Design and implementation of stress measurement system for steel structures members

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ABSTRACT: Non-destructive measurement of stress can provide an effective way to explore the service life and performance degradation status of steel structures. In this paper, a measurement system is designed and developed, which includes both hardware and software systems. The hardware system consists of three modules: signal transmitting, signal conversion and signal receiving. The software system consists of four modules: signal storage, signal de-noising, calibration of stress to acoustic time difference factor, and stress calculation. To examine the performance of the system, a group of axial forces are applied on two steel members and axial stresses are measured on designed system. The strain gauge method is used for verification. The results show that the designed system is reliable and agrees with the results from strain gauge method. It has high potential to be applied in the field stress evaluation to monitor the structure, from pre-operation stage to service operation stage.

KEYWORDS: stress measurement system; stress non-destructive measurement; ultrasonic method; steel members; structural health monitoring

1 INTRODUCTION
Stress is one of the main factors determining the design and analysis of steel structures. The effective and reliable measurement of stress can provide useful information that allows the safety of existing structures to be evaluated. For that reason, stress analysis is a compulsory stage in the process of design and evaluating steel structures. However, traditional stress measurement methods, such as the sectioning method (Shadley et al. 1987), hole-drilling method (Bateman et al. 2005), strain gauge method (Watanabe et al. 2010) and diffraction methods (Monin et al. 2014, Seok-Hoon et al. 2009), cannot measure stress of in-service structural steel members accurately and reliably. This may increase the risk of structural failure.

Ultrasonic wave propagation in a solid medium is dependent on the stress of the medium (Guz’ et al. 2000). In the range of elasticity, the velocity of ultrasonic wave propagation in solids is dependent on the stress, which is called acoustic-elasticity (Hughes et al. 1953). Compared with traditional methods, ultrasonic stress measurement methods have advantages in terms of both cost and flexibility. This makes ultrasonic method one of the most promising directions in stress nondestructive measurement (Rossini et al. 2012). According to the different wave types employed, stress measurement using ultrasonic methods can be classified into three groups. The first group aims to directly use the time-of-flight (TOF) of ultrasonic wave, mainly for longitudinal waves (Joshi et al. 1984, Kyung-Young et al. 2006). The second group combines information from both longitudinal and transverse waves for stress measurement (Chaki et al. 2007). The third group employs critically re-fracted longitudinal (Lcr) waves to measure stress (Egle et al. 1976, Dos Santos et al. 2002, Bray et al. 2001, Javadi et al. 2015). Although certain progress has been achieved in the development of different experimental techniques, methods and devices that investigate the application of ultrasonic methods to measure the stress of in-service structural steel members remain rare in the literature (Rossini et al. 2012). A considerable effort is still required to develop efficient and cost-effective methods of in-service structural steel members stress measurement.

In this paper, a practical non-destructive evaluation approach to determine the stress of in-service structural steel members using Lcr waves is proposed. A portable system utilizing modern components and parts for measurement of stress in laboratory and in real steel structures was designed and developed, which includes both hardware and software systems. The hardware system consists of signal transmitting, signal conversion and signal receiving. The software system consists of modules for signal storage, signal de-noising, calibration of stress to acoustic time difference (SATD) factor and stress calculation. An example of the practical application of the developed technique and system for stress measurement is present and verified by using the traditional strain gauge method.
2 METHODOLOGY

2.1 Theory

In this study, structural steel member material is assumed to be isotropic and homogeneous. Further, it is assumed to be in its elastic range. The speed of the Lcr wave traveling parallel to the load can be related to stress by the following expression (Bray et al. 2001):

\[
\rho_0 V^2 = \lambda + 2\mu + \frac{\sigma}{3\lambda + 2\mu} \left[ \frac{\lambda + \mu}{\mu} (4\lambda + 10\mu + 4m) + \lambda + 2\mu \right]
\]  

(1)

where \(\rho_0\) is the material density before deformation; \(V\) is the velocity of the Lcr wave when the steel member is under stress; \(\sigma\) is the stress of the steel member; \(\lambda\) and \(\mu\) are the second order elastic constants of the material; and I, m, and n are the third order elastic constants of the material. The relationship between stress and velocity is not practically convenient for stress measurement.

