 6z_1 \int_{z_1}^{H} \frac{\sigma_m(z)}{z^2} \, dz. \quad (6.71)$$

The integrands can be expanded in a Taylor’s series referred to the surface values. After the expansion, the final form of the correction is

$$\sigma(z_1) = -4\sigma_m(H) \left( \frac{H - z_1}{H} \right) + \left[ \sigma_m(H) + 2H\sigma'_m(H) \right] \left( \frac{H - z_1}{H} \right)^2$$

$$+ \frac{1}{3} \left[ 2\sigma_m(H) + H\sigma'_m(H) - 2H^2\sigma''_m(H) \right] \times \left( \frac{H - z_1}{H} \right)^3 + \ldots, \quad (6.72)$$

where $\sigma_m(H)$, and $\sigma'_m(H)$ are the true surface stress and successive derivative with respect to $z$ at the surface respectively.

For thin layers removed, only the first term of the series can be used which leads to the below equation that is usually used in the practical case.

$$c(z_1) = -4\sigma_m(H) \frac{\Delta z_1}{H}. \quad (6.73)$$
where $\Delta z_1 = H - z_1$.

Therefore, in a flat sample the corrected (true) stress $\sigma(z_1)$ at depth $z_1$ can be calculated from the measured stress $\sigma_m(z_1)$ after layer removal in each step as

$$\sigma(z_1) = \sigma_m(z_1) - 4\sigma_m(H) \frac{\Delta z_1}{H}.$$  \hspace{1cm} (6.74)

In this thesis the original thickness of the sample was $H = 2\ mm$ and 5 layers of $\Delta z_1 = 0.2\ mm$ were removed and the corrected stress $\sigma(z_1)$ determined.

The corrected stress measured over the half of the thickness is equivalent to the residual stress in the material and was plotted as a function of the normalised strip thickness ($z = \frac{z_1}{H}$).

The longitudinal ($\sigma_x$) measured and true (corrected) residual stress distribution over the normalised thickness of the samples with $1\%$, and $2.3\%$ thickness reduction in the thickness reduction rolling process are shown in Figure 6.33, and Figure 6.34 respectively.
Both thickness reduction rolling conditions lead to the introduction of tensile residual stress in the material surface, and compressive residual stress in the center. The maximum tensile residual stress appears at the material surface for both conditions is $144.4 \pm 15.1$ MPa, and $104.4 \pm 20$ MPa for 1% and 2.3% thickness reduction respectively. At the mid surface for both conditions the
maximum compressive residual stress can be found. The maximum compressive residual stresses are $-185 \pm 12.5$ MPa, and $-162.2 \pm 13.9$ MPa in the 1%, and 2.3% thickness reduced material respectively.

It should be mentioned that when there is not any external forces on the material, the internal stresses have to be balanced. It is shown in the above figures that the integral of the measured residual stresses over the normalised thickness of the material is approximately zero in both cases of 1%, and 2.3% thickness reduced strips. This suggests that

$$\int_0^1 \sigma_z \, dz = 0,$$  \hspace{1cm} (6.75)

where $z$ is the thickness direction.

**6.11 Experimental verification of the inverse routine**

The material properties, stress relieving, and thickness reduction rolling operations used in both inverse and experimental approaches are the same. Therefore, the results of XRD with layer removal can be applied for verification of the inverse approach. A comparison between the residual stress profiles through the thickness of the material from the inverse approach to the experimental data using XRD with layer removal method is shown in Figure 6.35.
Figure 6.35: A comparison between the residual stress profiles from inverse approach to the experimental data using XRD with layer removal method a) 1% thickness reduction and b) 2.3% thickness reduction.

It is shown in the above figure that the residual stress profile through the material thickness from the inverse routine is in a good agreement to the experimental measurements in both cases of 1% and 2.3% thickness reduction levels. Therefore, it can be concluded that the inverse approach is accurate enough to predict residual stresses through the thickness of the material due to the thickness reduction rolling process.
6.12 Summary

The new bend tester that has been developed in Chapter 5, was used to bend the material and predict the through thickness residual stresses in an inverse approach. In this chapter not only has a residual stress profile for as-received material been determined for roll forming applications, but also an in-depth understanding of the effects this residual stress profile has on the bending type deformation.

Finite element simulation showed that acceptable model accuracy can be achieved if material data from a tensile test are applied in numerical simulation of bending of non-thickness reduced (stress relieved) material. Yield transition point in FEA is close to the experimental bending data. If tensile data of a thickness reduced material is used to model the bend test, the yield transition point increases in FEA due to thickness reduction rolling, while experiments show the material softening and early yielding as a result of thickness reduction rolling. Thus, tensile data are not accurate to model the bending response of a thickness reduced material.

Including a residual stress profile in the bending simulation can detect early yielding. However, residual stresses due to cold forming, a thickness reduction rolling in this thesis, are always accompanied with plastic strain and a combined effect of those parameters needs to be considered to represent the actual material behaviour in the bend test. Existence of a residual stress profile in the material leads to early yielding in a bend test, while bending moment increases at higher curvatures due to the strain hardening effect as a result of presence of plastic strain in the material after thickness reduction rolling.

An inverse approach was introduced to consider the experimental bending data of a thickness reduced material as a target graph and obtain the material parameters for FEA which can represent the experimental moment–curvature data. It was proven that early yielding in the material due to existence of a
residual stress profile cannot be detected by simply suppressing the yield transition point in the material model. Residual stresses in the material need to be included in the inverse approach to precisely detect the transition from elastic to plastic region in the bend test. The results of inverse routine were compared to the obtained results from 2D numerical simulation of thickness reduction rolling process and a reasonable accuracy was observed.

XRD with layer removal was performed to measure residual stresses through the thickness of the material. Comparison between the inverse results and the experimental data showed a good agreement. Thus, it can be concluded that the inverse routine is accurate enough to predict residual stresses through the thickness of a thickness reduced material.

