Damage detection in bent plates using shear horizontal guided waves

Nazeer, Nakash; Ratassepp, Madis; Fan, Zheng

2016

Nazeer, N., Ratassepp, M., & Fan, Z. (2016). Damage detection in bent plates using shear horizontal guided waves. *Ultrasonics*, 75, 155-163.

<https://hdl.handle.net/10356/84990>

<https://doi.org/10.1016/j.ultras.2016.11.020>

© 2016 Elsevier B.V. This is the author created version of a work that has been peer reviewed and accepted for publication by *Ultrasonics*, Elsevier B.V. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [<http://dx.doi.org/10.1016/j.ultras.2016.11.020>].

Downloaded on 26 Apr 2023 20:32:30 SGT

Damage detection in bent plates using shear horizontal guided waves

Nakash Nazeer, Madis Ratassepp, Zheng Fan*

*School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50
Nanyang Avenue, Singapore 639798, Singapore*

Abstract

Study of the interaction of shear horizontal guided mode with defects in the bend region of an isotropic top hat stiffener is presented. Compared with the SH0 wave in a plate, the shear mode in the bend is dispersive and its wavefield characteristics are affected by the curvature of the bend. The scattering studies showed that the sensitivity of the wave to outer surface cracks in the bend increases with increasing frequency compared to inner surface cracks. Further numerical simulations demonstrated that the shear mode is sensitive to the delamination in the bend due to non-zero transverse shear stress. Results of finite element modeling were validated by experiments and reasonably good agreements were obtained.

Keywords:

shear horizontal mode, defect scattering, curvature effect

1. Introduction

Top-hat stiffened plates provide an efficient structure for many engineering applications. For example, in aircraft applications, skin-to-stiffener joints are very common in fuselage panels and wings [1] as they help to prevent skin buckling during wing loading and increase the bending strength of the joint. Being manufactured either from metal or composite materials, various types of

*Corresponding Author
Email address: ZFAN@ntu.edu.sg (Zheng Fan)

in-service damage may occur. In aluminum alloys the main concern is the corrosion fatigue cracking [2] which may grow excessively under heavy loads and finally lead to failure. The stiffeners made of composite laminates are prone to delaminate due to excessive interlaminar stresses. Splitting delamination in the bends is one of the primary mode of failure [3]. To ensure the aircraft's airworthiness it is vital that these defects are found and quantified before becoming critical.

The main issue with the Nondestructive Evaluation (NDE) of the top-hat stiffener is that there is usually no direct access to it. For example, being in the wing, the conventional point-by point testing techniques require the structure to be disassembled which may cause disruptions and significant increase in maintenance cost. An alternative could be to use ultrasonic guided waves which can be excited on the wing skin and then can propagate through the natural waveguide geometry of the stiffener. Thus, a cross-section of the structure from a single test location can be inspected which makes the procedure fast and efficient [4, 5]. This can be extended further to a full volumetric scan by introducing a roller type mechanism that runs along the length of the stiffener while simultaneously inspecting for defects across it. Another attractive approach for the inspection could be to use built-in actuators and sensors which implement the same guided wave concept and provide a continuous monitoring possibility [6, 7].

In this paper we investigate the potential of Shear Horizontal (SH0) mode for NDE of stiffener bend. The SH0 mode has a simple wave structure and a non-dispersive nature in a plate. Its incident pulse signals maintain their waveforms and can propagate long distances with small attenuation. Its wavefield is uniform through the thickness of the plate so it is expected to be equally sensitive to surface and interior defects [8, 9]. Furthermore, at low frequencies it is the only mode in the shear wave family that can propagate in the stiffener [10], thus excluding the complicated multimodal pulses to propagate. The inspection can also be carried out by using Lamb modes S0 and A0 [11, 12, 13]. However, mode conversions are likely to occur when modes are excited and propagate from the skin to stiffener through bond lap joints [14, 15] thus making the

interpretation of the signals much more complicated.