When steel member is under stress-free condition, the velocity of the Lcr wave is:

\[
\rho_0 V_0^2 = \lambda + 2\mu
\]  

(2)

where \(V_0\) is the Lcr wave velocity when steel member is under zero-stress condition. By substituting Eq. (2) into Eq. (1), a new formula can be obtained:

\[
V^2 = V_0^2 (1 + k\sigma)
\]  

(3)

where \(k\) is a constant related to the material properties:

\[
k = \frac{4\lambda + 10\mu + 4m + 2\lambda - 3\lambda - 10\mu - 4m}{3\lambda + 2\mu}
\]  

(4)

The derivative form of Eq. (3) is:

\[
d\sigma = 2V kV_0 \cdot dV
\]  

(5)

Based on previous studies, the Lcr wave velocity is not very sensitive to stress conditions of the steel members (Li et al. 2016, Javadi et al. 2014, Javadi et al. 2013). For example, a 100 MPa stress change corresponds with less than a 1% velocity change. Therefore, Lcr wave velocity under stress conditions and stress-free condition is almost equal. To further simplify the relationship between stress and Lcr wave velocity, Lcr wave velocities under stress and stress-free conditions are regarded as equal. This assumption leads to the following formula:

\[
d\sigma = 2V kV_0 \cdot dV
\]  

(6)

where \(d\sigma\) is the variation of stress and \(dV\) is the variation of Lcr wave velocity. By integrating Eq. (6), a linear relationship between stress and Lcr wave velocity can be obtained:

\[
\sigma - \sigma_0 = \frac{2V}{k} \frac{V - V_0}{V_0}
\]  

(7)

where \(\sigma_0\) represents the steel member’s initial stress condition, which can be set to zero, i.e. \(\sigma_0 = 0\). Then, Eq. (7) reduces to:

\[
\sigma = \frac{2}{k} \frac{V - V_0}{V_0}
\]  

(8)

Eq. (8) represents the relationship between stress and Lcr wave velocity as a linear function.

As stated above, the velocity change of Lcr waves caused by stress is too small to be measured, so further simplification is necessary. Based on the fixed acoustic path method (Li et al. 2016, Javadi et al. 2015), this study transforms the relationship between stress and velocity to the relationship between stress and TOF in a fixed acoustic path.

By assuming that Lcr waves propagate in a fixed acoustic path, L, in a steel member, the TOF of Lcr waves in the path are \(t_0\) and \(t\) respectively when steel member is under stress-free and stress conditions.

By substituting \(V = \frac{L}{t}\), and \(V_0 = \frac{L}{t_0}\), into Eq. (8), it becomes:

\[
\sigma = \frac{2}{k} \frac{t_0 - t}{t_0}
\]  

(9)

In actual measurements, when the Lcr wave propagates to a length of 100 mm in steel members, the stress change of 100 MPa induces less than a 0.2% change of TOF. Therefore, Eq. (9) can be further simplified, by replacing the denominator \(t\) with \(t_0\):

\[
\sigma = \frac{2L}{kt_0} (t_0 - t)
\]  

(10)

The relationship between stress and the TOF of an Lcr wave can be further simplified as:

\[
\sigma = B(t_0 - t)
\]  

(11)

where \(B\) is defined as Stress to Acoustic Time Difference (SATD) factor, which represents the linear relationship between stress and the TOF of an Lcr wave:

\[
B = \frac{1}{Kt_0}
\]  

(12)

2.2 Design of stress measurement system

Based on above theory, a measurement system is designed and developed in this study. The measurement system includes both hardware and software systems. The hardware system consists of signal transmitting, signal conversion and signal receiving. The software system consists of modules for signal storage, signal de-noising, calibration of SATD factors and stress calculation.

2.2.1 Design of hardware system

The schematic diagram and the photo of the designed hardware system are shown in Figure 1 and Figure 2, respectively. As can be seen, there are a total of eight components in hardware system. ① is the loading device, which is used to generate measurable loading.
on the test specimens. ② is the oscilloscope. It can capture, display, and record signals from the transducers and work with a resolution of 0.4 ns which allows very precise measurements of TOF. ③ is an ultrasonic preamplifier. Its function is to amplify the received signals. ④ is the static resistance strain gauge and ⑤ is the ultrasonic generator. ⑥ is a computer and it is used to process the collected signal using the software system. ⑦ and ⑧ are the transmitting probe and receiving probe, respectively. They are responsible for signal transmission and reception. Probes are connected to the signal amplifier and oscilloscope through wires.

