Identification of damage in composite structures based on feature guided ultrasonic waves

Yu, Xudong

2018

Yu, X. (2018). Identification of damage in composite structures based on feature guided ultrasonic waves. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/73449>

<https://doi.org/10.32657/10356/73449>

IDENTIFICATION OF DAMAGE IN COMPOSITE STRUCTURES BASED ON FEATURE GUIDED ULTRASONIC WAVES

by

Xudong Yu

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

School of Mechanical and Aerospace Engineering
Nanyang Technological University

February 2018

Abstract

Complex-shaped composite laminates are increasingly utilized as Principal Structural Elements (PSE) such as spars, ribs, and the skin-stiffener combination in the aerospace industry. However, due to the stress concentration and out-of-plane impacts during the service life, various types of defects can be initiated in these structures, which have to be identified timely in case they propagate at subsurface laminae and ultimately lead to catastrophic failure. Therefore, this thesis explores the potential of exploiting a special type of ultrasonic guided wave, i.e. feature guided wave (FGW), for rapid screening of long-range composite structures. Such FGWs are capable of focusing their wave energy along the structural feature, with limited leakage into the adjacent plate. Two typical composite features are investigated in the thesis, which are laminated bends and adhesive composite joints, and the results are encouraging.

Modal analysis of the laminated bend is carried out by using the Semi-Analytical Finite Element (SAFE) approach, in which the spatially-varying anisotropy is implemented to reveal the existing FGW modes. A shear horizontal type bend-guided (SH_B) mode has been identified. The mode is almost non-dispersive and non-leaky, with strong energy confinement in the bend region, which is attractive to be applied as a screening tool for composite bends. Both 3D Finite Element (FE) simulations and experiments are performed to cross-validate the propagation characteristics of the SH_B mode and to study its interaction with different defects occurred in the bend region, such as the interlaminar delamination and cracks, showing good agreement. The wave-defect resonance phenomenon and the reflection behaviour are investigated for localizing these two types of defects, and the capabilities of the SH_B mode for efficient damage detection in long-range composite bends have been well demonstrated.

Also, adhesive bonding is widely used in aerospace composites, and its integrity is crucial to the performance of the entire structure. This motivates the investigation of FGWs in another typical composite assembly, namely the stiffener-adhesive bond-

composite skin combination. The SAFE method is employed to understand the modal properties of the FGWs that exist in such assembly, and criteria are suggested to choose proper mode-frequency combination that is sensitive to adhesive defects. An SH type FGW mode has been identified to be well suited, as it produces sufficient power flow in the bond layer and is little-dispersive and low-attenuative, as well as easy to generate. Its scattering by adhesive defects is studied both numerically and experimentally, and the modelling approaches have been validated. The reflection coefficient spectra of the selected FGW mode and the variation of its wave energy along the propagation path are calculated, identifying the adhesive defect between the stiffener and the composite panel. Additionally, parametric studies of defect geometry illustrate the influences of the variation in defect size and bond thickness on the reflection behaviour, shedding light on its practical employment.

This thesis has also extended the study of FGWs to structural health monitoring (SHM) applications. In contrast to conventional guided wave SHM schemes, the structural features are no longer regarded as interference but special ‘local’ waveguides for the transport of the guided wave energy. Proper FGWs with strong energy confinement are exploited for rapid condition screening of the feature area, and an array of sensors permanently attached to the adjacent plate captures the scattered waves from the localized damage. This technique is combined with the synthetic focusing method for the damage reconstruction. The defect can be identified by the indications coherently enhanced in the reconstructed image. Information about the location and severity of the defect can thus be obtained. The proposed FGW based SHM strategy potentially offers enhanced interrogation of the feature area, which can also be implemented in conjunction with the existing guided wave SHM system to yield richer information about the health state of the entire structure.

Acknowledgements

“诗人对宇宙人生，须入乎其内，又须出乎其外。入乎其内，故能写之。出乎其外，故能观之。入乎其内，故有生气。出乎其外，故有高致。”

‘The poet, in dealing with the universe and with human life, must penetrate to their very core and at the same time must stand apart from them. By penetrating to their core he is thus able to describe them accurately; by standing apart from them he is able to observe them objectively. By penetrating to their core his works achieve life and vital force; by standing apart from them his works achieve loftiness.’

Wang Kuo-wei, 1877~1927, Chinese scholar, writer and poet

I would like to express my sincere gratitude to Professor Zheng (David) Fan for his excellent guidance and supervision throughout this work. It is invaluable experience to work with him, as his first Ph.D. student, to create everything from scratch. I have always been inspired by his scientific vision, educational philosophy, and passion for research, which shed light on my future professional career.

I would also like to thank Professor Michel Castaings from Université de Bordeaux and Professor Prabhu Rajagopal from Indian Institute of Technology Madras for our continuous fruitful collaborations, and I’ve indeed benefited a lot from their guidance. My sincere appreciation goes to Professor Zhongqing Su from Hong Kong Polytechnic University, Professor Michael Lowe from Imperial College London, and Professor Tribikram Kundu from University of Arizona as well for their helpful suggestions to this work.

A special thanks to Dr. Madis Ratassepp and Dr. Maria Felice for numerous insightful discussions and all the interesting lunchtime talks. I would also like to extend my thanks to all colleagues in the NDT group, for their help and for making the working environment enjoyable.

Finally, I am always indebted to my parents and my girlfriend for their continuous understanding, patience and support, which I will forever treasure. This thesis is dedicated to them.

Contents

1	Introduction	26
1.1	Motivation	26
1.2	Thesis Objectives	35
1.3	Thesis Outline	36
2	Ultrasonic Guided Waves in Complex Structures: A Review	39
2.1	Background	39
2.2	Guided Waves in Isotropic Media	40
2.2.1	Dispersion curves	41
2.2.2	Mode shapes	43
2.2.3	Attenuation	45
2.3	Guided Waves in Anisotropic Media	48
2.3.1	Directional dependence of wave velocity	49
2.3.2	Steering effect	52
2.4	Guided Waves Confined to Structural Features	54
2.4.1	Concept of the feature guided wave (FGW)	54

2.4.2	Semi-Analytical Finite Element (SAFE) method	58
2.5	Summary	64
3	Feature Guided Waves in Isotropic Metal Bends	66
3.1	Background	66
3.2	Methodology	67
3.2.1	SAFE modelling	67
3.2.2	3D finite element simulation	69
3.2.3	Experiment	71
3.3	Properties of the Shear Horizontal Bend-guided (SH_B) Mode	72
3.3.1	Energy concentration	72
3.3.2	Mode shapes	76
3.3.3	Dispersion curves	77
3.3.4	Leakage of the bend-guided mode	80
3.4	Discussion on Feature Guiding Phenomena	81
3.4.1	Explanation of the energy trapping effect	81
3.4.2	Factors affecting energy concentration	83
3.4.3	Relation with wedge acoustic waves	86
3.5	Interaction of the Bend-guided Mode with Defects	87
3.5.1	Transverse cracks	88
3.5.2	Longitudinal cracks	91
3.6	Summary	94

4	Feature Guiding Phenomena in Anisotropic Bends with Unidirectional Layups	96
4.1	Background	96
4.2	Numerical Modelling and Post-processing of Anisotropic Bends	97
4.2.1	SAFE modelling	98
4.2.2	3D finite element simulation	102
4.3	Validation Experiments	104
4.3.1	Experimental setup and procedures	104
4.3.2	Experimental results	106
4.4	Discussion	107
4.4.1	Influence of fibre orientation on energy trapping effect	107
4.4.2	Effect of frequency on energy concentration	110
4.5	Summary	112
5	Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves	113
5.1	Background	113
5.2	Modal Study of Composite Bends	115
5.2.1	SAFE modelling	115
5.2.2	Shear horizontal bend-guided mode	117
5.3	Validation of Propagation Characteristics	120
5.3.1	3D finite element simulation	120

5.3.2	Experiments	121
5.4	Interaction of the Bend-guided Mode with Different Defects	124
5.4.1	Interlaminar delamination in the bend region	124
5.4.2	Transverse cracks across the bend	127
5.5	Summary	130
6	Feature Guided Wave Inspection of Adhesive Composite Joints	132
6.1	Background	132
6.2	FGWs in Stiffened Composite Panels	134
6.2.1	SAFE modelling	134
6.2.2	Typical mode shapes	137
6.3	Mode Selection for Detecting Adhesive Defects	138
6.3.1	Power flow in the bond layer	138
6.3.2	Dispersion characteristics	141
6.3.3	Mode excitability	142
6.4	Defect Scattering Study of the Selected Mode	145
6.5	Experiments	150
6.5.1	Experimental setup and procedure	150
6.5.2	Comparison of experimental results with modelling	153
6.6	Summary	157
7	An Extended Study: from NDT to SHM	159

7.1	Background	159
7.2	SHM Scheme Using Diffraction from Defects	162
7.3	Synthetically Focused Imaging	167
7.4	Experimental Validation	172
7.4.1	Experimental setup	172
7.4.2	Experimental results	173
7.5	Discussions	175
7.5.1	Imaging defects with varying sizes	176
7.5.2	Defect imaging under different densities of sensors	178
7.5.3	Extension to damage detection in composite bends	179
7.6	Summary	181
8	Conclusions	183
8.1	Thesis Review	183
8.2	Summary of Findings	186
8.2.1	FGW screening of composite structures	186
8.2.2	Development of FGW based SHM strategy	188
8.3	Future Work	189
A	Effective Elastic Constants of Anisotropic Layered Structures	191
	References	219
	List of Publications	220

List of Figures

- 1.1 *Increase of composite components in commercial airplane models over time, indicated by percentage of the total aircraft weight [2].* 27
- 1.2 *Illustration of (a) an aircraft wing assembly composed of skins, spars, ribs, and stringers; (b) C-shaped and Z-shaped wing spars consisting of two composite bent plates; the adhesive bonding between the spar and skins shown.* 29
- 1.3 *Schematic of (a) wind turbine blades; (b) structural configuration of a blade consisting of a rectangular shaped spar and skins.* 29
- 1.4 *Strain field distributions in a symmetrically loaded L-shaped composite beam under the non-failed state: (a) radial strain ε_r , (b) hoop strain ε_φ , (c) cylindrical shear strain $\gamma_{r\varphi}$, and (d) principal deformation; (e) failed composite specimen with indications of the first failure and subsequent delaminations occurred in the bend region due to continued loading [15].* 30
- 1.5 *(a) Illustration of the loading and boundary conditions applied to an L-shaped laminate; its predicted failure mode shown; (b) predicted delamination process in the L-shaped laminate; (c) comparison between the measured and predicted structural response for intact laminates [25]. 32*

1.6	(a) Photograph of the experimental setup and the unidirectional carbon fibre/epoxy thin-curved laminate; damaged specimens with 2 mm laminate thickness but varying inner bend radius: (b) $r_i=10$ mm, (c) $r_i=15$ mm, and (d) $r_i=20$ mm [26].	32
1.7	Schematic of a compressional feature guided wave propagating in a welded plate; a pulse-like excitation indicated; propagation of other wave modes in adjacent plates shown [56].	35
2.1	Schematic of a guided wave propagation in a free plate; internally reflecting bulk waves shown.	40
2.2	The (a) phase velocity and (b) group velocity dispersion curves for different guide modes (S_i mode: red; A_i mode: blue; SH_i : green) propagating in a steel plate in vacuum.	42
2.3	Diagrams of (a) 5-cycle Hanning windowed toneburst signal centred at 1.5 MHz as excitation; (b) S_0 wave and (c) SH_0 wave signals monitored on a 1 mm thick steel plate after 200 mm propagation distance.	43
2.4	Displacement mode shapes of (a) S_0 mode, (b) SH_0 mode, and (c) A_0 mode at 0.41 MHz-mm in a steel plate; (d) illustration of the reference coordinate system.	44
2.5	Stress mode shapes of (a) S_0 mode, (b) SH_0 mode, and (c) A_0 mode at 0.41 MHz-mm in a steel plate.	45
2.6	Illustration of a guided mode travelling in a leaky waveguide, which leaks bulk waves at a characteristic angle; wavelengths in different domains shown.	48
2.7	(a) Reference coordinates for the unidirectional fibre reinforced laminate; wave propagation angle with respect to fibre orientation labelled; (b) dispersion curves of guided modes propagating along the fibre direction.	50

2.8	<i>Anisotropic propagation of fundamental guided modes in laminates: (a) slowness curves at 300 kHz; (b),(c) and (d) three-dimensional dispersion surfaces of the S_0 mode, the SH_0 mode, and the A_0 mode.</i>	51
2.9	<i>(a) Geometric relation between the phase and energy velocity vectors (arbitrary magnitudes); steering angle ϕ denoted; fibres lie in the direction $\theta = 0^\circ$; (b) difference between energy and phase velocity directions for the fundamental guided modes in the unidirectional laminate at 300 kHz; results were calculated by the SAFE method (shown later in this chapter).</i>	53
2.10	<i>Illustration of the trapped guided mode due to the difference of wave velocities in the feature and in the adjacent plate [56].</i>	55
2.11	<i>Mode shapes of four fundamental guided modes that exist in the weld at 100 kHz: (a) longitudinal mode, (b) torsional mode, (c) flexural mode 1, and (d) flexural mode 2; arrows represent the particle displacement in the cross section [55].</i>	56
2.12	<i>Dispersion curves of the fundamental guided modes in the steel weld and in the 6-mm thick steel plate [55].</i>	57
2.13	<i>Two-dimensional model for a solid waveguide embedded in infinite medium with the absorbing region or perfectly matched layer (PML) shown.</i>	59
3.1	<i>Schematic of SAFE model of a bent plate with absorbing region shown (not to scale).</i>	68
3.2	<i>Schematic of 3D FE model of the bent plate; shear horizontal wave excitation location and absorbing region indicated; different wave modes labelled; colour coding shows relative amplitudes of propagating modes at 1 MHz excitation frequency (blue: low to red: high).</i>	70

3.3	<i>Photograph showing (a) a view of the experimental setup; (b) the PZT crystal bonded on the edge of the bent plate through a conductive sheet; (c) the sample bent plate with an attached reflective film.</i>	71
3.4	<i>(a) Normalized axial power flow in bent plate, derived from the SAFE model at 1 MHz; bend-guided mode with energy concentrated in the vicinity of bend region (solid line), unwanted modes (dash-dotted lines); and bend region (shaded) indicated; (b) axial power flow illustration of the bend-guided SH type mode propagating along the bend; colour coding shows relative axial power flow (blue: low to red: high); and outer boundary of the bent plate (dashed line) indicated; (c) normalized axial component of power flow of the SH_B mode zoomed around the bend region.</i>	73
3.5	<i>Illustration of the in-plane displacement calculation.</i>	74
3.6	<i>Plot of the normalized amplitude of the in-plane displacement of the SH_B mode, obtained from the SAFE method (solid), 3D FE simulations (squares) and experiment (dashed, circles) at 1 MHz.</i>	75
3.7	<i>Illustration of the experimental configuration for measuring the in-plane displacement on the bend surface.</i>	76
3.8	<i>Mode shape of the SH_B mode, calculated from the SAFE model at 1MHz: (a) schematic of the modal structure and the axial power flow around the bend region; cutline 1 and cutline 2 (dashed lines) indicated; (b) displacement mode shape extracted along cutline 1; (c) displacement mode shape extracted along cutline 2.</i>	77
3.9	<i>Group velocity dispersion curves obtained from SAFE (solid, asterisks) and FE (squares) models as well as experiments (dashed, circles).</i>	78
3.10	<i>Attenuation dispersion curves derived through SAFE predications (solid, asterisks), 3D FE simulations (dotted, squares) and experiments (dashed, circles).</i>	79

3.11	(a) Phase velocity of the SH_B mode in the bend and the A_0 mode in the flat plate; (b) schematic showing the leaky SH_B mode, which leaks the A_0 mode at an angle θ_{rad}	81
3.12	Mode shapes of (a) the shear horizontal mode in the bend region and (b) the SH_0 mode in flat plate; (c) phase velocity dispersion curves for all the propagating mode in the bend region; phase velocity of the SH_0 mode in the flat plate indicated.	82
3.13	Illustration of the FWHM of the SH_B mode, obtained from the SAFE model at 1 MHz; the maximum axial power flow and half of its peak amplitude indicated.	83
3.14	Spectrum of the FWHM from 50 to 1200 kHz, predicted by the SAFE model.	84
3.15	Schematic for the FWHM in bent plates with varying bend radius and plate thickness: (a) fixed plate thickness = 1 mm; (b) fixed bend radius = 4.5 mm.	85
3.16	Distribution of the axial power flow of the SH_B mode in (a) 60° bent plate at 80 kHz, (b) 120° bent plate at 1 MHz, and (c) 150° bent plate at 1 MHz; arrows represent the particular displacement in the cross section.	85
3.17	Through-thickness distribution of the axial power flow, derived from SAFE models at frequencies ranged from 50 kHz to 1 MHz.	86
3.18	Geometric illustration of the ‘transverse’ and ‘longitudinal’ crack cut sections in the bent plate; the length of crack l and the crack depth b labelled; the source and excited SH_B mode indicated.	87

3.19	<i>Time snapshots of the shear bend-guided mode at 650 kHz propagating along the bend and interacting with the defect: (a) and (b) show the excited wave field; (c) and (d) show the reflected and diffracted waves from the transverse crack of length $5 \lambda_{SH_B}$.</i>	89
3.20	<i>Time trace of the SH_B waves monitored at 200 mm from the excitation and 50 mm from the transverse defect, extracted from the 3D FE simulation at 650 kHz.</i>	89
3.21	<i>Reflection spectra of the SH_B mode for through-thickness transverse cracks with varying lengths expressed in terms of wavelength (i.e. l/λ_{SH_B}), obtained from both 3D FE simulations and experiments.</i>	90
3.22	<i>Reflection coefficient of the SH_B mode for transverse cracks with varying depths, obtained from both the 3D FE simulation and the experiment.</i>	91
3.23	<i>Time snapshots of the SH_B wave interacting with the longitudinal defect: (a) and (b) show the excited wave field; (c) and (d) show the reflected and diffracted waves for the crack of length $1 \lambda_{SH_B}$.</i>	92
3.24	<i>Time trace of the SH_B waves monitored at 200 mm from the excitation and 50 mm from the longitudinal defect, derived from the 3D FE simulation.</i>	92
3.25	<i>Reflection spectra of the SH_B mode for longitudinal short cracks with lengths expressed in terms of wavelength, obtained from both 3D FE simulations and experiments.</i>	93
3.26	<i>Reflection spectra of the SH_B mode for longitudinal long cracks with varying lengths.</i>	94
4.1	<i>Schematics of the SAFE model of anisotropic CF/EP structural bends; global and local coordinates indicated; an example of curvature-based rotation of the stiffness matrix shown for the bend with 90° fibre angle.</i>	99

4.2	<i>Identified SH_0-like and S_0-like bend-guided modes in the unidirectional CF/EP bend with fibres along the bend direction: (a) and (d) axial power flow variation of two modes in the cross section, derived from the SAFE model at 500 kHz and 350 kHz, respectively; (b) and (e) normalized amplitude of axial power flow along the outer boundary (dashed line, black) of the bent plate; (c) and (f) displacement mode shape extracted along the through-thickness cutline (dashed line, red).</i>	101
4.3	<i>Snapshot of the wave propagation in the CF/EP laminated bend: (a) SH_0-like bend-guided wave excited by 2-cycle tone burst centred at 300 kHz; (b) S_0-like bend-guided wave at 300 kHz; excitation location indicated; colour coding shows relative displacement amplitude of propagation modes (blue: low to red: high).</i>	103
4.4	<i>Normalized wavenumber-frequency spectra in dB scale, derived from the 2D-FFT method: (a) SH_0-like bend-guided mode; (b) S_0-like bend-guided mode; in comparison with the SAFE predictions (dashed line) and experimental results (diamond marker).</i>	103
4.5	<i>(a) Photograph of experimental setup; CF/EP bend specimen positioned for the measurement of the S_0-like mode; shear transducer clamped at the top surface of the bent plate; (b) specimen position for testing the SH_0-like mode; shear transducer mounted at the bend end.</i>	105
4.6	<i>(a) Normalized amplitude of the in-plane displacement of the S_0-like bend-guided wave across the bend at 400 kHz; (b) and (c) time history of measured responses at the bend in point A and in the adjacent plate in point B.</i>	106
4.7	<i>(a) Normalized amplitude of the in-plane displacement of the SH_0-like bend-guided wave across the bend at 200 kHz; the amplitude variation of the SH_0 wave indicated; (b) and (c) time history of measured responses.</i>	107

4.8	(a) Power flow variation of the S_0 -like mode around the bend with varying fibre orientations; (b) normalized axial power flow extracted along the bend arc.	108
4.9	Phase velocities of the S_0 mode (solid) in the laminate and the longitudinal mode (dashed) in the separate bend region with respect to different fibre angles.	108
4.10	(a) and (b) Through-thickness displacement mode shapes of the longitudinal mode in separate bend region with 0° and 4° fibre directions; (c) and (d) displacement mode shapes of the S_0 mode in flat laminates with fibres orientated along 0° and 4° directions.	110
4.11	FWHM-frequency spectrum for the two bend-guided modes, calculated by the SAFE method.	111
5.1	Schematics of (a) the conventional technique used to inspect bends; (b) surface-adaptive ultrasound (SAUL) phased array inspection of composite laminated bends [152].	114
5.2	Schematic of the SAFE model of a quasi-isotropic CF/EP bent plate; global and local coordinates shown; absorbing region indicated.	116
5.3	(a) Mode shape illustration of the feature guided wave propagating along the bend, derived by the SAFE method at 300 kHz; colour coding shows relative amplitude of the axial power flow, normalized by the maximum value in the bend region; arrows present the particle displacement in the cross section; (b) variation of the amplitude of axial power flow extracted from the bend surface; and bend region (shaded) indicated; mode shapes of (c) displacement and (d) stress along the bend thickness.	118
5.4	SAFE predictions of (a) the FWHM of the feature guided mode at 300 kHz and (b) the spectrum of the FWHM from 50 to 400 kHz.	118

5.5	<i>SAFE predictions of (a) the phase velocity and (b) the attenuation dispersion curves of the identified feature guided mode.</i>	119
5.6	<i>(a) Snapshot of the bend-guided wave propagating in a quasi-isotropic CF/EP bent plate (size: 360 mm×300 mm×2.4 mm); the colour contour indicates the relative amplitude of resultant displacement of propagating modes at 300 kHz (blue: low to red: high); (b) schematic of the mesh distribution zoomed around the bend region; excitation along the through-thickness nodes and an example local coordinate system indicated; (c) cross-sectional view of the wave propagation cut along the plane at Z=150 mm.</i>	120
5.7	<i>(a) Photograph of the experimental setup with the illustration of laser beams and reference coordinates; (b) reflective film attached to the bend surface, parallel and perpendicular to the propagation path; (c) shear transducer coupled at the plate end.</i>	122
5.8	<i>Normalized amplitude of the in-plane motion of the SH_B mode over the bend region at 300 kHz, obtained from the 3D FE simulation (solid) and the experiment (asterisk).</i>	123
5.9	<i>Phase velocity dispersion curves derived from the SAFE calculation (solid), the 3D FE simulation (diamonds) and the experiment (circles).</i>	123
5.10	<i>Typical time traces of the in-plane motion (u_x) measured along the central axis of the delaminated bent plate: (a) 3D FE results; (b) experimental results; the location of monitors indicated.</i>	125
5.11	<i>Energy contained by temporal signals measured along the propagation path at 300 kHz: (a) 3D FE result; (b) experimental result; defect area indicated by grey band</i>	126

5.12	<i>(a) Cross-sectional illustration of the part-thickness transverse crack introduced to the composite bent plate; (b) time responses of the bend-guided waves scattering by the transverse crack, monitored at 60 mm and 150 mm away from the source.</i>	128
5.13	<i>Typical time traces of the in-plane motion (u_x) measured along the cracked bent plate: (a) 100 mm from the source; (b) 150 mm from the source.</i>	128
5.14	<i>Reflection coefficient spectra for the transverse crack, derived from the 3D FE simulation (solid) and the experiment (asterisk).</i>	129
5.15	<i>Reflection coefficient spectra for the transverse crack with varying depths, derived from the 3D FE simulation.</i>	130
6.1	<i>Schematic of the SAFE model of a stiffened CF/EP plate, with adhesive bond line and perfectly matched layers shown (not to scale). . . .</i>	135
6.2	<i>(a) Phase velocity and (b) attenuation dispersion curves of guided modes propagating in the 1.6 mm thick base plate with different layups (along 0° fibre direction), derived from the SAFE calculation of the laminates.</i>	135
6.3	<i>Mode shape illustration of typical feature guided waves propagating along the stiffener, calculated by the SAFE method: (a) $L(1)$ mode at 150 kHz; (b) $SH(3)$ mode at 100 kHz; (c) $F(1)$ mode at 150 kHz; colour coding for each mode indicates the relative amplitude of axial power flow (blue: low to red: high).</i>	137

6.4	<i>Potential feature guided waves sensitive to adhesive defects: (a) SH(3) mode at 100 kHz; (b) SH(4) mode at 160 kHz; (c) L(2) mode at 150 kHz; (d) L(1) mode at 150 kHz; colour coding shows the relative amplitude of axial power flow (blue: low to red: high); cutline (dashed) running through assembled components indicated; the stiffener-adhesive interface (dash-dot line) shown.</i>	139
6.5	<i>Variation of the amplitude of the out-of-plane power flow for the shortlisted FGW modes: (a) P_{x_1} along the cutline running through the assembled components, normalized by the corresponding maximum magnitude of P_{x_1} for each feature guided mode; (b) P_{x_1} along the stiffener-adhesive interface, normalized by the corresponding maximum amplitude of P_{x_3}.</i>	140
6.6	<i>Phase velocity (a) and attenuation (b) of identified feature guided wave modes propagating along the stiffened CF/EP plate, calculated by the SAFE method from 50 to 200 kHz.</i>	142
6.7	<i>Schematic of the 3D FE model of a CF/EP plate (size: 800 mm×800 mm×1.6 mm) with an aluminium T-shaped stiffener and the adhesive bond; shear excitation at the plate end, monitors and absorbing regions (width: 120 mm) shown; colour coding indicates the relative amplitude of resultant displacement of propagating modes at 100 kHz (blue: low to red: high).</i>	143
6.8	<i>Normalized wavenumber-frequency spectra in dB scale, derived from the two-dimensional Fourier transform (2D-FFT) method: (a) forcing in the x_3 direction at 150 kHz; (b) forcing in the x_1 direction at 150 kHz; (c) forcing in the x_2 direction at 150 kHz; (d) forcing in the x_2 direction at 100 kHz.</i>	144

6.9	<i>FE results of time snapshots of (a) the shear horizontal feature guide mode propagation along the stiffener excited at 100 kHz, (b) diffracted waves by the full-width adhesive defect (length: 22.75 mm; 450 mm from the source); and (d) reflected shear mode by the defect.</i>	146
6.10	<i>Normalized wavenumber-frequency spectra (in dB scale) for both the incidence and reflection of the SH(3) mode.</i>	147
6.11	<i>Shear mode reflection coefficient spectra for (a) full-width and half-width adhesive defects (L: 22.75 mm; T: 0.75 mm); (b) full-width adhesive defects with varied lengths (T: 0.75 mm); (c) full-width adhesive defects with different bond thicknesses (L: 0.8λ).</i>	148
6.12	<i>(a) Phase velocity and (b) attenuation dispersion curves for the SH type FGW modes existing in the assembly with varying bond thicknesses.</i>	149
6.13	<i>Variation of the amplitude of normalized out-of-plane power flow of the SH(3) mode for different bond thicknesses: (a) P_{x_1} along the cut-line running through the assembled components; (b) P_{x_1} along the stiffener-adhesive interface.</i>	150
6.14	<i>(a) Photograph of experimental setup; monitoring line, illustration of laser beam and reference coordinates depicted; (b) two shear transducers coupled at the end of the stiffener; contact positions indicated; (c) distribution of the normalized in-plane displacement (u_2) of the SH(3) mode over the stiffener region, derived from the SAFE calculation at 100 kHz; the positive and negative signs indicate the shear motion in opposite directions.</i>	151
6.15	<i>Typical experimental time traces measured along the base of the stiffener.</i>	152

6.16	(a) Experimentally measured phase velocity dispersion curves in comparison with the SAFE predictions; both forward and backward running waves shown; (b) wave structures (deformation) of the SH(1) and the SH(2) modes over the cross section, calculated from the SAFE model at 100 kHz; arrows indicate the dominant vibration motion. . .	154
6.17	Measured reflection coefficient spectrum for the full-width adhesive defect (length: 0.8λ), compared with the FE result.	155
6.18	Energy contained by temporal signals picked up along the propagation path (on the top surface of stiffener base): (a) experimental results; (b) FE results; defect area indicated by grey band.	156
7.1	Illustration of the FGW based SHM scheme in the 3D FE simulation (plate size: $800\text{ mm} \times 800\text{ mm} \times 1.6\text{ mm}$); diffracted waves from the adhesive defect, shear excitation at the stiffener end, and the configuration of monitors shown.	163
7.2	Orthogonal displacement components extracted from a particular monitoring point $((x_2, x_3) = (300, 600)\text{ mm})$, marked with a star in Fig. 7.1) in FE simulations; both the reference and diffraction signals shown. .	164
7.3	(a) Arrangement of a slanted monitoring line along the 38° direction with respect to the stiffener axis to measure the diffraction from the adhesive defect; (b) normalized wavenumber-frequency spectra (in dB scale) of the diffracted wave field, in comparison with SAFE predictions (dashed lines).	165
7.4	(a) Energy velocity and (b) attenuation of the SH type feature guided modes, calculated by the SAFE method from 50 to 200 kHz; frequencies of interest indicated by the grey band.	166
7.5	Illustration of the principle of the synthetic focusing approach by using the diffraction of feature guided waves propagating along the bond line.	168

7.6	<i>Illustration of the complex-valued signal amplitude (envelope) contributed to the intensity of separate damaged and undamaged pixels.</i>	168
7.7	<i>Imaging results obtained from the FE data (in dB scale): (a) the complete image of the bond line ($x_2 : 390 \sim 410$ mm, $x_3 : 0 \sim 800$ mm), with the geometry of the base plate (size: 800 mm$\times$800 mm) as well as the configuration of receivers (red circles) depicted; (b) image zoomed around the damage indication; the actual contour of the adhesive defect ($x_2 : 390 \sim 410$ mm, $x_3 : 450 \sim 473$ mm) indicated by the red dashed rectangle; (c) image intensity extracted along the central bond line axis $x_2 = 400$ mm.</i>	170
7.8	<i>Comparison between the image intensity derived from processes without baseline subtraction (solid) and with baseline subtraction (dashed-dotted).</i>	171
7.9	<i>(a) Photograph of experimental setup; transmitters coupled at the end of the stiffener and PZT sensors pasted on the surface of the composite panel (dimensions: 500 mm$\times$900 mm$\times$1.6 mm) shown; (b) illustration of the adhesive disbond location, the spacing between PZT elements, and the used reference coordinates for the SHM scheme.</i>	173
7.10	<i>Typical time traces measured by PZT sensors on either side of the stiffener; the SH_0 wave and diffracted waves as well as edge reflections labelled.</i>	174
7.11	<i>Experimental imaging results derived from data sets by both sensor arrays: (a) complete image of the bond line, with geometry of the actual composite panel (size: 500 mm$\times$900 mm) and locations of PZT elements depicted; (b) image zoomed around damage indications; the actual contour of the disbond area ($x_2 : 240 \sim 260$ mm, $x_3 : 308 \sim 332$ mm) indicated by the red dashed rectangle; (c) intensity of image pixels extracted along the central axis of the feature $x_2=250$ mm.</i>	175

7.12	<i>FE imaging results of the adhesive defect with varying lengths: (a) 2λ, (b) 0.2λ, (c) 0.5λ, and (d) 0.2λ; the contour of the defined disbond area depicted by red dot lines.</i>	176
7.13	<i>Synthetically focused imaging of the adhesive defect with different widths in 3D FE simulations: (a) full width and (b) half width; the contour of the created disbond area indicated by red dashed lines. . . .</i>	177
7.14	<i>Normalized intensity of the pixel along the central axis of the bond line, derived from the FE imaging with different densities of sensors; damage area indicated by the grey band.</i>	178
7.15	<i>Illustration of the bend-guided wave SHM scheme in the 3D FE simulation at 300 kHz; diffracted waves from the axial crack, shear excitation at the bend end, and the configuration of monitors shown. . . .</i>	180
7.16	<i>Imaging results obtained from FE data: (a) complete image of the bend area ($x_2 : -0.006 \sim 0.006$ m, $x_3 : 0 \sim 0.3$ m); the geometry of the unrolled bent plate (size: 0.3 m$\times$$0.3$ m) and the configuration of receivers (marked by red circles) depicted; (b) image zoomed around the damage indication; the actual location of the axial crack ($x_3 : 0.20 \sim 0.21$ m) indicated by the white solid line; (c) image intensity extracted along the bend axis $x_2 = 0$ m.</i>	181

List of Tables

4.1	Characterized elastic constants (in GPa) for the CF/EP composites used in the present study.	98
4.2	Rotation angles of the stiffness matrix about the global axes.	99
5.1	Properties (in GPa) of the composites used in the present study; the mass density is 1540 kg/m ³ ; the ply thickness is 0.15 mm.	116
6.1	Density, thickness, and viscoelastic properties (in GPa) of the materials used in the present study.	136

Chapter 1

Introduction

1.1 Motivation

Fibre reinforced polymer composites are increasingly utilized in high-performance structural applications in aerospace, energy, naval, and automotive industries, because of their high specific strength and stiffness, lightweight, inherent corrosion resistance, and low electromagnetic reflectance [1]. As evident from Fig. 1.1, in recent decades, a significantly increasing fraction of composite components have been incorporated into commercial airplanes. They have replaced the traditionally applied metallic materials, serving in both primary and secondary structures, such as the fuselage, wings, the tail section, and fuel tanks, in order to reduce fuel consumption. For instance, the Boeing 787 Dreamliner is composed of 50% composite by weight (80% composite by volume), excluding the engines, and the new-generation Airbus A350 XWB is also made primarily of composite materials, approximately 53% by weight. However, considering sustainability, some industry observers have raised concerns about the state of science underpinning the rapid expansion in the use of composites in commercial aircrafts and the preparedness of authorities for this transition [2], such as the Federal Aviation Administration (FAA) in the United States and the European Aviation Safety Agency (EASA) in the European Union.