A number of studies on the interaction of shear type guided waves with
 40 defects have been reported in plates, pipes [16, 17, 18, 19, 20, 21, 22] and in
 complex shaped waveguides [23, 24, 25, 26, 27]. These studies provided a great
 deal of knowledge on the behavior and defect sensitivity of the shear mode
 propagating in these waveguides. However, none of these works examined the
 curvature effect on the shear wave scattering from defects. When SH waves
 45 propagate through the stiffener, their wave-field might be affected by the cur-
 vature of the bends [28] and thus the interaction with defects in the bend can
 be rather different compared to the interaction in regular waveguides such as a
 plate. The aim of this paper is to explore this through detailed defect scattering
 studies.

50 The study focuses on the interaction of the shear horizontal guided mode
 SH0 with two types of defects, namely transverse cracks running along the
 bend and delamination in the bend. For simplicity, the stiffener with isotropic
 material properties is considered. The results of this study are important to
 understand the physical nature of the phenomena and provide some insight
 55 into the possibility of detecting and characterizing these type of defect using
 ultrasonic guided waves. Finite element simulations and experiments on a top
 hat stiffener were used for this study. The influence of the bend curvature on
 the reflection of guided shear mode is investigated for a range of crack length
 and depths at various frequencies.

60 This paper first reviews the properties of shear guided modes propagating
 in the curved waveguides in Section 2. Then the finite element modeling of
 shear mode interacting with defects is introduced in Section 3, followed by
 experimental work in Section 4. Results and discussion on scattering of the shear
 guided mode from different type of defects is presented in Section 5. Finally,
 65 Section 6 draws conclusions with directions for future work.

2. SH mode propagation characteristics in a bent plate

This section briefly introduces the properties of the Shear Horizontal guided mode propagating in the top hat stiffener, shown in Fig. 1. The wave traveling across the stiffener passes two different waveguides - straight plates and circumferential bend regions connecting the plates. The wave propagation characteristics in these two separate waveguides is well known [29, 30, 31] and is useful for better understanding of the effect of guided wave transmitting from one waveguide to another. In the following, the mode characteristics for the guided shear waves propagating in the plate and circumferentially in the bend is presented using DISPERSE [32].

Figure 2 shows the group velocity dispersion curves for SH waves propagating in an aluminum plate and in a circumferential bend with wall thickness $t = 2$ mm for different curvature parameter a/b . In this work we focus on the 0th order Shear Horizontal wave mode (SH0) below the cut-off frequency of SH1 mode which is around 1.6 MHz-mm. Higher order modes have also been shown in Fig. 2 to verify that the cut-off frequency values are around the given value when the curvature changes. It can be seen that this mode is non-dispersive in a plate, but in case of circumferential propagation, its group velocity decreases with frequency and with an increasing rate for smaller curvature ratios. This causes a slight dispersion in the wavepackets passing through the bends. There is also a possibility for scattering at the bends due to abrupt impedance change between the plate and the bend part. However, the magnitude of these scattered waves remain small. Additional FE studies proved that the bend reflection amplitude could reach up to -30dB relative to the incident mode in the most unfavorable case at high frequencies and with the smallest curvature parameter. For a typical curvature value of $a/b > 0.5$ met in practice, the reflection amplitude is much smaller and would not influence the monitoring.

In order to evaluate the sensitivity of the SH0 mode to defects that can be present in different locations within the bend region, the normalized axial displacement and stress field values were calculated. Figure 3 shows the in-plane

displacement U_z variation of the SH0 mode in the waveguide wall for a plate and a circumferential bend at 0.4 MHz-mm and 1.5 MHz-mm, respectively. In the plate, the displacement remains constant through the thickness over the entire frequency spectrum while in the bend, the displacement near the outer bend surface largely increases with frequency when compared to the displacement near the inner bend surface.

A slightly different behavior can be seen in the variation of the in-plane shear stress $\tau_{\theta z}$ shown in Fig. 4. At lower frequencies (Fig. 4a) the stress is larger at the inner surface of the bend but the maximum value shifts towards the outer bend at higher frequencies (Fig. 4b). This different variation behavior suggests that the sensitivity in the bend region can not be judged solely on the observation of U_z or $\tau_{\theta z}$.

Fig. 5 shows the variation of strain energy density (SED) which takes into account both the displacement and stress quantities and is more appropriate for sensitivity evaluation. Similar trend to $\tau_{\theta z}$ stress distribution can be seen for circumferential modes which means that at lower frequencies (Fig. 5a) the wave is more sensitive to defects in the inner bend region and at higher frequencies (Fig. 5b) to defects in the outer bend region. For the plate the energy distribution is constant.

