INTEGRATED HEALTH MONITORING FOR A STEEL BEAM: AN EXPERIMENTAL STUDY

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ABSTRACT

Civil infrastructures begin to deteriorate once they are built and used. Detecting damages in a structure to maintain its safety is a topic that has received considerable attention in the literature in recent years. Many methods are developed, including global vibration-based methods and local GW-based methods. The global vibration-based method uses changes in modal properties to detect damage. The advantage of this approach is that the vibration properties are straightforward to be measured. The disadvantage of this method is that it might not be sensitive to small damage. On the other hand, local method, such as the guided waves (GW) based method is sensitive to small damage, but its sensing range is small. In this paper, an integrated structural health monitoring test scheme is developed to detect damage in a steel beam. Different saw cuts of various depths are made to simulate crack damage. Vibration tests and guided wave tests are conducted after each cut. The vibration method is used to detect the overall condition change of the beam, whereas the GW method is used to locate and quantify the damage. Experimental results show that the integrated method is efficient to detect and quantify local crack damage in steel structures and its influence on the global structure conditions.

1. INTRODUCTION

In recent years, structural health monitoring (SHM) has been increasingly recognized as a viable tool for improving the safety and reliability of civil structures [1]. The massive methods can be generally classified as either global or local. Global approaches are based on relatively low-frequency vibration measurements of the structure. The first few modes are used to assess the locations and the severity of damage. However, a small number of the global modes are not sufficient to reliably detect minor damage in a structure. Another limitation of these techniques is that they often require a high-fidelity model of the structure to start with, which is usually not available. Therefore using the global approaches along is sometimes not sufficient to detect a relatively small damage. On the other hand, Guided wave (GW)-based method [2] and many conventional non-destructive evaluation (NDT) methods, such as

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radiography, acoustic emission (AE), magnetic field, eddy-current, thermal field and ultrasonic techniques, which are classified as visual or localized methods [3], could be very sensitive to small structural damage. However, the testing range of these methods is not as big as that of the global method. It will be extremely time consuming and costly to only use local methods to detect conditions of a realistic civil infrastructure.

Therefore, the combination of the global and local methods is believed to provide more credible information of the structural condition. Some researchers have already attempted to integrate these methods for structural damage detection. In order to assess the state of an aluminium bar both qualitatively and quantitatively, Park et al [4] introduced an integrated health monitoring method by combining the impedance-based method with a spectral element model-based technique. Mal et al published a series of papers [5-7] on damage identification of a plate using vibration and wave propagation data. A damage index is introduced to define the damage state of a structure. A unified automatic data analysis procedure is proposed to identify damage based on vibration and wave propagation data. Ratnam et al [8] utilize a finite element method to analyse the vibration of a plate. Based on wave propagation results, velocity of the Lamb wave can be determined. The velocity is influenced by Young's modulus of the structure, which will further change the vibration characteristics of the structure. In order to assess damage of a frame structure, Ikeshita et al [9] proposed a comprehensive damage identification method using modal data and wave propagation results. Frequency change is used to identify damage at the story level. Mode shape is used to detect damage at the member level. Then, wave separation method is used to localize and quantify damage. However, all above studies only make use of the derived parameters of wave propagation results. A more detailed experimental study of both vibration and wave propagation properties is promising to provide more information about structural damage.

In order to take advantage of the merits of the global and local methods, an integrated health monitoring system is proposed in this research. It includes both global vibration tests and local GW tests. To verify the method, a rectangular steel bar is tested in the laboratory. GW data and vibration-based data have the potential to be used to identify and quantify damage. The efficiency and reliability of the proposed method in damage identification is demonstrated.

2. INTEGRATED HEALTH MONITORING SYSTEM

2.1. Specimen and sensor location

The integrated health monitoring test is carried out on a rectangular steel bar of 1.500 m length and 0.025*0.025 m cross section. The material parameters of the steel bar are: Young's modulus 206 GPa, and mass density 7850 kg/m^3. The steel beam was suspended by two flexible rubber bands at the two ends to simulate free-free boundary condition. For the forced vibration test, five accelerometers were attached on top of the steel beam via their magnetic base, as shown in Figure 1, to measure acceleration time histories at the five points. An instrumented impact hammer was used to generate an impulsive force to excite the structure. The hammer hitting point A is 0.050 m on the left of the mid span of the beam. The actuator and sensor for generating and recording stress waves were mounted on the steel bar at 0.250 m from the left and right ends of the bar, respectively. The distance between the actuator and the sensor is 1.000 m.

