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Cheng, L.; Xin, H.; Veljkovic, M.

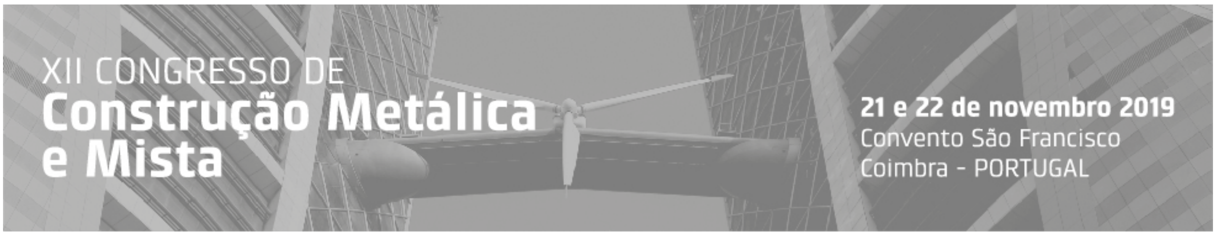
DOI
10.1002/cepa.1176

Publication date
2020

Document Version
Final published version

Published in
ce/papers

ce/papers
The online collection for conference papers in civil engineering
Ernst & Sohn
A Wiley Brand



ACOUSTIC EMISSION SOURCE LOCATION IN I GIRDER BASED ON EXPERIMENTAL STUDY AND LAMB WAVE PROPAGATION SIMULATION

Lu Cheng[a], Haohui Xin[b*] and Milan Veljkovic[c]

[a,b,c] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands*

[*] Author for contact. Haohui Xin - E-mail: H. Xin@tudelft.nl

Abstract: Acoustic Emission (AE) is used in various fields of engineering and recently has been gained increasing attention in crack detection of cyclically loaded engineering structures. The crack location strategies are rather complicated for realistic structures with complex geometry. In this paper, pencil leads breaking (PLB) experiments and finite element simulation of lamb wave propagation are conducted to give a rational interpretation on acoustic wave propagation within composite structures. Identification of the fundamental extensional mode (S_0) and flexural mode (A_0) is successfully carried out. The proposed FE models are proven to be a suitable alternative/complement to the experiments, in the monitoring of realistic structures.

1. Introduction

The growth of fatigue cracks in realistic structures calls for the implementation of a sound and rigorous bridge monitoring system that can reduce the maintenance costs and extend the service life. Recently, Acoustic Emission (AE) technique has been gained wide application in detecting the integrity of structures in terms of its age and usage.

https://doi.org/10.1002/cepa.1176

AE technique is a passive tool for providing real-time and continuous examination via permanently installed sensors. In most cases, a piezoelectric (PZT) element in a protective housing is utilized in traditional sensors. Transient elastic wave is a phenomenon generated by the rapid release of stored energy from defects such as cracks or broken fibres within materials. These waves can be detected and then converted into electric signals by these sensors during propagation. Further analysis of the collected AE signals can contribute to an overall view of the health of the structures. In general, both global monitoring and local monitoring can be performed according to the received signals.

Utilization of AE technique for monitoring complex and realistic structures has not been fully exploited. One of the main characteristics of AE technique is the ability to localize a crack position. The most popular method to carry out source location is based on the time of arrival (TOA) of certain wave types like P-waves (longitudinal waves), S-waves (transverse waves), Rayleigh (surface) waves or Lamb waves. Among all the waves, Lamb wave has been verified as a common form of propagation in plate-like structures, if the wavelength is shorter than the thickness of the structure. The primary assumption of this method is that the structure is homogenous, and the wave velocity is constant in all directions. This method has been demonstrated to be effective in detecting structures with simple geometry features and small size. In complex structural geometries and complex materials such as composites, this assumption is no longer valid. Significant errors can be introduced due to the reasons listed below: a) The irregular boundaries of a complex structure will cause reflections or scattered waves, which interfere in the signals and thus have negative influence on obvious onset time; b) the velocity varies with propagation paths and angles within different materials; c) The method to determine the TOA in commercial AE acquisition system is using threshold method, while the user-defined threshold maybe not suitable for the common long-span thin-walled structures. Thus, detecting damage in composite structures is quite challenging.