Finally, the transverse shear stress τ_{rz} for the SH0 mode is shown in Fig. 6. Its amplitude is normalized by the maximum amplitude of $\tau_{\theta z}$. Interestingly, in the bend it is no longer zero like in the plate and its values increase with decreasing curvature parameter a/b . The maxima are slightly shifted towards the inner bend for lower frequencies (Fig. 6a) while for higher frequencies (Fig. 6b) the stresses increase and the curves are roughly symmetric with respect to the mid-thickness plane. In general, the stress distribution of the waves resembles the shear stress of the A0 Lamb mode. It is known that A0 mode is sensitive to delamination in a plate [33]. Thus similarly, the delamination in the bend region could affect the propagation of SH0 mode and the resulting scattering could be useful in the detection of defects.

3. Finite Element (FE) Modeling

The modeling was performed using the ABAQUS software [34]. Initially, the wave propagation was studied in two-dimension (2D) with a model shown in Fig. 7a. 2D model substantially reduces the simulation time and complexity compared to three-dimensional (3D) full model. It is not directly possible to use the pure 2D model as the SH wave propagation in plates is 3D. A "2D like" model was achieved by using one 3D brick element along the thickness in z-direction. The displacement of the nodes in x and y direction were constrained such that only SH waves can propagate [35].

The material used was aluminum ($E = 70 \text{ GPa}$, $\nu = 0.33$, $\rho = 2712 \text{ kg/m}^3$). The mesh consisted of linear eight noded brick elements with a length of 0.2mm, 0.2mm and 0.3 mm in the x, y and z direction, respectively. This results more than 15 elements per wavelength of the SH0 mode which satisfies the limit of accurate modeling [16].

SH0 mode was excited by force excitation in the z-direction which was applied at the edge with a toneburst signal at 500kHz modulated by a 2 cycle Hanning window. This allows the results to be obtained in a wide frequency bandwidth. This study focuses in the range of 200 kHz to 750 kHz.

Two monitoring points to measure U_z displacement component were set at a distance of 75 mm from either ends of the stiffener, as shown in Fig. 7a. Monitor-1 was placed to monitor the incident and reflected SH0 mode while monitor-2 monitored the transmitted wave after passing through four bend regions. Typical time-domain signals obtained at monitoring points of the spar with a curvature ratio $a/b=0.5$ are shown in Fig. 8 and their spectrums are compared in Fig. 9. It can be seen that the waveform of the transmitted wave has been affected by the dispersion which is caused by the velocity change in the bends. However, the energy spectrum of the transmitted signal is almost intact in the studied frequency range which suggests similar scattering strength if the defect would be located in any of the bends.

Variants of spatial models were set up in order to model the spar with

different bend curvature ratios (a/b) and cracks. Four different defects were modeled, as shown in Fig. 7b.

- 1) *Flat plate transverse crack*
- 2) *Inner bend transverse crack*
- 160 3) *Outer bend transverse crack*
- 4) *Delamination*

These discontinuities were achieved by disconnecting adjacent elements in the FE model.

The reflection coefficient was obtained by dividing the amplitude of the reflected signals by the amplitude of the incident signal in the frequency domain
165 by using the Fast Fourier Transform (FFT).

Secondly, a full 3D model as shown in Fig. 10a was used to investigate the scattering from a finite size inner bend and outer bend transverse notches and to compare the results with the experimental results. The curvature ratio in this
170 case was $a/b = 0.5$. The single layer mesh of the "2D like" model was extended up to 1333 elements in the z-direction and was surrounded by absorbing regions to avoid unwanted reflections from the edges [36]. The notches were introduced by deleting elements from the model in the middle of the stiffener's length and at the first bend, as shown in Fig. 10b. The lengths of the inner and the outer
175 bend notches were 19 mm and 20 mm, respectively. Both the notches were 1 mm in width and 1.1 mm in depth. A similar tone burst was used as in the 2D model for the excitation of SH0 mode.

