In-line shape compensation for roll forming through process parameter monitoring

By

Buddhika Nuwan Abeyrathna, BSc. Eng (Hons)

Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

Deakin University

October, 2014
I am the author of the thesis entitled

**In-line shape compensation for roll forming through process parameter monitoring**

submitted for the degree of **Doctor of Philosophy**

This thesis may be made available for consultation, loan and limited copying in accordance with the Copyright Act 1968.

'I certify that I am the student named below and that the information provided in the form is correct'

**Full Name:** Buddhika Nuwan Abeyrathna

(Please Print)

**Signed:** [Signature Redacted by Library]

**Date:** 30/01/2015
DEAKIN UNIVERSITY
CANDIDATE DECLARATION

I certify the following about the thesis entitled

**In-line shape compensation for roll forming through process parameter monitoring**

submitted for the degree of **Doctor of Philosophy**

a. I am the creator of all or part of the whole work(s) (including content and layout) and that where reference is made to the work of others, due acknowledgment is given.

b. The work(s) are not in any way a violation or infringement of any copyright, trademark, patent, or other rights whatsoever of any person.

c. That if the work(s) have been commissioned, sponsored or supported by any organisation, I have fulfilled all of the obligations required by such contract or agreement.

I also certify that any material in the thesis which has been accepted for a degree or diploma by any university or institution is identified in the text.

'I certify that I am the student named below and that the information provided in the form is correct'

**Full Name:** Buddhika Nuwan Abeyrathna

**Signed:** [Signature Redacted by Library]

**Date:** 27/10/2014

Deakin University CRICOS Provider Code 00113B
Acknowledgement

This research accomplishment owes much dedication and admiration to numerous individuals and organizations who have contributed in many ways. Therefore, I take this opportunity to convey my gratefulness to every one of them.

First and foremost respectively, I am greatly indebted my Principal supervisor Dr. Matthias Weiss for the given interest, encouragement, gentle guidance and invaluable support offered during last three and half years. I am also obliged to him for the constructing criticisms and most importantly for his extraordinary patience.

I also convey my earnest thanks to Prof. Peter Hodgson not only as my Associate supervisor but, also for providing me with this valuable opportunity to study at Deakin. Furthermore I would like to thank A/Prof. Bernard Rolfe for his numerous support especially in analytical, statistical and numerical simulation related work during my PhD.

Emeritus professor John Duncan should not be left without acknowledgement, as he was a key contributor to the knowledge on research methodologies and analytical work throughout my PhD journey.

It is my duty to highly appreciate the assistance provided to me by Dr. Joseba Mendiguran and Dr. Jon Larranaga from Mondragon University for priceless ideas in finite element modelling and simulation.

I would also gratefully recognize Mr. Henry Wolfkamp as my industrial partner for providing me with ideas and giving me access to his roll forming facility.

Without the assistance obtained from Technicians, namely Messrs. Lynton Leigh, Alex Orokity and John Vella for technical support, and IFM IT staff, namely Mr. John Robin and Mrs. Sandy Benness for installing software and all the IT support this research would not have been possible. Therefore, I wish to express my greatest appreciation to all who contributed to this study for their ideas, valuable assistance and especially their commitment towards this thesis and the precious time they spent to make this thesis successful.
It is also my obligation to acknowledge the assistance offered by Dr. Manjula Nanayakkara in University of Peradeniya for introducing me to Prof. Peter Hodgson.

I take this opportunity to thank the entire roll forming group including Messrs. Jascha Dominic Marnette, Akbar Abvabi and Ahmad Erfani for their kind assistance in many ways.

Last, but not least, I give my immeasurable thanks to my wife, Dishari Chamika Abeyrathna for supporting and tolerating me during this time, and my sincere thanks to my beloved parents and family for encouraging me throughout my life and giving me an outstanding support to make this thesis a success.
List of Publications

Journal Papers


Conference Papers


# Table of content

Abstract ......................................................................................................................... i

1 Introduction .......................................................................................................... 1
  1.1 Research objective and the methodology ...................................................... 3
  1.2 Structure of the Thesis ................................................................................... 4

2 Literature review .................................................................................................. 7
  2.1 Roll forming................................................................................................... 8
  2.1.1 Deformation modes in roll forming...................................................... 13
  2.1.2 Longitudinal edge strain ....................................................................... 14
  2.2 Roll formed product defects and the influence of the process parameters .. 21
  2.2.1 Edge waviness ...................................................................................... 22
  2.2.2 Longitudinal bow ................................................................................. 24
  2.2.3 Springback............................................................................................ 29
  2.2.4 Twist..................................................................................................... 31
  2.3 Roll load and torque..................................................................................... 33
  2.4 Defect compensation ................................................................................... 36
  2.5 Summary...................................................................................................... 40

3 Experimental procedures and the numerical model ........................................... 44
  3.1 Introduction.................................................................................................. 44
  3.2 Experimental procedures ............................................................................. 44
  3.2.1 Tensile test............................................................................................ 44
  3.2.2 Technique applied to measure strain with strain gauges ................. 48
  3.2.3 V-profile roll forming trials................................................................. 49
  3.2.4 Laboratory roll former for trapezoidal section roll forming.............. 51
  3.2.5 Measurement of roll load and torque ................................................... 54
  3.2.6 Measurement of bow ............................................................................ 56
Abstract

Roll forming allows the production of long parts with complex cross section from sheet materials that show high strength combined with limited formability. It therefore is increasingly being used in the automotive industry for the manufacture of structural and crash components from Advanced High Strength (AHSS) and Ultra High Strength Steels (UHSS). Due to the high strength of AHSS and UHSS, even small variations in material properties from coil to coil can have a significant effect on the product quality of roll formed profiles, where shape defects are generally due to very small plastic strains in the material. This requires frequent re-adjustment of line settings to maintain part quality and leads to machine downtimes and reduced productivity.

This research aims to develop a fundamental understanding of the effect of yield strength, hardening and geometric parameters on final shape in the roll formed parts and to establish a link between changes in material properties and process parameters such as roll load and torque that can be measured in-line. Based on this a compensation method is proposed that based on the measurement of roll load and torque allows the estimation of material property variation and corresponding change in the final shape. This represents the first step towards a “smart roll former” where changes in part shape due to material property variation are compensated through the automated re-adjustment of the roll tooling.

The literature review revealed that longitudinal edge strain is significant parameter that determines shape defects in roll forming. Therefore a basic analytical model was developed and applied to understand the material behaviour in roll forming and to obtain longitudinal edge strain information. This model was able to produce the longitudinal edge strain variation during the roll forming process by simply analysing the information given by the bending sequence (flower pattern). Even though the model does not take into account the local deformation at the rolls, it could be successfully applied to obtain a comparative idea with regard to the edge strain distribution of the process; this allows identifying the optimum flower pattern for any given part shape and process conditions.

The basic analytical model proposed that the longitudinal edge strain depends on the flange length, forming angle, inter-station distance and material thickness and in
chapter five the effect of those parameters on the peak longitudinal edge strain, longitudinal bow and springback was experimentally investigated for three different AHSS and UHSS that allowed the targeted variation of material yield strength and hardening. It was revealed that not only the yield strength but also the hardening behaviour has a significant influence on the peak longitudinal edge strain, longitudinal bow and springback in the roll forming of AHSS and UHSS. In addition to that some significant finding could be obtained with regard to the effect of process and geometrical parameters on peak longitudinal edge strain, longitudinal bow and springback.

The literature review revealed that the roll load and torque are functions of material yield strength, some geometrical and process parameters and this suggests that it may be possible to estimate material properties based on the measurement of roll load and torque. In chapter six a numerical study was conducted to investigate the effect of material (including yield strength and material hardening) on roll load, torque and bow. The results suggests that in the roll forming of AHSS and UHSS material hardening has a significant effect on roll load and torque. A multiple linear regression equation was obtained that allowed to represent the roll load and torque in terms of material yield strength and hardening exponent with high accuracy if process and geometrical parameters are kept constant and only the properties of the incoming material were changed. The model was extended to predict the amount of longitudinal bow in terms of roll load and torque and the concept numerically validated for three AHSS and UHSS grades. The results suggest that changes in longitudinal bow as a results of material property changes can be identified by roll load and torque measurements performed during the process.

Industrial practice involves the forming of various profile shapes, and geometrical as well as roll forming process parameters may affect how roll load and torque changes with material yield and hardening. In chapter seven therefore an extensive numerical study was carried out to identify the most influential factors on roll load and torque other than the yield strength and the hardening. It could be identified material thickness and the forming angle as the most influential parameters on roll load and torque. In addition to that the bottom roll diameter and the frictional coefficient showed significant influence on the roll torque. The identified parameters were then applied to
develop a robust regression model for predicting longitudinal bow in the roll forming of a trapezoidal section with any cross sectional profile. The model showed reasonable accuracy and was experimentally verified for three AHSS and UHSS steel grades achieving more than 75% accuracy.

Finally a simple technique was introduced that allows the in-line compensation of longitudinal bow. In this technique longitudinal bow is compensated at the end of the roll forming process, at the last station by rotating the station that counter bends the web area and eliminate the bow. It could be seen that the compensation rotation of the stand not only depends on the amount of bow in the part but also the material properties and the part geometry as well. Therefore further analysis needs to be carried out to determine complete solution space for the exact compensation rotation for any given profile with different material properties. As a whole this technique together with the predicted bow by means of roll load, torque and other parameters can be combined together to develop an automated in-line bow compensation system in roll forming. This effort can be considered as the “grass roots” project of achieving such control system in roll forming.
1 Introduction

Roll forming is a sequential process in which a strip is incrementally bent to the required profile by many sets of rolls placed one after the other. Long parts with complex cross-section can readily be produced by roll forming in sheets having high strength and limited formability [1]. On the other hand Advanced High Strength (AHSS) and Ultra High Strength Steels (UHSS) are increasingly used in the automotive industry for the manufacture of light weight structural and crash components [2]; Figure 1.1 shows the increasing trend in AHSS usage in the automotive industry. Therefore roll forming is increasingly used to form automotive components from AHSS and UHSS [1, 3].

![Figure 1.1: North America light vehicle metallic material trends (4)](image)

It has been shown that a 10% weight reduction of an automobile will reduce fuel consumption by 6-8% [3] resulting in low CO₂ emission as well. In a typical automobile about 20% of the weight is resulting from the Body-In-White (BIW), which is the skeleton of the automobile [5]. Therefore reducing the mass of the BIW weight has a great potential to reduce the overall weight of an automobile. As a results AHSS and UHSS are mainly used in the BIW design as shown in Figure 1.2.
In automotive parts manufacturing, the finish and the dimensional accuracy of the component are more important than it is the case for conventionally roll formed products such as gutters, roofing, windows, doors and other building products. Therefore, roll forming to tight tolerances is a new challenge that the industry is facing today. Additionally, in AHSS and UHSS even small variations of material properties from coil to coil or even over the coil length can lead to significant changes in material yield and through that final shape of roll formed sections; for example if the yield strength changes from 5% to 10% of a material with 1000MPa yield, then the actual yield strength may vary from 50-100MPa over the length of the coil. If the product becomes out of specification due to changes in the incoming material, wear or environmental conditions, the line needs to be stopped and re-adjusted – which reduces productivity.

In contrast, a multi-stand strip rolling mill, that produces cold-rolled steel sheet, will operate under an advanced feed-back control system to ensure that the final sheet stays within the specification. Many sensors gather information on variables such as roll force and torque, inter-stand tension, and strip thickness. The information is fed to a computer model of the process which provides the signals for continuous adjustment of the settings. The existing systems were developed over many decades and are now a standard part of any steel mill. The present project aims to contribute to the development of a control system that works according to the given instructions of its inbuilt memory for roll forming. Clearly this is a “grass roots” project. The topics
covered in this work will provide some of the essential concepts and groundwork necessary for longer term progress towards this goal.

1.1 Research objective and the methodology

The overall objective of this research is to further understand the effect of material and process parameters on shape defects in the roll forming of AHSS and UHSS and to develop a technique to identify the degree of defect in a given cross sectional profile during the roll forming process. Eventually a defect compensation technique will be introduced in order to rectify the identified defects during the process. Therefore the research question of this work is:

What is the effect of material properties and process parameters on the roll forming defects and longitudinal edge strain, and how can these defects be identified while roll forming? The research question results in three major objectives.

- Identify the effect of process and geometric parameters on shape defects and longitudinal edge strain in the roll forming process.
- Determine the link between material properties and the roll formed product defects.
- Develop a routine that links roll load and torque (process parameters measured during the process) to shape defects allowing their compensation.

To address the above, an analytical model is developed to link process parameters and geometric properties to longitudinal strain in the strip edge; this can be used as the first step to expand the value of the traditional flower diagram in basic process design. To determine the link between material parameters, geometric and process parameters in the roll forming process, experimental roll forming trials will be performed on various materials; this will involve the measurement of the longitudinal edge strain and final shape. Further studies will be carried out to identify the link between material properties, shape defects and process parameters such as roll load and roll torque. Using Finite Element Analysis (FEA) a compensation techniques will be developed that will allow the elimination of some shape defects using special roll tooling.
1.2 Structure of the Thesis

This thesis will consist of nine chapters. The remaining chapters are summarised below.

Chapter 2

Chapter 2 critically reviews the literature of the related work and will identify gaps which give rise to the research question. First, the roll forming process and the major material deformation modes in roll forming are introduced. After that some roll forming product defects that are due to redundant deformation in the part are discussed. Permanent longitudinal edge strain in the strip edge is one of the major reasons for shape defects in roll forming and current process design optimization techniques focus on the minimization of edge strain to establish a robust roll forming process. The major reasons for the development of edge strain in a roll formed part are presented and the effect of material properties, process parameters, geometric parameters and other parameters is discussed. This identifies significant gaps and contradictions in the literature with regard to the longitudinal edge strain in the roll forming process.

Following that, roll load and torque related studies are presented and the link between material properties and roll load and torque identified. Hence some gaps and possible improvements are suggested to apply this link in identifying the material property changes during the roll forming process.

Finally, shape compensation techniques that are currently used are presented and discussed with regard to their applicability and how they may lead to the development of new defect compensation techniques which have not been addressed in the literature.

Chapter 3

Chapter 3 explains the experimental procedures and numerical modelling techniques applied in this work. This includes the standard tensile test procedure to generate material input for the experimental and numerical analysis, the methodology for edge strain measurement during roll forming, the roll forming of a simple V-section which is used for the development of the basic analytical model of roll forming, the 3D scanning technique and analysis software that is used for longitudinal bow
measurements of the parts and the trapezoidal section forming equipment which has been equipped with roll load and torque measuring equipment. A new adaptive roll former is employed to investigate the effect of inter-station distance, flange length, forming angle, material thickness and incoming material properties on longitudinal edge strain, bow, roll load and torque. Further, a special defect compensation routine for longitudinal bow compensation is also introduced with this roll former. Finally, the simulation model used in this work to investigate different aspects of the roll forming process is presented.

Chapter 4

This chapter introduces a new analytical model to predict the different components of longitudinal edge strain introduced in the part during roll forming. Longitudinal edge strain is one of the main indicators of final shape defects and this chapter introduces two analytical equations to predict the amount of mid-surface strain and the bending strain at the edge of the flange. There is no other method reported in the literature to evaluate a given forming sequence (flower pattern) in roll forming. Therefore this understanding can be utilised in the traditional flower pattern design process and provides a way to optimise the flower diagram.

Chapter 5

The analytical model discussed in Chapter 4 suggested that the surface strain depends on the forming angle, flange length, material thickness and the inter-station distance. In this chapter, the effect of those parameters on peak longitudinal edge strain in the actual roll forming process are studied. This is necessary since the peak longitudinal edge strain cannot be readily predicted by the analytical model. Further this study extends this understanding towards the product defects such as longitudinal bow and springback. This bridges peak longitudinal edge strain and the main product defects; further the effect of other geometrical and process parameters on this link is also investigated.

Chapter 6

This chapter investigates the effect of material properties on the roll load, torque and the final product quality, since the previous chapter showed that the material properties...
significantly affect the peak longitudinal edge strain and the final part quality. Major focus will be on AHSS and UHSS given that these material are increasingly roll formed to automotive sections. Additionally, due to their high material strength levels even small variation in material properties can lead to significant changes in product quality. The author believes that roll load and torque can identify those deviations of the material properties in the incoming material, however only few investigations appear in the literature about the effect of yield strength on roll load and torque in the roll forming process. The author further believes that the roll load and torque not only depend on the material yield strength but also on the hardening behaviour as well. Therefore in this chapter, the effect of the hardening and the yield strength on the roll load, torque and the longitudinal bow is investigated via numerical analysis.

Chapter 7

In the roll forming process, the amount of longitudinal bow varies with material properties, process parameters and the part geometry. Therefore this study broadly investigates the effect of those variables on the final longitudinal bow which is one of the major shape defects observed in roll formed sections. Both numerical and statistical methods are applied to carry out this investigation. Finally, a regression equation is generated to predict the amount of longitudinal bow in terms of roll load and torque and other variables. This is the first step towards an in-line defect monitoring system.

Chapter 8

In this chapter a new roll stand is introduced that will enable to correct the longitudinal bow in the final product. This adaptive stand can adjust itself according to the amount of bow of the final product predicted by the regression equation obtained in the previous chapter. In this chapter, the operation of the new roll stand is numerically tested under different geometric and material parameters.

Chapter 9

This chapter summarises and discusses the results of this work and gives recommendations for future studies.
CHAPTER TWO

2 Literature review

As mentioned in Chapter 1 AHSS and UHSS materials are increasingly used in automotive applications due to their high strength, low weight and crashworthiness [3]. However the main drawback in AHSS and UHSS forming is their low formability and high tendency to springback which often results in unacceptable product quality [7]. Therefore roll forming can be identified as a suitable forming process for such materials, since its incremental forming action reduces the strain localisation resulting in reduced springback without introducing additional complicated tooling [4]. Roll forming also allows the forming of smaller profile radii than possible in simple bending [8] and possesses other advantages such as lower investment cost compared to stamping [8], less tool wear and the ability to form complex shapes. This has opened a wide range of research areas with regard to roll forming of AHSS and UHSS steel. The aim of this research is to understand the effect of different process and geometrical parameters on edge strain and product defects in AHSS and UHSS roll forming. This understanding will be applied to develop a routine for shape defect identification via the on-line measurement of process parameters. Finally a defect compensation technique will be developed based on measured changes in process parameters that will allow the compensation of product defects without the need for stopping the roll forming line.

This chapter deeply analyses the available literature with regard to this matter and will be divided in four main sub sections for clarity and simplicity. Those are

- The roll forming process: This section will introduce the roll forming process and discuss the major deformation modes in roll forming. In addition to that longitudinal edge strain related studies will be reviewed as it is the major...
measure for redundant deformation in roll forming and gives a clear indication about the occurrence of some of the defects.

- Shape defects and causes: In this section the main roll forming defects and their causes will be discussed. Further the effect of process, geometrical and material parameters will be reviewed. This will lead to the identification of the factors affecting roll forming product defects and the significance of material properties with regard to these defects.

- Roll load and torque in the roll forming process: In this section studies related to roll load and torque will be reviewed. This will identify the concept of applying roll load and torque measurements to detect variations in material properties during the roll forming process.

- Defect compensation methods: This section critically reviews defect compensation techniques currently available in roll forming.

2.1 Roll forming

Roll forming is a sheet forming process in which a flat metal sheet is bent to the desired shape by deformation imposed by rotating rolls that act in tandem in a roll forming line. Figure 2.1 shows a five stand roll forming mill used to form a simple U section.

![Figure 2.1: Roll forming operation [9]](image)

A typical roll forming mill is shown in Figure 2.2. It consists of an uncoiler to feed material from a coil continuously during the operation. This is followed by the flattener that levels the material coming out of the coil. After that optionally a pre-punch press is placed which performs pre punching if needed. Then the material is guided through the entry guide or feeder which feeds the material with the proper alignment. Next a
number of roll stands are placed one after the other to bend the material incrementally into the desired shape. After that the straightener is in place to perform some minor adjustment to rectify some of the defects and finally a cut-off press that cuts the final part into the required length [1].
Figure 2.2: Roll forming mill[1]
In the roll forming process, deformation takes place at the individual roll stations. A conventional roll forming stand is shown in Figure 2.3. The tooling fits into the top and bottom shafts. Bearings are connected to both edges of the shafts and the bearing housing can be smoothly inserted into the frame which is fixed to the mill bed. Shafts are driven by a motor where the power is transmitted through a set of gear trains. In the roll forming process, generally the gap between the top and bottom tooling is set to be same as the thickness of the incoming material and the first station consists of two flat rollers which firmly feed the material forward into the forming rolls.

Nowadays this process is being increasingly used to form automotive components such as bumpers, door beams, frame rails, seat components, side impact beams, bottom sill reinforcements and roof bows. [8, 10] and some of those parts are shown in Figure 2.4.

The deformation at each station can be represented by a single diagram called a “flower diagram”, which is a superimposed diagram of deformed geometry at each forming station (Figure 2.5). The number of forming passes applied is determined by the complexity of the final shape. The depth of the finished product is also a major factor which determines the number of passes [1]. If the number of passes is higher, then tooling cost will be higher. On the other hand there may be shape defects if the number
of passes is insufficient. Therefore, optimisation of the number of passes is an important task in the roll forming process design.

Only a limited number of previous studies has focused on developing profile specific routines for determining the optimum number of forming passes required. Angel [13] introduced a methodology to determine the number of passes required to form a single bend in the roll forming process. The forming sequence was determined as shown in Figure 2.6. The number of passes was determined by Equation (2.1) where \( n \) is the number of passes, \( h \) is the height of the profile, \( d \) is the inter-station distance and \( \alpha \) was taken as 1.42° from experience. According to that model, the level of forming at the final stages is always greater than that in the initial stages to reduce shape defects. The optimum parameters determined by the model were experimentally verified. Further the method was criticised by Noble and Sarantidis [14] as it does not consider for the deformation at the rollers.

The roll forming industry started to develop CAD/CAM systems to design the roll forming process in the 1980’s [15-17], and today it has been progressed up to finite element simulations to model the process more realistically than ever before [18-26]. However research is still being developed for more accurate finite element models in
roll forming, since the field is still in its developing stage. Therefore currently the setup of roll forming lines is often based on a trial-and-error or a “rule-book” method and the quality of the roll formed product strongly relies on the experience of the engineer and operator; involvement of analytical methods and fundamental knowledge is not as extensive as might be desired. Thus, there is an urgent need to define the fundamental relationships between material properties, process parameters and the roll formed product defects.

2.1.1 Deformation modes in roll forming

In roll forming, different modes of material deformation take place due to the complexity of the forming process. Ideally, the material should be only transversally bent; other types of deformation do not contribute to the required shape change and are called redundant deformation [1]. It has been established that redundant deformation contributes to roll formed product defects as a result of residual stresses induced into the sheet [1]. Therefore the degree of defect in a roll formed part is greatly influenced by the properties of the roll formed material. Redundant deformation types are illustrated in Figure 2.7 (except the shear deformation) and can be categorized as follows [1].

1. Longitudinal bending and bending back
2. Longitudinal elongation or shrinkage
3. Transverse elongation or shrinkage
4. Shear in the plane of the sheet
5. Shear in the thickness direction
Due to the complexity of the roll forming operation, limited attempts were reported with regard to the investigation of material behaviour in roll forming. Panton et al. [27] analysed the amount of longitudinal stretching, longitudinal bending, transverse bending and shear in the roll forming of a section with a single active bend. They derived equations to determine the strain and work done in the above four deformation types, assuming the material is rigid and perfectly plastic. They found that the shear strain is the greatest in magnitude of all redundant deformation types and is an important factor in roll forming. This investigation has proven the existence of redundant deformation in the practical roll forming process. Panton et al. [28] further showed in an analytical analysis that only either shear or longitudinal deformation can occur at any time for the ideal case of roll forming a top hat section. Nevertheless actual practice has shown that both deformation modes can co-exist and that the amount of redundant deformation varies with the material properties, part geometry and the forming severity.

2.1.2 Longitudinal edge strain

Longitudinal stretching and bending are the two main deformations types in roll forming as mentioned above. Further it can be seen that these two deformation types cause most of the defects in roll forming such as longitudinal, bow, twist, edge wave and partially springback [29] which will be discussed later in this chapter. Nevertheless both of these strain components can be represented by the measured longitudinal surface strains and this information can be used in the product design to minimise the
number of passes required to form a specific profile. Therefore great attention will be paid on the variation of longitudinal edge strain depending on process and material parameters in this research.

The theoretical flow of material when a strip is formed to an angle of \( \theta \) is shown in Figure 2.8. The bend line travels along a straight line from A to B \((l)\) while the edge travels along a helical path from C to D \((s)\).

\[ \varepsilon = \frac{s - l}{l} \]  

(2.2)

As shown in Figure 2.8 longitudinal straining is unavoidable in the roll forming process. However longitudinal straining of the flange cannot be represented by the simple model given in Equation (2.2). In reality there is localised longitudinal flange deformation at the rollers over the deformation length (Figure 2.9).
Bhattacharyya et al. [30] derived a semi empirical equation based on the principle of deformation energy to determine the deformation length (Equation (2.3)). The deformation length is an important parameter when determining the peak longitudinal strain and the minimum inter-station distance [30]. The relation for deformation length in Equation (2.3) was derived by minimising the energy required for bending and stretching at a roll station.

\[
L = \frac{8a^3\Delta \theta}{3t}
\]  

(2.3)

In Equation (2.3) \(L\) is the deformation length, \(a\) is the flange length, \(\Delta \theta\) is the forming angle increment and \(t\) is the material thickness.

The highest longitudinal edge strain can be seen at the flange edge when it passes the rollers (within the deformation length). Further, according to the experiments conducted by Fong [31], this peak longitudinal edge strain can be seen just before the centreline of the rollers. Longitudinal edge strain distribution on the top surface at the longitudinal middle for roll forming a V- section with 10°-05°-05°-15°-15° bend angle increment is shown in Figure 2.10. It can be seen that the peak strain increases when the forming angle increases except of the first and last stations. Because at those two stations the strip is supported by either front or back alone unlike the middle stations where the strip is supported by both sides. Therefore at the middle stations the strip is deformed under tension, resulting in higher peak strain than the first and last stations even though the bending angle is the same.
Eventually, it is the objective of the product and process designers to maintain the peak longitudinal edge strain under the elastic limit of the material, if possible, to minimise shape defects due to plastic deformation of the flange and the resulting residual stresses. Therefore, it is very important to understand the effect of process parameters and the material properties on peak longitudinal edge strain of the product. Several studies [31, 33-44] can be found that investigated the effect of various parameters on peak longitudinal edge strain. Those can be categorized under three main factors, material properties, geometric parameters and process/machine parameters.

**Material properties**

Han et al. [43, 44] observed an increase in peak longitudinal strain with the material yield strength in their numerical analysis of a single station U section forming process. In contrast to that Lindgren [37, 40] and Azizitafti [33] observed the opposite trend in their numerical studies of the roll forming of a U-channel. No further studies were performed and currently the effect of material yield and material hardening on longitudinal strain in the flange region is still unclear.

**Geometric parameters**

According to the literature, geometric parameters that influence the peak longitudinal edge strain are the material thickness, the forming angle, the width of the web and the flange length (Figure 2.11).
Han et al. [43, 44] observed a decrease in peak longitudinal strain with an increase in the flange length in his numerical study. The same trend is predicted by an equation developed by Lindgren [40] based on the results of a numerical model. Further two equations developed by Fong [31] based on the deformation energy principle, proposed a decrease in peak longitudinal strain with increasing flange length. In contrast to the previous studies a geometrical model applied by Zhu et al. [42] observed an increase in peak strain with flange length up to a flange length level of 5mm followed by a continuous decreased (Figure 2.12). This observation was confirmed by a numerical study performed by Azizitafti et al. [33]. However this trend has not been experimentally validated according to the available literature.

![Figure 2.11: Effect of various parameters on the longitudinal edge strain](image)

In a number of numerical studies [33, 43, 44] and analytical equations [31, 40, 42], it was observed that the peak longitudinal strain increases with material thickness. This trend was experimentally verified by Fong [31] with mild steel having a maximum thickness of 1mm. As explained by Zhu et al. [42], when the strip thickness increases the deformation length decreases (Figure 2.13). If the deformation length is smaller, then deformation takes place over a shorter distance which results in higher peak longitudinal strain. However when it comes to AHSS and UHSS the flange may not
wrap that easily around the rolls as in that case of mild steel and this may affect the link between material thickness and the peak longitudinal strain for this class of materials.

![Figure 2.13: Effect of thickness on the peak longitudinal edge strain](image)

Figure 2.13: Effect of thickness on the peak longitudinal edge strain [42]

Most numerical and analytical studies [31, 33, 40, 42] did not observe any effect of the web length on the peak longitudinal strain. However Fong [31] observed a slight increase in peak longitudinal edge strain with decreasing web length in his experiments and the same trend was obtained by Han et al. [43, 44] in their numerical studies. Therefore web length may have a slight influence on the peak longitudinal edge strain, however it may not be as significant as other parameters.

Peak longitudinal edge strain decreases with increasing bottom roll diameter [42]. As explained by Zhu et al. [42] the rate of change in angle formed reduces with the increase in bottom roll diameter and results in lower peak longitudinal strains. This concept was utilised by Ding [45] to implement a new forming technique where the forming is done by set of dies attached to a chain to increase the apparent roll diameter, hence the residual strains were minimised (Figure 2.14).

![Figure 2.14: Chain die forming stand](image)

Figure 2.14: Chain die forming stand [46]
Process parameters

Peak longitudinal strain increases with the forming angle increment between two stations [19, 31, 33, 39, 40, 42-44, 47]. According to Equation (2.3), deformation length increases with the forming angle; i.e. more stretching is introduced at the flange edge, resulting in the increase in peak longitudinal edge strain with the increase in bending angle.

According to the numerical studies found in the literature [19, 41, 43, 44], peak longitudinal strain decreases with an increase in distance between two roll stations. A larger station distance allows a more progressive deformation, which reduces the peak strain [19]. However AHSS and UHSS may not be sensitive to the station distance as much as softer materials due to their higher yield strength levels. It has been numerically shown that the peak longitudinal strain is independent of the line speed and the frictional coefficient [19, 41].

As a summary of this section, roll forming defects are due to the introduction of redundant deformations into a part during the process. While redundant deformation cannot be eliminated it can be reduced to an acceptable level by proper machine settings (such as roll gap, inter-station distance and tool design) and forming approach (such as the flower design). Therefore it is immensely important to identify the link between the process, product parameters and redundant deformation that leads to roll forming defects.

Longitudinal stretching and bending have been identified as one of the main redundant deformation types in roll forming which leads to a number of defects. Unlike the other redundant deformations, this redundant deformation can be measured during the roll forming process by means of electrical resistance strain gauges. Therefore a number of investigations have been reported with regard to the effect of different parameters on the peak longitudinal edge strain. Redundant deformations are greatly influenced by the material properties. This effect is more significant when it comes to the AHSS and UHSS; because, as previously explained, the material yield strength may vary from coil to coil or within the same coil resulting in different degrees of defects in the final part. However, the effect of material yield strength and hardening on peak longitudinal edge strain has not been experimentally investigated before for AHSS and
UHSS. Additionally, previous numerical studies carried out for softer material grades showed contradictions with regard to the effect of flange length and the material yield strength. Nevertheless, the available experimental validations with regard to the effect of different parameters on peak longitudinal strain were carried out with low thick and softer materials such as mild steel and aluminium. Therefore AHSS and UHSS with higher thickness need to be experimentally tested as they are being increasingly used in the automotive applications. As a result, following questions need to be answered during this research.

- **What is the link between the material properties and peak longitudinal edge strain in AHSS and UHSS roll forming?**
- **How do the process and geometrical parameters affect the peak longitudinal edge strain in AHSS and UHSS roll forming?**

### 2.2 Roll formed product defects and the influence of the process parameters

As mentioned, rolled formed part defects are due to the development of residual stresses during the forming process. Residual stresses can be introduced as a result of pre-pierced holes and notches, embossing, incorrect settings in the tooling and the machine [48]. If these stresses exceed a certain limit, a number of shape defects can result as shown in Figure 2.15 [48]. Thereby the degree of defect may vary depending on the properties of the incoming material, process parameters, and the geometry of the roll formed part.

![Roll formed product defects](image)  
**Figure 2.15: Roll formed product defects [48]**
In actual practice, above defects can be identified during or after the roll forming process. Therefore it is vital to know the causes for these defects in advance of the actual production. Only then the process can be re-adjusted to minimise the defects. In this sub chapter previous studies that focused on investigating common rolled formed product defects and their causes will be investigated. Thereby special attention will be given to the influence of material properties as it is a significant factor in AHSS and UHSS roll forming.

2.2.1 Edge waviness

In roll forming, material at the edge of the work piece, travels further than that in the centre as may be seen in Figure 2.8. This length difference causes curving down of the metal strip after each set of rolls (Figure 2.16); however in the next station it is taken back to the original horizontal position. Therefore, the outer fibres are first stretched and then compressed. If this stretching exceed a certain limit, then it is difficult to compress it back. This will causes edge waviness [29]. Therefore in the roll forming process, longitudinal edge strain needs to be maintained below a certain limit to avoid edge waviness. For that possible process and design parameters such as inter-station distance, forming sequence, bottom roll diameter need to be maintained at their optimum levels.

Farzin et al. [25] introduced the “buckling limit strain” (BLS) in roll forming based on the results of a numerical analysis; BLS is the maximum allowable longitudinal edge strain (compressive) leading to a product without any waviness. In their analysis, done with a channel section, it was found that the BLS is a function of the material properties and the thickness to flange length ratio of the part but independent of the bending angle.
Theherani et al. [49] investigated the reasons for edge buckling of a U-channel section. According to their finite element simulation, the fold angle at the very first station should be kept below a specific limit or else the reverse bend deformation introduced by the second roll station will be too high, leading to edge buckling (edge waviness). This study also found that changing the fold angle in the subsequent stations has no effect on edge buckling. The reverse bending exerted at the second station depends on the amount of bending introduced by the first station. Therefore the angle at the first station is more significant than that of the second station in terms of the edge buckling control. Theherani et al. [50] used the same model set up to investigate the forming of a circular tube section and found that the profile angle of the first station should be kept below a critical value to avoid edge buckling confirming their previous results [49].

In the numerical study of Bui and Ponthot [21], it was found that low work hardening materials (higher hardening exponent) lead to reduced edge waviness (Figure 2.17(a)). The low work hardening material has less accumulated plastic strain. Therefore it reduces the development of permanent plastic strain at the flange during the roll forming process resulting in decreased edge waviness with increasing work hardening exponent [21]. In addition to that, according to their numerical simulation, yield strength did not show a significant influence on edge waviness (Figure 2.17(b)) which contradicts the previous observations made by Farzin et al. [25].