In addition, a vast majority of the experimental database of AE testing is required to interpret the signals correctly. This is because the wave properties are sensitive to the cross-section and the specimen layout of an investigated structure. A large number of experiments may be necessary for purely experimental AE database. In order to reduce the required number of experiments, FE simulation is proposed to investigate the underlying mechanism of AE. Most of the existing studies using FE model for wave propagation simulation are focused on flat plates with simple geometry [1,2]. In real structures, FE analysis is mainly used to identify regions for possible crack locations which can then be regarded as primary areas of concern for structural monitoring [3]. As far as the authors' knowledge, the research using FE analysis to simulate Lamb wave propagation within a realistic structure is extremely limited.

The main objective of this study is to gain an understanding of AE monitoring of a composite beam. Laboratory studies on a 8.3m I-girder are presented to explore the feasibility of the traditional TOA method for source location of the composite girder. In parallel, a numerical Lamb wave propagation simulation of the tested girder is conducted. The purpose is to identify whether using FE simulation data from a numerical model can be a surrogate process of acquiring database from actual trials. Based on both the experimentally acquired and numerically simulated data, several onset detection methods are compared to identify the fundamental extensional mode (S_0) and flexural mode (A_0). Furthermore, a proposed method for determining TOA based on reliable FE models is demonstrated.

2. Experimental investigation

2.1 Experiment setup

Experiments are performed on an I-girder (IPE 400), which is a part of a composite steel-concrete girder, as schematically illustrated in Fig. 1. For detecting AE signals, seven AE sensors with 150 kHz resonance frequency (R15, PAC) are mounted on the surface of the specimen. To provide a suitable acoustic transmission, a silicone grease is used as a couplant. All signals are detected using an Express-8 acquisition system with 40 dB pre-amplification, 42 dB threshold level and 10 MSPS sampling rate (one sample per 0.1 µs). A Band Pass Filter of 20-400kHz is set in the AEwin acquisition software control.

The classical Hsu-Nielsen source (Pencil leads breaking test) [4] is used to generate a crack-like AE signal on the steel beam web. The exciter positions where the signals generate and sensors are denoted as E and S respectively. The sequence and arrangement of exciters and sensors are distinguished by a number. Each pencil breaking test is repeated 3 times at the same location on the beam. To confirm the accuracy of the tests, almost equal lengths of pencil leads (4.0mm) are broken with the same angle around 35 to 40 degree (Fig. 2 (c)) to the surface of the beam. Two types of sensor layout are designed as shown in Fig. 2, namely the linear layout of seven sensors (Fig. 2 (a)) for speed calculation and the rectangular array of four sensors (Fig. 2 (b)) for source localization.