2.2. Vibration test system

A typical vibration test measures the acceleration time histories of beam responses under impulsive loading. The experimental system mainly consists of three parts: 1) an impact hammer to provide impulse load; 2) accelerometers and force transducers to measure acceleration and loading histories on the structure; 3) the data transmission devices to collect data from sensors and to transfer them to the computer.

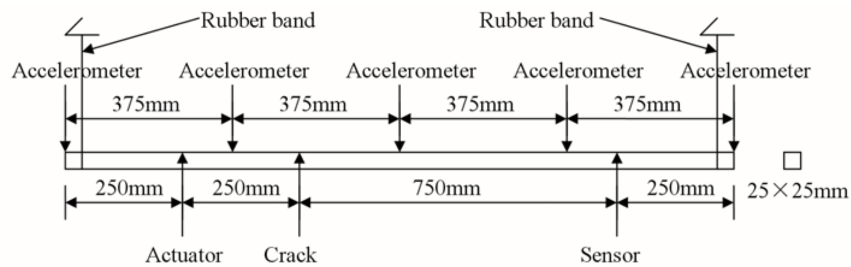


Figure 1: The specimen of steel beam

To induce dynamic loading, an instrumented hammer attached to the computer system was used to generate and record the impact force as shown in Figure 2(a). In this study, six impact tests were conducted at each loading level to allow an average to be taken to reduce possible noises. The Impact Hammer of Type 8206 from Bruel & Kjaer Company was used. Several accelerometers were used in this test, as shown in Figure 2(b), to record acceleration time histories. These capacitive accelerometers are very good for low level, low frequency vibration measurement.

In the tests, the sensing data were transmitted by signal conditioners connected by several unit boxes. All the unit boxes were connected to data acquisition system where data were recorded in the hard disk of the computer shown in Figure 2(c). The accelerometers employed throughout a test must measure the amplitude of acceleration signals that occur at frequencies within a bandwidth of interest. An in-house Labview based program was used to record the results whereby a sampling rate of 2000 Hz was employed for all the dynamic tests, which resulted in a frequency bandwidth of 0-1000 Hz. In each test, acceleration responses were recorded for 10 seconds that resulted in 20,480 data points in each channel.

a) Impact hammer　　b) Accelerometer　　c) Unit boxes and computer

Figure 2: Photos for vibration test system

2.3. Active sensing system for wave propagation tests

The experimental system for wave propagation tests, shown in Figure 3, includes two parts: a) the actuating part to provide the excitation or input of the system. It includes the actuator based on piezoelectric strips and the power amplifier that provides the power supply of the actuator; b) the piezo sensing element to measure the response. This part includes the piezo film element and its charge amplifier.

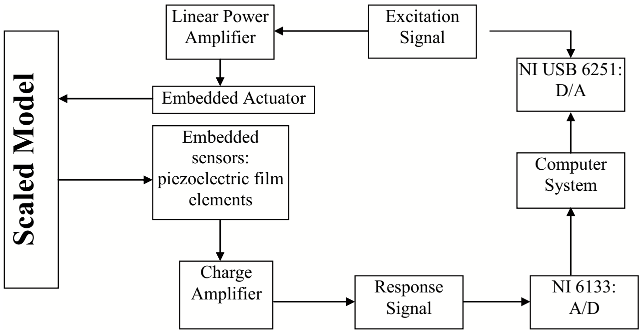
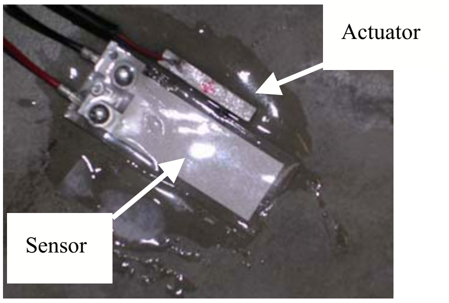


Figure 3: Guided wave test system

The actuators were mounted on surface of the structure with Araldite Kit K138. The strip actuators from APC International, Ltd. were selected as actuators in this study. The actuator includes two thin strips of piezoelectric ceramic that are bonded together, with the direction of polarization coinciding with each other and are electrically connected in parallel. When electrical input is applied, one ceramic layer expands and the other contracts, causing the actuator to flex. In this study, only one ceramic layer was applied with the electrical input so that it would generate the longitudinal waves. NI USB-6251 was used to provide the short-time Morlet wavelet for actuating the structure by a linear power amplifier. The frequency and the number of cycles can be adjusted to optimize the wave propagation along the structure.



a) Actuator and sensor

b) GW test system

Figure 4: Photos of guided wave test system

The DT1 series piezo film elements from Measurement Specialties, Inc. were selected as the sensors. The sensors were also glued to the reinforcement bars and the surface of concrete beam with Araldite Kit K138. Signals from sensors were collected by a data acquisition system made with NI PCI-6133. The sampling frequency of the system is up to 2MHz. The photo for actuator and sensor is shown in Figure 4(a). Figure 4(b) shows the test system.