It was discussed in Chapter 4 that including residual stress information of the material can improve the model accuracy in finite element simulation of a roll forming process. Inverse approach is an effective and reliable way to obtain that information. Thus, applying the material data and residual stress profile obtained from the developed inverse routine to finite element simulation of a roll forming process will be explored in the next chapter.
Chapter 7

Application of the Inverse Routine in Roll Forming Industry

7.1 Introduction

Chapter 4 showed that including a residual stress profile can improve the accuracy of a V-section roll forming simulation using DP780 steel. However, a precise residual stress profile needs to be known in the incoming material to industrialise the concept of including initial residual stresses in a roll forming simulation. Chapter 6 introduced an inverse routine by which residual stresses in the metal sheet can be predicted through a bend test. An extra low carbon stainless steel, 304L, was used in the experiment to verify the developed inverse routine.

This chapter will show the application of the inverse routine for a simple roll forming case. The 304L stainless steel material will now be used in the U-channel roll forming process. Thickness reduction rolling will be performed to introduce a residual stress profile into the 304L stainless steel and followed by the roll forming of non-thickness reduced and thickness reduced strips. Material data delivered from a tensile test and that obtained from the inverse routine which includes a residual stress profile in the material will be used to simulate the roll forming process and the FEA predictions will be compared to the experimental results.
In a conventional roll forming simulation, material input based on the tensile test is usually applied to define the material model in FEA and, to the author’s knowledge, it is the first time that the simulation of a roll forming process is carried out using the material input that takes into account a pre-existing residual stress profile in the material.

Last part of this chapter will discuss about the influence of material properties and cross sectional geometry on the severity of the effect of a residual stress profile in the material on final product in a roll forming process.

### 7.2 Roll forming of a U-channel

A U-channel roll forming process was developed with COPRA-RF [144] using the constant radius forming method (the flower diagram is shown in Figure 7.1).

The U-channel profile with a radius of $4.8\,\text{mm}$ was formed using a sequence of four forming stations. Both top and bottom rolls were driven at a strip speed of $17.5\,\text{mm/s}$ and the distance between the stations was $400\,\text{mm}$. The precut strip (1500 mm length) was fed into the roll former using a feeder and no lubrication was used. Figure 7.2 shows the experimental arrangement of the U-channel roll forming process.
7.3 Thickness reduction rolling

Thickness reduction rolling was performed to introduce a residual stress profile into the 304L stainless steel. Similar to the DP steel, that was used in Chapter 4, the as-received material should be heat treated to eliminate any pre-existing residual stress before thickness reduction rolling but the equipment to stress relief 1500 mm strip material was not available.

Chapters 5 and 6 showed that residual stresses in the material lead to early yielding in the bend test. Thus, a bend test applying the set-up introduced in Section 6.6 was carried out on the as-received stainless steel strip material. A comparison of the moment–curvature response of the as-received and the stress relieved stainless steel tested in Chapter 6, is shown in Figure 7.3. The figure indicates that the bending response of the as-received stainless steel is similar to that of the stress relieved material. It therefore was assumed that the residual stresses in the as-received stainless steel used here were not significant.
Figure 7.3 A comparison between the bend test data of as-received and stress relieved 304L stainless steel.

Thickness reduction rolling operation performed in this section applied the same process parameters as used in Section 6.5.2 (1% and 2.3% thickness reduction). Nevertheless, in contrast to section 6.5.2 larger strips, 1500 \text{mm}, and 150 \text{mm} in length and width were used.

### 7.4 Bow, springback, and end flare measurement

Longitudinal bow, springback angle, and end flare were compared after roll forming of the non-thickness reduced and thickness reduced material. The definitions for bow, springback angle, and end flare were explained in detail in Chapters 3 and 4, Sections 3.4.4, 3.3.5, and 4.2.5, for the roll forming of a V-section profile. A similar approach was applied in the current roll forming trials (see Figure 7.4). Note that in this chapter end flare was measured at the rear of the U-channel, along its length, due to the distortion that was observed in the experiment when the front of the strip hit the rolls during the initial contact in each station.
7.5 Roll forming simulation

A roll forming simulation including the effect of friction was applied in this chapter (see Figure 7.5), note that the roll forming model of V-section in Section 4.2.4 also considered the effect of friction. The strip is pulled in $Z$ direction in the first step to initiate contact between the strip and the rolls, then the strip moves as a result of the contact between the rotating upper and lower rolls. The rolls rotate at $\omega_{\text{roll}}$ to give a strip speed of $V_{\text{line}} = 17.5 \text{ mm/s}$ as in the experimental arrangement. This keeps the slip between the rolls and the strip at zero following

$$\omega_{\text{roll}} = \frac{V_{\text{line}}}{r_{\text{roll}}}, \quad (7.1)$$

with the roll radius $r_{\text{roll}}$. One solid-shell elements with 11 integration points was used through the thickness to simulate the strip resulting into a total

Figure 7.4 Definition of a) bow curvature, b) springback angle, and c) end flare in the U-channel roll forming process.
number of 10000 elements. The rolls were modelled as contact rigid bodies and the strip was fixed in X direction along the mid-plane to consider for symmetry. The feeder was included in the numerical model and a frictionless contact was assumed between the surface of the sheet and the feeder. A node to segment contact control was applied between the strip and the rigid rolls and the friction coefficient was chosen to be 0.2 same as the model used DP steel in Chapter 4.

![Figure 7.5 U-channel roll forming simulation.](image)

### 7.5.1 Material model for FEA

The material model of Chapter 6, Section 6.5.3, is used to define the material properties. Two approaches for defining the material parameters in the U-channel roll forming simulation of the thickness reduced strips were investigated.

- **Approach 1: tensile data**– The material parameters of the thickness reduced stainless steel strip delivered from the tensile test, see Table 6.4, were used.
- **Approach 2: inverse data**– The material parameters of the thickness reduced stainless steel strip obtained from the inverse routine, see
Table 6.6, were applied. An initial residual stress profile exists through the thickness of the material using this approach.

