Continuous fatigue crack monitoring without baseline data

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ABSTRACT In order to overcome the susceptibility of conventional non-destructive testing (NDT) techniques to operational and environmental variations, a new damage detection technique that does not require direct comparison with baseline data was previously developed by the authors for detecting a crack in a plate structure. This reference-free technique employs two pairs of collocated lead zirconate titanate transducers (PZTs) placed on both sides of the plate to generate and measure Lamb waves. Then, the existence of mode conversion due to the crack is identified from the Lamb wave signals instantly measured by PZTs. In this study, the effectiveness of the proposed technique is tested using a steel girder specimen. A cyclic loading is applied to the girder resulting in fatigue cracks, and the proposed technique detects the appearance of fatigue damage solely based on the measured Lamb waves at the present stage. Experimental results are presented to demonstrate the applicability of the proposed technique to fatigue crack monitoring, and issues related to PZT installation are discussed.

Keywords fatigue cracks; Lamb wave; mode conversion; non-destructive testing (NDT); piezoelectric polarization; reference-free damage detection.

INTRODUCTION

The recent collapse of I-35 Mississippi River Bridge in Minnesota, United States, has increased the needs for adopting structural health monitoring (SHM) and non-destructive testing (NDT) systems for continuous monitoring of ageing aircraft, civil infrastructure and mechanical systems. For SHM/NDT, guided waves have received a great deal of attention and have been a topic of considerable interest1–5 because they can propagate over considerable distances with little attenuation. Conventional guided wave studies have focused on schemes where baseline signals are measured so that changes from the baseline can be detected. However, there are significant technical challenges to realizing this pattern comparison. For instance, structural defects typically take place long after the initial baseline data are collected. In addition, other operational and environmental variations of the system can produce significant changes in the measured response, masking any potential signal changes due to structural defects.6

As an alternative that can overcome the drawbacks of the conventional NDT methods, a new concept of NDT technique, which does not rely on previously obtained baseline data, was proposed by the authors for crack detection in plate-like structures.7 The proposed technique utilizes the polarity of piezoelectric materials and employs two pairs of collocated lead zirconate titanate transducers (PZTs) placed on both sides of the specimen to generate and measure Lamb waves. In terms of excitation, PZTs produce deformation (strain) when exposed to an applied electric field. On the other hand, PZT materials develop an electrical charge or voltage when a mechanical pressure is applied, acting as sensors. PZTs are crystalline materials that are artificially polarized through a thermal poling process. The overall behaviour of a piezoelectric material as well as its electrical characteristics is governed by the polarization direction of the material. That is, the ‘sign’ of the output voltage depends on the bending direction of the PZT with respect to its poling direction. When Lamb waves propagate through a crack, mode conversion occurs. Due to this mode conversion, a single Lamb wave mode is divided into multiple modes at the discontinuous point such as a crack. The uniqueness of the proposed crack detection technique is that this mode conversion due to a crack is instantly identified without using prior baseline data. By removing the dependency on the prior baseline data, the proposed damage detection system becomes less vulnerable to operational and environmental...
variations that might occur throughout the life span of the structures being monitored. In this study, the effectiveness of the proposed NDT technique for continuous fatigue crack monitoring within a steel girder commonly used for civil applications is tested. For the test, a scaled girder is fabricated and subjected to cyclic loading, resulting in fatigue cracks on its flange. Then, the proposed technique detects the appearance of fatigue damage by extracting damage-sensitive features from instantly measured Lamb wave signals and without using any previously established threshold for damage classification.

This paper is organized as follows. First, the effect of a PZT polarization direction on Lamb wave generation and measurement is reviewed, and the main idea of the proposed reference-free diagnosis technique is described. Then, a reference-free thresholding technique is presented to determine the existence of crack damage autonomously. Numerical and experimental studies are conducted to investigate the applicability of the proposed NDT technique to crack detection. Finally, this paper concludes with a brief summary of findings and discussions for future improvements.

THEORETICAL DEVELOPMENT

In this section, the theoretical development in Kim and Sohn is briefly reviewed for the completeness of the paper. First, it is explained how the PZT polarity affects Lamb wave generation and sensing. Then, additional Lamb wave modes created by crack formation are extracted from the measured Lamb waves using the polarization characteristics of the PZTs. Finally, a reference-free crack classifier that operates on the extracted mode conversion is introduced for autonomous decision making.

The effect of PZT poling directionality on Lamb wave propagation

Piezoelectric materials are naturally or artificially polarized ceramics that have piezoelectricity, and these materials develop an electrical charge or voltage when a mechanical pressure is applied. Conversely, piezoelectric materials produce deformation (strain) when exposed to an applied electric field. Due to this unique nature of the piezoelectric materials, they are commonly used as both sensors and actuators in many applications. The overall behaviour of a piezoelectric material as well as its electrical characteristics is governed by the poling direction of the material. In this section, it is illustrated how the phase of a Lamb wave mode changes depending on: (1) the poling directions of exciting and sensing PZT wafer transducers and (2) whether a wafer transducer is attached either on the top or bottom surface of a plate.