The major reason for such concerns is that composite laminates are susceptible

Figure 1.1: Increase of composite components in commercial airplane models over time, indicated by percentage of the total aircraft weight [2].

to various types of defects, subjected to mechanical loads and/or environmental exposure (e.g. moisture, temperature) [3] during the in-service use. These defects can be at a lamina-scale (i.e. matrix cracking, fibre-matrix debonding, fibre breakage), laminate-scale (i.e. interlaminar delamination), or structural-scale (i.e. extensive component damage) [4]. The initiation and propagation of defects can severely degrade mechanical properties of the composite materials and compromise the structural integrity. In addition, composite laminated components are sensitive to impacts [5], and severe impact damage can be hidden deep in the subsurface laminae with very limited surface indentation - known as *barely-visible impact damage* [6], thus making them more difficult to detect than that occurred in metallic materials.

In a recent technical report [2] issued by the US Government Accountability Office, these aviation safety-related concerns have been identified and categorized into four key areas: (1) limited information on the behaviour of composite airframe structures, (2) technical concerns related to the unique properties of composite materials, (3) limited standardization of composite materials and repair techniques, and (4) level of training and awareness in using composite materials. Specifically, as inferred

from item (1), reliable damage behaviour predictions are difficult to attain, due to the limited amount of in-service performance data of aircraft composites and their ageing process. Also, technical issues mentioned in item (2) and (3) mainly include challenges in detecting and characterizing damage in composite structures, as well as in offering adequate composite repairs (e.g. scarf patches) [7]. In this regard, with immature design rules [8], manufacturing processes and joining technologies, in comparison to metallic materials, the safety and efficiency of composite aircrafts will largely rely on structural maintenance and repair [9, 10].

Recently, owing to advances in manufacturing techniques, the use of fibre reinforced composites has been extended from plate-like structures (e.g. fuselage and wing skins) to critical reinforcing components having complex shapes, such as spars, ribs, and stiffeners [11]. A representative assembly of an airplane wing containing these components is presented in Fig. 1.2(a). Skins are supported longitudinally by spars and transversely by ribs, and the bonded stiffeners/stringers are used to increase the structural stiffness as well as to enhance the stability of skins [12]. Noteworthy, according to the airworthiness certification specifications [13] issued by the EASA, spars, ribs, and the bonded skin-stringer combination have been identified as the *Principal Structural Elements (PSE)* which contribute significantly to carrying flight, ground, and pressurization loads, and their failure could result in catastrophic failure of the entire airplane. Therefore, the performance of these composite structures with complex shapes is crucial to the safe operation of airplanes, and they are thus vital elements to be inspected during the life cycle.

Composite laminated bends, also named as *L-shaped composite laminates*, usually act as fundamental structural features to compose complex geometries. For example, the typical cross section of wing spars is in ‘C’ or ‘Z’ shape, as shown in Fig. 1.2(b), comprising of two 90° structural bends. Also, serving as the primary load carrying members, spars with rectangular cross section are extensively used in the wind turbine blades, as shown in Fig. 1.3, which can be degraded into four L-shaped composite bent plates. In addition, adhesive bonding is frequently encountered in aircraft composite structures as the joining technique to combine skins

Figure 1.2: Illustration of (a) an aircraft wing assembly composed of skins, spars, ribs, and stringers; (b) C-shaped and Z-shaped wing spars consisting of two composite bent plates; the adhesive bonding between the spar and skins shown.

Figure 1.3: Schematic of (a) wind turbine blades; (b) structural configuration of a blade consisting of a rectangular shaped spar and skins.

and reinforcing elements (see Fig. 1.2(b)) or the lightweight layer of core material (e.g. honeycomb, foam). Adhesively bonded joints are increasing alternatives to conventional mechanical fasteners due to their lower structural weight, improved damage tolerance, and design flexibility [14]. In the aerospace industry, the structural integrity of laminated bends and adhesive composite joints will significantly affect the performance of PSEs and ultimately the reliability of the whole system. Considering the associated scientific value as well, they have been chosen as the representative structures investigated in this thesis.

Evidences have been provided to account for the vulnerability of the curvature or junction region of composite structures [15–17]. These complex-shaped laminates are usually manufactured by stacking prepreg materials (i.e. unidirectional fibres with pre-impregnated resin) at desired fibre orientations on a rigid lay-up tool of the required geometry, and vacuum bagging techniques and autoclave curing are subsequently applied to the assembly. It has been reported that such manufacturing is a sensitive process, where the cure cycle, curvature radius, ply orientation, bagging configuration, and resin system can directly affect the quality of final composite products, in terms of thickness variation, void content, radius tolerance, straightness of plies, and homogeneity of resin [18–21]. Some manufacturing defects such as resin richness, fibre wrinkling, and porosity can be caused during this stage [22,23], consequently creating risks for the structure’s in-service use.

Figure 1.4: Strain field distributions in a symmetrically loaded L-shaped composite beam under the non-failed state: (a) radial strain ε_r , (b) hoop strain ε_ϕ , (c) cylindrical shear strain $\gamma_{r\phi}$, and (d) principal deformation; (e) failed composite specimen with indications of the first failure and subsequent delaminations occurred in the bend region due to continued loading [15].

Furthermore, subjected to cyclic loading [12] during the structure’s service life, stress

concentration can be induced in the curvature region, thus making it prone to multiple types of defects. An experimental investigation [15] has been performed on an L-shaped woven fabric composite beam under quasi-static tensile loading, and the through-thickness strain fields in the curved region were measured optically, as shown in Fig. 1.4(a)~(d). Pronounced strain concentrations can be observed in the bend region, based on which the strong local stress concentration and strain rate dependent strength were characterized. Subsequent experimental results at elevated loading velocities show that the first failure always occurs perpendicular to the radius direction as a delamination, as presented in Fig. 1.4 (e). Delamination is the interfacial failure between two plies and is normally caused by normal or shear tractions acting on the interface. Such damage can substantially reduce the structural stiffness and the load carrying capacity, and has hence been identified as one of the most critical failure modes in L-shaped composite laminates [24].

Also, delamination emergence and its growth in a cross-ply L-shaped laminate made of unidirectional carbon fibre/epoxy plies were predicted computationally and tested experimentally [25]. As shown in Fig. 1.5 (a), the curved zone is the critically loaded area of the L-shaped laminate subjected to quasi-static loading, where the initial damage is supposed to form; and delamination has been predicted as the dominant failure mode in the investigated laminate. Fig. 1.5 (b) then shows the non-linear structural response caused by the delamination process. It can be seen that the pristine structure is loaded and the delamination emergence load is reached at point 1. Keeping the applied displacement constant, the critical initial delamination occurs, resulting in the reduction of both the structural stiffness and the reaction force, namely the state at point 2. Maintaining the displacement load, the structure enters into unstable delamination growth stage, which is accompanied by dynamic effects, leading to a rapid increase in the delaminated area. Following that (point 3), the delamination growth becomes stable, and the increasing displacement load causes further delamination growth. The predicted process of damage propagation has been validated experimentally, as indicated by Fig. 1.5(c). Knowing the mechanism of delamination growth, it can be confirmed that such damage has to be detected timely in composite laminated bends in case it turns into catastrophic failure.

Figure 1.5: (a) Illustration of the loading and boundary conditions applied to an L-shaped laminate; its predicted failure mode shown; (b) predicted delamination process in the L-shaped laminate; (c) comparison between the measured and predicted structural response for intact laminates [25].

Figure 1.6: (a) Photograph of the experimental setup and the unidirectional carbon fibre/epoxy thin-curved laminate; damaged specimens with 2 mm laminate thickness but varying inner bend radius: (b) $r_i = 10$ mm, (c) $r_i = 15$ mm, and (d) $r_i = 20$ mm [26].

In addition, it has been reported that the fracture patterns of thin-curved composite beams under tensile loads are strongly related to the curvature geometry (i.e. bend radius and laminate thickness) [26]. The curved laminates with smaller thickness or larger bend radius tend to show compressive fracture on the curved surface, whereas the laminates with larger thickness or smaller bend radius have a tendency to induce interlaminar fracture (i.e. delamination) in the bend region, as shown in Fig. 1.6. This provides a *priori* knowledge about the types of defects occurring in composite laminated bends and offers guidance to their inspection.

As mentioned above, another motivation of the thesis is related to the inspection of adhesively bonded joints in composite structures. In the aerospace industry, adhesive bonding is the common join process to fix skins to reinforcing members, such as spars and stiffeners, since it can provide uniform stresses (i.e. low stress concentration) across the bond line, increased joint strength, and good sealing performance. Also, compared to mechanical fastenings and welding, such bonding allows complex shapes and dissimilar materials to be joined with ease, and smoother external surfaces are attained. However, the adhesive bonds are susceptible to failure where the composite structures are under fatigue loading [27,28] and exposed to variation in temperature and/or humidity [14,29] during the in-service use. This can lead to crack formation, reduced interfacial strength, and even more severe deterioration of the entire structure [4]. Thus, there is also considerable interest in assessing the bond quality in the assembly of composite structures [30–36].

Among available non-destructive testing (NDT) techniques to inspect composites, ultrasonic testing methods have been the most applied, because they are easy to implement, and have high penetration depth as well as good sensitivity to small defects [4,37–40]. The conventional bulk wave ultrasonic testing may be carried out either with a single transducer in pulse-echo mode or with two transducers in through-transmission mode. Both cases usually necessitate couplant (e.g. gel or water) between the transducer(s) and the structure because of the severe impedance mismatch between air and solid materials, although some air-coupled techniques can be used [41,42]. For damage detection in composite structures with complex

shapes, the normal practice is to use ultrasonic C-scan to implement a point-by-point local inspection, by manually scanning the probe combined with the bespoke curved wedges and gel coupling over the whole region of interest. This technique is therefore time consuming and tedious for the inspection of long-range structural features, and it becomes challenging or even infeasible when limited access to the tested structure is provided.

Under such circumstance, ultrasonic guided wave testing can be an effective alternative for the inspection of composite laminates [43–52], since it potentially allows for rapid screening of large areas with a fixed transducer position and remote inspection of structures with difficult access. In recent years, one particular branch of guided waves confined to local structural variation, i.e. feature guided waves (FGW), have attracted considerable interest and been studied extensively in the literature. The investigation of FGWs started from guided waves in welded joints. The existence of a compressional ‘weld-guided’ mode was first experimentally revealed in a welded steel plate [53,54]. As shown in Fig. 1.7, the launched weld-guided mode can propagate along the weld direction, with wave energy strongly concentrated in the weld region, rather than decay as quickly as it would in a regular plate structure. Also, some leaky waves are radiated in the adjacent plate, indicating the loss of wave energy during the propagation of such FGW mode (i.e. partially-trapped mode). A shear type weld-guided mode [55] was subsequently discovered to be attractive for quick screening of long-range welds due to its non-leaky and almost non-dispersive characteristics (i.e. perfectly-trapped mode). Similar FGW modes have also been reported to exist in a wide range of geometries, such as lap joints, the interconnected heat exchanger tube plate [56], bonded stiffeners [57], and structural bends [58,59]. Such feature guiding phenomenon can be very promising to the NDT of long-range topographical features on plate-like structures, as it potentially allows guided waves confined to the feature area to propagate long distances and to particularly interrogate such features rather than the entire structure.

The investigation on feature guided waves has, to date, been primarily focused on isotropic topographical features. Whereas there is little research on composite

Figure 1.7: *Schematic of a compressional feature guided wave propagating in a welded plate; a pulse-like excitation indicated; propagation of other wave modes in adjacent plates shown [56].*

structural features, in which both the geometric variation and anisotropic material properties will impact on the guided wave propagation, thus adding complexity to the FGW based inspection of these structures. Therefore, there is a clear need for comprehensive understanding of the feature guiding phenomenon that possibly exists in laminated composites, towards real-world NDT/SHM applications.

1.2 Thesis Objectives

One of the objectives of this thesis is to develop FGW based screening tools for rapid inspection of defects occurring in or around composite structural features. As discussed in the introduction above, two typical aerospace composite structures are investigated, including composite laminated bends and the stiffener-adhesive-composite skin assembly. Modal studies of these waveguides are essential, in order to understand propagation characteristics of existing guided modes and to select proper mode-frequency combination for inspection. Also, time-domain simulations are required to investigate the FGW scattering by different defects. Both studies

will necessitate powerful numerical tools, so that the work presented in this thesis also aims to develop generic tools to deal with guided mode problems in waveguides involving both arbitrary geometry and anisotropic constitution. All the numerical predictions need to be validated with experimental measurements.

Another objective of the thesis is to propose a novel FGW based structural health monitoring (SHM) strategy for composite features, concerned specifically with the detection of unexpected localized damage that may occur in or around the feature area. In contrast to conventional guided wave SHM schemes, the structural features are no longer regarded as interference but special ‘local waveguides’, and proper FGWs with strong energy confinement will be exploited for rapid condition screening of the feature area. This technique will be combined with an imaging algorithm to reconstruct the localized damage. The proposed SHM strategy potentially offers enhanced interrogation of the feature area, which can be implemented in conjunction with the conventional guided wave SHM system to yield richer information about the health state of the entire structure.

1.3 Thesis Outline

The thesis investigates feature guided wave based NDT/SHM techniques for composite structures with complex shapes. Chapter 2 reviews the guided wave propagation in complex waveguides, in term of anisotropic nature and geometric variation. Chapters 3, 4, and 5 are dedicated to the investigation of FGWs in bend structures with isotropic and anisotropic properties. Chapters 6 and 7 demonstrate the exploitation of FGWs in composite adhesive joints for NDT and SHM applications. Specifically, the thesis is structured as follows.

Chapter 2 first introduces the fundamentals of guided waves in isotropic media. Since these are well documented in classical textbooks, the explanation will be restricted to the characteristics that are frequently used to describe FGW propagation. The anisotropic effects on guided wave propagation are demonstrated in an example carbon fibre/epoxy (CF/EP) laminate with a unidirectional layup. This part of work

is original, and such material is subsequently used to manufacture bend structures in the following chapters. Then the concept of feature guided waves is reviewed, in light of physics underlying the energy trapping effect. The SAFE approach is outlined, to predict existing guided modes and their properties in waveguides with arbitrary cross section. The calculation of Poynting vector and energy velocity is also illustrated, as essential parameters associated with the study of FGWs.

Chapter 3 presents a comprehensive study of the properties of FGWs in an isotropic metal plate bend, by using the SAFE method, the 3D FE simulation, and the experiment. A shear horizontal bend-guided (SH_B) mode is identified to be attractive for the long-range screening due to its strong mode confinement in the bend region as well as little-dispersive and low-attenuative characteristics. The defect scattering using such FGW mode is also investigated. This work is important for a series of FGW investigations in composite structural features.

Chapter 4 examines the extension of feature guided phenomena in the isotropic plate bend to the case of anisotropic laminated bends comprising aligned unidirectional fibres. Both the S_0 -like and the SH_0 -like FGW modes are investigated by the developed SAFE approach and the 3D FE simulation, in both of which the spatially-varying anisotropy is implemented. The existence of discovered FGW modes is validated experimentally. The influence of the fibre orientation on energy trapping effect of FGWs is also studied, shedding light on the exploration of feature guiding phenomena owed to both geometric variation and anisotropy.

Chapter 5 investigates the further extension of FGWs in the isotropic plate bend and the unidirectional anisotropic plate bend cases to the case of multi-layered quasi-isotropic (QI) composite bends, which are more commonly used in engineering applications. The SH_B mode is identified with strong energy concentration, and is thus exploited for interaction with different defects occurring in the bend region, including interlaminar delamination and transverse cracks. The defect scattering is quantitatively studied by examining the spatial variation of FGW energy along the bend and its reflection behaviour.

Chapter 6 launches the investigation of FGWs in another representative composite feature, i.e. the stiffener-adhesive-composite skin assembly. Multiple potential FGW modes are identified in such structure, and criteria are suggested to select proper modes that are sensitive to adhesive defects. Likewise, both the wave energy variation and reflection coefficient of the selected FGW mode are investigated numerically and experimentally, for identifying adhesive defects between the stiffener and the composite panel. Parametric studies are also carried out in 3D FE simulations by varying the defect size and the bond thickness to understand the influence on the reflection behaviour of the mode.

Chapter 7 starts another phase of FGW studies in composite structures by proposing a novel FGW based SHM strategy. The approach is illustrated based on the two typical structures investigated in the thesis, with emphasis on explaining its implementation in monitoring adhesive composite joints. It is first rigorously tested in the 3D FE simulation by applying the synthetic focusing technique, and is subsequently validated by the experimental measurement. Indications of the prescribed adhesive defect can be clearly captured in both reconstructed images of the bond line, showing the potential of defect sizing and characterization. From the viewpoint of robustness, the performance of the imaging algorithm is also evaluated by varying the defect size and the sensor density in the FE models. The proposed SHM approach is also used to detect an axial crack in the QI composite bend (studied in Chapter 5), and the damage location can also be identified, so that the universality of such strategy has been verified.

Chapter 8 summarizes the findings of the thesis and suggests the potential areas for future work.

Chapter 2

Ultrasonic Guided Waves in Complex Structures: A Review

2.1 Background

Ultrasonic guided waves have been proven to be attractive for the large area inspection due to their capability of long distance propagation, through-thickness penetration, and remote inspection of structures with difficult access. Today guided waves are applied across a wide range of problems where they provide improved non-destructive testing and process control capabilities [60–65]. In recent years, one particular branch of guided waves confined to structural variation, i.e. feature guided waves (FGW), have received considerable research interest and have been discussed in the literature extensively.

Prior to being able to exploit FGWs for the inspection of composite structures with complex shapes, it is essential to thoroughly understand two major complications: effects of geometric complexity and anisotropic material properties on the propagation of guided waves. To achieve this, the chapter first introduces the fundamentals of guided waves in isotropic bounded media, including dispersion curves, mode shapes, and attenuation. Then, some unique characteristics of guided waves propagating in anisotropic media are illustrated, such as directional dependence of wave

speed and steering effect. Following that, the state-of-the-art knowledge of guided waves confined to structural features is reviewed, in light of physics underlying the energy trapping effect. To perform modal studies of complex waveguides involving both complications mentioned above, some powerful numerical tools are required. This chapter hence outlines the well-known Semi-Analytical Finite Element (SAFE) method, in which the modal solution extraction and representation of leaky guided waves are discussed.

2.2 Guided Waves in Isotropic Media

The propagation of bulk waves (either of compressional or shear nature) in an unbound elastic medium is dependent only on the material properties, and their velocity is constant with frequency. However, when elastic waves travel in bounded media such as in plate-like structures, they are repeatedly reflected at both surfaces, and the resulting wave field from their mutual interference is guided along the structure, as illustrated in Fig. 2.1. Thus guided waves can be regarded as a superposition of bulk wave components interacting at boundaries of the structure [66], leading to frequency-dependent characteristics. These wave motions can be categorized into families of wave modes according to their wave structures, which tend to be increasingly complex at higher frequencies. Moreover, the velocity of guided wave modes becomes a function of frequency, which can be characterized by dispersion curves.

Figure 2.1: *Schematic of a guided wave propagation in a free plate; internally reflecting bulk waves shown.*

2.2.1 Dispersion curves

Guided waves are generally dispersive, which means their phase or group velocity varies with frequency. The phase velocity (V_{ph}) of a guided wave denotes the rate at which individual crests of the wave move, and can be derived from the following relation:

$$V_{ph} = \frac{\omega}{k}, \quad (2.1)$$

where $\omega = 2\pi f$ is the angular frequency and k is the real wavenumber. The group velocity (V_{gr}) describes the propagating speed of a guided wave packet (or envelope) with components of similar frequencies, and its quantity can be calculated as

$$V_{gr} = \frac{\partial \omega}{\partial k}. \quad (2.2)$$

Guided waves in isotropic free plates are classified into three types of modes according to the wave structure. The Lamb waves [67] with deformation shapes symmetric and anti-symmetric about the mid-plane $y = 0$ of the plate are characterized as symmetric and anti-symmetric modes, symbolized by S_i and A_i ($i = 0, 1, 2, \dots$) modes, respectively. The wave field of S_i modes is dominated by the radial in-plane displacement of particles, which is parallel to the direction of propagation, and they are often denoted as ‘compressional’ modes, showing thickness bulging and contracting. Whereas A_i modes predominantly have the out-of-plane displacement and are described as ‘flexural’ modes due to the through-thickness flexing behaviour. In addition to the Lamb wave modes, there also exists another set of wave motions [68] known as shear horizontal (SH) modes, where particles vibrate in the x - z plane only, perpendicular to the wave propagation direction. Likewise, SH_i ($i = 0, 1, 2, \dots$) modes are either symmetric or anti-symmetric, depending on the order of the mode.

Typical dispersion curves of guided modes in a steel plate were calculated by DISPERSE software [69] and are presented in Fig. 2.2, showing the variation of phase and group velocities of these three wave mode families with respect to frequency. Each family comprises an infinite number of modes, and they are numbered according to their sequence to appear in the dispersion curves from low to high frequency.

The SH_0 mode is completely non-dispersive in the investigated range of frequency-thickness products, whereas all the other guided modes, i.e. S_i modes, A_i modes, and higher order SH modes, have different extents of dispersion at different frequencies.

Figure 2.2: The (a) phase velocity and (b) group velocity dispersion curves for different guide modes (S_i mode: red; A_i mode: blue; SH_i : green) propagating in a steel plate in vacuum.

The dispersion curves can be used to predict how much dispersion will occur to a given wave packet. Any excited wave of a finite time period would have a certain frequency bandwidth, which depends on the number of cycles in the wave packet, as well as on the shape of the packet. Each frequency component in the wave packet may travel at a different group velocity. If the difference of velocities over the frequency range of interest is large, different frequency components arrive at different times, which will result in the distortion of the shape of a wave packet as it propagates. By contrast, if the group velocities are very close over the generated frequency range, the wave packet will maintain a similar shape throughout its entire propagation.

In order to illustrate such dispersion effect, the example signals of S_0 mode and SH_0 mode in a steel plate after propagating 200 mm were simulated by DISPERSE as well, and the results are compared in Fig. 2.3. The excitation is a 5-cycle Hanning windowed toneburst signal centred at 1.5 MHz, where the S_0 mode is highly

Figure 2.3: *Diagrams of (a) 5-cycle Hanning windowed toneburst signal centred at 1.5 MHz as excitation; (b) S_0 wave and (c) SH_0 wave signals monitored on a 1 mm thick steel plate after 200 mm propagation distance.*

dispersive. The shape of the S_0 wave packet becomes distorted as it propagates, with decreasing amplitude and increasing wave packet duration. Whereas the SH_0 mode has no dispersion such that its wave packet remains the same shape as the excitation.

In practical long-range NDT/SHM applications, the favourable guided modes ought to be little-dispersive so that the detected signals will be simpler to interpret. If it is necessary to operate in a dispersive region, some compensation techniques [70,71] are required. On the other hand, the dispersive nature of guided waves can be utilized for dealing with some specific problems, such as evaluation of the quality of adhesive bonds [57,72], tomography of the localized corrosion [73], and analysis of prestressed waveguides [74].

2.2.2 Mode shapes

The mode shapes of guided modes are the distributions of wave field quantities (displacements, stresses, power flows etc.) over the cross section of the waveguide. The displacement mode shapes can not only be used to distinguish different wave mode families, but also to offer guidance for evaluating the excitability of a guided

mode [75].

Figure 2.4 shows through-thickness displacement mode shapes of three fundamental guided modes in 1 mm thick steel plate at 0.41 MHz. It can be seen that the wave field of the S_0 mode at this frequency is dominated by the in-plane displacement U_z , with small out-of-plane component U_y ; the A_0 mode is dominated by the out-of-plane displacement but has in-plane component U_z of comparable amplitude. There is no displacement U_x in the mode shape of both guided modes. By contrast, the SH_0 mode has in-plane motion U_x only, and propagates at the same velocity as the bulk shear wave. Noteworthily, the mode shape of a guided mode may vary with frequency. For instance, the S_0 mode exhibits simple extensional behaviour at very low frequency but its deformation shape changes gradually as the frequency increases. It ultimately acts like a pair of Rayleigh-type waves [76] propagating on the top and bottom surfaces of the plate, with energy and displacement concentrated in the outer portions of the plate.

Figure 2.4: Displacement mode shapes of (a) S_0 mode, (b) SH_0 mode, and (c) A_0 mode at 0.41 MHz-mm in a steel plate; (d) illustration of the reference coordinate system.

Also, the stress mode shapes are of importance in NDT applications, which give

a good indication of the likely sensitivity to defects at different positions through the plate or shell thickness [77], although the precise sensitivity may be determined either experimentally or by finite element simulations. Guided waves having significant stresses at certain depth will show good sensitivity to defects that occur at that position [78–80]. The corresponding stress mode shapes are shown in Fig. 2.5. It can be observed that the S_0 mode is characterized by its dominant stress component σ_{zz} along the propagation direction, and the SH_0 mode is dominated by the shear stress σ_{xz} . The A_0 mode has two significant stress components, namely out-of-plane shear stress σ_{yz} and axial stress σ_{zz} , and the different sign of σ_{zz} represents the compression or tensile stress resulted from the bending motion.

Figure 2.5: Stress mode shapes of (a) S_0 mode, (b) SH_0 mode, and (c) A_0 mode at 0.41 MHz-mm in a steel plate.

2.2.3 Attenuation

The attenuation describes the amplitude decay of guided waves during their propagation. In a perfectly elastic system in vacuum, the attenuation is always zero. In this section, the attenuating waves are modelled for two kinds of scenarios (which may exist together): (1) structures with damping material properties (defined by the viscoelasticity) such that the energy of the waves is absorbed as they propagate; (2) structures which are immersed in a fluid or embedded in a solid so that the wave energy radiates (leaks) into the surrounding medium. Both types of attenuation can be described by an exponential reduction with the propagation distance, which can be expressed by a complex wavenumber (usually in unit of nepers per meter,

Np/m):

$$\mathbf{k} = \mathbf{k}' + I\mathbf{k}'', I = \sqrt{-1}, \quad (2.3)$$

where the real part of the wavenumber $k' = 2\pi/\lambda$ (λ being the wavelength), corresponds to the propagation of the wave, and the imaginary part of the wavenumber, k'' , describes the attenuation of the wave in space. A general form of the wave equation in terms of displacement u can thus be written as

$$u = Ae^{I(\mathbf{k} \cdot \mathbf{x} - \omega t)} = Ae^{I\mathbf{k}' \cdot \mathbf{x} - \omega t} e^{-\mathbf{k}'' \cdot \mathbf{x}}, \quad (2.4)$$

where these two exponential terms denote the harmonic propagation and the amplitude decay of the wave along the x axis, respectively. An attenuation of κ nepers per meter means that a wave of unit amplitude is reduced to an amplitude of $e^{-\kappa}$ after travelling one meter. In practice, attenuation shown in unit of decibels (dB) per meter is also commonly used, and they are simply related: $1 \text{ Np/m} = 20 \log_{10} e \text{ dB/m} \approx 8.686 \text{ dB/m}$.