For the non-thickness reduced, stress relieved strip material data delivered from a conventional tensile test, see Table 6.3, was used for the simulation. Note that, Section 6.6.1 showed that the material parameters delivered from a tensile test lead to high model accuracy if there is no initial residual stress in the material.

### 7.6 Results and discussion

**7.6.1 Application of the inverse routine in U-channel roll forming**

The maximum bow height for various thickness reduction levels predicted by the FEA using the two numerical approaches for material definition are compared to the experimental result in Figure 7.6. The figure shows that the maximum bow height decreases with increasing thickness reduction level and this is in agreement with the results of Chapter 4, Section 4.3.3. It was previously shown that the maximum bow height decreases due to the effect of material hardening which is related to plastic deformation of the material during thickness reduction. Conventional tensile input allows to numerically predict this phenomena. However in chapter 4 it was also shown that a residual stress profile leads to a further reduction of the maximum bow height. A similar trend can be observed in Figure 7.6 where especially for a thickness reduction of 1%, maximum bow height predicted by the inverse data model is lower compared to that predicted by the model applying conventional tensile input. Nevertheless the effect of residual stress observed in the U-channel forming of the stainless steels is significantly lower compared to the effect observed for the V-section roll forming of DP780 steel. The residual stresses introduced in the DP780 during thickness reduction rolling are significantly higher compared to those observed in the thickness reduction rolled stainless steel; comparing Figure 4.10 and Figure 6.35 illustrates this difference in
magnitude clearly. The low magnitude of residual stress introduced into the stainless steel could be one of the reasons why there is only a minor difference in model accuracy observed here between the numerical model applying conventional tensile data and the model which accounts for the effect of residual stress. There is also a discrepancy between the numerical and experimental results which will be addressed later.

![Graph showing maximum bow height for various thickness reduction levels](image)

**Figure 7.6** Maximum bow height for various thickness reduction levels in the models using tensile material data and material properties from the inverse routine.

The springback angles predicted in the FEA for the different thickness reduction levels are compared to the experimental results in Figure 7.7. The experimental results show that the thickness reduction rolling did not have a significant effect on the springback angle which was very close to 0° for all thickness reduction levels. The springback angle was negative in most of the experiments and in all FEA results, which is most likely due to the very small bending radius to material thickness ratio present in the U-channel roll forming trials. When the bending radius to thickness ratio is too small in a roll forming process, the material tends to increase the forming angle after passing each station due to high concentration of the bending force in the corner area (see Figure 7.8). The experimental results indicate a slight increase in the
springback angle (reduction in the negative value of springback in the U-channel) with thickness reduction level and this is in agreement with the results of Chapter 4. The finite element models using material data from inverse routine were able to detect the increase in the springback angle while the models using tensile data predicted a decrease in the springback angle due to thickness reduction rolling. It was shown in Chapter 4 that the springback angle variation is mainly due to a change in yield strength of the material as a result of strain hardening after the thickness reduction rolling process. An increase in the material strength due to thickness reduction rolling increases the springback angle, thus a reduction in the springback angle in Figure 7.7 is not an actual decrease in springback. The higher negative value is due to more tendency in the material to increase the forming angle as a result of high concentration of the force in the bending area. Although the springback is more if the strength of material is higher, more forming of the material shows a reduction in springback angle in the figure. An increase in the springback angle in the models that use material data from the inverse routine could be due to the lower elastic modulus in the material data delivered from the inverse routine. The bend test in the inverse routine observed the evolution of elastic modulus with plastic strain while the elastic modulus was constant in the material data delivered from the tensile test. However, the final springback angle in numerical simulation depends on a combined effect of various parameters in the material model. Springback angle increases when the ratio of initial yield stress to elastic modulus is higher and an increase the material hardening coefficient, $m$, increases the springback angle. The discrepancies between the results of experiment and numerical simulation will be addressed later.
Figure 7.7 Springback angle for various thickness reduction levels in the models using tensile material data and material properties from the inverse routine.

Figure 7.8 Forming of the strip in the last station of the U-channel roll forming simulation.

Figure 7.9 shows the comparison for end flare between the FEA and the experimental results. The experiments only indicate a minor effect of
thickness reduction rolling and through that residual stress on end flare. The results of Chapter 4 showed that the end flare in the strip is a combination of the effect of an increasing material strength due to the plastic deformation in the thickness reduction rolling process and the existence of residual stresses in the material. Increasing the strength of material due to plastic deformation reduces the end flare, while on the other hand existence of an initial residual stress profile in the material due to thickness reduction rolling increases the variation of final residual stress at the end of the strip which leads to higher end flare. The final end flare increased with thickness reduction level in the V-section roll forming of the DP780 steel investigated in Chapter 4. This was related to the high residual stress after the thickness reduction rolling process. In contrast to that, the level of residual stress introduced in the stainless steel during thickness reduction rolling is small. This may have led to the strain hardening effect balancing out the effect of residual stress which explain the minor effect of thickness reduction rolling on end flare observed in Figure 7.9 for both the experimental trials and the numerical results.

The FEA results achieved with the two approaches are very similar but the predictions made using the inverse material model approach show more reduction of end flare due to thickness reduction rolling. The existence of a residual stress profile in the material model delivered from inverse routine increases the end flare, though the level of strain in the U-channel roll forming process is high, due to the forming of a small profile radius, and through that the effect of strain hardening which reduces end flare is dominant. A comparison between Table 6.4 and Table 6.6 shows that the material hardening coefficient derived from the inverse routine, \( m \) in the power law equation, is higher than that determined from the tensile test for both thickness reduction levels. A Higher hardening coefficient reduces end flare again compared to the models use tensile data. The decrease in end flare due to thickness reduction rolling observed in the FEA is in agreement with the
results of Chapter 4, Section 4.3.3, when only tensile data used to simulate the roll forming process or longitudinal residual stresses were introduced to the model. It was previously discussed that to detect the actual effect of a thickness reduction rolling process on end flare, residual stresses in other directions also need to be included in FEA.