The excitation was a 3 cycle Hanning windowed toneburst at a center frequency of 500 kHz and was applied in the z-direction in the mid point at the
180 bottom plate edge. This generated the Rayleigh and S0 modes, with their principal direction parallel to the excitation direction and the SH0 modes propagating perpendicularly to the plate edge. No A0 modes were generated due to symmetric in-plane excitation.

To obtain the reflection coefficient for plane waves interacting with the notch,
185 it is necessary to consider the beam spreading of the propagating waves [16]. As the waves in the model decay cylindrically away from the source and the defect,

the reduction of the amplitudes in both cases is inversely proportional to the square root of the propagation distance from the source. Thus,

$$RC = \frac{R(f)\sqrt{l+l_2}}{I(f)\sqrt{l_1}} \quad (1)$$

where $R(f)$ and $I(f)$ are the amplitudes of the reflected and incident signal
 190 in the frequency domain, l is the distance between the source and the defect, l_1
 is the distance of the source from the monitoring point and l_2 is the distance of
 the defect from the monitoring point.

4. Experimental Procedures

Setup of the experiment is shown in Fig. 11. The cross-section of the exper-
 195 imental stiffener is the same as that of the FE model, shown in Fig. 7a , but
 with a length of 800 mm in the z-direction. For the experimental study, a larger
 width was used so that time taken for the faster S0 waves to travel towards the
 sides and get reflected take longer, which ensures that there is absolutely no
 interaction with the SH0 wavefront/measurements. Two part thickness trans-
 200 verse notches, one originating from the inner and the other from the outer bend
 surface, were machined each in one stiffener along the first bend. The notches
 were 1 mm wide and 1.1 mm deep. The inner and outer bend notches were 19
 mm and 20 mm long, respectively.

The SH0 mode was excited by a wideband piezoelectric shear transducer
 205 (Panametrics V154, 2.25 MHz center frequency) coupled to the plate edge with
 a small metal disc in order to simulate a point source excitation. An ultrasonic
 shear gel couplant (Magnaflux) was used to enhance the wave transmission to the
 plate. The toneburst signal was a 3 cycle Hanning window at 500kHz generated
 using a (RITEC RAM-5000) computer controlled ultrasonic system. The input
 210 voltage amplitude used was 150V peak to peak. The monitoring and detection
 of the incident and reflected signals were attained by the means of a (Polytec
 OFV-5000) vibrometer controller. Beams originating from two (Polytec OFV-
 505) laser heads oriented at +30 and -30 to the normal and pointing at the same

spot measured the in-plane displacement U_z . Thin reflecting tapes were placed
 215 on the monitoring points to improve the optical backscatter. The quality of the
 measured signals were further increased by applying a bandpass filter and taking
 400 averages. The data was collected using an (Teledyne Lecroy) oscilloscope.
 The reflection coefficients for reflected signals were calculated analogously to
 that introduced in FE modeling.

220 5. Results and Discussion

5.1. 2D Guided Wave Scattering From a Transverse Crack

The interaction of SH0 with a transverse crack in the plate and in the in-
 ner/outer bend is investigated through finite element analyses in Fig. 12 where
 the reflection ratio as a function of crack depth is shown. The bends were mod-
 225 eled with the curvature ratio of $a/b = 0.5$ and the results are shown for the
 frequencies 200, 500 and 750 kHz.

On considering either of the defects, it is observed that the reflection ratio
 increases non-linearly with the increase in defect depth. For a lower frequency,
 the reflection ratio is very low and detection of shallow defects would be difficult.
 230 The curve becomes increasingly concave as the crack depth increases. On the
 other hand, for a higher frequency the curve takes up more of a convex path
 denoting the sensitivity improvement compared to lower frequencies. Slightly
 different behavior can be seen comparing the reflection coefficients from cracks
 arising from different bend surfaces. At lower frequencies the wave is more
 235 sensitive to inner bend surface crack whereas at higher frequencies the cracks
 on the outer surface can be more easily detected. This effect can be explained
 by the strain energy density distribution across the bend studied in Section
 2. At lower frequencies the strain energy density is larger at the inner surface
 and at higher frequencies shifts towards the outer surface. The variation of
 240 reflection ratio between the inner and outer bend defect is more prominent for
 a higher frequency. The trend in the variation of reflection coefficient with
 respect to the defect depth and frequency is similar to the study carried out in

an earlier published work [21]. However, this work additionally demonstrates the importance of the curvature on the reflection characteristics.