Specifically, in composite materials such as carbon or glass fibre reinforced epoxy laminates, the matrix phase is mainly responsible for the viscous damping that causes the absorption of the wave energy. Such viscoelasticity can be expressed by using a complex stiffness tensor:

$$\mathbf{C}_{ijkl}^* = \mathbf{C}_{ijkl}' - I\mathbf{C}_{ijkl}'', I = \sqrt{-1}, \quad (2.5)$$

where $\mathbf{C}_{ijkl}'$ corresponds to the energy storage, and $\mathbf{C}_{ijkl}''$ corresponds to the damping resulted from the material viscosity. Two well-established models, namely the hysteretic model and the Kelvin-Voigt model can be used to account for the damped waveguide. The hysteretic model [81] assumes that $\mathbf{C}_{ijkl}''$ term is independent of frequency, so that Eq. (2.5) can be rewritten using the loss, η_{ijkl} , as

$$\mathbf{C}_{ijkl}^* = \mathbf{C}_{ijkl}' - I\eta_{ijkl}. \quad (2.6)$$

Whereas the Kelvin-Voigt model [82] assumes a linear dependence of $\mathbf{C}_{ijkl}''$ on the frequency, thus the complex stiffness tensor at a generic frequency f can be given

as

$$\mathbf{C}_{ijkl}^* = \mathbf{C}_{ijkl}' - I \frac{f}{f_0} \eta_{ijkl}, \quad (2.7)$$

where the viscosity tensor η_{ijkl} is measured at a reference frequency f_0 (i.e. the characterization frequency). The attenuation of bulk waves is commonly modelled as proportional to the frequency times the imaginary part of the stiffness tensor $\mathbf{C}_{ijkl}''$ [83,84]. According to Eqs. (2.6) and (2.7), the attenuation is thus a quadratic function of frequency in the case of the Kelvin-Voigt model, but a linear function of frequency in the case of the hysteretic model. It is evident that both models give the same prediction of attenuation at the characterization frequency f_0 , while the Kelvin-Voigt model provides a smaller attenuation than the hysteretic model when $f < f_0$ and implies a much larger attenuation when $f > f_0$. Similar differences have also been obtained for the attenuation of Lamb waves in lossy anisotropic plates [85]. In composite NDE literature, the hysteretic model has proven to be more frequently used [81,85].

Another mechanism for attenuation is that in an immersed or embedded waveguide the energy of guided waves may be transmitted across the interface and leaks into the surrounding liquid or solid medium [86–88]. Such leakage is schematically shown in Fig. 2.6. It can be seen that a guided wave propagating along the waveguide attenuates as it couples energy into the surrounding medium, creating bulk waves that carry energy away from the system. The leakage angle, θ_{leak} , can be determined by the Snell's law [83]:

$$\theta_{leak} = \sin^{-1}\left(\frac{V_m}{V_{ph}}\right), \quad (2.8)$$

where V_m is the bulk velocity of the surrounding medium, and V_{ph} denotes the phase velocity of the guided wave. According to Eq. (2.8), the leakage angle becomes imaginary if the phase velocity is smaller than the bulk velocity of the surrounding medium. This means that instead of creating a wave that propagates away from the waveguide, the displacements die away exponentially and the energy is thus trapped in the waveguide [88]. Therefore, the guided mode will not leak if its phase

velocity is less than the bulk velocity of any waves that can exist in the surrounding medium, hence terms *non-leaky* mode (whose attenuation is zero if the waveguide is also undamped).

Figure 2.6: *Illustration of a guided mode travelling in a leaky waveguide, which leaks bulk waves at a characteristic angle; wavelengths in different domains shown.*

2.3 Guided Waves in Anisotropic Media

The propagation of elastic waves in anisotropic media such as composite laminates is also governed by the Christoffel equation [83], in a similar manner to that in isotropic media, but exhibits much more complicated characteristics due to the anisotropic nature [89–92]. From the viewpoint of lamina micromechanics, the fibre reinforced composite material comprises continuous fibres embedded in a resin system, so that the mechanical properties of the reinforcement (i.e. fibres), matrix (i.e. resin) and reinforcement-matrix interface contribute to the composite properties and failure mechanisms [93]. Among these material phases, the fibre system is mainly responsible for the anisotropic behaviour of composites. With variation in the fibre orientation, the mechanical properties (e.g. elastic moduli) of the laminates can be tailored to be high in the directions that are expected to withstand heavy loads while remaining the moduli considerably lower in other directions, which offers higher stiffness to weight ratio and greater design freedom compared to metallic materials. Such directional dependence of material properties of fibre reinforced

composites classifies them as anisotropic media.

Guided wave propagation in these composite laminates is complex. Multiple modes usually exist, and their dispersion behaviour is critically influenced by anisotropic properties of each lamina and also by the stacking sequence of the laminate [91, 94, 95]. Moreover, such anisotropy introduces many unique wave phenomena (to be detailed in this section) such as directional dependence of wave velocity, steering effect, mode coupling, and multiple phase directions corresponding to an energy direction [85, 96]. In addition, attenuation of guided waves in composites is much higher than that in most metallic materials [97], which is mainly resulted from viscosity of the resin system and inherent scattering loss, and the attenuation is both frequency and mode shape dependent [85]. Therefore, a clear understanding of the anisotropic propagation of guided waves is of primary importance for the full exploitation of their inspection potential in composite structures.

2.3.1 Directional dependence of wave velocity

The unidirectional fibre reinforced composite constitutes a degenerate case of the general anisotropic system (characterized by 21 independent elastic constants) and is often referred to as transversely-isotropic (determined by 5 independent elastic constants). This means that its material properties are identical along all the directions perpendicular to the fibre orientation. This section discusses guided wave propagation in a unidirectional laminate composed of 14 parallel plies of T700/340 carbon fibre/epoxy (CF/EP) laminae (stacking thickness: 2.28 mm), which are also used to manufacture composite bend structures in the subsequent chapters.

The continuous fibre reinforced laminate can be assumed to be elastic (undamped) and homogeneous in the low frequency range [98, 99]. The homogeneity assumption suffices as the wavelength of the guided waves in the material is much larger than the size of fibres (5~15 microns in diameter for carbon and glass fibres). In the reference coordinates shown in Fig. 2.7(a), the fibres lie parallel to the x_3 direction, and the x_1 direction is normal to the mid-plane of the laminate. Noteworthily,

the unidirectional laminated plate exhibits strong in-plane anisotropy (in the x_2 - x_3 plane), so that it was chosen as an example to study the directional-dependent propagation of guided waves.

Figure 2.7: (a) Reference coordinates for the unidirectional fibre reinforced laminate; wave propagation angle with respect to fibre orientation labelled; (b) dispersion curves of guided modes propagating along the fibre direction.

Figure 2.7(b) shows the phase velocity dispersion curves (derived by the DISPERSE) for guided wave modes propagating along the fibre direction (i.e. $\theta = 0^\circ$). Hereby the relatively low frequency range from 100 to 500 kHz was selected for demonstration. In practical NDT/SHM applications it may be preferred to operate at frequencies below the higher order cut-off frequency where only fundamental guided modes exist. Also, in viscoelastic media, the attenuation of guided waves is frequency dependent, and its magnitude is normally low in such frequency range [85].

For propagation in the principal directions, parallel and normal to the fibres, the Lamb type modes and the SH type modes are de-coupled [82] and behave similarly to the equivalent modes in regular isotropic materials, as indicated in Fig. 2.7(b). However, due to anisotropy the wave propagation in non-principal directions is no longer this case. The Lamb type and SH type modes are effectively coupled [82, 85, 99], and their wave structures have displacement components in all three orthogonal directions, which makes it impossible to excite a pure S_0 or SH_0 mode along non-

principal directions in anisotropic plates [96]. Therefore, guided wave propagation characteristics in such laminates are directionally dependent.

Figure 2.8: Anisotropic propagation of fundamental guided modes in laminates: (a) slowness curves at 300 kHz; (b), (c) and (d) three-dimensional dispersion surfaces of the S_0 mode, the SH_0 mode, and the A_0 mode.

To illustrate this, the phase *slowness surface* (the reciprocal of velocity, $1/V_{ph}(\theta)$) of fundamental Lamb modes (the symmetric mode S_0 and the anti-symmetric mode A_0) and the SH_0 mode with respect to propagation angles were calculated by the SAFE approach (shown later in this chapter) at 300 kHz, and the results are presented in Fig. 2.8(a). It can be seen that the velocity of each mode changes with the propagation direction, and the shape of slowness surfaces varies with modes. As the propagation angle with respect to the fibre axis increases, the phase velocity of both S_0 and A_0 modes decreases, while the SH_0 mode exhibits more complicated variation in phase velocity. Such directional dependence of wave velocity can also be characterized by the *angular dispersion*. Fig. 2.8(b), (c) and (d) show the three-dimensional dispersion surface of the guided modes, which summarizes dispersion curves of the mode at all propagation angles. It can be seen from Fig. 2.8(b) and

(d) that the phase velocity of the A_0 mode is less affected by anisotropy than the S_0 mode, showing a slower decrease in the velocity with the increasing propagation angle. This trend is consistent with the observations reported in the literature [91, 94]. This may be due to that the predominant out-of-plane displacement of the A_0 mode is perpendicular to the plane that exhibits strong anisotropy while the predominant in-plane motion of the S_0 mode is parallel to such anisotropic plane, so that its wave propagation characteristics are less dependent on the anisotropic material properties. As indicated in Fig. 2.8(c), the SH_0 mode is non-dispersive in the 0° and 90° directions, but has different degrees of dispersion at other angles.

2.3.2 Steering effect

Besides the angular dispersion, another unique propagation phenomenon caused by the anisotropy of composites is the steering effect, which leads to the difference between the energy and phase velocity directions. As shown in Fig. 2.9(a), at a fixed phase direction θ , the energy velocity (i.e. group velocity in lossless media) vector is normal to the phase slowness curve [83], and the angle formed by the energy and phase velocity vectors is called the *steering angle*.

In isotropic materials, these two velocity vectors are in the same direction. Fig. 2.9(b) shows their relationship for fundamental guided wave modes at 300 kHz in the investigated unidirectional CF/EP laminate. It can be seen that the direction of energy transport of the modes coincides with the wave front (phase front) only in 0° and 90° directions, where there is no occurrence of the steering effect. However, at other phase directions, the steering angle can be large. For instance, as for the S_0 mode propagating in the 60° phase direction, its wave energy travels approximately along the 5° direction. This leads to a energy focusing phenomenon, where the wave energy of the guided mode is strongly focused in the vicinity of the fibre orientation. It also occurs for the A_0 mode at the investigated frequency, but with much smaller steering angles, which may be due to that the dominant particle motion of the A_0 mode is perpendicular to the fibres, so that its energy transport is less influenced by the anisotropy.

Figure 2.9: (a) Geometric relation between the phase and energy velocity vectors (arbitrary magnitudes); steering angle ϕ denoted; fibres lie in the direction $\theta = 0^\circ$; (b) difference between energy and phase velocity directions for the fundamental guided modes in the unidirectional laminate at 300 kHz; results were calculated by the SAFE method (shown later in this chapter).

Therefore, for guided wave NDT/SHM applications in composite structures, it is essential to know the steering angle for determining the energy transport direction from the excitation at a chosen phase direction, which is also the propagation direction of the wave packet. In addition, as indicated in Fig. 2.9(b), the same energy velocity direction of the SH_0 mode may correspond to three phase front directions. This means that multiple wave packets can propagate in the same energy direction (i.e. the observation direction), despite the fact that they have different phase directions and velocities, which will significantly complicate the received signals and create obstacles in its practical employment [85, 96].

In Section 2.3, the example of guided wave propagation in the unidirectional laminate was used to demonstrate the anisotropic effects. In most engineering applications, the fibre reinforced composites are fabricated by stacking the unidirectional laminae according to specific layups. The cross-ply and quasi-isotropic laminates are commonly used, with the stacking sequence of $[0/90]_{ns}$ and $[0/45/90/-45]_{ns}$ respectively, where the subscript 's' indicates the symmetric fibre orientation of laminates about the mid-plane, and the index 'n' denotes the repeat times of the group

of plies. Such laminates of orthotropic symmetry offer an improved torsional and transverse rigidity as compared to that with parallel unidirectional layup, at the expense of some loss in longitudinal stiffness.

The mode shapes of guided waves in these multi-directional laminated composites are quite different from those of the equivalent modes in isotropic media or in unidirectional composites, and sharp gradients [94] in particle displacements and stresses can often be seen through the thickness, which are caused by abrupt changes in the stiffness of adjacent layers. This situation will become less prominent as the number of layers and their angular variation increase, and the laminate behaviour approaches that of an isotropic plate [91, 99]. It has been reported that the guided wave propagation becomes almost independent of the direction in quasi-isotropic laminates, especially at low frequencies [82, 94, 95, 100]. Such directional independence is significant for studying guided waves in composite structures later in the thesis. Also, the scattering characteristics of guided waves in cross-ply and quasi-isotropic laminates have been widely investigated in the literature [50, 78, 101–106].

2.4 Guided Waves Confined to Structural Features

2.4.1 Concept of the feature guided wave (FGW)

Besides anisotropic effects, the local geometric variation also impacts on the guided wave propagation, leading to the discovery of a special type of guided wave confined to the structural features. This section first reviews the background and the state-of-the-art for feature guided wave studies, and then explains the physics underlying the energy trapping effect by an example of the weld-guided wave. Following that, a numerical tool - the SAFE approach is outlined, which is capable of dealing with waveguide problems involving arbitrary cross section and anisotropic properties.

Guided wave testing has been proven to be an attractive detection mechanism

that combines a reasonable sensitivity to damage with the significant propagation range [100, 107]. There is already an established NDT industry exploiting guided waves for the long-range inspection of pipelines [61, 108, 109] and rails [62, 64, 110], both of which can be regarded as one-dimensional structures along which the energy of the guided wave propagates. However, in two dimensional plate-like structures such as pressure vessels, storage tanks and an aircraft fuselage, guided waves can propagate in an infinite number of directions from a single transducer position. Furthermore, even without material damping, the energy of the guided wave decays with the propagation distance from the source due to the effect of beam spreading, thus the inspection over a large area becomes difficult. Another challenge for inspecting the plate-like structures used in industry is that benign features such as welds, bends, and stiffeners are often encountered, which will cause additional coherent noise in the received signals. When the feature density is high, the associated signals will merge together to obscure the scattered waves from damage [107].

Figure 2.10: *Illustration of the trapped guided mode due to the difference of wave velocities in the feature and in the adjacent plate [56].*

Instead of seeing the features as a problem in damage detection, they can act as special ‘local’ waveguides for the transport of guided wave energy. When elastic waves travel in the topographical feature on a plate-like structure, they alternately

interact with the irregularly shaped boundaries, and such complex interference may result in the wave field highly confined to the feature area. The investigation of such feature guided waves (FGW) started from an experimental observation of guided waves in welds [53, 54], and the existence of a compressional ‘weld-guided’ mode was revealed. The mode can propagate firmly along the weld joint with energy concentrated in the vicinity of the weld, rather than decay as quickly as it would in a flat plate. Subsequently a shear type weld-guided mode [55] was identified to be attractive for quick screening of long welds due to its non-leaky and almost non-dispersive characteristics. The physics for such energy trapping effect can be explained by the total internal reflection of the propagating waves in the feature. As schematically illustrated in Fig. 2.10, this is caused by the slower phase velocities of the guided modes in the feature than the corresponding modes in the adjacent plate and is enhanced by the similarity of their mode shapes in the separate regions.

Figure 2.11: *Mode shapes of four fundamental guided modes that exist in the weld at 100 kHz: (a) longitudinal mode, (b) torsional mode, (c) flexural mode 1, and (d) flexural mode 2; arrows represent the particle displacement in the cross section [55].*

FGWs can exist in various structures. Hereby the welded joint was used as an example for further demonstrating the energy trapping effect. Fan and Lowe [55]

calculated the mode shapes and dispersion curves of the guided modes in the separate steel weld and in the adjacent 6-mm thick steel plate. Four fundamental propagation modes were identified in the weld, and their cross-sectional displacement mode shapes are shown in Fig. 2.11. By comparing with the mode shapes of fundamental modes in the plate, it has been found that in the weld the longitudinal mode and flexural modes 1 and 2 possess similar mode shapes to the S_0 , SH_0 and A_0 plate modes respectively, while the torsional mode does not have any corresponding modes in the plate.

Figure 2.12: Dispersion curves of the fundamental guided modes in the steel weld and in the 6-mm thick steel plate [55].

The phase velocity dispersion curves of the four guided modes in the weld are shown in Fig. 2.12, in comparison with the dispersion curves of the fundamental plate modes. It can be seen that the phase velocities of the longitudinal mode and flexural mode 1 in the weld are slower than the corresponding S_0 and SH_0 mode, respectively. According to the Snell's law [83], when a wave encounters an interface between two media with different propagation velocities, the wave will be constrained in the medium with slower phase velocity and can retain the energy to propagate only along the interface. Therefore, when joining different domains, the energy of the guided modes propagating along the weld, of either compressional or shear nature, will be trapped in and around the weld. On the other hand, the phase velocity of

the flexural mode 2 is greater than its corresponding A_0 mode in the plate so that it cannot be trapped. It is also worth noting that the resulting propagation velocity along the waveguide (i.e. the weld joint) is somewhere between the phase velocity in the weld and that in the plate, which is less than the velocity of corresponding plate modes.

The FGW phenomenon can be very promising for quick inspection of defects in or around long-range features integrated in a plate-like structure, as it potentially allows guided waves retaining most of its energy in the features to propagate long distances and also to particularly interrogate such features rather than the entire structure. For instance, the scattering of weld guided modes by defects located around the weld was studied in Ref. [111], and their capabilities to inspect different types of defects such as cracks and flat-bottom holes have been well demonstrated. In the context of this study, although it may be difficult to apply the weld-guided mode to size the defect, it has been used as an attractive screening tool to efficiently localize the defect. Similar FGWs were also identified in bonded stiffeners, showing the potential to evaluate the shear modulus of the adhesive bond [57]. The feature guiding phenomena have also been reported to exist in a wide range of geometries, such as the lap joint, the interconnected heat exchanger tube plate [56], structural bends [58,59], as well as in the eccentric and elliptical annular cylinders [112,113].

2.4.2 Semi-Analytical Finite Element (SAFE) method

Guided wave based inspection is complicated because of its multi-modal and dispersive nature, and thus it is essential to perform modal studies of the waveguides to understand the properties of existing guided modes such as dispersion curves, mode shapes and attenuation to choose proper modes and frequencies for the inspection. For waveguides defined by simple geometry such as flat plates and cylinder structures, analytical solutions could be obtained to predict the properties of guided waves, while for waveguides with irregular cross section analytical solutions are often difficult to obtain. This requires to implement numerical approaches such as the well-known Semi-Analytical Finite Element (SAFE) method, which is also called

the spectral element or strip element method. The SAFE method was first demonstrated in the 1970s [114, 115], and has since gained its popularity to study guided waves in irregularly shaped waveguides such as railway lines [116–119], beams [120], stiffened plates [121], and even damped or leaky waveguides with arbitrary cross section [122–124].

This approach solves an eigenvalue problem of a solid with constant cross section to obtain wavenumbers of modes propagating along the waveguide at the chosen frequency. In the SAFE modelling, only the discretization of the cross section is required, and the harmonic behaviour is imposed along the waveguide, thus reducing a 3D problem to a 2D one (but still having three displacement components). Also, the method uses analytical description instead of the polynomial approximation for the displacement along the waveguide, therefore it can be applied to predict waves with very small wavelengths, where a traditional 3D approximation may fail [82, 122].

Figure 2.13: *Two-dimensional model for a solid waveguide embedded in infinite medium with the absorbing region or perfectly matched layer (PML) shown.*

Considering a wave propagating in a solid waveguide with constant cross section (that is to say a cross section that does not vary in the wave propagation direction), as shown in Fig. 2.13, the displacement vector in the waveguide can be given by

$$u_i(x_1, x_2, x_3, t) = U_i(x_1, x_2)e^{I(kx_3 - \omega t)}, I = \sqrt{-1}, \quad (2.9)$$

where k denotes the complex wavenumber; $\omega = 2\pi f$ is the angular frequency; t is the time variable; and the subscript $i = 1, 2, 3$ denotes the coordinate index. The waves are assumed to propagate harmonically along the x_3 direction. For general anisotropic materials, the equation of dynamic equilibrium associated with the elastic behaviour law is given by:

$$\sum_{j,k,l=1}^3 \left[C_{ikjl} \frac{\partial^2 u_j}{\partial x_k \partial x_l} \right] + \rho \omega^2 u_i = 0; i = 1, 2, 3, \quad (2.10)$$

where C_{ikjl} are the components of the stiffness tensor, and ρ is the mass density. Substituting Eq. (2.9) into Eq. (2.10), this differential equation of motion regarding an eigenvalue problem can be written as:

$$C_{ikjl} \frac{\partial^2 U_j}{\partial x_k \partial x_l} + I(C_{i3jk} + C_{ikj3}) \frac{\partial(kU_j)}{\partial x_k} - kC_{i3j3}(kU_j) + \rho \omega^2 \delta_{ij} U_j = 0, \quad (2.11)$$

with summation over the indices $j = 1, 2, 3$ and $k, l = 1, 2$; δ_{sr} is the Kronecker delta (when $s = r$, $\delta_{sr} = 1$; otherwise $\delta_{sr} = 0$). The equation can then be solved for the eigen-wavenumber k using a commercial FE package [125], and the input formalism for eigenvalue problems is as follows:

$$\nabla \cdot (c \nabla \tilde{U} + \alpha \tilde{U} - \gamma) - \beta \nabla \tilde{U} - a \tilde{U} + \lambda d_a \tilde{U} - \lambda^2 e_a \tilde{U} = 0, \quad (2.12)$$

in which all matrix coefficients can be complex valued, which is essential for viscoelastic materials; and $\tilde{U} = (U_1, U_2, U_3, V_1, V_2, V_3)$ represents the set of variables to be determined, with $V_i = kU_j$. Full implementation details for this method were given by Predoi *et al.* [126].

In order to describe the infinite exterior domain in the SAFE model, an absorbing region or perfectly matched layer (PML) of finite length is modelled all around the surrounding medium to absorb waves, as shown in Fig. 2.13. Both techniques are widely applied due to their robustness of performance in dealing with a variety of angles of incidence and kinds of waves [123].

The absorbing region [123, 127] is rendered increasingly viscoelastic as the distance from the region of interest increases, while it has the same mass density and elastic

properties as the medium of interest which it surrounds. The material damping, i.e. the imaginary parts of its elastic moduli, gradually increases according to the following law:

$$C_{ija} = C'_{ij} [1 + I\alpha (\frac{r - r_a}{L_a})^3] + IC''_{ij}, I = \sqrt{-1}, \quad (2.13)$$

where C_{ija} is the resulting viscoelastic moduli of the absorbing region; C'_{ij} denotes the stiffness of the medium surrounding the waveguide; C''_{ij} represents the viscoelasticity of the material itself; r_a is inner radius of the absorbing region from the centre of the waveguide; L_a is its radial length; r denotes the radial position in the region ($r > r_a$); and α is used to define the proportion, relative to stiffness, of the viscoelasticity at the outer limit of the absorbing region. This coefficient has to be optimized [128] such that reflections from the outer boundary of the absorbing region are negligible, while avoiding too brutal changes in the acoustic impedance between the surrounding medium and the absorbing region which would cause backscatter itself. Typically, for reliable absorption in the SAFE modelling, the length of the absorbing region should be equal to two to three times the longest wavelength of any radiated wave in the whole frequency range; α can take values between 4 and 1 for low and high frequencies.

An alternative approach accounting for leaky guided modes is to introduce the Perfectly Matched Layer (PML) in the SAFE model [129, 130], whose impedance perfectly matches with that of the surrounding medium so that almost all propagating waves of non-tangential angles of incidence and non-zero frequencies can be absorbed. This is achieved by analytically extending real coordinates of physical equations into the complex ones, and the original wave propagation eigenfunctions in an infinite medium can thus be mapped to exponentially decaying eigenfunctions in the model with PMLs of finite length [131]. Compared to absorbing region, the size of PMLs is expected to be significantly reduced, making it more computational efficient. It is worth noting that the existing research works on PMLs are mainly based on specific finite element codes without open access. In order to get rid of the expense of maintaining a homegrown source code, the SAFE-PML method has been

implemented in the same commercially available finite element package (COMSOL) as described before. This is joint work with another PhD candidate from the NDT group at NTU, and I have made contributions to the code development and model verification. The detailed implementation of such coupled SAFE-PML method has been reported in a journal article [132].

The nature of SAFE solution is to find the eigenwavenumber k (see Eq. (2.3)) for the chosen angular frequency ω . The real part k' describes the harmonic wave propagation. With the absorbing region or the PML attached to the domain of interest, radiating waves are no longer reflected from the exterior of the model, and the eigensolutions can hence include the guided modes which attenuate due to the radiation, leaking either bulk waves or guided waves into the surrounding medium. In such cases, the imaginary part of the solved eigenwavenumber presents the attenuation of the selected mode. Furthermore, in the context of the construction of dispersion curves, each solution containing multiple wavenumbers reveals all possible propagation modes at a chosen frequency, and the full spectrum of dispersion curve, including the phase/group/energy velocity and the attenuation can be obtained by repeating the eigenvalue solutions over the frequency range of interest.

In the modal study of complex waveguides, two important parameters associated with guided wave energy will be discussed in the following part, namely the Poynting vector and energy velocity. The Poynting's Theorem [133] is originated from the electromagnetism, in which the energy conservation relation is formulated based on Maxwell's equations. It interrelates the power supplied by sources of the waves, the power lost through dissipation mechanisms, the rate of change of energy stored in the wave fields, and the power flow in the waves. Using the electromagnetic-acoustic analogy, Auld derived an acoustic Poynting vector [83] that represents the power flow density of acoustic waves in solids. The Poynting vector is not only useful for investigating guided wave energy, but also plays a critical role in studies of guided wave field normalization and guided wave excitability, as well as skew angle determination for anisotropic waveguides [82].

The complex Poynting vector can be calculated from the particle velocity and stress

fields based on the following equation:

$$\mathbf{P} = -\frac{\mathbf{v}^* \cdot \boldsymbol{\sigma}}{2}, \quad (2.14)$$

where $\mathbf{v}^*$ denotes the conjugate of particle velocity vector and $\boldsymbol{\sigma}$ is the classical 3×3 stress tensor. Through the SAFE calculation, its quantity of the mode can be obtained at each nodal position over the cross section of the waveguide at all three orthogonal directions, thus achieving the cross-sectional distribution of power flow density of the guided mode at particular frequencies. Moreover, the integral of $\mathbf{P}_{\mathbf{x}_3}$ (the component in the wave propagation direction) over the cross section yields the power flow carried by the guided mode in the propagation direction.

Another important concept associated with guided wave energy is the energy velocity. In elastic waveguide, the group velocity defined by Eq. (2.2) also describes the speed of guided wave energy transport. Such definition is no longer valid in damped waveguides, either in viscoelastic or leaky system, although it is usually reasonably accurate if the attenuation is small. If the attenuation is large, the differentiation made with respect to the real part of the complex wavenumber would result in physically impossible solutions, such as infinite velocities at some locations of the dispersion curves. The energy velocity, V_e , is the appropriate property of guided modes in damped media [134], and it can be calculated based on the power flow in the wave propagation direction and the energy density of the wave field [83]:

$$V_e = \frac{\int_{\Omega} \mathbf{P} \cdot \hat{\mathbf{x}}_3 d\Omega}{\frac{1}{T} \int_T \left(\int_{\Omega} e_{tot} d\Omega \right) dt}, \quad (2.15)$$

where Ω represents the domain of interest; $\hat{\mathbf{x}}_3$ is the unit vector along the wave propagation direction; $\frac{1}{T} \int_T (.) dt = \langle (.) \rangle$ denotes the time average over one period T ; $\mathbf{P}$ is the time-average Poynting vector (real part only), which can be obtained by Eq. (2.14); and e_{tot} represents the total energy density in the system (kinetic and potential). The time-average energy for the kinetic component, $\langle e_k \rangle_t$, and the potential components, $\langle e_p \rangle_t$, can be quantified following the formulation in Ref. [85]:

$$\langle e_k \rangle_t = \frac{\omega^2}{4} \rho \mathbf{u}^T \mathbf{u}, \quad (2.16)$$

$$\langle e_p \rangle_t = \frac{1}{4} \boldsymbol{\varepsilon}^T C' \boldsymbol{\varepsilon}, \quad (2.17)$$

where C' is the elastic stiffness tensor (see Eq. (2.5)); the constant $1/4$ results from the time integration over the period T . Eq. (2.16) and (2.17) can be evaluated once the element nodal displacements (i.e. eigenvectors) are calculated from the eigenvalue problem (i.e. Eq. (2.11)), based on which the stress and strain fields are reconstructed.

2.5 Summary

In this chapter, the characteristics of guided waves in isotropic media have been introduced. In practice, the guided modes having little dispersion and low attenuation are preferred for inspection, since they are capable of propagating long distances in the structure and the shape of the wave packet remains almost unchanged as they propagate. Also, the displacement and stress mode shapes of fundamental plate modes were examined, which can be used to evaluate the mode excitability and their sensitivity to defects. The discussions in this part have provided a guideline for investigating guided waves in complex structures.

Two complexities have been demonstrated in the chapter, namely the anisotropic and geometric effects on guided wave propagation. Anisotropy of composites usually leads to the directional dependent wave behaviour, possibly accompanying the steering effect, mode coupling, energy focusing, and other unique wave phenomena, which were illustrated by the example of guided wave propagation in a unidirectional laminate. The geometric complexity has been discussed with regard to the guided waves confined to topographical features on a plate-like structure, such as welds, bends, and stiffeners. The concept of the feature guided wave (FGW) was introduced, with emphasis on explaining the physics for the energy trapping effect in the context of the weld-guided mode. FGWs existing in other geometries were briefed as well. Proper FGW modes can be used as an attractive screening tool for the inspection of long-range features owing to their increased propagation distances and

enhanced interrogation of such feature areas, arising from the strong mode confinement. The demonstration in this chapter has laid a foundation for the FGW studies in the subsequent chapters.

The Semi-Analytical Finite Element (SAFE) method is a powerful numerical tool, which can deal with waveguide problems involving both arbitrary cross section and anisotropy. Its mathematics framework was outlined. Coupling the SAFE model with the absorbing region or PML technique, an infinite exterior medium can be modelled to get rid of reflections from radiating waves and thus to give proper representation of leaky guided modes. The Poynting vector and energy velocity, as important parameters in FGW studies, were formulated in this chapter as well. The SAFE approach will be further developed in the thesis for the modal study of composite structures with arbitrary geometry and anisotropic constitution.

Chapter 3

Feature Guided Waves in Isotropic Metal Bends

3.1 Background

In the following three chapters, the investigation of feature guided waves (FGW) in metallic bends, in composite bends with a unidirectional layup, and in quasi-isotropic laminated bends will be presented. The logic underlying this series of studies is that the geometric effect on guided wave propagation has to be thoroughly understood in the isotropic bend prior to involving anisotropic material properties in the waveguide, as these two complexities may be coupled together to affect the mode's energy trapping effect. Meanwhile, the composite laminated bends are studied for both the unidirectional and multi-directional layups, which exhibit the transversely-isotropic symmetry and the orthotropic symmetry, respectively.