**Figure 7.9** End flare for various thickness reduction levels in the models using tensile material data and material properties from the inverse routine.

There are some discrepancies between the FEA prediction and the experimental results for bow, springback, and end flare. Some possible reasons for those discrepancies are given below.

- The bending radius formed in the U-channel roll forming process was 4.8 mm while the material thickness was 2 mm. The ratio of thickness to bending radius is small and only one solid-shell element was used through the material thickness in the numerical simulation. Although the accuracy of a model using only one solid-shell element for the simulation of a roll forming process with large radii profile was proven in Chapter 3, this element type may not be suitable to simulate a roll forming process with small bending radius. Thus, using more elements
in thickness direction and increasing the number of elements across the width in the bending area may lead to closer results to the experiment.

- The strips used in the thickness reduction rolling operation of this chapter are wider than those used in Chapter 6. Thus, the residual stress profiles in the material due to thickness reduction rolling may be slightly different to those delivered from the inverse routine.

- Variation of the total equivalent plastic strain during the U-channel roll forming process is given in Figure 7.10. It is shown in this figure that the maximum total equivalent plastic strain in the bending area is around 19% at the final forming station. Nevertheless material data generated by the inverse routine and the tensile test is restricted to 3% strain. Thus, using this data may not accurately represent the material behaviour due to the higher strain values experienced by the material in the U-channel roll forming process.

![Variation of the total equivalent plastic strain at the strip during the U-channel roll forming process.](image)

**Figure 7.10** Variation of the “total equivalent plastic strain” at the strip during the U-channel roll forming process.

### 7.6.2 Discussion

The application of using material data delivered from an inverse routine that takes into account a residual stress profile in the material was shown in...
numerical simulation of a U-channel roll forming process. It was explored that residual stresses in the material did not have a substantial effect on final shape in U-channel roll forming process using 304L stainless steel. However, Chapter 4 of this thesis and the investigations of Scott [31] showed more significant effect of residual stresses on final shape in a roll forming process. It was explored in [31] that residual stresses in the material lead to observation of oil canning and edge ripple in roll forming of wide flat pan profiles using thin high strength materials. Those profiles are usually used in the construction industry and the length of the web to thickness ratio in the present U-channel in this chapter is small which prevents the formation of oil canning or edge ripple. However, Chapter 4 of this thesis showed a considerable effect of residual stresses in the material on V-section roll forming process using DP780 steel. An overview on some possible explanations why the effect of residual stresses in the material are more significant in the V-section roll forming process of Chapter 4 compared to the U-channel roll forming process using 304L stainless steel in the current chapter are listed below.

- Stainless steel was applied in roll forming due to the existence of material data from inverse routine. However, stainless steel is a soft material and residual stresses are higher in high strength steel materials and the effect of residual stresses on final shape is clearer if those materials are used in roll forming.
- Figure 7.10 showed that the level of strain in the U-channel roll forming process is high, and effect of hardening is dominant in this process due to forming of the material to high strain values which wipes out the effect of material softening as a result of existence of a residual stress profile in the material. The maximum total equivalent plastic strain during the U-channel roll forming process was 19%, nevertheless Figure 7.11 shows that the maximum total equivalent plastic strain in
the V-section roll forming process of Chapter 4 was 7%. Thus material deformation in the V-section roll forming process was closer to the yield and effect of residual stresses in the material were more dominant. Note that higher strain values in roll forming process of U-channel compared to the roll forming process of V-section is due to forming of the material to a smaller profile radius.

- The bending radius to thickness ratio is 2.4 in the U-channel while this ratio was 7.5 in the V-section roll forming process. The small bending radius to thickness ratio in the U-channel roll forming process leads to very small springback and through that not much difference to measure after the thickness reduction rolling process.

- It was previously shown in [196] that forming to a small bending radius leads to less bow in a roll forming process. It can explain why the value of bow is small in the U-channel and potentially why less differences exist to be measured due to existence of residual stresses in the material.

**Figure 7.11** Variation of the “total equivalent plastic strain” at the strip during the V-section roll forming process of Chapter 4.

Therefore, it can be concluded that effect of residual stresses in the material on a roll forming process is more significant when a thin high strength
material is formed to a profile with high bending radius to thickness ratio or to a profile with a wide flat pan.

### 7.7 Summary

Industrial application of the developed inverse routine for residual stress prediction was explored for the first time in this chapter. A U-channel roll forming process was applied with non-thickness reduced and thickness reduced 304L stainless steel. Two approaches were used in FEA to explore the application of the inverse routine. In the first approach material parameters from a conventional tensile test were used, while the second approach used the material data delivered from the developed inverse routine. The overall trend in the results due to the thickness reduction rolling process was similar to the results of Chapter 4. However, it was shown that effect of residual stresses in the stainless steel was not substantial on roll forming of the U-channel. A considerable effect of residual stresses in the material was previously shown in Chapter 4. Thus a comparison between the results of this chapter and Chapter 4 suggested that residual stresses have more significant effect on final product in roll forming of high strength steel materials in which residual stresses are higher than stainless steel. The high strength steel material needs to be formed to a cross sectional geometry with large bending radius, high bending radius to thickness ratio, to observe higher bow and springback angle and through that more variation in the final product geometry due to existence of a residual stress profile in the material.

Finally, it can be concluded that analytical, numerical, and experimental analyses presented in this thesis, has provided a valuable insight in roll forming industry. Not only has a novel approach been introduced to obtain residual stress information in the incoming material, but also an in-depth understanding provided for the effects this residual stress profile has on a bending and a roll forming process. It is evident that future work is required to show the application of the inverse routine in roll forming of high strength
steel and advanced high strength steel materials which are commonly used in automobile industry.
Chapter 8

Conclusions and Recommendations

The objective of this thesis was to investigate the effect of residual stress in the material on final product in a roll forming process. Roll forming is a gradually bending operation, thus the effect of residual stresses due to a thickness reduction rolling operation on bending and roll forming processes was deeply explored. A strategy was suggested by which a residual stress profile can be achieved in the incoming material for a roll forming process and then that information can be used to improve modelling accuracy in numerical simulation of a roll forming process. In order to achieve the goals of this thesis a combined numerical, analytical, and experimental approaches were used.