In order to illustrate the phase change of a Lamb wave mode due to PZT poling directionality, it is assumed four identical PZT wafer transducers are attached to the plate as shown in Fig. 1a (Configuration I). The arrows

Fig. 1 The effect of the PZT poling directions on the phases of the $S_0$ and $A_0$ modes.
in the figure indicate positive poling directions of PZT transducers. Two identical PZTs A and D are placed exactly at the same position but on the other side of the plate. PZTs B and C are positioned in a similar fashion.

It is assumed that a narrowband tone-burst signal is applied as an input. Furthermore, the driving frequency is chosen such that only the fundamental symmetric ($S_0$) and anti-symmetric ($A_0$) modes are generated.

When PZT A is excited, the $S_0$ and $A_0$ modes are generated and measured at PZTs B and C. In an ideal condition, the amplitude and arrival time of the $S_0$ modes measured at PZTs B and C should be identical because of the symmetric nature of the $S_0$ mode (Figs 1b & 2a). As far as the $A_0$ mode is concerned, PZT C is subjected to the opposite bending compared to PZT B (Fig. 1b). Therefore, the $A_0$ modes measured at PZTs B and C are out-of-phase (Fig. 2a). However, when the poling direction of PZT C is switched upwards (Fig. 1c), PZTs B and C will produce out-of-phase $S_0$ modes and in-phase $A_0$ modes (Figs 1d & 2b). In the following subsection, this idea of using PZT poling directionality is further advanced so that the mode conversion due to crack formation can be extracted from the measured Lamb wave signals.

Detection of crack-induced mode conversion using a PZT poling direction

Mode conversion of Lamb waves occurs if Lamb waves propagating along a thin plate with a uniform thickness encounter a discontinuity such as a sudden thickness change of the plate. When an $S_0$ mode arrives at the discontinuity, the transmitted wave is separated into $S_0$ and $A_0$ modes (denoted as $S_0/S_0$ and $A_0/A_0$, respectively).

In a similar manner, an $A_0$ mode is also divided into $S_0$ and $A_0$ modes ($S_0/A_0$, and $A_0/A_0$). In this section, the polarization characteristic of the PZT material is utilized to detect this mode conversion due to crack formation without using any prior baseline data.

In Fig. 3a and b, the phases of the $S_0$ and $A_0$ modes in signals AB and CD are compared when the specimen is in an intact condition. When the $S_0$ and $A_0$ modes generated by PZT A are defined to be positive, PZT C creates a negative $S_0$ mode and a positive $A_0$ mode because the poling direction of PZT C is the same to PZT A (Fig. 3a). However, because the poling directions of PZTs B and D are also the same to each other, the $S_0$ modes produce same bending at PZT B and D (Fig. 3b). For the same reason, PZTs B and D measure in-phase $A_0$ modes (Fig. 3b). Therefore, when the plate is in a pristine condition and four identical PZTs are instrumented as shown in Fig. 3a, it is concluded that signal AB becomes identical to signal CD as shown in Fig. 3b.

However, signal AB is no longer identical to signal CD when there is a crack between PZTs A and B (or PZTs C and D) as shown in Fig. 3c and d. As for signal AB, the $S_0$ mode is followed by the $S_0/A_0, A_0/S_0$, and $A_0$ modes when the notch is located closer to PZT A (assuming that the $S_0$ mode travels faster than the $A_0$ mode). According to the sign convention defined in Kim and Sohn,7 all the modes in signal AB including $S_0/A_0$ and $A_0/S_0$ modes become positive. On the other hand, the $S_0$ mode is followed by the $A_0/S_0, S_0/A_0$, and $A_0$ modes in signal CD, and the $A_0/S_0$ and $S_0/A_0$ modes become negative while the $S_0$ and $A_0$ modes are positive.7

In Fig. 3d, signals AB and CD are drawn considering only the arrival times of each mode, but also their relative phases. Note that while the $S_0$ and $A_0$ modes in Fig. 3d are in-phase, the $S_0/A_0$ and $A_0/S_0$ modes in signals AB and CD are fully out-of-phase. Therefore, the additional modes generated by the crack damage can be extracted simply by subtracting signal AB from signal CD as shown in Fig. 3d. In addition to signals AB and CD, it can be readily shown that the $S_0$ and $A_0$ modes in signals AC and BD are identical while the $S_0/A_0$ and $A_0/S_0$ modes are fully out-of-phase. Note that this approach relies only on the comparison of two instantaneous signals obtained at the current state of the system rather than comparison with previously recorded reference data. Therefore, it is expected that this approach may reduce false alarms of defects due to changing operational and environmental conditions of the system. The robustness of the proposed methods needs to be further evaluated through practical experiments.