This chapter explores the feasibility of using FGWs for rapid screening of 90° metallic transverse bends which are typical structures in the aerospace industry and wind turbine blades. The traditional approach to inspect such bends requires scanning a proper wedge transducer over the whole region of interest, which is time consuming and tedious. Ramdhas *et al.* [58, 59] reported that the plate bend can be potentially inspected by the A_0 -like and S_0 -like modes which are confined to the bend. However

these two modes are dispersive, and have relatively strong leakage, which limits their use in the long-range inspection. In the chapter, a new FGW mode with similar mode shape to the SH_0 mode in flat plates is identified. The mode is almost non-dispersive and has low attenuation, and its wave energy can be strongly concentrated in the bend region. Therefore, this mode retaining its energy at the feature can propagate much longer distance, which is more attractive for rapid screening of 90° transverse bends.

The chapter starts with a summary of methods to identify and understand guided waves that exist in the transverse bend and adjacent plates. Modal studies of the bent plate are carried out by using the Semi-Analytical Finite Element (SAFE) method, while both three-dimensional finite element (FE) modelling and experiment are performed to confirm the existence of the bend-guided mode and to cross validate its properties predicted by the SAFE method. Mode shapes and dispersion curves are investigated, and the energy concentration phenomenon as well as the leakage of the bend-guided mode are discussed. Following that, the physics behind the energy trapping effect is explained, and parametric studies are performed in order to understand influences of the frequency and the geometry on such energy concentration. The relation between the bend-guided wave and wedge acoustic waves is also discussed. Finally, interaction of the selected bend-guided mode with defects is demonstrated. The results presented in this chapters have been published [135,136].

3.2 Methodology

3.2.1 SAFE modelling

The first task in the study is to identify and understand the guided wave modes that exist in the bend and adjacent plates, thus requiring modal studies of irregularly shaped waveguides. The SAFE method was adopted for these studies, in which only the cross section of the waveguide needs to be meshed by finite elements while the waves are assumed to propagate harmonically along the waveguide. The details of

this approach have been demonstrated in Section 2.4.2.

Figure 3.1: Schematic of SAFE model of a bent plate with absorbing region shown (not to scale).

The schematic of the SAFE model is shown in Fig. 3.1, in which the bend radius R_B is 4 mm and thickness of bent plate is 2 mm. Quadratic triangular elements were used to mesh the entire model with finer element size in the bend region than that in adjacent plates. Stress-free boundary conditions were applied to boundaries enclosing the plate. The material used in the model is mild steel, with density $\rho = 7932 \text{ kg/m}^3$ and material elastic constants $C_{11} = 281.8 \text{ GPa}$ and $C_{66} = 84.3 \text{ GPa}$. When modelling the wave propagation along the bend, plate sides were extended by absorbing regions to avoid the interference by edge reflections. The absorbing region has the same mass density and elastic properties as the adjacent plate, but the viscoelasticity, i.e., the imaginary parts of their stiffness, gradually increases as the distance away from the bend increases, which can be expressed by rewriting Eq. (2.13) as

$$C_{ija} = C_{ij} [1 + I\alpha_1 (\frac{|x_1 - r_a|}{L_a})^3], I = \sqrt{-1}, \quad (3.1)$$

where C_{ija} represents the resulting viscoelastic moduli of the absorbing region; C_{ij} is the stiffness constant of the adjacent plate; r_a denotes the distance between the

central axis and the inner boundary of the absorbing region; L_a is its length projected on the x_1 direction; and α_1 is used to define the proportion, relative to stiffness, of the viscoelasticity at the outer limit of the absorbing region, which has been detailed in Section 2.4.2.

The SAFE method solves an eigenvalue problem to find the wavenumber k ($k = k' + Ik''$, $I = \sqrt{-1}$) along the waveguide at the chosen angular frequency ω . The real part k' describes the harmonic wave propagation while its imaginary part k'' presents the attenuation of the selected mode. The key issue when processing the eigenvalue results is to identify and to separate the guided wave solutions from unwanted eigenvalues representing resonances of the entire structure. Upon selecting the guided modes of interest, the phase/group velocity and attenuation dispersion curves can be traced by repeating the eigenvalue solutions over the investigated frequency range. Meanwhile, the displacement and stress mode shapes of guided modes can be extracted from the eigensolutions, characterizing their wave structures.

3.2.2 3D finite element simulation

In order to visualize the propagation of FGWs in the bent plate and also to validate their modal properties, three-dimensional FE models were created in a commercially available FE package [137]. For example, the illustration of the FE model used is shown in Fig. 3.2. The model was set up to represent the same geometry and properties as that used in the SAFE modelling.

The FE model was meshed by 8-node brick elements (C3D8R). The element size is selected such that it has at least 12 elements per wavelength of the bend-guided SH type mode [61]. The model was solved in the time domain at frequencies ranged from 200 to 1000 kHz. In order to optimize the computational resource, the bent plate was modelled with two different dimensions where both include Absorbing Layers using Increasing Damping (ALID) with length of at least three times the largest wavelength of all propagating modes [138, 139]. The model was excited by applying a time-varying force in the x_1 direction along all nodes of a through-thickness nodal

Figure 3.2: Schematic of 3D FE model of the bent plate; shear horizontal wave excitation location and absorbing region indicated; different wave modes labelled; colour coding shows relative amplitudes of propagating modes at 1 MHz excitation frequency (blue: low to red: high).

line at the plate end bisecting the bend region. The input force signal is a 5-cycle Hanning windowed tone burst centred at the required frequency. An iteration step time of $2\text{e-}8$ seconds was used in the simulation according to the stability criterion such that $\Delta t \leq 0.8\Delta x/c_{max}$ (Δx is the element size and c_{max} denotes the velocity of the wave that travels fastest through the material) [140,141].

Figure 3.2 presents an instant snapshot of the propagation of the bend-guided mode at the centre frequency of 1 MHz, with colour contours showing magnitudes of resultant displacement. It can be observed that the chosen wave mode is confined in the vicinity of the transverse bend, which is similar to the localization seen in the studies of weld-guided modes [55] and other bend-guided modes [58,59].

3.2.3 Experiment

Experiments were carried out on a steel plate of dimension $500\text{ mm} \times 600\text{ mm} \times 2\text{ mm}$ with a fillet radius of 4 mm, cold-bent symmetrically along the plate's central line at an angle of 90° . The photograph of the experimental setup including the bent plate specimen is shown in Fig. 3.3(a).

Figure 3.3: Photograph showing (a) a view of the experimental setup; (b) the PZT crystal bonded on the edge of the bent plate through a conductive sheet; (c) the sample bent plate with an attached reflective film.

A commercially available shear-polarized PZT crystal (Piezoceramic - dimensions: $10\text{ mm} \times 10\text{ mm} \times 1\text{ mm}$) was used for the wave generation, which was driven by a RITEC RPR 4000 pulser-receiver (Ritec Inc., USA). As shown in Fig. 3.3(b), the PZT crystal was bonded at the bend end with its polarization direction along the horizontal direction, which generated a 5-cycle Hanning windowed toneburst signal at 1 MHz. The signals were monitored using an in-plane laser vibrometer with dual differential fibre optic lines (Polytec OFV 552). A thin reflective film was attached to the top surface of the bent plate, as shown in Fig. 3.3(c), to enhance the optical backscattering of the laser beam. The two laser beams aligned at an angle of 60° were focused on the same spot, thus the difference between these two signals gives the amplitude of the in-plane displacement [56]. Therefore the laser vibrometer reads

in-plane displacements perpendicular to the direction of wave propagation and picks up SH type guided modes. The output from the laser controller was sent to a digital storage oscilloscope (Agilent DSO 7012B), which operates at a sampling rate of 2 GHz. The displacements were measured at different monitoring points along the bend direction and also across the bend region, in a similar manner to that in the FE simulation (see Fig. 3.2).

3.3 Properties of the Shear Horizontal Bend-guided (SH_B) Mode

3.3.1 Energy concentration

Potential feature guided wave modes can be identified by examining the time-average power flow (i.e. Poynting vector, demonstrated in Section 2.4.2) along the wave propagation direction, which can be quantified as

$$P_{x_3} = -Re[(\frac{I\omega}{2})(u_1^*\sigma_{31} + u_2^*\sigma_{32} + u_3^*\sigma_{33})], I = \sqrt{-1}, \quad (3.2)$$

where σ_{31} , σ_{32} and σ_{33} are components of the axial stress; u_1^* , u_2^* and u_3^* denote the complex conjugate of the horizontal, vertical, and axial displacements of the modes, respectively. Fig. 3.4(a) shows the variation of the axial power flow P_{x_3} along the outer boundary of the bent plate for different modes calculated at 1 MHz using the SAFE method. The quantities were normalized by the peak value in the bend region at each frequency.

The purpose of this study is to find eigenvalue solutions that represent guided wave modes propagating along the bend and possibly radiating energy into the adjacent plates, in a similar manner to the previous SAFE studies of leaky wave problems [55, 57, 123]. At each frequency, multiple eigen-wavenumbers k were obtained, including the wanted bend-guided modes with energy concentrated in the feature area (as an example shown in Fig. 3.4(a) by the solid line), as well as unwanted modes that

Figure 3.4: (a) Normalized axial power flow in bent plate, derived from the SAFE model at 1 MHz; bend-guided mode with energy concentrated in the vicinity of bend region (solid line), unwanted modes (dash-dotted lines); and bend region (shaded) indicated; (b) axial power flow illustration of the bend-guided SH type mode propagating along the bend; colour coding shows relative axial power flow (blue: low to red: high); and outer boundary of the bent plate (dashed line) indicated; (c) normalized axial component of power flow of the SH_B mode zoomed around the bend region.

represented resonances of the whole domain and had to be separated and discarded. At studied frequencies, the identified bend-guided waves have a mode shape similar to the fundamental shear horizontal mode (SH_0) in flat plates, which is dominated by the in-plane displacement. Hence the new FGW mode was defined as the bend-guided shear horizontal mode and was referred to as the SH_B mode. Fig. 3.4(b) visualizes the axial power flow in the cross section with colour coding denoting its relative amplitude, and Fig. 3.4(c) plots a zoomed part of the solid curve in Fig. 3.4(a). Both figures have demonstrated the strong energy concentration of the

SH_B mode around the bend region.

In order to validate the energy concentration phenomenon in the bend region, both 3D FE simulations and experiments were carried out. In the 3D FE model, the amplitude of displacement of the SH_B wave were obtained from all monitoring points along the surface of the plate that cross the bend region at a distance of 150 mm from the excitation, as shown in Fig. 3.2. It is worth noting that for the case of guided wave excited by an in-plane force, the mode amplitude for SH type waves is measured by the amplitude of in-plane surface displacement in the tangential direction [75]. Thus, the in-plane displacements in the bend region and adjacent plates were calculated using the following displacement transformation:

$$u_t = \begin{cases} |u_1 \sin\theta - u_2 \cos\theta|, & \text{in the bend region;} \\ \frac{\sqrt{2}}{2} |u_1 \pm u_2|, & \text{in adjacent plates,} \end{cases} \quad (3.3)$$

where θ is the angle between x_1 direction and line AO shown in Fig. 3.5; u_1 and u_2 are the measured horizontal and vertical displacements; and u_t represents the resultant in-plane displacement.

Figure 3.5: *Illustration of the in-plane displacement calculation.*

Figure 3.6 shows the amplitude variation in the in-plane displacement of the SH_B wave front around the bend region at 1 MHz, normalized by the peak amplitude

Figure 3.6: Plot of the normalized amplitude of the in-plane displacement of the SH_B mode, obtained from the SAFE method (solid), 3D FE simulations (squares) and experiment (dashed, circles) at 1 MHz.

in the bend region. It can be seen that the amplitude of displacement quickly decays as the distance away from the bent plate's central axis increases, indicating that the energy is highly focused in the bend region. There is a close agreement between the results obtained from the 3D FE simulation and the SAFE modelling. Experiments were designed to validate these predicted results. Since it may be difficult to accurately measure the in-plane displacement in the bend area by the method shown in Fig. 3.5, two positions of the bent plate were placed during the measurements. When picking up signals from monitors located at the central axis, the position shown in Fig. 3.3(a) was chosen. When measuring other monitoring points across the bend, the bent plate was kept in an 'L' position, as shown in Fig. 3.7. Two laser beams were focused on the same spot A located at the bend curve, which measures the horizontal displacement U_1 . However the actual in-plane displacement u_t is tangential to this spot on the bend curve, so that the measured amplitude at monitoring points (apart from the one at the central axis) were smaller than the actual values, which can be observed from Fig. 3.6. Nevertheless, the experimental result can still prove the finding of energy concentration in the bend

region, which is consistent with the modelling results.

Figure 3.7: *Illustration of the experimental configuration for measuring the in-plane displacement on the bend surface.*

3.3.2 Mode shapes

In order to understand the mode shape of the SH_B mode, the in-plane and out-of-plane displacements were obtained from the SAFE model at 1 MHz and are plotted in Fig. 3.8. The in-plane displacement is calculated by $u_{in-plane} = \sqrt{u_t^2 + u_3^2}$ (u_t is the tangential displacement calculated from u_1 and u_2 in the cross section according to Eq. (3.3); u_3 is the axial displacement perpendicular to the cross section), while the out-of-plane displacement is obtained normal to the bent plate. The arrow shown in Fig. 3.8(a) represents the particle displacement in the cross section with its length proportional to the magnitude of particle displacement. The colour coding shows the relative amplitude of axial power flow around the bend region.

To illustrate the mode shapes in the bend and in the adjacent plate, two typical through-thickness cutlines were selected, shown in Fig. 3.8(a). Cutline 1 bisects the bend while cutline 2 locates at the boundary between the bend region and the adjacent plate. The results shown in Fig. 3.8(b) and (c) were normalized by the maximum displacement value through the thickness. It can be observed that the

Figure 3.8: Mode shape of the SH_B mode, calculated from the SAFE model at 1MHz: (a) schematic of the modal structure and the axial power flow around the bend region; cutline 1 and cutline 2 (dashed lines) indicated; (b) displacement mode shape extracted along cutline 1; (c) displacement mode shape extracted along cutline 2.

in-plane motion dominates in the wave field of the propagation mode around the bend. Along the central axis of bend region (cutline 1), the in-plane displacement component increases from the inner towards the outer surface, while the out-of-plane displacement is negligible. Along the cutline 2, the in-plane displacement remains almost constant, and the small out-of-plane component suggests that the SH_B mode will leak the A_0 mode into adjacent plates although most of the energy is still concentrated in the bend region. Such leaky A_0 mode can also be observed in Fig. 3.2 as the wave spreading behind the SH_B wave.

3.3.3 Dispersion curves

To further investigate the properties of the SH_B mode, dispersion curves, showing the dependence of the group velocity and the attenuation with the frequency, were obtained from the SAFE method, 3D FE simulations and experiments. The results

are shown in Fig. 3.9 and Fig. 3.10, respectively.

Figure 3.9: Group velocity dispersion curves obtained from SAFE (solid, asterisks) and FE (squares) models as well as experiments (dashed, circles).

Group velocity dispersion curves for the SH_B mode are shown in Fig. 3.9. The bend-guided mode in the SAFE model was identified by examining if the axial power flow was concentrated in the bend region for each eigen-wavenumber at each frequency step. The group velocity of the SH_B mode is calculated as $V_{gr} = \partial\omega/\partial k'$ (k' is the real wavenumber). It is worth noting that the energy velocity should be the exact solution of the velocity of the wave packet, at which the wave carries its potential and kinetic energy along the structure [83, 134]. However, it is reasonably accurate if the attenuation is small and only the real part of the wavenumber is used for the calculation. Using the 3D FE approach, nine separate models were excited by the toneburst signal with its centre frequency ranged from 200 to 1000 kHz. In these models, the tangential displacements (along the x_1 direction, see Fig. 3.2 for illustration of coordinate axes) at the top surface of the bend with several distances away from the source were monitored. The same method as FE calculations was adopted in the experiment using commercially available shear-polarized PZTs for several frequencies. It can be seen that the mode is almost non-dispersive in the

studied frequency range. The results obtained by these methods agree well.

Figure 3.10: Attenuation dispersion curves derived through SAFE predications (solid, asterisks), 3D FE simulations (dotted, squares) and experiments (dashed, circles).

The attenuation as a function of frequency of the SH_B mode is plotted in Fig. 3.10. In the SAFE calculation, the imaginary part of the eigen-wavenumber k denotes the attenuation of the mode at the chosen frequency, and the result is depicted by the line with asterisks. It can be observed that the attenuation of the SH_B mode is relatively low and is even smaller at higher frequencies. Similar trend can be seen through all the results obtained with different methods. Decreasing attenuation at higher frequencies indicates that the energy radiation of the mode to adjacent plates is small, which makes the mode very attractive for screening bends over long distances.

The attenuation was also calculated from 3D FE simulations and experiments using the natural logarithm of the ratio of monitored displacement amplitude. Considering the energy conservation, the beam spreading effect can be compensated for a cylindrical wave by using the Hankel function which encapsulates the decay in amplitude with distance. Except in a region very close to the source, it can be approximated with high accuracy using a well-known factor that is inversely proportional to the

square root of the propagation distance r , namely $1/\sqrt{r}$ [75]. According to this, the measured amplitude of the displacement was multiplied by $\sqrt{r}$ to calculate the attenuation in both FE models and experiments, and the results are shown by square and circle markers separately in Fig. 3.10. It can be seen that results obtained with these methods are generally consistent with the SAFE predication but not in perfect agreement. One possible reason is that for the SH_B waves guided by the bend structure, the energy of the wave is concentrated in the bend, so that the wave is no longer circularly crested, and therefore the amplitude decay factor does not follow the form of $1/\sqrt{r}$ exactly. Another possibility is that more than one bend-guided modes are generated, and therefore the measurement of the amplitude of the SH_B mode may not be accurate if the propagation distance is not long enough to separate different modes.

3.3.4 Leakage of the bend-guided mode

To better understand the attenuation of the SH_B mode, its leakage should also be discussed. The guided waves propagating in the embedded waveguide attenuate due to the wave energy partially leaks into the surrounding media, which has been explained in Section 2.2.3. As to the propagation of the SH_B mode, although most of its energy is concentrated in the bend region, small energy radiation still exits. This can also be explained by the Snell-Descartes law [142] that the modes in the adjacent plate can be radiated if they have smaller phase velocities than that of guided modes confined in the structural feature. It can be seen from Fig. 3.11(a) that the phase velocity of the A_0 mode in a plate is slower than that of the SH_B mode, therefore the A_0 mode is the possible mode that can be leaked into the plate at the investigated frequencies. Fig. 3.11 (b) shows a schematic of the leaky waveguide from the top view of the bent plate (in a similar manner to Fig. 2.6), where the SH_B mode in the bend leaks the A_0 mode in the side plate at a radiation angle θ_{rad} , which can be determined by the Snell-Descartes as

$$\sin(\theta_{rad}) = \frac{V_{A_0}}{V_{SH_B}} = \frac{\lambda_{A_0}}{\lambda_{SH_B}}, \quad (3.4)$$

where V_{A_0} and V_{SH_B} denote the phase velocities of the A_0 mode and the SH_B mode, respectively; λ_{A_0} and λ_{SH_B} are their wavelengths. The SH_B mode is almost non-dispersive in the studied frequency range (V_{SH_B} is almost constant) while V_{A_0} increases with the frequency, thus the radiation angle increases with the frequency.

Figure 3.11: (a) Phase velocity of the SH_B mode in the bend and the A_0 mode in the flat plate; (b) schematic showing the leaky SH_B mode, which leaks the A_0 mode at an angle θ_{rad} .

From the results shown in this section, it can be summarized that the SH_B mode is dominated by the in-plane displacement with the energy strongly focusing in the bend region. This mode has little dispersion and low attenuation, limiting energy radiation to the adjacent plate.

3.4 Discussion on Feature Guiding Phenomena

3.4.1 Explanation of the energy trapping effect

The physics of the energy trapping effect has been demonstrated in Section 2.4.1. Two criteria have to be satisfied for the feature guided waves to exist: the guided modes in the feature, which in our case is the bend region, should have similar mode

shapes to the adjacent plate and their phase velocities should be slower. This can be explained by the Snell-Descartes law that when a wave encounters an interface between two media with different propagation velocities, the wave will be constrained in the medium with slower phase velocity and can retain the energy to propagate only along the interface.

To illustrate this, the mode shapes and phase velocities for the separate bend region (without extended plates) and the adjacent plate were calculated by the SAFE and analytical methods [69], respectively. Fig. 3.12(a) and (b) show the displacement field of the shear horizontal mode in the bend region and the SH_0 mode in a plate, respectively. It can be seen that these modes have a very similar wave field dominated by in-plane displacement to that of the SH_B mode. Fig. 3.12(c) shows the phase velocity dispersion curves for all the propagating modes in the bend region. It can be seen that the phase velocity of the shear horizontal mode is slower than that of its similar mode (SH_0 mode) in a plate. This difference in velocities causes the energy of the SH_B mode to be confined in the bend region, arising from total internal reflections due to impedance mismatch.

Figure 3.12: Mode shapes of (a) the shear horizontal mode in the bend region and (b) the SH_0 mode in flat plate; (c) phase velocity dispersion curves for all the propagating mode in the bend region; phase velocity of the SH_0 mode in the flat plate indicated.

3.4.2 Factors affecting energy concentration

In this part, the energy focusing in the bend region will be demonstrated quantitatively. The width of the lobe of axial power flow can be measured using the full width at half maximum (FWHM), which is also called the -6 dB Width (W6dB). It is presented graphically by Fig. 3.13, which shows the zoomed axial power flow of the SH_B mode at 1 MHz with respect to the arc length of the bend. The FWHM is the width of axial power flow between two points on the curves whose values are half of the maximum. The smaller the value of the FWHM is, the more the energy is concentrated in and around the bend. Thus, the FWHM is used as an indicator to study influences of the frequency and the geometric parameters on the energy trapping effect of the SH_B mode in following discussions.

Figure 3.13: Illustration of the FWHM of the SH_B mode, obtained from the SAFE model at 1 MHz; the maximum axial power flow and half of its peak amplitude indicated.

Figure 3.14 presents the spectrum of the FWHM of the SH_B mode from 200 kHz to 1.2 MHz. It can be seen that the FWHM decreases as the frequency increases, which indicates that the energy concentrates more and more in the bend region at higher frequencies.

In order to understand the influence of the bend geometry in causing mode confinement, a parametric study was carried out by varying the plate thickness and bend

Figure 3.14: Spectrum of the FWHM from 50 to 1200 kHz, predicted by the SAFE model.

radius in SAFE models at 1 MHz. The results are depicted in Fig. 3.15. It can be observed from Fig. 3.15(a) that the FWHM of the SH_B mode increases with the bend radius at the fixed 1 mm plate thickness. This trend is confirmed by replicating the study at different thicknesses, namely 1.5 mm, 2 mm, and 2.5 mm, showing that the energy concentrates more in the bend with smaller bend radius. Likewise, Fig. 3.15(b) shows the FWHM of the SH_B mode for varying plate thicknesses with the fixed bend radius of 4.5 mm. It can be seen that stronger energy focusing exists in the bent plate with smaller plate thickness, which is also verified in other geometries with different bend radius such as 5 mm and 6 mm.

The effect of bend angle on such bend-guiding phenomenon was also studied by the SAFE method. It has been found that the SH_B mode exists in the bent plate (thickness: 2mm; bend radius: 4 mm) with other bend angles as well, such as 60° and 120° , at certain frequency range. Meanwhile, the bent plate gradually loses its ability to retain the wave energy in the feature as the bend angle continues increasing, more resembling flat plates. As an example shown in Fig. 3.16(c), the wave energy of the mode in 150° bent plate tends to be evenly distributed in the entire structure, behaving similarly to the SH_0 mode in regular plates. In addition, it has been found that the SH_B mode in the bent plate of lower bent angles only

Figure 3.15: Schematic for the FWHM in bent plates with varying bend radius and plate thickness: (a) fixed plate thickness = 1 mm; (b) fixed bend radius = 4.5 mm.

Figure 3.16: Distribution of the axial power flow of the SH_B mode in (a) 60° bent plate at 80 kHz, (b) 120° bent plate at 1 MHz, and (c) 150° bent plate at 1 MHz; arrows represent the particular displacement in the cross section.

exists at lower frequencies. For instance, the SH_B mode comes into existence in a 60° steel bent plate when the frequency is below 100 kHz. Similar observation has been reported for the S_0 -like and A_0 -like bend-guided modes at lower frequencies [58, 59]. Therefore, the investigated bend-guiding phenomenon is significantly related to the bend geometry, and higher curvature and thinner plate lead to stronger mode confinement.

3.4.3 Relation with wedge acoustic waves

The bent plate presented in this chapter can be considered as an ‘annular wedge’. This section hence compared the bend-guided waves with the wedge acoustic waves which have been widely studied in literature [114,143,144]. When waves propagate in wedge structures, the energy resides within the wedge portion and is tightly bound to the apex with particle displacement decaying exponentially away from the apex, so that the wedge acoustic waves are usually taken as ‘edge waves’ confined to the tip of wedges. The SH_B mode concentrates energy strongly in the bend region but exists throughout the thickness of the bent plate, which differs from the energy distribution of wedge acoustic waves.

Figure 3.17: Through-thickness distribution of the axial power flow, derived from SAFE models at frequencies ranged from 50 kHz to 1 MHz.

In order to understand this better, the through-thickness normalized axial power flow (along cutline 1 in Fig. 3.8(a)) was extracted at frequencies ranged from 50 kHz to 1 MHz, and results are plotted in Fig. 3.17. It can be observed that the wave energy of the SH_B mode becomes more concentrated towards the bend surface as the frequency increases, suggesting that the SH_B waves at higher frequencies resemble more closely the wedge acoustic waves. This has a strong analogy to the

classical Rayleigh-Lamb wave phenomena, where Rayleigh surface waves are thought to emerge from Lamb waves at higher frequencies.

3.5 Interaction of the Bend-guided Mode with Defects

The propagation characteristics of the identified SH_B mode and the physics underlying the feature guiding phenomena have been demonstrated in previous sections, this section will investigate the interaction of the SH_B mode with two types of defects postulated to occur in the bend region, which are transverse cracks across the bend and longitudinal cracks running along the bend direction, as schematically illustrated in Fig. 3.18.

Figure 3.18: *Geometric illustration of the ‘transverse’ and ‘longitudinal’ crack cut sections in the bent plate; the length of crack l and the crack depth b labelled; the source and excited SH_B mode indicated.*

Both 3D FE simulations and experiments were carried out for the study of defect scattering. Zero-width cracks were introduced in the FE model, where the nodes on elements of adjacent faces are disconnected, and this type of crack defect has

been widely studied in the guided wave scattering in the literature [141, 145–147]. In the experiment, the defects were made to the tested bent plate in the form of notches, which were cut by electrical discharge machining and the width is 0.5 mm. Such width is at least 10 times smaller than the wavelength of the SH_B mode in the frequency range of interest to effectively simulate the shape of cracks. The centre frequency of 650 kHz was chosen for scattering studies, at which the bend-guided mode has minimum attenuation, as indicated in Fig. 3.10. This is a collaborative work with the Centre of Nondestructive Evaluation in Indian Institute of Technology (IIT) Madras, and the details can be found in the joint publication [136].

3.5.1 Transverse cracks

The scattering of the bend-guided mode from transverse cracks was first studied. The 3D FE simulation visualizes the scattered wave field, and the results are quantitatively compared with experiment in terms of reflection coefficient spectrum for validation.

Figure 3.19 presents typical time snapshots of the resultant displacement contour of the SH_B mode propagation. Fig. 3.19 (a) and (b) show the instants soon after the excitation, before the mode's striking the defect. The fundamental symmetric Lamb mode S_0 was excited in the adjacent plate, which will decay cylindrically away from the bend and be damped by the absorbing region on the lateral edges, so that it will have no interaction with the created defect. Leaky A_0 waves were also observed, propagating after the SH_B mode, and the physics of the leakage has been explained in Section 3.3.4. The SH_B wave interaction with a through-thickness transverse crack of $5 \lambda_{SH_B}$ is shown in Fig. 3.19 (c) and (d). The scattered wave field consists of reflected SH_B waves from the crack face and diffracted waves from the crack edges. Such local interaction is similar to the SH_0 wave scattering from a transverse crack in a flat plate [146]. Strong energy reflected from the crack face can be observed, which is confirmed by a time trace of displacement in the x_1 direction monitored between the source and the defect, as shown in Fig. 3.20.

Figure 3.19: Time snapshots of the shear bend-guided mode at 650 kHz propagating along the bend and interacting with the defect: (a) and (b) show the excited wave field; (c) and (d) show the reflected and diffracted waves from the transverse crack of length $5 \lambda_{SH_B}$.

Figure 3.20: Time trace of the SH_B waves monitored at 200 mm from the excitation and 50 mm from the transverse defect, extracted from the 3D FE simulation at 650 kHz.

In order to quantify the reflection behaviour of the SH_B mode, the reflection ratio was calculated, in terms of a frequency domain ratio of the amplitude of the reflected wave to that of the incident wave. A number of 3D FE models were created with different crack lengths, up to $10 \lambda_{SH_B}$, and they were excited at a centre frequency of 650 kHz to understand the effect of crack length on the SH_B reflection. The result is

shown in Fig. 3.21, showing close agreement with the experimental result. It can be seen that the reflection coefficient initially increases linearly with the crack length till $3 \lambda_{SH_B}$, which is followed by an oscillatory regime as the crack length continues increasing. The physics underlying such oscillation in the reflection spectrum has been demonstrated by Rajagopal and Lowe [146] for the case of SH_0 mode in flat plates. It can be explained that for smaller cracks (of length less than $3\lambda_{SH_B}$) the superposition of the waves diffracted from crack edges and the waves reflected from the crack faces enhances reflection ratio. As the crack length increases, such superposition may be constructive or destructive, depending on the signal's delay, thus causing the oscillations in amplitude of resulting reflection coefficient.

Figure 3.21: Reflection spectra of the SH_B mode for through-thickness transverse cracks with varying lengths expressed in terms of wavelength (i.e. l/λ_{SH_B}), obtained from both 3D FE simulations and experiments.