This chapter will summarise the main conclusions of this thesis, highlight the originality and the significance of the contributions made, and provide author’s recommendations for future work in this field.

8.1 Conclusions

The overview of the main conclusions drawn from this research, which will be discussed in further detail in the following section, is given below. However, detailed conclusions per each research topic have been provided at the end of each chapter.
(i) **Element type**

Accuracy of using a solid-shell element in numerical simulation of bending and roll forming processes was investigated by comparing the results to the experimental data and the numerical results of using multilayer solid elements in the model. The solid-shell element was trialled, because this type of element can enable the inclusion of residual stress profile through the thickness of the sheet. The numerical results showed that reasonable model accuracy can be achieved using only one solid-shell element through the material thickness (Chapter 3).

(ii) **Effect of residual stress on roll forming**

A thickness reduction rolling process was used to introduce residual stresses into a metal strip. The initial and thickness reduced materials then be used in the experimental V-section roll forming process to identify the effect of residual stress on the final shape. It was shown that the thickness reduction leads to the introduction of tensile residual stress at the material surface, and compressive residual stress in the mid-plane center of the sheet. The accumulated plastic strain in the center of the material after the thickness reduction rolling process is more than that in the surface. The combined effect of residual stress and accumulated plastic strain needs be used to quantify the amount of cold work in the material.

Thickness reduction rolling will increase the final springback angle and end flare in the roll forming of a V-section while the maximum bow height decreases due to the thickness reduction operation. It was shown that using tensile test is not sufficient enough to capture the shape defects in a roll forming process if a residual stress profile exists in the material. Including the residual stress and accumulated plastic strain information as an initial condition leads to improved model accuracy (Chapter 4).
(iii) **Observation of a residual stress profile**

A new bend test set-up was developed that allows the bending of thin strip to high bending strains while maintaining high measurement accuracy at low forming strains and close to material yield. This bend tester can be used to observe a residual stress profile in the incoming material for a roll forming process.

Parallel specimens can be used in the experiments if a clip-on gauge is used to capture the displacement of the bending test-piece and calculate the curvature. The comparison of experimental and numerical results has shown that the deflection of the tooling leads to inaccuracies in the elastic range if cross-head displacement data is used for moment-curvature analysis. One solution to correct the results is the use of shouldered specimens.

The effect of initial residual stresses on the material response in the tensile and in the developed bend test were compared numerically. Both tensile and bend test simulations show early yielding in the material due to pre-existing residual stresses. Early yielding in the material can be detected reliably if a 0.02% instead of the common 0.2% offset approach is used. It was shown that the bend test offers advantages for capturing the effect of residual stresses (Chapter 5).

(iv) **Development of an inverse routine**

Thickness reduction rolling, as introduced in Chapter 4, was applied to introduce residual through thickness stress into stress relieved steel sheet. The thickness reduced strips were bent using the bend tester developed in Chapter 5 to determine the moment-curvature response. An inverse routine was developed that, combined with experimental bend test data, allows the determination of the residual stress profile of incoming material. X-ray diffraction (XRD) with layer removal was used to analyse residual stress
through the thickness of the thickness reduced materials and to verify the results of the inverse approach. It was shown that the developed inverse routine combined with experimental bend test data allows to determine residual stress in incoming steel strip with high accuracy (Chapter 6).

(v) Industrial application of the inverse routine

The application of the inverse routine was shown for U-channel roll forming case. Thickness reduction rolling was performed to introduce a residual stress profile into the material and followed by the roll forming of non-thickness reduced and thickness reduced strips. Material data delivered from the inverse routine which includes a residual stress profile in the material was used to simulate the roll forming process and the FEA predictions were compared to the experimental results. The overall trend in the results due to the thickness reduction rolling process was similar to the results of Chapter 4. However, it was shown that effect of residual stresses in the stainless steel was not substantial on roll forming of the U-channel. It was proven that material data delivered from the inverse routine can be applied for roll forming simulations with a reasonable model accuracy. Some discrepancies still exist between the FEA predictions and experimental results which need further modification of the inverse routine (Chapter 7).

8.2 Contributions and significance

The original contribution to knowledge in this filed, associated with each of the above conclusions, will be summarised in this section. Where relevant, the theoretical and/or practical significance will also be highlighted.

Contribution One

One solid element through the thickness for the simulation of a roll formed strip has been typically used by many researchers. However, it is not possible to implement a residual stress profile through the thickness by using one solid
element in thickness direction. Using one layer of solid-shell elements in the
model is an alternative way in which the residual stresses can vary at each
integration point of this element. Multiple layers of solid elements can be also
used to simulate the strip and vary the initial residual stresses through the
thickness, however this is computationally expensive. It was shown in
Chapter 3 that a solid-shell element provides benefits with regard to forming
behaviour and computational time, it also enables residual stresses to be
included in a simulation.

The accuracy of roll forming models was improved if the effect of friction is
included compared to using a frictionless contact condition. The obtained
results of using three layers of solid elements or one layer of solid-shell
elements had similar model accuracy, while the use of solid-shell elements led
to a significant reduction in CPU time. So, applying solid-shell element in finite
element simulation of a roll forming process to capture the effect of pre-
existing residual stresses in the material is more practical compare to use of a
model with multiple layers of solid element.

Shaft deflection in the experiment had a crucial effect on the shape defects
especially the springback angle in the roll forming of a V-section channel. Shaft
deflection compensation showed that deflection of the shafts increases the roll
gap and leads to higher springback angle in the experiment. Although various
studies have been performed by other researchers to predict springback angle
in a roll forming process, to the author’s knowledge, they did not consider the
effect of shaft deflection in the experiment.