Detection of crack-induced mode conversion using a PZT poling direction

Fig. 2 A schematic comparison of the $S_0$ and $A_0$ modes measured from Configurations I (Fig. 1a) and Configuration II (Fig 1c), respectively: AB (a dash line) and AC (a solid line) denote the response signals measured at PZTs B and C when a tone-burst input is applied at PZT A.
Decomposition of individual Lamb wave modes from measured time signals

So far, it is theoretically shown that signals AB and CD are indistinguishable when there is no crack as shown in Fig. 3. This is based on the assumption that all PZT transducers are identical and PZTs A and D (or PZTs B and C) are perfectly collocated. In practice, these assumptions cannot be fully satisfied because of variations in PZT size, alignment and bonding condition. This imperfection in PZTs may generate initial differences in signals AB and CD even in the absence of crack and lead to positive false alarms.

In order to tackle this issue, the authors developed a damage diagnosis scheme based on the premise that mode conversion produces signal differences between signals AB and CD that were bigger than the initial differences due to PZT imperfection. This proposed technique takes advantage of not only signals AB and CD, but also signals AC and BD to extract mode conversion in the presence of variations of the PZT size, alignment and bonding. For an illustration purpose, signal AB is drawn in Fig. 4, which shows that signal AB is a simple superposition of signals $S_0$, $MC_1$, $MC_2$ and $A_0$. In Fig. 5, not only signal AB but also signals AC, BD and CD are schematically drawn. Figure 4 is drawn emphasizing relative phase information of these signals when the notch is closer to PZT A than PZT B. The $S_0$ and $MC_1$ modes in signal AC are out-of-phase compared to these modes in signal AB (Fig. 5). When the relative phase information of each mode is considered, it is possible to extract $S_0$, $A_0$ and two converted modes from measured Lamb wave signals. For instance, the $S_0$ mode can be extracted by adding signals AB and CD and subtracting signals AC and BD. This procedure can be expressed as follows:

$$
\begin{bmatrix}
\text{Signal } S_0 + \varepsilon_S \\
\text{Signal } MC_1 + \varepsilon_{MC_1} \\
\text{Signal } MC_2 + \varepsilon_{MC_2} \\
\text{Signal } A_0 + \varepsilon_A
\end{bmatrix} = \frac{1}{4} \begin{bmatrix}
1 & -1 & -1 & 1 \\
1 & -1 & -1 & 1 \\
1 & 1 & -1 & -1 \\
1 & 1 & 1 & 1
\end{bmatrix} \times \begin{bmatrix}
\text{Signal AB} + \varepsilon_{AB} \\
\text{Signal AC} + \varepsilon_{AC} \\
\text{Signal BD} + \varepsilon_{BD} \\
\text{Signal CD} + \varepsilon_{CD}
\end{bmatrix}.
$$

(1)
should be zeros in the absence of damage. However, because of measurement errors and variations in PZT size, alignment and bonding condition, error terms are to be added in Eq. (1) in practice. Here, $e_{AB}$ is an error signal in the measured signal $AB$ that is superimposed to the exact signal $AB$, and $e_{AC}$, $e_{BD}$ and $e_{CD}$ are defined similarly. While $e_S$, $e_{MC_1}$, $e_{MC_2}$ and $e_A$ represent error signals in each decomposed Lamb mode signals. Because $e_{MC_1}$ and $e_{MC_2}$ are superimposed to the exact signals $MC_1$ and $MC_2$, the decomposed signals $MC_1$ and $MC_2$ may not be zeros even without damage. Because $e_{MC_1}$ and $e_{MC_2}$ cannot be extracted from signals $MC_1$ and $MC_2$ using Eq. (1), it is challenging to determine whether additional modes in these signals are due to mode conversion or PZT imperfections. Therefore, a new damage classifier is developed in this study to determine if the non-zero responses in signals $MC_1$ and $MC_2$ are due to mode conversion or simply due to initial errors.

**Reference-free damage classification using instantaneously measured Lamb wave signals**

The proposed damage identification scheme starts from the decomposition of individual Lamb mode signals from measured signals using Eq. (1). Next, the maximum absolute amplitude of the error components, $e_S$ and $e_A$, in signals $S_0$ and $A_0$ are estimated. Because the arrival time of the $S_0$ mode in signal $S_0$ is known, the non-zero response of signal $S_0$ outside the $S_0$ mode is mainly attributed to $e_S$. Therefore, the maximum amplitude of $e_S$ can be estimated from the rest of signal $S_0$ where the $S_0$ mode does not exist. The maximum absolute amplitude of $e_A$ can also be estimated from signal $A_0$ in a similar fashion. Then, the threshold value for damage classification is set to be the maximum absolute amplitude of $e_S$ and $e_A$. Finally, the existence of damage is determined by comparing the amplitudes of signals $MC_1$ and $MC_2$ with respect to the threshold value. In this way, a crack can be detected if the crack produces $MC_1$ and $MC_2$ modes that are bigger than the initial differences resulted from PZT imperfection and measurement errors. Note that no predetermined threshold values are required during this damage classification procedure because the threshold value is obtained from instantaneously measured signals $AB$, $AC$, $BD$ and $CD$. The applicability of the proposed thresholding technique is numerically and experimentally investigated in the following sections.