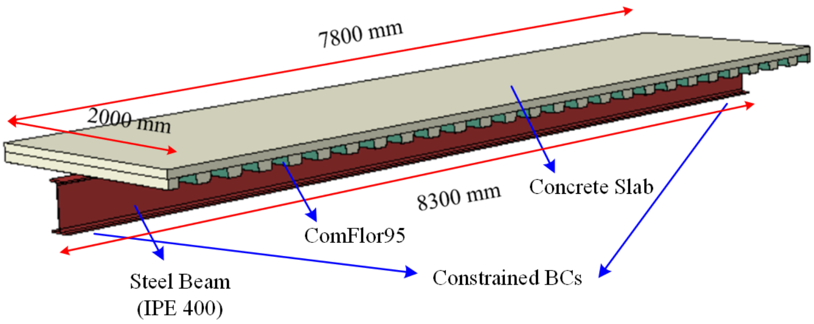


Fig. 1: Dimension of the composite steel-concrete girder

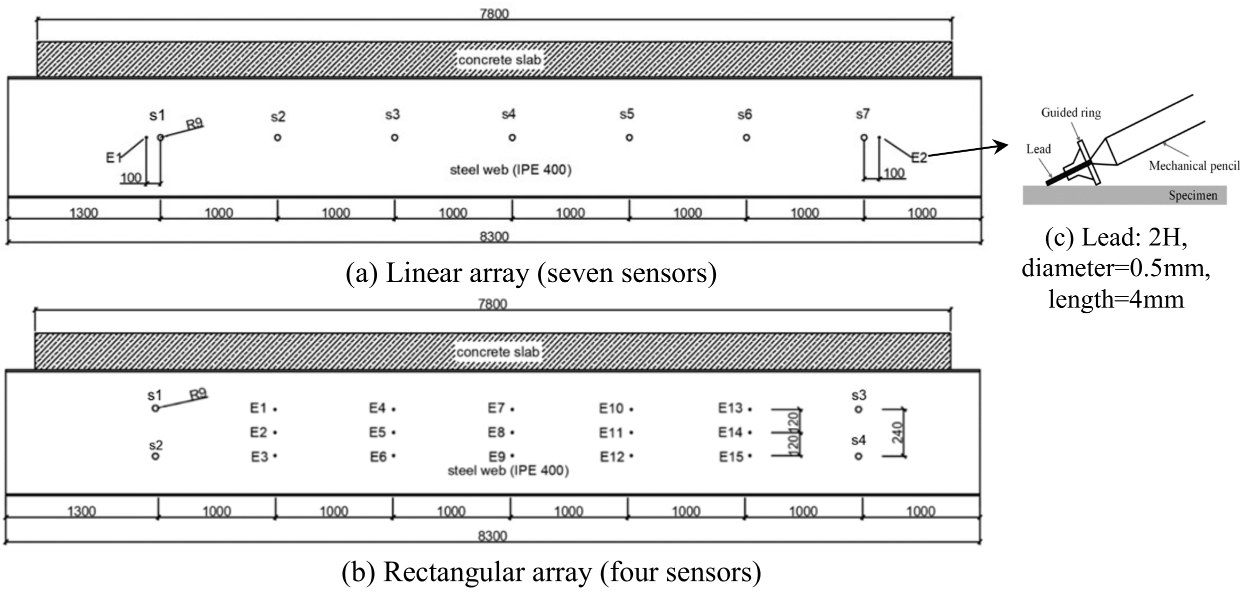


Fig. 2: Measurement setup including source location and sensor layout: Schematic view

2.2 Source localization

Based on the measured results of the line array, the wave propagation velocity within the span of the girder can be obtained. The average wave velocity is determined as 5219 m/s based on the time difference and the distance between each sensor (1 m). After computing the wave velocity, a common localization method is applied to identify its feasibility in the test of the rectangular array. The procedures of the classical TOA method for two-dimensional source location is described briefly below: a) Construct a grid on the interesting area where AE events will be located. Each node position within the grid is regarded as a possible source location; b) the arrival time from any point in the grid to each sensor is computed from trials or a user-defined velocity model. It is suggested that the grid can be made as fine as what is computationally feasible. c) comparison of the measured ($\Delta t_{i,\mathrm{mea}}$) and calculated ($\Delta t_{i,\mathrm{calc}}$) arrival time difference is used to determine the point of best agreement between the measured and calculated arrival times. The minimisation of the objective function X [5] is expressed in Eq. (1) and (2):

$$X = \sum (\Delta t_{i,\mathrm{mea}} - \Delta t_{i,\mathrm{calc}})^2 \tag{1}$$

$$\Delta t_{i,\mathrm{calc}} = \left[\sqrt{(X_i - X_s)^2 + (Y_i - Y_s)^2} - \sqrt{(X_1 - X_s)^2 + (Y_1 - Y_s)^2} \right] / v \tag{2}$$

where: X_k and Y_k are the coordinate, if the subscript is “S”, it denotes the expected source position; otherwise, it means the location of the ith sensors; v is the wave propagation speed used in the calculations.

Analytical results are presented in Fig. 3, including sensor locations, experimental and predicted positions of excitation. The results of E8 was removed due to the initial defection at this point. From Fig. 3, it is seen that the accurate source positions in the middle section of the beam can be predicted. However, the increasing errors can be observed when the location of excitation moves from the center to the flanges. Specifically, the calculated source locations of E7, 9, 10 and 12 are opposite to experimental results. For instance, the predicted source location of E7 is at E9 according to the TOA method. It can be concluded that the classical method is not suitable for source location in composite structures. In that case, it is difficult to make a reliable interpretation of the data from acoustic emission signals.