Solid-shell element was used for roll forming simulation in this thesis.
Nevertheless, this thesis was performed on the very simplified case of roll
forming a V-section with a large profile radius and is therefore not necessarily
representative of complex roll forming applications. Further work is needed
to prove the functionality of solid-shell element for the numerical simulation of industrial roll forming processes.

**Contribution Two**

Using solid-shell element with an arbitrary numbers of integration points through the thickness made it possible to simulate thickness reduction rolling and roll forming in a single 3D analysis with a reasonable computational time. Various integration points in the thickness direction of solid-shell element can be also used to change residual stresses through the thickness in a roll forming simulation to apply an initial condition in the sheet. According to the author’s knowledge, this was the first time the effect of pre-existing residual stress on final part shape in a roll forming process was investigated in-depth with regard to the literature on roll forming.

Thickness reduction rolling reduces the difference between the final longitudinal strain at the edge and the middle of the strip. Non-thickness reduced material has the highest strain difference and maximum bow height is also higher compared to the thickness reduced materials. In general bow height increases with variation of final longitudinal strain across the width of the strip. The magnitude of permanent longitudinal strain at the surface of the strip also changes the bow height. Existence of tensile residual stresses at the surface of the strip due to thickness reduction rolling increases the permanent longitudinal strain at the strip surface after the roll forming process. The higher is permanent longitudinal strain at the strip surface, the lower is maximum bow height. More accuracy in the results can be achieved by including the residual stress information compared to the model using only tensile test data.

The springback angle variation in the roll forming process is mainly due to change in material strength due to plastic deformation during thickness reduction rolling. This can be captured by a conventional tensile test and
including the effect of residual stress in the FEA did not significantly affect the springback angle prediction.

The final end flare in the strip is a combination of the effect of an increasing material strength due to plastic deformation in the thickness reduction rolling process and the variation of residual stresses at the front of the strip. Increasing the strength of the material due to plastic deformation reduces the end flare, while end flare increases with increasing the variation of longitudinal residual stress at the front of the strip. Including the residual stress information increased the accuracy of roll forming model to predict the end flare compared to the model which uses only tensile data.

It can be concluded that using tensile test is not sufficient enough to capture the shape defects in a roll forming process if a residual stress profile exists in the material. Including the residual stress and accumulated plastic strain information as an initial condition leads to improved model accuracy.

**Contribution Three**

The new bend tester which was developed in this thesis is a novel arrangement. Using a simple procedure and not expensive components, it can bend thin materials to high strain values. This bending arrangement can be used in similar studies to obtain material properties for a roll forming or other bending type simulations. Using material data delivered from the developed bend tester promises to significantly improve the modelling accuracy in simulation of bending type processes compared to using conventional material data delivered from a tensile test.

It was shown that how higher strain tests can be performed using a shouldered specimen in the bend test. Reducing the sample length increases the achievable bending curvature. Thus a shouldered specimen with shorter gauge length can be applied in the bend test to use the cross-head
displacement data for calculation of the curvature in the moment–curvature curve with reasonable accuracy without using a clip–on gauge. The effective bending length method was introduced for the first time, to the author’s knowledge, to calculate the moment–curvature data in a shouldered specimen.

A detailed comparison between the effect of residual stresses on elastic–plastic transition in a bend and a tensile test was performed, to the author’s knowledge, for the first time with regard to the literature. Both tensile and bend test simulations show early yielding in the material due to pre-existing residual stresses. The benefits of using a bend test instead of using a tensile test to obtain material data for roll forming simulation are as below.

- Roll forming is an incremental bending deformation so material properties from a bend test are more relevant compared with those from a tensile test.
- Incoming material for a roll forming process has usually some residual stresses due to steel processing or uncoiling. The effect of those residual stresses can be clearly detected in the bend test.

**Contribution Four**

In this thesis not only has a residual stress profile for as-received material been determined for roll forming applications, but also an in-depth understanding of the effects this residual stress profile has on the bending type deformation.

Finite element simulation showed that acceptable model accuracy can be achieved if material data from a tensile test are applied in numerical simulation of bending of non-thickness reduced (stress relieved) material. Yield transition point in FEA is close to the experimental bending data. If tensile data of a thickness reduced material is used to model the bend test, the yield transition point increases in FEA due to thickness reduction rolling,
while experiments show the material softening and early yielding as a result of thickness reduction rolling. Thus, tensile data are not accurate to model the bending response of a thickness reduced material.

The inverse approach was introduced to consider the experimental bending data of a thickness reduced material as a target graph and obtain the material parameters for FEA which can represent the experimental moment-curvature data. It was proven that early yielding in the material due to existence of a residual stress profile cannot be detected by simply suppressing the yield transition point in the material model. Residual stresses in the material need to be included in the inverse approach to precisely detect the transition from elastic to plastic region in the bend test.

XRD with layer removal was performed to measure residual stresses through the thickness of the material. Comparison between the inverse results and the experimental data showed a good agreement. Thus, it can be concluded that the inverse routine is accurate enough to predict residual stresses through the thickness of a thickness reduced material.

It was discussed in Chapter 4 that including residual stress information of the material can improve the model accuracy in finite element simulation of a roll forming process. Inverse approach is an effective and reliable way to obtain that information. Thus, applying the material data and residual stress profile obtained from the developed inverse routine to finite element simulation of a roll forming process can improve the model accuracy.

**Contribution Five**

In a conventional roll forming simulation, material input based on the tensile test is usually applied to define the material model in FEA and, to the author's knowledge, it is the first time that the simulation of a roll forming process is
carried out using the material input that takes into account a pre-existing residual stress profile in the material.

It was shown that effect of residual stresses in the stainless steel was not substantial on roll forming of the U-channel. A considerable effect of residual stresses in the material was previously shown in Chapter 4. Thus a comparison between the results of U-channel and V-section suggested that residual stresses have more significant effect on final product in roll forming of high strength steel materials in which residual stresses are higher than stainless steel. The high strength steel material needs to be formed to a cross sectional geometry with large bending radius, high bending radius to thickness ratio, to observe higher bow and springback angle and through that more variation in the final product geometry due to existence of a residual stress profile in the material.