![Figure 2.17](image)

**Figure 2.17** Effect of (a) hardening exponent (b) yield strength on edge waviness

It is clear that the edge waviness is affected by the hardening exponent of the material, given that the edge waviness is due to the longitudinal stretching and subsequent compression of the material during the roll forming process. Therefore this thesis will
seek to clarify how the material hardening exponent (independent of yield strength) affects the peak longitudinal edge strain.

### 2.2.2 Longitudinal bow

Longitudinal bow is the longitudinal curvature of the roll formed product (Figure 2.18). In the roll forming process, as explained in Section 2.2.1, the outer fibre first stretches compared to the web and then compresses due to the reverse bending at the next station. This results in different levels of longitudinal membrane strains in the web and in the flange and results in longitudinal bow [29]. Therefore longitudinal bow can be considered as a defect that occurs due to the longitudinal stretching/compressing and bending during the roll forming process [51].

![Figure 2.18: Longitudinal bow of a roll formed part](image)

According to the longitudinal membrane strain distribution along the transverse direction, longitudinal bow can be either concave upwards or concave downwards, as shown in Figure 2.19 [29].

![Figure 2.19: Longitudinal membrane strain distribution along the width of the final part](image)
Kiuchi et al. [51] experimentally studied the effect of different geometrical and process parameters on the longitudinal bow of V, trapezoidal and circular cross sections. They found that the longitudinal bow of a trapezoidal section was greatly affected by the apparent inlet angle $\alpha$ (ratio between the height of the forming roll and inter-station distance as shown in Figure 2.20), the bending angle and the width ratio between the sheet and the web ($2b/W$ in Figure 2.21). Longitudinal bow decreased with the apparent inlet angle and $2b/W$.

Figure 2.20: Apparent inlet angle [51]

As shown in Figure 2.22, if the apparent inlet angle is negative, then it will introduce compressive residual strain at the flange edge resulting in negative bow; while when positive, then the flange edge undergoes more stretching compared to the web resulting in tensile residual strains in the flange, which leads to positive bow. When $2b/W$ increases, the depth of the part increases which increases the bending rigidity and this reduces bow. Further, despite of the increase in bending rigidity with the increasing forming angle Kiuchi et al. [51] found that the longitudinal bow increases with the forming angle. Here two mild steel and two brass grades were used as the materials. These trends may therefore be different from those found for AHSS and UHSS which
have higher yield strength and elastic limits which may allow them to form at higher stress-strain levels with minimum defects.

Figure 2.22: Development of residual strain according to apprent inlet angle [51] Jimma and Ona [52] experimentally investigated the effect of the forming sequence on longitudinal bow. They observed that the forming angle at the last stations are more important than the number of forming stations with regard to reducing bow. In their study they observed a decrease in bow when smaller angles are formed in the last roll stands; this contradicts with the forming method introduced by Angel [13] who proposed to form larger angles in the last forming stations (Figure 2.6) to reduce edge strain.

Fong [31] experimentally investigated the effect of flange length, web length and sheet thickness on the longitudinal bow of a trapezoidal section formed with mild steel. He used two different forming setups; one was single pass forming where the forming was done at one single station, the other was a multi pass forming process where a number of stations were applied. He found that in multi pass forming longitudinal bow decreased with an increasing number of forming stations, but that beyond a certain number of stations there was no further reduction in bow. This indicates that an increasing number of stations does not always completely avoid shape defects in the roll forming process. Fong [31] also showed that in single pass roll forming longitudinal bow increased with the forming angle; while it only increased with flange length up to a flange length level of 7 mm, followed by a continuous decrease. Longitudinal bow decreased with increase in web length and increased with increase
in material thickness for the profiles with flange length higher than 5mm. It showed different trends for the profiles with 5mm flange length. Fong concluded that longitudinal bow is proportional to the residual strain difference between the edge and the flange. He observed considerable tensile residual strain at the flange edge due to the longitudinal stretching of the material and very small compressive residual strain at the web due to the lack of longitudinal deformation at the web area. On the other hand when it comes to high strength steels with higher thicknesses such as 2mm, bow was observed even though there was no residual strain in the flange edge [32]. Additionally, different types of materials that showed almost zero longitudinal residual strain at the edge gave different about of bow after forming [32, 53]. Therefore it is difficult to make conclusions based on the observed residual strain in a part. In addition to that available analytical equations in the literature can predict only the peak longitudinal edge strain or longitudinal membrane strain [31, 40, 47, 54] and therefore cannot be used to explain the occurrence of longitudinal bow in roll forming. As a result it is immensely important to identify the link between peak longitudinal edge strain and longitudinal bow.

Azizitafti et al. [33] also numerically investigated the effect of different parameters on the longitudinal bow of a trapezoidal section roll formed in a single pass. According to their finite element model longitudinal bow increased with increase in forming angle and the material thickness, while it decreased with increase in yield strength and web length. Additionally, longitudinal bow increased with increase in flange length until a certain limit of flange length, and then it decreased continuously as observed by Fong [31].

Galdos et al. [55] numerically and experimentally investigated the effect of material properties on the longitudinal bow and found that bow decreases with increasing material yield strength. However a martensitic grade steel did not fit into this trend. This suggests that longitudinal bow depends not only on material yield strength, but that also some other factors such as hardening or microstructure may have an effect.

Jeong et al. [24] investigated the occurrence of longitudinal bow for two roll forming sequences of an upper member of an under-rail (Figure 2.23).
Their simulation showed very high bow for flower pattern (a) compared to flower pattern (b) (Figure 2.24). Also flower pattern (a) showed the highest peak edge strain, hence induced more plastic deformation into the formed part resulting in higher bow in the part. This suggests that the quality of a roll formed part can be improved by proper product designing and the peak longitudinal edge strain can be used as an important indicator to determine the amount of longitudinal bow in a part.

This review has shown limited experimental investigations are available in the literature on longitudinal bow. Even though some similar results were obtained by a number of researchers with regards to the effect of different parameters on longitudinal bow, the effect of both material yield strength and the hardening on the longitudinal bow and its relationship with the peak longitudinal edge strain has not been investigated for AHSS and UHSS materials. Previous experimental work was only carried out for softer materials such as mild steel, brass and the general trends may therefore differ from those for AHSS and UHSS. Additionally, the previous section has revealed that part quality in roll forming can be improved by proper product and process design and peak longitudinal edge strain can be used as an indicator for defects.
2.2.3 Springback

Springback is a common defect in roll forming and can be defined as the elastic recovery of the material when the forming force is released from the roll formed part leading to cross sectional deviation in the finished product as illustrated in the cross sectional view in Figure 2.25. Springback in roll forming is due to both transverse and longitudinal strains [48].

The available literature mostly discusses springback in die bending and folding [56-59]. However there is a limited amount of previous work reported on the springback behaviour in roll forming process [1, 7, 21, 60-62], and there is only one previous study developing an equation for the prediction of springback in the roll forming process [63].

Kiuchi [63] developed two analytical equations to predict springback in the roll forming process. The first is a one-dimensional formula that is based on the simple bending theory, while the other is a two-dimensional formula that considers two-dimensional material deformation in roll forming. He observed that the predicted springback from the two dimensional formula was in good agreement with the experimental results, whereas the one-dimensional formula overestimated the experimental values. Weiss et al. [7] roll formed a V-section profile via simple V-die bending and roll forming with 5 forming stations. Their study showed for all five grades tested springback in roll forming was significantly lower compared to that in V-die forming, experimentally verifying Kiuchi’s results [63]. Badr et al. [62] conducted incremental V-die forming experiments and found that springback decreases with the number of incremental steps in V-die forming. This suggests that
the lower springback in roll forming maybe due to some extend to the incremental nature of the process, where the sheet is incrementally bent into shape in consecutive roll stations. This idea is numerically confirmed by Badr et al. [64] which showed a decrease in springback with increase in the number of stations employed in roll forming a V-channel section.

Even though the springback in roll forming is different from the V-die bending or pure bending due to the complex deformation behaviour in the roll forming process, some of the springback related problems can be explained by the simple bending theory.

According to the previous studies springback in roll forming increases with the increase in yield strength and the tensile strength [1, 21, 55, 60, 61] of the material. When yield strength and the tensile strength increases, the elastic limit of the material increases. Therefore the elastic recovery (springback) increases as a result of an increase in yield strength and the tensile strength.

Springback in roll forming is found to decrease with an increase in Young’s modulus [1]. When the Young’s modulus increases, generally the elastic recovery of the material decreases. Therefore springback decreases with the increase in Young’s modulus.

In roll forming, the springback increases with the increase in bending radius to thickness ratio (r:t ratio) [1, 61]. According to the simple pure bending operation, the bending strain at the outer surface of the bend is given by Equation (2.4) [65]. It indicates that the bending strain at the outer surface decreases with the increase in r:t ratio. Therefore when r:t ratio increases, the material forms more elastically resulting an increase in springback. However an increase in springback was observed with increase in material thickness (t) and bending radius (r) in the simulation performed by Groche and Henkelmann [60], which was conducted on high strength steel. Further their simulation model underestimated the experimental results, and sufficient evidence was not recorded with regard to the experimental results. However their work suggests that the simple bending theory alone cannot explain the springback behavior in the roll forming process, given that longitudinal stretching and compression may influence the amount of springback.
31

\[ \varepsilon_b \approx \frac{t}{2r} \approx \frac{1}{2} \left( \frac{t}{r} \right) \]  

(2.4)

where \( \varepsilon_b \) is the bending strain, \( t \) is the material thickness and \( r \) is the bending radius of the neutral axis.

Previous numerical studies further suggest that springback in roll forming is not affected by the inter-station distance [21].

It is clear that some of the springback trends cannot be explained by the simple pure bending theory such as the effect of the \( r:t \) ratio. The springback in roll forming is smaller in magnitude compared to the pure bending operation and to some extend this may be due to the incremental nature of the roll forming process. Springback in roll forming may also be affected by other factors which do not exist in a simple bending operation such as longitudinal stretching and compression. It therefore is important to investigate the effect of longitudinal edge strain on springback behavior in roll forming. Further the effect of parameters that influence other roll forming defects such as flange length, forming angle, inter-station distance and material thickness on the springback has not been experimentally investigated before. It is vital to establish the link among peak longitudinal strain, process parameters, product geometry and springback in roll forming as springback is one of the main challenges in the roll forming of AHSS and UHSS.

2.2.4 Twist

Twist is another common defect found in roll-formed products (Figure 2.15). The main reason for twist is an uneven plastic deformation on each side of the strip. This results in the uneven distribution of longitudinal membrane strain along the transverse direction of the final product [29] as shown in Figure 2.26.

Fewtrell [66] showed that the twist depends on the imbalances in roll load, symmetry of the tooling and alignment of the rolls. In the investigation of Watari and Ona [67], asymmetrically pre notched (only one side was pre notched) sheet was roll formed into a channel section and the variation of twist with the hole spacing was measured. The torsion per unit length was taken as a measure for twist and it was concluded that twist decreases with the increase in hole spacing. When the distance between the holes are increased, the number of holes in the part will decrease which reduces the asymmetry
in terms of material and surface area. This may have led to the reduction in twist with increase in spacing between the holes observed.

Figure 2.26: Non uniform longitudinal membrane strain distribution [1]

There are limited studies available in the literature with regard to the twisting in roll forming. However it can be seen that twisting is related to an uneven distribution of longitudinal strain. Therefore edge strain may be used as a tool in determining the occurrence of twist in a part. As a result it is vital to understand the effect of geometrical and process parameters on longitudinal edge strain.

As the summary of this section it could be seen that the roll forming defects are due to the introduction of the residual stresses into the part during the roll forming process. This section discussed four main roll forming defects. They are: edge waviness, longitudinal bow and twist, which are mainly due to the longitudinal residual strain; additionally, there is springback, which is due to both the longitudinal and transverse residual stresses in the final product. Therefore it is clear that the longitudinal residual stresses cause a number of defects. However it is not easy to measure the residual stresses. In the roll forming process longitudinal residual strain has been found to be proportional to the peak longitudinal strain [31]. Therefore peak longitudinal edge strain can be used as an alternative indicator for the longitudinal residual stress level at the flange edge of a part.

Even though the effect of yield strength on product defects has been investigated before, the combined effect of yield strength and hardening on product defects and
their relationship with the peak longitudinal edge strain is still not known. Further the effect of geometric and process parameters on longitudinal bow and springback in AHSS and UHSS roll forming has not been established. Therefore following questions need to be answered during this research.

- **What is the relationship between the material properties (i.e. yield strength and material hardening) and roll forming product defects (longitudinal bow in this thesis) for AHSS and UHSS roll forming?**
- **How does the above relationship link with the peak longitudinal edge strain?**

### 2.3 Roll load and torque

There are two main process parameters in roll forming that can be measured during the process; those are roll load and torque. The roll load is generally defined as the vertical load exerted on the top roll during the material deformation at a particular station. Roll torque is the torque applied on the bottom or the top roll during the forming operation. They can be easily measured by introducing a load cell and a torque sensor to the roll station as shown in Figure 2.27 where the load cell measures the load exerted on the top roll and the torque sensor measures the torque applied on the bottom roll during the roll forming process.

![Figure 2.27: Roll load and torque measuring technique](68)

Kiuchi [51] introduced four separate roll load components in the roll forming process. Those are:
1. The roll load due to pure transverse bending of the sheet ($P_n$ in Figure 2.28)
2. The roll load due to longitudinal bending along the pass line ($Q_n$ in Figure 2.28)
3. The roll load for clamping the sheet ($Q_n$ in Figure 2.28), which is applicable only if the roll gap is less than the material thickness.
4. The vertical roll load component due to tension or compression of the sheet ($S_n$ in Figure 2.28), which is applicable only if the pass height changes.

Figure 2.28: Roll load components [51]

According to their experiments when roll forming a trapezoidal section with two forming stations (flat rolls as the first station and a forming station as the second one), the following conclusions were made.

When the ratio between the strip width and the web length ($2b/W$) was increased both the roll load and torque at the bottom roll increased (see Figure 2.21) until a certain limit, and then decreased continuously after that [51]. This limit may be determined by the rigidity of the cross sectional profile, however no explanation was given for this trend. In this study the web length was kept constant and only the strip width was changed. Therefore the variation in roll load with the ratio between the strip width and the web length ($2b/W$) is solely due to the effect of the flange length of the trapezoidal section. When $2b$ increases (given $W$ is constant), it increases the transverse bending.
moment and reduces the transverse bending load. Additionally, if 2b increases then the longitudinal bending modulus (bending rigidity) increases resulting in a higher roll load. As a combined effect of all these factors the above mentioned variation in roll load and torque could be observed with changes in 2b/W. Roll load and torque increased with increase in material thickness due to the increase in transverse bending force, while the apparent inlet angle exhibited only a minor influence on both roll load and torque.

Bhattacharyya et al. [69] introduced a semi empirical method to calculate the roll load by equating the external work to the total deformation work (bending and stretching). A trapezoidal channel section was taken into account for the investigation. According to their equation, roll load is a function of yield strength \( (Y) \) material thickness \( (t) \), fold angle \( (\theta) \) and the flange length \( (a) \) as given in Equation (2.5). However there was an error of 0-20% between the experimental and calculated values.

\[
F = Y \frac{2at^3\theta^3}{3\sin\theta}
\]

(2.5)

Figure 2.29: Factors affecting the roll load [69]

Lindgren [68] also derived two equations for the roll load and roll torque, including the same parameters as used in Bhattacharya’s study, but he excluded the effect of the flange length. Again the forming of a trapezoidal section was investigated and his model showed a good agreement with the experimental results for both roll load and torque. Nevertheless Lindgren derived the exponents and coefficients of the equations from the experimental results and that is why those equations are limited to the experimental set up analyzed but are not applicable in general. The equations derived for roll load and torque in Lindgren’s study are given in the Equation (2.6) and (2.7)
respectively. Here \( k_1 \) and \( k_4 \) are functions of the forming angle while \( k_2, k_3, k_5 \) and \( k_6 \) are constants identified in the experimental trials.

\[
F = k_1 t^{k_2} Y^{k_3} \tag{2.6}
\]
\[
T = k_4 t^{k_5} Y^{k_6} \tag{2.7}
\]

Davoodi et al. [70] numerically analyzed the roll forming of a U-section profile to determine the effect of all parameters mentioned above on the roll load and torque. Their simulation results revealed that roll load and torque increase with yield strength (\( Y \)), sheet thickness (\( t \)) and forming angle (\( \theta \)). Additionally, it was found that roll load increases with flange length (\( a \)) while roll torque decreases. Their trends agreed well with those derived by Bhattacharyya’s and Lindgren’s equations.

As a summary of this section, previous studies have shown that roll load and torque depend on material yield strength and thickness. This suggests that a roll load and torque measurement system may be applicable to determine the deviations in the material thickness and properties in the roll forming process, if the bending angle and the flange length are kept unchanged. If we can set the roll gap slightly higher than the material thickness to compensate for the variations in material thickness in the incoming materials then the roll load and torque measurements can be used to represent the changes in material yield strength. However, as far as the AHSS and UHSS are concerned, not only yield strength but also the material hardening may influence the roll load and torque. Therefore it is important to investigate the effect of material hardening on the roll load and torque. Finally this methodology can be applied to identify the deviations in the material properties in terms of the measured roll load and torque in the roll forming process. Therefore following questions need to be answered during this research.

- **How do both material yield strength and hardening influence the roll load and torque?**
- **How can roll load and torque be used for defect identification?**

### 2.4 Defect compensation

Twisting of the roll formed products can be compensated by counter twisting at the last one or two forming stations [1]. The most common way to eliminate twist is the use of a Turks head to counter twist the part after the final roll forming stations [1, 71]
as shown in Figure 2.30. However it is mainly a manual trial and error method where the amount of counter twisting depends on the actual twisting in the product.

Figure 2.30: Turks-head straightener

Ona and Jimma [71] experimentally investigated a method to eliminate twist, bow and camber of a symmetrical channel section. They used an exit straightener, roll pressure adjustment, transverse shift of the rolls, over-bending of the strip and a twist forming stand as the correction methodologies. Five types of asymmetric U profiles with the same web length and different flange lengths were used for the experiments as shown in Figure 2.31. Twist (Ø), camber (k1) and bow (k2) were measured in the experiments. The rotation about the centroid of the cross-section per unit length was taken as the twist and the horizontal and vertical coordinates of the locus of the centroid along the channel length were defined as k1 and k2 respectively. Seven forming schedules were used for the investigation. Finally, the following conclusions were drawn from the experiment.

• Exit straightening can be used to correct mild distortions up to 21:15 channels (21:15 represents the lengths of flanges in mm as shown in Figure 2.31).

• Transverse shifting of upper and lower rolls, at the final stand, toward the lower flange can eliminate twist and the shifting of rollers towards the higher flange can eliminate camber.

• Increasing roll pressure can be used to reduce bow. However this may result in the coining of the material when softer materials are roll formed.
• Over-bending in the front of the final station has a considerable effect on twist and bow compensation.

• Over-bending rolls together with twist forming (Figure 2.32), transverse shift and pressure adjustment stands is the most effective way of compensating twist, bow and camber (up to 30:6).

This methodology is based on trial and error and is not practical especially when UHSS and AHSS are roll formed as their material properties are continuously changing which would lead to frequent machine stoppages and readjustments. As a result roll forming needs more advanced compensation methods to overcome its inherent defects to achieve tight dimensional tolerances.

Figure 2.31: Cross section of the roll-formed profile [39]

Figure 2.32: Twist forming stand [39]
Groche et al. [9] introduced an in-line springback compensation method for high and ultra-high strength steels. It is always difficult to predict the exact springback value in roll forming, since material properties, such as yield strength, are changing from coil to coil and over the length of the same coil. To overcome this problem they introduced a simple closed-loop control system to compensate for springback. In their method, two laser cameras were used to take images of the end profile at 0.2s intervals in a U-channel roll forming process. Also those images of the profile were used to measure the springback with reference to the ideal cross section by using the COPRA®ProfileCheck software. Then the profile was over-bent according to the springback value by means of two moveable side rolls placed just before the laser camera (Figure 2.33). According to their study this concept allowed to compensate for springback irrespective of the properties of the incoming material (Figure 2.34).

![Figure 2.33: Calibration stand [12]](image-url)
This method is a trial and error method and a feed-back signal is a must in this control system. The development of a control system without a feed-back signal which works according to the given instructions of its inbuilt memory would be a more convenient and cost effective method. The inbuilt memory may consist of data with regard to the relationship among the measured process parameters, amount of shape defects in the part and the required machine adjustment for the compensation of those shape defects for any given profile. For that identification of the relationship among material properties, profile geometry, process parameters and roll-formed product defects is important. This relationship could be used to develop instructions for a potential control system allowing to adjust the machine settings to overcome the defects during the process. To achieve this the following question needs to be answered.

- **How can a defect compensation routine be established for the roll forming process that functions according to given instructions of an inbuilt memory?**
- **How can such a defect compensation routine be practically implemented in the roll forming process?**

### 2.5 Summary

In the first part of the literature review the roll forming process and its deformation modes were introduced. It was shown that transverse bending is the major deformation...
mode in roll forming, however there are other unwanted deformation types taking place, which are called redundant deformations. These redundant deformations introduce residual stresses into the part causing defects in the final product.

The literature review showed that the effect of material properties, and process parameters on edge strain in roll forming is not fully understood. Significant gaps in knowledge have been identified with regard to the effect of the material yield strength and hardening on longitudinal edge strain in AHSS and UHSS roll forming. While some studies suggest that high material yield reduces edge strain other studies report the opposite. The literature review has further identified that only a limited amount of experimental work has focused on edge strain in roll forming, which is possibly due to the high difficulty involved in achieving reliable edge strain measurements. Given that the reduction of edge strain in the part is one of the main factors currently used in the design and optimisation of roll forming processes further work is required to fully understand the effect of material and process parameters on edge strain in the roll forming process.

Furthermore, longitudinal edge strain was identified as a measure for two main redundant deformation types, longitudinal stretching and bending, and as an important parameter that determines the occurrence of some roll forming defects. Moreover longitudinal edge strain was identified as a basic tool for product design in the roll forming process. However, the link between peak longitudinal edge strain and product defects is still not fully established and needs further investigation.

Edge waviness, longitudinal bow, springback and twist were discussed as the most common defects in roll forming. All of them were influenced by longitudinal residual stress. However longitudinal bow and springback will be mainly considered in this research. It has been found that the residual strain difference between the flange and web determines the amount of longitudinal bow in a part. However bow can be seen in parts made from AHSS and UHSS where the residual strains are extremely small or non-existent. Therefore residual strain alone cannot determine the amount of longitudinal bow in a part. As far as springback in roll forming is concerned, there are only a few previous studies recorded in the literature. Most of the springback trends can be explained by the simple pure bending theory. However the influence of some
parameters such as flange length and inter-station distance cannot be explained by the simple bending theory. Moreover an increase in springback could be seen with material thickness when high strength steel was formed which does not comply with the simple bending theory. This suggests that the material properties have a great influence on the longitudinal edge strain and roll forming shape defects. This effect is more significant in the AHSS and UHSS due to their high material strength and may be different to softer materials.

The next part of this chapter analysed previous studies investigating roll load and torque. It was shown that roll load and torque are mainly dependant on the forming angle, material yield strength and thickness. The author further believes that material hardening may influence roll load and torque especially in AHSS and UHSS roll forming given that those materials show significantly higher material hardening compared to materials traditionally roll formed. Therefore roll load and torque can be considered as possible observer variables that can be applied to predict property changes in incoming material.

The final part of the literature review further showed that there are no guidelines with regard to shape compensation techniques in roll forming. Shape compensation in roll forming is still mostly based on trial and error, and in most cases does not utilise any analytical knowledge. With the increasing use of the roll forming technology to form AHSS and UHSS in the automobile and the aerospace industry, with their tight tolerance and delivery requirements, a trial and error approach is not feasible. These material grades can have high variation with regard to material strength from coil to coil which affects part quality and their forming will require online shape compensation techniques that adjust the tooling automatically during the process depending on the changes in material properties. Roll load and torque have a great potential to identify those material properties variations during the roll forming process, as they are directly related to the yield strength of the material.

As a whole following questions will be answered during this research to answer the identified gaps in this literature review.

- What is the link between the material properties and peak longitudinal edge strain in AHSS and UHSS roll forming?
• How do the process and geometrical parameters affect the peak longitudinal edge strain in AHSS and UHSS roll forming?
• What is the relationship between the material properties (i.e. yield strength and material hardening) and roll forming product defects (longitudinal bow in this thesis)?
• How does the above relationship link with the peak longitudinal edge strain?
• How do both material yield strength and hardening influence the roll load and torque?
• How can roll load and torque be used for defect identification?
• How does a defect compensation routine establish in roll forming which works according to the given instructions of an inbuilt memory?
• How can such a defect compensation routine be practically implemented in the roll forming process?
3 Experimental procedures and the numerical model

3.1 Introduction

This chapter describes the experimental procedures and the numerical model used in this study. This includes standard tensile tests, the methodology applied to measure edge strain during experimental roll forming trials, the experimental set up for the roll forming of a simple V and a U-channel, springback measuring technique and the 3D scanning technique used to analyse longitudinal bow after roll forming. Additionally, the numerical model used in this work to investigate the effect of process and material parameters on roll load, torque and shape defects in the roll forming process and to develop the bow compensation routine is presented.

3.2 Experimental procedures

3.2.1 Tensile test

The tensile tests were conducted based on the standard ASTM E8/E8M [72] on bone shaped samples (Figure 3.1) oriented 0, 45 and 90° to the rolling direction. An Instron 5967 with a 30kN load cell was used and the test speed was 0.025 mms⁻¹ giving a strain rate of 0.001 s⁻¹.

![Figure 3.1: Dimensions of the tensile sample](image)
A high strain electrical resistance strain gauge was glued in the gauge section of the sample to obtain a precise measurement of the Young’s modulus, which will be explained in Section 3.2.2. The tensile sample was held between the jaws of the Instron, before the test as shown in Figure 3.2.

Figure 3.2: The tensile specimen positioned in the jaws of the Instron tensile tester

Engineering strain data was obtained from the strain gauges, which will be explained in Section 3.2.2. Engineering stress was determined using Equation (3.1) with the load \( F \), the initial width \( w_0 \) and the initial thickness \( t_0 \) of the sample. Load was recorded by the load cell in the Instron; the initial sample width and thickness were measured manually by a Vernier calliper and a micrometre respectively.

\[
\sigma_e = \frac{F}{w_0 \times t_0}
\]  

(3.1)

The yield strength was calculated applying the 0.2% strain offset. For this a parallel line was drawn to the linear elastic region of the engineering stress strain plot with a 0.002 (0.2%) strain offset as shown in Figure 3.3. The Young’s modulus, \( E \), was given by the gradient of that line.
Engineering stress and strain were converted to true stress and strain applying Equations (3.2) and (3.3).

\[ \varepsilon = \ln(1 + \varepsilon_e) \] (3.2)

\[ \sigma = \sigma_e(1 + \varepsilon_e) \] (3.3)

where \( \varepsilon \) is the true strain and \( \sigma \) is the true stress.

The Hooke’s stress-strain relationship given in Equation (3.4) was used to define the material behaviour within the elastic limit of the material. The yield strength was defined with the 0.2% strain offset as explained before (Figure 3.3).

\[ \sigma = E\varepsilon \] (3.4)

The effective plastic strain (\( \varepsilon_{eps} \)) was calculated from Equation (3.5)

\[ \varepsilon_{eps} = \varepsilon - \frac{\sigma}{E} \] (3.5)

Typical true stress-strain and true stress-effective plastic strain graphs are shown in Figure 3.4.
Figure 3.4: True stress-strain and true stress effective plastic strain graph for DP780

The Hollomon’s power law (Equation (3.6)) was fitted to the true stress-effective plastic strain graph to determine the hardening parameters; hardening exponent (n) and strength coefficient (k). Reasonable correlation was aimed for similar to that illustrated in Figure 3.5.

\[ \sigma = k\varepsilon_{\text{eps}}^n \]  

(3.6)

where \( \varepsilon_{\text{eps}} \) is the effective plastic strain.

Figure 3.5: True stress effective plastic strain and Hollomon’s graph for DP780
3.2.2 Technique applied to measure strain with strain gauges

Strain measurements were a critical task of this research. Strain measurements were recorded mainly at two occasions in this work, during the tensile tests and the roll forming trials. For that two types of single element TML electrical resistance strain gauges [73] with 120Ω gauge resistance were used. High strain (up to 15%) strain gauges were applied in the tensile test, while low strain (measure up to 3%) strain gauges were used to measure longitudinal strain in the strip edge in the roll forming trials. The procedure for application is the same for both types of strain gauges and only the adhesive used for gluing was different.

First the metal surface was cleaned with abrasive paper while using three chemicals to treat the surface at the same time. They are acetone, BC 710 Conditioner and BN 820 Neutraliser respectively. Then the strain gauge was glued onto the clean and dry metal surface with CN adhesive. In the tensile samples, the strain gauge was glued at the middle of the gauge length as shown in Figure 3.6 while for the roll forming trials, it was glued with 1.5mm clearance to the edge of the longitudinal middle of the strip as shown in Figure 3.7. In some roll forming samples the strain gauges were glued both on the top and bottom surfaces when the mid surface strain had to be calculated.

![Figure 3.6: Tensile sample with strain gauge attached in the gauge section](image)

![Figure 3.7: Location of the strain gauge on the strip used for the roll forming trials](image)

After that the two lead wires of the strain gauge were connected to a 120Ω equal resistance Wheatstone bridge with quarter bridge configuration as shown in Figure 3.8.
Figure 3.8: Bridging circuit used in combination with the strain gauges

The bridging circuit was connected to an ALMEMO 2590-4S universal data logger to record the output data from the Wheatstone bridge which produces a voltage output. During the forming process, the resistance of the strain gauge continuously changes due to the stretching and compression of the material which produces imbalanced voltage outputs in the Wheatstone bridge. This voltage output is proportional to the strain on the strain gauge glued surface and can be converted into the engineering strain values by Equation (3.7).

$$\varepsilon_e = \frac{4 \times V_o}{k \times V_i} \quad (3.7)$$

where $V_o$ is the output voltage, $k$ is the gauge factor which is provided by the strain gauge supplier and $V_i$ is the excitation voltage.

3.2.3 V-profile roll forming trials

A conventional industrial roll former was used to form a V-profile and longitudinal strain in the strip edge measured during the process to validate the geometrical roll forming model developed in Chapter 4. In the roll former all bottom shafts are fixed at the same vertical height and the top shafts are adjustable vertically to adjust for material thickness. The roll gap was set to be the same as the material thickness with feeler gauges. Spacers were used to locate the tooling properly in the shafts as shown in Figure 3.9. The blank shaft diameter is 48mm and the spacer diameter is 80 mm. As the total shaft length is only 300mm, the influence of shaft deflection was assumed to be negligible.
All top and bottom shafts are driven by a centralised motor and a set of sprockets and chains. The inter-station distance is fixed at 305mm (Figure 3.10). It is possible to obtain different line speeds in the machine by changing the rotational speed of the centralised motor. However a constant line speed of $7.7 \text{mms}^{-1}$ was used in all experiments without lubrication. There are three forming stations and a feeder to feed the material into the first forming station as shown in Figure 3.10. Schematic drawings of the top and bottom rolls used in the three forming stations are shown in Appendix A.

The tooling was designed according to the “constant arc length” forming method. In the constant arc length method the length of the neutral line in the bend section remains constant throughout all forming passes, while the bend radius decreases gradually (Figure 3.11).
CHAPTER THREE

Figure 3.11 Constant arc length roll forming [74]

Strips of 2000 mm length 75 mm width and 2 mm thickness were cut from a bigger coil having the same width and thickness. After that they were sent through an electric roller leveller to reduce residual stresses and improve strip flatness.

A bending progression with a constant forming angle increment of 10° was chosen and the corresponding flower pattern is given in Figure 3.12. The cross-sectional dimensions of the profile at each forming station are given in Figure 3.13.

Figure 3.12: Flower pattern for the 0-10°-10°-10° forming sequence

Figure 3.13: Cross-sectional dimensions of the strip at each roll station

Longitudinal edge strain was measured in the strip edge facing the machine (Figure 3.9) given that the V-section is axis symmetric and the author believe that the side where the strain gauge is glued will not affect the strain pattern.

3.2.4 Laboratory roll former for trapezoidal section roll forming

A specially designed laboratory roll former was applied to investigate the effect of different parameters on roll load, torque and product defects (Figure 3.14). Ultimately
a new roll forming stand designed for the compensation of longitudinal bow based on
the measured roll load and torque, will be introduced. Therefore this machine is
equipped with roll load and torque measuring equipment.

There are five roll stands in the machine and each bottom shaft is separately driven by
five identical AC motors. Each motor consists of variable speed drivers, so that they
can be driven with different speeds. However, a minimum line speed in all stations
\(17.3 \text{ mms}^{-1}\) was used to maximise the data collecting frequency in the measurement
of longitudinal edge strain, roll load and torque. Further only two stations were used
in the experiments.

![Figure 3.14: Schematic of a roll stand in laboratory roll former](image1)

Interconnecting spacers were applied as shown in Figure 3.15, which increases the
stiffness of the shafts by enhancing the effective shaft diameter. The blank shaft
diameter is 45mm but the effective shaft diameter becomes 101.6mm with the spacers.

![Figure 3.15: Method of increasing the stiffness of the shafts with interconnecting
spacers](image2)

Further it is possible to change the station distance by sliding the base plate on the
railings attached to the base frame as shown in Figure 3.16(a). The frame has holes
and adjustable bolts to locate the base plate at the required position according to the selected station distance. Further the vertical position of the bottom shaft can be varied by adjustable bolts placed underneath the bottom shafts (Figure 3.16(a)), however all the bottom shafts were fixed at the same pass height in all experiments.

The roll forming trials were performed under unlubricated conditions and the roll gap was set to be the same as the material thickness with feeler gauges. In the station where the roll load and torque measurements were performed a roll gap slightly higher than the material thickness was used.