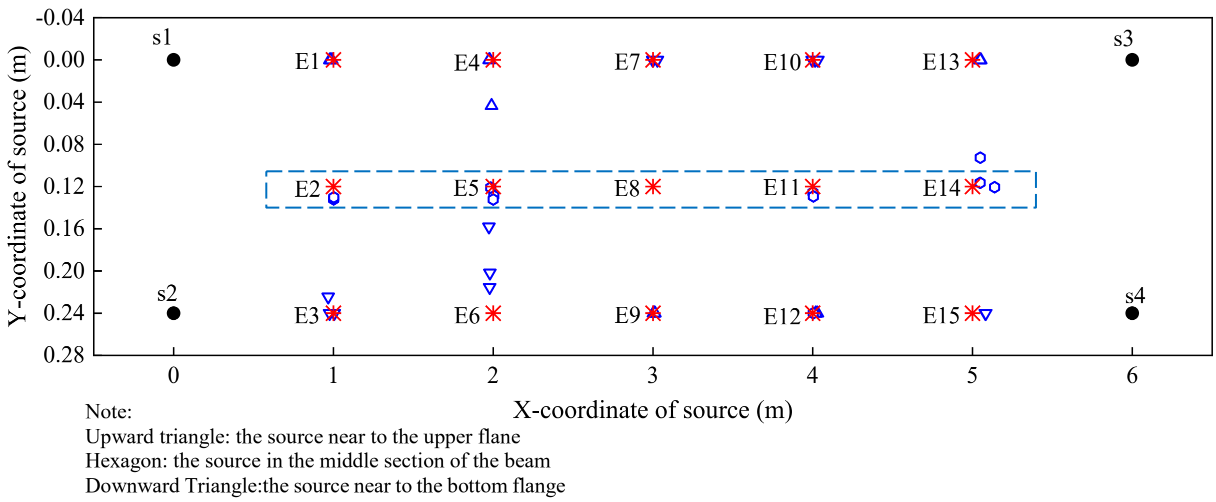


Fig. 3: Source location results

3. Lamb wave propagation simulation

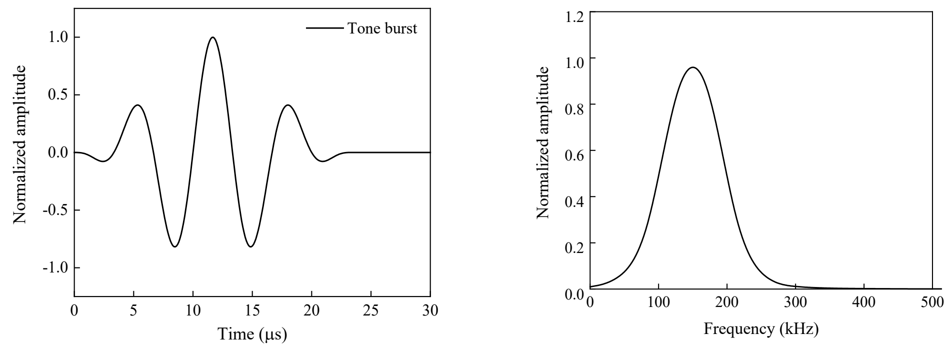
3.1 Numerical modeling

As shown in Fig. 1, an FE model is created to perform a Lamb wave propagation simulation within this complex structure using ABAQUS software [6]. A force in direction X (see coordinate axis in Fig. 1) is used as the exciter in this study. To alleviate the dispersion phenomenon, a 3.5 cycle tone burst signal with a center frequency (f_c) of 150 kHz and an amplitude value of

1 is used for excitation, as shown in Fig. 4. The equation of the tone burst signal is expressed below:

$$y(t) = \begin{cases} \sin(2\pi f_c t)[1-\cos(\frac{2\pi f_c t}{3.5})], & for 0 \le t \le t_1 \\ 0, & for\ 0 > t_1 \end{cases} \tag{3}$$

where t_1 = 23.3 μs is the total signal time.



(a) (b)

Fig. 4: The waveform used to generate signals: (a) time domain and (b) frequency domain

In order to ensure sufficient temporal and spatial resolution, the mesh size is recommended to be 10 times smaller than the wavelength. Considering the numerical accuracy and computational efficiency, the mesh size of the steel beam and time increment are selected as 4 mm and 0.1 μs, respectively.

3.2 Experimental verification

To verify the FE model, the results with linear array sensors are firstly compared to the experimental results. The Lamb waves propagate in a circular-crested pattern along with the web of the steel girder, see Fig. 5. Displacement of sensor nodes is extracted in the direction along the ray path between excitation and sensor nodes. Fig. 6 depicts the comparison between experimental and FE simulation of the signal excited at E1 and sensed by sensor 3 and sensor 6. Good agreement in detecting Lamb waves can be observed. It is noted that the received wave based on the FE simulation is earlier than the experiment with a higher amplitude. This variation can be attributed to the assumption of a perfectly smooth surface in the FE model. A possible geometrical imperfection of the girder is not considered in the FE model which could slow down the wave propagation and cause more attenuation.