245 5.2. 2D Guided Wave Scattering From a Delamination

A number of 2D FE simulations were performed of the SH0 mode interacting with a delamination having lengths 0.25λ , 0.5λ and 0.75λ (λ - wavelength of SH0 at 500kHz). The distance of the delamination from the inner bend was also varied to be 10, 50 and 90% of the thickness. The curvature ratio $a/b = 0.5$ was
250 used for this study. Fig. 13 shows the time trace of a signal obtained at the edge from a delamination of 0.75λ located at 50% thickness from the inner bend. A significant reflection from the delamination can be seen which is followed by the weakening trail of reflections. This refers to wave trapping at the delamination with repeated scattering which is caused by lower acoustic impedance in one of
255 the sub-waveguides.

Fig. 14 shows the reflection coefficient of the SH0 mode from the delamination with various lengths and locations. Due to multiple reflections, the resonating behavior of the coefficient can be observed. In case of a small delamination 0.25λ there is only a single peak in the curve. As the length of the
260 delamination increases, the number of peaks (appearing with regular interval) also increases. The down shift of the resonance frequencies is implicative to the inverse relationship between the resonance frequency and delamination length. Also, the location of the defects affect the resonance behavior of the scattered waves. It can be seen from the figures that for the same delamination length
265 the resonance frequencies are lower for the mid-surface defect and are increasing when the defect moves towards the inner or outer surfaces of the bend. This is due to the phase velocity change in the circumferential waveguides separated by the delamination. The results suggest that the waves are trapped in a thinner part of the bend waveguide where the phase velocity is higher and thus causing
270 the increase of the resonance frequencies. Another characteristic influenced by the defect location is the amplitude of the resonance. When the delamination is located in the mid-surface, the amplitude of the peaks seem to be larger when

compared to other positions. As the transverse shear stress τ_{rz} of the SH0 mode is affected by the delamination and is maximum in the mid-thickness of the bend, as was shown in Fig. 6, stronger reflection are expected. For other positions the amplitude of the peaks seems to be similar and smaller as the shear stress through the thickness decreases roughly equally towards the inner and outer surface of the bend.

5.3. 3D Guided Wave Scattering From a Transverse Notch

Figure 15 presents the time snapshots of the contour of the magnitude of resultant displacement from 3D FE simulations. A time instant soon after the interaction of the SH0 mode with a part-through transverse notch arising from the outer and inner bend is shown in figures 15a and 15b, respectively. The strongest component in the scattered wavefield is the reflected SH0 mode. Some weak SH0 modes are diffracted from the tips of the notch and some mode converted S0 modes are reflected and diffracted from the notch. Qualitatively, it can be seen that the wavefields scattered from the outer bend notch are stronger compared to the ones from the inner bend notch. This can also be verified from figures 16aa and 16b which depict the time trace of the experimental signals from the inner and outer bend notch, respectively. It can be seen that for a similar defect, the one present in the outer bend region had a higher reflected amplitude compared to the one in the inner bend region.

Figure 17 shows the comparison between the FE and experimentally obtained reflection coefficients as a function of frequency for both the notches. For both the notches, with increasing frequency, the reflection coefficient initially increases almost linearly. On reaching higher frequency values the reflection coefficient for the inner bend notch gradually starts to decrease while for the outer bend notch it continues to increase. There is a good agreement in the trends between the FE and experimental results. It is observed that the experimental values of the reflection coefficient are smaller than the values from the FE study. It is believed that these differences were caused due to the different bend curvature in the experimental specimen and the machined notches which

can have small variations in depth and width.

It is of interest to understand the main reason behind the different reflection behaviors from inner and outer bend defects and also how the shown results compare with those of the scattering results obtained from defects in straight plates. In general, 3D scattering problems are much more complicated than the 2D cases. Including depth and frequency, the scattering is also affected by the length and width of the notch and the distance of the monitoring point [17]. A similar case to this work has been reported by Rajagopal et al [17] where the reflection ratio as a function of the crack length was presented. The trend of the result is very similar to the one obtained in this work with a FE model having a 1.1 mm deep inner bend notch. Initially, the ratio rises almost linearly with crack length and then falls, which is indicative to the diffraction effects in a short range scattering. Interestingly, this falling trend is not followed for defects present towards the outer bend but rather keeps on increasing. In addition, it was observed in Fig. 15 that the diffractions were very weak and thus could not cause the oscillatory phenomenon in the reflection ratio. The reason for this difference is the curvature effect which enhances the wave propagation energy density towards the outer bend and reduces it towards the inner bend at higher frequencies resulting in the drop of the reflection ratio.