The generation of Lcr wave is shown in Figure 2. When ultrasonic longitudinal wave reaches interface between two different acoustic impedance media, wave mode conversion will occur. At that time, part of the energy is reflected by the interface to the first medium, and the incident angle equals to the reflected angle. The other part of the energy refracts into the second medium, and the refracted longitudinal wave and refracted shear wave are generated. According to Snell law (Godin et al. 2009), when ultrasonic velocity in the second medium is greater than in the first one, the angles of refracted longitudinal wave and refracted shear wave increase with the increase of longitudinal wave incidence angle. When the incident longitudinal wave angle increases to a certain value, the refracted longitudinal wave travels parallel to member surface. Now, the refracted longitudinal wave becomes the critically refracted longitudinal wave, namely, Lcr wave. In this study, the medium Ⅰ is PMMA material and medium Ⅱ is steel material. As a special ultrasonic wave mode, Lcr wave travels parallel to member surface and propagates beneath the surface at a certain depth. The propagation depth of Lcr wave is a function of frequency, but an explicit form of this function has not been derived yet (Li et al. 2016, Javadi et al. 2015). In this paper, frequency of Lcr wave is 5MHz and its propagation depth is about 1.1 mm under member surface (Javadi et al. 2014b).

The most important part of ultrasonic stress measurement is measuring the TOF related to the Lcr wave. According to measurement system schematic diagram in Figure 1, the mechanism of measuring the TOF related to the Lcr wave can be explained as follows.

1. The ultrasonic generator can be controlled to transmit a chain of pulse signals, and shunts them into a transmitting signal and synchronization signal by a transfer head.

2. After wave mode conversion, the Lcr wave is generated in steel structural member. The Lcr wave propagates in steel structural member and will be received by the receiving probe.

3. The received Lcr wave will be displayed on the oscilloscope after being amplified by ultrasonic preamplifier.

4. Meanwhile, the synchronization signal of the ultrasonic signal is directly inputted to the oscilloscope. The oscilloscope captures and displays two signals: one is received signal and the other is synchronization signal.

5. The time difference between these two signals is the TOF of the Lcr wave, which can be measured by using software system.

2.2.2 Design of software system
An in-house software is designed on the Labview platform. The data processing of the software system is illustrated in Figure 3. It can be seen that the software system consists of modules for signal storage, signal de-noising, calibration of SATD factor, and stress calculation for in-service structural steel members.
A series of pulse signals are generated by the ultrasonic generator. The received signal and synchronization signal are displayed in the oscilloscope and then identified by the software system.

The received signal and synchronization signal are filtered by using wavelet transform method. This program is written in MATLAB software and embedded in Labview platform, which combination takes the advantages of both software. The comparison results of the waveform before and after signal de-noising is shown in Figure 4. After signal de-noising, the feature point is captured by using threshold method. The software interface of feature point capture is shown in Figure 5.

![Waveform before signal de-noising](image1)

![Waveform after signal de-noising](image2)

Figure 4. Comparison of the waveform before and after signal de-noising

![Feature point capture](image3)

Figure 5. Feature point capture

A set of stresses can be measured and corresponding flight time can be recorded by software system. The SATD factor can be calculated using least square method. By measuring the Lcr wave flight time of in-service structural steel members, stress can then be determined. The software interface of calibration of SATD factor and stress calculation is shown in Figure 6, in which SATD factor is 1.8834 MPa/ns and stress output value is 125.23 MPa.

2.3 Implementation of stress measurement system

Flow chart of ultrasonic method to measure stress of steel structure members is shown in Figure 7. There are five steps of stress measurement by designed system:

- Step one, copy of in-service structural steel member. Steel structure member is non-removable after installation. Mass and standardization production of steel structural member makes it possible to copy a steel member with same materials and dimensions. A steel member with the same material and geometrical parameters should be selected as a copy member.