**NUMERICAL SIMULATION**

The idea of using a PZT poling direction for fatigue crack detection was first validated by numerical simulation. Using COMSOL 3.3a Multiphysics software...
(www.comsol.com), Lamb wave propagation in a two-dimensional steel plate with an infinite width was simulated using the combination of plane strain, piezoelectric strain, and electrodynamics modules in COMSOL software. The length of the plate was 50.5 cm, and its thickness was 6.4 mm. Four identical PZTs with 10 mm length and 0.508 mm thickness were attached to the plate model as shown in Fig. 6. The dimensions of the steel plate model and sensor locations were determined based on the experimental steel girder specimen examined in the next section. Because the steel girder specimen used for the experiments had a stiffener 12.75 cm away from PZT A, PZT A in the numerical model was also placed 12.75 cm from the boundary. Note that PZTs A and D were collocated but on the other side of the plate with the same poling direction. PZTs B and C were placed in a similar fashion. In this numerical model, the influence of the PZT bonding layer on Lamb wave propagation is not considered. The parameter values used in the numerical simulation are listed in Table 1. A narrowband tone-burst signal at 150 kHz frequency was used as an input signal. In this study, the driving frequency was selected based on the Lamb wave dispersion curve in order to generate only $S_0$ and $A_0$ modes. In the simulation, Rayleigh damping coefficients were set to $10^{-4}$ for a mass damping coefficient and 0 for a stiffness damping coefficient, respectively. The simulation results were obtained using a time-dependent solver, and a time step was set to 0.25 $\mu$s, which was equivalent to 4 MS/s. To control the error in each integration step, relative tolerance and absolute tolerance for the solution were chosen to be $10^{-4}$ and $10^{-10}$, respectively. The maximum order of the backward differentiation formula (BDF) for interpolating polynomials in the time-stepping method was set to be two. Finally, the model was meshed using a mapped mesh option, and the size of each mesh was limited to 1 mm x 1 mm.

Figure 7a illustrates that signals AB and CD were almost identical and this well matches with the theory. Because the numerical model assumes symmetrical boundary conditions, the $S_0$ reflections from the left and right boundaries superpose together as shown in Fig. 7a. In addition to signals AB and CD, signals AC and BD were also identical without damage as shown in Fig. 7b. Once a notch of 3 mm depth and 1 mm width was introduced 25 mm away from PZT A towards PZT B, signal AB (AC) became different from signal CD (BD) as a result of the mode conversion induced by the crack as illustrated in Fig. 8.

After signals AB, AC, BD, and CD were obtained, the decomposition process described in Eq. (1) was conducted and the decoupled Lamb mode signals were shown in Fig. 9. Because the effect of PZT imperfection was neglected in modelling, individual Lamb wave modes ($S_0$, $A_0$, $MC_1$ and $MC_2$ modes) were clearly extracted. In Fig. 9a, only direct and reflective $S_0$ modes were shown without the $A_0$, $MC_1$ or $MC_2$ modes. Also, the effect of mode conversion did not appear in signal $A_0$ of Fig. 9b while the $A_0$ mode was clearly decomposed. On the other hand, signals $MC_1$ or $MC_2$ in Fig. 9c and d show that the additional modes due to mode conversion were isolated from the $S_0$ and $A_0$ modes.

Note that a notch was simulated in the numerical model while a fatigue crack was introduced in the subsequent experimental study. As long as a notch or a crack produces sudden reduction in thickness, it is expected that they do produce mode conversion. However, the characteristics of a breathing crack can be different from those of a notch because the breathing crack can produce crack opening and closing while the notch remains open. Therefore, the amplitude of the mode conversion may decrease for the

Table 1 Parameters used in numerical simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exciting frequency</td>
<td>150 kHz</td>
</tr>
<tr>
<td>$\alpha$ (Mass damping coefficient)</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\beta$ (Stiffness damping coefficient)</td>
<td>0</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>4 MS/s</td>
</tr>
<tr>
<td>Relative tolerance</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Absolute tolerance</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Maximum BDF order</td>
<td>2</td>
</tr>
<tr>
<td>Mesh size (Mapped mesh)</td>
<td>1 mm x 1 mm maximum</td>
</tr>
</tbody>
</table>

Table 2 Test results from the left flange of the girder at different loading steps

<table>
<thead>
<tr>
<th>Loading step</th>
<th>The maximum absolute amplitude ($S_0$ region)</th>
<th>Threshold value</th>
<th>If $MC_1$ or $MC_2$ exceeds the threshold value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>$0.001498$</td>
<td>None</td>
</tr>
<tr>
<td>5000</td>
<td>$0.001786$</td>
<td>$0.003759$</td>
<td>None</td>
</tr>
<tr>
<td>10 054</td>
<td>$0.002694$</td>
<td>$0.002162$</td>
<td>$MC_1$ only</td>
</tr>
<tr>
<td>15 001</td>
<td>$0.003302$</td>
<td>$0.002453$</td>
<td>$MC_1$ only</td>
</tr>
<tr>
<td>24 081</td>
<td>$0.004912$</td>
<td>$0.003498$</td>
<td>$MC_1$ only</td>
</tr>
</tbody>
</table>

Fig. 6 Dimension of a steel plate used in numerical simulation.
Fig. 7 Comparison of signals AB and CD (or signals AC and BD) when there is no notch.