The tooling was designed according to the “constant radius” forming method with a formed profile radius of 4.8mm. In the constant radius method, the segments of the arc element is bent into the final radius in each forming step and keeping the bending radius a constant. Thereby the arc length is increased gradually (Figure 3.17). Strips which were 1000mm in length and with various cross sectional widths were roll formed. Only two stations were used in the experiments where the first station feeds the material with flat top and bottom rollers and the second station bends the material into shape to either 20 or 30 degrees.
3.2.5 Measurement of roll load and torque

Roll load was measured applying a BCM Model 1311 shear web compression load cell connected between the bearing housing of the top roll shaft and the arch of the frame as shown in Figure 3.18(a). The load applied on the top shaft is measured by the load cell as a compressive load and needs to be doubled to receive the total upwards force. The weight of the top shaft is added to the total upward force to get the exact forming load as the weight of the shaft acts against the forming load as shown in Figure 3.18(b). The measuring range of the load cell was 0-25kN and the accuracy was 0.02% to the full scale.

In contrast to the conventional forming station in the roll stand where load was measured the roll gap was set to be 0.1mm higher than the material thickness to avoid excessive loads applied on the top shaft [68] due to variations in thickness of the
incoming material. The same ALMEMO 2590-4S universal data logger that as used for the data recording with the strain gauges was applied to record roll load and torque.

Roll torque was measured using a LORENZ DR-2 slipring type rotational torque transducer that was attached between the bottom roll shaft and the AC motor shaft through a set of shaft to shaft jaw couplings as shown in Figure 3.19. Roll load and torque were recorded in the same forming station. The torque transducer has a measuring range of 0-500Nm with an accuracy of 0.1%. The measured torque value represents the total torque applied to the bottom shaft while roll forming.

![Figure 3.19: Schematic of the torque measuring system](image)

The roll stand with the roll load and torque measuring equipment is shown in Figure 3.20.

![Figure 3.20: Station with the load and torque measuring system](image)

A typical roll torque output is shown in Figure 3.21(a). To reduce the scatter, a five point moving average was calculated as shown Figure 3.21(b) and the average of the uniform region defined as the value for torque. The same procedure was also followed to determine roll load.
3.2.6 Measurement of bow

A new technique was introduced by the author to measure the longitudinal bow of the final roll formed parts. For this the outer surface of the roll formed part was scanned using an “ExaScan” 3D scanner [75] as shown in Figure 3.22. Black and white circular stickers, called targets, were pasted on the outer surface of the roll formed part and the background allowing the 3D scanner to identify the exact surface topology. Then the scanner was moved along the part (Figure 3.22(a)) until it captured the whole outer surface as shown in Figure 3.22(b). The resolution of the scanned surface was 0.05mm giving an accuracy of 0.04mm.

The scanned surface was then aligned with the ideal roll formed surface generated by SolidWorks [76] as shown in Figure 3.23(a) using the software package “Geomagic” [77]. The longitudinal cross section through the symmetric centre of the part was considered to evaluate bow (Figure 3.23(b)).
Figure 3.23(a). Alignment of parts (b). Cross section through the centre

The longitudinal bow is defined as the vertical height deviation of the scanned part along that cross section as shown in Figure 3.24.

Figure 3.24: Definition of Longitudinal bow

3.2.7 Springback measurement

For measuring springback after roll forming in this study it is assumed that the ideal part has a final bending angle that corresponds to the profile of the bottom roll in the last forming station. Therefore springback can be considered as the angle difference between the roll formed part ($\theta$) and the final forming roll angle ($\theta'$) as shown in Figure 3.25. This difference needs to be multiplied by two to find the complete springback angle due to symmetry. Springback of the roll formed parts was measured manually by a protractor as shown in Figure 3.26.

![Figure 3.25: Springback definition](image)

Springback = $2(\theta - \theta')$

Figure 3.25: Springback definition
CHAPTER THREE

Figure 3.26: Springback measuring equipment

Then the difference between the measured angle and the final forming angle was taken as the springback of one side. Six readings were taken from both sides at three different locations of the roll formed part 300 mm away from the front and the back ends to exclude end flare effects (Figure 3.27) and then averaged.

Figure 3.27: Location of the springback measurements in the roll formed part

3.3 The numerical model

In previous numerical roll forming studies the forming rolls were considered as rigid and stationery bodies and deformations in the frame, the shafts, and the bearings were not taken into account [12, 20, 41, 78]. This led to the overestimation of roll load and torque [79]. The numerical model applied in this study accounts for the deflection of the shafts and frame components to enable the accurate analysis of roll load and torque, similar to the approach employed by Groche et al. [80].

The commercial software package Copra RF/FEA [18] was applied for the process design and the numerical analysis. Copra FEA is based on MSC Marc and uses an implicit solver.
3.3.1 Meshing

Two main element types have been used in roll forming simulations in the literature. They are solid [22, 81-87] and shell [26, 38, 88-92] elements. It has been found that solid elements can more accurately predict the roll load compared to shell elements [93], and the accuracy can be further improved by using a higher number of elements through the material thickness [20]; however, this drastically increases computational time. Therefore, the strip was modelled by fully integration, hexahedral, type 7 arbitrarily distorted brick elements available in the MSC MARC software element library [94] and only one element through the thickness was applied to save the computational time. Each element consists of 8 integration points as shown in Figure 3.28. Since the basic form of these elements shows poor performance in bending and shear, the element formulation has been advanced by an alternative interpolation function [94].

![Integration points in the type 7 element](image)

The stiffness of the roll stand and shafts was taken into account to improve the model accuracy [95] which will be discussed later in this chapter. Only half of the strip was modelled due to the symmetry of the trapezoidal section and a finer mesh was applied in the bending region where deformation was the highest (Figure 3.29). Similar to the actual roll forming process the forming of precut sheet of 1m length was modeled.
3.3.2 Material model

Material input for the numerical model was taken from the true stress-strain data obtained from the standard tensile test as explained in Section 3.2.1. The elastic behaviour of the material was represented by the Hooke’s stress-strain relationship given by Equation (3.4). The Young’s modulus was taken as 200GPa for DP780 and the Poisson’s ratio was taken as 0.3 [96].

Isotropic material behaviour was assumed [19, 41, 79] and the von Mises yield criteria applied to define plastic material behaviour. Additionally, the tested materials as explained in Section 3.2.1, supported this assumption and the corresponding material parameters will be presented later in this thesis. For the verification of the numerical model with experimental roll forming results true stress-effective plastic strain data obtained for the DP780 material and fitted by the Hollomon’s power equation was used.

3.3.3 Contact and boundary conditions

A Coulomb friction model was adopted and the coefficient of friction between the strip and the rolls was assumed to be 0.1 [12]. The forming rolls and the feeder were modelled as rigid bodies while the strip was defined as a deformable body (Figure 3.30). The friction between the feeder and the strip was considered to be zero. The roll dimensions correspond to those given in Appendix A.
In the model the rolls are fixed in space while the strip moves forward through the stations due to frictional force. Three boundary conditions were introduced as shown in Figure 3.31.

The X-lock boundary condition is applied to all nodes along the symmetric line of the part and restricts the material movement in X direction due to symmetry. The Y-lock is applied to the last three bottom nodes along the symmetric line and keeps symmetric centre at the same vertical position throughout the forming process. The Z-entry is applied to the first six top and bottom nodes from the symmetric corner and introduces a displacement in Z direction until the strip enters the first roll gap. After that, since the top and bottom rollers are rotating clockwise and counter clockwise respectively, the strip moves forward due to the friction between rolls and the strip. The rotational speed of the bottom roll was set to be 3.25rpm giving a line speed of $17.3 \text{mms}^{-1}$ as in the experiments.
3.3.4 Roll stand design

In this study the stiffness of the main components of the roll forming station was taken into account. In previous numerical studies those components were considered to be fixed rigid bodies [19, 20, 64, 78] which has led to an overestimation of the roll load [20, 95]. To minimise this the deformation in the roll stand as a result of the roll load needs to be accounted for. To achieve this, first the loading behaviour of the main roll stand components was investigated. This identified the top shaft, the bottom shaft and frame components as the main components that influence roll stand rigidity. To determine their particular stiffness properties those three components were analysed separately. The resultant stiffness that was introduced into the simulation model represents the summed up stiffness values of the top and bottom shafts and the frame components.

*Top and bottom shafts*

For the stiffness analysis of the top and bottom shafts, half of the shaft was considered as in the numerical analysis only half of the strip is modelled due to part symmetry (Figure 3.32(a)). The shafts were considered as cantilever beams (Figure 3.32(b)) since it is the best approximation of a shaft which undergoes a point load at one end and the other end is fixed. If the other closest approximation is considered where the both sides are horizontally fixed and one side moves vertically, then it may significantly deviate from the reality since both sides are free to move horizontally in the actual system. It was assumed that the shafts have a uniform cross section with an effective diameter 101.6mm (with spacers) and that a point load is applied at the free end of the shaft due to the vertical forming force.

![Figure 3.32: (a) Load acting on the shafts (b) Free body diagram of the top shaft](image)

Figure 3.32: (a) Load acting on the shafts (b) Free body diagram of the top shaft
The deflection, \( \delta \), of a cantilever beam that is fixed at one end and loaded with a pointed load at the other is given by Equation (3.8) [97].

\[
\delta = \frac{FL^3}{3EI}
\]  

(3.8)

Where \( F \) is the roll load, \( L \) is the shaft length and \( E \) is the Young’s modulus of the material, which is given as 210 GPa. \( I \) is the moment of inertia of the circular cross section of radius \( r \) given by the relation below.

\[
I = \frac{\pi r^4}{4}
\]

The stiffness, \( k_1 \), of the shaft is therefore

\[
k_1 = \frac{F}{\delta} = \frac{3EI}{L^3}
\]  

(3.9)

\[
k_1 = \frac{3 \times 210000 \times \left(\frac{\pi \times 50.8^4}{4}\right)}{340^3}
\]

\[
k_1 = 83839 \text{ N/mm}
\]

**Frame components**

The Frame consists of two columns, one arch, two frame connecting bolts and one adjustment bolt as shown in Figure 3.33. While the columns and the frame can be assumed to be either under tensile or compressive load the arch is considered as a fixed body supported at two ends and loaded at the centre.

Figure 3.33: Frame components considered for the stiffness calculation
The formulas used to determine the stiffness are given in Table 3.1 together with the corresponding dimensions and the stiffness values.

Table 3.1: Stiffness of the frame components and their dimensions

<table>
<thead>
<tr>
<th>Component</th>
<th>Dimensions</th>
<th>Stiffness formula</th>
<th>Stiffness(N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column ((k_2))</td>
<td>40mm×40mm×400mm</td>
<td>(k = \frac{AE}{L})</td>
<td>(k_2 = 840000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where (A =) cross-sectional area, (E =) Young’s modulus, (L =) Length, (R =) Radius</td>
<td>(k_3 = 359189)</td>
</tr>
<tr>
<td>Connecting bolts ((k_3))</td>
<td>(R = 7)mm, (L = 90)mm</td>
<td></td>
<td>(k_4 = 431026)</td>
</tr>
<tr>
<td>Adjusting bolts ((k_4))</td>
<td>(R = 7)mm, (L = 150)mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arch ((k_5))</td>
<td>40mm×50mm×240mm</td>
<td>(k = \frac{48EI}{L^3})</td>
<td>(k_5 = 303819)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where (I) is the moment of inertia</td>
<td></td>
</tr>
</tbody>
</table>

The overall stiffness of the frame including the rolls can then be calculated as follows;

\[
k_{total} = \left( \frac{2}{k_1} + \frac{1}{2k_2} + \frac{1}{2k_3} + \frac{1}{k_4} + \frac{1}{k_5} \right)^{-1}
\]  \(3.10\)

\(k_{total} = 31792\) \(N/mm\)

To introduce the stiffness obtained from Equation (3.10) in the finite element model, a spring connection was introduced between the centre (control node) of the top shaft and a second node positioned vertically above the centre node as shown in Figure 3.34. The stiffness of the spring was taken as the stiffness determined above for the whole frame \((k_{total})\) which was \(31792\) \(N/mm\). The spring allows the top roll to move vertically to represent the deflection in the system as a result of the shafts and the frame components being deformed due to the roll load.

Figure 3.34: Introduction of the shaft deflection in the model
3.3.5 Measurement of roll load and torque

In the finite element model roll load and torque corresponding to the experimentally measured load and torque were obtained. Therefore the roll gap was set to be same as the material thickness in the 1st station, while it was adjusted to be 0.1mm higher than the material thickness in the 2nd station, which corresponds to the experimental set up in Section 3.2.5.

The vertical upward force measured on the top roll in the second station and the torsion on the bottom roll correspond to half of the roll load and torque in the system due to symmetry. In the finite element model, the vertical reaction force on the central node of the top roll was measured as the roll load and the torque applied on the bottom roll axis was measured as the roll torque. After that a five point moving average was calculated for both roll and torque measurements to reduce the data scatter and the average of the uniform region was calculated as the roll load and torque as explained in Section 3.2.5. Finally the average values were multiplied by two to get the complete roll load and torque for the whole system.

3.3.6 Measurement of longitudinal bow

Longitudinal bow was measured on the final roll formed parts in the simulation. For that the symmetric centre line of the strip was considered in the numerical model. The vertical displacement of the bottom nodes along the symmetric centre was considered as the bow height variation corresponding to experimental bow height given in Section 3.2.6.
CHAPTER FOUR

4 Geometric model of the roll forming process

4.1 Introduction

In roll forming, material is formed incrementally to the final shape as shown in Figure 4.1; this is unlike other traditional sheet forming process such as stamping or brake forming where the forming is achieved in a single action. Material deformation during the roll forming process is complicated and not well understood as explained in Chapter 2. A number of defects such as twisting, bowing, and wrinkling in the final product may appear if the process is not carried out under controlled conditions and the proper product and process design methodology is not followed. The design of the rolls to form a particular profile is often based on experience and intuition, but in recent years Computer-Aided Design (CAD) and Finite Element Analysis (FEA) systems have become available [17, 21, 24, 86, 98, 99]. Detailed analysis is difficult and time-consuming because, although the strains are small, displacements are large. Amongst other factors, understanding the forming path and the strain pattern at the edge of the flange during the process is important in process design. There are some studies [30, 31, 36, 54] that focus on the conditions in the deformation length which is the region between successive rolls where deformation occurs as explained in Chapter 2. However the forming behaviour at the deformation length alone may not be sufficient to decide the quality of a given forming sequence. This emphasises the need of a methodology to determine the overall performance of a given forming sequence which will be addressed in this chapter.
Some analytical models in the literature discuss the strain variation at the deformation length in roll forming. Fong [31] developed two models to determine the longitudinal mid-surface strain in the flange, based on Bhattacharyya’s [30] study on deformation length. In his first model (Ref. 1 in Table 4.1), the longitudinal strain varied along the deformation length and the peak longitudinal strain was 3 times larger than the experimental values; his second model (Ref. 2 in Table 4.1) proposed a constant longitudinal strain within the deformation length, and this was slightly lower than the experimental peak longitudinal strain. Panton et al. [27] derived equations for the mid-surface and bending strains (Ref. 3 in Table 4.1), in a small element in roll forming with a single active bend. Their equations need to be applied separately to each bend and the overall strain distribution of the whole process cannot be readily obtained. Lindgren [40] introduced an equation to predict the peak longitudinal edge strain (Ref. 4 in Table 4.1) using a finite element model in combination with a statistical technique; but the model does not allow for analysing material behaviour during the forming process.

Figure 4.1: Cross-sectional change during brake forming and roll forming [48]
Table 4.1: Edge strain related equations

<table>
<thead>
<tr>
<th>Reference</th>
<th>Equation</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fong [31]</td>
<td>$e_m = \frac{9}{32} \frac{t^2}{a^6} r^2 z^2 \left[0 \leq r \leq a \atop 0 \leq z \leq L \right]$</td>
<td>$e_m$ - mid surface strain \n $r$ - flange length \n $z$ - deformation length \n $t$ - sheet thickness</td>
</tr>
<tr>
<td>2 Fong [31]</td>
<td>$e_m = \sqrt{1 + \frac{3t}{4a\Delta \theta} (1 - \cos \Delta \theta) - 1}$</td>
<td>$e_m$ - mid surface strain \n $a$ - flange length \n $t$ - sheet thickness \n $\Delta \theta$ - forming angle</td>
</tr>
<tr>
<td>3 Panton et al. [27]</td>
<td>$e_m = \frac{1}{2} r^2 \left( \frac{d\theta}{dz} \right)^2$ \n $e_b = h \left( - p \left( \frac{d\theta}{dz} \right)^2 + s \left( \frac{d^2 \theta}{dz^2} \right) \right)$</td>
<td>$e_m$ - mid surface strain \n $e_b$ - bending strain \n $r$ - flange length \n $p, \theta, s$ - refer Figure 4.2 and Figure 4.3</td>
</tr>
<tr>
<td>4 Lindgren [40]</td>
<td>$e_p = 0.67 \sqrt[0.085]{\frac{\Delta \theta^{1.9}}{a^{0.28} S^{0.28} R^{0.15}}}$</td>
<td>$e_p$ - peak strain \n $a$ - flange length \n $t$ - sheet thickness \n $\Delta \theta$ - forming angle \n $R$ - effective roll radius</td>
</tr>
</tbody>
</table>

Where $R = a \times \tan \Delta \theta + \frac{r}{\cos \Delta \theta}$

Figure 4.2: Small element isolated from the roll forming process with a single active bend [27]
As mentioned, the above studies mainly focused on material deformation over the deformation length. To understand the overall performance of a given forming sequence, these equations need to be applied separately to each station, even though the optimum forming sequence is still not known. In addition to that some process parameters such as inter-station distance that was found to be a significant parameter with regard to the peak longitudinal strain, as explained in Chapter 2, are not taken into account. Therefore this chapter will introduce a new concept to determine the strain variation along the forming path of a point in the strip during the roll forming process. This will enhance the understanding of material deformation during the whole process of roll forming. Further it can be used as a basic guideline to determine the most suitable flower pattern to roll form any given cross-sectional profile.

4.2 Methodology

The roll forming of a simple V-section is considered using a similar approach to the work referenced above by Panton et al. [27]. This chapter will introduce a new diagram obtained from the flower pattern diagram to transform and display the trajectory of a point on the strip. The instantaneous trajectory of a point on a roll formed strip as specified by the flower pattern diagram can easily be determined by standard CAD systems. This is a space curve and the problem is that it is difficult to visualise how the shape of this three-dimensional curve is related to deformation in the process. In this chapter a method is proposed to transform this space curve into a two-dimensional, or plane curve that retains important features of the process, specifically the instantaneous mid-surface strain and the bending strain. If both mid-surface and bending strains are known, then the top and bottom surface strains can be calculated.
In this way, the forming path and the strain variation during the roll forming process for any given flower pattern can be calculated and the suitable flower pattern can be obtained based on the calculated strain values.

After calculating the theoretical strains on the top and bottom surface of the sheet, the experimental strains are measured using electrical resistance strain gauges applied to either side of the sheet at a chosen point. These experimental strain measurements are used to obtain an improved determination of the trajectory. This provides insight into the local deformation of the strip in the small region near the point of contact with each roll.

4.3 Expansion of the flower pattern diagram

Traditionally, the design of rolls has been based on the so-called “flower pattern diagram”. In this diagram, as explained in Chapter 2, the cross-section of the strip as it passed through the centreline of each roll stand is superimposed on a single plane [1]. It is a two-dimensional representation of the three-dimensional process. The diagram has been used for many years by process designers to assist in the intuitive selection of rolls to achieve the required shape.

In this chapter the roll forming of a simple V-channel shown in Figure 4.4(a) is considered. The part is formed in three stations and the flower pattern diagram is shown in Figure 4.4(b).

![Figure 4.4: (a) Roll formed channel. (b) Flower pattern diagram of the V-channel section](image)

As the section is symmetric, it is sufficient to analyse the forming of one flange only and half of the flower pattern diagram and the machine layout are shown in Figure 4.5.
Figure 4.5: (a) Flower pattern diagram for the initial stages of forming of the flange. (b) Roll forming arrangement

The diagram in Figure 4.5(a) shows the mid-surface of the strip with a sharp crease or zero radius bend at the centre. The flange is assumed to rotate at a uniform rate without a change in width, i.e., $h$, remains constant, so that the edge points of the flower pattern lie on a circular arc, ABCD, as shown. In Figure 4.6(a) the flower pattern diagram is extended to three dimensions by creating the surface on where these points lie. This is clearly part of a cylindrical surface of radius, $h$, having its axis along the centreline of the strip. In this diagram, the scale along the $z$ axis has been dramatically reduced so that the diagram is fore-shortened in this direction. This has been done to illustrate the curvature of the sheet and of the trajectory or forming path, AD, of the edge as shown in Figure 4.6(b).
Figure 4.6 illustrates the three major deformation modes in roll forming. The first is plastic bending at the centreline of the strip; this is not addressed in this chapter. The second is the longitudinal extension of the strip along the forming path as clearly the length of the curve at the edge of the flange is greater than the original length of the edge. The third is the curving of the flange. Both of the latter are redundant deformations; after forming, the length of the edge will be the same as that of the centreline which is assumed not to extend; also the flange is flat both at the entry and the exit of the machine so the curvature must be reversed at the exit.

As indicated, the trajectory will lie on a cylindrical surface. Such a surface is a developable that can be transformed or flattened into its plane development [100]. It is a property of this transformation that the length of a surface curve is not changed and also that the angles between intersecting curves are preserved. The plane development is a two-dimensional curve which can be used to examine the trajectory. For the case considered in which the rate of rotation of the flange is constant, the trajectory is a straight line in the plane development as shown in Figure 4.7. In the three dimensional diagram in Figure 4.6, the trajectory is a regular helix.
4.3.1 3. Axial strain along the trajectory or forming path

Figure 4.8(a) shows a small increment in the process where the edge moves from $p$ to $p'$; the point will move longitudinally by $dz$, and around the circular arc by a distance $dg$, where,

$$dg = h \, d\theta$$  \hspace{1cm} (4.1)

Transforming this displacement on the cylindrical surface to the plane development, we obtain the diagram in Figure 4.8(b). Assuming that the longitudinal strain at the axis is zero, the original length of the line element, $dz$, has become, $ds$, in the trajectory, where, $ds$, is,
\[ ds = \sqrt{(h \, d\theta)^2 + dz^2} \]  

(4.2)

The longitudinal strain (along the trajectory) at the mid-surface is,

\[ \varepsilon_m = \ln \frac{ds}{dz} = \ln \sqrt{(h \, d\theta)^2 + dz^2} \]

\[ \varepsilon_m = \ln \left[ \left( \frac{h \, d\theta}{dz} \right)^2 + 1 \right]^{1/2} \]  

(4.3)

Given that the diagram is much foreshortened in the, \( z \), direction and \( h \, \frac{d\theta}{dz} \ll 1 \), the above relation may be approximated by the Taylor series expansion as,

\[ \varepsilon_m \approx \frac{1}{2} \left( \frac{h \, d\theta}{dz} \right)^2 \]  

(4.4)

where the subscript, \( m \), indicates that this is the strain at the mid-surface. The relation in Equation (4.4) is identical with that obtained by a slightly different approach by Panton et al. [4]. In Figure 4.8(b) the angle the trajectory makes with the axis, \( \beta \), is also very small. From the diagram,

\[ \tan \beta = \frac{h \, d\theta}{dz} \approx \beta \]  

(4.5)

And therefore the mid-surface longitudinal strain may be written as,

\[ \varepsilon_m \approx \frac{1}{2} \beta^2 \]  

(4.6)

Equation (4.6) is useful in that it gives an immediate connection between the slope of the trajectory in the plane development and the longitudinal mid-surface strain.

**4.3.2 Curvature of the flange along the forming path**

In the transformation from a developable surface to its plane development, lengths and angles are preserved, but curvature is not. To determine the curvature of the sheet near the edge, the geometric properties of the forming path need to be examined. As shown in Figure 4.7, for the case chosen, the trajectory of the edge in the plane development is straight, while the actual trajectory is a space curve, i.e. a regular helix. The flange is also curved.
One method of describing a space curve is by applying a moving trihedral as shown in Figure 4.9 where $t$, $n$ and $b$ are the tangent, normal and bi-normal unit vectors of the curve respectively. Each vector has a curvature and a torsion, or twist described by the Frenet Serret relations [101];

$$\frac{dt}{ds} = -\kappa n; \quad \frac{dn}{ds} = -\kappa t + \tau b \quad \text{and} \quad \frac{db}{ds} = -m$$

where, $\kappa$, is the curvature and, $\tau$, is the twist of the vector.

![Figure 4.9. Forming path as a space curve](image)

The curvature of the sheet, $\frac{1}{\rho}$, for the case in which the flange remains straight and rotates about the, $z$, axis is given by the curvature of the bi-normal, i.e.

$$\frac{1}{\rho} = \frac{dB}{ds} = -m$$  \hspace{1cm} (4.7)

where $\tau$ is the twist of the normal. The properties of a helix are covered in standard texts, e.g. Ref. [101] and the torsion is,

$$\tau = \frac{1}{h^2 + \left(\frac{1}{d\theta/dz}\right)^2}$$  \hspace{1cm} (4.8)

In this case, $\frac{1}{d\theta/dz} \gg h$ and the above can be approximated as,

$$\frac{1}{\rho} = -\frac{d\theta}{dz}$$  \hspace{1cm} (4.9)

In the example chosen, the rate of rotation of the flange is constant and hence the curvature is uniform in the flange. For the general case, it may be seen from Figure 4.8 and Equation (4.5) that,

$$\beta \cdot dz \approx h \cdot d\theta$$  \hspace{1cm} (4.10)
hence, as given above,
\[
\frac{d\theta}{dz} \approx \frac{\beta}{h}
\]  
(4.11)

Equation (4.9) can therefore be rewritten as,
\[
\frac{1}{\rho} = -\frac{\beta}{h}
\]  
(4.12)

Again, this is a useful relation as it shows that the curvature of the flange is simply related to the slope of the forming path in the plane development. The analysis contains several approximations and is restricted to the case where a line in the flange perpendicular to the centreline rotates about the axis and remains straight. As indicated, Equation (4.12) is valid for the case of constant rate of bending; it also indicates the local curvature near the edge can vary when the rate of bending varies. Therefore \( \beta \) may not be constant and it can be represented as,
\[
\beta = f(z)
\]  
(4.13)

4.3.3 Surface strains in the strip

As indicated Hu et al. [65], the bending strain is given by Equation (4.14). The strains on the top and bottom surfaces of the strip are composed of the mid-surface longitudinal strain, given by Equation (4.6) and the bending strains derived from the curvature, Equation (4.14). The combined effect of mid surface strain and the bending strain give the surface strains as shown in Figure 4.10.
\[
\varepsilon_b = \pm \frac{t}{2\rho} = \pm \frac{t \cdot \beta}{2h}
\]  
(4.14)

![Figure 4.10: Variation of strain through the depth of the sheet at the edge of the flange for combined axial extension and bending.](image)
For the case shown in Figure 4.6 where the upper surface is concave upwards, the bending strain is compressive and the total strain is,

$$\varepsilon_{upper} = \varepsilon_m - \varepsilon_b = \frac{1}{2}\beta^2 - \frac{t.\beta}{2h}$$  \hspace{1cm} (4.15)

For the lower surface, the total strain is,

$$\varepsilon_{lower} = \varepsilon_m + \varepsilon_b = \frac{1}{2}\beta^2 + \frac{t.\beta}{2h}$$  \hspace{1cm} (4.16)

4.4 Analytical examples

In this section, the strain distribution will be calculated for different flower patterns. It will give an insight into the applicability of this new technique of edge strain prediction in industrial practice. Following the usual view of the flower pattern diagram approach, the trajectory will be taken as a step-wise linear path between each stage; this will indicate how the effect of changes in the angle increment between each stage can be determined and how an improved flower design for a given profile can be obtained.

4.4.1 Constant angle increment forming

From the above, the theoretical strains for the example shown in Figure 4.4 and Figure 4.5 can be calculated. The input data is given in Table 4.2. This information pertains to the V-profile roll forming process described in Section 3.2.3 and the actual results will be presented later in this chapter.

Table 4.2: Numerical data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip thickness</td>
<td>( t )</td>
<td>2mm</td>
</tr>
<tr>
<td>Inter-stand length</td>
<td>( \ell )</td>
<td>305mm</td>
</tr>
<tr>
<td>Flange length</td>
<td>( h )</td>
<td>31.5mm</td>
</tr>
<tr>
<td>Bend angle increment</td>
<td>( \Delta\theta )</td>
<td>( 10^0 )</td>
</tr>
</tbody>
</table>

The flange length in this example is not taken as half of the strip width as there is a finite forming radius along the centreline and the given value corresponds to the effective straight line length of the flange in the flower pattern.

Assuming that the distance between the forming stands, \( \ell \), and the bending increment, \( \Delta\theta \), are both constant, the rate of bending is,
The mid-surface longitudinal strain and the strains on the upper and lower surfaces can be calculated from Equation (4.6), (4.15) and (4.16) respectively.

\[
\frac{d\theta}{dz} \approx \frac{\beta}{h} = \frac{\pi \times 10/180}{305} = 5.72 \times 10^{-4} \text{rad/mm}
\]

\[\varepsilon_m = 162 \text{ microstrain}\]
\[\varepsilon_{upper} = -410 \text{ microstrain}\]
\[\varepsilon_{lower} = 734 \text{ microstrain}\]

These are illustrated in Figure 4.11. The slope of the of the trajectory is, \(\beta = 0.018 \text{ rad.} = 1.03^\circ\). The radius of curvature of the flange at the edge is, from Equation (4.12), \(\rho = 1.75 \text{ m concave upwards}\).

Figure 4.11: Theoretical surface strains calculated from the simple model above for the process described in Table 4.2

4.4.2 Forming path for a tube forming process.

To apply this new concept to another roll forming set up, the tube roll forming process will be considered in this section. For that, a flower pattern available in the literature was used and approximate dimensions not given in the reference were assumed. The diameter of the tube was taken as 80mm and the station distance was selected as 400mm. Only half of the tube was considered due to symmetry (Figure 4.12). The total distance moved by the edge (\(u\)) was manually calculated according to the dimension of the flower pattern.
Figure 4.12: Flower pattern diagram for tube roll forming [102]

Figure 4.13 indicates the plane development corresponding to the flower pattern shown in Figure 4.12.

The trajectory of the edge shown in Figure 4.13 can be either fitted by a linear or a quadratic equation. The quadratic equation was found to lead to a more precise fit and the coefficient of determination ($R^2$) confirms it. The derived equation is given by Equation (4.17).

$$u = -3 \times 10^{-6}z^2 + 0.0732z$$  \hspace{1cm} (4.17)

The slope of the trajectory is given by:

$$\beta = \frac{du}{dz} = -6 \times 10^{-6}z + 0.0732$$  \hspace{1cm} (4.18)
From the above, the mid-surface strain can be calculated using Equation (4.6) which is shown in the Figure 4.14. This shows that the longitudinal strain is greatest at the start and diminishes towards the end of the process. It should be noted that the flower pattern diagram from Ref. [102] was probably developed on the basis of extensive experience and experimentation and is likely to represent the optimum forming sequence for this part; this is confirmed by the forming path given in Figure 4.13 as it is almost linear which leads to the minimum amount of longitudinal stretching in the edge; it is also clear that experience has led to a process in which the axial strain is greatest in the early stages and falls by about 40% as forming progresses.

![Figure 4.14: Mid-surface axial strain calculated from the forming path in Figure 4.13](image)

4.4.3 Comparison of three forming sequences

To further understand the developed concept of forming path, three forming sequences are analysed in this section with reference to the work carried out by Abeyrathna et al. [32]. The corresponding flower patterns are given in Figure 4.15 and the other process and geometric parameters are the same as the given in Table 4.2; this excludes the forming sequence. For convenience, the flower patterns shown by Figure 4.15(a), (b) and (c) will be considered as Type 1, Type 2 and Type 3 respectively.
Type 1 has a lower bend angle increment in the final stage of forming, while Type 2 has a higher angle increment. Type 3 shows equal angle increment throughout the process. The corresponding diagram of the forming paths of those three flower patterns are shown in Figure 4.16. It can be seen that the Type 3 flower pattern indicates the shortest distance between the starting point and the finishing point, whereas Type 1 and Type 2 have the same forming path until the 2nd station and then deviate from each other onwards.

Figure 4.16: Distance travelled by the edge for three flower patterns

Figure 4.17 shows the corresponding mid surface strain obtained with Equation (4.6). Here only the mid surface strain is considered for simplicity.
A constant strain variation can be observed for the Type 3 flower pattern as it has a straight forming path. In contrast to that Type 1 and 2 show a very uneven strain variation during forming. Type 1 shows the same strain level as Type 2 and 3 at the beginning of forming and reaches a maximum followed by a lower strain level compared to Type 3 at the end of the process. Type 2 starts with the same strain level as Types 1 and 3 reaches a maximum, which is followed by a minimum in strain level. At the end of the process the Type 2 forming sequence shows a higher strain level compared to Types 1 and 3. Figure 4.17 illustrates that even though the changes in the plane development (Figure 4.16) seem minor, the longitudinal strain levels are very different. The trends given by the basic model were very similar to the peak strain variation obtained by Abeyrathna et al. [32] even though small in magnitude. In addition to that, based on the plane development given in Figure 4.16 the Type 3 forming sequence indicates the least distance between the start and the end resulting in the lowest stretching in the flange edge compared to the other forming sequences. Therefore Type 3 can be considered as the optimum forming sequence for this operation.

The objective of the work in [32] was to analyse bow and springback associated with different forming angle increments. Because it has been identified that the forming sequence at the last stations were significant than that of the first stations with regard to the bow reduction [52]. As far as the longitudinal bow is concerned Abeyrathna et al. [32] observed the lowest bow in the Type 3 forming sequence which agrees with basic model as it gives the lowest stretching in the flange.
4.5 Experimental results

The previous sections have provided a theoretical framework to consider the strains in the roll forming process for a given flower pattern. The next step is to verify these results with experimental data; this will be done in this section. The flower pattern and the forming conditions for roll forming the V-channel considered here are given in Figure 4.5(a) and Table 4.3. In addition, the experimental procedure has been explained in Section 3.2.3.

Table 4.3: Process and material parameters

<table>
<thead>
<tr>
<th>Forming sequence</th>
<th>0° - 10° - 10° - 10°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forming method</td>
<td>Constant arc length forming</td>
</tr>
<tr>
<td>Flange length, $h$</td>
<td>31.5 mm</td>
</tr>
<tr>
<td>Station distance, $\ell$</td>
<td>305 mm</td>
</tr>
<tr>
<td>Material</td>
<td>DP780</td>
</tr>
<tr>
<td>Sheet thickness, $t$</td>
<td>2 mm</td>
</tr>
<tr>
<td>Blank sheet dimensions</td>
<td>2000mm×75mm</td>
</tr>
<tr>
<td>Lubrication</td>
<td>No lubricants</td>
</tr>
</tbody>
</table>

Electrical resistance strain gauges were attached to the top and bottom surfaces midway along the length of the strip and 1.5 mm in from the edge. Longitudinal edge strain was measured during the process as explained in Section 3.2.2. The output strain variation is shown in Figure 4.18.