The effect of the depth of transverse cracks on the reflection behaviour of the SH_B mode was also investigated, and the result is shown in Fig. 3.22. The length of the crack was selected to be $3 \lambda_{SH_B}$, where the reflection coefficient reaches a peak value in Fig. 3.21. It can be seen that the amplitude of reflection coefficient increases with the crack depth, as more wave energy gets reflected from the crack face. Also, the trend curve obtained from 3D FE simulations can be well fitted by a higher order polynomial function of crack depth. It is worth noting that for the SH_0 mode in the flat plate, Kirchhoff theory predicts linear variation of reflection ratio with

Figure 3.22: *Reflection coefficient of the SH_B mode for transverse cracks with varying depths, obtained from both the 3D FE simulation and the experiment.*

crack depth [148], which is due to its constant wave field across the plate thickness. However, the wave field of the SH_B mode is thickness-dependent, as demonstrated in Section 3.3.2, leading to non-linear reflection behaviour with respect to the crack depth. In the experiment, cracks with depths of 25%, 50%, 75% and 100% of the bend thickness were introduced to the tested bent plates, and the measured reflection coefficients are in good agreement with the predicted values, thus validating the modelling results.

3.5.2 Longitudinal cracks

Similarly, the scattering of the bend-guided mode from longitudinal cracks was investigated. Fig. 3.23 visualizes the scattered wave field of the SH_B mode at 650 kHz, which comprises the reflection of much weaker amplitude and diffracted waves from the crack tips. The corresponding time trace of x_1 motion is shown in Fig. 3.24. The mechanism of reflection from longitudinal cracks is more complicated than that of transverse ones, which will be demonstrated in this part.

Figure 3.25 presents the reflection ratio of the SH_B mode for longitudinal cracks of

Figure 3.23: Time snapshots of the SH_B wave interacting with the longitudinal defect: (a) and (b) show the excited wave field; (c) and (d) show the reflected and diffracted waves for the crack of length $1 \lambda_{SH_B}$.

Figure 3.24: Time trace of the SH_B waves monitored at 200 mm from the excitation and 50 mm from the longitudinal defect, derived from the 3D FE simulation.

lengths comparable to the incident wavelength. In such cases, the direct reflection includes components from both the near and far crack tips, which are difficult to separate. From both the predicted and experimental results, it can be seen that the reflection coefficient first increases with the crack length, and subsequently experiences an oscillation for the continuously increasing crack length. A similar trend

was also observed in the scattering of shear horizontal weld-guided waves from longitudinal cracks parallel to the weld [111].

Figure 3.25: Reflection spectra of the SH_B mode for longitudinal short cracks with lengths expressed in terms of wavelength, obtained from both 3D FE simulations and experiments.

The oscillation is caused by the interference between the reflections from the near and far tips of the crack, which has been explained by Ratassepp *et al.* [147] in the scattering of the SH_0 mode with longitudinal cracks in flat plates. The reflection from the far tip of the crack is time-retarded with respect to that from the near tip, and their superposition in the resulting reflected signal may be constructive or destructive, depending on the duration of the delay. Moreover, the delayed far tip reflection was probably caused by the conversion of the incident SH type waves into Rayleigh type surface waves that propagate along the crack faces and are radiated at the crack tips into the plate. As for short cracks, the near tip and far tip reflections are superimposed to form an undulating pattern in the resulting reflection.

These two reflection components become separable in the case of long cracks. The reflection behaviour of the SH_B mode interacting with long cracks (of the length varying from 2 to $10 \lambda_{SH_B}$) was studied numerically and experimentally. The reflection component from the near tip was used, and both results are in good agreement, as shown in Fig. 3.26. It can be observed that the reflection coefficient remains almost constant as the crack length increases, which indicates that the reflection

coefficient is independent of the crack length when it is greater than $2 \lambda_{SH_B}$. This corresponds with the observation in Ref. [147] as well.

Figure 3.26: *Reflection spectra of the SH_B mode for longitudinal long cracks with varying lengths.*

3.6 Summary

Feature guided waves are attractive for inspecting complex geometric or topographical features. In this chapter, a promising feature guided mode, named the bend-guided shear horizontal (SH_B) mode, has been identified in metallic bends by applying the SAFE method, and its modal properties have been cross verified by the 3D FE simulation and the experiment. The mode is dominated by shear type in-plane displacements, with limited leakage to adjacent plates. The little-dispersive and low-attenuative characteristics make the SH_B mode very attractive for the rapid screening of 90° transverse bends. The FWHM has been adopted to understand the energy concentration of the SH_B mode, which suggests that the energy is concentrated more in the bend region at higher frequencies. Parametric studies have been carried out to investigate the influence of the bend geometry on the extent of energy concentration, showing that stronger mode confinement occurs in the bent plate with smaller bend radius or thinner plate thickness. Investigation on the physics of the

energy trapping effect has shown that the shear horizontal mode in the bend region has similar mode shape to the SH_0 mode in adjacent plates, but has slower phase velocity. This is the basis for the SH_B mode confinement within the bend. The relation between the SH_B wave and wedge acoustic waves has also been found that when the frequency increases, the SH_B mode resembles more closely the classical wedge acoustic waves.

The interaction of the SH_B mode with two types of defects, i.e. transverse cracks and longitudinal cracks has been studied. The reflection behaviour has been quantitatively examined by both 3D FE simulations and experiments, showing good agreement. The potential of using feature guide waves for identification of damage in bends has been well demonstrated.

The practical inspection of an aircraft bend structure can be realized by coupling a shear transducer at the bend end, working in the pulse-echo mode. The arrival time of reflected signals can be used to determine the location of the damage occurring in the bend region, and its severity can be infer from the amplitude of the reflection coefficient. In this regard, a remote assessment of the bend structure can be made by using SH_B mode without follow-up inspections. However, the possibility of multiple bend-guided modes need to be concerned about, especially when operating the SH_B mode at higher frequencies. In addition, the leaky A_0 waves from the propagating SH_B mode may be reflected by lateral edges of the adjacent structures, interfering with the wave propagation along the bend. Such interference is actually separable, since the A_0 mode is dominated by the out-of-plane displacement, which is perpendicular to the predominant in-plane motion of the SH_B mode.

In this chapter, the investigation of propagation and scattering characteristics of FGWs in isotropic metal bends has laid a foundation for the FGW studies in anisotropic composite bend structures.

Chapter 4

Feature Guiding Phenomena in Anisotropic Bends with Unidirectional Layups

4.1 Background

Ultrasonic guided waves have been proven to be attractive to the long-range testing of composite laminates. As complex-shaped composite components are increasingly incorporated in high-performance structures, understanding of both anisotropic and geometric effects on guided wave propagation is essential to select proper mode and operational frequencies for their inspection. This leads to the exploration of feature guided waves (FGW) phenomena in composite structures. Its concept has been introduced in Section 2.4.1, and a typical case study of bend-guided waves has been performed in isotropic media (see Chapter 3). As demonstrated in Section 2.3, anisotropic constitution of composite waveguides yields unique wave phenomena, such as directional dependence of wave velocity, steering effect, and mode coupling. It can be foreseen that the behaviour of guided waves propagating in anisotropic structural variations will be much more complicated, since these two complexities may be coupled together, concurrently making an impact on the energy trapping

effect.

To address this, the chapter investigates both anisotropic and geometric effects on guided wave propagation in carbon fibre/epoxy (CF/EP) laminated bent plates comprising aligned unidirectional fibres, being highly anisotropic plate-like structures with bend features. Having understood the bend-guiding phenomena in isotropic media, the work presented in this chapter is considered as the intermediate step towards the exploitation of FGWs in composite bends with multi-directional layups, which are more common in the industry. To study characteristics of guided waves in anisotropic bends, both the SAFE method and the 3D FE simulation that were used in Chapter 3 need to be implemented in a new way to account for the anisotropy varying with the bend curvature.

In this study, two special types of modes are identified with their propagation energy strongly confined in the bend region, which indicates that the anisotropic structural feature can also be a special, ‘local’ waveguide for the transport of guided wave energy. Then, the energy concentration phenomenon in the composite bends is investigated by the 3D FE simulation and is validated by the experiment. Finally, the influence of the fibre orientation and the frequency on such energy trapping effect is discussed. The work performed in this chapter has been reported in a journal article [149].

4.2 Numerical Modelling and Post-processing of Anisotropic Bends

The composite material used in the present study is T700/340 CF/EP lamina (detailed later in Section 4.3). A 14-ply unidirectional laminate was manufactured with stacking thickness of 2.28 mm, and its mass density is 1480 kg/m³. The laminated plate is considered to be elastic (undamped) and transversely isotropic. The reference coordinate system is set such that the fibres are aligned in the x_1 direction, and the x_3 axis is along the lamination direction. Its elastic properties were determined

Table 4.1: Characterized elastic constants (in GPa) for the CF/EP composites used in the present study.

C_{11}	C_{12}	C_{13}	C_{22}	C_{23}	C_{33}	C_{44}	C_{55}	C_{66}
10.31	4.24	4.51	10.31	4.51	107.8	4.45	4.45	3.04

by a hybrid elastic wave method using pure bulk wave velocities and Lamb wave dispersion [150], and are given in Table 4.1. The anisotropic propagation of fundamental guided modes in such a laminate has been studied in Section 2.3. Hereby the laminates are formed into 90° bent plates, being typical structures investigated in the thesis.

4.2.1 SAFE modelling

Modal studies of representative composite bent plates were carried out by applying the Semi-Analytical Finite Element (SAFE) method. This approach solves an eigenvalue problem of the solid waveguide with constant cross section to find all possible guided modes along the wave propagation direction at a chosen frequency. Details can be found in Section 2.4.2.

The schematic of the SAFE model is shown in Fig. 4.1, in which the bend radius R_B is 4 mm and the thickness of the bent plate is 2.28 mm. Stress-free boundary conditions were applied to boundaries enclosing the plate. The elastic constants of the laminate were assigned to the cross section with required fibre orientations, which necessitates implementation of rotating the stiffness matrix defined in the principal coordinates (i.e. reference coordinates mentioned above) around each global axis in sequence. A set of material orientation can be specified by a rotation (ψ) about the x_1 axis, followed by a rotation (θ) about the x_2 axis and a rotation (φ) about the x_3 axis, according to the following transformation:

$$C'_{ijkl} = \omega_{im}\omega_{jn}\omega_{kr}\omega_{ls}C_{mnrs}, \quad (4.1)$$

Figure 4.1: Schematics of the SAFE model of anisotropic CF/EP structural bends; global and local coordinates indicated; an example of curvature-based rotation of the stiffness matrix shown for the bend with 90° fibre angle.

Table 4.2: Rotation angles of the stiffness matrix about the global axes.

<i>(a) First set of rotations</i>		
$\psi^{(1)}$	$\theta^{(1)}$	$\varphi^{(1)}$
0°	0°	-90°
<i>(b) Second set of rotations</i>		
$\psi^{(2)}$	$\theta^{(2)}$	$\varphi^{(2)}$
0°	fibre angle	$\varphi = g(x_1, x_2)$
	(range: $0^\circ \sim 90^\circ$)	(range: $-45^\circ \sim 45^\circ$)

where $i, j, k, l, m, n, r, s = 1, 2, 3$; C'_{ijkl} is the transformed fourth-rank elastic stiffness tensor; C_{mnrs} is the stiffness tensor given in the original coordinate system; orthogonal rotation tensor $\omega_{ij} = \mathbf{e}'_i \cdot \mathbf{e}_j = |\mathbf{e}'_i| |\mathbf{e}_j| \cos \theta_{ij}$, with $\mathbf{e}'_i$ and $\mathbf{e}_j$ being unit vectors in the rotated and original axes, respectively.

Let the fibre alignment with the bend direction (i.e. the direction of the wave propagation) be the 0° fibre angle. As indicated in Table 4.2, the anisotropic bend with any fibre angles can be defined by two sets of rotations of the stiffness matrix (bonded to local coordinates) about the global axes, which have to be implemented in

sequence. Hereby, a positive rotation angle is defined as a counterclockwise rotation as viewed from the positive end of each axis. Noteworthily, the second rotation angle about the x_3 axis, $\varphi = g(x_1, x_2)$, is a coordinate-based function, which can be calculated based on the varied curvature at different nodal positions in the cross section. Such angle corresponding to the bend region gradually varies from -45° to 45° as the nodal position shifts from the left-hand side (LHS) to the right-hand side (RHS) portion, while its value equals to -45° and 45° for the LHS and RHS adjacent plates, respectively. Fig. 4.1 also shows an example of the transformed local coordinates for the bend with 90° fibre angle, according to the material rotation listed in Table 4.2.

In this study, the case of a composite bend with 0° fibre orientation (i.e. fibres area along the bend direction), which is also the direction of propagation of the wave) was chosen for investigation in the frequency range from 100 to 500 kHz, where the understanding of guided wave propagation in similar laminates had been obtained in Section 2.3. In order to select the modes of interest at each frequency, the axial component of time-average power flow, namely the acoustic Poynting vector (detailed in Section 2.4.2) of modes was calculated using the following formula at each nodal position of the mesh and utilized to demonstrate the energy variation over the cross section.

$$P_{x_3} = -Re[(\frac{I\omega}{2})(u_1^*\sigma_{31} + u_2^*\sigma_{32} + u_3^*\sigma_{33})], I = \sqrt{-1}, \quad (4.2)$$

where σ_{31} , σ_{32} and σ_{33} are components of the axial stress; u_1^* , u_2^* and u_3^* denote the complex conjugates of the horizontal, vertical, and axial displacements of the modes, respectively. By examining the distribution of axial power flow carried by the modes, two special type of guided modes, namely the SH_0 -like and the S_0 -like bend-guided modes have been identified in the composite bend, as illustrated by Fig. 4.2(a) and (d). The colour coding represents the relative magnitude of axial power flow, and the arrows indicate the particle vibration in the cross section. It can be readily seen that the identified modes with different vibrational patterns are able to propagate with energy strongly concentrated in the bend region, and this

4. Feature Guiding Phenomena in Anisotropic Bends with Unidirectional Layups

capability is very attractive to the inspection of such anisotropic structural feature as it potentially allows guided waves for particularly interrogating the bend region instead of the entire structure.

Figure 4.2: Identified SH_0 -like and S_0 -like bend-guided modes in the unidirectional CF/EP bend with fibres along the bend direction: (a) and (d) axial power flow variation of two modes in the cross section, derived from the SAFE model at 500 kHz and 350 kHz, respectively; (b) and (e) normalized amplitude of axial power flow along the outer boundary (dashed line, black) of the bent plate; (c) and (f) displacement mode shape extracted along the through-thickness cutline (dashed line, red).

Figure 4.2(b) and (e) show the normalized amplitude of the axial power flow of the two modes, which was extracted from the outer surface of the bent plate. It can be observed that for both modes the axial power flow decays quickly with the distance away from the central axis, which demonstrates the wave energy focusing in and around the bend. The oscillation of the SH_0 -like mode represents the leakage of the A_0 mode in the adjacent plate, and the separation distance between the oscillation peaks corresponds with the projection of the wavelength of the leaky A_0 mode along the x_1 direction. By contrast, almost no oscillation was observed in the power flow curve of the S_0 -like mode, indicating substantially reduced energy radiation in the

plate, which will be appealing to the long-range propagation. Besides cross-sectional representation, the vibration pattern of guided modes can also be expressed by the through-thickness displacement mode shape, as shown in Fig. 4.2(c) and (f), which quantifies the orthogonal components of particle displacement and can be used to distinguish different mode families. The quantities were extracted from the solved eigenvectors and normalized by corresponding peak amplitudes. The mode shape of the SH_0 -like mode is similar to the fundamental shear horizontal mode (SH_0) propagating in the laminate along the fibre direction, which is dominated by the in-plane displacement, but with variation through the thickness. The mode shape of the S_0 -like mode, similar to the compressional mode (S_0) in the laminate, is dominated by the axial displacement, and also has small out-of-plane displacement.

4.2.2 3D finite element simulation

In order to cross-verify the energy trapping effect studied in Section 4.2.1, three-dimensional time-domain FE simulations were performed. A unidirectional CF/EP structural bend was modelled with the same geometry and elastic properties as had studied with the SAFE model, also in accordance with the later experimental validation. In the FE model accounting for the anisotropic complex structure, local coordinate systems have to be defined based on the varied curvature for the material properties assignment to the meshed elements.

To observe the wave propagation over the frequency range of interest, a broadband 2-cycle Hanning windowed tone burst centred at 300 kHz was applied at the bend end, as a force in the x_1 or x_3 direction to excite the identified SH_0 -like and S_0 -like bend-guided modes, respectively. Fig. 4.3 presents a snapshot of the wave fields of both modes, with colour contour indicating the relative amplitude of the resultant displacement. It can be seen that in both displacement wave fields the magnitude in the bend region is much higher than that in the adjacent plate, which indicates that the propagation energy is highly focused in and around the bend. It can also be observed that the SH_0 -like bend-guided wave leaks A_0 waves into adjacent plates, spreading behind the dominating wave front, whereas the S_0 -like wave is almost

Figure 4.3: Snapshot of the wave propagation in the CF/EP laminated bend: (a) SH_0 -like bend-guided wave excited by 2-cycle tone burst centred at 300 kHz; (b) S_0 -like bend-guided wave at 300 kHz; excitation location indicated; colour coding shows relative displacement amplitude of propagation modes (blue: low to red: high).

non-leaky and shows strong mode confinement, which also corresponds to the SAFE predictions.

Figure 4.4: Normalized wavenumber-frequency spectra in dB scale, derived from the 2D-FFT method: (a) SH_0 -like bend-guided mode; (b) S_0 -like bend-guided mode; in comparison with the SAFE predictions (dashed line) and experimental results (diamond marker).

To quantitatively measure the two propagating bend-guided waves, the classical spatial two-dimensional Fast Fourier Transform (2D-FFT) [151] was implemented on a set of time traces which were obtained from 301 equally spaced monitors along the central axis of the bend surface with a space step of 0.4 mm. Fig. 4.4 shows the normalized modulus of the 2D-FFT results in dB scale versus frequency and wavenumber. We find very good agreement between the wavenumbers obtained from the FE and SAFE methods. The results are also compared with the experimental measurements (shown later) carried out for the SH_0 -like and S_0 -like mode at 200 kHz and 400 kHz, respectively. Good agreement can be observed. Also, it is worth noting that the SH_0 -like mode exists in the full frequency range of interest, whereas the amplitude of the S_0 -like mode becomes much smaller at the frequency components around 450 kHz, which matches the SAFE prediction that no energy concentration has been found at 450 kHz and 500 kHz in the bend.

4.3 Validation Experiments

4.3.1 Experimental setup and procedures

The experimental setup for ultrasonic measurements is shown in Fig. 4.5. The experiments were performed on a CF/EP bent plate with the same elastic properties and critical geometry as those used for modelling. The composite bend was manufactured by laminating and moulding 14 plies of SE84LV prepregs (Gurit Inc., USA) containing the T700 carbon fibres embedded in #340 epoxy resin, with the fibres orientated along the bend direction. The ultrasonic excitation was launched by coupling a commercially available broadband shear transducer V154 (Panametrics, Olympus Inc.) to the edge of the bend. The excitation signal sent to the transmitter was a 5-cycle Hanning windowed tone burst with the centre frequency of 400 kHz or 200 kHz to separately excite the S_0 -like and the SH_0 -like bend-guided waves. The frequencies chosen were found to give relatively high amplitude responses in such anisotropic bend along the fibre direction.

4. Feature Guiding Phenomena in Anisotropic Bends with Unidirectional Layups

A RITEC RAM-5000 high power ultrasonics pulser (Ritec Inc., USA) was used for the wave generation, and the signals were monitored by the in-plane laser vibrometer (Polytec OFV-5000) with dual sensor headers. Their positions can be accurately controlled by a programmable scanning frame, which allows the wave motions in the whole bend region to be measured without altering the position of the bent plate (that was previously implemented in Section 3.2.3). As shown in Fig. 4.5(b), the two laser beams aligned at 60° [56] were focused on the same spot on the thin reflective film attached on the bend surface, and thus the difference between these two signals gave the amplitude of the in-plane displacement. The received signals were processed by a digital storage oscilloscope (Teledyne LeCroy HDO 6054), which is capable of operating at a maximum sampling rate of 2.5 GHz.

Figure 4.5: (a) Photograph of experimental setup; CF/EP bend specimen positioned for the measurement of the S_0 -like mode; shear transducer clamped at the top surface of the bent plate; (b) specimen position for testing the SH_0 -like mode; shear transducer mounted at the bend end.

To further verify the energy focusing capability carried by the two bend-guided modes, the amplitude of their dominating in-plane motion was separately measured at two monitoring lines on the bend surface at a distance of 110 mm and 50 mm away from the source, across the bend region. Notably, the in-plane motion of the S_0 -like mode is parallel to the bend direction, while that of the SH_0 -like mode is tangential to the bend arc.

4.3.2 Experimental results

The experimental results are presented in Fig. 4.6 and Fig. 4.7. Fig. 4.6(a) shows the amplitude variation of the in-plane motion of the S_0 -like mode around the bend region, at different distances away from the central axis, which was derived in the frequency domain by using FFT. The amplitude of the displacements is normalized by the peak value measured in the central axis. The S_0 mode in the flat laminate under the same excitation was measured in a similar manner, in comparison with the S_0 -like mode. It can be seen that the amplitude of the S_0 -like mode decays quickly as the distance increases, whereas the amplitude of the plate wave is almost constant in the studied range of distance. This demonstrates that the energy of the bend-guided mode is highly focused in the bend region, which is caused by the geometric variation. Fig. 4.6(b) and (c) shows the time history of measured response at the central axis (point A) and adjacent point (point B) using 200 averages, and the evident amplitude difference can be observed.

Figure 4.6: (a) Normalized amplitude of the in-plane displacement of the S_0 -like bend-guided wave across the bend at 400 kHz; (b) and (c) time history of measured responses at the bend in point A and in the adjacent plate in point B.

Likewise, Fig. 4.7(a) depicts the normalized amplitude distribution of the SH_0 -like wave in the bend and the SH_0 wave in the plate. The amplitude of the SH_0 -like wave

decreases much faster than the plate wave owing to the bend curvature. In the time traces extracted from point C and D, as shown in Fig. 4.7(b) and (c), the amplitude of the SH_0 -like wave in the centre is much higher than in the neighbourhood as well. Along the bend direction, another bend-guided wave was also observed propagating ahead of the SH_0 -like wave, as predicted in Fig. 4.4(a).

Figure 4.7: (a) Normalized amplitude of the in-plane displacement of the SH_0 -like bend-guided wave across the bend at 200 kHz; the amplitude variation of the SH_0 wave indicated; (b) and (c) time history of measured responses.

4.4 Discussion

4.4.1 Influence of fibre orientation on energy trapping effect

The guided wave energy trapping effect in the composite bend has been predicted by the SAFE method, supported by 3D FE simulations and validated by experiments. To further understand its physics, factors affecting such effect were investigated. Varied fibre angles ($0^\circ \sim 5^\circ$) were assigned to the SAFE model of the bend (the implementation has been illustrated in Section 4.2.1) at 300 kHz to study the influence of fibre direction on the energy concentration capability of the bend-guided modes.

4. Feature Guiding Phenomena in Anisotropic Bends with Unidirectional Layups

Fig. 4.8 shows the variation of axial power flow of the S_0 -like mode over the bent plate with different fibre angles. It can be seen that there is a gradual shift of the wave energy from the bend towards the adjacent plate as the fibres deviate from 0° , leading to the energy being no longer trapped in the bend region. Similar trends were also found for the SH_0 -like mode, and its energy focusing disappears at even smaller angles.

Figure 4.8: (a) Power flow variation of the S_0 -like mode around the bend with varying fibre orientations; (b) normalized axial power flow extracted along the bend arc.

Figure 4.9: Phase velocities of the S_0 mode (solid) in the laminate and the longitudinal mode (dashed) in the separate bend region with respect to different fibre angles.

To explain this, we examined the S_0 -like mode propagation in separate parts of the bent plate: in the bend region and in the flat laminate. The physics of the energy trapping effect in isotropic structural features has been demonstrated in Section 2.4.1 and been examined for the case of metallic bends in Section 3.4.1. Two conditions contribute to its existence: (1) the guided modes in the feature should have similar mode shapes to the corresponding modes in the adjacent plate; (2) the phase velocity of the guided mode in the feature should be slower. As indicated in Fig. 4.9, the velocity condition holds for the investigated fibre angles.

Figure 4.10 shows the through-thickness displacement mode shapes of separate regions with 0° and 4° fibre angles, respectively. It can be seen from Fig. 4.10(a) and (c) that at 0° fibre orientation (the principal direction), mode shapes in both the bend and the laminate are dominated by the axial displacement (u_3) with other components (u_1 and u_2) negligible, and such similarity enables the two modes to be joined together when propagating along the bend, causing the wave energy to be trapped in the bend region with slower phase velocity, arising from the total internal reflection. However, at other fibre angles (non-principal directions), for example, in the 4° case shown in Fig. 4.10(b) and (d), the amplitude of shear horizontal displacement (u_1) increases in both mode shapes due to the coupling between S_0 and SH type modes, and it has larger fraction in the bend region than the laminate, varying through the thickness, which significantly weakens the similarity between their modes shapes and prevents the energy from being confined to the bend. Therefore, the mode shape condition can only be satisfied when the fibre angle is close to 0° , ultimately yielding the energy concentration in the bend with immediate vicinity of 0° fibre orientation.

Notably, apart from the conditions proposed for isotropic features, the preferred direction of energy transport will also affect the energy concentration in anisotropic structural features. As demonstrated in Section 2.3.2, the energy direction of the S_0 mode in the laminate is strongly biased toward fibres. Thus, fibres aligning with the bend direction also contributes to retaining significant energy in and around the bend region. This is somewhat different from the findings in the isotropic bend

Figure 4.10: (a) and (b) Through-thickness displacement mode shapes of the longitudinal mode in separate bend region with 0° and 4° fibre directions; (c) and (d) displacement mode shapes of the S_0 mode in flat laminates with fibres orientated along 0° and 4° directions.

study [59] where it was found that energy trapping disappears when the bend angle is larger than 75° . Another evidence to support the influence of the preferred energy direction is that the energy concentration area is readily skewed when varying the orientation of fibres. In this regard, the energy trapping effect in the composite bends is caused by the geometric variation and is strongly influenced by the anisotropic properties.

4.4.2 Effect of frequency on energy concentration

To quantitatively demonstrate the energy trapping effect, the full width at half maximum (FWHM) was introduced, which can be measured as the -6dB width of the lobe of axial power flow curve shown in Fig. 4.2(b) and (e). The narrower width indicates stronger energy concentration in and around the bend. Thus the FWHM

is used as an indicator to investigate the influence of the frequency on such effect.

Figure 4.11: *FWHM-frequency spectrum for the two bend-guided modes, calculated by the SAFE method.*

Figure 4.11 presents the FWHM spectrum versus the frequency for two bend-guided modes, calculated by the SAFE method. It can be seen that the FWHM of both modes decreases as the frequency increases, which suggests that more energy is concentrated in the bend at higher frequencies. It can be observed that the SH_0 -like mode shows stronger mode confinement in the investigated frequency range, while the S_0 -like mode shows much variation of the energy concentration with the frequency. Revisiting the experimental results shown in Fig. 4.6 and Fig. 4.7, the amplitude of the S_0 -like bend guided wave at 400 kHz drops more quickly than that of the SH_0 -like wave at 200 kHz, suggesting the former shows stronger energy trapping effect at particular frequency, which corresponds with the SAFE prediction here. Also, no energy concentration phenomenon was found above 450 kHz in the search of the S_0 -like mode because of higher phase velocity in the bend region and dissimilar mode shape to the laminate.

Besides the fibre direction and operational frequency, geometric parameters such as the bend curvature, bend angle and plate thickness also influence the energy trapping effect in the anisotropic bend. Similar studies have been carried out for

isotropic media in Section 3.4.2.

4.5 Summary

In this chapter, anisotropic and geometric effects on ultrasonic guided wave propagation have been studied in unidirectional CF/EP structural bends. The energy trapping effect carried by two types of bend-guided modes has been found in such anisotropic bends by applying the SAFE method, which is supported by the 3D FE simulations and validated by the experiments.

The discovered energy focusing capability is attractive for long-range rapid inspection of composite bends, in which guided waves are potentially able to propagate long distances with significant energy confined to the bend, in particular interrogating the bend region for possible occurrence of defects in or around it. Results indicate that a combination of Rayleigh-Lamb and SH family of bend-guided modes could potentially yield rich information about through-thickness damage covering both surface and sub-surface features. For better understanding of such energy trapping effect, the influences of the fibre orientation and the operational frequency have been investigated in light of its physics. It has been found that the energy can be concentrated in the bend with immediate vicinity of 0° fibre orientation, and the energy concentration is owed to both the geometric variation and anisotropic properties. Also, the energy is focusing more in the bend region at higher frequencies.

From the perspective of numerical modelling, the SAFE and 3D FE approaches newly implemented in this chapter can be generic tools to deal with waveguide problems with both arbitrary cross section and anisotropic material properties. The overall study has laid a foundation for exploring the feasibility of using proper guided wave modes for quick screening of multi-layered quasi-isotropic composite bends, which are more frequently used in the industry.

Chapter 5

Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

5.1 Background

Upon the foundation laid in the previous two chapters, the present chapter investigates a particular case - the 90° quasi-isotropic composite laminated bends, which are common in aircraft structures, such as the rectangular or C-shaped wing spars. The current technique to inspect such bends requires scanning the whole region of interest point by point by using the ultrasonic probe combined with selected wedges, as illustrated in Fig. 5.1(a), which is time consuming and tedious. Moreover, different wedges are needed for different bend curvatures, and they are worn easily during the measurement. Although some advanced water-immersed phased array techniques [152] were then applied for the inspection free of wedges, sophisticated delay laws are required to adapt to the complex surface geometry (i.e. Surface-Adaptive Ultrasound, SAUL) and to compensate for the probe misalignment [152, 153], as

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

shown in Fig. 5.1(b), which is expensive and complicated for the testing of large composite bends. In addition, such water immersion configuration disfavours its application to *in-situ* measurement.

Figure 5.1: Schematics of (a) the conventional technique used to inspect bends; (b) surface-adaptive ultrasound (SAUL) phased array inspection of composite laminated bends [152].

Under such circumstance, ultrasonic testing based on feature guided wave can be an effective alternative as it potentially allows for rapid screening of large areas with a fixed transducer position and remote inspection of structures with difficult access. This chapter explores the potential of exploiting FGWs for quick inspection of quasi-isotropic composite bends for possible occurrence of delaminations or cracks. The understanding of FGWs scattering characteristics is essential for their successful employment. However, the scattering of guided waves from a defect in the flat composite plate is already a complex problem [104, 106] due to its anisotropic and inhomogeneous nature. The scattered wave field normally shows directional and depth dependency and possibly accompanies mode conversion and wave trapping phenomena [103, 154–156]. As to the composite bend, both the geometrical variation and anisotropic material properties will influence the propagation of guided waves,

thus adding complexity to the FGW based damage detection.