6. Conclusion

This paper studied the interaction of the shear horizontal guided wave mode with defects present in the bend region of an isotropic top hat stiffener. The group velocity dispersion curves and wavefield distribution of the SH0 mode were shown to be highly dependent on the curvature of the bend. At lower frequencies the strain energy of the mode was concentrated more towards the inner surface whereas at higher frequencies towards the outer surface. This determined the sensitivity to transverse cracks. 3D scattering studies supported by experiments confirmed the importance of the curvature effect on the different sensitivity to inner and outer bend defects. The interaction of SH0 mode with a

delamination revealed an interesting phenomenon. A series of wave pulses with gradually decaying amplitude was seen to be reflecting from the defect which lead to a periodic peak-like structure in the frequency spectrum. The resonance
335 frequencies were affected by the length and location of the defect. The reflection amplitude was seen to be the highest when the delamination was present in the mid thickness. The same principle demonstrated here could be readily extended to the case of composite stiffeners and stiffeners with different bend angles. Studies can further be extended to understand SH mode propagation through
340 lap joints.

7. Acknowledgements

This work was supported by the Singapore Maritime Institute under SMI Simulation & Modelling R&D Programme.

References

- 345 [1] T. H. G. Megson, Aircraft structures for engineering students., Elsevier aerospace engineering series, Oxford ; Waltham, MA : Butterworth-Heinemann, c2013., 2013.
- [2] Federal Aviation Administration, Corrosion and corrosion fatigue of airframe materials., DOT/FAA/AR-00/22, Washington, D.C: U.S., 2004.
- 350 [3] Raju, B. G. Prusty, D. W. Kelly, Delamination failure of composite top-hat stiffeners using finite element analysis., Proceedings of the Institution of Mechanical Engineers – Part M – Journal of Engineering for the Maritime Environment (Sage Publications, Ltd.) 227 (1) (2013) 61–80.
- [4] K. J. Sun, D. Kishoni, Feasibility of using lamb waves for corrosion detection in layered aluminum aircraft structures., ULTRASONICS SYMPOSIUM 2 (1993) 733–736.
355

- [5] P. C. R. P. Dalton, M. J. S. Lowe, The potential of guided waves for monitoring large areas of metallic aircraft fuselage structure., *Journal of Nondestructive Evaluation* 20 (1) (2001) 29–46.
- 360 [6] V. Giurgiutiu, C. Soutis, Enhanced composites integrity through structural health monitoring., *Applied Composite Materials* 19 (5) (2001) 13–29.
- [7] Z. Su, X. Wang, Z. Chen, L. Ye, D. Wang, A built-in active sensor network for health monitoring of composite structures., *Smart Mater. Struct.* 15 (6) (2006) 1939 – 1949.
- 365 [8] C. Fortunko, R. King, M. Tan, Nondestructive evaluation of planar defects in plates using low-frequency shear horizontal waves., *Journal of Applied Physics* 53 (5) (1982) 3450 – 3458.
- [9] Z. Abduljabbar, S. Datta, A. Shah, Diffraction of horizontally polarized shear waves by normal edge cracks in a plate., *Journal of Applied Physics* 370 54 (2) (1983) 461 – 472.
- [10] M. Castaings, Sh ultrasonic guided waves for the evaluation of interfacial adhesion., *Ultrasonics*. 54 (2014) 1760 – 1775.
- [11] D. N. Alleyne, P. Cawley, The interaction of lamb waves with defects., *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*. 39 (3) (1992) 381–397.
- 375 [12] M. J. S. Lowe, O. Diligent, Low-frequency reflection characteristics of the s_0 lamb wave from a rectangular notch in a plate., *J. Acoust. Soc. Am.* 111 (2002) 64–74.
- 380 [13] M. J. S. Lowe, P. Cawley, J. Y. Kao, O. Diligent, The low frequency reflection characteristics of the fundamental antisymmetric lamb wave a_0 from a rectangular notch in a plate., *J. Acoust. Soc. Am.* 112 (2002) 2612–2622.
- [14] F. L. di Scalea, P. Rizzo, A. Marzani, Propagation of ultrasonic guided waves in lap-shear adhesive joints: Case of incident a_0 lamb wave., *J. Acoust. Soc. Am.* 115 (1) (2004) 146 – 156.