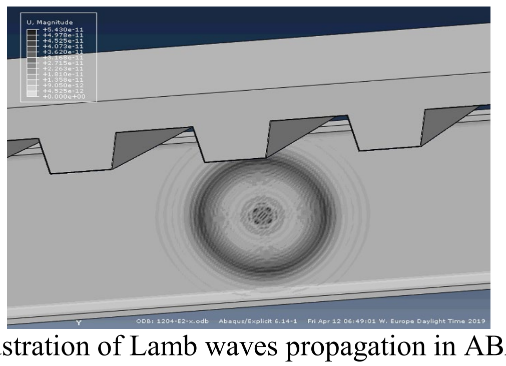


Fig. 5: Illustration of Lamb waves propagation in ABAQUS

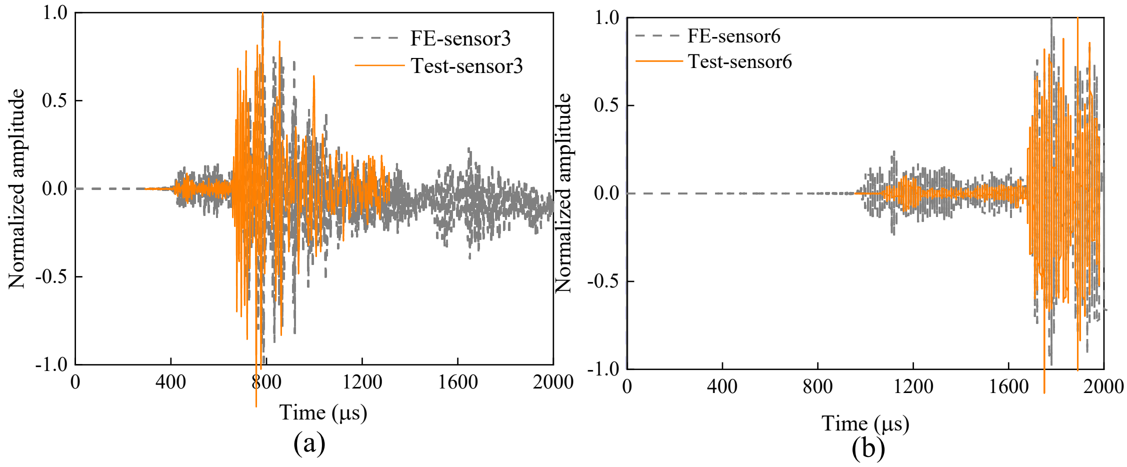


Fig. 6: Experimental vs. numerical received signal of (a) sensor 3 and (b) sensor 6 at linear array excited from E1

3.3 Determination of TOA

Accurate determination of the first arrival time of a signal is of paramount importance for the accuracy of the source location. The method to determine the TOA in commercial AE acquisition system is known as 'first threshold crossing'. However, the performance of this method is strongly dependent on the choice of the selected threshold value. The errors caused by an inappropriate selection of threshold value is illustrated in Fig. 7. It is noted that early triggering or missing true arrival time could occur with an arbitrarily set threshold value. Additionally, in complex structure systems, the irregular boundaries will cause reflections or scattered waves, which interfere in the signals and thus increase the difficulty for obvious onset detection. Therefore, it is necessary to find a suitable and sound way to determine the time of arrival for both experimental and numerical results.

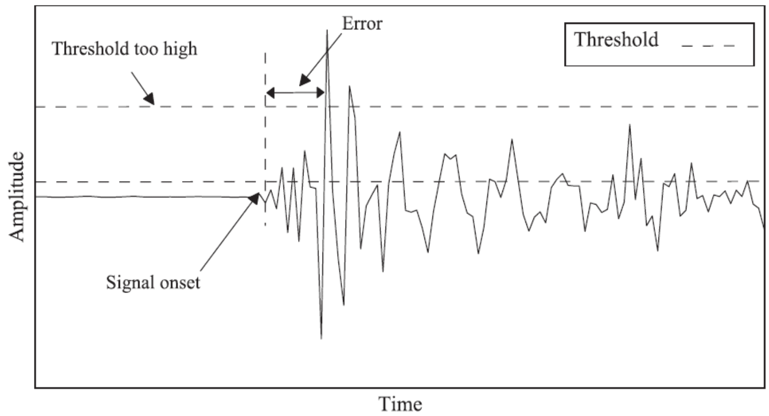


Fig. 7: Potential errors using the fixed threshold value method [7]

Over the past few decades, various digital processing methods have been proposed for automatic detection of the wave arrival time. In order to overcome the limitation of traditional threshold method, the practicality of Hinkley criterion [8-9], cumulative energy [10], power curve [11] and Bai's CWT-based binary map method [7] are verified through analysing the recorded waveform of AE signals from experiments as well as displacement curves obtained from numerical model.