The chapter starts with the modal analysis of FGW modes existing in the composite bent plate by applying the SAFE method. A shear horizontal bend-guided (SH_B) mode has been identified as a promising candidate for inspecting defects occurred in the bend region, and its propagation characteristics are subsequently validated by both experiments and 3D Finite Element (FE) simulations. Following that, the interaction of the SH_B mode with different defects are experimentally investigated. In comparison with 3D FE results, good agreement can be observed. This series of results presented in this chapter have been published in a journal paper [157].

5.2 Modal Study of Composite Bends

5.2.1 SAFE modelling

Modal studies of the 90° composite bent plate were performed by applying the SAFE approach. With the improved computational efficiency, this method has gained its popularity to extract modal solutions for guided waves in irregularly shaped waveguides [55, 116, 117, 120, 122, 123] and in composite laminates [47, 126, 149, 158]. The schematic of the SAFE model is shown in Fig. 5.2, in which the bend radius R_B is 4 mm and the thickness of the bent plate is 2.4 mm. The entire geometry was meshed by quadratic Lagrange triangular elements, with finer element size in the bend region. Stress-free conditions were applied to the outer boundaries enclosing the whole domain. Absorbing regions were added to both sides of the plate to get rid of standing wave modes and to allow for proper representation of possible radiating waves [123].

The composite material used in the present study is a 16-ply carbon fibre/epoxy (CF/EP) laminate with a quasi-isotropic stacking sequence $[0/45/90/-45]_{2s}$. Such multi-layered structure is deemed to behave as a homogeneous orthotropic plate based on the homogenization assumption [159]. Its effective stiffness matrix was

Figure 5.2: Schematic of the SAFE model of a quasi-isotropic CF/EP bent plate; global and local coordinates shown; absorbing region indicated.

Table 5.1: Properties (in GPa) of the composites used in the present study; the mass density is 1540 kg/m³; the ply thickness is 0.15 mm.

(a) Elastic properties of the unidirectional SE84LV prepreg ply

C_{11}	C_{12}	C_{13}	C_{22}	C_{23}	C_{33}	C_{44}	C_{55}	C_{66}
10.31	4.24	4.51	10.31	4.51	107.8	4.45	4.45	3.04

(b) Estimated effective stiffness components for the quasi-isotropic laminate

C_{11}	C_{12}	C_{13}	C_{22}	C_{23}	C_{33}	C_{44}	C_{55}	C_{66}
10.31	4.38	4.38	47.64	15.92	47.64	15.86	3.61	3.61

calculated from ply properties using the Backus averaging method [160–162] (see details in Appendix A) and is given in Table 5.1. Noteworthily, the equivalent homogeneous properties are suitable for simulating the propagation of elastic waves at low frequency [162], since their wavelength is much larger than the layer thickness.

The elastic properties of the unidirectional lamina of transversely isotropic symmetry were characterized by a hybrid elastic wave method [150], in a similar manner to that shown in Section 4.2. The reference coordinate system used to define fibrous materials is set such that the fibres lie along the x_3 axis and the layer interfaces are normal to the x_1 axis, which is consistent throughout the thesis. To assign the

material properties to the cross section, the stiffness matrix defined in the principal coordinates has to be rotated around each global axis in sequence, according to the transformation illustrated in Section 4.2.1. The rotated local coordinates are shown at three typical nodal positions in Fig. 5.2. The problem was solved in the frequency range from 50 to 400 kHz with a step of 50 kHz.

5.2.2 Shear horizontal bend-guided mode

Potential feature guided modes are capable of propagating with wave energy confined in and along the feature (i.e. bend region in this chapter), which can be identified in the SAFE calculation by examining the axial component of the time-average power flow P_{x_3} , in a similar manner to that as had been studied in Sections 3.3.1 and 4.2.1.

Figure 5.3(a) visualizes its variation of the identified SH_B mode over the cross section at 300 kHz, with colour coding denoting its relative amplitude. Its quantity was also extracted along the bend surface (dashed curve), normalized by the maximum magnitude in the bend region, as shown in Fig. 5.3(b). It can be observed that the mode energy is strongly concentrated in the bend region, and its amplitude quickly decays as the distance from the bend increases. This property is very attractive for the screening of composite bends as it offers the potential of using the FGW to particularly interrogate such structural features and to interact with defects that occur in the bend region. Fig. 5.3(c) and (d) depict the normalized through-thickness displacement and stress mode shapes, respectively. It can be seen that the wave-field is dominated by the shear horizontal displacement (u_1) which is tangential to the bend arc, and the stress field is dominated by the in-plane shear component (σ_{13}). The thickness-dependent mode shapes also distinguish the bend-guided mode from the fundamental shear horizontal mode (SH_0) in flat plates, which has constant dominant displacement and symmetric stress along the plate thickness.

In order to quantitatively describe the extent of energy focusing in the bend region, the full width at half maximum (FWHM) was introduced, which can be measured

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

Figure 5.3: (a) Mode shape illustration of the feature guided wave propagating along the bend, derived by the SAFE method at 300 kHz; colour coding shows relative amplitude of the axial power flow, normalized by the maximum value in the bend region; arrows present the particle displacement in the cross section; (b) variation of the amplitude of axial power flow extracted from the bend surface; and bend region (shaded) indicated; mode shapes of (c) displacement and (d) stress along the bend thickness.

Figure 5.4: SAFE predictions of (a) the FWHM of the feature guided mode at 300 kHz and (b) the spectrum of the FWHM from 50 to 400 kHz.

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

as the -6dB width of the lobe of axial power flow with respect to the bend arc, as graphically presented in Fig. 5.4(a) (i.e. Fig. 5.3(b) zoomed around the bend region). The narrower width indicates stronger energy concentration in the vicinity of the bend. Fig. 5.4(b) shows the spectrum of the FWHM of the SH_B mode from 50 to 400 kHz. It can be confirmed that the FWHM decreases as the frequency increases, suggesting that more energy is concentrated in the bend region at higher frequencies.

Figure 5.5: *SAFE predictions of (a) the phase velocity and (b) the attenuation dispersion curves of the identified feature guided mode.*

Figure 5.5 presents the calculated dispersion characteristics of the SH_B mode including the phase velocity and the attenuation. In practical NDT/SHM applications the favourable ultrasonic guided modes ought to be little-dispersive and low-attenuative so that they can propagate long distances and the detected signals will be simpler to interpret. It can be observed that the SH_B mode is almost non-dispersive in the investigated frequency range, and its attenuation decreases as the frequency increases, indicating reduced energy radiation into the adjacent plate at higher frequencies. It is worth noting that material damping is not considered in the model, thus the calculated attenuation only quantifies the leakage of the investigated guided mode. As the material damping significantly increases with the frequency [85], the operation of the SH_B mode is normally constrained in lower frequencies.

5.3 Validation of Propagation Characteristics

5.3.1 3D finite element simulation

To cross-verify the propagation of the FGW in the composite bent plate, three-dimensional time-domain FE simulations were carried out using the proprietary code Abaqus Explicit [137]. The model was created with the same cross-sectional geometry and elastic properties as had been studied in the SAFE model, in accordance with the experiment shown later. The entire bent plate was meshed by 8-node brick elements (C3D8R), with size of 0.3 mm along the length and width directions and 0.15 mm along the thickness direction, to ensure at least one element for each ply thickness, as shown in Fig. 5.6(b). Local coordinate systems were defined to assign anisotropic properties to the meshed elements.

Figure 5.6: (a) Snapshot of the bend-guided wave propagating in a quasi-isotropic CF/EP bent plate (size: 360 mm×300 mm×2.4 mm); the colour contour indicates the relative amplitude of resultant displacement of propagating modes at 300 kHz (blue: low to red: high); (b) schematic of the mesh distribution zoomed around the bend region; excitation along the through-thickness nodes and an example local coordinate system indicated; (c) cross-sectional view of the wave propagation cut along the plane at Z=150 mm.

Figure 5.6(a) presents a snapshot of the excited wave field of the SH_B mode, with the colour contour denoting the amplitude of the resultant displacement. A 5-cycle Hanning windowed toneburst signal centred at 300 kHz was applied on the through-thickness nodes at the bend end (Fig. 5.6(b)), forcing in the X direction. The monitors were located across the bend region and along the bend direction for the transverse and longitudinal measurements, respectively. It can be seen that the chosen wave mode propagates with strong energy confinement in the bend. Also, as indicated in the cross-sectional view extracted along the plane at $Z=150$ mm (shown in Fig. 5.6(c)), the majority of the wave energy is concentrated towards the upper part of the bend region, which agrees with the SAFE predictions.

5.3.2 Experiments

The experimental setup is shown in Fig. 5.7. Measurements were performed on a CF/EP bent plate of dimensions of 800 mm×500 mm×2.4 mm with a fillet radius of 4 mm. The composite specimen was made of 16 plies of unidirectional SE84LV prepregs (Gurit Inc., USA) containing the T700 carbon fibres embedded in the #340 epoxy resin, which is the same composite material as that used in Chapter 4. A quasi-isotropic layup of $[0/45/90/-45]_{2s}$ was adopted with 0° fibres orientated along the bend direction. Upon stacking the unconsolidated prepregs on the mould of high temperature resistance, a moulding fleece and a vacuum bag were added. With the hot pressing technique, the material was subsequently cured in an autoclave at 125°C under pressure of 4 bar, and no significant spring-back effects were observed during the demoulding process.

The ultrasonic excitation was launched by coupling a commercially available shear transducer V154 (Panametrics, Olympus Inc.) to the end of the manufactured bent plate, as shown in Fig. 5.7(c), which was driven by a RITEC RAM-5000 high power ultrasonics pulser (Ritec Inc., USA) producing Hanning windowed toneburst signals centred at the required frequency. The wave motion was monitored by a laser vibrometer (Polytec OFV-5000) with dual sensor heads whose position was programmably controlled by a scanning frame. As shown in Fig. 5.7(a) and (b),

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

Figure 5.7: (a) Photograph of the experimental setup with the illustration of laser beams and reference coordinates; (b) reflective film attached to the bend surface, parallel and perpendicular to the propagation path; (c) shear transducer coupled at the plate end.

the two laser beams aligned at 60° were focused on the same spot on the thin reflective film attached to the bend surface, thus the difference between these two signals gave the amplitude of the in-plane displacement. It is worth noting that the actually obtained horizontal and vertical displacements have to be transformed to the tangential components when measuring at points away from the central axis of the bend, and such transformation has been illustrated in Section 3.3.1. The wave reception signals were processed by a digital storage oscilloscope (Teledyne LeCroy HDO 6054).

Figure 5.8 presents the experimental in-plane displacements (tangential to the bend arc) across the bend region measured at 200 mm from the source at 300 kHz, in comparison with the 3D FE results. The displacement amplitude was normalized by the corresponding maximum value in the bend region. The energy trapping effect is well demonstrated in both cases. It can be seen that the amplitude quickly decays with the increasing distance from the bend, indicating that the energy is highly focused in the bend region. Also, a set of time-domain signals of the in-plane displacement was extracted from 151 monitors equally spaced along the bend surface (along the Z direction) covering distance range from 50 to 200 mm away from the

Figure 5.8: *Normalized amplitude of the in-plane motion of the SH_B mode over the bend region at 300 kHz, obtained from the 3D FE simulation (solid) and the experiment (asterisk).*

Figure 5.9: *Phase velocity dispersion curves derived from the SAFE calculation (solid), the 3D FE simulation (diamonds) and the experiment (circles).*

source. The time traces were processed by the spatial two-dimensional Fast Fourier Transform (2D-FFT) [151], and the calculated phase velocity dispersion curve is shown in Fig. 5.9, where both the 3D FE results derived in a similar manner and

the SAFE predictions obtained in Section 5.2.2 are compared. Good agreement can be found among the results, while the slight deviation from the experimental result can be due to the accuracy in the estimation of material properties in the models.

5.4 Interaction of the Bend-guided Mode with Different Defects

In order to further evaluate the suitability of the SH_B mode to damage detection in the composite bend, its scattering by the interlaminar delamination and transverse cracks has been investigated in this section by both experiments and 3D FE simulations.

5.4.1 Interlaminar delamination in the bend region

A rectangular delamination was introduced to the bent plate by inserting a thin Teflon sheet (width:20 mm; length:10 mm) between the top two layers, i.e. the upper 0° and 45° plies (about 7% depth from the top surface) during the lay-up process. The created delamination is symmetric about the central axis with its front edge 200 mm away from the excitation location. In the 3D FE simulation, the delamination was modelled by a volume split [78,104,163]. The FE nodes across the delamination surface were separated by a very small but constant radial distance, which can be considered as a good approximation to the real delamination.

Figure 5.10 shows typical time traces of the in-plane motion measured along the bend direction in both the FE simulation and the experiment at 300 kHz, and the monitors were located at $Z=100$ mm (between the source and delamination), $Z=250$ mm (after delamination), and $Z=205$ mm (central position of the delamination). It can be seen from both sets of time traces that the incident SH_B wave remains almost the same shape in the propagation, which confirms that the chosen FGW mode has little dispersion, contributing to its practical employment for rapid screening of the

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

Figure 5.10: Typical time traces of the in-plane motion (u_x) measured along the central axis of the delaminated bent plate: (a) 3D FE results; (b) experimental results; the location of monitors indicated.

structure. It should be noted that in FE simulations a linear elastic wave problem is solved. As the force applied to excite the FE model is in small magnitude, the magnitude of signals extracted from the calculated wave field will be in even smaller order.

In principle, the localization of the delamination can be achieved by estimating the propagation speed and time of flight from the reflected signal [46, 101]. However, as indicated by the time history measured prior to the defect (at $Z=100$ mm), the amplitude of the reflected waves is quite small in both cases, which makes it difficult to be used to infer the delaminated location. This can be explained that the guided waves propagate individually in the two regions divided by the delamination, and large reflections only occur when there are evident phase differences between the divided two regions or when pronounced discontinuity is caused in the through-thickness stress field at the delaminated interfaces [154]. The small reflection of the SH_B mode observed here may be owed to its limited resulting phase difference or stress discontinuity. Also, the wave field of the SH_B mode is dominated by

the in-plane displacement, which is parallel to the interlaminar delamination, thus disfavours the strong wave reflection.

Figure 5.11: Energy contained by temporal signals measured along the propagation path at 300 kHz: (a) 3D FE result; (b) experimental result; defect area indicated by grey band

Notably, as shown in the time traces monitored at the defect centre ($Z=205$ mm), some wave oscillations exist after the incident wave, indicating some trapping phenomena occurred within the delamination region. Therefore we explore another approach for identifying the delamination in this section, by calculating the amplitude of wave energy along the propagation path. According to the Parseval's theorem [164], the total energy (E) of a signal can be obtained as follows:

$$E = \int_{-\infty}^{\infty} |s(t)|^2 dt = \int_{-\infty}^{\infty} |S(f)|^2 df, \quad (5.1)$$

where $S(f)$ denotes the Fourier transform of the temporal signal $s(t)$. Numerically, applying the discrete Fourier transform (DFT) on filtered or windowed temporal signals, the relation becomes:

$$E = df \sum_{k=1}^{N_{FFT}} |S[k]|^2, \quad (5.2)$$

where k is the index of the frequency sample, such that $f[k] = kdf$ (k varies from 0 to $N_{FFT} - 1$); $df = f_e/N_{FFT}$, f_e being the sampling frequency. Hereby the wave

energy was calculated in both the 3D FE simulation and the experiment covering the distance range from 100 to 300 mm away from the excitation, and the results are depicted in Fig. 5.11. Local peaks of the energy can be readily seen in the defect area in both cases. This can be explained that the FGWs propagate separately in the upper and lower portions upon entering the delamination region, and part of the wave energy is then trapped with the waves bouncing back and forth inside the defect area, ultimately leading to a wave-defect resonance. Similar occurrences have been reported in the scattered wave field of composite plates [155,156]. Within the delamination region, the number of local peaks of the wave energy is determined by the ratio of the wavelength of the standing wave to the length of the defect. The NDE implication of delamination detection is that FGWs can be used as a source to screen the composite bends and then scan a detector (e.g. laser vibrometer) along the bend direction. It is also possible for inspecting a delamination that is deeper in the bend thickness as long as such wave internal resonance occurs in the delaminated area.

5.4.2 Transverse cracks across the bend

A separate composite bent plate having the same stacking configuration and dimensions as the delaminated one, was cut transversely in the bend region to create a crack with the length (l) of 20 mm and the depth (d) of 1.2 mm, reaching half of the plate thickness, as illustrated in Fig. 5.12(a). The transverse crack is 0.5 mm wide and located at 210 mm away from the source. The operational frequency was chosen as 200 kHz, at which high amplitude responses and low material damping were found in this ultrasonic measurement. A crack with the same geometry and location was modelled in 3D FE simulations as well, by axially disconnecting adjacent elements having zero stress on the shared element faces.

Figure 5.12(b) shows the superposed two time-series responses monitored at 60 mm and 150 mm from the source in the FE model. Both the incident wave and the reflected wave from the crack can be observed, and their magnitudes remain almost constant in the propagation, suggesting the low leakage of the SH_B mode. Fig. 5.13

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

Figure 5.12: (a) Cross-sectional illustration of the part-thickness transverse crack introduced to the composite bent plate; (b) time responses of the bend-guided waves scattering by the transverse crack, monitored at 60 mm and 150 mm away from the source.

Figure 5.13: Typical time traces of the in-plane motion (u_x) measured along the cracked bent plate: (a) 100 mm from the source; (b) 150 mm from the source.

5. Damage Detection in Multi-layered Quasi-isotropic Composite Bends Using Bend-guided Waves

extracts two typical time traces of defect scattering experimentally measured at 100 mm and 150 mm from the excitation location. It can be clearly seen that the reflected wave travels between the incident wave and the edge reflection (S_0 wave reflected from the lateral edge of the bent plate). Also, it is worth noting that the amplitude of the SH_B waves propagating in the actual specimen does not decay much, which indicates relatively low attenuation at the chosen frequency.

Figure 5.14: *Reflection coefficient spectra for the transverse crack, derived from the 3D FE simulation (solid) and the experiment (asterisk).*

To quantitatively study the reflection behaviour of the SH_B mode, its reflection coefficient was calculated, in terms of a frequency domain ratio of the amplitude of the reflected wave to that of the incident wave, which were extracted from the temporal signal monitored at 150 mm from the source (i.e. Fig. 5.13(b)). The resulting reflection spectrum as a function of frequency is shown in Fig. 5.14, with the crack length expressed as a fraction of the wavelength of the incident wave. The experimental and FE results show close agreement. It can be observed that the reflection coefficient increases as the wavelength decreases (the frequency increases), as stronger energy concentration occurs in the bend region at higher frequencies and thus more wave energy gets reflected by the crack. However, the choice of the incident wavelength is constrained by significantly increased material damping at

high frequencies.

Figure 5.15: *Reflection coefficient spectra for the transverse crack with varying depths, derived from the 3D FE simulation.*

Also, the effect of crack depth on the reflection behaviour of SH_B mode was studied, and the result is shown in Fig. 5.15. Larger reflection coefficient can be obtained for deeper cracks, as more wave energy gets reflected. A similar phenomenon has been observed in the metallic bend in Section 3.5.1. In addition, the reflection coefficient increases more quickly when the crack depth varies in the upper portion of bend. This can be explained that more wave energy of the SH_B mode concentrates towards the upper bend during its propagation, which potentially enables the mode to be more sensitive to the defects occurred there. Summarized from the results in this section, the feasibility of using the reflection behaviour for crack detection is well demonstrated.

5.5 Summary

In this chapter, the confined FGWs have been studied for the rapid inspection of defects occurred in the quasi-isotropic CF/EP composite bends. The modal analysis

is performed by the SAFE method, and a shear horizontal type bend-guided mode (the SH_B mode) has been identified to be well suited. The mode is almost non-dispersive and non-leaky, and is potentially capable of propagating long distances with significant wave energy concentrated in the bend. Also, due to the mode confinement it can be exploited in particular to interrogate the bend region rather than the entire structure. Both 3D FE simulations and experiments have been carried out to validate the propagation characteristics of the SH_B mode and to study its interaction with different defects in the bend, including the interlaminar delamination and transverse cracks. Close agreement has been observed between the numerical predictions and experimental measurements. To quantify the scattered wave field from the defect, both variation of the wave energy along the propagation path and the reflection spectra were calculated for localizing the delamination and the cracks, respectively. The capability of the FGW for damage detection in composite bends is well demonstrated.

Noteworthily, the method proposed in this chapter is a screening technique to identify the location of possible defects, and the conventional method can then be applied at that location to characterize the defect.

Chapter 6

Feature Guided Wave Inspection of Adhesive Composite Joints

6.1 Background

Adhesively bonded joints are increasing alternatives to mechanical joints in engineering applications and can offer many advantages over conventional mechanical fastenings and welding, such as more uniform stress distribution across the bond line, improved impact tolerance, and increased vibration damping. In the aerospace industry, the application of these joints in structural components or assemblies made of fibre reinforced composites has steadily increased in recent years. The traditional fasteners such as bolts and rivets usually require cutting of fibres, and hence the introduction of stress concentration, which would compromise the structural integrity. By contrast, the adhesive bonding retains the assembly components intact and allows complex shapes and dissimilar materials to be joined with ease. Also, better sealing performance and smoother external surfaces are attained. Therefore, adhesively bonded joints have extensively been applied, in the form of composite lap joints [165], the stiffener-bond-skin combination, sandwich structures, as well as the scarf repair configuration [166, 167].

However, the adhesive bonds are susceptible to failure where the composite struc-

tures are under fatigue loading [27, 28] and exposed to variation in temperature and/or humidity [14, 29] during the in-service use. This can lead to crack formation, reduced interfacial strength, and even more severe deterioration of the entire structure [4]. Thus, there is considerable interest in assessing the bond quality in the aerospace industry [30–36, 57], and its efficient inspection contributes to another motivation of the thesis.

In this chapter, a particular case is investigated - a metallic stiffener bonded onto a flat composite panel, being typical components in airplane wings and in an aircraft fuselage. Such assembly is sensitive to the thermal loads, since large difference in thermal expansion characteristics between adherends (e.g. carbon fibres have much lower thermal expansion than metals) can cause considerably high thermal stresses [168], thus initiating debonding areas on the interface. The normal practice to test such bond is to use ultrasonic C-scan to implement a point-by-point inspection on the other side of the stiffened panels, which is tedious and sometimes infeasible when the panels are difficult to access or bonded to honeycomb cores. Ultrasonic guided wave testing can be an effective alternative for bond diagnosis due to its capability of long-range inspection with a fixed transducer position and the flexibility in selecting sensitive mode-frequency combinations. It has been reported that proper guided waves propagating in a parent material can be used to monitor the condition of its bonded components of different materials, such as patches or spars on skins [36, 47], and the sensitive guided modes can normally provide high energy levels in adhesive bonds at operational frequencies.

Therefore, this study explores the potential of using feature guided waves (FGW) for rapid inspection of defects in the adhesive bonds between stiffeners and composite skins. An earlier investigation of FGWs in a similar metallic bonded joint has been reported in the literature [57], which however focused on determining the adhesive shear modulus from FGW measurements and only involved isotropic materials. The present work has further developed the numerical approaches to account for both complex geometry and multi-layered anisotropic constitution, and has mainly delved into the FGW scattering by adhesive defects. The work and relevant physics

presented in this chapter are thus original and new, which have been published in a journal article [169]. The chapter starts with modal studies of a stiffener attached to a composite panel by using the SAFE-PML method. Multiple potential feature guided modes are identified. The criteria are then used to select proper modes that are sensitive to adhesive defects and also have little dispersion and low attenuation. Following that, the defect scattering study using the selected mode is carried out by 3D FE simulations, and validated by experimental measurements.

6.2 FGWs in Stiffened Composite Panels

6.2.1 SAFE modelling

To identify and understand guided modes existing in a stiffened composite panel, the SAFE modelling was carried out. The schematic of the SAFE model is shown in Fig. 6.1, consisting of three different material components: a viscoelastic orthotropic composite plate, a viscoelastic isotropic adhesive layer, and an elastic isotropic T-shaped aluminium stiffener. The composite plate is made of 8 carbon epoxy plies with a quasi-isotropic layup $[0/45/90/-45]_s$. Its stacking thickness is 1.6 mm and the mass density is 1.58 g/cm^3 . The viscoelastic moduli were measured by a well-established ultrasonic technique [170,171], and are shown in Table 6.1.

Actually, different ply orientations such as $[0/90]_{2s}$ and $[0/45/-45/0]_s$ were also considered for the composite base plate, and the dispersion curves of guided modes in these laminates are significantly different, as shown in Fig. 6.2. Hence, it can be expected that the ply orientation of the base plate will influence the FGWs propagating along the stiffened plate. The present chapter investigates the most commonly used quasi-isotropic layup for demonstration. The epoxy adhesive is 0.75 mm thick and its material properties (presented in Table 6.1) were characterized to simulate a properly cured bond condition.

Besides accounting for anisotropic viscoelastic materials, another major improve-

Figure 6.1: Schematic of the SAFE model of a stiffened CF/EP plate, with adhesive bond line and perfectly matched layers shown (not to scale).

Figure 6.2: (a) Phase velocity and (b) attenuation dispersion curves of guided modes propagating in the 1.6 mm thick base plate with different layups (along 0° fibre direction), derived from the SAFE calculation of the laminates.

ment compared to the earlier work [57] is to introduce Perfectly Matched Layers (PML) in the SAFE model (to replace the absorb region) for damping possible leaking waves. The PMLs of 20 mm length were attached to either side of the composite plate, in which a complex coordinate stretching is implemented. The original wave

Table 6.1: Density, thickness, and viscoelastic properties (in GPa) of the materials used in the present study.

	Carbon Epoxy	Adhesive	Aluminium
Density (g/cm ³)	1.58	1.05	2.7
Thickness (mm)	1.6	0.75	1.6
C_{11}	13.1+0.4i	5.6+0.5i	107.84
C_{12}	6.97+0.11i	4.5+0.4i	54.76
C_{13}	6.97+0.11i	4.5+0.4i	54.76
C_{22}	63.7+3.1i	5.6+0.5i	107.84
C_{23}	20.4+0.82i	4.5+0.4i	54.76
C_{33}	63.7+3.1i	5.6+0.5i	107.84
C_{44}	21.6+0.86i	0.5+0.05i	26.54
C_{55}	3.9+0.11i	0.5+0.05i	26.54
C_{66}	3.9+0.11i	0.5+0.05i	26.54

propagation eigenfunctions in an infinite medium can thus be mapped to exponentially decaying eigenfunctions in the model with PMLs. Its direct implementations in a commercially available software package (COMSOL) can be found in a published joint journal article [132]. The use of PML approaches can significantly reduce the computational cost of the SAFE modelling and effectively get rid of many spurious modes, and the attenuation of guided modes along the waveguide can be represented by the imaginary part of the solved wavenumber.

Continuity of displacements and stresses was imposed at interfaces between the stiffener, the adhesive layer and the composite plate. Stress-free conditions were applied to the outer boundaries enclosing the whole domain. The entire geometry was meshed by quadratic Lagrange triangular elements, with finer element size in the stiffener section (including the stiffener, the adhesive bond, and the stiffened zone of the composite plate immediately underneath the bond). The total number of degrees of freedom is approximately 94,000, and the problem was solved in the frequency range from 50 to 200 kHz with a step of 10 kHz.

6.2.2 Typical mode shapes

In order to choose proper guided modes and operational frequency range for inspection, their modal properties were investigated through the SAFE calculation. The feature guided modes of interest are able to propagate with energy confined in and around the stiffener region, which can be identified by examining the axial component of the time-average power flow (i.e. acoustic Poynting vector [83]) of modes over the cross section. Its quantity can be calculated by the following formula at each nodal position:

$$P_{x_3} = -Re[(\frac{I\omega}{2})(u_1^*\sigma_{31} + u_2^*\sigma_{32} + u_3^*\sigma_{33})], I = \sqrt{-1}, \quad (6.1)$$

where σ_{31} , σ_{32} and σ_{33} are components of the axial stress; u_1^* , u_2^* and u_3^* denote the complex conjugates of the vertical, horizontal, and axial displacements of the modes, respectively.

Figure 6.3: Mode shape illustration of typical feature guided waves propagating along the stiffener, calculated by the SAFE method: (a) $L(1)$ mode at 150 kHz; (b) $SH(3)$ mode at 100 kHz; (c) $F(1)$ mode at 150 kHz; colour coding for each mode indicates the relative amplitude of axial power flow (blue: low to red: high).

Figure 6.3 illustrates the variation of power flow P_{x_3} around the stiffener region

of identified feature guided modes at particular frequencies. The arrows indicate the particle vibration in the cross section. It can be seen that the modes with varied vibrational patterns focus the energy either in the base or in the beam of the stiffener. To characterize such energy focusing phenomena, the modes were broadly categorized into three branches of feature guided waves according to their mode shapes. As shown in Fig. 6.3(a), the orthogonal displacement components were extracted along the thickness of the stiffened plate (white dashed line). Its mode shape indicates that the wave field is dominated by the axial displacement (in the x_3 direction), hence terms longitudinal (L) mode. Likewise, as shown in Fig. 6.3(b) and (c), the modes dominated by horizontal and vertical displacements were characterized as shear horizontal (SH) and flexural (F) modes, respectively. In the frequency range of interest, there are multiple modes in each of the family, and they are numbered according to their sequence to appear in the dispersion curve from low to high frequency. Noteworthy, the modal study of the composite assembly in this work has revealed the existence of much more wave modes and their even more complicated modal properties, as compared to that reported in the earlier work [57].

6.3 Mode Selection for Detecting Adhesive Defects

This section evaluates the performance of different FGWs in the composite structure and selects proper mode(s) for the bond line inspection. To achieve this, following criteria are suggested: (1) sufficient power flow in the bond layer; (2) little dispersion; (3) low attenuation; (4) easy to generate. They will be discussed in details in this section.

6.3.1 Power flow in the bond layer

To ensure the sensitivity of modes to bond line defects, there should be sufficient power flow in the bond layer, which can be calculated by the SAFE method. The

axial power flow P_{x_3} that can be obtained by Eq. (6.1) was first used to select potential modes. Fig. 6.4 shortlists several feature guided modes at different frequencies based on their distribution of P_{x_3} over the cross section. It can be seen that these candidates propagate with significant energy concentrated in the base of the stiffener, which might indicate that some of the wave's energy can enter into the adhesive bond underneath.

Figure 6.4: Potential feature guided waves sensitive to adhesive defects: (a) $SH(3)$ mode at 100 kHz; (b) $SH(4)$ mode at 160 kHz; (c) $L(2)$ mode at 150 kHz; (d) $L(1)$ mode at 150 kHz; colour coding shows the relative amplitude of axial power flow (blue: low to red: high); cutline (dashed) running through assembled components indicated; the stiffener-adhesive interface (dash-dot line) shown.

