Guided Waves Methods for Local Damage Assessments in Steel Structural Members

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ABSTRACT

In this paper, guided waves methods are presented for effective assessments of small local damages in slender steel structural members, such as beams. Piezo-electric sensors are used as actuators and receivers. Semi-analytical finite element (SAFE) method is employed for understanding the wave dispersion characteristics regarding the wave modes, exciting frequencies, and the propagation speed. Based on the measured wave signals, local damage detection is carried out using pattern recognition techniques such as principal component analysis (PCA). Time of flight information (ToF) is analyzed for damage localizations. Laboratory experiments were conducted for identification of the small cut and additional mass in a weld zone of an I-shaped beam.

1. INTRODUCTION

Ultrasonic guided waves based damage detection method has been proven to be a promising approach in the inspection of structures having long and slender dimensions. It has been widely applied to inspect pipelines, plates, rods and etc. To carry out damage detection using guided waves, enough wave energy shall be focused on the area of interest to enhance detection efficiency and accuracy. Therefore, SAFE analysis (Hayashi 2003) shall be performed to learn the wave propagation characteristics at first, especially for the structural members with complex geometric cross sections.

I-shaped steel beams are widely used for their good performances on carrying bending moment and shear force. During the service period under complicated working environment, different types of damages will occur and accelerate the structural degradation. Fillet weld is one of the most common ways to connect the web plate and
flange plate. The damage development in fillet weld zone would possibly cause the failure of the beam and even the collapse of the entire structure. The ultrasonic waves based structural health monitoring system (SHM) can reliably detect and localize damages. This will contribute a lot to the extension of the structural service life and also avoid fatal accidents. However, the area of the weld zone in the I-shape beam is usually less than 2% of the whole cross section. And some parts of the structural cross section are usually connected to other structural members. Therefore, appropriate sensor type, sensor locations, and exciting frequency range shall be considered carefully (Fan 2009).

2. WAVE PROPAGATION CHARACTERISTICS IN I-SHAPED STEEL BEAM

The dimension and physical parameters of the I-shaped steel beam tested in this paper are shown in Table 1. The total length of the beam is 1 meter. Dispersion curve for phase velocity was obtained by SAFE method as shown in Fig. 1. Proper wave modes were searched for higher energy concentration in the weld zone. Considering the performance of the experimental instrument, the searching frequency range was set from 30 to 70 kHz. Fig. 2 shows the 12th wave mode at 40 kHz. The energy ratio of the bottom weld zone to the whole cross section is 2.22% for this mode. The 13th wave mode shows the same energy ratio as its wave structure is horizontal axisymmetric about the web. The energy ratio of these two modes is relatively high compared with the other wave modes. Hence the 12th and 13th wave mode at 40 kHz was chosen as the exciting wave mode for damage detection in the weld zone. 11 locations were considered for both actuating and sensing as shown in Fig. 4. SAFE analysis results indicate that Locations 5 and 6 are the best to excite desired wave modes. 3D wave propagation analysis was carried out for verification using ABAQUS. Fig. 6 shows the 2D-FFT curve for a set of simulated time-history signals along the welding line, which shows good agreement with SAFE results.

**Table 1** Geometrical dimensions and physical parameters of I-shape beam

<table>
<thead>
<tr>
<th>Young Modulus</th>
<th>Poisson’s Ratio</th>
<th>Density</th>
<th>Thickness</th>
<th>Flange Width</th>
<th>Web Height</th>
<th>Weld Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>206Gpa</td>
<td>0.28</td>
<td>7850kg/m3</td>
<td>6mm</td>
<td>120mm</td>
<td>100mm</td>
<td>5mm</td>
</tr>
</tbody>
</table>

Fig. 1 Dispersion curve
Fig. 2 12th wave structure at
Fig. 3 13th wave structure
The simulations were also carried out with different excitation frequency from 30 kHz to 70 kHz. The damage location was estimated based on the ToF information and group velocity. It could be found that the most accurate localization result was obtained when the excitation frequency was 40 kHz. The reason can be
explained by the higher energy concentration in the weld zone at this frequency.