![Figure 4.18: Measured longitudinal edge strains at the top and bottom surface at the edge of the flange](image)

-0.008 Surface strain(m/m) -0.004 0 0.004 0.008
0 305 610 915 Length(mm)

- Upper surface - Lower surface - Upper surface-Model - Lower surface-Model
The strains calculated from above model are also shown together with the measured strain history in Figure 4.18. The experimental total strains are very small for a distance of about half the inter-station distance; following this, the strains increase rapidly; this suggests that the actual forming length in the process is, \( l_d \approx 150 \text{ mm} \), which is about half the inter-station distance of 305 mm. The peak value of strain can be seen just before the roll centre and it greatly exceeds the values calculated from the analytical Equations (4.11) and (4.12) due to the local deformation at the rolls which will be discussed later in this chapter. However it is important to note that the developed basic model does not calculate the peak longitudinal edge strain of the process. It only calculates the possible longitudinal edge strain represented by the two dimensional flower pattern without taking into account the local deformation at the rolls. The previous examples showed that it is sufficient to get a comparative idea with regard to the forming sequence.

4.5.1 Measured longitudinal and bending strains

The experimentally determined surface strain, \( \varepsilon_{upper} \), and, \( \varepsilon_{lower} \), in Figure 4.18 can be decomposed into a mean, or mid-surface strain, \( \varepsilon_m \), and bending strains, \( \varepsilon_b \), where,

\[
\varepsilon_m = \frac{1}{2} \{ \varepsilon_{upper} + \varepsilon_{lower} \} \quad \text{and} \quad \varepsilon_b = \varepsilon - \varepsilon_m
\]  

(4.19)

The values are shown in Figure 4.19 and Figure 4.20 together with the mid-surface and bending strains predicted by the simple model.

![Figure 4.19: Variation of the longitudinal mid-surface strain, or axial strain](image-url)
Figure 4.20: Variation of the longitudinal bending strain on the upper surface

The experimental mid-surface strain, $\varepsilon_m$, and bending strain, $\varepsilon_b$, in Figure 4.19 and Figure 4.20 are only significant as the strip passes over the rolls. The bending component of strain, $\varepsilon_b$, derived from the experimentally measured strains on the upper surface, and shown in Figure 4.20, is close to zero about mid-way between stations and then becomes negative or compressive indicating that the strip acquires a concave upwards curvature as it climbs towards contact with the roll; this corresponds with Zone 1 in Figure 4.21. Following this, the bending strain becomes positive indicating a concave downwards curvature as the element passes over the roll as shown in Zone 2 in Figure 4.21. This is followed by a smaller negative value indicating a concave upwards shape and this could be considered as a form of springback downstream of the roll in Zone 3 in Figure 4.21. This deformation behaviour of the flange obtained from the bending strain given in Figure 4.20 enhances the understanding of material flow in roll forming process and has not been explained before.
Figure 4.21: Three distinct zones of material flow over the rolls

To examine these strains more closely, we select the measured strains before and after the 2nd roll stage as shown in Figure 4.22. The limiting elastic strains (with 0.2% strain offset) are also indicated in this figure and the diagram suggests that the material becomes plastic on both surfaces near the point of contact with the rolls. For this particular example, it is probable that plasticity does not extend through the whole sheet thickness as shown in Figure 4.23, leading to elastic recovery of the material.

Figure 4.22: Measured strains on the top and bottom surfaces near the 2nd station
4.5.2 Experimentally determined curvature of the strip

The bending strain, $\varepsilon_b$, can be determined from the measured strains as indicated in Equation (4.19); from this the curvature of the strip can be calculated as,

$$\kappa = \frac{1}{\rho} = \frac{2\varepsilon_b}{t} \quad (4.20)$$

The curvature determined from the measured strain before and after the second roll stage is shown in Figure 4.24, together with the curvature calculated from the flower pattern diagram from Equation (4.9), which is constant. Negative curvature is concave upwards as shown in Figure 4.6(b).

These variations are influenced by the bottom roll diameter as explained by Ding et al. [104] and the peak strain can be reduced by increasing the bottom roll diameter. However there are some practical limitations in increasing the bottom roll diameter in the traditional roll forming process. In the experiments of this chapter, the radius of
curvature of the strip determined from the measured strains as it passes over the roll is approximately 175 mm (see Figure 4.25(a)); the radius of the lower roll at the point where the edge contacts is 81.75 mm (see Figure 4.25(b)).

![Diagram of curvature and roll radii](image)

Figure 4.25: (a) Radius of the flange edge (b) Radius of the bottom roll at the 2nd station

Even though the radius of the tool at the flange edge is 81.75mm concave downwards, it is apparent that the radius of curvature of the strip near the roll stand determined from the strain measurements is 175mm concave downwards. This indicates that the strip does not completely wrap around the tool when it passes the roll centre (see Figure 4.25(a)). In addition to that these values are very different from the calculated radius of curvature from the simple model in Section 4.4.1 which is 1.75m concave upwards. This suggests that the actual forming path of the strip near the point of contact with a roll will influence the helical trajectory obtained from the flower pattern diagram (rather than assuming the path is constant through the roll). This problem will be addressed in the next section.

### 4.6 Modification of the forming path

This section will suggest a method of determining a trajectory in which a curvature closer to that shown in Figure 4.24 is obtained. The curvature of the flange near the edge calculated from the flower pattern diagram above was concave upwards with a uniform value of \(-0.00057 \, mm^{-1}\); as shown in Figure 4.24. This corresponds with the helical forming path that transforms to a straight line in the plane projection. The experimental curvature measured from the bending strains, as shown in Figure 4.24, varies along the path and has a peak magnitude of \(+0.006 \, mm^{-1}\) near the point of contact with the roll. The curvature is concave downwards at this peak. The flange
movement according to the analytical model and the actual roll forming process is shown in Figure 4.26.

![Figure 4.26: Schematic of flange movement according to the (a) analytical model (b) actual roll forming process](image)

The experimentally determined curvature is an order of magnitude greater than that given by the simple model and opposite in direction. According to Figure 4.26, it is clear that the local deformation at the roll introduces opposite curvature with a higher magnitude compared to the basic model and this constitutes a significant deviation between the basic model and the actual forming process. The objective of this section is to find a method of modifying the helical trajectory from the simple model to one that has curvatures closer to those measured, i.e. to use the experimentally determined strains to obtain a better indication of the forming path. To do this, an algebraic function was chosen to represent the empirical forming path; this is described in Appendix B. The curvature is given by the second derivative of the proposed algebraic function of the forming path in Appendix B. The fitted curvature and the curvature deduced from the experimental strain measurements is shown in Figure 4.27. The accuracy of the fit is not high, but any additional improvement would involve greater complexity.
Figure 4.27: Curvature of the trajectory of the empirical derived curve compared with that calculated from strain measurements.

The modified trajectory plotted in the plane projection is shown in Figure 4.28. In this diagram, the path corresponding to the simple helical path is plotted as a straight line. The modified path is determined from the displacement in Equation (B 1) in Appendix B and fitted to the helical path as shown so that both coincide near the point of contact with the roll. The departure of the modified path from the plot of the helical path in Figure 4.28 is not large (2 mm), however the slope of the path as the point passes through the roll stand is very different from the slope, $\beta_0$, of the path determined from the simple, helical model above. The slope of the modified curve is given by the first derivative of the empirical function added to the slope of the helical curve in the plane development, i.e.

$$\beta \approx \tan \beta \approx \frac{df(x)}{dx} + \beta_0$$

(4.21)

This slope is illustrated in Figure 4.28.
Figure 4.28: Modified trajectory in the vicinity of the roll stand plotted in the plane projection

It has been shown that the longitudinal strain is a function of the slope of the forming path by Equation (4.5). The calculated mid-surface strain from the slope of the trajectory in Figure 4.28 and the experimentally obtained data for the 2nd station from Figure 4.19 are shown in Figure 4.29; the discrepancy is a reflection on the limited accuracy of the curve fitting process but indicates that the axial strain varies significantly in the immediate vicinity of the contact point with the roll.

Figure 4.29: Longitudinal strain in the vicinity of the 2nd roll stage calculated from the slope of the trajectory in Figure 4.28 and the experiment

This modification to the forming path helps to understand the behaviour of the strip at the rolls and gives a clear understanding of the deviation of the forming path from the
actual roll forming process from that derived from the simple model. Since this modification is derived from experimental results, it cannot be applied to a flower pattern during the process design stage. Despite the local deformation at the rolls, the basic model can be applied in the process design to obtain a comparative idea of the suitability of different forming sequences as shown in Section 4.4.3.

4.7 Summary

A new technique was introduced to evaluate the performance of the roll forming operation by analysing the simple flower pattern diagram. It estimates both mid-surface strain and the bending strain in the strip edge in terms of the information given by the flower pattern. According to this method the mid-surface strain in the flange edge of any cross sectional profile can be obtained by transferring the three dimensional forming path of the flange edge given by the flower pattern into a two dimensional plane development. The bending strain was determined by considering the curvature of the flange edge for the case in which a perpendicular section of the flange remains straight and rotates about the axis of forming. Both bending and mid-surface strains were found to be functions of the slope of the forming path in the plane development; therefore we can determine the flower pattern diagram if we know the plane development or the plane development if we know the flower pattern. Therefore this concept can be applied to optimise a given flower pattern. In addition to that the obtained relationships showed that the longitudinal edge strain depends on the material thickness, forming angle (forming sequence), flange length and the inter-station distance.

The obtained equations were applied to an example found in the literature and it was observed that the flower pattern with the least flange movement, proposed by the simple model shows the lowest longitudinal bow in the product. Therefore this technique may be applied as an initial tool to determine the optimum flower pattern in terms of longitudinal edge strain without utilising time-consuming finite element analysis.

The actual strain measurements indicated some sudden deviation of the trajectory near the rolls and consequently a major change in strain. This variation helped to understand that the actual deformation takes place at the rolls and three significant regions could
be identified where it deviated from the trajectory proposed by the analytical model. Since the simple analytical model does not take this into account, a Laplacian of Gaussian (LoG) curve was employed to describe the forming path at the rolls by fitting the curvature of the LoG curve given by its second derivative, with the curvature of the sheet that was experimentally obtained. Figure 4.30 illustrates the deviation of the new trajectory in the plane development after this modification.

![Figure 4.30: Modified plane development](image)

The modified path in the plane development was made contiguous with the path given by the simple model near the point of contact of the strip with the lower roll. The deviation between the modified trajectory and that given by the simple flower pattern diagram is about 2mm (Figure 4.28). The actual shape of this modified trajectory might be a function of material thickness and mechanical properties.

Finally it can be concluded that, even though the localised deformation at the rolls are not represented by the basic analytical model, it is capable of identifying an improved flower pattern for a given roll forming operation using simple relations which has not been possible before.
5 The effect of process and geometric parameters on longitudinal edge strain and product defects

5.1 Introduction

In the previous chapter an analytical model was developed to predict the longitudinal strain components at the flange edge during the roll forming process. In the experiments, it was observed that the highest longitudinal edge strain develops when the strip passes the rolls due to the local deformation of the flange. This peak longitudinal edge strain was found to be higher than the elastic limit of the material; it therefore has a significant effect on shape defects in a roll formed part. Nevertheless, even though the developed equations can be applied to investigate the effect of the bending angle, flange length, material thickness and the inter-station distance on the surface strain they cannot readily predict the peak longitudinal edge strain in the strip edge. Therefore the effect of process and material parameters as well as part shape on the peak longitudinal edge strain and shape defects will be investigated in this chapter for the roll forming of AHSS and UHSS. Longitudinal bow and springback will be considered as they are the most common defects in a symmetric channel section.

Previous studies gave contradictive results with regard to the effect of material properties on the peak longitudinal edge strain. Han et al. [43, 44] observed an increase in peak longitudinal strain with material yield, while Lindgren [37, 40] and Azizitafti [33] observed the opposite trend in numerical studies performed on a U-channel profile. Understanding the effect of material properties on the peak longitudinal strain it is important given that it is directly related to most of the product defects commonly observed in the roll forming process. Moreover the available studies are limited to the traditional softer material grades and high strength grades may show different trends.
Additionally, the effect of material properties on longitudinal bow, one of the major shape defects observed in roll forming, is still not understood sufficiently and only a limited amount of experimental studies can be found in the literature [36, 37, 53]. It has been found out that longitudinal bow is due to the uneven longitudinal residual strain distribution through the cross section of a part [29]. Since the residual strain is a material dependent parameter, bow is greatly affected by the material properties. On the other hand, in some materials with higher thicknesses such as 2mm, bow can be seen even though the residual strain at the flange edge is zero [53]. In addition to that, residual strain of the material after forming cannot be measured easily. Instead, peak longitudinal edge strain may be used as a possible indicator of longitudinal bow since it can be easily measured and analytically calculated. Both peak longitudinal strain and longitudinal bow are influenced by the process parameters and the geometry of the roll formed part in addition to the material properties, and major contradictions were identified in the literature review with regard to their effect on longitudinal bow. Therefore, establishing a general rule with regards to the effect of material properties, process parameters, and part shape on longitudinal bow is required.

Springback is a significant defect in roll forming of AHSS and UHSS. Unlike in V die forming or folding processes, there are very few investigations that focused on springback in roll forming [1, 7, 21, 60, 61, 105]. It can be seen that the springback is considerably smaller in roll forming compared to the V die forming [7, 63] and some studies have related this to the incremental nature of the process [7]. Another investigation suggested that the low level of springback observed in roll forming is the result of redundant deformation [1] and this would indicate that it may be a function of roll forming process parameters. The effect of process and geometrical parameters such as inter-station distance, forming angle, and flange length has not been investigated before. In addition to that, there are some contradictions with regard to the effect of material thickness on springback. Groche and Henkelmann [60] observed an increase in springback with material thickness for some grades of high strength steel which opposes the general trend proposed by the simple bending theory [65].

This chapter will experimentally investigate the effect of the bending angle, the flange length, the material thickness, and the inter-station distance on the peak longitudinal edge strain, longitudinal bow, and springback in the roll forming process. Additionally,
the effect of material parameters such as yield strength and material hardening will be investigated by performing roll forming trials on three different types of AHSS and UHSS, a DP600, a DP1000 and a MS900 steel. The DP600 and the DP1000 steel show different levels of material yield with similar hardening characteristics. The DP1000 and the MS900 have higher yield strengths and are different in material hardening. This allows separation of the effect of material hardening and yield strength on longitudinal edge strain, bow and springback which, to the author’s knowledge, has not been experimentally done before.

5.2 Methodology

Set of experiments was designed to carry out an extensive study on longitudinal peak edge strain, longitudinal bow and springback in the roll forming of AHSS and UHSS. Trapezoidal sections were roll formed under different combinations of flange length, bending angle, inter-station distance and material thickness for three different materials (Figure 5.1).

![Figure 5.1: Part geometry parameters analysed in this study](image)

Two different values were investigated for each parameter as shown in Table 5.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange length (mm)</td>
<td>36</td>
<td>48.5</td>
</tr>
<tr>
<td>Forming angle (degrees)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Station distance (mm)</td>
<td>250</td>
<td>400</td>
</tr>
<tr>
<td>Material thickness (mm)</td>
<td>1.5</td>
<td>2</td>
</tr>
</tbody>
</table>

As there are four different factors with two different levels each, 16 possible combinations of factors can be identified for the experiments as shown in Table 5.2. All the experiments were carried out with the laboratory roll former and the
longitudinal edge strain was measured during the process; further springback and
longitudinal bow of the roll formed section were analysed (more details will be
provided later in the next section). Finally the results were recorded separately for the
three different material combinations and statistically analysed applying the
commercial software code MINITAB [106].

Table 5.2: Experiment plan for the experimental investigation

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Flange length (mm)</th>
<th>Forming angle (degrees)</th>
<th>Station distance (mm)</th>
<th>Material thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.0</td>
<td>20</td>
<td>250</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>36.0</td>
<td>20</td>
<td>250</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>36.0</td>
<td>20</td>
<td>400</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>36.0</td>
<td>20</td>
<td>400</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>36.0</td>
<td>30</td>
<td>250</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>36.0</td>
<td>30</td>
<td>250</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>36.0</td>
<td>30</td>
<td>400</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>36.0</td>
<td>30</td>
<td>400</td>
<td>2.0</td>
</tr>
<tr>
<td>9</td>
<td>48.5</td>
<td>20</td>
<td>250</td>
<td>1.5</td>
</tr>
<tr>
<td>10</td>
<td>48.5</td>
<td>20</td>
<td>250</td>
<td>2.0</td>
</tr>
<tr>
<td>11</td>
<td>48.5</td>
<td>20</td>
<td>400</td>
<td>1.5</td>
</tr>
<tr>
<td>12</td>
<td>48.5</td>
<td>20</td>
<td>400</td>
<td>2.0</td>
</tr>
<tr>
<td>13</td>
<td>48.5</td>
<td>30</td>
<td>250</td>
<td>1.5</td>
</tr>
<tr>
<td>14</td>
<td>48.5</td>
<td>30</td>
<td>250</td>
<td>2.0</td>
</tr>
<tr>
<td>15</td>
<td>48.5</td>
<td>30</td>
<td>400</td>
<td>1.5</td>
</tr>
<tr>
<td>16</td>
<td>48.5</td>
<td>30</td>
<td>400</td>
<td>2.0</td>
</tr>
</tbody>
</table>

5.3 Experiments

5.3.1 Materials

Three different material grades with two different thicknesses provided by Svenskt
Stål AB (SSAB) Steel Company [107] were used for the experiments. They are a
DP600, a DP1000 and a MS900 (martensitic grade) steel. The materials were in sheet
form and were cut into strips by water jet cutting to avoid the introduction of unwanted
residual stresses. Tensile test were carried out 0, 45 and 90 ° to the rolling direction as
explained in Section 3.2.1. The average true stress strain curves obtained from the samples oriented in rolling direction are shown in Figure 5.2. For this three samples were considered from each material; i.e. each curve given in Figure 5.2 is the average curve of three true stress strain curves.

![Figure 5.2: Averaged true stress strain curve for the samples tested along the rolling direction](image)

The material parameters determined for the three materials based on the procedure given in Section 3.2.1 are given in Table 5.3.

Table 5.3: Material properties determined by fitting the Hollomon’s equation to the tensile true stress strain curves determined in rolling direction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Angle to the rolling direction(°)</th>
<th>Yield Strength (MPa)</th>
<th>Young’s Modulus (GPa)</th>
<th>Ultimate tensile strength(MPa)</th>
<th>Elastic limit (m/m)</th>
<th>n</th>
<th>K (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP600</td>
<td>0</td>
<td>446.5</td>
<td>200</td>
<td>767.7</td>
<td>0.00422</td>
<td>0.117</td>
<td>926.3</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>435.6</td>
<td>200</td>
<td>750.2</td>
<td>0.00418</td>
<td>0.117</td>
<td>901.5</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>467.3</td>
<td>200</td>
<td>790.1</td>
<td>0.00434</td>
<td>0.115</td>
<td>951.5</td>
</tr>
<tr>
<td>DP1000</td>
<td>0</td>
<td>764.1</td>
<td>200</td>
<td>1194.3</td>
<td>0.00580</td>
<td>0.122</td>
<td>1632.8</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>767.9</td>
<td>200</td>
<td>1177.6</td>
<td>0.00586</td>
<td>0.118</td>
<td>1592.3</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>779.1</td>
<td>200</td>
<td>1194.6</td>
<td>0.00589</td>
<td>0.120</td>
<td>1639.1</td>
</tr>
<tr>
<td>MS900</td>
<td>0</td>
<td>931.9</td>
<td>205</td>
<td>1102.7</td>
<td>0.00653</td>
<td>0.058</td>
<td>1337.8</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>946.1</td>
<td>205</td>
<td>1080.4</td>
<td>0.00661</td>
<td>0.056</td>
<td>1339.4</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>945.8</td>
<td>205</td>
<td>1106.4</td>
<td>0.00661</td>
<td>0.059</td>
<td>1364.2</td>
</tr>
</tbody>
</table>

5.3.2 Roll forming

Trapezoidal sections were roll formed as previously explained in Section 3.2.4 applying one feeding stand with flat rolls followed by one forming stand. The bending
radius and the web-length were kept constant at 4.8mm and 50mm respectively while the forming angle and the station distance as well as the material thickness and the flange length were varied according to Figure 5.1.

5.3.3 Longitudinal edge strain

The longitudinal edge strain was measured during the roll forming process with conventional single axis strain gauges as described in Section 3.2.2.

5.3.4 Longitudinal bow and springback

The longitudinal bow and springback of the final product were determined as described in Section 3.2.6 and Section 3.2.7 respectively.

5.4 Results and discussion

The experimental results for longitudinal edge strain, longitudinal bow and transverse springback are shown in Table 5.4. They will be extensively analysed in this chapter.

<table>
<thead>
<tr>
<th>EXP</th>
<th>Peak strain (m/m)</th>
<th>Maximum bow (mm)</th>
<th>Springback (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DP600</td>
<td>DP1000</td>
<td>MS900</td>
</tr>
<tr>
<td>1</td>
<td>0.0060</td>
<td>0.0075</td>
<td>0.0078</td>
</tr>
<tr>
<td>2</td>
<td>0.0091</td>
<td>0.0105</td>
<td>0.0114</td>
</tr>
<tr>
<td>3</td>
<td>0.0056</td>
<td>0.0073</td>
<td>0.0065</td>
</tr>
<tr>
<td>4</td>
<td>0.0087</td>
<td>0.0103</td>
<td>0.0108</td>
</tr>
<tr>
<td>5</td>
<td>0.0085</td>
<td>0.0099</td>
<td>0.0092</td>
</tr>
<tr>
<td>6</td>
<td>0.0119</td>
<td>0.0127</td>
<td>0.0126</td>
</tr>
<tr>
<td>7</td>
<td>0.0077</td>
<td>0.0100</td>
<td>0.0098</td>
</tr>
<tr>
<td>8</td>
<td>0.0119</td>
<td>0.0122</td>
<td>0.0128</td>
</tr>
<tr>
<td>9</td>
<td>0.0045</td>
<td>0.0061</td>
<td>0.0051</td>
</tr>
<tr>
<td>10</td>
<td>0.0073</td>
<td>0.0082</td>
<td>0.0089</td>
</tr>
<tr>
<td>11</td>
<td>0.0046</td>
<td>0.0064</td>
<td>0.0053</td>
</tr>
<tr>
<td>12</td>
<td>0.0070</td>
<td>0.0085</td>
<td>0.0103</td>
</tr>
<tr>
<td>13</td>
<td>0.0067</td>
<td>0.0081</td>
<td>0.0067</td>
</tr>
<tr>
<td>14</td>
<td>0.0106</td>
<td>0.0113</td>
<td>0.0125</td>
</tr>
<tr>
<td>15</td>
<td>0.0073</td>
<td>0.0091</td>
<td>0.0080</td>
</tr>
<tr>
<td>16</td>
<td>0.0105</td>
<td>0.0116</td>
<td>0.0130</td>
</tr>
</tbody>
</table>
5.4.1 Peak longitudinal strain

The variation of longitudinal edge strain during the progression of the strip through the roll stand was discussed in detail in the previous chapter. A typical longitudinal strain pattern at the edge of the flange on the top surface during roll forming with a single station is shown in Figure 5.3. Only the peak strain, tabulated in Table 5.4, will be utilised in the analysis.

![Figure 5.3: The distribution of longitudinal edge strain for the roll forming with a single forming station](image)

5.4.1.1 Main effects on peak strain

To identify the overall effect of the various process and material parameters on the longitudinal peak strain, the "main effect" was determined [78]. The main effect determines the influence independent variables have on a dependent variable while averaging across the other independent variables. For example, when we determine the main effect of the forming angle on the peak longitudinal strain, the effect of the variation of other parameters such as the station distance on peak longitudinal strain is averaged out. In this study the main effect was determined separately for the high and the low levels of the input parameters. The below equations give an example on how the main effect of the forming angle on the peak longitudinal strain was determined. The main effect of each of the other parameters was determined in the same way.

\[
Main\ effect\ of\ (FA^+) = \frac{\sum Strain(FA^+)}{n/2}
\]  

(5.1)
Main effect of \( FA^- \) = \( \frac{\sum \text{Strain}(FA^-)}{n/2} \) (5.2)

where \( \text{Strain}(FA^+) \) is the strain value for a high level of forming angle while \( \text{Strain}(FA^-) \) is the strain value for a low level of the forming angle and \( n \) is the number of experiments, which in our case are 16.

The main effect of the flange length on the peak longitudinal strain is shown in Figure 5.4.

![Figure 5.4: The main effect of flange length on peak strain](image)

It can be seen that the DP1000 and MS900 steel show similar levels of peak strain considerably higher than that observed for DP600. This indicates that the peak longitudinal edge strain increases with the yield strength of the material. However, at higher material strength levels an increase in yield strength has a less significant effect given that the yield strength of the MS900 steel is higher compared to that of the DP1000 steel (Table 5.3). While the DP1000 steel has a lower yield point than the MS900 steel it shows higher material hardening (Figure 5.2) and this suggests that not only material yield but also the hardening exponent influence longitudinal edge strain. This is a significant finding as the previous studies mainly discussed only the effect of yield strength on the peak longitudinal edge strain [33, 37, 40, 43, 44]. This may be due to the significant lower hardening of the soft material grades investigated in those studies.

According to Figure 5.4, the peak longitudinal strain decreases with the flange length of the part for all three materials. When the flange length is smaller, the flange edge needs to pass a shorter radius at the rollers during forming compared to the longer flange length as schematically illustrated in Figure 5.5. Therefore more bending strain
is developed on the shorter flange edges compared to the longer ones resulting in higher peak longitudinal surface strain with shorter flange length. This experimentally confirms the numerical and analytical results of previous studies [40, 42-44].

Figure 5.5: Effective radius of flange edge when pass the roll station

The peak strain increases with the forming angle for all materials as shown in Figure 5.6. Because when the angle increases more stretching will occur at the flange as the flange edge travels a higher distance compared to the lower forming angles as explained in Section 2.1.2. The same trend was reported in the literature for all experimental, analytical and numerical work [19, 31, 33, 39, 42-44]. This study confirms this for AHSS and UHSS. Further it can be said that if the flange length is longer, then higher bending angles can be achieved due to their inverse relationship with the peak longitudinal edge strain.

Figure 5.6: The main effect of forming angle on peak strain
There is no influence of inter-station distance on the peak longitudinal strain (Figure 5.7).

![Graph showing the relationship between peak strain and station distance for different materials.

Figure 5.7: Main effect of inter-station distance on peak longitudinal strain

Usually if the deformation length is less than the inter-station distance, then the peak strain is affected by the inter-station distance due the lack of space for the material to deform. The deformation length can be calculated from Equation (2.2). According to Equation (2.2), the maximum deformation lengths calculated for the experimental set up of this section are 325.9mm and the same for both inter-station distances. This is higher than the shorter inter-station distance of 250mm and suggests that the longitudinal peak strain should when the station distance is reduced to 250mm. Nevertheless, only a minor variation in longitudinal edge strain with changing station distance is observed in Figure 5.7. Equation (2.2) is purely based on geometric features and does not take into account the effect of material strength. Our results suggests that for higher levels of material strength Equation (2.2) may not be applicable to accurately estimate forming length especially for the AHSS and UHSS tested here.

Figure 5.8 shows that the peak longitudinal strain increases with the material thickness which agrees with previous studies [31, 33, 40, 42-44]. With increasing material thickness the bending strain increases [65] and this leads to higher material surface strains and through that to an increase in longitudinal edge strain.
It can be seen in Figure 5.8 that the DP600 steel shows the lowest level of yield strength and longitudinal peak edge strain. For both steel grades DP1000 and MS900 the maximum longitudinal edge strain increases with material thickness. Nevertheless, the slope of this increase is different between the materials. A lower longitudinal edge strain can be seen for DP1000 at 2 mm material thickness while at a thickness of 1.5 mm the DP1000 shows a higher level of longitudinal edge strain compared to the MS900. This cannot be explained on the basis of the current experimental results and further studies are needed to investigate this trend.

5.4.1.2 Interaction effect on peak strain

To achieve a deeper understanding the interaction effect will be analysed for the DP600. Similar trends were observed for the DP1000 and the MS900 steel and are shown in Appendix C. It should be noted that the 16 samples available do not allow for statistically significant findings, however the effects may provide some insight into the roll forming process. The interaction effect considers two input parameters at a time and determines their average influence on one particular output parameter while averaging out the effect of other parameters. Also here the interaction effect was separately determined for the high and the low levels of input parameters. The interaction effect of the flange length and the forming angle is given by Equation (5.3) and (5.4). The interaction effect of the other parameters was determined in the same way.
where \( \text{Strain}(FL \text{ and } FA)^+ \) is the strain when the flange length and forming angle levels are high, \( \text{Strain}(FL \text{ and } FA)^- \) is the strains when the flange length and the forming angle levels are low and \( n \) is the number of experiments which is 16.

The interaction plot for DP600 was determined by applying the MINITAB software and is shown in Figure 5.9 where the flange length, the forming angle, the station distance and the thickness are abbreviated as FL, FA, SD and \( t \) respectively. The unit of the forming angle is degrees and the other three parameters are given in millimetres for all interaction plots of this section. The rows represent the two levels of flange length, forming angle and station distance respectively while the corresponding legends for the two levels of each parameter are given in the right hand side. The vertical axis represents the peak longitudinal strain which is unitless.

![Interaction plot for DP600](image)

**Figure 5.9: Interaction plot for DP600 – Peak longitudinal edge strain.**

The first row in Figure 5.9 shows that the peak longitudinal strain decreases with increasing flange length for all forming conditions while it increases with forming angle and material thickness for both flange lengths. The station distance has a minor effect on the peak strain for any level of flange length. As far as peak longitudinal
strain is concerned, both flange length levels were equally influenced by the forming angle, the inter-station distance and the material thickness which suggests that the effect of those parameters on the peak longitudinal strain is independent of the flange length.

The second row in Figure 5.9 indicates that the peak strain increases with forming angle while it does not change with station distance for both forming angles. Additionally, the peak longitudinal strain increases with material thickness for both forming angles. The effect of the inter-station distance and of the material thickness on the peak longitudinal strain appears to be independent of the forming angle.

The last row in Figure 5.9 shows that the station distance does not have a big influence on the peak longitudinal strain. Therefore, as explained before the equation for the deformation length calculation available in the literature may not be accurate enough to predict the deformation length in AHSS and UHSS steel roll forming. Further the peak strain increases with material thickness for both station distances.

As far as the main effect on peak longitudinal edge strain is concerned some significant findings could be obtained with regard to the material effect in roll forming. It was observed that the peak longitudinal edge strain increases with the increase in material yield strength for the materials with similar hardening properties. In addition to that the hardening behaviour appears to be significant when higher strain levels are exerted in the flange edge. Further, the calculated deformation length from the equation available in the literature is not appropriate for AHSS and UHSS due to the significant influence of material properties which is not taken into account in that equation. Moreover the interaction study confirms the obtained trends for different parameter levels. According to the interaction plot of DP600 given in Figure 5.9, peak longitudinal strain is mostly insensitive to the parameter levels; i.e. the trends observed for peak longitudinal strain to not vary significantly with the parameter levels.

5.4.2 Longitudinal bow

The longitudinal bow after roll forming was analysed with the ExaScan 3D scanner and the Geomagic software as explained in Section 3.2.6. A typical graph of the bow height variation along the length of a part is given in Figure 5.10. The maximum bow height deviation is positioned approximately at the centre of the strip. Only the
maximum bow height of the part will be considered in this chapter as a measure for bow.

![Figure 5.10: Bow variation along the length of a part](image)

5.4.2.1 Main effect on longitudinal bow

The main effect of different input parameters on the longitudinal bow was individually analysed for the three different materials as previously explained in Section 5.4.1.1.

The main effect of the flange length on the longitudinal bow is shown in Figure 5.11. Even though the DP600 steel showed the lowest level of maximum longitudinal edge strain in the previous analysis it has the highest magnitude of bow. The reason for this may be the yield strength of DP 600 which is significantly lower compared to those of DP1000 and MS900 (Table 5.3). A lower yield strength leads to less resistance of the material to permanent deformation, i.e., there is a higher likelihood for longitudinal strain to be permanent in the strip edge. This leads to a higher magnitude of longitudinal bow in the DP600 steel even though the peak longitudinal edge strain is lower compared to the DP1000 and the MS900 steel (Figure 5.4). An increased level of longitudinal bow with decreasing material yield strength has been previously observed for softer steel grades [33, 51]. This suggests that the level of the maximum longitudinal edge strain alone cannot not give a measure for longitudinal bow since the magnitude of permanent deformation depends on the yield strength of the material. As reported before [29] the magnitude of longitudinal bow is a function of the mismatch between residual longitudinal strain in the edge and the web of the section,
i.e., a higher level permanent longitudinal strain in the edge results in higher values for bow.

Bow is higher for the MS900 steel compared to the DP1000. This is a surprising result given that both steels shown very similar levels of longitudinal edge strain (Figure 5.4). The yield strength of the MS900 is significantly higher compared to that of the DP1000 steel (Table 5.3) and this would suggest a higher resistance to permanent deformation in the edge, i.e., less bow. Material hardening in the DP1000 steel close to yield is significantly higher compared to the MS900 (Figure 5.2) and this may have led to a higher resistance to permanent longitudinal deformation than suggested by the yield point. Further it can be seen in Table 5.4 (parameters are given in Table 5.3) that DP1000 shows less bow than MS900 if the longitudinal strain levels are considerably high which confirms the significance of the hardening properties on longitudinal bow at higher strain levels. This suggests that with regard to longitudinal bow not only the yield strength, but also the level of material hardening are important especially in AHSS and UHSS roll forming. This is a significant finding and has not been identified before by experimental or numerical methods.

Figure 5.11 also shows that longitudinal bow decreases with increasing flange length. This corresponds to Figure 5.4 which showed that the peak longitudinal edge strain decreases with increasing flange length, i.e., the level of permanent longitudinal strain in the edge is lower at higher flange lengths resulting in less bow. Nevertheless comparing Figure 5.11 and Figure 5.4 suggests that the magnitude of decrease in
longitudinal strain is significantly lower compared to that observed for bow (For the DP 1000 steel an increase in the flange length from 36 to 48.5 mm leads to a reduction in maximum longitudinal edge strain of 13.6%, but this leads to a decrease in bow of 64.3%). This is due to a higher flange length elevating the bending rigidity of the part, which increases the resistance to bow. In his experiments [31], Fong observed an increase in bow with flange length up to a flange length level of 7mm followed by a continuous decrease. Even though Azizitafiti et al. [33] observed the same trend in their numerical model, bow was found to decrease above a flange length of 45mm. Therefore the results shown here partially confirm the Fong’s experiments [31].