However, the amplitude of axial power flow within the bond layer is limited compared to that in the base of the stiffener. Thus the out-of-plane power flow P_{x_1} of these modes indicating the rate of energy transfer between the assembled components was examined, which can be calculated as

$$P_{x_1} = -Re\left[\left(\frac{I\omega}{2}\right)(u_1^*\sigma_{11} + u_2^*\sigma_{12} + u_3^*\sigma_{13})\right], I = \sqrt{-1}, \quad (6.2)$$

where σ_{11} , σ_{12} and σ_{13} are components of the vertical stress. Its quantity along a

typical cutline (vertical dashed line in Fig. 6.4(a)) running through the composite plate, the adhesive bond and the stiffener base is shown in Fig. 6.5(a). The amplitude of P_{x_1} of each mode was normalized by its own maximum value picked up along the chosen cutline. It can be observed that compared to other candidates, the SH(3) mode produces much larger out-of-plane power flow inside the bond layer, which means more efficient energy transfer exists between the adhesive bond, the stiffener, and the base plate. The defects occurred in the bond layer will be more likely to change the propagation of the SH(3) mode, and this mode is thus more sensitive to the adhesive defects. As shown in Fig. 6.5(b), the amplitude of P_{x_1} of each mode was also extracted along the stiffener-adhesive interface (horizontal dashed-dot line in Fig. 6.4(a)), normalized by its own maximum magnitude of the axial power flow P_{x_3} along the given interface, which is dominated in the base of the stiffener. The result confirms that the SH(3) mode possesses sufficient out-of-plane power flow in the bond layer, with its magnitude level more comparable to the axial power flow than other modes, and therefore has the best potential to interact with adhesive defects.

Figure 6.5: Variation of the amplitude of the out-of-plane power flow for the shortlisted FGW modes: (a) P_{x_1} along the cutline running through the assembled components, normalized by the corresponding maximum magnitude of P_{x_1} for each feature guided mode; (b) P_{x_1} along the stiffener-adhesive interface, normalized by the corresponding maximum amplitude of P_{x_3} .

6.3.2 Dispersion characteristics

The dispersion characteristics including the phase velocity and the attenuation of feature guided modes were calculated in the SAFE model from 50 to 200 kHz, and the results are shown in Fig. 6.6. In practical NDT/SHM techniques the favourable guided modes ought to be little-dispersive and low-attenuative in certain frequency range such that they can propagate long distances and the detected signals will be simpler to interpret. In this regard, the SH type modes from 100 to 150 kHz could be good candidates. Among them, the SH(3) mode of most potential, although having little dispersion, is quite attenuative below 100 kHz, which has also been validated in the experiment shown later. However, its attenuation decreases rapidly at higher frequencies, for instance, varying from 4.8 to 1.7 Np/m in the frequency range from 100 to 120 kHz, which makes its use possible for NDT and SHM applications.

Also, it is worth noting that in total four SH type feature guided modes have been found in the frequency range of interest. As indicated by examples (i.e. the SH(3) and SH(4) modes) shown in Fig. 6.4(a) and (b), a bending motion exists in the upper part of the stiffener, which is determined by the ratio of the wavelength to the length of the beam, thus yielding more possible higher order modes. In this wave family, different modes have varied shear deformation and energy distribution in the stiffener region. For example, the SH(1) and SH(2) modes at the investigated frequencies keep significant power flow in the beam of the stiffener rather than in the vicinity of the bond layer, thus making them less sensitive to the adhesive defects. More longitudinal and flexural guided modes have been identified at higher frequencies as well. This may cause multi-modal wave propagation along the stiffener if these modes have similar mode shapes and are thus excited simultaneously, which would create complications for the practical employment of the identified feature guided waves. Therefore, the excitability of the candidates has to be carefully examined.

Figure 6.6: Phase velocity (a) and attenuation (b) of identified feature guided wave modes propagating along the stiffened CF/EP plate, calculated by the SAFE method from 50 to 200 kHz.

6.3.3 Mode excitability

To visualize the wave propagation and to check the excitability of identified feature guided modes, three-dimensional time-domain FE simulations were carried out using the proprietary code Abaqus Explicit [137]. The FE model presented in Fig. 6.7

was created with the same cross-sectional geometry and material properties as in the SAFE model, and in accordance with the experiments as well. The carbon epoxy composite plate was modelled with a dimension of $800\text{ mm} \times 800\text{ mm} \times 1.6\text{ mm}$, including absorbing regions of 120 mm width on lateral edges. The stiffener and the composite plate were meshed by 8-node brick elements (C3D8R) with size of 0.4 mm along all three dimensions, while the bond layer was meshed by a finer element of 0.25 mm to ensure at least 3 elements in the thickness direction. Different parts were assembled by applying the surface-based tie constraints on the interfaces to enforce the continuity of displacements and stresses.

Figure 6.7: Schematic of the 3D FE model of a CF/EP plate (size: $800\text{ mm} \times 800\text{ mm} \times 1.6\text{ mm}$) with an aluminium T-shaped stiffener and the adhesive bond; shear excitation at the plate end, monitors and absorbing regions (width: 120 mm) shown; colour coding indicates the relative amplitude of resultant displacement of propagating modes at 100 kHz (blue: low to red: high).

The model was excited at the front edge of the stiffener base by a 5-cycle Hanning windowed toneburst, forcing in one of the orthogonal directions. The monitoring nodes were located on the top surface of the stiffener base as shown in Fig. 6.7, covering the distance range from 100 to 600 mm along the stiffener with a step of 0.4 mm . The set of time traces of different dominating motions was extracted and processed by the spatial two-dimensional Fast Fourier Transform (2D-FFT) [151]. The results of propagating modes are shown in Fig. 6.8, depicting the normalized

modulus in dB scale versus frequency and wavenumber. Excellent agreement can be observed in all cases between the wavenumbers obtained from the FE and the SAFE methods, hence the cross-validation between modelling results was achieved.

Figure 6.8: Normalized wavenumber-frequency spectra in dB scale, derived from the two-dimensional Fourier transform (2D-FFT) method: (a) forcing in the x_3 direction at 150 kHz; (b) forcing in the x_1 direction at 150 kHz; (c) forcing in the x_2 direction at 150 kHz; (d) forcing in the x_2 direction at 100 kHz.

Specifically, it can be seen from Fig. 6.8(a) that all three longitudinal modes were excited when applying the axial force (in the x_3 direction) at 150 kHz. Also, as their mode shapes contain out-of-plane components, these longitudinal modes were generated in the stiffener when the model was excited in the x_1 direction at 150 kHz, together with the flexural modes, as indicated in Fig. 6.8(b). It is foreseen that the multi-modal characteristics of F and L type modes make them difficult to be employed in the practical inspection. By contrast, as shown in Fig. 6.8(c), only higher order SH type modes, namely the SH(3) and SH(4) modes were generated

under the shear excitation (in the x_2 direction) at 150 kHz. Notably, as shown in Fig. 6.8(d), the SH(3) mode is capable of propagating in an attractive single-mode fashion along the stiffener when reducing the excitation frequency to 100 kHz. However, as predicted in Section 6.3.2, the use of the SH(3) mode would be constrained by much larger attenuation when the operational frequency is below 100 kHz, which agrees with its decreased wave modulus shown here at such frequency components. Also, as commonly done in ultrasonic NDT, the number of incident modes should be kept as small as possible in order to avoid too complex wave fields scattered by defects. Therefore, if the SH(3) mode is used, then the frequency should be chosen below the frequency cut-off of the SH(4) mode, which is about 120~130 kHz according to Fig. 6.6.

To summarize from the results shown in this section, the SH(3) mode from 100 to 120 kHz has the most potential to be explored for the bond line inspection in the particular structure investigated in this paper, because it has strong energy confinement around the bond layer, and propagates with little dispersion and relatively low attenuation, as well as being easy to excite with high mode purity.

6.4 Defect Scattering Study of the Selected Mode

In order to further evaluate the suitability of the selected SH(3) mode to the damage detection, and to confirm the optimal frequency range, its scattering by a local disbond has been studied in this section by the 3D FE simulation, and will be compared with experimental measurements shown later.

Figure 6.9 presents typical time snapshots of the scattered wave field of the SH(3) mode, with the colour contour indicating the relative magnitude of the resultant displacement. The notch-like defect (marked in red) was introduced to simulate the lack of adhesive over the whole thickness and width of the bond layer, running along the x_3 -axis with a length of 22.75 mm, which is around 0.8 times the wavelength of the selected incident guided mode. Its front edge is 450 mm away from the source. Figure 6.9(a) shows an instant of wave propagation right before encountering the

Figure 6.9: FE results of time snapshots of (a) the shear horizontal feature guide mode propagation along the stiffener excited at 100 kHz, (b) diffracted waves by the full-width adhesive defect (length: 22.75 mm; 450 mm from the source); and (d) reflected shear mode by the defect.

defect. It can be seen that the SH(3) mode propagates with the energy concentrated in the stiffener region, with A_0 waves leaking into the adjacent plate. Other plate wave modes (i.e. the S_0 , SH_0 , and A_0 modes) were also generated in the composite panel, which were damped by the absorbing region on the lateral edges. Figure 6.9(b) presents the snapshot of the SH(3) wave locally interacting with the defect, where the strong wave diffraction into composite base plate can be observed. A clear reflected signal by the defect can be seen in Fig. 6.9(c), which is guided by the stiffener as well.

To quantitatively study the reflection behaviour of the SH(3) mode, the reflection coefficient (RC) was calculated, in terms of a frequency domain ratio of the amplitude of the reflected wave to that of the incident wave. Normally it can be achieved by extracting the incidence and the reflection from the time domain signal monitored at a single point located between the generator and the defect [111,141,145,147,172]. In this chapter, a slightly different approach was adopted to quantify the reflection coefficient through the 2D-FFT processing. A set of time traces of the shear horizontal displacement was extracted from 851 monitors equally spaced along the stiffener base from 100 to 440 mm away from the generator. The 2D-FFT results from all monitoring points are presented in Fig. 6.10, showing the normalized amplitude-

Figure 6.10: Normalized wavenumber-frequency spectra (in dB scale) for both the incidence and reflection of the $SH(3)$ mode.

wavenumber-frequency information (in dB scale). It can be seen that both the positive and negative wavenumbers (k) were obtained, representing the incident and the reflected waves, respectively. The reflection coefficient can be calculated as follows. At a fixed frequency f_0 , the maximum FFT modulus (A_i) corresponds to the propagation mode at that frequency with the wavenumber k_0 . The amplitude of the reflected wave (A_r) can be obtained at the negative wavenumber $-k_0$. Hence the reflection coefficient at f_0 can be calculated as

$$R(f_0) = 10^{(A_r - A_i)/20}. \quad (6.3)$$

The calculated RC as a function of frequency is shown by the red solid curve in Fig. 6.11(a). Noteworthy, in the scattering of guided waves (e.g. SH_0 mode) in flat plates, the frequency dependent RC can normally be presented with defect length (L) expressed as a fraction of the input wavelength (λ), thus substituting the frequency with L/λ ratio. However, when it comes to the FGWs, the frequency will affect more factors concerning the reflection behaviour, such as the extent of energy concentration and mode shapes, and hence is preferred when describing their RC

spectra.

Figure 6.11: Shear mode reflection coefficient spectra for (a) full-width and half-width adhesive defects (L : 22.75 mm; T : 0.75 mm); (b) full-width adhesive defects with varied lengths (T : 0.75 mm); (c) full-width adhesive defects with different bond thicknesses (L : 0.8λ).

It can be seen from Fig. 6.11(a) that the RC rises as the frequency increases and reaches a maxima at about 106 kHz. Its amplitude starts to decrease as the frequency keeps increasing, and a local minima is obtained at around 112 kHz. Reducing the width (W) of the adhesive defect by half with its length (L) and thickness (T) unchanged, the RC spectrum was obtained in a similar manner and is shown by the black dashed line, which keeps a consistent trend with that of the full-width defect, but has much smaller magnitude. The oscillation in RC spectra is mainly caused by the interference between the reflections from the front and back edges of the disbond area, and their superposition in the resulting reflected wave packet may be constructive or destructive. Similar phenomena have been reported in the scattering of the SH_0 mode in plates [145, 147] and also of the feature guided modes

in welds [111] and bends [136].

Figure 6.12: (a) Phase velocity and (b) attenuation dispersion curves for the SH type FGW modes existing in the assembly with varying bond thicknesses.

In order to further understand the influence of the defect geometry on the reflection behaviour, a parametric study was carried out by varying the defect length and the bond thickness in 3D FE simulations under the same excitation. It can be observed from Fig. 6.11(b) that the amplitude of RC increases with the length of defect when fixing its width (full width) and thickness (T: 0.75 mm). Also, a realistic variation of the bond thickness between 0.5 mm and 1.0 mm was investigated in the SAFE model. The dispersion curves of the SH type FGW modes are presented in Fig. 6.12. As for the selected SH(3) mode, the variation in bond thickness will not affect the overall shape of its dispersion curves and suitable frequency range for the bond line inspection in the particular structure. As the bond thickness doubles, the average change in the phase velocity is about 5% from 100 to 120 kHz, and the average variation in attenuation is less than 20%, over the same frequency range. Different bond thicknesses, i.e. 0.5 mm, 0.75 mm, and 1.0 mm were defined in the 3D FE models, and full-width adhesive defects were created throughout each bond thickness with the length in a fixed proportion to the input SH(3) wavelengths ($L: 0.8\lambda$). Their RC spectra with respect to the frequency are compared, as shown in Fig. 6.11(c). It can be seen that the amplitude of RC increases as the bond thickness decreases, and the RC obtained for the case of 0.5 mm is 10% ~14% in the frequency range of

interest, much greater than that of 0.75 mm.

Figure 6.13: Variation of the amplitude of normalized out-of-plane power flow of the $SH(3)$ mode for different bond thicknesses: (a) P_{x_1} along the cutline running through the assembled components; (b) P_{x_1} along the stiffener-adhesive interface.

To explain this, the out-of-plane power flow of the selected mode in such bonds was calculated by the SAFE method, in a similar manner to that demonstrated in Section 6.3.1. As shown in Fig. 6.13(a) and (b), the amplitude of P_{x_1} of each case was extracted along the vertical cutline and horizontal interface (depicted in Fig. 6.4(a)) respectively, which was normalized by its own maximum value of P_{x_1} and P_{x_3} at given positions. It can be confirmed that larger out-of-plane power flow is produced by the $SH(3)$ mode within the 0.5 mm thick bond layer, thus causing stronger interaction with the adhesive defect and greater reflection coefficient.

6.5 Experiments

6.5.1 Experimental setup and procedure

The experimental setup is shown in Fig. 6.14. The composite plate (dimensions: 500 mm $\times$ 900 mm $\times$ 1.6 mm) was manufactured by laminating 8 plies of unidirectional carbon epoxy prepregs (Hexcel Inc.), containing the T800S carbon fibres embedded

in the M21 epoxy resin, with a quasi-isotropic $[0/45/90/-45]_s$ stacking sequence. The bonded T-shaped aluminium stiffener has the same cross-sectional geometry as that had been studied in the modelling, and its length is 900 mm. A two-component epoxy adhesive consisting of a premium resin Araldite GY-784 and an Aradur 125 curing agent, was used to bond the stiffener to the composite plate.

Figure 6.14: (a) Photograph of experimental setup; monitoring line, illustration of laser beam and reference coordinates depicted; (b) two shear transducers coupled at the end of the stiffener; contact positions indicated; (c) distribution of the normalized in-plane displacement (u_2) of the SH(3) mode over the stiffener region, derived from the SAFE calculation at 100 kHz; the positive and negative signs indicate the shear motion in opposite directions.

The bond line was properly cured and controlled to have almost constant thickness along the length of the stiffener (i.e. x_3 -axis), measured as 0.737 mm with about $\pm 9\%$ accuracy (the thickness of 0.75 mm was used in the modelling). The adhesive bonding is continuous throughout the interfaces except at an artificially created full-width local disbond area with the length of 24 mm, starting 308 mm from the excitation location. This defect was made with a metal foil wrapped in a self-

adhesive paper on one side and releasing on the other. Its whole thickness is very close to the thickness of the adhesive bond, while its length is longer than the width of the joint. This resistant and slippery insert was removed from the bond when the adhesive is approximately hardened to 70% ~80% of its strength.

Figure 6.15: Typical experimental time traces measured along the base of the stiffener.

As shown in Fig. 6.14(b), two shear transducers (manufactured by Guided Ultrasonics Ltd.) producing in-phase orthoradial displacements (u_2) were coupled to the edge of the stiffener, at x_1 positions where the targeted SH(3) mode is supposed to have such in-phase shear motion. For the purpose of reinforcing the excitation of wanted wave mode, the lower transducer was mounted to the base of the stiffener and to the adhesive bond as well, and the upper transducer was positioned at a height of about 14 mm above the top surface of stiffener base, according to the mode shape of the SH(3) mode illustrated in Fig. 6.14(c). The excitation signal sent to both transducers is a 5-cycle Hanning windowed toneburst centred at 100 kHz with an amplitude of 200 V (peak-to-peak voltage). The displacements produced by the SH type guided waves were measured using a Polytec Doppler velocimeter of $0.005 \text{ ms}^{-1}/\text{V}$ sensitivity. To pick up the dominant in-plane displacement u_2 , the laser probe was oriented at 30° with respect to the vertical direction (actually $u_2 \sin 30^\circ$ is detected). A retro-reflective tape was attached to the base of the stiffener for en-

hancing optical backscattering of the laser beam. The monitors along the stiffener cover the x_3 positions from 25 to 590 mm with a distance step of 1 mm, and 200 times averaging was applied to the time history of the measured response.

Figure 6.15 shows typical time traces measured along the propagation path, from $x_3=25$ mm (the source is at 0 mm) to $x_3=590$ mm including $x_3=320$ mm, which is the central position of the adhesive defect. Both the incident and reflected signals were monitored. As predicted in Section 6.3.2, the wave mode propagates with little dispersion along the stiffener, which is beneficial to its practical employment for the bond line inspection. Also, the amplitude of the signals decays with the propagation distance, mainly resulted from the leakage of the guided mode and the material damping. Notably, in the time trace monitored at the defect centre some wave oscillations exist after the incident wave, indicating some wave trapping phenomena occurred in the defect area. This will be explained later for the localization of the adhesive defect.

6.5.2 Comparison of experimental results with modelling

The experimentally measured phase velocity dispersion curves are shown by diamond and plus sign markers in Fig. 6.16(a), in comparison with the SAFE predictions (solid and dashed curves) obtained in Section 6.3.2. Excellent agreement can be found between these results, thus quantitatively validating dispersion characteristics of the excited modes.

It can be seen that other SH type modes besides the targeted SH(3) mode were also launched experimentally. This may be due to that the upper transducer coupled to the stiffener beam had reinforced not only the SH(3) mode, but also the SH(1) and the SH(2) modes which produce large shear horizontal displacements on the beam as well, as shown in Fig. 6.16(b). Whereas the SH(1) and SH(2) modes produce almost no wave energy (including both the axial and out-of-plane power flow) in the vicinity of the adhesive layer, thus ought to have negligible interaction with the defect in the adhesive layer. By contrast, the SH(3) mode carries sufficient power

Figure 6.16: (a) Experimentally measured phase velocity dispersion curves in comparison with the SAFE predictions; both forward and backward running waves shown; (b) wave structures (deformation) of the SH(1) and the SH(2) modes over the cross section, calculated from the SAFE model at 100 kHz; arrows indicate the dominant vibration motion.

flow along the adhesive layer (illustrated in Section 6.3.1), so that the scattering occurring at the adhesive defect is mainly caused by the SH(3) mode. This can be confirmed by the backward propagation shown by plus sign markers in Fig. 6.16(a), which indicates that the reflected SH(3) wave plays a primary role in the measured reflected wave packet, behaving very similarly to its incidence. Therefore, from the perspectives of wave reflection, the guided mode interacting with the adhesive defect can be considered as a pure SH(3) mode, as in the FE model.

Figure 6.17 shows the RC spectra calculated by both the 3D FE simulation and the experiment, using the 2D-FFT method illustrated in Section 6.4. close agreement in the order of RC magnitude can be observed between the experimental measurements and the numerical predictions. In the 3D FE simulations, the material damping is

Figure 6.17: *Measured reflection coefficient spectrum for the full-width adhesive defect (length: 0.8λ), compared with the FE result.*

not considered. Since the operational frequencies used here are relatively low, it is not necessary to take viscoelasticity into account in the FE model for the numerical predictions to fit the experimental measurements. The dissimilar oscillation pattern in the measured RC spectrum is probably caused by the three incident modes. As indicated in Fig. 6.16, the incident SH(2) and SH(1) waves could not be eliminated in the experiments, and due to the limited length of the monitoring line (230 mm used) between the defect and the emitting PZT transducer, the three detected incident modes were not sufficiently resolved in the wavenumber domain, thus causing the disturbances in the estimation of the amplitude of the incident SH(3) mode, ultimately leading to the oscillations observed in the experimentally measured RC spectrum. Nevertheless, as the incident SH(3) mode has dominant amplitude compared to both other modes, the estimation of its amplitude is not so erroneous, and the order of the magnitude of the measured RC is then very close to that of the predicted RC.

Also, it should be noted that the reflection coefficient shown here (about 8%) can be larger when the launched SH(3) mode interacts with larger adhesive defects or as the epoxy bond thickness decreases, as discussed in Section 6.4. In this study, the 0.8λ

defect length and the 0.75 mm bond thickness are representative values chosen for investigation, and the feasibility of examining the reflection behaviour from 100 to 120 kHz for the bond line inspection is well demonstrated in the particular structure.

Figure 6.18: *Energy contained by temporal signals picked up along the propagation path (on the top surface of stiffener base): (a) experimental results; (b) FE results; defect area indicated by grey band.*

As mentioned in Section 6.5.1, another approach for identifying the adhesive defect has been exploited, by calculating the amplitude of wave energy along the propagation path. According to the Parseval's theorem [164], the total energy (E) of a signal can be obtained based on the following relation:

$$E = \int_{-\infty}^{\infty} |s(t)|^2 dt = \int_{-\infty}^{\infty} |S(f)|^2 df, \quad (6.4)$$

where $S(f)$ denotes the Fourier transform of the temporal signal $s(t)$. Numerically, applying the discrete Fourier transform (DFT) on filtered or windowed temporal signals, the relation becomes:

$$E = df \sum_{k=1}^{N_{FFT}} |S[k]|^2, \quad (6.5)$$

where k is the index of the frequency sample, such that $f[k] = kdf$ (k varies from 0 to $N_{FFT} - 1$); $df = f_e/N_{FFT}$, f_e being the sampling frequency. Hereby the wave energy was calculated in both the 3D FE simulation and the experiment over the distance range from $x_3 = -150$ mm to $x_3 = +150$ mm with respect to the defect centre. The results are separately shown in Fig. 6.18(a) and (b), and agree quite well. Local peaks of the energy can be observed in the defect area, which can be explained that when the guided waves pass the adhesive defect, part of the wave energy is trapped, with the waves bouncing back and forth inside the disbond area, ultimately leading to a wave-defect resonance. Similar phenomenon was observed in the scattering of guided waves by the delamination in composites [155, 156]. The energy-space distribution can be readily employed for the defect localization in the bond layer.

6.6 Summary

Intended for the quick inspection of defects in the bond line between a stiffener and a composite panel, FGWs confined to the stiffener section have been investigated by using the SAFE method. Through the modal analysis, the performance of different FGW modes existing in such structure has been evaluated, and the criteria to select proper mode sensitive to adhesive defects are suggested. A SH type FGW (i.e. the SH(3) mode) has been identified to be well suited. The mode has sufficient power flow in the bond layer and is little-dispersive and low-attenuative, as well as easy to generate. Both 3D FE simulations and experiments are carried out to study the interaction between the selected FGW and a local disbond located in the adhesive layer. Close agreement has been observed between the numerical predictions and experimental measurements, thus the exploited modelling methods have been validated. To quantify the defect scattered wave field, both the reflection coefficient spectra and the wave energy along the propagation path are calculated, identifying the adhesive defect between the stiffener and the composite panel. The capability of the FGW for inspecting the bond line defects is well demonstrated.

The investigation methodology for mode selection demonstrated in the chapter can

be used to evaluate the performance of FGWs for inspecting adhesives bonds existing in more complicated assemblies, such as with composite stiffeners or between more complex shapes, which are increasingly utilized in the aerospace industry. In addition, this work has laid a foundation for the development of FGW based SHM techniques using integrated ultrasonic sensors, for the purpose of *in-situ* testing.

Chapter 7

An Extended Study: from NDT to SHM

7.1 Background

Chapters 4~6 have extended the investigation of feature guided waves (FGW) to composite structures, which are either complex-shaped laminated components or adhesive composite joints with complex geometries. The identified FGWs with strong mode confinement have been used as a screening tool for rapid inspection of long-range composite structural features, so that their NDT capabilities have been manifested. This chapter launches another phase of FGW studies by exploring its exploitation in a structural health monitoring (SHM) system.

The SHM technique is different from the non-destructive evaluation (NDE) process, and the key difference between NDE and SHM probably lies in the implementation of sensing. The former normally uses movable transducers while the latter prefers permanently installed built-in sensors. Also, the NDE mainly aims at identifying defects in a structure over space. Whereas the SHM involves the observation of the structure over time using spatially-spaced measurements, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health [173]. The long-term

SHM process periodically evaluates and updates the system information with regard to the ability of the structure to continue to perform its intended function, considering the inevitable ageing and damage accumulation resulted from operational environments. On the other hand, the condition-based SHM process, inspired by more cost-effective maintenance philosophies, monitors the system response for rapid condition screening under scheduled (e.g. aircraft landing) or unscheduled discrete events (e.g. earthquake or blast loading) and then reports warnings about the detection of defects. It accordingly requires more sophisticated interpretation of the measured data [174].

SHM using ultrasonic guided waves is one of the most attractive detection mechanisms [107,175], which features the combination of a reasonable sensitivity to damage and significant propagation range. In such guided wave based SHM systems, substantial efforts have been devoted to the design of transducers [176–182], the mode-frequency selection [35,51], signal processing techniques [183–186] as well as pattern recognition strategies [187,188]. The typical configuration of these systems is that a sparse array of sensors is permanently attached to or embedded [189,190] in the test structure to excite the desired wave modes and to receive the scattered signals, and localized damage occurring anywhere in the structure can then be identified by interpreting the captured wave signals.

In principle, these sensors work either in the pulse-echo mode or in the pitch-catch mode, and defects are detected by the appearance of a new reflected signal or a new diffracted signal, respectively. Both cases would largely rely on the reference (or baseline) signal subtraction [107,191] for detecting the damage. The reference signals contain the reflections from structural features as well as from boundaries of the structure, in the absence of critical defects. Subtraction of a current signal from such a baseline will eliminate the coherent noise, and the residual signals will only contain changes in the signals that are caused by defects. This potentially allows for guided wave monitoring of complex structures [192,193], in which the quality of baseline subtraction critically influences the sensitivity of the SHM system to defects [107]. However, the optimal baseline subtraction is often difficult to achieve,

since environmental effects such as stress [194], ambient temperature variation [195], and liquid loading will affect the velocity and the amplitude of guided waves by modifying the received time traces, which ultimately leads to mistaken residual signals for damage. Among these effects, temperature variation is most commonly encountered, which has been shown to cause significant errors in the baseline subtraction SHM approach [196]. It will require complicated temperature compensation strategies [197–199] to ensure the accuracy of residual signals after subtraction. In this regard, SHM schemes which can be implemented free of baseline subtraction may be more practically applicable.

More importantly, in conventional SHM of plate-like structures, some topographical features such as welds, flanges, bends, and stiffeners are always regarded as interference causing ‘coherent noise’ in the received signals. When the structure has a high feature density, the associated signals will merge together obscuring the scattered waves by defects, which makes the identification of damage in such structure very challenging. This problem becomes even worse as the damage occurs in or close to these structural features. Under such circumstance, this chapter proposes a novel FGW based SHM strategy, in which the proper FGWs are used as a screening tool to rapidly interrogate the structural feature and an array of sensors around such feature is used to capture scattered waves from the localized damage. This technique is combined with an imaging approach, and the damage reconstruction is achieved by the synthetic focusing algorithm using these scattered signals.

The chapter specifically deals with the case of monitoring defects in the bond line between a carbon fibre/epoxy (CF/EP) panel and a metallic stiffener. The existing FGW modes and the defect scattering using selected SH type mode in this structure have been carefully examined in Chapter 6. The results suggest that there may exist practical difficulties in measuring the reflected FGWs due to the relatively low magnitude, which can be caused by small reflectivity of the defect and damping effect arising from viscoelasticity and heterogeneity of composites, as well as viscoelasticity in the adhesive. However, as indicated from the defect scattering demonstrated in Section 6.4, strong diffracted waves had been generated when the selected FGW

locally interacted with the adhesive defect. These diffraction signals can be recorded by sensors placed in the vicinity of the bond line on the composite base plate, so that they can be obtained with larger amplitude than that of the reflected waves. Furthermore, the proposed SHM scheme using such diffraction from defects can be implemented free of rigorously subtracting the baseline signals, showing practical potential in the SHM of adhesive composite joints.

The chapter is structured as follows. The diffracted wave field from the adhesive defect is quantitatively studied by 3D FE simulations. Then, principles of the synthetic focusing approach are demonstrated, and this method is exploited to reconstruct the entire bond line area. Experiments are performed to validate the modelling results, showing good agreement. Following that, parametric studies of the defect size and the sensor density are carried out to evaluate the performance of such imaging algorithm for damage identification. Without loss of generality, the FGW based SHM scheme is used for composite structural bends as well, and the axial crack introduced in the bend region can be identified clearly. The SHM work conducted in the present chapter has also been published in a journal paper [200].

7.2 SHM Scheme Using Diffraction from Defects

A proof-of-concept study of the SHM application was first performed in the 3D time-marching FE simulation. The FE models were created with the same parameters as that had been investigated in Chapter 6. It was demonstrated previously that the SH(3) mode in the frequency range 100~130 kHz is sensitive to defects in the adhesive due to its large out-of-plane power flow within the adhesive, which indicates high energy transfer rate among the assembled components. It was also found that the interaction of the mode with the defect caused considerable diffraction in the base plate. Thus, the SH(3) mode was chosen for the SHM purpose in the present study. This section quantitatively examines such diffracted wave field, which is intended for defect reconstruction using the synthetic focusing approach. In order to cover the frequency range of interest, the model was excited by a 10-cycle Hanning

windowed toneburst centred at 120 kHz, as illustrated in Fig. 7.1. The force in the x_2 direction was applied to the front edge of the stiffener base.

Figure 7.1: Illustration of the FGW based SHM scheme in the 3D FE simulation (plate size: 800 mm×800 mm×1.6 mm); diffracted waves from the adhesive defect, shear excitation at the stiffener end, and the configuration of monitors shown.