- Step two, measurement of Lcr wave TOF for the replication member under stress-free condition. The object to be measured is to in Eq. (11). Transmitting probe and receiving probe should be placed with a fixed distance on the replication member. In stress-free condition, the oscilloscope captures the arrival time of the two signals. The acoustic time difference (ATD) of two signals can be obtained.

- Step three, calibration of the SATD factor for the replication member. The SATD factor is measured by using a uniaxial tensile test in the replication member. A set of axial stresses are applied and a set of data (\((t_1, \sigma_1), (t_2, \sigma_2), \ldots, (t_n, \sigma_n)\)) can be obtained. The SATD factor can be fitted using least square method.

- Step four, measurement of the Lcr waves TOF in the in-service structural steel member. Transmitting probe and receiving probe should be placed with same distance with step (2) on in-service structural steel member.

- Step five, by putting the results of step (1)-(4) in Eq. (11), stress of in-service structural steel member can be calculated.

![Flow chart of ultrasonic method](image4)

Figure 7. Flow chart of ultrasonic method
3 EXPERIMENTAL PROGRAM

3.1 Materials used and preparation of specimens

Two steel members made of Q235 steel are used as test specimens. The first member is steel plate and the second is angle steel. Their dimensions are 450 mm × 40 mm × 12 mm and ∠80 mm × 80 mm × 6 mm, respectively.

3.2 Stress measurement of steel structures members

In order to install the transmitting probe and receiving probe convenience during stress measurement, the distance between the transmitting and receiving probes was 150 mm and 100 mm for steel plate and angle steel, respectively. In accordance with the introduction of section 2.3, the stress values and corresponding ATD of two members could be measured. The corresponding SATD factors can be fitted, as shown in Figure 8.

![Figure 8. Fitting line between stress and TOF of steel plate and angle steel](image)

The stress can be calculated by measuring Lcr wave TOF in in-service structural steel members. A group of unknown axial forces were applied to replication members to simulate the unknown stress condition of two structural steel members. The stresses were measured by the proposed method and designed system. The results for steel plate and angle steel are shown in Figure 9 and Figure 10.

3.3 Validation of the designed system

Traditional strain gauge method was employed to verify the stress values measured by the designed system. Strain gauges were attached on the surface of steel plate and angle steel. As the load applied to the steel members can produce uniformly distributed axial stress, the surface and stresses are equal. Then, the stress values can be represented by the surface stress values. The results measured by both methods are compared and listed in Figure 9 and Figure 10.

![Figure 9. Comparison between two methods of steel plate](image)

![Figure 10. Comparison between two methods of angle steel](image)

4 RESULTS AND DISCUSSION

It can be seen from Figure 8 that the SATD factor of steel plate and angle steel was observed to be 1.8263 MPa/ns, 2.3467 MPa/ns, respectively. The fitting degrees were not less than 0.95. The results illustrate that the stress in two steel members and Lcr wave ATD demonstrate a nearly perfect linear relationship. The essential reason for this phenomenon is that the velocity of Lcr wave propagation in solids is dependent on the stress in the range of elasticity. The experimental validation results presented in this study are consistent with other scholars’ research results (Egle et al. 1976, Javadi et al. 2015, Li et al. 2016).

The measured stresses of the ultrasonic method and the strain gauge method were shown in Figure 9 and Figure 10. The error between two methods results is less than 5%. The results show that the proposed method and designed system is reliable and have high potential to be applied in the field measurement.

It should be pointed out that there are some advantages of proposed method and designed system. The whole process of measurement is nondestructive, which meet demands of not damaging existing structures. In addition, the designed system is consisted of portable equipment, and the equipment is
low cost. These advantages make it convenient for field stress evaluation, from pre-operation stage to the service operation.

5 CONCLUSIONS

This paper confirms the potential of the ultrasonic method in measurement of the stress of in-service structural steel members. Based on acoustic-elasticity theory and steel member measurement demands, a stress measurement formula is derived and a measurement system is designed. Stresses of two steel members are measured by using the designed system. The results show that Lcr wave ATD and corresponding stress in steel member exhibits an almost perfect linear relationship. The strain gauge method was employed to validate the results measured by ultrasonic method. The error between two methods results is less than 5%, which confirms the effectiveness of the designed system. The experimental results from this study show that the proposed measurement process is convenient, and the designed system is reliable.

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7 REFERENCES