3. LABORATORY STUDY

In this test, the bar was cut at 0.250 m from the actuator and 0.750 m from the sensor. The cutting depth was 3.0 mm, 6.0 mm, 9.0 mm and 12.5 mm respectively (12%, 24%, 36% and 50% of the bar dimension). Before and after each cut, vibration test and wave propagation test in the bar were conducted.

3.1. Vibration test

In this study, 2000 Hz was taken as sampling rate. It means that only the frequencies lower than 1000 Hz can be identified. Table 1 shows the first five modal frequencies of the beam. As can be seen, the changes between the tested frequencies of the intact and cracked beams are very small. Even when the crack depth reached 50% of the cross section, the frequency shifts are still very small (the maximum change is only 5.2%). It indicates that the existence of a crack only impairs the stiffness of a steel beam slightly. Furthermore, when the crack depth is small, some of the tested frequencies even increase a little. It may be caused by the measurement noises. Another possible explanation is that the crack location is at 1/3 of the beam. In some modes, the displacement of this point is very small, which results in the insignificant influence of damage at this point to the overall beam vibration frequencies. These results imply that the global methods are not sensitive to this localized damage.

Frequency	1st Mode	2nd Mode	3rd Mode	4th Mode	5th Mode
Intact	54.9	150.2	291.1	495.1	738.2
Crack depth: 3 mm	55.2 (0.5%)	150.0 (-0.1%)	292.0 (0.3%)	493.3 (-0.4%)	742.7 (0.6%)
Crack depth: 6 mm	54.8 (-0.2%)	150.3 (0.1%)	291.7 (0.2%)	494.0 (-0.2%)	741.2 (0.4%)
Crack depth: 9 mm	54.2 (-1.3%)	147.4 (-1.9%)	291.8 (0.2%)	494.6 (-0.1%)	738.7 (0.1%)
Crack depth: 12.5 mm	53.1 (-3.3%)	144.5 (-3.8%)	290.7 (-0.1%)	484.9 (-2.1%)	699.8 (-5.2%)

Table 1: Modal parameters of the steel bar based on experimental and numerical results (Hz)

3.2. GW test

In the test, stress waves were generated to propagate in the structure and recorded by the PVDF sensor. The frequency of the generated waves is 40 kHz and the number of the wave cycles is 5. Other excitation frequencies between 30 kHz and 60 kHz were also used in the tests. Similar results, which are not shown here, are obtained.

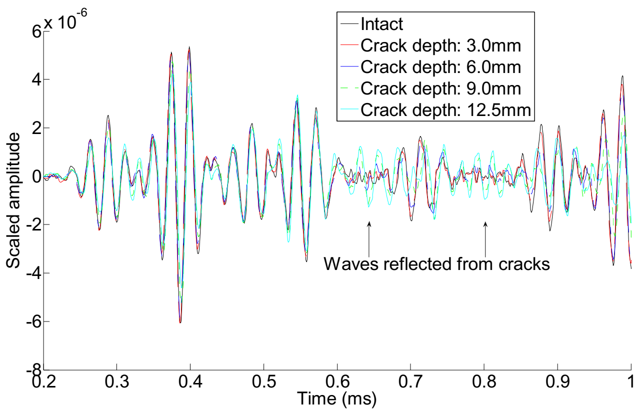


Figure 5: GW test results

Figure 5 shows the comparison of the recorded stress wave histories in the intact and cracked steel bar. Compared with those in the intact steel bar, there are two new waves after the first three waves. They are reflected waves by the crack. The time intervals between these two waves and the excitation wave are 0.5805ms and 0.6785ms, respectively; implying their travelling distances are 3.0m and 3.5m. Further investigation of the results will be conducted in the near future. The amplitudes of the new waves are smaller than other waves, because only part of the wave energy is reflected at the crack location. When crack depth increases, the amplitude of reflected wave increases correspondingly. These results demonstrate that the GW-based method can be used to identify crack damage in a steel bar. Clearly, numerical models are very important for quantitative damage identification by integrating vibration-based and GW methods.

4. CONCLUSIONS

An integrated health monitoring system is developed with the combination of vibration and GW data. Vibration test system focuses on the measurement of modal parameters, which can be used in model updating. GW test system is used to transmit and receive high-frequency waves propagating in the structure in order to identify small damage. Experimental results on a steel beam demonstrate the efficiency and effectiveness of the proposed method. Combining these data can give a better performance of damage identification, which will be studied in the future.

5. ACKNOWLEDGEMENT

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