It was concluded that effect of residual stresses in the material on a roll forming process is more significant when a thin high strength material is formed to a profile with high bending radius to thickness ratio or to a profile with a wide flat pan.

### 8.3 Recommendations for future work

Based on the gained knowledge in this thesis, the following recommendations are made for future research in this area. These research areas will either expand some of the work detailed in this thesis, open a new topic for a similar research, or explore some of the research topics that were beyond the scope of this thesis.

#### Element type

It was shown in Chapter 3 that a solid-shell element can be used for a simple roll forming simulation with reasonable model accuracy. Nevertheless the simulation was performed for a cross sectional geometry with large profile
radius and is therefore not necessarily representative of complex roll forming applications. There were also some discrepancies between the numerical and experimental data using solid-shell element for roll forming simulation of a U-channel with small profile radius in Chapter 7 that may be due to performance of the solid-shell element for simulation of the strip. Thus, further analysis is needed to prove the functionality of solid-shell element for the numerical simulation of industrial roll forming processes.

**Material model**

Roll forming simulation was carried out using an isotropic hardening material model in this thesis. Acceptable model accuracy was achieved for simple roll forming processes, though applying more advanced material models to consider material plasticity phenomena such as kinematic hardening or the evolution of elastic modulus with plastic deformation is suggested for the future work in this area.

Furthermore, an isotropic hardening material model was used to simulate the thickness reduction rolling process and bend test in this thesis. Some discrepancies were detected between the residual stress profiles delivered from inverse routine, or experiments, to the FEA results in Chapter 6. Considering a kinematic hardening material model in FEA may change the final residual stress profile. Although bend test was carried out only in one direction and the assumption of isotropic hardening material model is reasonable for the bend test, load reversal may happen in the bend test of a thickness reduced material, due to existence of a residual stress profile through the thickness, hence applying a kinematic or combined hardening material model is suggested for future work.
**Bend test/Inverse routine**

The maximum strain at the surface of the sample using the developed bend tester, in Chapter 5, is 2% and it can bend the strips only in one direction. The aim of this thesis was concentrating on material properties close to yield to observe the effect of residual stresses. However, development of another bending device to bend the material in both bending and reverse bending directions to higher strain values for identification of the material kinematic hardening parameters is recommended for future work.

The material model delivered from the inverse routine is also restricted to the maximum achievable strain in the developed bend tester and the results of Chapter 7 showed that it may not be a good representative for material behaviour at higher strain values in an actual roll forming process. Therefore the inverse routine needs to be performed using material input at higher strain values in future.

Finally, more investigation is needed in future to show the application of the inverse routine for prediction of residual stresses in the material due to a forming process different from the thickness reduction rolling.

**Effect of residual stress on roll forming**

Effect of residual stress in the material on final shape in a roll forming process was investigated in this thesis. Two roll forming processes, a V-section and a U-channel, were studied. Although residual stresses in the material had a considerable effect on V-section roll forming process using DP780 steel, only a minor effect was detected due to existence of residual stresses in the U-channel roll forming process made from stainless steel. It is recommended that to show a significant effect of residual stresses in the material on a roll forming process, a thin high strength steel is formed to a profile with high bending radius to thickness ratio or to a profile with a wide flat pan. In addition
to the shape defects that were investigated in this thesis, other shape defects such as twist, oil canning, and edge ripple also need to be explored.

During roll forming flanges are not only bent around the intended bending edge, but also twice around an axis in vertical direction. This bending procedure could have effects similar to a conventional straightening operation that would imply a reduction of residual stresses. It is recommended that this aspect is considered for the future work in this area.
Appendix A

Roll Forming Models

A.1 Finite element studies to simulate a roll forming process

Previous finite element studies to simulate a roll forming process, the accuracy of those models (using experimental validation), and the capability of implementing a pre-existing residual stress information in the model are briefly reviewed in Table A.1. Note that in all cases solid, shell, or solid-shell elements were used for simulation of the sheet and the rolls were modelled as rigid bodies.