3.4 Results

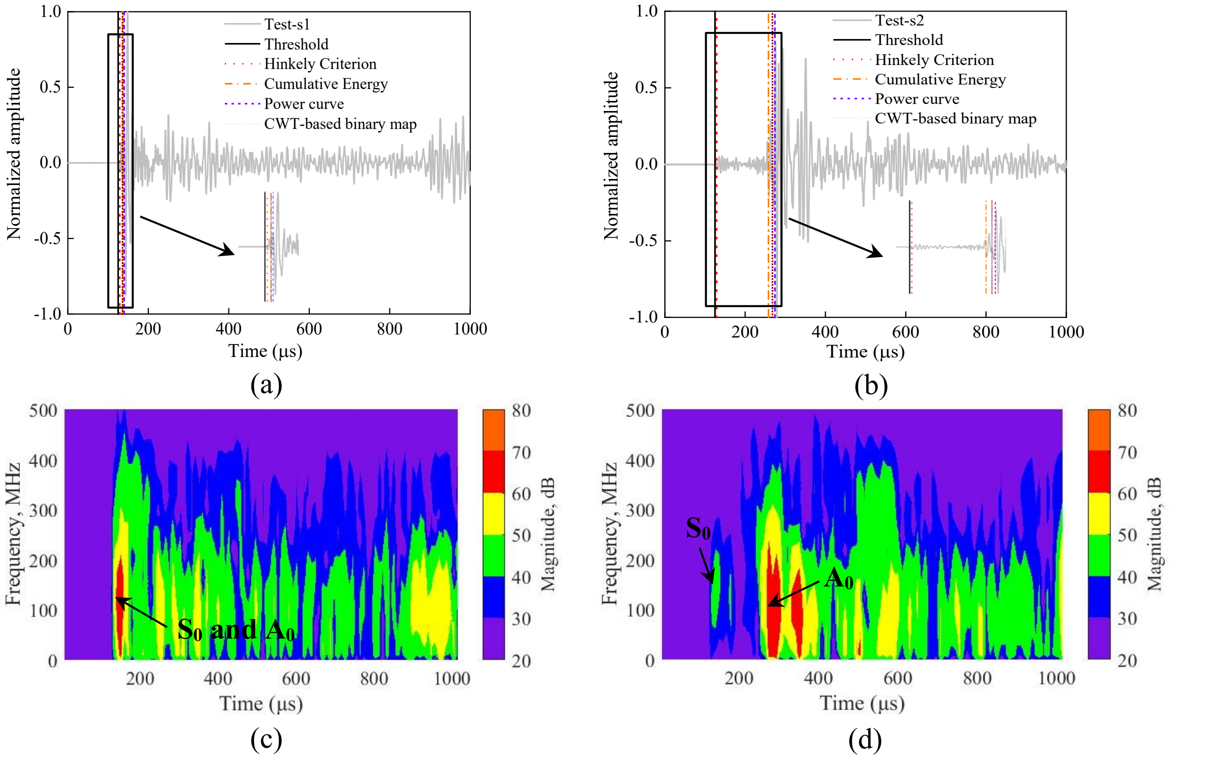


Fig. 8: Onset detection using selected methods of linear array obtained from tests: signals at (a) sensor 1 and (b) sensor 2; Amplitude spectrogram of signals at (c) sensor 1 and (d) sensor 2