Fig. 8 Comparison of signals AB and CD (or signals AC and BD) with a notch of 3 mm depth and 1 mm width.

Fig. 9 Decomposition of individual Lamb mode signals $S_0$, $A_0$, $MC_1$, and $MC_2$ from measured signals AB, AC, BD and CD using Eq. (1) (damaged case).
crack when the crack is closed. Therefore, the applicability of the proposed technique to fatigue crack detection was investigated in the following experimental study. Another reference-free approach based on nonlinear acoustics that may result from crack opening and closing is also applied to the following experiments and reported in Dutta et al.¹⁵

**EXPERIMENTAL SETUP**

To investigate the effectiveness of the proposed reference-free NDT technique, experimental tests have been conducted on the steel I-beam shown in Fig. 10. The length of the beam between two simple supports was 2.75 m, and the height and width of the beam were 15.24 cm and 15.18 cm, respectively (Fig. 10a and b). The beam was made of three 0.64 cm thickness steel plates (Fig. 10b). In the middle of the beam, full-depth stiffeners were attached on both sides of the beam’s web in order to prevent local buckling failure of the beam (Fig. 10c). In the steel beam, two wide but sharp notches were made near the centre of the beam-span expecting that the fatigue crack would initiate from the tips of the notches (Fig. 10c).

In the right and left flange of the beam, a total of eight PSI-5A4E-type PZT wafer transducers (1.0 cm × 1.0 cm × 0.0508 cm) were mounted (Fig. 11). In the left flange, PZTs A and D were collocated near the notch and attached on the opposite side of the specimen, and PZTs B and C were mounted to the specimen in a similar fashion (Fig. 11). The PZTs were attached so that their poling directions were identical to configuration II shown in Fig. 3. PZTs A and B (or PZTs C and D) were 25 cm apart each other. The PZTs attached on the right flange were denoted as PZTs A’, B’, C’ and D’, respectively, and PZTs A’, B’, C’ and D’ were located similarly to those on the left flange. In this experiment, the PZT transducers were attached using a commercial cyanoacrylate adhesive. In addition, two crack gauges were attached near the notches to monitor crack initiation and propagation (Fig. 11). The data obtained from the crack gauges were then compared with those from the PZT transducers.

The overall configuration of the data acquisition system is shown in Fig. 12. The data acquisition system was composed of a 100 MS/s 14-bit arbitrary waveform generator (AWG), a 100 MHz 14-bit high-speed signal digitizer (DIG), a low-noise preamplifier (LNP), a power amplifier and a 500 MHz multiplexer. The beam was subjected to continuous, low-frequency cyclic loading using a hydraulic actuator (Fig. 12b), and the loading was temporarily paused at several steps to collect data necessary for the proposed damage detection method. A sinusoidal loading with 1 Hz driving frequency and a loading range of 0 to 35.6 kN (8000 lbs) was applied to the beam. During experiments, Lamb wave signals were measured at 0, 1024, 5020, 10054, and 15001 and 24081 loading

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**Fig. 10** The dimension and shape of the steel I-beam.
cycles. Using the AWG and the power amplifier, a tone-burst signal with ±20 peak-to-peak voltage and a driving frequency of 150 kHz was generated and applied. Here, the frequency was selected based on the Lamb wave dispersion curve in order to generate only $S_0$ and $A_0$ modes. First, PZT A in the left flange (Fig. 11) was excited using the tone-burst waveform. Then, PZT A generated elastic waves, and the response was measured at PZT B. When the waves arrived at PZT B, the voltage output from PZT B was amplified by the LNP with a gain of 20 and measured by the DIG. The sampling rate of the DIG was 20 MS/s. In order to improve the signal-to-noise ratio, the response signals were measured 10 times and averaged in the time domain. After the Lamb wave signal from PZT A to PZT B (signal AB) were measured, the same process was repeated by measuring signals AC, BD and CD. After Lamb wave signals were measured from the left flange, the same procedure was repeated in the right flange. The entire experimental process without averaging took less than 10 s. Detailed test results are described in the following section.