The longitudinal bow increases with the forming angle (Figure 5.12) for all three materials, and this is in accordance with previous literature that focused on bow in the roll forming of mild steel grades [31, 33, 51]. The results of Section 5.4.1.1 (Figure 5.6) have shown that the peak longitudinal edge strain increases with the forming angle and this leads to a higher level of permanent longitudinal deformation in the edge and explains the trend shown in Figure 5.12. Nevertheless while in Figure 5.6 all three steels show a similar level of increase in maximum longitudinal edge strain with forming angle, in Figure 5.12 for DP1000, only a minor effect of the forming angle on longitudinal bow can be observed. This would suggest that when roll forming DP1000 steel a smaller number of forming stations can be applied compared to MS900 despite the fact that the yield strength of DP1000 is significantly lower compared to MS900. Further the higher deviation in longitudinal bow between DP1000 and MS900 at 30° can be due to the dominant effect of material hardening of DP1000 at 30°. This is in contrast with previous studies which suggests that a higher yield strength generally leads to less bow [33, 55]. The results indicate that longitudinal bow is not only a function of the level of longitudinal strain introduced in the edge and material yield, but that it is also influenced by other factors such as material hardening which represents the only major difference between the DP1000 and the MS900 steel.
Figure 5.12: Main effect of forming angle on bow
The longitudinal bow decreases with increasing station distance as shown in Figure 5.13, thereby the influence of the station distance is the highest for the DP600 steel and relatively small for the two UHSS. This cannot be explained by the results shown in Figure 5.7 where the influence of the station distance on the peak longitudinal strain was minor. When the station distance increases, it allows a smoother bending progression which probably results in lower residual stresses compared to the shorter station distance; this may influence the decrease in longitudinal bow with increasing in inter-station distance. However it may not influence the peak longitudinal strain as the same forming angle is applied in both cases.

Figure 5.13: Main effect of station distance on bow
For all three materials longitudinal bow increases with the material thickness (Figure 5.14) and this conforms to the increase in maximum longitudinal strain with material thickness shown in Figure 5.8. Nevertheless the effect of material thickness on longitudinal bow appears to be significantly higher compared to its influence on the
maximum longitudinal edge strain. While for the case of the MS900 steel an increase in material thickness from 1.5 to 2 mm leads to an elevation of maximum longitudinal edge strain by 58.3% (Figure 5.8), bow in the section increases more than twofold (Figure 5.14). Bending rigidity should increase with material thickness and restrict the development of bow. The current results suggests that the increasing effect of material thickness on bow dominates that of the bending rigidity.

![Figure 5.14: Main effect of material thickness on bow](image)

5.4.2.2 Interaction effect on longitudinal bow

The interaction effect was analysed for the longitudinal bow in the same way as explained in Section 5.4.1.2. It should be again noted that the 16 samples available do not allow for statistically significant findings, however the effects may provide some insight into the roll forming process. Only the DP600 material was considered and the results are shown in Figure 5.15. The vertical axis represents the maximum longitudinal bow in the part which is in millimetres. Other interaction plots are given in Appendix C.
CHAPTER FIVE

The first row of Figure 5.15 indicates that longitudinal bow increases with decreasing flange length for all forming conditions and the reason for this was explained previously. Longitudinal bow further decreases with increasing inter-station distance and increases with increasing forming angle and material thickness for both flange lengths. The smaller the flange length the higher the sensitivity of longitudinal bow to the forming angle, the station distance and the material thickness. A smaller flange length reduces the bending rigidity of the part and makes it more prone for developing a curvature, which may be one reason for the higher sensitivity of longitudinal bow to process and material parameters. The bending rigidity or the flexural rigidity of a section is given by Equation (5.5) [108]. For example if it considers the part with 48.5 mm flange, the bending rigidity increases by 2.85Nm² when it is formed from a bending angle of 20° to 30°, whereas this increase is only 1.34Nm² for a section with a 36mm flange length. This clearly indicates the reason for the higher sensitivity of longitudinal bow to process parameters if the flange length is low.

\[ \text{Bending rigidity} = E \times I \]  

(5.5)

Where \( E \) is the Young’s modulus of the material and \( I \) is the second moment of inertia of the profile cross section.

The second row in Figure 5.15 shows that bow increases with increasing forming angle. For both bending angles bow decreases with increasing station distance and increases with the increasing material thickness. It can be seen that the sensitivity of

Figure 5.15: Interaction plot for DP600- Longitudinal bow
the higher forming angle to changes in material thickness and station distance is slightly higher than that of the lower forming angle. Material deformation is considerable higher when forming a bending angle of 30° compared to 20° (see Figure 5.6) which may explain the higher sensitivity of bow to material thickness and station distance if the forming angle is high.

The last row in Figure 5.15 clearly indicates that the longitudinal bow decreases with increasing station distance. Further longitudinal bow increases with increasing material thickness for both station distances whereby the increase is higher when the station distance is small. According to Equation (2.2), the deformation length is a function of material thickness. As a result material thickness is a critical factor for bow.

In summary, a decrease in longitudinal bow with increasing material yield strength was observed for the materials with similar hardening behaviour. Moreover the hardening behaviour showed a significant effect on bow especially at higher forming strain levels. Despite its lower yield strength, DP1000 showed lower bow than MS900 in almost all cases. This may be related to the higher hardening of DP1000 which resists the occurrence of permanent longitudinal strain and bow in the part. Bow decreased with increasing inter-station distance even though only a slight deviation in the peak longitudinal edge strain was observed. That is may be due to a smoother forming progression if the distance between stations is high and cannot be explained in terms of peak longitudinal edge strain. However this effect is minor for the two UHSS grades, i.e. DP1000 and MS900. It is important to note that there is a significant effect of factor level on the corresponding longitudinal bow even though the peak strain is insensitive to the factor levels (see Figure 5.9). This confirms that the changes in the longitudinal bow are not proportional to that of the peak longitudinal edge strain. The reason for this is the bending rigidity of the profile which influences longitudinal bow and varies depending on the part geometry formed.

5.4.3 Springback

Springback of the roll formed parts was measured manually with a protractor as explained in Section 3.2.7.
5.4.3.1 Main effect on springback

The main effect of different parameters on the final springback angle was calculated as explained earlier in this chapter. The main effect of the flange length on springback is shown in Figure 5.16.

![Figure 5.16: The main effect of flange length on springback](image)

The highest springback is observed for the DP1000 steel, while springback is the lowest for DP600. The lower tendency to springback of the DP600 is due to its lower yield strength. This becomes clear when comparing schematically the true stress strain curves of the DP1000 and the DP600 steel (Figure 5.17) for loading and after elastic recovery. The elastic stress is recovered when the load is released and the resulting elastic recovery is a measure for springback. The springback is higher in DP1000 compared to DP600 due to the higher forming stresses under load, which result in a higher recovery of elastic strain (Figure 5.17).

![Figure 5.17: Schematic relationship between yield strength and material hardening on springback](image)
As shown in Figure 5.16 springback is lower for the MS900 steel compared to the DP1000 despite the significantly higher yield strength in the MS900 steel (Table 5.3). Comparing the true stress-strain curves of the two material grades in Figure 5.2 shows that the DP1000 has a higher stress level compared to the MS900 at strain levels greater than 0.031 m/m. The bending strain exerted in this process can be determined by Equation (4.14) and is 0.172 m/m. At this particular level of strain the DP1000 shows higher levels of true stress than the MS900 due to its higher material hardening which leads higher springback after release.

For some forming conditions negative springback was observed for the DP600 (Figure 5.16). This negative springback (springforward) has been reported before for press braking operations [109]. If a softer material is formed into a large angle with a sharp radius, then springforward can take place due to coining of the material at the corner of the bend. This scenario is also observed in industrial roll forming practice [110]. For this reason in the industrial case the roll gap is generally set as a fraction larger than the material thickness. However in the current experiments the same roll gap was maintained for all three materials to maintain consistency. However negative springback was only observed for the relatively soft DP600 steel at high levels of forming angle and flange length.

Figure 5.16 further indicates that springback decreases with increasing flange length for all three material grades. Previous studies only related springback in roll forming to the yield strength, the ultimate tensile strength, the Young’s modulus, the bending radius, the material thickness and the roll gap [1, 21, 60, 61]. Even though the flange length has not been identified as an influential factor, it has a considerable effect on springback. When the flange length increases the deformation in the bending region will not change, but only the length of the flange outside the bend increases. This indicates that not only the bending area, but also the amount of material outside the bend influences springback in roll forming. In addition to that it has been identified that the springback in roll forming is affected by both transverse and longitudinal strain distribution [1, 48]. Therefore springback may be influenced by the flange length of the material given that our previous results have shown that longitudinal edge strain is significantly affected by the flange length of the part (Figure 5.4).
The level of springback decreases with the forming angle (Figure 5.18) for all material grades. When the forming angle increases, in constant radius forming, the region that is plastically deformed increases as illustrated in Figure 5.19. This results in lower springback with increasing bending angle. Nevertheless, as can be seen in Figure 5.18 this effect is very minor for DP1000. The interaction effect may give a better insight into the effect of forming angle on the level of springback.

![Figure 5.18: The main effect of the forming angle on springback](image)

According to the numerical simulation of Bui and Ponthot [21], springback in roll forming is not affected by the inter-station distance. However, the experiments shown here clearly indicate for all three materials investigated that springback increases with inter-station distance (Figure 5.20). Previous work suggested that springback reduces with increasing level of redundant deformation that is introduced into the part [1], however Figure 5.7 revealed that for the roll forming process analysed here redundant deformation in form of permanent longitudinal strain is independent of the station.
distance. Section 2.1.1 showed that in addition to longitudinal edge strain there are several additional forms of redundant deformation in a roll formed part which were not experimentally measured here. A higher station distance leads to a smoother and more progressive deformation in the strip [21] and this may reduce the overall level of redundant deformation in the section potentially leading to an increased level of springback. This an important finding, even though the previous numerical results reported that the springback in roll forming is independent of the inter-station distance this study experimentally showed that it has a significant effect on springback.

![Graph showing the main effect of station distance on springback](image)

**Figure 5.20: The main effect of station distance on springback**

No clear the effect of material thickness on springback was observed (Figure 5.21). According to the literature springback increases with r:t ratio [1, 61] which suggests that if the bending radius remains constant, then the springback decreases with increasing material thickness. Both dual phase grades follow this trend, even though springback in DP600 is only slightly affected by the material thickness. The MS900 steel shows an opposite trend and this confirms previous observations made by Groche and Henkelmann [60] using numerical analysis. The reason for this behaviour is unclear and further work is required to fully understand the springback behaviour of martensitic grade steel in the roll forming process.
5.4.3.2 Interaction effect on springback

The interaction effect was analysed for springback in the same way as explained in Section 5.4.1.2. The interaction plot of DP1000 and MS900 were investigated since in contrast to bow and longitudinal edge strain significant difference in springback trends were observed for those materials, especially with regard to the changing material thickness. The interaction of DP600 is shown in Appendix C and it will not be discussed here as it shows a similar trend as DP1000. Again it should be noted that the 16 samples available do not allow for statistically significant findings, however the effects may provide some insight into the roll forming process.

The Interaction effect of the different parameters on springback is shown for the DP1000 steel in Figure 5.22. The vertical axis represents the springback in the part which is in degrees. The first row in Figure 5.22 indicates that springback increases with decreasing flange length for all forming conditions. It can be seen that springback is not greatly changed with the forming angle for both flange lengths. Springback increases with the station distance for both flange lengths, where it is more sensitive to the station distance for the higher flange length than the lower one. In addition to that springback decreases with the material thickness for both flange lengths, where springback is almost equally sensitive to the material thickness for both flange lengths.
Figure 5.22: Interaction plot for DP1000 – Springback

Even though the main effect plot in Figure 5.18 indicates that there is no big influence of forming angle on springback, according to the second row of Figure 5.22 it is difficult to define a general trend for the effect of forming angle on springback. Because this effect depends on the other forming conditions. As far as springback is concerned, a higher forming angle is extremely sensitive to the inter-station distance compared to the smaller forming angle. In addition to that it can be seen that springback is smaller for the higher angle roll forming if the station distance is lower; whereas the opposite trend can be seen if the station distance is large. Therefore, if higher forming angles are formed, the station distance needs to be set as small as possible to reduce springback in the part. In addition to that, this suggests that the effect of station distance on springback depends on the forming angle and confirms the importance of the inter-station distance as a controlling parameter of springback. Further springback decreases with material thickness for both forming angles but a higher forming angle is more sensitive to the material thickness with regard to the springback.

The third row of Figure 5.22 suggests an increase in springback with increasing station distance and decreases with increasing material thickness for both inter-station distances. Springback shows a higher sensitivity to the material thickness when a higher station distance is employed.
Figure 5.23 shows the interaction effect of different parameters on springback for MS900. The first row of Figure 5.23 shows higher springback for the smaller flange length for almost all forming conditions. Unlike in DP1000, springback slightly decreases with the forming angle for both flange lengths. Similar to DP1000, springback increases with the station distance for both flange lengths but is more sensitive to the station distance if higher flange length are formed. Therefore a low inter-station distance is preferred when roll forming parts with high flange length to reduce springback. In contrast to DP1000, in MS900 springback increases with the material thickness for both flange lengths and is more sensitive to the material thickness for higher flange length. Further there is no difference in the springback for both flange lengths when the thickness is 2mm; i.e. the effect of flange length on springback becomes negligible when the material thickness is high.

The second row of Figure 5.23 shows higher springback for lower forming angles except for one forming condition. Unlike in DP1000, springback increases with the inter-station distance for both forming angles with similar sensitivity. In addition to that springback increases with the material thickness for both forming angles and it is highly sensitive to the material thickness at higher forming angles. Additionally, a high forming angle only shows slightly higher springback when the material thickness is 2mm. This illustrates the lack of influence of the forming angle on springback in MS900 when the material thickness is high.
The third row of Figure 5.23 indicates increasing springback with increasing station distance. In addition to that springback increases with the material thickness for both station distances where the sensitivity of springback to the material thickness is slightly higher at the lower station distance.

In summary, despite of the higher yield strength in MS900, DP1000 showed the highest springback in most of the cases. This is due to the higher hardening of DP1000 which results in higher stress levels compared to MS900 at the bending region under normal operating conditions. In addition to that springback is highly affected by the flange length and forming angle and to the author’s knowledge, this has not been reported before. The experimental results further show that the inter-station distance has a significant influence on springback in AHSS and UHSS roll forming even though it was found to be negligible in the previous numerical studies [21]. Further the effect of material thickness on the springback showed opposite trends with regard to the DP1000 and MS900. According to the interaction plot of DP1000 and MS900 given in Figure 5.22 and Figure 5.23 respectively, springback is sensitive to the parameter levels in most of the cases; i.e. the trends in springback significantly vary with the parameter levels in most of the cases.

5.5 Summary

The effect of flange length, forming angle, station distance and material thickness on the peak longitudinal edge strain, longitudinal bow and springback was experimentally investigated. For that a number of experimental trials were carried out with three different materials namely DP600, DP1000 and MS900. Trapezoidal sections with different dimensions were roll formed at two stations applying a laboratory roll former.

**Peak longitudinal edge strain**

The lowest peak longitudinal edge strain was observed for the DP600 for all forming conditions DP1000 and MS900 showed similar peak strain in most of the cases. Even though the DP1000 steel has a lower yield point than the MS900 steel it shows significantly higher material hardening and this suggests that not only material yield but also the hardening influence longitudinal edge strain. This is a significant finding and to the author’s knowledge, the effect of material hardening on longitudinal edge strain has not been investigated before.
Even though the inter-station distance was smaller than the deformation length for some experiments, peak longitudinal strain was not affected by the inter-station distance for all three materials. The calculated deformation length was higher than the station distance for some of the samples however it did not show any influence on the peak longitudinal strain. As a result it can be concluded that the forming length for AHSS and UHSS may not be accurately estimated using the available equation since it does not take into account the effect of material strength. Moreover the interaction study showed that the effect of different parameters on the peak longitudinal strain is mostly insensitive to the parameter levels.

**Longitudinal Bow**

Even though DP600 has the lowest peak edge strain, bow was highest at DP600 for all forming conditions. This is due to the lower yield strength of DP600 which gives less resistance to the permanent plastic deformation given that the amount of permanent plastic deformation is determined by the material yield strength. Therefore peak strain alone cannot be used to estimate the level of bow in a part produced from different materials unless the material properties are similar. Even though MS900 has a higher yield strength than DP1000, MS900 showed higher bow than DP1000 for most of the cases. This suggests that DP1000 has a higher resistance to permanent deformation despite of its lower yield strength compared to MS900. This is due to the higher level of material hardening close to yield in DP1000 and it can be concluded that not only the material yield strength but also the material hardening influence longitudinal bow in roll forming. Previous studies have not identified an effect of material hardening on longitudinal bow which may be due to the lack of hardening in the softer material grades analysed in those studies.

Even though the station distance does not influence the peak longitudinal strain of the material, it does influence longitudinal bow. This may be due to a smoother forming progression if the station distance is high and may not be related to peak longitudinal edge strain variation.

In addition to that, it was observed that the peak longitudinal edge strain is insensitive to the factor levels. However longitudinal bow was considerably affected by the factor levels. The reason for this may be the bending rigidity of the part which changes
Springback

The lowest springback was observed in DP600 due its lower yield strength compared to the other two materials. Despite of the higher yield strength of MS900, DP1000 showed the highest springback in the most of the cases. For the forming angles analysed here the stress levels reached in DP1000 in the transverse bending region where higher due to higher material hardening compared to those of MS900 resulting in higher springback. This is a significant finding and confirms the significance of hardening properties with regard to springback in AHSS and UHSS roll forming. In addition to that springforward (negative springback) was observed for some forming cases involving DP600 material. This was related to the introduction of excessive plastic stresses and can be observed in practice when a relatively soft material is roll formed into high forming angles.

A decrease in springback with flange length was observed for all three materials. This suggests that not only the bending region, but also the adjacent regions (flange area) influences springback in roll forming. This is a new finding and to the author’s knowledge has not been reported before.

Springback decreases with increasing forming angle for DP600 and MS900 materials, however the interaction study showed that a general trend cannot be defined for DP1000 in this regard. For DP1000 the effect of the forming angle on springback depends on other geometrical and process parameters.

An increase in springback with inter-station distance was observed. Previous studies suggest that springback decreases with increasing level of redundant deformation introduced into a part during the roll forming operation. When the inter-station distance increases more progressive bending will take place which reduces redundant deformation and leads to an increase in springback.

The general trend of the effect of material thickness on the springback varied from one material to another. Springback decreased with material thickness for DP600 and DP1000 which confirms the general trend observed in the literature. However the
effect is minor for the DP600. On the other hand springback increased with material thickness for MS900. Further studies are required to understand this trend.
6 Effect of material properties on product defects in the roll forming process.

6.1 Introduction

In the previous chapter the effect of process and geometric parameters on the longitudinal edge strain, bow and springback was experimentally investigated. It was shown that the material properties influence both the peak longitudinal edge strain levels and part shape defects. Therefore greater attention needs to be given to the effect material properties on the final product quality.

Further in the previous chapter it was observed that DP600 sheet material shows the highest levels of longitudinal bow, noting that the DP600 material has the lowest yield strength of all the materials. The lowest bow was observed in most of the cases for the DP1000 which showed the highest level of springback in contrast to DP600 which showed the lowest. Overall the previous experimental results suggest that roll forming shape defects have a strong dependency on the yield strength and hardening behaviour of the material. Previous studies have shown that even small changes in material yield can have a major effect on the process and the final shape of the roll formed component [111]. Most shape defects in roll forming are due to small permanent longitudinal deformation in the strip [29] and a reduction in yield stress reduces the resistance of the material for unwanted plastic deformation.

The major problem when forming AHSS and UHSS is that even small and common proportional changes in material strength and hardening characteristic can lead to major variations in yield stress (10% reduction in material strength for a material with $\text{YP}_{0.2\%}=1000\text{MPa}$ leads to a reduction in yield stress by 100 MPa [112]). This requires
the re-adjustment of tooling to compensate for shape defects and maintain part geometry and results in costly equipment downtimes which are unacceptable in the industry. Therefore methods need to be developed that enable the compensation of shape defects without stopping the roll forming line. An in-line shape compensation method would require the monitoring of process parameters that enable the estimation of material property variations in the process. Additionally, the effect of changes in material properties on the final part shape needs to be known to re-adjust the tooling accordingly and compensate for shape defects. For this the effect of material property variation on common shape defects observed in the roll forming process as well as measurable process parameters such as and roll load and torque needs to be understood.

Only a few investigations have analysed roll load and torque in the roll forming process and revealed that both parameters are a function of material yield [68, 69]. A numerical study performed by Azizitafti et al. [33] observed that longitudinal bow decreases with increasing yield strength of the roll formed material and this has been verified by experimental work performed by Abeyrathna et al. [32]. This suggests that it may be possible to directly estimate the level of longitudinal bow in a roll formed section by directly monitoring the change in roll forming load and torque during the process if the other parameters stay constant. In addition to that, as per the work carried out so far in this thesis, not only the yield strength but also the material hardening found to be significant with regard to shape defects in roll forming. Material hardening may also have a significant influence on the roll load and torque especially in AHSS and UHSS roll forming given that some UHSS such as DP1000 steel show very high initial hardening rates [113].

Therefore the aim of this chapter is to investigate the effect of yield strength and material hardening on roll load and torque. Furthermore longitudinal bow, as a material property dependent shape defect, will be investigated with regard to the effect of yield strength and the hardening exponent. Finally, the applicability of roll load and torque to predict deviations in longitudinal bow due to material property changes will be analysed which has not been done before. It is important to note that this approach will allow the in-line compensation of any common roll forming defect as long as there is
fundamental understanding of the link between changes in material properties and particular forming defect.

6.2 Methodology

First the effect of yield strength and the hardening exponent on roll load and torque will be investigated. For that, a set of virtual materials will be generated based on DP780 material properties with six different yield strengths and five hardening exponents for each yield strength level. Those two sets of material properties, when coupled, can produce thirty different material inputs for a simulation model in COPRA FEA. The simulation model will be validated for longitudinal bow, roll load and torque with experimental roll forming trials performed on DP780 steel. To reduce the complexity of the problem, only a single forming station will be considered.

Then the validated model will be used with all the combinations of material inputs as mentioned above to perform a numerical investigation. Longitudinal bow, roll load and torque will be evaluated in each simulation, which will be statistically analysed to obtain the potential relationships. It is expected to establish the following links.

- The link between material properties and longitudinal bow.
- The link between material properties and roll load.
- The link between material properties and roll torque.
- The link between longitudinal bow and roll load and torque

Regression analysis together with analysis of variance (ANOVA) will be employed to establish the above relationships.

6.3 Experiments

6.3.1 Materials

Experiments were carried out with DP780 material provided by Nippon Steel, Japan. The material was cut from the coil by a manual guillotine into the required length. The strips were then sent through a roller leveller to improve the flatness and eliminate any pre-existing residual stress. Standard tensile tests were carried out as explained in Section 3.2.1 and the average true stress-strain curve for samples cut along the rolling direction is shown in Figure 6.1.
Figure 6.1: Average true stress strain curve along the rolling direction for DP780

The tensile parameters (see Table 6.1) were calculated according to the procedure given in Section 3.2.1.

Table 6.1: Material properties calculated for DP780

<table>
<thead>
<tr>
<th>Material</th>
<th>Angle to the rolling direction(°)</th>
<th>Yield Strength (MPa)</th>
<th>Young’s Modulus (GPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Elastic limit (m/m)</th>
<th>n</th>
<th>K (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP780</td>
<td>0</td>
<td>594.4</td>
<td>200</td>
<td>960.6</td>
<td>0.0051</td>
<td>0.118</td>
<td>1228.2</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>606.7</td>
<td>200</td>
<td>982.1</td>
<td>0.0051</td>
<td>0.113</td>
<td>1268.0</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>590.5</td>
<td>200</td>
<td>950.6</td>
<td>0.0050</td>
<td>0.113</td>
<td>1220.3</td>
</tr>
</tbody>
</table>

6.3.2 Roll forming

The experiments were carried out on the laboratory roll former described in Section 3.2.4 using two roll forming stations. The first station is equipped with flat top and bottom rolls and feeds in the material, while the second station forms the sheet up by 20°, as shown in the flower pattern in Figure 6.2. The strips have a width and thickness of 150mm and 2mm respectively and have a length of 1 m. The station distance was set to 400mm and the line speed was 17.3 mms⁻¹.

Figure 6.2: Flower diagram
6.3.3 Roll load and torque

Roll load and torque were measured at the 2nd station with a load cell and a torque transducer as explained in Section 3.2.5. Even though the material thickness was 2mm, the roll gap was set to 2.1mm to overcome excessive loads applied on the top tooling due to possible variations in material thickness along the strip length.

6.3.4 Longitudinal bow

Longitudinal bow of the product was analysed following the same procedure as given in Section 3.2.6.

6.4 Simulation model

The numerical model described in Section 3.3 was used in this investigation. Stiffness of the shaft and the frame components was taken into account when designing the model as explained in Section 3.3.4. The material models used will now be described in the following section.

6.4.1 Development of artificial material data

For this analysis 30 artificial true stress strain relationships were developed giving six levels of yield strength ($Y$) with five different hardening exponents ($n$) each. This enabled the detailed analysis of the interplay between material hardening and yield strength and the effect on roll load, torque and bow. The Hollomon’s power law was employed for the artificial material data development. In the Hollomon power law equation the strength coefficient ($k$) is a dependent variable that varies with the yield strength $Y$ and the hardening exponent $n$. To generate true stress strain curves with distinct combinations of $Y$ and $n$, $k$ was determined for each material model based on the stress-strain relationship at the yield point (see Figure 6.3). Equation (6.1) determines the elastic strain, $\varepsilon_e$, at any given yield point. The corresponding strength coefficient, $k$, was calculated using Equation (6.2) for the values of $Y$ and $n$ selected. Then the Hollomon’s power law of isotropic strain hardening given by Equation (6.3) was used to produce the effective stress-strain data that was applied as material input in the numerical model. The 30 material input variations developed this way are given in Table 6.2.
Figure 6.3: Typical true stress-strain graph

\[ \varepsilon_0 = \frac{Y}{E} \]  \hspace{1cm} (6.1)

where \( Y \) is the yield strength, and \( \varepsilon_0 \) is the elastic strain corresponding to the yield strength.

\[ k = \frac{Y}{\varepsilon_0^n} \]  \hspace{1cm} (6.2)

where \( k \) is the strength coefficient, and \( n \) is the hardening exponent

\[ \sigma_{true} = k \varepsilon_{eps}^n \]  \hspace{1cm} (6.3)

where \( \varepsilon_{eps} \) is the specific plastic strain and \( \sigma_{true} \) is the true stress.
Table 6.2: Artificial Material Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>$Y$ (MPa)</th>
<th>$n$</th>
<th>Model</th>
<th>$Y$ (MPa)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>490</td>
<td>0.15</td>
<td>Model 16</td>
<td>790</td>
<td>0.15</td>
</tr>
<tr>
<td>Model 2</td>
<td>490</td>
<td>0.20</td>
<td>Model 17</td>
<td>790</td>
<td>0.20</td>
</tr>
<tr>
<td>Model 3</td>
<td>490</td>
<td>0.25</td>
<td>Model 18</td>
<td>790</td>
<td>0.25</td>
</tr>
<tr>
<td>Model 4</td>
<td>490</td>
<td>0.30</td>
<td>Model 19</td>
<td>790</td>
<td>0.30</td>
</tr>
<tr>
<td>Model 5</td>
<td>490</td>
<td>0.35</td>
<td>Model 20</td>
<td>790</td>
<td>0.35</td>
</tr>
<tr>
<td>Model 6</td>
<td>590</td>
<td>0.15</td>
<td>Model 21</td>
<td>890</td>
<td>0.15</td>
</tr>
<tr>
<td>Model 7</td>
<td>590</td>
<td>0.20</td>
<td>Model 22</td>
<td>890</td>
<td>0.20</td>
</tr>
<tr>
<td>Model 8</td>
<td>590</td>
<td>0.25</td>
<td>Model 23</td>
<td>890</td>
<td>0.25</td>
</tr>
<tr>
<td>Model 9</td>
<td>590</td>
<td>0.30</td>
<td>Model 24</td>
<td>890</td>
<td>0.30</td>
</tr>
<tr>
<td>Model 10</td>
<td>590</td>
<td>0.35</td>
<td>Model 25</td>
<td>890</td>
<td>0.35</td>
</tr>
<tr>
<td>Model 11</td>
<td>690</td>
<td>0.15</td>
<td>Model 26</td>
<td>990</td>
<td>0.15</td>
</tr>
<tr>
<td>Model 12</td>
<td>690</td>
<td>0.20</td>
<td>Model 27</td>
<td>990</td>
<td>0.20</td>
</tr>
<tr>
<td>Model 13</td>
<td>690</td>
<td>0.25</td>
<td>Model 28</td>
<td>990</td>
<td>0.25</td>
</tr>
<tr>
<td>Model 14</td>
<td>690</td>
<td>0.30</td>
<td>Model 29</td>
<td>990</td>
<td>0.30</td>
</tr>
<tr>
<td>Model 15</td>
<td>690</td>
<td>0.35</td>
<td>Model 30</td>
<td>990</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 6.4 shows some material input curves given in Table 6.2; where Figure 6.4(a) shows the same level of yield combined with different hardening levels, Figure 6.4(b) depicts the different level of yield combined with same hardening levels and different yield strength levels combined with different hardening levels are shown in Figure 6.4(c).
Figure 6.4: True stress effective plastic strain data showing (a) same Y with different n (b) different Y with same n (c) different Y with different n

6.5 Model validation

For the validation of the numerical model, numerical results for longitudinal bow, roll load and torque obtained for DP780 were compared with experimental trials. A five point moving average was calculated, as explained in Section 3.2.5, to smoothen the roll load and torque variation in both the experimental and the numerical results.

6.5.1 Roll torque

The variation of roll torque at the bottom shaft of the 2nd station is shown in Figure 6.5 for the experimental trials and the numerical prediction. From the roll torque signal it can be seen that the roll torque is very small within the first 25s of the process, since initially only the bottom roll is driven without any material forming. When the sheet comes into contact with the rolls, the torque quickly reaches its maximum and stays constant until the sheet passes the rolls. For torque the maximum error of the numerical model is around 15.9% and one reasons for this error may be the underestimation of the coefficient of friction between the strip and the rolls which directly affects roll...
torque. Other authors proposed coefficients of frictions as high as 0.2 [33, 64] while in this study a coefficient of friction of 0.1 was applied [37].

![Figure 6.5: Comparison between the experimental and numerical roll torque at the bottom shaft of the 2nd station](image)

**6.5.2 Roll load**

The comparison between the numerical and experimental roll load results are shown in Figure 6.6. It can be seen that the roll load is zero within the first 25 seconds until the sheet contacts the rolls. Soon after that the strip reaches the roll gap and the roll load reaches its maximum value where it remains unchanged until the strip leaves the station.

![Figure 6.6: Comparison between the experimental and numerical roll load on the top shaft of the 2nd station](image)

The experimental roll load is over estimated by the numerical model by approximately 29%. In the simulation only some of the frame and shaft components were considered while other parts such as the bearings and bearing housings were not taken into
account. In addition to that, as far as the experimental setup is concerned, it can be seen that the bearing housing tends to slide against the frame when the forming load is applied on the top shaft, as shown in Figure 6.7. Therefore the frictional effect between the bearing housing and the frame may significantly influence the experimental roll load.

![Figure 6.7: Frictional effect between the bearing housing and the frame](image)

6.5.3 Longitudinal bow

The comparison between the numerical and the experimental longitudinal bow is shown in Figure 6.8. There is a good agreement between the numerical and experimental results for the maximum longitudinal bow and the error is below 10%. Overall, the results show that the current numerical model sufficiently represents the experimental set up. It is important to note that this validation has only been carried out for the profile shape given in Section 6.3.2.

![Figure 6.8: Comparison between the experimental and numerical longitudinal bow](image)
6.6 Results and discussion

The longitudinal bow, roll load and torque determined in each of the 30 simulated yield strength and hardening exponent combinations are shown in Table D.1 in Appendix D. Those results will be used in the regression analysis to determine the empirical relationships. Here the yield strength and the hardening exponent are considered as the input parameters, while the longitudinal bow, roll load and torque are considered to be the output parameters. The relationship between the output parameters will also be established to determine the link between longitudinal bow, roll load and torque.

6.6.1 Linear regression model

The first order multiple linear regression model can be represented as

\[ P_l = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \]  

(6.4)

where \( P_l \) represents the output parameters and \( x_1, x_2 \) are the yield strength, \( Y \), and the hardening exponent, \( n \), respectively. For the regression analysis the commercial software package MINITAB [106] was applied and the linear equations suggested are given in Table 6.3. The coefficient of determination \( (R^2) \) and \( R^2_{adj} \) are also shown and gives a measure for the accuracy of the suggested equation. \( R^2 \) determines the capability of the model to represent the output parameters and the higher \( R^2 \) the better the model is. If \( R^2 \) is close to \( R^2_{adj} \) all parameters in the model are significant (see Appendix E for further information). Therefore the regression models given in Table 6.3 are significant in terms of \( R^2 \) and \( R^2_{adj} \).

Table 6.3: Regression equations proposed by the MINITAB software for bow, load and torque

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regression equation</th>
<th>( R^2 ) (%)</th>
<th>( R^2_{adj} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>11.8 – 0.014 ( Y ) + 0.78 ( n )</td>
<td>96.9</td>
<td>96.7</td>
</tr>
<tr>
<td>Load</td>
<td>3.94 + 0.00778 ( Y ) + 23.8 ( n )</td>
<td>99.9</td>
<td>99.9</td>
</tr>
<tr>
<td>Torque</td>
<td>14.9 + 0.0342 ( Y ) + 124 ( n )</td>
<td>99.5</td>
<td>99.4</td>
</tr>
</tbody>
</table>

Additionally, the results of the variance analysis are given for each output variable in Table 6.4.
Table 6.4: Analysis of variance (ANOVA)-I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>DoF</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>Model</td>
<td>2</td>
<td>174.462</td>
<td>87.231</td>
<td>423.31</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual error</td>
<td>27</td>
<td>5.564</td>
<td>0.206</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>29</td>
<td>180.026</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>Model</td>
<td>2</td>
<td>137.575</td>
<td>68.788</td>
<td>13895.54</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual error</td>
<td>27</td>
<td>0.134</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>29</td>
<td>137.709</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Model</td>
<td>2</td>
<td>3322.8</td>
<td>1661.4</td>
<td>2597.35</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual error</td>
<td>27</td>
<td>17.3</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>29</td>
<td>3340</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the variance test results in Table 6.4, the suggested F value should be greater than F (2, 27) where 2 indicates the degree of freedom (DoF) of the regression model and 27 indicates the DoF of the residual error. If the significance level, $\alpha$ is taken as 0.001 then F (2, 27) needs to be greater than 9.02 (this value is taken from the standard F statistic table) for the regression model to be of statistical significance. Considering this the F values shown in Table 6.4 suggest that the linear regression models are acceptable for longitudinal bow, load and torque as they are significantly higher than 9.02. Therefore it can be concluded that the proposed linear regression models given in Table 6.4 can predict the numerical results accurately. To further understand the information given by the regression equations presented in Table 6.3, the main effect plots between input and output parameters will be considered.