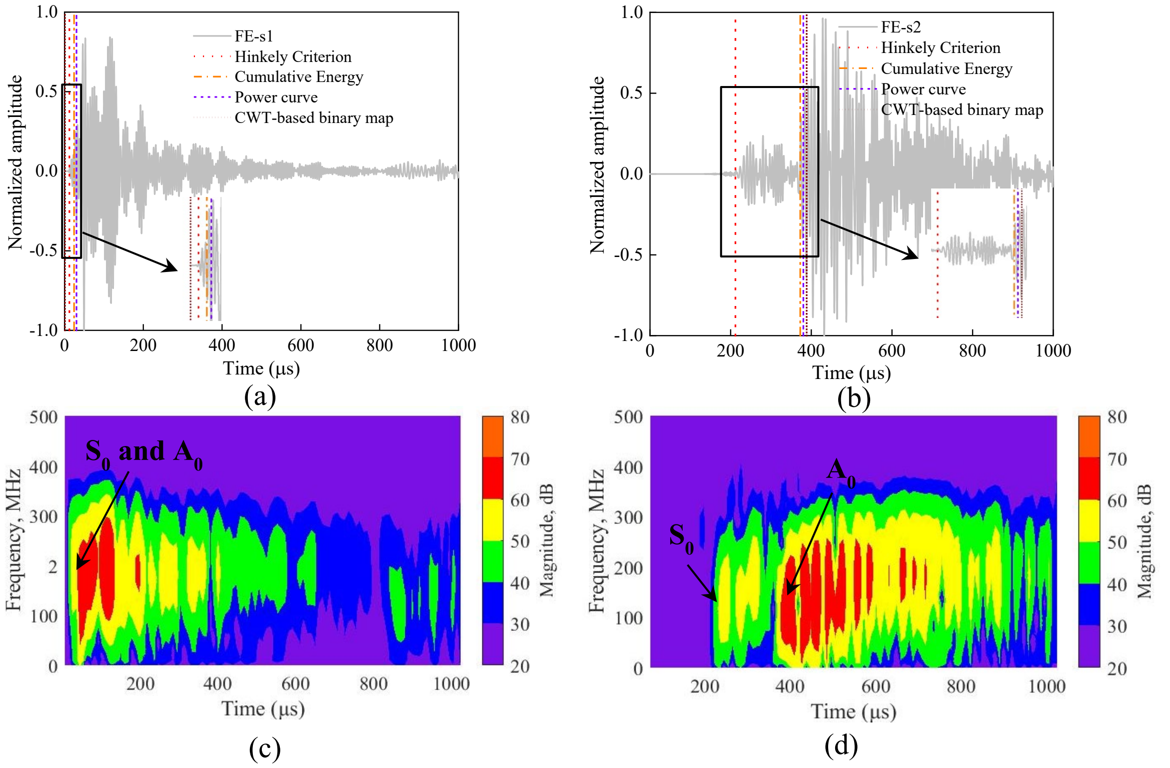


Fig. 9: Onset detection using selected methods of linear array obtained from FE model: signals at (a) sensor 1 and (b) sensor 2; Amplitude spectrogram of signals at (c) sensor 1 and (d) sensor 2

The PLB tests excited in E1 at sensor 1 and sensor 2 at linear array are shown as an example. Besides, Short-time Fourier transform (STFT) is commutated to provide a time-frequency representation of the signal as the amplitude spectrogram. Fig. 8 shows the performance of the selected methods for the same signal obtained from tests. It is noted that the length of the pre-trigger signal is set to 125 µs for recording in the data acquisition system. Therefore, the signal with a duration of 125 µs is recorded before the signal amplitude reached to the user-defined threshold. The dashed line in different colour indicates the detected arrival time applying various methods. Based on the displacement versus time curves from FE results, the arrival time of signals can be determined through these methods as shown in Fig. 9.

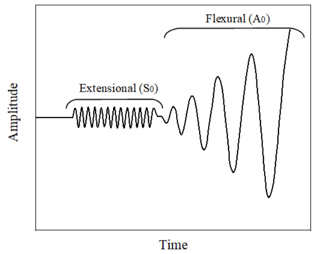


Fig. 10: Basic wave modes: Extensional (S_0) and Flexural (A_0)

There are two fundamental wave modes as Lamb waves travel in a plate, namely extensional or symmetric mode (S_0) and flexural or antisymmetric mode (A_0), as shown in Fig. 10. Both wave modes are detected in Fig. 8 (c)-(d) and Fig. 9 (c)-(d). As it could be observed, both wave modes are gathered at the same time at sensor 1. The distance from sensor 1 to E1 is 100 mm, which means the signal generated in close approximation to the sensor. Then, these two wave modes separate gradually and a noticeable separation can be observed with sufficient distance. It can be attributed to the fact that S_0 has a relatively small amplitude but faster propagation speed comparing to A_0.

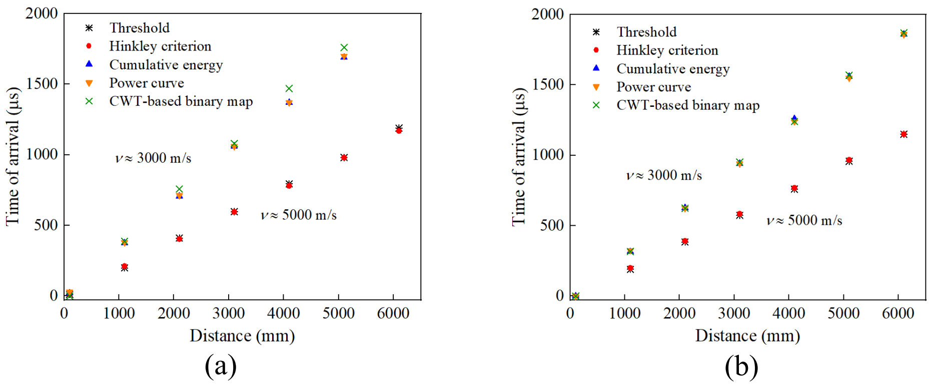


Fig. 11: Onset time versus distance curves excited at E1: (a) Test results; (b) FE model