EXPERIMENTAL RESULTS

Test results from the left flange of the girder

In this section, Lamb wave signals measured from the left flange of the I-beam are presented along with strain signals obtained from the crack gauges. Figure 13 shows the initiation and propagation of cracks recorded using the crack gauges. Figure 13 shows the initiation and propagation of cracks recorded using the crack gauges. Based on the readings of the crack gauges shown in Fig. 13, it was estimated that the cracks on the left flange as well as on the right flange were formed between 5020 cycles and 10 054 cycles. Therefore, the results of the proposed reference-free damage detection obtained at 0, 5020 and 10 054 loading cycles were presented below. The test results obtained from the remaining loading steps are summarized at the end of this section, and the ones from the right flange are presented in the next section.

In Fig. 14, signals AB, AC, BD and CD measured instantaneously from the pristine condition of the I-beam are shown. In signal AB, the $S_0$ mode arrived first, and it is followed by the $A_0$ mode. Then, the reflections from the
stiffeners in the middle of the beam arrived. As expected, signals AB and CD shows small differences without crack damage (Fig. 14a). Similar to signals AB and CD, signals AC and BD are close to each other as shown in Fig. 14b. However, due to imperfections in PZT alignment, size and bonding condition, the $A_0$ modes in signals AB and CD display small phase and amplitude differences (Fig. 14a) and similar differences of the $A_0$ modes is observed in signals AC and BD (Fig. 14b). In comparison with the previous numerical simulation, the arrival times of these modes are in a good agreement with the ones obtained from the numerical simulation results shown in Fig. 7. However, the relative amplitude of the $S_0$ mode with respect to the $A_0$ mode from the experimental results is smaller than the one from the numerical simulation. It is speculated that this discrepancy is primarily caused by the fact that the bonding layer is not modelled in the simulation. Typically, the relative amplitudes between the $S_0$ and $A_0$ modes are affected not only by the PZT size, but also by the bonding layers between the PZT and host structure.\textsuperscript{16}

To determine the existence of mode conversion, the proposed damage diagnosis scheme was applied to the measured Lamb wave signals. First, each Lamb mode signal was decomposed from the measured signals AB, AC, BD and CD. Figure 15 displays individual Lamb mode signals decomposed using Eq. (1). Once the individual Lamb mode signals were decomposed, the threshold value for damage classification was set to be the maximum absolute amplitude of error components, $\epsilon_S$ and $\epsilon_A$, obtained from signals $S_0$ and $A_0$. As described in the previous section, the estimated signal $S_0$ is composed of the exact signal $S_0$ and $\epsilon_S$. Furthermore, it can be shown that the $S_0$ mode exists only in a certain portion of the estimated signal $S_0$ while $\epsilon_S$ is present for the entire length of the estimated signal $S_0$. Therefore, the maximum absolute amplitude of $\epsilon_S$ can be estimated only from the portion of the estimated signal $S_0$ where the $S_0$ mode does not exist.\textsuperscript{7}

To estimate $\epsilon_S$, the estimated signal $S_0$ was divided into two regions, the $S_0$ and $A_0$ regions as shown in Fig. 15. The $S_0$ region represents a certain time range where only $S_0$ mode exists. On the other hand, the $A_0$ region...
Fig. 15 Decomposition of individual Lamb mode signals $S_0$, $MC_1$, $MC_2$ and $A_0$ from signals $AB$, $AC$, $BD$ and $CD$ measured at 0 loading cycle using Eq. (1): Max(abs$e_S$, $e_A$) denotes the maximum absolute value of $e_S$ and $e_A$.

corresponds to the time segment where only $A_0$ mode is present. The boundary between two regions is placed exactly in the middle of the $S_0$ and $A_0$ modes. Then, the maximum absolute amplitude of $e_S$ was estimated from the $A_0$ region as shown in Fig. 15a. Note that the $S_0$ mode and the $A_0$ mode could not be well separated in this experiment because of the short distance between the PZTs. Furthermore, some overlaps between the $A_0$ mode and the reflections from the stiffeners were observed. Therefore, $e_S$ was determined from the $A_0$ region of signal $S_0$ after excluding these modes (only from the dotted box in Fig. 15 a). Note that if the $A_0$ region had been determined including reflections, the amplitude of $e_S$ could have been overestimated. In a similar manner, the maximum absolute amplitude of $e_A$ was estimated from the $S_0$ region of signals $A_0$ excluding the overlapped $A_0$ mode as shown in Fig. 15b.