3. DAMAGE DETECTION AND LOCALIZATION ON WELD ZONE

Laboratory experiments were conducted on a steel beam with same properties as in the simulation study. A pair of piezo-electric transducers were installed at Location 5 and 6. Tests were conducted at three conditions: intact specimen, specimen with an additional mass (1cm*5mm quadrate cross section) at 0.7m and specimen with a cut (5mm*5mm triangular cross section, 1cm long) on the weld zone in the middle as shown in Fig. 9. Sinusoidal wave with Hanning-window at 40 kHz center frequency was used as the excitation signal at 2 sensors. The sampling rate is 500 kHz and the total time for wave propagation is set as 0.002s. The experimental instruments and piezoelectric sensors are shown in Fig. 10. The signal received at the intact state is shown in Fig. 11. The acoustic distance was calculated for wave packet using the ToF information. Fig. 12 shows the signals obtained from the cut damage state and mass-added state respectively. Damage detection was carried out using residual signals between the damaged and intact signals as shown in Fig. 13. To improve the damage identification, cross-correlation analysis was performed. Each time history was divided into 20 segments, and the cross-correlation coefficient was calculated at each time segment. Results of the damage existence and localization are shown in Fig. 14.
To investigate the temperature effect on wave signals, the test beam was placed in a temperature chamber to obtain signals at 15 - 40 °C. Signals at the intact state under various temperature are shown in Fig. 15. It indicates that the cross-correlation analysis under large temperature variation may cause false alarm in damage detection. Thus, PCA (Mujica 2011) was carried out to detect abnormity under various ambient temperature.

The main purpose of using PCA is to remove the influence of environmental effects and extract structural damage features. The collected signals are arranged in matrix $𝐗 (𝑛 \times 𝑚)$. $𝑛$ is the number of the measurement trials and $𝑚$ is the number of time instants. A $𝑚 \times 𝑛$ linear transformation matrix $𝐏$ is used to transform the original data matrix $𝐗$ into the new space as $𝐓 = 𝐋𝐏$. The covariance of the new data matrix $𝐓$ is diagonal to achieve the minimal redundancy goal. And it is usually called the score matrix, as each column vector in $𝐓$ is the projection of original signals over the direction of one principal component (PC) in $𝐏$. By choosing a reduced number $𝑟$ of PCs ($𝑟 < 𝑛$), the original data can be reconstructed as $𝐗̂ (𝑛 \times 𝑚) = 𝐋𝐏̂$. And the residual data can be obtained as $𝐗 = 𝐋 − 𝐋̂$. To observe the changes that are not explained by the model of principal components, Q-statistic is introduced as $𝐒_i = 𝐱_i𝐱_i^T$ (the $𝑖$th measurement in $𝐗$). To perform the damage detection, a baseline shall be built from the data under desired or confirmed state. The new data to be tested would be projected onto some of the first PCs and the Q-statistic could be obtained.

In this paper, 105 measurements from intact condition were used as the base signals for PCA. Large number of measurements were obtained as test signals: 200 from intact condition, 230 from cut damage and 100 from mass-added condition. The scores of the baseline signals and test signals corresponding to the first PC are shown in Fig. 17. It could be found that the first PC is highly correlated with the temperature variations. The scores corresponding to the following PCs were also checked for their
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intrinsic meanings behind. Then Q-statistic was evaluated for each test signal using the first 4 PCs determined from the baseline signals. The damage existence was determined by observing the step change in Q-statistic as in Fig. 18. To estimate the damage location, residual signals were reconstructed by eliminating the temperature effect and environmental noises using the first 4 PCs. The locations of the cut and additional mass can be predicted as shown in Fig. 19.

The attached mass increases the cross-section area of the weld zone by 50 mm², and the inflicted cut only reduces the cross-section area by 12.5 mm². Thus the Q-statistic values in mass-added cases are more obvious than those in cut damage cases. And the amplitude of reflected waves from the additional mass location is larger than that from the cut damage. To eliminate other environmental effects and random sensor vibrations, signal processing methods that are more applicable to acoustic characteristics shall be performed to deal with acoustic signals.

![Fig. 15: Signals under different temperatures: a) original signals; b) Hilbert envelopes](image1.png)

![Fig. 16: Ambient temperature at each measurement: a) baseline; b) test signals](image2.png)

![Fig. 17: Scores corresponding to the 1st PC: a) baseline; b) test signals](image3.png)

![Fig. 18: Q-statistic](image4.png)
4. CONCLUSIONS

Guided wave based damage detection is presented for an I-shape steel beam. SAFE analysis and 3D simulation on wave propagation were performed for selecting sensor locations and excitation frequency. Laboratory experiments were conducted under different damage states. At first, the damage detection was carried out based on the residual signals between the damaged and intact cases using the ToF information. PCA was then employed to eliminate the temperature effect and detect the abnormality. Residual signals were obtained to achieve the damage localization.

REFERENCES