- [15] M. J. S. Lowe, R. E. Challis, C. W. Chan, The transmission of lamb waves across adhesively bonded lap joints., *J. Acoust. Soc. Am.* 107 (3) (2000) 1333 – 1345.
- [16] P. Rajagopal, M. J. S. Lowe, Short range scattering of the fundamental shear horizontal guided wave mode normally incident at a through-thickness crack in an isotropic plate., *J. Acoust. Soc. Am.* 122 (3) (2007) 1527–1538.
- [17] P. Rajagopal, M. J. S. Lowe, Scattering of the fundamental shear horizontal guided wave by a part-thickness crack in an isotropic plate., *J. Acoust. Soc. Am.* 124 (5) (2008) 2895–2904.
- [18] P. Rajagopal, M. J. S. Lowe, Angular influence on the scattering of fundamental shear horizontal guided waves by a through-thickness crack in an isotropic plate., *J. Acoust. Soc. Am.* 124 (4) (2008) 2021–2030.
- [19] M. Ratassepp, M. J. S. Lowe, P. Cawley, A. Klauson, Scattering of the fundamental shear horizontal mode in a plate when incident at a through crack aligned in the propagation direction of the mode., *J. Acoust. Soc. Am.* 124 (5) (2008) 2873–2882.
- [20] Nurmalia, N. Nakamura, H. Ogi, M. Hirao, K. Nakahata, Mode conversion behavior of sh guided wave in a tapered plate., *NDT & E Int.* 45 (2012) 156–161.
- [21] A. Demma, P. Cawley, M. Lowe, A. G. Roosenbrand, The reflection of the fundamental torsional mode from cracks and notches in pipes., *J. Acoust. Soc. Am.* 114 (2) (2003) 611–625.
- [22] A. Demma, P. Cawley, M. Lowe, Scattering of the fundamental shear horizontal mode from steps and notches in plates., *J. Acoust. Soc. Am.* 113 (4 pt 1) (2003) 1880–1891.
- [23] Z. Fan, M. J. S. Lowe, Interaction of weld-guided waves with defects., *NDT & E Int.* 47 (2012) 124–133.

- [24] X. Yu, M. Ratassepp, Z. Fan, P. Rajagopal, Anisotropic effects on ultrasonic guided waves propagation in composite bends., Ultrasonics 95-105 (2016) 370–379.
- [25] P. Manogharan, X. Yu, Z. Fan, P. Rajagopal, Interaction of shear horizontal bend (sh_b) guided mode with defects., Ultrasonics 75 (2015) 39–47.
- [26] X. Yu, P. Manogharan, Z. Fan, P. Rajagopal, Shear horizontal feature guided ultrasonic waves in plate structures with 90° transverse bends., Ultrasonics 65 (2016) 370–379.
- [27] P. Manogharan, P. Rajagopal, K. Balasubramaniam, Longitudinal guided waves confined in radius filler regions of composite joints., The Journal of the Acoustical Society of America 140 (2016) 334–343.
- [28] J. Fong, M. J. S. Lowe, Curvature effect on the properties of guided waves in plates., AIP CONFERENCE PROCEEDINGS 23 (700) (2003) 126–133.
- [29] X. Zhao, J. L. Rose, Guided circumferential shear horizontal waves in an isotropic hollow cylinder., J. Acoust. Soc. Am. 115 (5) (2004) 1912–1916.
- [30] D. C. Gazis, Three-dimensional investigation of the propagation of waves in hollow circular cylinder. i. analytical foundation., J. Acoust. Soc. Am. 31 (5) (1959) 568–573.
- [31] I. A. Viktorov, Rayleigh and Lamb waves : physical theory and applications., Ultrasonic technology, New York : Plenum Press, 1967., 1967.
- [32] B. Pavlakovic, M. Lowe, D. Alleyne, P. Cawley, Disperse: A general purpose program for creating dispersion curves, PLENUM PRESS DIV PLENUM PUBLISHING CORP, 1997, pp. 185–192.
- [33] C. Ramadas, K. Balasubramaniam, M. Joshi, C. V. Krishnamurthy, Interaction of guided lamb waves with an asymmetrically located delamination in a laminated composite plate., Smart Mater. Struct. 19 (6) (2010) 1–11.
- [34] ABAQUS v6.13-1, Analysis User's Manual (2004).