6.6.2 The Main effect plot

The main effect plots were obtained from MINITAB to investigate the influence of the yield strength and the hardening exponent on the three output parameters roll load, torque and bow. They also graphically represent the relationships obtained by the regression equations in Table 6.3. The main effect is determined as explained in Section 5.4.1.1.

Figure 6.9 shows the main effect of the yield strength and the hardening exponent on longitudinal bow. It indicates a negative relationship between yield strength and
longitudinal bow while a minor positive relationship with the hardening exponent can be observed. This means longitudinal bow decreases with increasing yield strength while it slightly increases with the hardening exponent.

![Figure 6.9: Main effect plot for longitudinal bow](image)

As previously explained in Chapter 2 when the strip is bent in the roll forming station a point on the edge of the strip travels a longer distance compared to one positioned in the center. This leads to the development of longitudinal strain in the edge. If the magnitude of longitudinal edge strain exceeds the elastic limit of the material it is permanent and an imbalance in longitudinal strain between the strip edge and the center results which leads to bow [29]. When the yield strength of the material is high the elastic limit of the material increases. This will allow the material to longitudinally deform within the elastic limit during roll forming leading to a lower level of longitudinal bow [32, 33]. In contrast to that according to the regression model, the effect of material hardening has only a minor effect on bow (Figure 6.9). This is in contrast to the experimental results of Chapter 5 where the material hardening had a significant influence on bow. Chapter 5 showed (Figure 5.12) that the effect of hardening is more dominant when a forming angle of $30^\circ$ compared to the forming angle of $20^\circ$ which is used in the current analysis. A higher forming angle leads to an increase in longitudinal strain and higher plasticization in the strip edge, i.e., there is substantial hardening. If the forming angle is low the plastic longitudinal deformation in the edge will be low and this results in reduced material hardening and a lower effect of the hardening coefficient on bow as observed here. In summary it can be concluded that the material hardening has a significant effect if there is high longitudinal deformation in the flange, while for low longitudinal edge strain levels it may not be significant.
For roll load and torque direct positive relationships with the yield strength and the material hardening are observed (Figure 6.10 and Figure 6.11); i.e. roll load and torque increase with yield strength and material hardening. When the yield strength of the material is high the deformation energy required to form the material increases [69] and this leads to higher levels of roll load and torque. This was observed by several researchers in previous experimental and numerical studies [68, 70, 79]. However the effect of hardening on the roll load and torque has not been investigated before. It is important to note that the material hardening has a significant effect on the roll load and torque which will be discussed further in the next section.

![Figure 6.10: Main effect plot for roll load](image)

![Figure 6.11: Main effect plot for roll torque](image)

### 6.6.3 Percentage influence plot

According to the main effect plot obtained in Section 6.6.2, the general trends were identified between the input and output parameters. However this is not sufficient to make quantitative conclusions. Therefore all thirty models were taken to analyse the percentage influence of input parameters on the output parameters to quantitatively determine their relationship.
The percentage influence of material yield strength and the material hardening on the longitudinal bow, roll load and torque is shown in Figure 6.12. It becomes clear that longitudinal bow is almost entirely influenced by the material yield strength, rather than by material hardening. As explained above the reason for this may be the small bending angle formed which leads to low levels of plastic longitudinal strain in the strip edge and through this low material hardening effects.

Figure 6.12: Percentage influence of the input parameters yield strength and hardening exponent on the output parameters bow, roll load and torque

It can be seen in Figure 6.12 that the hardening exponent has a higher influence on roll load and torque compared to the material yield strength. The magnitude of roll load and torque are mainly related to the transverse bending of the part which is the main deformation mode in roll forming and generally high plastic strain levels are reached. For example, according to the simple pure bending theory, the transverse bending strain in the outer surface of a bent strip can be calculated by Equation (4.14) [65] and is 0.172 m/m for the profile roll formed in this chapter. This strain level is considerably higher than the elastic limit of the material (see Table 6.1 for the elastic limit of DP780).

Previous studies mostly focused on the effect of the yield strength on roll load and torque while the influence of material hardening was disregarded; this was probably due to the roll forming materials analysed being restricted to mild steel grades [68-70, 79]. In AHSS material hardening is significantly higher and the results from this chapter indicate that for these steel grades material hardening may have a higher effect on roll load and roll torque compared to the milder steel types conventionally roll formed.
6.6.4 Link between bow, roll load and torque

In a final step the linear regression analysis is applied to analyse if there is a relationship between the output parameters (bow, roll load and torque). Again the results obtained for the 30 different material combinations given in Table 6.2 were applied. According to the multiple linear regression model proposed by MINITAB the longitudinal bow can be expressed as a function of roll load and torque using the following relation.

\[ \text{Bow} = 21.5 - 9.01 \times \text{Load} + 1.7 \times \text{Torque} \]  

The corresponding \( R^2 \) and \( R_{adj}^2 \) values are 83.3% and 82.1% respectively, which indicates a reasonable fit in the regression line. The corresponding ANOVA data is given in Table 6.5 where the high magnitude of F confirms the significance of the model.

Table 6.5: Analysis of variance (ANOVA)-II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>DoF</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>Model</td>
<td>2</td>
<td>149.996</td>
<td>74.998</td>
<td>67.43</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual error</td>
<td>27</td>
<td>30.03</td>
<td>1.112</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>29</td>
<td>180.026</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The link between longitudinal bow, roll load and torque proposed by the regression model suggests that, for the roll forming process analysed here, Equation (6.5) can be applied to estimate bow if roll load and torque are known and only the material properties are changing. This represents the conditions present when roll forming automotive components from AHSS and UHSS where the process set up remains the same while the yield strength and the hardening characteristics of the material change due to property variations from coil to coil.

6.6.5 Example

To verify the idea of predicting the magnitude of bow in a roll forming process based on the measurement of roll load and torque, the roll forming process set up of this study is numerically analysed for three different types of steel using the FEA model described above and the amount of bow measured. Additionally, roll load and torque are determined. This is done for a DP600, a DP1000 and a MS900 steel which represent one AHSS and two UHSS respectively with distinct differences in yield.
strength and hardening characteristic. The average true stress strain curves of the three steel types analysed is shown in Figure 5.2.

The values for roll load and torque predicted by the numerical analyses were applied to estimate the maximum magnitude of bow using Equation (6.5). The comparison of the maximum bow estimated with Equation (6.5) and the numerically determined values for bow are shown in Figure 6.13.

![Figure 6.13: Numerically measured and statistically predicted bow for DP600, DP1000 and MS900](image)

While the DP600 and the DP1000 steel show positive values for bow, the MS900 shows an opposite trend. This confirms the trend indicated by Figure 6.9 where it shows negative bow after a certain limit of the yield strength. For all three steel types a reasonable correlation is achieved (Figure 6.13) between the maximum bow estimated with Equation (6.5) and the bow given by the numerical model. The percentage error was 10.5%, 16% and 17.88% for the DP600, the DP1000 and the MS900 steel respectively. The material models that were applied to generate the relationship in Equation (6.5) were obtained based on the DP780 tensile data and this may explain why a higher error is observed for the MS900 which shows significantly higher levels of yield combined with less hardening than conventional dual phase steels. This error may be reduced by performing additional numerical work with high yield - low hardening material models that are more representative for the material behaviour of martensite steel and by including the results in the regression analysis.
However the regression model given by Equation (6.5) can be successfully applied for the prediction of longitudinal bow on the basis of roll load and torque measured in the process; this has not been shown before. It is important to note that precise roll load and torque values are needed to accurately predict longitudinal bow in terms of roll load and torque. Also the equation developed can be only applied to this particular flower pattern given that the level of roll load and torque may vary with the geometry of the roll formed profile that is formed.

6.7 Summary

The effect of material yield strength and hardening exponent on longitudinal bow as well as roll load and torque for the roll forming of a trapezoidal section was investigated using a numerical model. First the numerical set up was verified by experimental roll forming trials performed with DP780 steel. After that a regression analysis combined with Analysis of Variance (ANOVA) techniques was employed to establish the relationships between the process and material parameters and to determine their percentage influence on longitudinal bow, roll load and torque. The analysis was performed for 30 artificial true stress strain relationships which represents six different levels of yield stress combined with five different hardening characteristics for each yield strength level. Major focus was on analysing the effect of yield strength and material hardening on bow, roll load and torque.

Bow and material properties

Both $R^2$ and F values confirmed the significance of the relationship between longitudinal bow, roll load and torque. Longitudinal bow has a linear negative relationship with yield strength. This confirms the reduction in bow with the yield strength of the material observed in previous studies [33, 55]. Nevertheless depending on the forming conditions and profile geometry this trend may change as observed by the author and co-workers [53]. There was a linear positive relationship with the hardening exponent (Table 6.3) however this was insignificant (Figure 6.12) for the process parameters analysed here. Comparison with the results of Chapter 5 suggests that the influence of the material hardening on bow highly depends on the amount of permanent longitudinal strain introduced in the strip edge is less dominate when forming a small angle of 20° as applied here.
Roll load, torque and material properties

Both $R^2_{adj}$ and F values confirmed the significant of the proposed regression models for roll load and torque. Roll load and torque show a linear positive relationship with yield strength and the hardening exponent (Table 6.3, Figure 6.10 and Figure 6.11) whereby the effect of material hardening is the highest for both roll load and torque. There also is a considerable influence of yield strength (Figure 6.12) and this is confirmed by previous studies [68, 69]. A significant influence of the material hardening has not been reported before and this is probably due to the roll forming materials analysed previously being restricted to mild steel grades [68-70, 79]. In AHSS and UHSS material hardening is significantly higher leading to a higher effect of the material hardening on roll load and torque.

Bow prediction with roll load and torque

Using multiple linear regression analysis a relationship between the longitudinal bow and roll load and torque is developed that allows the estimation of bow if the values for roll load and torque are known if the process set up is kept constant. The significance of the developed relationship was confirmed by both $R^2_{adj}$ and F values and its functionality proven for a DP600, a DP1000 and a MS900 steel representing one AHSS and two UHSS respectively. Good correlation between the numerical predictions for bow and those estimated based on the developed relationship is observed. This suggests that for the particular roll forming set up presented here changes in bow due to the variation of material properties can be successfully estimated based on changes in roll load and torque determined in one forming station. However the predicted bow is highly sensitive to the measured roll load and torque; precise load and torque measurements are therefore needed for an accurate prediction. Moreover in the industrial practice not only the material properties but also the profile geometry may vary. Therefore separate regression models needs to be developed from one profile to another and not only the material properties but also the profile geometry and process parameters need to be taken into account when designing a robust model for bow prediction.
7 The relationship between process and material parameters and roll load and torque

7.1 Introduction

In the previous chapter the effect of material properties on longitudinal bow, roll load and torque was investigated. It was found that changes in the material properties can be identified by roll load and torque measurements. This is an important finding; the final shape quality can vary for the same material grade from one coil to another, even though the machine setup is kept unchanged. If changes in material properties can be identified in advance by measuring roll load and torque, corrective action can be taken if the sensitivity of those defects to the material properties is known. However the developed model in Chapter 6 is very sensitive to the load and torque measurements. Moreover in industrial practice the profile geometry and the process parameters vary depending on the products to be manufactured and this will alter the level of sensitivity of roll load and torque on material property changes. Further, as observed throughout this thesis, in the roll forming process different degrees of defects can be seen in the final roll formed part depending on the incoming material properties, geometric parameters of the part and the process variables. In addition to that some related literature was presented in Chapter 2. Therefore, understanding about the effect of process and material parameters as well as part geometry on final part shape is required to successfully implement an automated defect compensation routine.

Longitudinal bow has been found to be dependent on geometrical parameters and material yield strength [31, 33, 51, 53, 55]; on the other hand roll load and torque are functions of the bending angle, material thickness, flange length and material yield
strength [68, 69]. In addition to that, according to the previous chapter, roll load and torque found to be dependent on the hardening exponent as well. As a result, understanding the combined effect of those process, geometric parameters and changes in material properties on roll load and torque as well as part shape is vital for developing a reliable defect compensation routine. The aim of this chapter is to identify the effect of all major variables for the roll forming of a trapezoidal section profile, such as material, geometrical and process parameters on longitudinal bow, roll load and torque; hence to establish a relationship between process and geometric parameters that will allow to estimate the material properties of incoming material and longitudinal bow based on roll load and torque for any given trapezoidal profile shape.

7.2 Methodology

In this chapter, first, all the geometric, process and material parameters that may have an influence on roll load, torque and longitudinal bow are listed as input parameters. They are material yield strength, hardening exponent, bending radius, material thickness, forming angle, friction coefficient between the rollers and the sheet, web length of the trapezoidal section, flange length and bottom roll diameter of the forming rolls. The effect of those parameters on longitudinal bow, roll load and torque (output parameters) will be investigated with a set of simulation models. The response surface methodology will be applied to obtain the different response surfaces to represent roll load, torque and longitudinal bow; then the best model will be used together with the regression analysis to obtain a regression model to represent longitudinal bow. Finally, a relationship will be established between longitudinal bow and the significant input parameters; thereby the material property parameters (i.e. yield strength and the material hardening) will be replaced by roll load and torque. This relationship will be experimentally tested for three AHSS and UHSS.

7.3 Experiment, material and simulation model

The numerical model already applied and experimental verified in the previous chapter was used in this chapter. The material input for the different simulation models was obtained based on the yield strength and the hardening exponent of a DP780 steel as explained in Section 6.4.1 using Equations (6.1), (6.2) and (6.3).
A number of simulations was carried out with different combinations of input parameters. The input parameters were chosen based on the literature and the new findings of the author. Some of the input parameters are shown in Figure 7.1. Other than that material yield strength, hardening exponent, inter-station distance and frictional coefficient between the strip and the rollers were considered as input parameters.

![Figure 7.1](image)

Figure 7.1: Some of the parameters considered as input parameters for the investigation

Three levels from each parameter above were analysed to account for non-linearity. The list of input parameters and their different levels are given in Table 7.1. The parameter levels were chosen based on the general roll forming conditions and the capacity of the machine explained in Section 3.2.4. Both coded and uncoded variables are given in Table 7.1. In coded variables low, middle and high parameter levels are represented by -1, 0 and 1 respectively; whereas in the uncoded representation, original parameter levels are chosen. The relationship between the coded and the uncoded variables for each parameter is given by Equations (7.1) to (7.9). Note that the *Italic* parameters represent the uncoded variables.
Table 7.1: Input parameters and their levels

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Uncoded variables</th>
<th>Coded variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Frictional coefficient (FC)</td>
<td>0.1 0.15 0.2</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>2 Yield strength (YS) / MPa</td>
<td>590 740 890</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>3 Hardening exponent (n)</td>
<td>0.15 0.25 0.35</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>4 Flange length (FL) / mm</td>
<td>36 48.5 61</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>5 Material thickness (t) / mm</td>
<td>1 2 3</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>6 Web length (WL) / mm</td>
<td>50 70 90</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>7 Bottom roll diameter (BRD) / mm</td>
<td>101.6 121.6 141.6</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>8 Forming angle (FA) / degrees</td>
<td>10 20 30</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>9 Bending radius (BR) / mm</td>
<td>4.8 8.8 12.8</td>
<td>-1 0 1</td>
</tr>
</tbody>
</table>

\[
FC = \frac{FC - 1.5}{0.05} 
\]  
\[
YS = \frac{YS - 740}{150} 
\]  
\[
n = \frac{n - 0.25}{0.1} 
\]  
\[
FL = \frac{FL - 48.5}{12.5} 
\]  
\[
t = \frac{t - 2}{1} 
\]  
\[
WL = \frac{WL - 70}{20} 
\]  
\[
BRD = \frac{BRD - 121.6}{20} 
\]  
\[
FA = \frac{FA - 20}{10} 
\]  
\[
BR = \frac{BR - 8.8}{4} 
\]  

7.4 Response surface methodology

Myers and Montgomery [114] define the response surface methodology (RSM) as a mathematical and statistical way of developing, improving and optimisation a process. This methodology can be used to investigate the effect of two or more independent variables on a specific dependent variable. Therefore we can use this method in
combination with finite element simulation for optimising the process prior to actual try-outs. The method requires a limited number of experiments for the analysis. Figure 7.2 shows a typical response surface plot. It indicates the effect of two independent variables on a dependent variable.

![Figure 7.2: Typical response surface plot [115].](image)

In the RSM different surfaces can be approximated to represent the relationship between the input and output parameters such as first order, second order and so on. In this analysis four models will be introduced and the best model will be used for the subsequent analysis.

The first response surface model defines a linear relationship between the input and output parameters by Equation (7.10). The second one is the two factor interaction model where only the interaction between the factors other than the linear terms are considered (Equation (7.11)). Next is the linear and quadratic model where only the linear and quadratic terms are taken into account as shown in Equation (7.12). The last is the full quadratic model where the complete second order relationship between the input and output parameters including two factor interactions is fitted by Equation (7.13).

After this an analysis of variance (ANOVA) study is carried out in combination with a regression analysis to determine the significance of each model (see Appendix E for further details).

\[
y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i \quad (7.10)
\]
\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=2}^{k} \beta_{ij} x_i x_j \] (7.11)

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 \] (7.12)

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \] (7.13)

In Equations (7.10) - (7.13) \( y \) is an output parameter, \( x_i \) and \( x_j \) are input parameters, \( \beta_i \), \( \beta_{ij} \) and \( \beta_{ii} \) are the regression coefficients of linear, interaction and square terms respectively.

### 7.4.1 Box-Behnken design

Box-Behnken is a response surface design which is especially developed for second order model generation. In this method three levels from each parameter are considered for the analysis. The general factors selection criteria for the three-factor Box-Behnken design is shown in Figure 7.3 where it considers only the mid-term combinations among the factors. The standard Box-Behnken design for nine input parameters consists of 130 different combinations of input parameters. Therefore 130 numerical models were developed as proposed by the MINITAB software package \[106\] and they were analysed to obtain the best response surface.

![Figure 7.3: Selection of the factor levels in the Box-Behnken design](image)
7.5 Selection of most influential factors

Nine factors were chosen as the input parameters as explained before. However not all of these will influence longitudinal bow, roll load or torque. It therefore is important to identify the most influential input parameters on the output parameters before going ahead with further analysis. Appendix F shows all the regression coefficients and their corresponding P (calculated probability) and T values (t-statistic) of all the input parameters for the four models described by Equation (7.10), (7.11), (7.12) and (7.13). If P value < $\alpha$ ($\alpha$ was taken as 0.001), then the parameter is significant. Further the T value should be greater than $t_{\alpha/2, n-k-1}$ from the standard t-test table to be a significant factor (see Appendix E). Table 7.2 shows the identified significant parameters for each model from the response surface results shown in Appendix F.

Table 7.2: Significant factors determined for the four different models described above.

<table>
<thead>
<tr>
<th>Model</th>
<th>Output parameters</th>
<th>Significant input parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Load</td>
<td>YS, n, t, FA</td>
</tr>
<tr>
<td></td>
<td>Torque</td>
<td>FC, n, t, BRD, FA</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>YS, FL, t, FA</td>
</tr>
<tr>
<td>Linear + two factor</td>
<td>Load</td>
<td>YS, n, t, FA, YS×t, n×t, t×FA</td>
</tr>
<tr>
<td>interactions</td>
<td>Torque</td>
<td>FC, YS, n, t, BRD, FA, FC×t, FC×FA, n×t, t×BRD, t×FA</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>YS, FL, t, FA, FL×t, t×FA</td>
</tr>
<tr>
<td>Linear + squares</td>
<td>Load</td>
<td>YS, n, t, FA, t×t</td>
</tr>
<tr>
<td></td>
<td>Torque</td>
<td>FC, YS, n, t, BRD, FA, t×t</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>YS, FL, t, FA, t×t</td>
</tr>
<tr>
<td>Full quadratic</td>
<td>Load</td>
<td>YS, n, FL, t, WL, FA, BR, t×t, YS×t, YS×FA, n×t, n×FA, FL×FA, t×FA, FA×BR</td>
</tr>
<tr>
<td></td>
<td>Torque</td>
<td>FC, YS, n, t, BRD, FA, BR, t×t, FC×t, FC×BRD, FC×FA, YS×t, n×t, n×FA, t×BRD, t×FA, BRD×FA</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>YS, FL, t, FA, t×t, FL×t, FL×FA, t×FA</td>
</tr>
</tbody>
</table>
Table 7.2 only shows those input parameters that are significant while those parameters that are insignificant with regard to longitudinal bow, roll load and torque are not shown. Nevertheless above investigation does not identify the model that gives the best fit with the output parameters. Therefore the four models were re-generated, but this time, only the significant parameters identified were taken into account. The resulting model properties are shown in Table 7.3.

Table 7.3: Improved model parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>( R^2 ) (%)</th>
<th>( R_{adj}^2 ) (%)</th>
<th>PRESS</th>
<th>( R_{pred.}^2 ) (%)</th>
<th>DoF</th>
<th>Error</th>
<th>Model</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Load</td>
<td>93.91</td>
<td>93.71</td>
<td>689.18</td>
<td>92.9</td>
<td>125</td>
<td>4</td>
<td>481.66</td>
</tr>
<tr>
<td></td>
<td>Torque</td>
<td>89.71</td>
<td>89.29</td>
<td>167130</td>
<td>88.41</td>
<td>124</td>
<td>5</td>
<td>216.13</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>77.27</td>
<td>76.54</td>
<td>621.83</td>
<td>74.64</td>
<td>125</td>
<td>4</td>
<td>106.24</td>
</tr>
<tr>
<td>Linear + two factor</td>
<td>Load</td>
<td>98.53</td>
<td>98.44</td>
<td>176.44</td>
<td>98.18</td>
<td>122</td>
<td>7</td>
<td>1166.38</td>
</tr>
<tr>
<td>interactions</td>
<td>Torque</td>
<td>97.43</td>
<td>97.19</td>
<td>49164.4</td>
<td>96.59</td>
<td>118</td>
<td>11</td>
<td>428.04</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>83.43</td>
<td>82.67</td>
<td>468.447</td>
<td>80.90</td>
<td>123</td>
<td>6</td>
<td>113.81</td>
</tr>
<tr>
<td>Linear + squares</td>
<td>Load</td>
<td>94.98</td>
<td>94.77</td>
<td>595.75</td>
<td>93.87</td>
<td>124</td>
<td>5</td>
<td>468.84</td>
</tr>
<tr>
<td></td>
<td>Torque</td>
<td>91.74</td>
<td>91.26</td>
<td>144468</td>
<td>89.99</td>
<td>122</td>
<td>7</td>
<td>210.39</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>83.01</td>
<td>82.33</td>
<td>487.24</td>
<td>80.13</td>
<td>124</td>
<td>5</td>
<td>121.18</td>
</tr>
<tr>
<td>Full quadratic</td>
<td>Load</td>
<td>99.86</td>
<td>99.84</td>
<td>19.7898</td>
<td>99.80</td>
<td>114</td>
<td>15</td>
<td>5259.24</td>
</tr>
<tr>
<td></td>
<td>Torque</td>
<td>99.41</td>
<td>99.33</td>
<td>12879.0</td>
<td>99.11</td>
<td>112</td>
<td>17</td>
<td>1109.27</td>
</tr>
<tr>
<td></td>
<td>Bow</td>
<td>90.69</td>
<td>89.99</td>
<td>288.263</td>
<td>88.24</td>
<td>121</td>
<td>8</td>
<td>144.12</td>
</tr>
</tbody>
</table>

Table 7.3 includes all the important parameters to determine the best model. \( R^2 \) is a measure for the capability of the model to represent the output parameters and as higher \( R^2 \), the better is the model. If \( R^2 \) is close to \( R_{adj}^2 \), then all parameters in the model are significant. \( R_{pred.}^2 \) determines the ability of the model to predict the corresponding parameters. A low PRedicted Error Sum of Squares (PRESS) value and a high F value further ensure the accuracy of the model (see Appendix E).

By considering all the above parameters, the full quadratic model shows the highest accuracy among all models. It therefore is applied in the further study to analyse roll load, torque and bow.
7.6 Results and discussion

In this chapter an extensive numerical study on roll load, torque and longitudinal bow was carried out leading to a longitudinal bow predicting model for trapezoidal section roll forming. Some of the trends determined here have already been observed in Chapters 5 and 6 and therefore will not be discussed in detail. For example, according to the full quadratic model given in Table 7.2, longitudinal bow depends on yield strength, flange length, material thickness and forming angle and those trends were already experimentally investigated in combination with peak longitudinal edge strain in Chapter 5.

7.6.1 Roll load and torque

According to the full quadratic model both roll load and torque are influenced by yield strength, hardening exponent, material thickness, and forming angle (Table 7.2). Other than that roll load is influenced by the flange length, web length and bending radius, while torque is additionally influenced by the friction coefficient and the diameter of the bottom roll. However this analysis does not give any quantitative measure with regard to the significance of those factors.

In the upcoming section the effect of aforementioned parameters on roll load and torque will be investigated. Several previous studies investigated the link between roll load and torque and some geometrical factors and material yield strength [68, 69]. However the currently analysis will identify additional significant parameters that have not been reported yet in the literature. Furthermore previous trends were not investigated for AHSS and UHSS and given that our study has shown that the hardening behaviour plays a significant role with regard to the roll load and torque chapter those links need to be re-established for the case of AHSS and UHSS.

In the following analysis, when the effect of a certain parameter is investigated, the other parameters were kept constant at their medium levels which are given in Table 7.1. For example when the effect of material thickness on roll load and torque is investigated, other parameters such as yield strength, hardening exponent, flange length and so on are kept constant at their mediums levels.
7.6.1.1 Yield strength and hardening exponent

Both yield strength and the hardening exponent significantly influence the roll load and torque as shown in Figure 7.4. The same trend was observed in Chapter 6 and the main reason for this was also discussed there.

![Figure 7.4: Effect of (a) yield strength (b) hardening exponent on roll load and torque](image)

7.6.1.2 Material thickness

Material thickness is the most influential factor on roll load and torque given that the bending energy is proportional to the square of the material thickness as reported by Panton et al. [27]. Therefore both roll load and torque increase with material thickness in a quadratic fashion. Previous studies also have shown that roll load and torque are a function of the material thickness [68, 69]. Roll load shows a higher sensitivity to material thickness than roll torque and increases 7 fold compared to roll torque which only increased 5 fold when the material thickness changes from 1 to 3 mm. This suggests that even slight changes in material thickness can have a significant effect on roll load and torque and verifies our strategy to maintain some clearance between the forming roll and the sheet in the station where roll load and torque are measured to allow for potential material thickness deviations. Comparison with previous studies reveals that the sensitivity of roll load to the material thickness is considerably higher in the high strength steels investigated here compared to the mild steel grades analysed in [69]. Figure 7.5 further suggests that the material thickness should be considered to represent material properties in terms of roll load and torque.
7.6.1.3 Forming angle

The forming angle is the second most influential factor on roll load and torque which both linearly increase with the forming angle as shown in Figure 7.6. It has been revealed previously that the transverse bending energy in roll forming increases with the increase in forming angle [27]. Therefore roll load and torque also increase with the increase in forming angle and our results agree with those previous studies [68, 69]. The sensitivity of roll torque to the bending angle is slightly higher compared to the roll load. In addition to that it is clear that the roll load and torque are greatly influenced by the forming angle and this effect needs to be considered if the material property changes are represented by the roll load and torque for a given profile.

Figure 7.5: Effect of material thickness on roll load and torque

Figure 7.6: Effect of forming angle on roll load and torque
7.6.1.4 Bending radius

While in roll forming the bending radius is inversely proportional to the transverse bending strain [27] the transverse bending energy is independent of the bending radius [27, 69]. There is a slight decrease of roll load and torque with increasing profile radius but this influence is minor compared to that observed for the forming angle and the material thickness.

![Figure 7.7: Effect of the bending radius on roll load and torque](image)

7.6.1.5 Bottom roll diameter

The bottom roll diameter only influences roll torque while the roll load is independent of the bottom roll diameter (Figure 7.8). When the roll diameter increases, the contact area between the rolls and the strip increases which results in higher frictional forces. In addition to that, a higher bottom roll diameter increases the distance between the axis of rotation and the contact surface leading to an increase in roll torque with bottom roll diameter. This has not been investigated before and our results indicate that roll torque can independently vary with parameters while the roll load stays unchanged.
7.6.1.6 The coefficient of friction

The effect of the coefficient of friction on roll load and torque is shown in Figure 7.9. The coefficient of friction does not influence the level of the roll load, because the frictional force mostly influence the horizontal movement of the sheet while its vertical component is very small. However, since roll torque relies on the horizontal forces acting on the bottom roll, it increases with the frictional coefficient in a linear fashion. The power consumption of a roll former may therefore be greatly reduced by enhancing lubrication. Moreover this shows the importance of choosing the correct frictional coefficient in the finite element analysis of the roll forming process when analysing roll torque.
7.6.1.7 Flange length

Even though the initial analysis identified the flange length to be a statistically significant factor for longitudinal bow, it only has a minor effect on roll load and it does not influence roll torque (Figure 7.10). This is in contrast to previous studies which found that the roll load is a function of the flange length [69]. The results however confirm the studies performed by Lindgren [68] and Panton et al. [27] who both suggest that the flange length does not influence transverse bending and through that should not influence on roll load and torque.

![Figure 7.10: Effect of flange length on roll load and torque](image)

7.6.1.8 Web length

The roll load slightly increases with web length but the effect is minor compared to the other factors investigated above (Figure 7.11). Even though increasing the web length leads to a higher contact area between the forming rolls and the part, it has no effect on the level of roll torque.

![Figure 7.11: Effect of the web length on roll load and torque](image)
7.6.2 Introduction of roll load and torque for longitudinal bow prediction

According to the experiments of Chapter 5 longitudinal bow depends on the material yield and hardening properties, flange length, forming angle and the material thickness. This was confirmed by the numerical analysis carried out in this chapter. In addition to that it was found that longitudinal bow is independent of the web length, bending radius, frictional coefficient and bottom roll diameter (Appendix F). In the previous chapter it was found that changes in material properties can be represented by the roll load and torque of the process. Additionally, above results have shown that roll load and torque not only depend on the material properties but also on geometrical parameters such as the material thickness, the flange length and the web length as well as process parameters such as the forming angle, the bending radius, the bottom roll diameter and the coefficient of friction. Therefore the link between material properties, roll load and torque depends on the part geometry and the process parameters. As a result, if we want to represent the material properties in terms of roll load and torque, the process and geometry factors that have an effect on roll load and torque need to be considered. This requires a regression analysis for longitudinal bow that considers all input parameters given in Table 7.1, their square terms and the two factor interactions. Thereby yield strength and hardening exponent are replaced by roll load and torque given that the previous chapter has shown that there is a direct relationship between roll load and torque and the material properties (Chapter 6). In addition to that the square root terms of roll load and torque are taken into account as they are very significant parameters in this investigation; this may help to obtain a robust regression model to represent longitudinal bow. The regression equation obtained this way is given by Equation (7.14) and the corresponding ANOVA analysis is shown in Table 7.4. Not only the P value but also the F value confirms the significance of the model. Additionally, the high values determined for $R^2$, $R^2_{adj}$ and $R^2_{prediction}$ of 88.5%, 87.9% and 86.91% respectively confirm the significance and the ability of the developed relationship for predicting bow.
As given in Equation (7.14), bow is affected by material thickness, the forming angle, the flange length and the material properties (yield strength and material hardening) which is represented by roll load and torque. In addition to that the coefficient of friction, the web length, the bottom roll diameter and the bending radius are not significant factors in defining longitudinal bow. Theoretically Equation (7.14) can be applied to any given trapezoidal section to determine the amount of longitudinal bow in the part based on measured values of roll load and torque. It is important to note that very precise load and torque measurements are needed for the accurate prediction of the longitudinal bow as those are the only variables measured during the roll forming process.

### 7.6.3 Example

To apply the equation obtained above in a real roll forming application 3 materials were experimentally tested, a DP600, a DP1000 and a MS900; their true stress-strain graphs are given in Figure 5.2 and the corresponding material properties are given in Table 5.3. Strips, 1m in length, 125mm in width and 2mm in thickness were roll formed in two stations in the laboratory roll former as explained in Section 3.2.4. The strips were formed to 20 degrees while the roll load and torque were measured during the process as explained in Section 3.2.5. A summary of the model parameters is given in Table 7.5. Finally longitudinal bow was measured as explained in in Section 3.2.6.

---

### Table 7.4: ANOVA table for longitudinal bow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>DoF</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>Model</td>
<td>6</td>
<td>2169.3</td>
<td>361.55</td>
<td>157.29</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual error</td>
<td>123</td>
<td>282.73</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>129</td>
<td>2452.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.5: Details of the numerical model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frictional coefficient</td>
<td>0.1</td>
</tr>
<tr>
<td>Inter-station distance</td>
<td>400</td>
</tr>
<tr>
<td>Flange length/mm</td>
<td>36</td>
</tr>
<tr>
<td>Material thickness/mm</td>
<td>2</td>
</tr>
<tr>
<td>Web length/mm</td>
<td>50</td>
</tr>
<tr>
<td>Bending radius/mm</td>
<td>4.8</td>
</tr>
<tr>
<td>Bottom roll diameter/mm</td>
<td>101.6</td>
</tr>
<tr>
<td>Top roll diameter/mm</td>
<td>196.8</td>
</tr>
<tr>
<td>Forming sequence</td>
<td>0 - 20°-free</td>
</tr>
</tbody>
</table>

Table 7.6 shows the values for the measured longitudinal bow and those predicted by Equation (7.14) for the three different materials analysed.