Table A.1 A comparison between previous studies on simulation of a roll forming process.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Software</th>
<th>Strip element type</th>
<th>Output results</th>
<th>Experimental validation</th>
<th>Capability of implementing a residual stress profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>[73, 83]</td>
<td>LS-DYNA</td>
<td>Solid</td>
<td>Longitudinal and shear strains, and springback</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>[76]</td>
<td>ANSYS/LS-DYNA</td>
<td>Solid</td>
<td>Longitudinal and shear strains</td>
<td>Good agreement for longitudinal strain with experimental results of the literature</td>
<td>No</td>
</tr>
<tr>
<td>[50]</td>
<td>MSC-Marc</td>
<td>Solid</td>
<td>Longitudinal strain, transversal strain, roll load, roll torque, and springback</td>
<td>Some discrepancies were shown for springback and transversal strain</td>
<td>No</td>
</tr>
<tr>
<td>Reference</td>
<td>Software</td>
<td>Analysis Type</td>
<td>Results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>---------------</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[64]</td>
<td>MSC-Marc</td>
<td>Longitudinal strain, longitudinal bow, and springback</td>
<td>Some discrepancies were shown, especially for springback measurement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[80]</td>
<td>MSC-Marc</td>
<td>Longitudinal strain</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[66]</td>
<td>MSC-Marc</td>
<td>Equivalent stress, plastic strain, and computational time</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[49]</td>
<td>COPRA-FEA</td>
<td>Longitudinal residual stresses</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[57]</td>
<td>COPRA-FEA</td>
<td>Cross section dimensions</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[48]</td>
<td>COPRA-FEA</td>
<td>Transverse and longitudinal residual strains, and longitudinal residual stresses</td>
<td>Reasonable agreement with the experimental data in the literature for peak strains</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[75]</td>
<td>Metafor</td>
<td>Longitudinal strain, and springback</td>
<td>Good agreement with experimental data in the literature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[60]</td>
<td>Metafor</td>
<td>Twist, and springback</td>
<td>Good agreement with experimental data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[55]</td>
<td>Metafor</td>
<td>Corner strength enhancement</td>
<td>By using 4 layers of elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[78]</td>
<td>Abaqus</td>
<td>Springback, flange strain, contact pressure, and reaction force</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Software</td>
<td>Type</td>
<td>Parameters Validated</td>
<td>Validation Method</td>
<td>Comments</td>
</tr>
<tr>
<td>-----------</td>
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</tr>
<tr>
<td>[65]</td>
<td>Abaqus Solid</td>
<td></td>
<td>Longitudinal plastic strain, and load</td>
<td>Contact normal forces were validated experimentally</td>
<td>By using 3 layers of elements</td>
</tr>
<tr>
<td>[54]</td>
<td>PAM-STAMP Solid</td>
<td></td>
<td>Longitudinal strain, and springback</td>
<td>Good accuracy for maximum longitudinal strains and the cross sectional geometry</td>
<td>No</td>
</tr>
<tr>
<td>[67]</td>
<td>SHAPE-RF Solid</td>
<td></td>
<td>Longitudinal strain, bow, and camber</td>
<td>–</td>
<td>By using 3 layers of elements</td>
</tr>
<tr>
<td>[68]</td>
<td>SHAPE-RF Solid</td>
<td></td>
<td>Buckling, thickness variation, and simulation time</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>[77]</td>
<td>– Solid</td>
<td></td>
<td>Longitudinal strain, bow, and twist</td>
<td>Good agreement with experimental data</td>
<td>No</td>
</tr>
<tr>
<td>[74]</td>
<td>ANSYS/LS-DYNA Shell</td>
<td></td>
<td>Elastic longitudinal strain, shear strain, total strain through the thickness, and springback</td>
<td>–</td>
<td>By using 5 integration points through the thickness</td>
</tr>
<tr>
<td>[51]</td>
<td>Abaqus Shell</td>
<td></td>
<td>Longitudinal membrane strain</td>
<td>Good agreement with experiment for peak and residual membrane strain</td>
<td>No</td>
</tr>
<tr>
<td>[58]</td>
<td>Abaqus Shell</td>
<td></td>
<td>Hydrostatic pressure, total plastic strain, and damage criterion</td>
<td>–</td>
<td>By using 9 integration points through the thickness</td>
</tr>
<tr>
<td>[59]</td>
<td>Abaqus Shell</td>
<td></td>
<td>Equivalent plastic strain, and stress</td>
<td>Hardness method was used for validation, some discrepancies were shown</td>
<td>No</td>
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<tr>
<td>Reference</td>
<td>Software</td>
<td>Analysis Type</td>
<td>Description</td>
<td>Integration Points</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>[61]</td>
<td>Abaqus</td>
<td>Longitudinal strain</td>
<td>Some discrepancies were shown between numerical results and experimental data of literature</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Springback</td>
<td>-</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>[81]</td>
<td>Abaqus</td>
<td>Transversal strain, thickness, and edge wave</td>
<td>Thickness in FEA was compared to the experiment</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>[71]</td>
<td>Abaqus</td>
<td>Local edge buckling</td>
<td>-</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>[84]</td>
<td>Abaqus</td>
<td>Longitudinal strain and edge wrinkling</td>
<td>Good agreement with experimental data</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>[52]</td>
<td>MSC-Marc</td>
<td>Longitudinal, lateral, and principal strains</td>
<td>A comparison between experimental and numerical results was shown clearly</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>[19]</td>
<td>MSC-Marc</td>
<td>Peak longitudinal strain, and springback</td>
<td>-</td>
<td>3</td>
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<tr>
<td>[79]</td>
<td>MSC-Marc</td>
<td>Longitudinal strain, and springback</td>
<td>-</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>[70]</td>
<td>MSC-Marc, LS-DYNA</td>
<td>Cross-sectional geometry, and longitudinal strain</td>
<td>Some discrepancies were detected in longitudinal strain prediction</td>
<td>5</td>
<td></td>
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<tr>
<td>[82]</td>
<td>LS-DYNA</td>
<td>Final product geometry</td>
<td>The experimental verification was not shown clearly</td>
<td>No</td>
<td></td>
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<tr>
<td>[56]</td>
<td>LUSAS</td>
<td>Longitudinal strain</td>
<td>Some discrepancies were shown between</td>
<td>No</td>
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<tr>
<td>Reference</td>
<td>Code</td>
<td>Type</td>
<td>Simulation Type</td>
<td>Simulation Description</td>
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<td>-----------</td>
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<td>------------</td>
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<tr>
<td>[53]</td>
<td>PROFIL</td>
<td>Shell</td>
<td>Membrane strain</td>
<td>Some discrepancies were shown</td>
<td>No</td>
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<tr>
<td>[62]</td>
<td>–</td>
<td>Solid-shell</td>
<td>Maximum equivalent strain</td>
<td>–</td>
<td>No</td>
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<tr>
<td>[63]</td>
<td>Abaqus</td>
<td>Solid-shell</td>
<td>Maximum longitudinal strain</td>
<td>Good agreement with experimental data of literature</td>
<td>No</td>
</tr>
<tr>
<td>[72]</td>
<td>LS-DYNA</td>
<td>Solid-shell</td>
<td>Strain distribution</td>
<td>–</td>
<td>No</td>
</tr>
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Appendix B

CAD Drawing of the Developed Bend Tester

B.1 Bend tester design

The CAD model and the experimental arrangement of the newly developed bending device in this thesis, see Chapter 5, are shown in Figure B.1 and Figure B.2 respectively. The bending arms are attached to the Instron machine and bending will happen in the sample by movement of the upper arm in $Y$ direction (see Figure B.1).

Figure B.1 CAD model of the new bend tester.
Figure B.2 Experimental set-up of the bend tester a) initial arrangement b) during bending.

2D CAD drawing of various components of the developed bend tester are presented in following pages.
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<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
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