From the estimated maximum absolute amplitude of $e_S$ and $e_A$, the upper and lower limits for damage diagnosis were established and compared with signals $MC_1$ and $MC_2$ as shown in Fig. 15c and d. In both figures, it was observed that some portion of signals $MC_1$ and $MC_2$ exceeded the threshold value even in the absence of crack damage. It is speculated that the shape and phase variations of the $A_0$ modes among signals $AB$, $AC$, $BD$ and $CD$ are the culprit of these initial errors. In the test, the amplitude of the $A_0$ mode was much higher than that of the $S_0$ mode. As a result, large error signals were found in the $A_0$ region of signals $MC_1$ and $MC_2$ (Fig. 15c and d). Although the proposed approach explicitly considers the imperfection of the PZTs, their variations should remain reasonably small to make the proposed technique effective. Therefore, detection of mode conversion was accomplished by inspecting only the $S_0$ regions in signals $MC_1$ and $MC_2$. It has been shown that the effect of mode conversion appears in the $S_0$ region of signal $MC_1$ but not in the $S_0$ region of the signal $MC_2$ when crack damage is near PZT A. Conversely, if the crack is closer to PZT B, the existence of mode conversion can be found only in the $S_0$ region of signal $MC_2$. Therefore, monitoring the $S_0$ regions of signals $MC_1$ and $MC_2$ is sufficient to identify and locate crack damage. Figure 15c and d illustrate that the amplitudes of signals $MC_1$ and $MC_2$ in the $S_0$ regions do not exceed the threshold value determined from $e_S$ and $e_A$ when there is no crack in the beam.

In Fig. 16, signals $AB$, $AC$, $BD$ and $CD$ obtained after 5020 loading cycles are illustrated. Based on Fig. 13, the crack was not detected using the crack gauge yet at this loading cycle. Figure 16a shows that signals $AB$ and $CD$ are still almost identical at this loading stage. However, comparison between signals $AB$ in Figs 14a and 16a shows that the shape and phase of the $A_0$ modes have changed much even without crack damage. It is speculated that the bonding conditions of the PZTs might have been slightly altered during the loading test because the shape and amplitudes of Lamb wave modes are closely related.
to the bonding conditions of exciting and sensing PZT transducers. In Fig. 16b, a large discrepancy between signals AC and BD is observed, and the possible reason for this discrepancy is that the bonding condition of the PZTs changes during the test. There is an ongoing study to monitor the variation of the PZT bonding condition regardless of damage presence in the host structures.

Figure 17 displays signals MC1 and MC2 decomposed from the measured Lamb wave signals at 5020 loading cycles. In spite of changes in the measured Lamb wave signals, the estimated modes in the $S_0$ regions of signals MC1 and MC2 did not exceed the threshold value determined from $e_S$ and $e_A$ at this loading stage.

Around 8000 loading cycles, a crack was initiated at the left flange and the crack length grew to 5 mm at 10,054 loading cycles (Fig. 13). In Fig. 18, signals AB, AC, BD and CD obtained after 10,054 loading cycles are displayed. Compared to the earlier loading cycles, signals AB and CD shows larger deviation around the $S_0$ modes (Fig. 18 a), and a similar observation can be made between signals AC and BD as shown in Fig. 18b. After decomposition, the amplitude of the $S_0$ region in signal
MC\textsubscript{1} exceeded the threshold value (Fig. 19a). However, the corresponding amplitude in signal MC\textsubscript{2} remained below the threshold (Fig. 19b). This observation leads to the conclusion that the mode conversion due to crack damage occurred and the crack was near PZT A.

Then, the exact crack location was estimated by measuring the arrival time of the MC\textsubscript{1} mode in signal MC\textsubscript{1}. From the $S\textsubscript{0}$ and $A\textsubscript{0}$ modes in Fig. 18, the group velocities of the $S\textsubscript{0}$ ($V\textsubscript{S}$) and $A\textsubscript{0}$ modes ($V\textsubscript{A}$) were estimated to be 4.840 m/ms and 2.939 m/ms, respectively. (From the material properties of the specimen, the theoretical group velocities were estimated to be $V\textsubscript{S} = 5.061$ m/ms and $V\textsubscript{A} = 3.100$ m/ms.) When the crack location is closer to PZT A than PZT B, the distance from PZT A to the notch can be estimated using Eq. (2):

$$\text{The arrival time of the } MC\textsubscript{1} \text{ mode} = \frac{s}{V\textsubscript{A}} + \frac{\text{Distance between PZT A and PZT B} - s}{V\textsubscript{S}},$$

where $s$ denotes the distance of the crack from PZT A. From the estimated arrival time of the MC\textsubscript{1} mode (0.0551 ms) and Eq. (2), $s$ is estimated to be 2.58 cm. This estimated distance was close to the actual distance to the fatigue crack (2.5 cm from PZT A, 3.2% error). At 15 001 and 24 081 loading steps, the existence and location of the fatigue crack were determined similarly (Figs 20 & 21). The amplitude of the response in the $S\textsubscript{0}$ region of Signal MC\textsubscript{1} exceeded the threshold value while the corresponding amplitude in signal MC\textsubscript{2} remained below the threshold at 15 001 and 24 081 loading steps.

Finally, an issue related to the driving frequency was raised from the test results. The amplitudes of mode-converted signals could have been higher if the relative amplitudes of the $S\textsubscript{0}$ and $A\textsubscript{0}$ modes had been kept similar. Therefore, it will be important to select the driving frequency so that both $S\textsubscript{0}$ and $A\textsubscript{0}$ modes have similar amplitudes in order to produce large mode conversion.