Table 7.6: Longitudinal bow determined experimentally via roll forming trials on the three different steel types and predicted by Equation (7.14)

<table>
<thead>
<tr>
<th>Material</th>
<th>DP600</th>
<th>DP1000</th>
<th>MS900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (kN)</td>
<td>5.1</td>
<td>6.9</td>
<td>7.64</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>44.9</td>
<td>65.12</td>
<td>71.24</td>
</tr>
<tr>
<td><strong>Bow (mm)- Measured</strong></td>
<td>9.34</td>
<td>8.06</td>
<td>6.63</td>
</tr>
<tr>
<td><strong>Bow (mm)- Predicted</strong></td>
<td>10.4</td>
<td>8.84</td>
<td>8.27</td>
</tr>
<tr>
<td>Error (%)</td>
<td>11.35</td>
<td>9.68</td>
<td>24.74</td>
</tr>
</tbody>
</table>

According to Table 7.6, the best agreement between the predicted and the experimentally measured bow can be seen for DP1000, while the highest error was observed for MS900. Additionally, the regression model given by Equation (7.14) over estimates bow for all three material grades tested. This may be due to several reasons. Since the regression model was obtained based on numerical simulation, the accuracy of the predicted bow depends on the accuracy of the numerical model. It was shown in Chapter 6, that the accuracy of the numerical model for roll load, torque and bow was 71%, 84% and 90% respectively. Therefore some error in the value for bow predicted by Equation (7.14) can be expected. In addition to that the $R^2_{prediction}$ value of the regression model is only 86.91% which suggests that a maximum error of
13.09% can be expected from the regression model. For the MS900 the lowest accuracy was achieved. This is most likely due to the numerical model being developed based on material properties derived from a dual phase steel (DP780) which shows significantly higher hardening compared to martensitic steel such as the MS900 steel. This suggests that for developing an equation that generates the relationship between bow and roll load and torque while taking into account the effect of process and geometric parameters, material input of the material that is actually formed should be applied.

7.7 Summary

Extensive finite element analysis was carried out to develop a longitudinal bow prediction model for the roll forming of a trapezoidal section. For that 130 numerical models were developed and analysed with different combinations of nine parameters consisting of material properties, geometric and process parameters. A trapezoidal section roll forming model with different levels of frictional coefficient, yield strength, hardening exponent, flange length, material thickness, web length, bottom roll diameter, forming angle and bending radius was considered for the investigation.

First it was identified that the full quadratic response surface model is the best model to represent the effect of process, material and part geometry parameters on roll load, torque and longitudinal bow an accuracy of over 90%. The analysis further showed that roll load is a function of flange and web length, while roll torque was mainly influenced by friction and the bottom roll diameter. Material thickness and forming angle were identified to have the highest effect on roll load and torque followed by the yield strength and material hardening which also had a considerable effect. The effect of the bending radius, the flange length and the web length on roll load and torque can be neglected for the profile shape and the process conditions analysed here.

Finally an alternative regression model was proposed by extending the response surface study to longitudinal bow. For that the linear, square and two factor interactions of all the input parameters were considered except of the yield strength and the hardening exponent which were replaced by roll load and torque. This was possible given that there is a direct relationship between roll load and torque and the material properties (Chapter 6). The square root terms of roll load and torque were
considered to obtain a robust regression model. It was found that friction, the web length, the bottom roll diameter and the bending radius had no effect on the amount of bow predicted while roll load, torque, flange length, material thickness and the forming angle were found to be significant factors. The developed model was confirmed with experimental results obtained for three AHSS and UHSS grades achieving an accuracy of 75% to 90% depending on the material. The error of the regression equation obtained may be related to inaccuracies in the numerical model that was applied for its establishment. In Chapter 6 the numerical model used here showed an error of 29% and 15.9% with regard to experimentally predicted roll load and torque respectively and it is likely that this error was carried forward into the regression equation. The least accuracy could be seen for the martensitic material (MS900). The material models applied in the regression analysis were based on the material properties derived from DP780 which generally shows significantly higher hardening than a martensitic grade steel such as MS900. Therefore to achieve high accuracy it is vital that the material models used for the numerical analysis are based on the material that is formed and that the numerical model is as accurate as possible.

The regression model developed in Chapter 6 was very sensitive to the material properties given that other parameters, such as material thickness, flange length and forming angle, were not taken into account. The new model developed here is more robust since it takes into account additional parameters that influence roll load and torque as well as bow. Further the regression model given by Equation (7.14) can be applied to any trapezoidal section that is roll formed in two stations with the set up analysed here to predict bow on the basis of roll load and torque measurements performed during the process.

As mentioned above, in AHSS and UHSS steel material properties significantly change from coil to coil or within the same coil and this affects longitudinal bow of the final product. However the regression model developed in this chapter suggests that for any given trapezoidal section changes in bow due to the variation of material properties or geometrical parameters can be successfully estimated based on the changes in roll load and torque determined in one forming station; this possibility has not been revealed before. Ultimately this method can be used together with adjustable
tooling or special shape compensation techniques which may allow the in-line compensation of longitudinal bow in future roll forming lines.
8 Defect compensation based on the measurement of roll load and torque

8.1 Introduction

In the previous chapter, the effect of process and material parameters, such as yield strength and material hardening on roll load and torque was investigated. It was found that the material thickness and the forming angle are the most significant parameters that influence roll load and torque additionally to the material yield strength and the hardening exponent. In Chapter 6 it was identified that the variation in material properties can be represented by the measured roll load and torque in the process for a selected profile. Further a link between longitudinal bow and the roll load and torque was established that allows the prediction of changes in the longitudinal bow due to material property changes. The previous chapter revealed that longitudinal bow not only depends on material parameters but that also geometrical and process parameters influence the degree of bow variation with material property change. Therefore a regression model was developed in Chapter 7 to represent the combined effect of material, process and geometrical parameters on longitudinal bow with the material property changes represented by roll load and torque. This regression model was successfully applied for predicting longitudinal bow on the basis of roll load and torque. This chapter will investigate a possible bow compensation methodology that can be applied to current roll forming set ups to compensate for bow based on the measurement of roll load and torque.

Even though longitudinal bow is a common defect in roll forming, trial and error is still often employed in the industry for its elimination. A Turks-head straightener is such a mechanism where some counter bending is introduced into the section to
eliminate longitudinal bow, twist and camber (see Figure 2.30). In this method compensation is carried out based on the experience of the operator and several parameters need be adjusted to get the exact compensation setting which is time consuming.

The aim of this chapter is to introduce a new mechanism which can be used to eliminate longitudinal bow during the roll forming process. Ultimately this operation can be automated in such a way that the adjustment can be made automatically according to the longitudinal bow predicted by the regression model without the interruption of the process.

8.2 Methodology

A new roll stand will be introduced which can be rotated around the bottom roll axis to compensate for bow. The applicability of this new stand will be numerically proven with finite element analysis.

The ultimate goal of this work can be represented by the flow chart given in Figure 8.1. We will simulate the roll forming of trapezoidal sections with different materials and geometries. The sensitivity of longitudinal bow to those parameters has been investigated in the previous chapter and a regression model was developed to predict the amount of bow based on roll load and torque. Successfully compensating for longitudinal bow applying the technique developed here requires the accurate tuning of the compensation action based on roll load and torque measurements. After achieving the complete solution space for the compensation action for any forming condition, the solution set can be stored in an inbuilt memory of a controller which gives the required corrective signal to the actuators to act accordingly. However this is not an easy task as the compensation action itself depends on material properties such as material yield, and hardening as well as geometric parameters such as the flange length, the material thickness and the forming angle. Therefore an extensive study needs to be conducted to identify the complete solution space. Nevertheless, this chapter will only introduce the basics of the compensation methodology and will identify those parameters that have a major effect on the compensation action.
8.3 New roll stand design

A simple modification to a traditional roll forming stand is introduced to compensate for longitudinal bow in the last station. For that the last station is designed in such a way that it can be rotated around the bottom roll axis as shown in Figure 8.2.
In contrast to the forming station, in the stand applied for compensation, the top roll needs to cover the full profile as it is illustrated in Figure 8.3. This ensures full support of the flange and avoids any unwanted deformation in the flange when introducing rebending at the web.

### 8.4 Simulation model

The simulation model already explained in Section 3.3 was applied with one additional last station that introduces the bow compensation action explained above (see Figure 8.4).
In the numerical model the bow compensation action is achieved by rotating the top roll around the bottom roll axis centre, A, as shown in Figure 8.5. This ensures maintaining the roll gap while introducing a counter bend onto the part.

![Figure 8.5: Bow compensation mechanism](image)

In this numerical study, the longitudinal bow compensation procedure was investigated under two different conditions. The first considered the effect of material properties, i.e. yield strength and material hardening while the effect of geometric parameters such as flange length, forming angle and material thickness was investigated in the second part of this study.

The Effect of material yield and hardening on the compensation action was investigated by numerically analysing the forming of the profile shape given in Figure 8.6 and applying the bow compensation routine introduced above.

![Figure 8.6: Dimensions of the roll formed profile](image)

Four different material models were included; those were obtained based on the yield strength and the material hardening of a DP780 steel as explained in Section 6.4.1
using Equations (6.1), (6.2) and (6.3). The selected material models are shown in Figure 8.7.

![Graph showing different material inputs](image)

**Figure 8.7: Different material inputs used for the numerical model**

The corresponding yield strength and the hardening exponent of the material inputs shown in Figure 8.7 are given in Table 8.1. Between Material 1, 2 and 3 the yield strength increases in 100 MPa increments while maintaining the same material hardening. Additionally, comparing Material 1 and 4 will allow to analyse the effect of material hardening on the compensation action required to compensate for bow.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength (MPa)</th>
<th>Hardening exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material 1</td>
<td>590</td>
<td>0.15</td>
</tr>
<tr>
<td>Material 2</td>
<td>690</td>
<td>0.15</td>
</tr>
<tr>
<td>Material 3</td>
<td>790</td>
<td>0.15</td>
</tr>
<tr>
<td>Material 4</td>
<td>590</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Table 8.1: Material properties represented by the true stress-effective plastic strain curves given in Figure 8.7.**

*The Effect of part geometry parameters on the compensation action* was investigated by numerically analysing four different sectional shapes which are shown in Figure 8.8. Material 1 (Table 8.1) was used for material input.
Comparing Profiles 1 and 2 will enable analysis of the effect of the profile angle on the compensation action required while analysing profiles 1 and 3 will give an understanding of the influence of material thickness. The effect of flange length will be investigated by analysing the compensation actions required for profiles 1 and 4.

For compensation, first longitudinal bow was “measured” without introducing any compensation (no rotation at the last station). After that the direction of rotation of the compensation stand was determined according to the direction of the measured longitudinal bow. If the value for measured bow is positive, then the corrective motion of the last station is anticlockwise whereas it is clockwise if bow is negative. After that an increasing rotation of the compensation stand was introduced in 2.5° increments until the bow defect was fully eliminated. Thereby the reduction of longitudinal bow with increasing rotation angle was plotted.

8.5 Results and discussion

8.5.1 Effect of material parameters on bow compensation action

Figure 8.9 shows the bow compensation action for the four material property combinations analysed.
Figure 8.9: Station rotation angle versus longitudinal bow

All four material combinations show positive values for bow requiring an anticlockwise rotation of the roll stand for compensation. It can be seen that the level of bow decreases with increasing yield strength of the material while hardening only has a minor effect on the initial level of bow. During compensation for all materials bow gradually decreases with the angle of rotation whereby the reduction in bow with rotation angle is less at the start and more rapid at the end of the compensation action. Even though bow is higher at lower material yield strength (Material 1) the level of rotation required for compensation is less compared to material that shows higher yield strength and less initial bow (Material 3). A higher hardening coefficient (Material 4) does not influence the initial level of longitudinal bow but results in higher compensation action required for bow compensation compared to a material with the same yield strength but less hardening (Material 1).

Above results suggest that the bow compensation path required may vary from one material to another and that a higher level of longitudinal bow does necessarily result in a higher angle of rotation required for bow compensation. This suggests that to achieve accurate bow compensation the link between material yield and hardening and the compensation movement required by the roll stand for compensation needs to be first established.
8.5.2 Effect of geometrical parameters on bow compensation action

The amount of rotation required to eliminate bow in Profiles 1 and 2 is shown in Figure 8.10.

![Figure 8.10: Comparison of compensation action for Profiles 1 and 2](image)

It can be seen that longitudinal bow is positive and higher for a lower profile angle formed. Longitudinal bow decreases with the anticlockwise rotation of the stand for both profiles resulting in zero bow at 4° and 7.5° rotation for profile 2 and profile 1 respectively. This suggests that for the case of the formed profile angle the compensation rotation is almost directly proportional to the initial bow in the part.

Figure 8.11 shows the change in longitudinal bow with rotation angle for Profile 1 and Profile 3 and it becomes clear that depending on the material thickness the effect of the station rotation on longitudinal bow varies over the compensation path. Nevertheless a higher level of initial bow results in a higher station rotation for compensation, i.e., similar to the profile angle when the material thickness changes the amount of rotation required for compensation is proportional to the initial bow in the section.
Figure 8.11: Comparison of compensation action for Profiles 1 and 3
The effect of the flange length on the compensation action is shown in Figure 8.12 and a higher flange length results in a lower level of longitudinal bow.

Figure 8.12: Comparison of compensation action for Profiles 1 and 4
Nevertheless in contrast to the material thickness and the profile angle where the station rotation required for compensation remained proportional to the level of initial bow, for the case of a changing flange length a higher initial bow requires less station rotation angle compensation. This may be due to a higher bending rigidity of Profile 4 which may result in a higher resistance against counter bending in the part. This suggests that the compensation action required depends on not only on the amount of initial bow, but also the part geometry.

8.5.3 Other observations
In this section some additional observation made in the finite element analysis will be presented. In Figure 8.9 - 8.12 it becomes clear that the direction of bow suddenly changes from positive to negative within a few degrees close to the zero bow location.
If bow is overcompensated (Figure 8.12) some unwanted deformation can be observed. To illustrate this the change in profile shape over three rotation increments is shown for Profile 1 (Figure 8.8(a)) in Figure 8.13. There is positive bow in the part when the angle of rotation is 5° and the flange stays stretched. When the angle of rotation is 7.5° the bow is fully compensated and the final part is straight. However when the angle of rotation becomes 10°, the part produces negative bow and this results in edge waves in the flange. This suggests that identifying the exact amount of rotation required for compensation is vital to achieve a defect free part.

![Figure 8.13: Part geometry during bow compensation for Profile 1](image)

The counter bending action required on the web for bow compensation can also result in the opening of the part or flange unfolding, i.e., the final profile angle of the section is larger than initially formed by the tooling. As it can be seen in Figure 8.13, the flange tends to unfold with increasing compensation rotation. If the web area is counter bent to overcome the positive curvature, then the natural tendency is to unfold in the flange area. Therefore in addition to the usually observed springback effect, flange unfolding during bow compensation will further increase the deviation of the actual to the desired part shape. This may be eliminated by overbending the profile prior to bow compensation.
8.5.4 Limitations

The proposed bow compensation method can be applied to eliminate bow in any given trapezoidal profile. The bow compensation was realised by introducing counter bending into the web and this may introduce some unwanted deformation into the flange area and produce defects such as flange unfolding or edge waves. In current roll forming practice springback is usually eliminated by overbending of the part [1] and the same technique may be applied to overcome the flange unfolding. Therefore flange unfolding may not be a significant defect to be discussed in this chapter. However there is no proper methodology to eliminate edge waves in roll forming. As a result the bow compensation needs to be carried out in a controlled manner to avoid the occurrence of bow overcompensation and edge waves. The first step is already taken by introducing complete solid top rolls into the compensation stand that cover the full surface of the part. Further it could be seen in the numerical model that the part tends to produce edge waves if the direction of bow changes due to the compensation action. For example if there is positive bow in the part, the compensation action reduces the bow continuously with the angle of rotation and reaches zero bow at one stage. If the compensation action continues further, the part will produce negative bow resulting in edge waviness in the flange. Therefore the compensation action needs to be very precise to avoid edge waves.

8.6 Summary

A new technique to compensate longitudinal bow in roll formed sections was introduced. According to the new concept, bow can be compensated for by rotating the last station clockwise or anticlockwise depending on the direction of bow.

The concept was numerically analysed which showed that the amount of counter bending depends not only on the amount of initial bow, but also on the part geometry and the material properties such as yield strength and material hardening. Therefore one direct path cannot be defined to compensate the longitudinal bow in any given trapezoidal section. As a result extensive study needs to be carried out to identify the exact compensation rotation required depending on the profile formed and the material parameters.
Additionally, the bow compensation needs to be carried out in a well-controlled manner. The development of wrinkles in the flange was observed if the stand rotation used for bow compensation was higher than required. This can only be avoided by applying the exact compensation action required. Flange unfolding is another shape defect resulting from the bow compensation action introduced here. This may be easily eliminated by overbending the part before bow compensation is performed.

For an automated bow compensation routine an extensive study needs to be carried out to identify the full solution space for bow compensation. This requires a set of simulations and the development of a regression equation to predict the compensation rotation. Therefore it will more practical to define the compensation routine for one selected profile as generally the part geometry only changes between products. Then the compensation routine would only change due to property deviations in incoming material. This would give a simpler solution and is more representative for AHSS and UHSS forming where material properties can change between coils. If we can estimate the range of material property variation within the coil or from coil to coil, the compensation routing can be obtained accordingly.

In addition to that, it is important to note that, as stated before, slight deviations in the material thickness were not taken into account during this analysis. This may influence the compensation action if thickness variations exist in the incoming material.

The proposed new roll stand needs to be automated in a way that allows adjusting according to the predicted longitudinal bow in terms of the roll load and torque. This is not an easy task and more process controlling aspects need to be taken into account to realise this concept.
9 Conclusions and future recommendations

9.1 Conclusions

The aim of this thesis is to identify the effect of material properties on roll forming product defects and longitudinal edge strain, to introduce a new technique to identify those defects in the roll forming process and to use this information to develop a defect compensation routine. To achieve this, analytical, experimental and numerical investigations were carried out. An analytical model was developed to understand the forming behaviour in roll forming; this was used as a basic tool to develop the optimum flower pattern in roll forming. The model identified peak longitudinal edge strain as a significant parameter that determines the degree of defect in a roll formed part. The effect of different geometric and process parameters (which are obtained from the analytical model) on peak longitudinal edge strain and some key shape defects was experimentally investigated. This showed that material properties have a significant influence on the final part shape in roll forming. It is known that AHSS and UHSS roll forming material properties can vary significantly from one coil to another and a new technique is proposed to identify property deviations in incoming material by measuring roll load and torque in the process. A relationship was developed to identify the change in longitudinal bow based on the measured roll load, torque and other process and geometric parameters. The applicability of this method in actual roll forming practice was tested and a new technique introduced to compensate longitudinal bow based on roll load and torque; this constitutes a first attempt to achieve an automatic in-line bow compensation routine. The main findings of this research are presented below.
Development of a new analytical model to find the optimum flower pattern design

A new analytical model was developed to determine the longitudinal strain components at the flange edge by extending the information given by the two-dimensional flower diagram. In the analytical model, first the flange movement of a point given by the flower pattern diagram was converted to a three-dimensional space curve which is shown to lie on a cylindrical surface for any given flower pattern. The space curve representing the forming path or trajectory of a point on the strip is converted to a plane curve by constructing the plane development of the cylindrical surface, noting that in this transformation, line lengths and angles of intersections of lines are preserved. For the simple case of equal increments in bend angle in the flower pattern, the trajectory is a helix and in the plane development this is a straight line. The analysis showed that the bending strain and the mid surface strain components are functions of the gradient of this line in the plane development. If the plane development is known, the longitudinal edge strain can be determined and any given flower pattern can be evaluated by means of this plane development. Even though this model does not take into account the local deformation at the rolls, it can be used to obtain the optimum flower pattern by minimising the flange movement during the roll forming process. The technique was applied to examples in the literature to verify the model.

The link between the material properties and the peak longitudinal edge strain

The experimental work showed that peak longitudinal edge strain increases with yield strength for the materials that have similar strain hardening behaviour. Material hardening also significantly influences the peak longitudinal strain, especially for severe forming conditions; for example, despite the considerably lower yield strength in DP1000 compared with MS900, both DP1000 and MS900 showed similar peak longitudinal peak strains due to the significantly higher material hardening in DP1000. It was concluded that peak longitudinal edge strain not only increases with increasing initial yield strength but also with increasing material hardening.

The link between the material properties and the product defects

The effect of material properties on longitudinal bow and springback was also experimentally analysed. Bow decreased with increasing material yield for the
materials that had a similar hardening exponent. However bow was lower in DP1000 compared with MS900 despite the lower yield of the DP1000. It was concluded that the higher material strain hardening of DP1000 restricts the plastic deformation in the flange giving less bow. This trend was mainly observed for forming with high forming angle increments which introduced higher longitudinal strains. As a general conclusion, it can be said that longitudinal bow is influenced by the yield strength under any forming condition, whereas the influence of material strain hardening only appears if the forming is severe, leading higher longitudinal edge strain. This is a significant finding as previous studies have only observed the effect of yield strength and not strain hardening on longitudinal bow.

The lowest springback was observed for DP600 as it has the lowest yield strength among all materials analysed. Despite of the higher yield strength of MS900, DP1000 showed the highest springback in most of the cases. The forming stresses in the bending region were higher for DP1000 compared to that of MS900 due to the higher strain hardening of the DP 1000. Therefore it can be concluded that not only the yield strength but also the strain hardening behaviour of the material influence springback in the roll forming process.

**Links between peak longitudinal strain, product defects process and geometric parameters**

Longitudinal edge strain is directly related to longitudinal bow. Nevertheless, it cannot be used alone to identify the amount of bow in a part since bow is a function of the permanent component of longitudinal strain which is a function of material yield strength. However the peak strain can be used to predict bow in a part if the material properties stay the same; this is illustrated Figure 9.1. In addition, it was shown in the interaction study that peak longitudinal edge strain is mostly insensitive to the level of the forming angle, the flange length, the inter-station distance and the material thickness while in contrast, longitudinal bow showed higher sensitivity to the levels of the above factors. This may be due to the effect of the factor levels on the bending rigidity of the part which restricts the curving of the section. Springback did not show a direct relationship with the peak longitudinal edge strain as it is mainly related to transverse bending. Further, springback is also greatly affected by the level of the aforementioned factors. In addition, springback in roll forming was found to decrease
with increasing flange length, which suggests than not only the bending region but also
the adjacent area influences the amount of springback in a part. Springback is found
to increase with increasing inter-station distance which is probably attributed to
reduced residual stresses in the part with higher inter-station distance.

Figure 9.1: Bow and peak longitudinal strain variation for DP600

As a whole, the link between the peak longitudinal strain, product defects, process and
generic parameters can be summarised in Table 9.1 where the flange length, the
forming angle, the station distance and the thickness are abbreviated as FL, FA, SD
and t respectively; an upwards arrow (↑) indicates an increasing trend while the
sensitivity is represented by the number of arrows. To the author’s knowledge, this is
the first full experimental study analysing the trends that affect edge strain, bow and
springback in the roll forming of AHSS and UHSS.

Table 9.1: Trend in edge strain and shape defects with increasing process and
generic parameters

<table>
<thead>
<tr>
<th>Parameter and trend</th>
<th>Peak longitudinal strain</th>
<th>Bow</th>
<th>Springback</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DP600</td>
<td>DP1000</td>
<td>MS900</td>
</tr>
<tr>
<td>FL ↑</td>
<td>↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA ↑</td>
<td>↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD ↑</td>
<td>— — — — — — — — — — —</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t ↑</td>
<td>↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Effect of material properties on the roll load and torque

A numerical model was used to study the effect of material properties on roll load and torque. Material yield strength has been identified before as a significant factor for roll load and torque. However this work revealed that when AHSS and UHSS are roll formed, not only material yield strength but also material strain hardening significantly influences roll load and torque. In roll forming, roll load is mainly due to the transverse bending of the material, and this deformation is plastic and well above the elastic limit of the material. Therefore strain hardening behaviour can greatly influence the roll load in the process. As roll load and torque are inter-connected parameters, roll torque is also influenced by the hardening behaviour of the material. The significance of material strain hardening on roll load and torque has not been reported before.

Use of roll load and torque for defect identification

As discussed throughout this thesis, changes in material properties can greatly influence the final shape. In addition, a direct relationship between roll load and torque and the material properties (i.e. yield strength and the material hardening) was observed. Therefore roll load and torque can be considered as possible process parameters to determine changes in the material properties. This could be used to establish a relationship between the roll load and torque and longitudinal bow for a selected roll forming profile (Chapter 6). A bow prediction model was developed using a set of numerical models combined with regression analysis and a reasonably accurate bow prediction based on roll load and torque was observed. The applicability of this technique to real roll forming applications however depends highly on the accuracy of the numerical model used to develop the regression equation. The regression model developed is very sensitive to roll load and torque and therefore requires precise load and torque measurements for accurate bow prediction. In addition to bow, the routine developed may potentially allow the prediction of other material property dependent defects such as springback and twist if the link between the defect and the material properties can be found.

Development of the foundation for a defect compensation routine

It was shown that material property variations could be represented by the measured roll load and torque in the roll forming process. However not only the material
properties but also part geometry and process parameters can vary in the actual roll forming practice resulting in different degrees of defects in the final part. Therefore, as far as defect identification is concerned, it is necessary to first identify the factors that influence the selected defect (which is longitudinal bow in this study). To do this, a response surface study was carried out and flange length, material thickness, forming angle and material properties were identified as the significant factors that influence the longitudinal bow in a part (Chapter 7). In addition, roll load and torque were found to be dependent on a number of process and geometric parameters other than the material properties. All these factors need to be considered in the development of a defect identification methodology in such a way that the changes in material parameters are represented by the measured roll load and torque. Finally, a complete regression equation was obtained to predict the amount of longitudinal bow in terms of all the significant parameters while replacing the material properties by roll load and torque. According to that regression model, longitudinal bow was identified to be a function of material thickness, forming angle, flange length, roll load and torque, where the changes in the material properties were represented by the measured roll load and torque. This model is more robust than the one obtained in Chapter 6 as it considers all possible factors that influence longitudinal bow. In addition, it enables the prediction of the amount of bow for any given trapezoidal profile with different material properties. The model was verified with experimental results. This can be considered as the first step towards the development of a new bow compensation routine in roll forming.

**Introduction of longitudinal bow compensation technique in roll forming**

A new bow compensation technique was proposed and numerically performed for different forming conditions. The advantage of this new technique is the ability to compensate bow with a simple adjustment of the last station. For that, the last station is rotated around the lower roll axis, so that bow is compensated by counter-bending introduced at the web area. The analysis showed that the compensation rotation not only depends on the amount of bow in the part but also on material properties and part geometry. To implement an in-line bow compensation routine, an extensive study needs to be carried out to identify the exact compensation action required, depending on the profile formed and the material parameters. In addition, the compensation needs
to be carried out in a controlled manner to avoid overcompensation which was shown to cause edge buckling in the flange and the opening of the section.

9.2 Recommendations for future work

Based on the work carried out in this thesis some recommendations can be made for the future.

- Chapter 5 showed that material strain hardening significantly influences both peak longitudinal edge strain and shape defects in roll forming. Therefore the hardening behaviour of the material needs to be taken into account in the roll forming process design, which may require the development of new material models.

- As shown in Table 9.1, the effect of material thickness on springback is opposite for the dual phase steel and the martensitic steel. This may be explained by their different microstructure and future research should focus on the effect of microstructure on shape defects in the roll forming process.

- In the numerical model of the roll forming process, a number of factors need to be improved to achieve a good accuracy. A correct coefficient of friction needs to be applied to obtain higher accuracy with regard to the predicted roll torque. For that sensitivity study can be carried out to identify the effect of frictional coefficient on roll load, torque and longitudinal bow and to improve the numerical model. In addition, in this study, an isotropic hardening model was applied which is simple and less time-consuming; however some more advanced material models may be used to achieve improved roll load prediction since the anisotropic behaviour of the material may influence the transverse bending in the roll forming process.

- A new technique to identify changes in material properties on the basis of roll load and torque was introduced and a link to one specific forming defect (longitudinal bow) established. The same method may be applicable to estimate springback and twist in a roll formed section and further analysis should be directed accordingly.

- The method proposed requires very accurate load and torque measurements. Proper roll load and torque sensors need to be used with the required accuracy
and range. Further, the experimental setup for load and torque measurements may need to be improved to enable smooth and more accurate measurements.

- In the bow compensation technique, the compensation action not only depends on the amount of bow in the part but also on the material thickness, flange length, bending angle and material properties. Therefore an extensive future study needs to be carried out to establish the complete solution space for the compensation action.

- Finally, the newly introduced forming stand has not been fully developed; further investigations may need to be carried out to improve the current design and introduce more features such as over-bending to compensate for springback and flange unfolding during bow compensation.
Appendix B

The empirical equation chosen for the modified forming path has the form of a Laplacian of Gaussian (LoG) curve (Equation A1). The LoG function is modified by the addition of a linear term, \( \tan(\beta_0) \), so that the base is inclined to the slope of the path from the simple model and also displaced by an amount, \( e \), so that the curve coincides with the linear path in the plane development at the peak value, as shown in Figure 4.28.

\[
y - e = a_1 \left(1 - \frac{x^2}{b^2}\right) \times \exp\left(\frac{-x^2}{c^2}\right) + \tan(\beta_0) \tag{B1}
\]

In this equation,

\[
c = \sqrt{\frac{-1 \times d^2}{\ln\left(a_2/a_1\left(\frac{d^2}{b^2}-1\right)\right)}}
\]

Unknown coefficients were selected in such a way that the second derivative of the above curve could be fitted to the experimentally obtained curvature curve as shown in Figure 4.25, because second derivative of the forming trajectory is equal to curvature of that forming path. The values of the constant obtained are:

\[
b = 120
\]

\[
d = 150
\]

\[
e = 3.596
\]

\[
c = \sqrt{\frac{-1 \times d^2}{\ln\left(a_2/a_1\left(\frac{d^2}{b^2}-1\right)\right)}} = 40.75
\]

\[
a_1 = 2.05
\]

\[
a_2 = 1.5 \times 10^{-6}
\]
Appendix C

Figure C.1: Interaction plot for DP1000 – Peak longitudinal edge strain

Figure C.2: Interaction plot for MS900 – Peak longitudinal edge strain
Figure C.3: Interaction plot for DP1000 – longitudinal bow

Figure C.4: Interaction plot for MS900 – longitudinal bow
Figure C.5: Interaction plot for DP1000 – Springback
Appendix D

Table D.1: Simulation results for Bow, roll load and torque

<table>
<thead>
<tr>
<th>Model</th>
<th>Y(MPa)</th>
<th>n</th>
<th>Maximum Bow(mm)</th>
<th>Load(kN)</th>
<th>Torque(Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>490</td>
<td>0.15</td>
<td>6.12</td>
<td>11.50</td>
<td>51.81</td>
</tr>
<tr>
<td>Model 2</td>
<td>490</td>
<td>0.20</td>
<td>5.55</td>
<td>12.51</td>
<td>56.95</td>
</tr>
<tr>
<td>Model 3</td>
<td>490</td>
<td>0.25</td>
<td>4.99</td>
<td>13.63</td>
<td>62.70</td>
</tr>
<tr>
<td>Model 4</td>
<td>490</td>
<td>0.30</td>
<td>4.51</td>
<td>14.82</td>
<td>68.78</td>
</tr>
<tr>
<td>Model 5</td>
<td>490</td>
<td>0.35</td>
<td>4.23</td>
<td>16.08</td>
<td>75.23</td>
</tr>
<tr>
<td>Model 6</td>
<td>590</td>
<td>0.15</td>
<td>4.07</td>
<td>12.21</td>
<td>54.79</td>
</tr>
<tr>
<td>Model 7</td>
<td>590</td>
<td>0.20</td>
<td>3.73</td>
<td>13.28</td>
<td>60.07</td>
</tr>
<tr>
<td>Model 8</td>
<td>590</td>
<td>0.25</td>
<td>3.52</td>
<td>14.40</td>
<td>65.64</td>
</tr>
<tr>
<td>Model 9</td>
<td>590</td>
<td>0.30</td>
<td>3.41</td>
<td>15.61</td>
<td>71.88</td>
</tr>
<tr>
<td>Model 10</td>
<td>590</td>
<td>0.35</td>
<td>3.37</td>
<td>16.89</td>
<td>78.38</td>
</tr>
<tr>
<td>Model 11</td>
<td>690</td>
<td>0.15</td>
<td>2.34</td>
<td>12.93</td>
<td>57.15</td>
</tr>
<tr>
<td>Model 12</td>
<td>690</td>
<td>0.20</td>
<td>2.24</td>
<td>14.01</td>
<td>62.45</td>
</tr>
<tr>
<td>Model 13</td>
<td>690</td>
<td>0.25</td>
<td>2.21</td>
<td>15.17</td>
<td>68.42</td>
</tr>
<tr>
<td>Model 14</td>
<td>690</td>
<td>0.30</td>
<td>2.44</td>
<td>16.39</td>
<td>74.53</td>
</tr>
<tr>
<td>Model 15</td>
<td>690</td>
<td>0.35</td>
<td>2.63</td>
<td>17.66</td>
<td>81.04</td>
</tr>
<tr>
<td>Model 16</td>
<td>790</td>
<td>0.15</td>
<td>0.54</td>
<td>13.65</td>
<td>59.96</td>
</tr>
<tr>
<td>Model 17</td>
<td>790</td>
<td>0.20</td>
<td>0.66</td>
<td>14.75</td>
<td>65.66</td>
</tr>
<tr>
<td>Model 18</td>
<td>790</td>
<td>0.25</td>
<td>0.88</td>
<td>16.01</td>
<td>72.75</td>
</tr>
<tr>
<td>Model 19</td>
<td>790</td>
<td>0.30</td>
<td>1.14</td>
<td>17.16</td>
<td>78.12</td>
</tr>
<tr>
<td>Model 20</td>
<td>790</td>
<td>0.35</td>
<td>1.32</td>
<td>18.45</td>
<td>84.99</td>
</tr>
<tr>
<td>Model 21</td>
<td>890</td>
<td>0.15</td>
<td>-1.17</td>
<td>14.42</td>
<td>63.31</td>
</tr>
<tr>
<td>Model 22</td>
<td>890</td>
<td>0.20</td>
<td>-0.92</td>
<td>15.54</td>
<td>69.17</td>
</tr>
<tr>
<td>Model 23</td>
<td>890</td>
<td>0.25</td>
<td>0.08</td>
<td>16.73</td>
<td>75.87</td>
</tr>
<tr>
<td>Model 24</td>
<td>890</td>
<td>0.30</td>
<td>0.47</td>
<td>17.95</td>
<td>82.09</td>
</tr>
<tr>
<td>Model 25</td>
<td>890</td>
<td>0.35</td>
<td>0.00</td>
<td>19.24</td>
<td>89.35</td>
</tr>
<tr>
<td>Model 26</td>
<td>990</td>
<td>0.15</td>
<td>-2.64</td>
<td>15.22</td>
<td>67.33</td>
</tr>
<tr>
<td>Model 27</td>
<td>990</td>
<td>0.20</td>
<td>-2.44</td>
<td>16.38</td>
<td>73.66</td>
</tr>
<tr>
<td>Model 28</td>
<td>990</td>
<td>0.25</td>
<td>-2.04</td>
<td>17.57</td>
<td>80.44</td>
</tr>
<tr>
<td>Model 29</td>
<td>990</td>
<td>0.30</td>
<td>-1.74</td>
<td>18.82</td>
<td>86.63</td>
</tr>
<tr>
<td>Model 30</td>
<td>990</td>
<td>0.35</td>
<td>-1.35</td>
<td>20.11</td>
<td>94.07</td>
</tr>
</tbody>
</table>
Appendix E

Multiple regression model

Multiple linear regression model with k independent variables and n observations can be written as

\[ y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} + \epsilon_i \]

\[ y_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} + \epsilon_i, \quad i = 1,2,3,\ldots,n \]

Where \( y_i \) is the observed output variable, \( x_{ij} \) is \( i^{th} \) observation of \( x_j^{th} \) variable, \( \beta_j \) is regression coefficient and \( \epsilon_i \) is the error.