- 440 [35] P. Belanger, Feasibility of thickness mapping using ultrasonic guided waves,
Ph.D. thesis, Imperial College London (2009).
- [36] M. Drozd, L. Moreau, M. Castaings, M. J. S. Lowe, P. Cawley, Efficient
numerical modelling of absorbing regions for boundaries of guided waves
problems, AIP Conference Proceedings. 820 (1) (2006) 126–133.

Figure 1: Geometry of the top hat stiffener under consideration

Figure 2: Group velocity dispersion curves for guided SH waves in an aluminum plate and circumferential bend. $t=2\text{mm}$, a -inner radius, b -outer radius

(a)

(b)

Figure 3: Particle displacement U_z distribution for guided SH waves in an aluminum plate and pipe. a) $f_{xt} = 0.4$ MHz-mm, b) $f_{xt} = 1.5$ MHz-mm. Dot-scatter points depict the distribution for $a/b = 0.67$ case taken from FE modeling, for verification.

(a)

(b)

Figure 4: Stress component $\tau_{\theta z}$ distribution for guided SH waves in an aluminum plate and pipe. a) $f_{xt} = 0.4$ MHz-mm, b) $f_{xt} = 1.5$ MHz-mm. Dot-scatter points depict the distribution for $a/b = 0.67$ case taken from FE modeling, for verification.

(a)

(b)

Figure 5: Strain energy distribution for guided SH waves in an aluminum plate and pipe. a) $f_{xt} = 0.4$ MHz-mm, b) $f_{xt} = 1.5$ MHz-mm.

(a)

(b)

Figure 6: Stress component τ_{rz} distribution for guided SH waves in an aluminum plate and pipe. a) $f_{xt} = 0.4$ MHz-mm, b) $f_{xt} = 1.5$ MHz-mm. Dot-scatter points depict the distribution for $a/b = 0.67$ case taken from FE modeling, for verification.

Figure 7: a) Schematic of the '2D like' FE model, b) Modeled defects

(a)

(b)

Figure 8: Typical time trace signal of the spar with curvature ratio $a/b=0.5$ monitored at a) monitor1 and b) monitor2

Figure 9: Comparison of energy spectrum of transmitted signal received at monitor-1 and monitor-2

Figure 10: 3D FE model a) Top-view showing the dimensions, source and receiving points, b) Part cross-section of the model depicting the defect region

Figure 11: Setup of the experiment

Figure 12: Reflection ratio as the function of crack depth

Figure 13: Typical time trace signal monitored at the plate edge from the excitation at 500kHz obtained from 2D FE simulation for a delamination of length 0.75λ located at the mid-thickness of the bend

(a)

(b)

(c)

Figure 14: Reflection coefficient as a function of frequency and location of the defect for different lengths a) 0.25λ , b) 0.5λ and c) 0.75λ

Figure 15: Contour snapshots of the magnitude of resultant displacement from 3D FE simulations for a) Outer bend notch and b) Inner bend notch

(a)

(b)

Figure 16: Time-trace of the experimentally obtained signals excited with a toneburst signal at 500kHz from the a)inner and b)outer bend notch of 1 mm width, 1.1 mm depth and lengths 19 mm and 20 mm, respectively

Figure 17: Reflection coefficient of SH0 mode as a function of frequency and crack length for FE and experiment for inner and outer bend notch

Highlights

- Investigation of the shear horizontal wave for the inspection of defects in top hat stiffener.
- The curvature effect on the SH wave is analyzed.
- The sensitivity of SH wave to different defects is discussed.