Test results from the right flange of the girder

In this section, Lamb wave signals measured from the right flange of the I-beam are presented. Similar to the left flange case, Lamb wave signals obtained at 0, 5020 and 10 054 loading cycles are discussed in this subsection. In Fig. 22, signals A'B', A'C', B'D' and C'D' measured at 0 loading cycle are shown. In comparison with Fig. 14 obtained from the left flange at 0 loading cycle, a large discrepancy between signals A'B' and C'D' was observed.
in Fig. 22a while signals A’C’ and B’D’ in Fig. 22b were reasonably close each other. After examining measured signals, it was revealed that the placement of PZT D’ is inconsistent with the other PZTs. Note that because the success of the proposed technique relies on the consistency of all four PZTs and precise placement, the large variations in the PZTs conditions resulted in degraded diagnosis in the right wing. Better test results could have been obtained by replacing the faulty PZT D’. However, it could not have been accomplished due to the tight test schedule.

In Fig. 23, the results from 5020 loading cycles are presented. In comparison with Fig. 22, the difference between signals A’B’ and C’D’ (or signals A’C’ and B’D’) did not increase. Therefore, it was concluded that damage did not occur at this loading state. When the loading reached 10 054 cycles, increased differences between signals A’B’ and C’D’ (or between signals A’C’ and B’D’) were observed as shown in Fig. 24. However, due to the large initial discrepancies at 0 loading cycle as described above, the damage classification based on the instantaneous thresholding could not identify the crack properly. Due to the
large initial errors in the measured Lamb wave signals, $e_S$ in signal $S_0$ was overestimated, and consequently the amplitude of signal $MC_1$ in the $S_0$ region did not exceed the threshold value (Fig. 25a). A similar result was observed from signal $MC_2$ in Fig. 25b.

The test results from the right wing show that consistent placement of the PZT transducers is critical to the success of the proposed technique and this implementation issue needs to be addressed before the proposed technique can be reliably applied to field structures. Due to the rough surface condition of the specimen, it was difficult to maintain consistent bonding conditions for all four PZTs. Furthermore, the precise collocation of two PZTs on different sides of the specimen was a challenging task. To address the PZT installation issue, a new concept of a PZT transducer is being investigated so that only two specially designed transducers can be placed on one side of the specimen instead of two pairs of collocated PZTs.\(^{17}\)

**CONCLUSION**

In this study, the effectiveness of a newly proposed NDT technique for fatigue crack detection was tested using a scaled steel girder under cyclic loading. The proposed technique utilizes the polarity of piezoelectric materials and employs two pairs of collocated PZTs placed on both sides of the specimen to identify mode conversion created by a crack. Due to the fact that the NDT technique does not rely on previously obtained baseline data for crack detection, it is expected that this approach minimizes false alarms of damage due to changing operational and environmental variations experienced by in-service structures. The effectiveness of the proposed reference-free NDT for detecting a notch in a plate structure was previously investigated by the authors. The uniqueness of this study lies in that: (1) the proposed NDT technique is employed for detecting a fatigue crack rather than a notch and (2) it is applied to a more complex structure like a steel girder with stiffeners rather than a simple plate structure.

As long as a notch or a crack produces sudden reduction in thickness, it is expected that they do produce mode conversion. However, the characteristics of a breathing crack can be different from those of a notch because the breathing crack can produce crack opening and closing while the notch remains open. Therefore, the applicability of the proposed technique to fatigue crack detection was investigated in this study. Note that the proposed technique can be also applied to detection of other types of defects such as corrosion in metallic plates and delamination in multi-layer isotropic/anisotropic composite plates. Relevant research is underway to numerically
and experimentally demonstrate the applicability of the proposed technique to these other types of defects and materials.

The PZT transducers were placed at the right and left wings of the steel girder beam and the specimen was subjected to cyclic loading. Then, the Lamb wave signals were measured from the PZTs at different loading steps. In the left wing case, the existence of mode conversion was successfully indicated using the proposed NDT technique, and the location of the damage was pinpointed as well. In the case of the right wing, the proposed technique could not identify the existence of damage due to the inconsistent placement of the PZT transducers. Note that the proposed NDT technique is based on the assumption that all four PZTs (two pairs of collocated PZTs on the both sides of the specimen) are identical in terms of PZT bonding and size, and the collocated PZTs are properly aligned. However, it was speculated that the PZTs on the right wing were not properly installed. The test results from the right wing raised an implementation issue that a consistent placement of the PZT transducers was critical to the success of the proposed technique.

To address the PZT installation issue, related research is underway to develop PZT transducer diagnosis schemes to monitor the bonding and performance of the PZT transducers. Furthermore, a new concept of a PZT transducer is being designed so that only two specially designed transducers can be placed on one side of the specimen instead of two pairs of collocated PZTs.

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