In the matrix form it can be written as

\[ Y = X\beta + \epsilon \]

Therefore the fitted regression model can be written as

\[ \hat{Y} = X\hat{\beta} \]

\[ \epsilon = Y - \hat{Y} \]

When checking the significance of a regression model following table need to be completed.

Figure E.1: ANOVA table for a multiple regression model [114]

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>( F_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>( SS_R )</td>
<td>( k )</td>
<td>( MS_R )</td>
<td>( MS_R/MS_E )</td>
</tr>
<tr>
<td>Error</td>
<td>( SS_E )</td>
<td>( n-k-1 )</td>
<td>( MS_E )</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>( S_{yy} )</td>
<td>( n-1 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where

\[ S_{yy} = SS_R + SS_E \]
\[ S_{yy} = Y'Y - \frac{(\sum_{i=1}^{n} y_i)^2}{n} \]
\[ S_R = \beta'X'Y - \frac{(\sum_{i=1}^{n} y_i)^2}{n} \]
\[ S_E = Y'Y - \beta'X'Y \]
\[ MS_R = \frac{SS_R}{k} \]
\[ MS_E = \frac{SS_E}{n - k - 1} \]

Coefficient of determination \((R^2)\) determines the closeness of the fitted values to the actual values.

\[ R^2 = \frac{SS_R}{S_{yy}} \]

\(R^2\) increases even when unwanted terms are adding to the model. Therefore adjusted \(R^2\) \((R^2_{adj})\) is defined which decreases when unwanted terms add in to the model [114].

\[ R^2_{adj} = 1 - \frac{SS_E/(n - k - 1)}{S_{yy}/(n - 1)} \]

The Prediction Error Sum of Squares (PRESS) is another indicator that represents the amount of error or residual in the modes. Following equation defines PRESS value of a model.

\[ PRESS = \sum_{i=1}^{n} \epsilon_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \]

There is another indicator, \(R^2_{prediction}\), which determines the ability of the regression model to predict the output.

\[ R^2_{prediction} = 1 - \frac{PRESS}{S_{yy}} \]

The significant of individual regression coefficient can be tested from the standard t-test. T value can be defined as below
where \( b_j \) is the regression coefficient and the \( SE \) is the standard error of the corresponding regression parameter. To be the regression parameter corresponding to \( b_j \) a significant one \(|t_0| > t_{\alpha/2, n-k-1} \)
### Appendix F

#### Table F.1: Coefficients, T and P values for the linear model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Load Coef</th>
<th>Load T</th>
<th>Load P</th>
<th>Torque Coef</th>
<th>Torque T</th>
<th>Torque P</th>
<th>Bow Coef</th>
<th>Bow T</th>
<th>Bow P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>16.30</td>
<td>84.57</td>
<td>0.00</td>
<td>173.27</td>
<td>58.16</td>
<td>0.00</td>
<td>2.38</td>
<td>12.89</td>
<td>0.00</td>
</tr>
<tr>
<td>FC</td>
<td>0.15</td>
<td>0.42</td>
<td>0.67</td>
<td>58.49</td>
<td>10.89</td>
<td>0.00</td>
<td>0.23</td>
<td>0.68</td>
<td>0.50</td>
</tr>
<tr>
<td>YS</td>
<td>1.34</td>
<td>3.86</td>
<td>0.00</td>
<td>14.90</td>
<td>2.78</td>
<td>0.01</td>
<td>-1.30</td>
<td>-3.90</td>
<td>0.00</td>
</tr>
<tr>
<td>n</td>
<td>2.36</td>
<td>6.80</td>
<td>0.00</td>
<td>23.62</td>
<td>4.40</td>
<td>0.00</td>
<td>-0.18</td>
<td>-0.56</td>
<td>0.58</td>
</tr>
<tr>
<td>FL</td>
<td>0.22</td>
<td>0.64</td>
<td>0.52</td>
<td>3.11</td>
<td>0.58</td>
<td>0.56</td>
<td>-2.51</td>
<td>-7.54</td>
<td>0.00</td>
</tr>
<tr>
<td>t</td>
<td>13.32</td>
<td>38.33</td>
<td>0.00</td>
<td>147.07</td>
<td>27.38</td>
<td>0.00</td>
<td>5.17</td>
<td>15.53</td>
<td>0.00</td>
</tr>
<tr>
<td>WL</td>
<td>0.22</td>
<td>0.62</td>
<td>0.53</td>
<td>1.43</td>
<td>0.27</td>
<td>0.79</td>
<td>-0.68</td>
<td>-2.04</td>
<td>0.04</td>
</tr>
<tr>
<td>BRD</td>
<td>-0.03</td>
<td>-0.09</td>
<td>0.93</td>
<td>26.80</td>
<td>4.99</td>
<td>0.00</td>
<td>-0.19</td>
<td>-0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>FA</td>
<td>6.58</td>
<td>18.93</td>
<td>0.00</td>
<td>77.63</td>
<td>14.45</td>
<td>0.00</td>
<td>3.56</td>
<td>10.71</td>
<td>0.00</td>
</tr>
<tr>
<td>BR</td>
<td>-0.43</td>
<td>-1.25</td>
<td>0.22</td>
<td>-4.14</td>
<td>-0.77</td>
<td>0.44</td>
<td>-0.26</td>
<td>-0.79</td>
<td>0.43</td>
</tr>
<tr>
<td>$R^2$</td>
<td>94.03%</td>
<td></td>
<td></td>
<td>90.40%</td>
<td></td>
<td></td>
<td>78.33%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td>93.59%</td>
<td></td>
<td></td>
<td>89.68%</td>
<td></td>
<td></td>
<td>76.71%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRESS</td>
<td>171.897</td>
<td></td>
<td></td>
<td>41105.8</td>
<td></td>
<td></td>
<td>629.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2_{prediction}$</td>
<td>92.92%</td>
<td></td>
<td></td>
<td>88.6%</td>
<td></td>
<td></td>
<td>74.34%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table F.2: Coefficients and P values for the linear + two factor interaction model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Load Coef</th>
<th>Load T</th>
<th>Load P</th>
<th>Torque Coef</th>
<th>Torque T</th>
<th>Torque P</th>
<th>Bow Coef</th>
<th>Bow T</th>
<th>Bow P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>16.30</td>
<td>159.78</td>
<td>0.00</td>
<td>173.27</td>
<td>110.27</td>
<td>0.00</td>
<td>2.38</td>
<td>13.71</td>
<td>0.00</td>
</tr>
<tr>
<td>FC</td>
<td>0.15</td>
<td>0.80</td>
<td>0.43</td>
<td>58.49</td>
<td>20.65</td>
<td>0.00</td>
<td>0.23</td>
<td>0.73</td>
<td>0.47</td>
</tr>
<tr>
<td>YS</td>
<td>1.34</td>
<td>7.29</td>
<td>0.00</td>
<td>14.90</td>
<td>5.26</td>
<td>0.00</td>
<td>-1.30</td>
<td>-4.14</td>
<td>0.00</td>
</tr>
<tr>
<td>n</td>
<td>2.36</td>
<td>12.85</td>
<td>0.00</td>
<td>23.62</td>
<td>8.34</td>
<td>0.00</td>
<td>-0.18</td>
<td>-0.59</td>
<td>0.56</td>
</tr>
<tr>
<td>FL</td>
<td>0.22</td>
<td>1.22</td>
<td>0.23</td>
<td>3.11</td>
<td>1.10</td>
<td>0.28</td>
<td>-2.51</td>
<td>-8.02</td>
<td>0.00</td>
</tr>
<tr>
<td>t</td>
<td>13.32</td>
<td>72.43</td>
<td>0.00</td>
<td>147.07</td>
<td>51.92</td>
<td>0.00</td>
<td>5.17</td>
<td>16.51</td>
<td>0.00</td>
</tr>
<tr>
<td>WL</td>
<td>0.22</td>
<td>1.18</td>
<td>0.24</td>
<td>1.43</td>
<td>0.50</td>
<td>0.62</td>
<td>-0.68</td>
<td>-2.17</td>
<td>0.03</td>
</tr>
<tr>
<td>BRD</td>
<td>-0.03</td>
<td>-0.17</td>
<td>0.86</td>
<td>26.80</td>
<td>9.46</td>
<td>0.00</td>
<td>-0.19</td>
<td>-0.61</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>6.58</td>
<td>35.76</td>
<td>0.00</td>
<td>77.63</td>
<td>27.41</td>
<td>0.00</td>
<td>3.56</td>
<td>11.39</td>
<td>0.00</td>
</tr>
<tr>
<td>----</td>
<td>------</td>
<td>-------</td>
<td>------</td>
<td>-------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>FA</td>
<td>-0.43</td>
<td>-2.36</td>
<td>0.02</td>
<td>-4.14</td>
<td>-1.46</td>
<td>0.15</td>
<td>-0.26</td>
<td>-0.84</td>
<td>0.40</td>
</tr>
<tr>
<td>BR</td>
<td>-0.17</td>
<td>-0.40</td>
<td>0.69</td>
<td>3.53</td>
<td>0.56</td>
<td>0.58</td>
<td>0.48</td>
<td>0.69</td>
<td>0.49</td>
</tr>
<tr>
<td>FC*YS</td>
<td>-0.38</td>
<td>-0.91</td>
<td>0.36</td>
<td>1.91</td>
<td>0.30</td>
<td>0.76</td>
<td>-0.41</td>
<td>-0.59</td>
<td>0.56</td>
</tr>
<tr>
<td>FC*n</td>
<td>-0.02</td>
<td>-0.06</td>
<td>0.95</td>
<td>1.08</td>
<td>0.24</td>
<td>0.81</td>
<td>0.05</td>
<td>0.11</td>
<td>0.92</td>
</tr>
<tr>
<td>FC*FL</td>
<td>0.05</td>
<td>0.12</td>
<td>0.90</td>
<td>47.71</td>
<td>7.53</td>
<td>0.00</td>
<td>0.60</td>
<td>0.86</td>
<td>0.39</td>
</tr>
<tr>
<td>FC*t</td>
<td>-0.01</td>
<td>-0.03</td>
<td>0.98</td>
<td>0.07</td>
<td>0.01</td>
<td>0.99</td>
<td>0.04</td>
<td>0.06</td>
<td>0.95</td>
</tr>
<tr>
<td>FC*BRD</td>
<td>0.01</td>
<td>0.02</td>
<td>0.99</td>
<td>8.55</td>
<td>1.91</td>
<td>0.06</td>
<td>-0.02</td>
<td>-0.04</td>
<td>0.97</td>
</tr>
<tr>
<td>FC*FA</td>
<td>0.05</td>
<td>0.12</td>
<td>0.91</td>
<td>24.03</td>
<td>3.79</td>
<td>0.00</td>
<td>0.06</td>
<td>0.09</td>
<td>0.93</td>
</tr>
<tr>
<td>FC*BR</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>-1.14</td>
<td>0.18</td>
<td>0.86</td>
<td>0.05</td>
<td>0.07</td>
<td>0.95</td>
</tr>
<tr>
<td>YS*n</td>
<td>0.26</td>
<td>0.63</td>
<td>0.53</td>
<td>1.98</td>
<td>0.31</td>
<td>0.76</td>
<td>-0.24</td>
<td>-0.35</td>
<td>0.73</td>
</tr>
<tr>
<td>YS*FL</td>
<td>0.00</td>
<td>-0.01</td>
<td>1.00</td>
<td>0.46</td>
<td>0.07</td>
<td>0.94</td>
<td>0.44</td>
<td>0.63</td>
<td>0.53</td>
</tr>
<tr>
<td>YS*t</td>
<td>1.09</td>
<td>3.74</td>
<td>0.00</td>
<td>12.86</td>
<td>2.87</td>
<td>0.01</td>
<td>-0.30</td>
<td>-0.60</td>
<td>0.55</td>
</tr>
<tr>
<td>YS*WL</td>
<td>0.09</td>
<td>0.21</td>
<td>0.83</td>
<td>0.73</td>
<td>0.12</td>
<td>0.91</td>
<td>0.20</td>
<td>0.29</td>
<td>0.77</td>
</tr>
<tr>
<td>YS*BRD</td>
<td>-0.01</td>
<td>-0.02</td>
<td>0.99</td>
<td>1.83</td>
<td>0.29</td>
<td>0.77</td>
<td>-0.08</td>
<td>-0.11</td>
<td>0.91</td>
</tr>
<tr>
<td>YS*FA</td>
<td>0.30</td>
<td>1.02</td>
<td>0.31</td>
<td>5.38</td>
<td>1.20</td>
<td>0.23</td>
<td>0.43</td>
<td>0.87</td>
<td>0.39</td>
</tr>
<tr>
<td>YS*BR</td>
<td>-0.02</td>
<td>-0.04</td>
<td>0.97</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>-0.06</td>
<td>-0.08</td>
<td>0.93</td>
</tr>
<tr>
<td>n*FL</td>
<td>0.03</td>
<td>0.07</td>
<td>0.94</td>
<td>-2.80</td>
<td>-0.44</td>
<td>0.66</td>
<td>-0.47</td>
<td>-0.67</td>
<td>0.51</td>
</tr>
<tr>
<td>n*t</td>
<td>1.99</td>
<td>4.85</td>
<td>0.00</td>
<td>20.39</td>
<td>3.22</td>
<td>0.00</td>
<td>-0.17</td>
<td>-0.25</td>
<td>0.81</td>
</tr>
<tr>
<td>n*WL</td>
<td>0.01</td>
<td>0.03</td>
<td>0.98</td>
<td>-0.04</td>
<td>-0.01</td>
<td>0.99</td>
<td>0.07</td>
<td>0.14</td>
<td>0.89</td>
</tr>
<tr>
<td>n*BRD</td>
<td>0.00</td>
<td>0.01</td>
<td>1.00</td>
<td>4.12</td>
<td>0.65</td>
<td>0.52</td>
<td>0.14</td>
<td>0.20</td>
<td>0.84</td>
</tr>
<tr>
<td>n*FA</td>
<td>1.04</td>
<td>2.53</td>
<td>0.01</td>
<td>12.49</td>
<td>1.97</td>
<td>0.05</td>
<td>0.24</td>
<td>0.35</td>
<td>0.73</td>
</tr>
<tr>
<td>n*BR</td>
<td>-0.21</td>
<td>-0.71</td>
<td>0.48</td>
<td>-1.96</td>
<td>-0.44</td>
<td>0.66</td>
<td>0.15</td>
<td>0.30</td>
<td>0.76</td>
</tr>
<tr>
<td>FL*t</td>
<td>0.06</td>
<td>0.15</td>
<td>0.88</td>
<td>4.53</td>
<td>0.72</td>
<td>0.48</td>
<td>-2.05</td>
<td>-2.92</td>
<td>0.00</td>
</tr>
<tr>
<td>FL*WL</td>
<td>-0.10</td>
<td>-0.23</td>
<td>0.82</td>
<td>-1.06</td>
<td>-0.17</td>
<td>0.87</td>
<td>0.01</td>
<td>0.02</td>
<td>0.99</td>
</tr>
<tr>
<td>FL*BRD</td>
<td>0.01</td>
<td>0.02</td>
<td>0.99</td>
<td>0.99</td>
<td>0.22</td>
<td>0.83</td>
<td>0.22</td>
<td>0.45</td>
<td>0.65</td>
</tr>
<tr>
<td>FL*FA</td>
<td>0.50</td>
<td>1.20</td>
<td>0.23</td>
<td>-2.17</td>
<td>-0.34</td>
<td>0.73</td>
<td>-1.49</td>
<td>-2.13</td>
<td>0.04</td>
</tr>
<tr>
<td>FL*BR</td>
<td>-0.01</td>
<td>-0.02</td>
<td>0.99</td>
<td>-0.05</td>
<td>-0.01</td>
<td>0.99</td>
<td>0.04</td>
<td>0.06</td>
<td>0.95</td>
</tr>
<tr>
<td>t*WL</td>
<td>0.24</td>
<td>0.57</td>
<td>0.57</td>
<td>1.60</td>
<td>0.25</td>
<td>0.80</td>
<td>-1.01</td>
<td>-1.44</td>
<td>0.15</td>
</tr>
<tr>
<td>t*BRD</td>
<td>-0.02</td>
<td>-0.04</td>
<td>0.97</td>
<td>20.03</td>
<td>3.16</td>
<td>0.00</td>
<td>-0.29</td>
<td>-0.41</td>
<td>0.68</td>
</tr>
<tr>
<td>t*FA</td>
<td>4.99</td>
<td>17.16</td>
<td>0.00</td>
<td>67.64</td>
<td>15.10</td>
<td>0.00</td>
<td>2.72</td>
<td>5.50</td>
<td>0.00</td>
</tr>
<tr>
<td>t*BR</td>
<td>-0.07</td>
<td>-0.17</td>
<td>0.87</td>
<td>-0.73</td>
<td>-0.12</td>
<td>0.91</td>
<td>0.21</td>
<td>0.30</td>
<td>0.77</td>
</tr>
</tbody>
</table>
### Table F.3: Coefficients and P values for the linear + square model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coef</th>
<th>T</th>
<th>P</th>
<th>Coef</th>
<th>T</th>
<th>P</th>
<th>Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>15.56</td>
<td>23.82</td>
<td>0.00</td>
<td>164.78</td>
<td>16.03</td>
<td>0.00</td>
<td>1.27</td>
<td>2.28</td>
<td>0.03</td>
</tr>
<tr>
<td>FC</td>
<td>0.15</td>
<td>0.45</td>
<td>0.66</td>
<td>58.49</td>
<td>11.38</td>
<td>0.00</td>
<td>0.23</td>
<td>0.81</td>
<td>0.42</td>
</tr>
<tr>
<td>YS</td>
<td>1.34</td>
<td>4.10</td>
<td>0.00</td>
<td>14.90</td>
<td>2.90</td>
<td>0.00</td>
<td>-1.30</td>
<td>-4.65</td>
<td>0.00</td>
</tr>
<tr>
<td>n</td>
<td>2.36</td>
<td>7.23</td>
<td>0.00</td>
<td>23.62</td>
<td>4.60</td>
<td>0.00</td>
<td>-0.18</td>
<td>-0.66</td>
<td>0.51</td>
</tr>
<tr>
<td>FL</td>
<td>0.22</td>
<td>0.68</td>
<td>0.50</td>
<td>3.11</td>
<td>0.61</td>
<td>0.55</td>
<td>-2.51</td>
<td>-9.00</td>
<td>0.00</td>
</tr>
<tr>
<td>t</td>
<td>13.32</td>
<td>40.77</td>
<td>0.00</td>
<td>147.07</td>
<td>28.62</td>
<td>0.00</td>
<td>5.17</td>
<td>18.54</td>
<td>0.00</td>
</tr>
<tr>
<td>WL</td>
<td>0.22</td>
<td>0.66</td>
<td>0.51</td>
<td>1.43</td>
<td>0.28</td>
<td>0.78</td>
<td>-0.68</td>
<td>-2.44</td>
<td>0.02</td>
</tr>
<tr>
<td>BRD</td>
<td>-0.03</td>
<td>-0.10</td>
<td>0.92</td>
<td>26.80</td>
<td>5.22</td>
<td>0.00</td>
<td>-0.19</td>
<td>-0.68</td>
<td>0.50</td>
</tr>
<tr>
<td>FA</td>
<td>6.58</td>
<td>20.13</td>
<td>0.00</td>
<td>77.63</td>
<td>15.11</td>
<td>0.00</td>
<td>3.56</td>
<td>12.79</td>
<td>0.00</td>
</tr>
<tr>
<td>BR</td>
<td>-0.43</td>
<td>-1.33</td>
<td>0.19</td>
<td>-4.14</td>
<td>-0.81</td>
<td>0.42</td>
<td>-0.26</td>
<td>-0.95</td>
<td>0.35</td>
</tr>
<tr>
<td>FC*FC</td>
<td>0.13</td>
<td>0.29</td>
<td>0.77</td>
<td>1.52</td>
<td>0.22</td>
<td>0.83</td>
<td>0.56</td>
<td>1.51</td>
<td>0.13</td>
</tr>
<tr>
<td>YS*YS</td>
<td>0.02</td>
<td>0.04</td>
<td>0.97</td>
<td>4.14</td>
<td>0.60</td>
<td>0.55</td>
<td>-0.04</td>
<td>-0.11</td>
<td>0.92</td>
</tr>
<tr>
<td>n*n</td>
<td>0.18</td>
<td>0.42</td>
<td>0.67</td>
<td>1.78</td>
<td>0.26</td>
<td>0.80</td>
<td>0.33</td>
<td>0.88</td>
<td>0.38</td>
</tr>
<tr>
<td>FL*FL</td>
<td>0.09</td>
<td>0.22</td>
<td>0.83</td>
<td>-0.32</td>
<td>-0.05</td>
<td>0.96</td>
<td>0.45</td>
<td>1.20</td>
<td>0.23</td>
</tr>
<tr>
<td>t*t</td>
<td>1.96</td>
<td>4.51</td>
<td>0.00</td>
<td>26.60</td>
<td>3.88</td>
<td>0.00</td>
<td>2.64</td>
<td>7.11</td>
<td>0.00</td>
</tr>
<tr>
<td>WL*WL</td>
<td>-0.10</td>
<td>-0.22</td>
<td>0.82</td>
<td>-1.77</td>
<td>-0.26</td>
<td>0.80</td>
<td>-0.07</td>
<td>-0.18</td>
<td>0.85</td>
</tr>
<tr>
<td>BRD*BRD</td>
<td>0.01</td>
<td>0.02</td>
<td>0.99</td>
<td>-1.26</td>
<td>-0.18</td>
<td>0.86</td>
<td>0.08</td>
<td>0.21</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Table F.4: Coefficients and P values for the complete quadratic model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Load Coef</th>
<th>T</th>
<th>P</th>
<th>Torque Coef</th>
<th>T</th>
<th>P</th>
<th>Bow Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>15.56</td>
<td>150.58</td>
<td>0.00</td>
<td>164.78</td>
<td>59.63</td>
<td>0.00</td>
<td>1.27</td>
<td>2.91</td>
<td>0.01</td>
</tr>
<tr>
<td>FC</td>
<td>0.15</td>
<td>2.84</td>
<td>0.01</td>
<td>58.49</td>
<td>42.33</td>
<td>0.00</td>
<td>0.23</td>
<td>1.04</td>
<td>0.30</td>
</tr>
<tr>
<td>YS</td>
<td>1.34</td>
<td>25.94</td>
<td>0.00</td>
<td>14.90</td>
<td>10.79</td>
<td>0.00</td>
<td>-1.30</td>
<td>-5.94</td>
<td>0.00</td>
</tr>
<tr>
<td>n</td>
<td>2.36</td>
<td>45.74</td>
<td>0.00</td>
<td>23.62</td>
<td>17.09</td>
<td>0.00</td>
<td>-0.18</td>
<td>-0.85</td>
<td>0.40</td>
</tr>
<tr>
<td>FL</td>
<td>0.22</td>
<td>4.33</td>
<td>0.00</td>
<td>3.11</td>
<td>2.25</td>
<td>0.03</td>
<td>-2.51</td>
<td>-11.5</td>
<td>0.00</td>
</tr>
<tr>
<td>t</td>
<td>13.32</td>
<td>257.76</td>
<td>0.00</td>
<td>147.07</td>
<td>106.44</td>
<td>0.00</td>
<td>5.17</td>
<td>23.69</td>
<td>0.00</td>
</tr>
<tr>
<td>WL</td>
<td>0.22</td>
<td>4.19</td>
<td>0.00</td>
<td>1.43</td>
<td>1.03</td>
<td>0.31</td>
<td>-0.68</td>
<td>-3.11</td>
<td>0.00</td>
</tr>
<tr>
<td>BRD</td>
<td>-0.03</td>
<td>-0.61</td>
<td>0.54</td>
<td>26.80</td>
<td>19.40</td>
<td>0.00</td>
<td>-0.19</td>
<td>-0.87</td>
<td>0.39</td>
</tr>
<tr>
<td>FA</td>
<td>6.58</td>
<td>127.28</td>
<td>0.00</td>
<td>77.63</td>
<td>56.18</td>
<td>0.00</td>
<td>3.56</td>
<td>16.34</td>
<td>0.00</td>
</tr>
<tr>
<td>BR</td>
<td>-0.43</td>
<td>-8.39</td>
<td>0.00</td>
<td>-4.14</td>
<td>-2.99</td>
<td>0.00</td>
<td>-0.26</td>
<td>-1.21</td>
<td>0.23</td>
</tr>
<tr>
<td>FC*FY</td>
<td>0.13</td>
<td>1.85</td>
<td>0.07</td>
<td>1.52</td>
<td>0.82</td>
<td>0.41</td>
<td>0.56</td>
<td>1.93</td>
<td>0.06</td>
</tr>
<tr>
<td>YS*YS</td>
<td>0.02</td>
<td>0.27</td>
<td>0.79</td>
<td>4.14</td>
<td>2.25</td>
<td>0.03</td>
<td>-0.04</td>
<td>-0.14</td>
<td>0.89</td>
</tr>
<tr>
<td>n*n</td>
<td>0.18</td>
<td>2.67</td>
<td>0.01</td>
<td>1.78</td>
<td>0.97</td>
<td>0.34</td>
<td>0.33</td>
<td>1.13</td>
<td>0.26</td>
</tr>
<tr>
<td>FL*FL</td>
<td>0.09</td>
<td>1.37</td>
<td>0.18</td>
<td>-0.32</td>
<td>-0.18</td>
<td>0.86</td>
<td>0.45</td>
<td>1.54</td>
<td>0.13</td>
</tr>
<tr>
<td>t*t</td>
<td>1.96</td>
<td>28.49</td>
<td>0.00</td>
<td>26.60</td>
<td>14.44</td>
<td>0.00</td>
<td>2.64</td>
<td>9.09</td>
<td>0.00</td>
</tr>
<tr>
<td>WL*WL</td>
<td>-0.10</td>
<td>-1.41</td>
<td>0.16</td>
<td>-1.77</td>
<td>-0.96</td>
<td>0.34</td>
<td>-0.07</td>
<td>-0.24</td>
<td>0.82</td>
</tr>
<tr>
<td>BRD*BRD</td>
<td>0.01</td>
<td>0.11</td>
<td>0.91</td>
<td>-1.26</td>
<td>-0.68</td>
<td>0.50</td>
<td>0.08</td>
<td>0.27</td>
<td>0.79</td>
</tr>
<tr>
<td>FA*FA</td>
<td>0.12</td>
<td>1.79</td>
<td>0.08</td>
<td>-1.73</td>
<td>-0.94</td>
<td>0.35</td>
<td>-0.79</td>
<td>-2.71</td>
<td>0.01</td>
</tr>
<tr>
<td>BR*BR</td>
<td>-0.02</td>
<td>-0.35</td>
<td>0.73</td>
<td>-1.37</td>
<td>-0.74</td>
<td>0.46</td>
<td>0.44</td>
<td>1.52</td>
<td>0.13</td>
</tr>
<tr>
<td>FC*YS</td>
<td>-0.17</td>
<td>-1.43</td>
<td>0.16</td>
<td>3.53</td>
<td>1.14</td>
<td>0.26</td>
<td>0.48</td>
<td>0.99</td>
<td>0.33</td>
</tr>
<tr>
<td>FC*n</td>
<td>-0.38</td>
<td>-3.25</td>
<td>0.00</td>
<td>1.91</td>
<td>0.62</td>
<td>0.54</td>
<td>-0.41</td>
<td>-0.85</td>
<td>0.40</td>
</tr>
</tbody>
</table>
### APPENDIX

|       | FC*FL | FC*t | FC*WL | FC*BRD | FC*FA | FC*BR | YS*n  | YS*FL | YS*t | YS*WL | YS*BRD | YS*FA | YS*BR | n*FL  | n*t   | n*WL  | n*BRD | n*FA  | n*BR | FL*t  | FL*WL | FL*BRD | FL*FA | FL*BR | t*WL  | t*BRD | t*FA  | t*BR | WL*BRD | WL*FA | WL*BR | BRD*FA |
|-------|-------|------|-------|--------|-------|-------|--------|-------|------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|       | -0.02 | 0.05 | -0.01 | 0.01   | 0.05  | 0.00  | 0.26   | 0.00  | 1.09 | 0.09  | -0.01  | 0.30  | -0.02 | 0.03   | 1.99  | 0.01  | 0.00  | 1.04  | -0.21 | 0.06  | 0.01  | 0.50  | -0.01 | 4.99  | -0.07 | 0.03  | -0.03  |
|       | -0.21 | 0.43 | -0.11 | 0.06   | 0.41  | 0.00  | 2.25   | 0.98  | 13.31| 0.76  | -0.07  | 3.64  | -0.15 | 0.26   | 17.25 | 0.11  | 0.92  | 0.02  | 9.00  | -2.53 | 0.52  | 0.06  | 4.29  | -0.07 | 61.05 | -0.15 | 0.28  | -0.03  |
|       | 0.83  | 0.67 | 0.91  | 0.95   | 0.68  | 1.00  | 0.03   | 0.98  | 0.00 | 0.45  | 0.45   | 0.00  | 0.88  | 0.60   | 20.39 | 0.92  | -0.04 | 0.00  | 12.49 | -1.96 | 0.41  | 0.00  | -2.17 | -0.05 | 0.00  | 0.05  | 0.83  |
|       | 1.08  | 47.71| 0.07  | 1.98   | 24.03 | -1.14 | -0.91  | 0.00  | 12.86| 0.73  | 0.03   | 5.38  | 0.00  | 0.91   | 6.60  | -0.04 | -0.02 | 0.00  | 4.04  | -0.90 | 0.41  | -2.80 | -0.02 | 0.00  | 0.05  | 1.83  |
|       | 0.49  | 15.44| 0.02  | 0.64   | 7.78  | -0.37 | 0.37   | 6.00  | 5.89 | 0.24  | 0.24   | 2.46  | 1.00  | 0.37   | 6.60  | -0.02 | -0.04 | 0.00  | 4.04  | -0.90 | 0.41  | -2.80 | 0.37  | 0.00  | 0.60  | 1.83  |
|       | 0.62  | 0.00 | 0.98  | 0.52   | 0.00  | 1.00  | 0.37   | 0.00  | 0.04 | 0.00  | 0.00   | 0.02  | 0.60  | 0.22   | 0.00  | 0.99  | 0.24  | 0.00  | 0.00  | 0.99  | 0.00  | 0.05  | -0.73 | 0.04  | 0.01  | 0.60  |
|       | 0.05  | 0.60 | 0.04  | 0.52   | 0.00  | 0.62  | 0.22   | 0.00  | 0.00 | 0.00  | 0.00   | 0.00  | 0.00  | 0.22   | 0.99  | 0.00  | 0.00  | 0.00  | 0.22  | 0.00  | 0.00  | 0.00  | 0.22  | 0.00  | 0.00  | 0.00  |
|       | 0.15  | 1.23 | 0.09  | -0.02  | 0.13  | 0.10  | 0.64   | 0.88  | 0.00 | 0.24  | 0.46   | 1.24  | -0.15 | 0.37   | -0.35 | 0.00  | 0.94  | 0.00  | 0.50  | 0.43  | 0.00  | -1.01 | -0.34 | 0.01  | 0.14  | 0.28  |
|       | 0.88  | 0.22 | 0.37  | 0.95   | 0.45  | 0.90  | 0.90   | 0.00  | 0.68 | 0.15  | 0.50   | 0.87  | 0.37  | 0.87   | 0.99  | 0.65  | 0.37  | 0.00  | 0.62  | 0.71  | 0.00  | -0.07 | -0.34 | 0.01  | 0.14  | 0.28  |
|       |       |      |       |        |       |       |        |       |     |       |        |       |       |        |       |       |       |       |       |       |       |       |       |       |       |       |       |

**Note:** The table represents a matrix of numerical values, possibly indicating correlations or coefficients in a statistical analysis. Each cell contains a single numeric value.
<table>
<thead>
<tr>
<th>BRD*BR</th>
<th>0.02</th>
<th>0.20</th>
<th>0.85</th>
<th>-0.19</th>
<th>-0.06</th>
<th>0.95</th>
<th>-0.77</th>
<th>-1.58</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA*BR</td>
<td>-0.47</td>
<td>-4.05</td>
<td>0.00</td>
<td>-5.30</td>
<td>-1.72</td>
<td>0.09</td>
<td>0.14</td>
<td>0.29</td>
<td>0.77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$R^2$</th>
<th>$R^2_{adj}$</th>
<th>PRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>99.92%</td>
<td>99.6%</td>
<td>94.18%</td>
</tr>
<tr>
<td></td>
<td>99.86%</td>
<td>99.32%</td>
<td>89.99%</td>
</tr>
<tr>
<td></td>
<td>8.023</td>
<td>5050.03</td>
<td>510.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$R^2_{prediction}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>99.67%</td>
</tr>
<tr>
<td></td>
<td>98.60%</td>
</tr>
<tr>
<td></td>
<td>79.19%</td>
</tr>
</tbody>
</table>
References

[20] J. Larrañaga, "Geometrical accuracy improvement in flexible roll forming process by means of local heating," PhD, Department of Mechanical and Industrial Production, Mondragon University, 2011.
REFERENCES


REFERENCES


REFERENCES


REFERENCES