Table 1: The classification of onset time detection methods

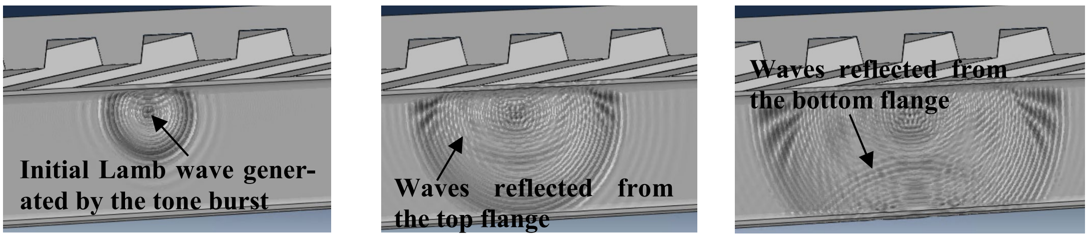
Methods for detecting S_0 modes	Methods for detecting A_0 modes
Hinkley criterion	Cumulative Energy
	Power curve
	CWT-based binary map

According to the dispersive curves for steel [12], the theoretical velocity of S_0 mode and A_0 mode at 150 kHz are around 5000 m/s and 3300 m/s, respectively. After calculation, the relationship between onset time and the distance from the sensor to the source E1 is depicted in Fig. 11. Velocity can be represented by the slope of the curves. In comparison to the theoretical velocity of wave modes, these methods can be categorised into two types as shown in Table 1 according to the detection of wave mode.

Modal identification can provide information about the nature of the source generating the waves. For example, the sources acting in the plane of a material such as crack growth will produce signals with large extensional mode whereas out-of-plane sources such as friction and noise will produce signals with more flexural components [13]. Hence, the determination of the methods directing at different wave modes can yield valuable information regarding source type as well as source location. In conclusion, the similar onset time of extensional wave mode (S_0) can be obtained through Hinkley Criterion in analysing FE and experimental results.

4. Scatter of wave propagation velocity

The reason for ineffective source location results can be figured out in conjunction with the validated FE model. Taking the excitation at E7 in the rectangular array as the example, sensor 1 or sensor 3 are supposed to receive the arrived wave at first. However, the wave arrived at sensors 4 firstly based on the experimental and numerical results, which is different from the results under the assumption of constant velocity. This may be explained by wave reflection phenomenon as shown in Fig. 12. The Lamb wave packet induced by the tone burst excited at FE model is shown in Fig. 12 (a). The wave propagation will be affected by flanges. The accurate arrival time and wave propagation velocity in different directions is calculated using Hinkley Criterion. Based on the FE results, the velocities from E9 to sensor 3 and sensor 4 are 5028 m/s and 5113 m/s, respectively. It can be concluded that the scattering generated by the top flange has a stronger influence on the propagation than the bottom flange because the position of the exciter is near the top flange. In that case, the sequence of receiving signals of sensors is affected. Therefore, the assumption of constant velocity is not suitable for source location in complex structures as a result of the influence of boundary reflection on the propagation path. The geometrical relationship between source and sensors also need to be considered.



(a) Time=60μs (b) Time=120μs (c) Time=180μs

Fig. 12: Simulation of Lamb wave propagation in the girder

5. Conclusions

Both experimental and numerical analysis is carried out on a composite steel-concrete girder to reveal the limitation of classical source localization method. The main conclusions are:

1. Classical TOA method could not predict the source location well in certain cases due to wave reflection effects in composite girder. Scatter of lamb wave propagation velocity is observed based on FE simulations, which influence the sequence of receiving signals of sensors.

2. The proposed FE model is capable of predicting lamb wave propagation and AE signals. The TOAs from pencil lead breaking (PLB) experiments are compared with FE simulation using a variety of onset detection methods. A good agreement on the onset time determination and wave speed calculation is observed.
3. Different AE signal onset detection techniques correspond to different wave propagation modes, including either extensional mode (S_0) or flexural mode (A_0). Hinkley criterion is suitable to detect S_0; cumulative energy, power curve and CWT-based binary map are suitable for detecting A_0. Hinkley criterion is recommended as S_0 is more easily distinguishable than A_0.
4. AE signals are subjected to many different influences which limited its implementation on monitoring complex structure. Identification of the source location in realistic and complex structures may be predicted more accurately in combination with FE analysis.

Acknowledgments

The first author wish to express her gratitude to the financial support of CSC Scholarship Council.

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