Figure 7.1 shows a typical time snapshot of the scattered wave field of the excited SH(3) mode. The colour contour denotes the relative amplitude of the resultant displacement. A similar notch-like adhesive defect (marked in red) was introduced into the bond line with its near end 450 mm away from the excitation location, running along the x_3 axis with a length of 23 mm. It can be seen that strong diffracted waves were generated as the launched FGWs locally interacted with the adhesive defect, propagating in the composite base plate. The leaky A_0 waves were also radiated in the base plate, and the leakage angles are dependent on the phase velocity ratio between the A_0 mode and the SH type FGW modes, according to the Snell's law, in a similar manner to that had been demonstrated in Section 3.3.4.

To measure the diffracted waves, two linear arrays of monitors were set on the base plate, symmetric about and parallel to the stiffener axis, covering the x_3 positions from 100 mm to 700 mm with the required spacing. Noteworthy, for such moni-

toring, the distance between the array of sensors and the feature should be carefully selected to avoid the incident FGWs, which will interfere with the received diffracted signals. The distance could be 2~3 times the longest wavelength of the diffracted plate modes, although a more reasonable distance may be determined by referring to the extent of energy concentration of the FGW modes in and around the feature area. Hereby the distance was chosen as 100 mm.

Figure 7.2: Orthogonal displacement components extracted from a particular monitoring point $((x_2, x_3)=(300, 600)$ mm, marked with a star in Fig. 7.1) in FE simulations; both the reference and diffraction signals shown.

Typical time traces of the diffracted waves were extracted from a particular monitoring point in the array, i.e. $(x_2, x_3)=(300, 600)$ mm, in comparison with the signals obtained from the reference state, as shown in Fig. 7.2. The reference signals were extracted from the corresponding 3D FE simulation in the absence of adhesive defects, under the same excitation. As indicated from the time traces, the S_0 and SH_0 waves directly from the source arrive first (which will be damped by the absorbing region on lateral edges), and they are followed by a diffracted wave packet possessing large in-plane displacement components U_2 and U_3 . As it is dominated by both

in-plane displacements, the main contribution to the diffracted wave field should be from S_0 and SH_0 waves. The A_0 waves leaked from the incident FGWs were also captured, lagging behind the first arrival of the diffraction. As indicated from the comparison of the out-plane displacement U_1 , a slight deviation from the reference signals can be observed, which may be caused by the possibly diffracted S_0 waves having small out-of-plane components, or by the defect's immediate effect on the leakage.

Figure 7.3: (a) Arrangement of a slanted monitoring line along the 38° direction with respect to the stiffener axis to measure the diffraction from the adhesive defect; (b) normalized wavenumber-frequency spectra (in dB scale) of the diffracted wave field, in comparison with SAFE predictions (dashed lines).

In order to understand explicitly the mode components contained in the diffracted wave packet, another set of 251 monitors was placed along the diffraction direction (approximately along the 38° direction with respect to the stiffener axis) to measure it, with an averaged space step of 0.65 mm, as illustrated in Fig. 7.3(a). The set of time traces of U_2 was used, subtracting the reference signals (derived from a separate defect-free FE simulation), and was then processed by the 2D-FFT technique. The calculated wavenumber-frequency spectra are shown in Fig. 7.3(b), compared with predicted dispersion curves of plate modes by the SAFE method. It can be clearly observed that the diffracted wave field is dominated by the SH_0 mode which is non-dispersive in the frequency range of interest, and the S_0 mode was also diffracted but with much lower magnitude. In addition, the small difference

of the in-plane displacement of the leaking A_0 mode (compared with the reference state) was also captured. Its wavenumbers are in close agreement with that of the A_0 mode projected onto the diffraction direction. With the known scattered wave field, the reconstruction algorithm can then be applied to image the feature area.

Figure 7.4: (a) Energy velocity and (b) attenuation of the SH type feature guided modes, calculated by the SAFE method from 50 to 200 kHz; frequencies of interest indicated by the grey band.

Another important parameter that will be used in the reconstruction phase is the energy velocity of feature guided modes. The energy velocity (V_e), rather than the group velocity, is the speed at which a wave packet travels in a viscoelastic medium or in a leaky system, which has been explained in Section 2.4.2. In a guided wave based NDT/SHM system, energy velocity is of use for determining the spatial position (r) of a defect or structural feature from the corresponding arrival time (t_{arr}) of a temporal signal, according to the relation $r = V_e t_{arr} / 2$, if the transducer operates in the pulse-echo configuration. It is also an essential parameter for implementing damage localization algorithms [184, 193, 201] which combine all the information collected from a sensor network to spatially localize the defect.

Hereby, the energy velocity of the SH type FGW modes was calculated by the SAFE method as a ratio between integration of axial power flow (in the wave propagation direction) over the domain of interest and integration of the energy density over the

same domain, according to Eqs. (2.15), (2.16), and (2.17). The stiffener section was chosen as the integration domain, which includes the stiffener, the adhesive bond, and the stiffened zone of the base plate. Both the energy velocity and attenuation dispersion curves are shown in Fig. 7.4, which confirms that the SH(3) mode at chosen frequency range has relatively small dispersion and low attenuation and can therefore propagate along the bonded stiffener over long distances, without causing much distortion to the shape of its wave packet.

7.3 Synthetically Focused Imaging

Upon understanding the scattered field from a typical defect, a reconstruction technique is proposed to image the object space, which is the bond line area in the present case. This section explains principles of the applied imaging algorithm, i.e. the synthetic focusing method, based on which an adhesive defect is reconstructed in the 3D FE simulation. The implications of the imaging results are analysed as well.

The synthetic focusing approach converts the signals recorded from the scattered wave field into coherently enhanced intensity at the scatterer locations in the image, and the image of the entire object space can be reconstructed from a single data acquisition. As reported in the literature, considerable efforts have been made to such post-processing of array data by using bulk waves [202–204], and it has also been exploited successfully in guided wave systems for imaging defects occurring in metallic plates [178, 205, 206] and pipes [207].

Figure 7.5 schematically illustrates the synthetic focusing process in the FGW based SHM system. An array of equi-spaced sensors is set parallel to the structural feature, running along the x_3 direction. The aperture of length a is sampled with the interval Δx_3 and contains $N = a/\Delta x_3 + 1$ sensors. Since the diffracted wave field is dominated by the SH_0 mode (demonstrated in Section 7.2), the displacement component in the x_2 direction is extracted from each monitored signal. Hence the scattered wave field $g(t, x_2^R, x_3^R)$ received at the array is a 2D data set over time t

Figure 7.5: Illustration of the principle of the synthetic focusing approach by using the diffraction of feature guided waves propagating along the bond line.

Figure 7.6: Illustration of the complex-valued signal amplitude (envelope) contributed to the intensity of separate damaged and undamaged pixels.

and linear transducer position (x_2^R, x_3^R) , which will be transformed into an image data set $I(x_2, x_3)$ of the entire bond line.

The post-processing algorithm proceeds by first discretising the bond line (in the x_2 - x_3 plane) into a grid. The signals from all the sensors are then summed to synthesize a focus at every point in the grid. Specifically, assume each pixel (x_2, x_3) in the bond line as a scatterer. The complete propagation path consists of the FGW (i.e. SH(3) mode) propagating from the source to the scatterer (distance: d_1)

and the diffracted guided waves (i.e. SH_0 mode) that travel from the scatterer to the receivers (distance: $d_2^{(i)}$, $i = 1, 2, \dots, N$). Then the intensity $I(x_2, x_3)$, at any pixel can be obtained as a sum of the amplitude of individually received signals at corresponding arriving time, which can be expressed as

$$I(x_2, x_3) = \left| \sum_{i=1}^N H_{x_2^R, x_3^R} (t_{arr}^{(i)} + T/2, x_2^{R(i)}, x_3^{R(i)}) \right|, \quad (7.1)$$

$$t_{arr}^{(i)} = d_1/V_{e1} + d_2^{(i)}/V_{e2},$$

where $H_{x_2^R, x_3^R}$ represents complex envelope of the temporal signal $g(t, x_2^R, x_3^R)$, derived by applying the Hilbert transform [208]; V_{e1} and V_{e2} are the energy velocities of the SH(3) mode and the SH_0 mode, respectively. The arrival time t_{arr} can be obtained with reasonably good accuracy, as the SH(3) mode is less-dispersive and the SH_0 mode is non-dispersive in the frequency range of interest. The addition of $T/2$ (T is the duration of the excitation signal) to the arrival time corresponds to the extraction of the peak amplitude in the diffraction envelope. The associated two propagation distances d_1 and d_2 can be given as

$$d_1 = |x_3|, \quad d_2^{(i)} = \sqrt{(x_2 - x_2^{R(i)})^2 + (x_3 - x_3^{R(i)})^2}. \quad (7.2)$$

Figure 7.6 further explains the implementation of the reconstruction algorithm by extracting damage-sensitive features to produce an image. In principle, different complex-valued amplitude of the envelope of a received temporal signal will be used to calculate the intensity of pixels corresponding to the damage and the intact area. The time trace of U_2 displacement shown in Fig. 7.2 was chosen as an example, which was recorded by a particular sensor in the array. If the pixel to be imaged is located in the damaged area in the bond line, high signal amplitude corresponding to the diffracted waves will be selected, otherwise, somewhere else on the envelope will be picked up to contribute to the intensity of this pixel. It can be predicted that by repeating such feature extractions over all the sensors, only the pixels corresponding to the real damage will have a coherent summation of the diffracted waveforms. Whereas the pixels corresponding to the undamaged area will have an

addition of incoherent data with randomly selected phase information, which leads to destructive interference and ultimately low intensity in the image.

Figure 7.7: Imaging results obtained from the FE data (in dB scale): (a) the complete image of the bond line ($x_2 : 390 \sim 410$ mm, $x_3 : 0 \sim 800$ mm), with the geometry of the base plate (size: 800 mm $\times$ 800 mm) as well as the configuration of receivers (red circles) depicted; (b) image zoomed around the damage indication; the actual contour of the adhesive defect ($x_2 : 390 \sim 410$ mm, $x_3 : 450 \sim 473$ mm) indicated by the red dashed rectangle; (c) image intensity extracted along the central bond line axis $x_2 = 400$ mm.

Figure 7.7 shows the FE imaging results of an adhesive defect whose location and geometry have been described in Section 7.2. The excitation signal used here is a 5-cycle toneburst centred at 100 kHz. Two linear arrays of receivers were placed on either side of the bond line, as presented in Fig.7.7(a). The space step between receivers is 40 mm, which is greater than one wavelength of the diffracted SH_0 mode at 100 kHz. The pixel size was set as 1 mm for the synthetically focused image of the bond line. The intensity of image pixels was normalized by its maximum value over the whole bond area except the portion near the source, and the relative magnitude is shown in dB scale. It is worth noting that although baseline subtraction was used previously to determine wave components in the diffraction packet, it is no

longer involved in both FE and experimental imaging processes, which enables this approach more applicable in practice.

Figure 7.8: Comparison between the image intensity derived from processes without baseline subtraction (solid) and with baseline subtraction (dashed-dotted).

As evident from Fig. 7.7(a), (b) and (c), the adhesive defect has been readily identified at the pixels with much enhanced intensity, and the positions of the first two indications agree very well with the near and far ends of the defect. Furthermore, the indication corresponding to the far end has higher intensity, as it is mainly contributed by much stronger forward diffractions from the defect. In addition, there exists another indication in the image, occurring beyond the far end of the defect, which is probably caused by the second or even third diffraction from the far end. It can be explained that when the FGWs propagate through the local disbond area, part of the wave energy is trapped, bouncing back and forth between two extremities of the defect (as demonstrated in Section 6.5.2), and multiple diffractions also take place at the ‘exit’. Every time the trapped waves interact with the boundaries of the defect, some wave energy will be radiated into the adjacent plate (i.e. diffraction) besides the portions of transmission and reflection. Thus, there is certain time delay between these distinct diffracted waves, showing progressive decrease in the amplitude. This can be supported by the diffraction signals presented in Fig. 7.2

that there indeed exist scattered waves of smaller amplitude propagating right after the main diffraction packet.

It is worth noting that although the baseline subtraction was implemented in Section 7.2 to study the diffracted wave field, it is no longer necessary to be used for reconstructing the defect in both the FE simulation and the experiment. To illustrate this, the imaging results obtained with and without baseline subtraction are compared in Fig. 7.8. It can be seen that the noise contained in the image can be reduced through the baseline subtraction, while it does not affect the damage indication much, so that the synthetic focusing algorithm can be applied free of rigorously subtracting baseline signals, which is attractive to its practical employment.

7.4 Experimental Validation

7.4.1 Experimental setup

The experimental setup is shown in Fig. 7.9. The same tested composite structure with a pre-defined adhesive defect as had been studied in Chapter 6 was used here for the SHM purpose. Similarly, two shear transmitters (in-phase configuration) were coupled at the edge of the stiffener to excite the selected SH(3) mode. They were driven by a gated amplifier (Ritec GA2500) producing a 5-cycle Hanning windowed toneburst centred at 100 kHz with an amplitude of $400 V_{p-p}$.

Two arrays of shear PZT sensors were permanently attached to the composite panel on either side of the stiffener for measuring the in-plane wave motion in the x_2 direction. The sensor is a thickness-shear (d_{15}) mode PZT-5A wafer with dimensions of 13 mm×3 mm×1 mm, and its polarization is along the 3 mm direction. The distance between the central axis of the stiffener and either PZT array is 100 mm, and their x_3 positions start from 200 mm to 560 mm away from the source (at $x_3 = 0$ mm), with a sensor spacing of 40 mm, which is in accordance with that used in the FE imaging. The notch-like local disbond was created at $x_3=308$ mm, with

Figure 7.9: (a) Photograph of experimental setup; transmitters coupled at the end of the stiffener and PZT sensors pasted on the surface of the composite panel (dimensions: $500\text{ mm} \times 900\text{ mm} \times 1.6\text{ mm}$) shown; (b) illustration of the adhesive disbond location, the spacing between PZT elements, and the used reference coordinates for the SHM scheme.

almost the same size as that studied in the FE simulation, so that the arranged PZT arrays are able to effectively capture the diffracted waves from the defect. During the measurement, a gain of 40 dB and a band-pass filter (frequency range: 30~500 kHz) were also applied to the received signals to improve the signal to noise ratio.

7.4.2 Experimental results

Typical temporal signals measured by the two PZT sensors ($x_3=480\text{ mm}$) on either side of the stiffener are compared in Fig. 7.10. Generally, the signal monitored by the left-hand side (LHS) sensor has higher amplitude than that measured by the right-hand side (RHS) sensor, which may be due to the non-uniform adhesive bond running along the stiffener (bonding quality might be better along one side than the other).

Data sets derived from both PZT arrays were used for imaging. Since the diffraction process from damage is not exactly symmetrical about the centre axis of the feature, separate coherent summations over the responses from each sensor array were performed to form images I_{LHS} and I_{RHS} , and then an incoherent sum of these image intensities was implemented to achieve the final image, i.e. $I_{final} = |I_{LHS}| + |I_{RHS}|$.

Figure 7.10: Typical time traces measured by PZT sensors on either side of the stiffener; the SH_0 wave and diffracted waves as well as edge reflections labelled.

The combined imaging results are shown in Fig 7.11. The defect indication with high intensity can be observed, and its location aligns well with that of the far end of the defect. However, such damage indication is surrounded by some other image indications of comparable amplitude. This may be due to the fact that multiple diffractions radiated from the far end are enhanced by the scattered waves from other distributed local disbonds or weak adhesion, which possibly exist in this homemade bond line. Another possibility is that the bonded PZT sensors may cause scattering themselves, which interferes with the diffracted wave field from the prescribed defect. This sort of errors can be minimised by applying baseline subtraction or using even more lightweight sensors [182].

Additionally, in the experimental result, the indication corresponding to the near end of the defect is not captured in a similar manner to that in the FE image. Since the viscoelasticity of the composite and of the adhesive is not considered in 3D FE simulations, the amplitude of diffracted waves observed in the experiment decays faster than that in the modelling. Among the caused diffracted waveforms, the magnitude of backward diffraction signals (mainly contributed to the image indication for the near end of the defect) had been damped to a quite low level that cannot be effectively measured by the PZT sensors, thus it may be difficult to size

Figure 7.11: *Experimental imaging results derived from data sets by both sensor arrays: (a) complete image of the bond line, with geometry of the actual composite panel (size: 500 mm×900 mm) and locations of PZT elements depicted; (b) image zoomed around damage indications; the actual contour of the disbond area (x_2 : 240 ~ 260 mm, x_3 : 308 ~ 332 mm) indicated by the red dashed rectangle; (c) intensity of image pixels extracted along the central axis of the feature $x_2=250$ mm.*

the adhesive defect through the present experimental measurement. Nevertheless, the location of the defect has been identified, so that the experimental result can still validate the feasibility of the proposed SHM strategy.

7.5 Discussions

In order to provide a guideline for practical employment of the proposed SHM scheme, parametric studies have been carried out in terms of varying defect sizes and densities of sensors. Considering the universality, such SHM strategy has also been extended to monitoring defects in the composite bend. These will be discussed in detail in this section.

7.5.1 Imaging defects with varying sizes

To examine the robustness of the applied synthetic focusing algorithm, notch-like adhesive defects with varying lengths and widths were introduced into separate 3D FE models, which were all excited by a 5-cycle Hanning windowed toneburst centred at 100 kHz, forcing along the x_2 direction. The launched $SH(3)$ mode locally interacted with different defects, and different scattering patterns were thus generated, where the diffracted waves propagated along varying directions but were all dominated by SH_0 waves, so that the imaging algorithm can be directly used without any modification.

Figure 7.12: FE imaging results of the adhesive defect with varying lengths: (a) 2λ , (b) 0.2λ , (c) 0.5λ , and (d) 0.2λ ; the contour of the defined disbond area depicted by red dot lines.

Figure 7.12 shows the reconstructed defects with varying lengths, expressed as dif-

ferent fractions of the incident SH(3) wavelength ($\lambda_{SH(3)} = 28.2mm$) at 100 kHz. Since this study aims at evaluating the imaging resolution, the amount of sensors more than needed was used for either array, and the sensor spacing was chosen as 10 mm. As evident from the imaging results, all these defects can be identified at the coherently enhanced pixels, and the two strongest indications in each image are in close agreement with the near and far ends of the defect, except for the 0.2λ long disbond (as for such small defect, its location can be well determined although it is unlikely to resolve its two end indications). This indicates that the FGW based SHM strategy potentially enables defect sizing and characterization in the feature area rather than merely identify its location.

Figure 7.13: *Synthetically focused imaging of the adhesive defect with different widths in 3D FE simulations: (a) full width and (b) half width; the contour of the created disbond area indicated by red dashed lines.*

Also, the adhesive defects with varying widths (fixed length: 0.5λ) were simulated in the FE modelling. Figure 7.13 shows the reconstruction of both full-width and half-width defects, and somewhat biased damage indications can be observed for the latter, as a result of unsymmetrical diffractions from the defect propagating in the base plate.

Noteworthy, the damage indication corresponding to multiple diffractions (as explained in Section 7.3) is always present in the FE and experimental images. However, getting rid of such indication is practically difficult and sometimes even impossible, due to the fact that there often exists a temporal overlap between the first

diffracted wave packet and the waveform of subsequent diffractions, particularly when the FGWs interact with sub-wavelength defects. Nevertheless, it is usually feasible to select the first two strongest indications to estimate severity of the damage, since the subsequent diffractions occur with certain time delay and will be captured by the sensors later, so that corresponding indications appear beyond the far end of the defect.

7.5.2 Defect imaging under different densities of sensors

A sparse array of sensors is always favourable to guided wave SHM systems as it can be potentially retrofitted to existing structures for *in-situ* measurements [107, 209]. Hence the performance of the synthetic focusing algorithm was evaluated by varying the density of sensors in the FE imaging to reconstruct the same adhesive defect (full width, length: $0.8\lambda_{SH(3)}$), rendering the density as low as possible.

Figure 7.14: Normalized intensity of the pixel along the central axis of the bond line, derived from the FE imaging with different densities of sensors; damage area indicated by the grey band.

Different sensor spacings ranged from 20 mm to 80 mm were used, while the aperture size remained constant. The intensity of image pixels was extracted along the central

axis of the bond line, and the results are compared in Fig. 7.14. These quantities were normalized by the maximum intensity of the damage indication. It can be predicted that using more coarsely distributed sensors would negatively affect the imaging resolution and the accuracy of damage indication. In turn, it is sensible that the damage indication would be coherently enhanced by more received signals that encapsulate the information of such damage, causing its intensity much higher than the noise and making the location of the defect less ambiguous. This means that an increased probability of detection can be attained by applying denser sensor arrays for the imaging. In the investigated case, the sensor spacing of 40 mm in the aperture is fine enough for producing reasonably good indications of the adhesive defect, and such spacing is still larger than one wavelength of the diffracted SH_0 mode at 100 kHz ($\lambda_{SH_0} = 37$ mm). It should be possible to further increase such spacing if some other signal processing techniques can be applied to suppress the noise arise during the imaging process.

7.5.3 Extension to damage detection in composite bends

In order to validate the universality of the demonstrated FGW based SHM scheme, it has also been applied to monitoring defects that occur in the quasi-isotropic CF/EP composite bend, as had been studied in Chapter 5.

Figure 7.15 visualizes the scattered wave field by an axial crack in the bend region. The through-thickness crack was created in the FE model by transversely separating the adjacent nodes on the shared element faces with a very small distance, and the crack length along the Z direction is 10 mm (approximately one wavelength of the SH_B mode at 300 kHz). When the SH_B wave strikes the crack, both strong diffraction and reflection can be observed. The diffracted waves were studied in a similar manner to that in Section 7.2, and were found to have both SH_0 and A_0 modes. As demonstrated in Section 3.5.2, the mechanism underlying such scattering is that the incident SH type waves are converted into Rayleigh-type surface waves at the cracking location, propagating along the crack faces and radiating other waves at the crack tips into adjacent plates. Here the SH_0 waves are generated mainly at

Figure 7.15: Illustration of the bend-guided wave SHM scheme in the 3D FE simulation at 300 kHz; diffracted waves from the axial crack, shear excitation at the bend end, and the configuration of monitors shown.

the far tip of the crack, while the A_0 waves diffract from both tips, with stronger amplitude in the forward direction.

Knowing the scattered wave field from the object space (i.e. the bend region), the diffracted SH_0 waves of non-dispersive nature were chosen for the synthetically focused imaging, with a sensor spacing of 18 mm (slightly less than two times the SH_B wavelength). The image of an unrolled bend region is shown in Fig. 7.16(a) and (b), and a very strong damage indication can be observed, and its location is in close agreement with that of the far tip of the axial crack. The intensity of image pixels was also extracted along the bend axis, and its variation is presented in Fig. 7.16(c). The strongest local peak is captured at the far crack tip, whose amplitude is much higher than the noise floor. Therefore, the FGW based SHM approach has been successfully applied for defect localization in the composite bend.

Figure 7.16: Imaging results obtained from FE data: (a) complete image of the bend area ($x_2 : -0.006 \sim 0.006$ m, $x_3 : 0 \sim 0.3$ m); the geometry of the unrolled bent plate (size: 0.3 m $\times$ 0.3 m) and the configuration of receivers (marked by red circles) depicted; (b) image zoomed around the damage indication; the actual location of the axial crack ($x_3 : 0.20 \sim 0.21$ m) indicated by the white solid line; (c) image intensity extracted along the bend axis $x_2 = 0$ m.

7.6 Summary

The aim of the work presented in this chapter was to develop an FGW based SHM strategy for features in complex-shaped composite structures, which is capable of detecting and even sizing defects present in the feature. The strategy uses the FGWs as a screening tool for rapid interrogation of the long-range structural feature, and the scattered waves from the defect are recorded by an array of permanently attached sensors. The received time-domain data set is processed by the imaging algorithm to reconstruct the defect. Information about the location and severity of defects can be obtained in the imaging results.

Such SHM scheme was first tested rigorously in the 3D FE simulation for monitoring the pre-defined defect in the composite adhesive joint. The caused diffracted

wave field was quantitatively studied and was found to be dominated by the SH_0 waves. The synthetic focusing technique was applied to reconstruct the defect, and the coherently enhanced indications in the image agree well with the extremities of the adhesive defect. Experiments were also carried out with the same transducer configuration as that in the modelling, and reasonably good results have been obtained, which has validated the proposed SHM approach. Parametric studies of the defect size and the sensor density have been performed, showing feasibility of defect characterization.

The FGW based SHM strategy can be very attractive to the *in-situ* maintenance of composite plate-like structures, especially when small defect reflectivity is encountered. However, the setup for SHM of large structures would normally require quite a lot of sensors, which is undesired in practical NDE. Nevertheless, the SHM strategy can still be applicable to some circumstances when it is important to monitor a particular location, which cannot be accessed frequently.

Chapter 8

Conclusions

8.1 Thesis Review

Complex-shaped composite components have been extensively incorporated as *Principal Structural Elements (PSE)* such as spars, ribs, and the skin-stringer combination in the aerospace industry. It has been proven that various types of defects can be initiated in the curvature region or in the bonded area of such composite structures due to the stress concentration and out-of-plane impacts during the in-service use, which have to be detected in a timely way in case they propagate at subsurface laminae and ultimately lead to catastrophic failure of the entire structure. This thesis has explored the feasibility of using feature guided ultrasonic waves (FGW) for rapid screening of composite plate-like structures with benign features, intended for localizing or even sizing defects in the feature area. Proper FGWs have been discovered for inspecting two representative composite structural features: (1) composite laminated bends in Chapters 4 and 5; (2) the stiffener-adhesive-composite skin assembly in Chapters 6 and 7. Their NDT and SHM capabilities have been well demonstrated.

Chapter 2 first identified two major complexities to be addressed in this work, which are geometric and anisotropic effects on guided wave propagation. To understand these effects in an uncoupled manner, the directional dependent wave behaviour

and steering effect were illustrated in a highly anisotropic unidirectional carbon fibre/epoxy (CF/EP) laminate, while physics of FGW phenomena were reviewed for isotropic structural features. The framework of Semi-Analytical Finite Element (SAFE) method was then outlined, and this approach implemented in a commercial FE package can deal with both complexities (even they are coupled) involved in the modal study of complex waveguides. The Poynting vector and the energy velocity were formulated in the SAFE calculation, which are essential parameters in the investigation of FGWs.

Chapter 3 investigated FGWs in metallic bend structures. An attractive shear horizontal bend-guided (SH_B) mode was identified with strong energy concentration in the bend region. Its modal properties were predicted by the SAFE method outlined in Chapter 2, supported by the 3D FE simulation, and validated by the experiment. The physics underlying the energy trapping effect was examined, and the influences of geometric parameters and frequency on the extent of energy concentration were also discussed. Its relation with classical wedge acoustic waves was indicated. Additionally, the interaction of the SH_B mode with different defects was studied numerically and experimentally, with regard to the reflection behaviour, and its NDT capabilities were proved. This study laid a foundation for the scattering study in composite structural bends in Chapter 5.

Chapter 4 studied the anisotropic and geometric effects on guided wave propagation in unidirectional CF/EP laminated bends. Two types of FGWs, namely the S_0 -like and the SH_0 -like bend-guided modes were found to be able to carry wave energy along the bend direction, with strong mode confinement in the bend region. A curvature-based rotation of the stiffness matrix and spatially varying local coordinate systems were implemented in the SAFE model and in the 3D FE simulation respectively, in order to assign the anisotropic material properties to the meshed elements in the bend region. These modelling approaches were experimentally validated. The effect of varying fibre orientations was investigated by the SAFE method, and it has been found that the energy can only be concentrated in the laminated bends with immediate vicinity of 0° fibre angle. Therefore, it can be concluded that

the energy trapping effect in composite structural features is owed to both geometric variation and anisotropic properties.

Chapter 5 extended the work in Chapter 4 by investigating the FGWs in quasi-isotropic (QI) CF/EP laminated bends, which are more frequently countered in industry. The shear horizontal bend-guided mode was identified by the SAFE method, and its interaction with different defects, i.e. delamination and transverse cracks were studied by both the 3D FE simulation and the experiment. These defects were detected by examining the presence of local peaks in the spatial variation of FGW energy along the propagation path and its reflection behaviour, respectively. The numerical predications were in close agreement with the experimental measurements. The potential of using FGWs for efficient damage detection in long-range composite bends has been well demonstrated.

Chapter 6 presented the investigation of FGWs in the stiffener-adhesive bond-composite skin combination, being a representative adhesive composite joint. Criteria were suggested to select a proper mode-frequency combination that is sensitive to adhesive defects. An SH type FGW was identified to be well suited, and its interaction with the adhesive defect was studied both numerically and experimentally. Both wave energy variation along the stiffener and the reflection coefficient were calculated, showing consistent results. Realistic variations in defect geometry and bond thickness were simulated in the 3D FE modelling to study their influences on the reflection behaviour, which offered practical implications of damage detection in composite bonded structures using FGWs.

Chapter 7 proceeded the work in Chapter 6 by proposing a novel FGW based structure health monitoring (SHM) strategy. The diffracted waves from a pre-defined adhesive defect were captured by an array of sensors adjacent to the bond line. The synthetic focusing approach was then applied to the received data for reconstructing the defect, and clear damage indications were identified in the image. Such SHM scheme was tested in both the FE modelling and in the experiment, showing good agreement. Parametric studies of both the defect size and the sensor density were carried out in the 3D FE simulation to evaluate the robustness of the applied imag-

ing algorithm, and the results demonstrate the potential of defect characterization by implementing this SHM scheme. An axial crack created in the QI composite bend (studied in Chapter 5) was also successfully identified through synthetically focused imaging. Therefore, the proposed FGW based SHM strategy was proven to be attractive for detecting localized damage in the feature areas of complex-shaped composite structures.

8.2 Summary of Findings

8.2.1 FGW screening of composite structures

The composite structures investigated in the thesis include complex-shaped laminated components (i.e. composite bends) and adhesive composite joints (i.e. bonded stiffeners) with complex geometry, being typical structural features in aircraft composites. In composite features, both geometric variation and anisotropic material properties impact on the guided wave propagation. Proper FGW modes were identified in these features by the SAFE approach, and their characteristics were cross-validated by both the time-domain 3D FE simulation and the experiment.

Two SH type feature guided modes were found to be well suited for screening of these composite features. Both modes have little dispersion and low attenuation as well as easy excitability in the frequency range of interest. Owing to strong energy concentration in the feature area, these modes are capable of particularly interrogating structural features for long distances, which is very attractive to the rapid screening of the features for damage identification.

Scattering of the selected FGW modes with different types of defects was studied, in which all the reflection, transmission and diffraction of the FGWs were captured to identify these defects. Specifically, when the SH_B mode strikes a delamination occurring in the bend region, it is often difficult to attain strong reflected signals. However, upon its transmission through the delamination, part of the wave energy is

trapped in the delaminated area, with waves bouncing back and forth between defect edges, ultimately leading to a wave-defect resonance. The delamination can thus be detected by examining the spatial variation of the FGW energy along the propagation path, with local peaks corresponding to the defect area. Since composite bends are one-dimensional structures, this approach becomes feasible by using the laser vibrometer to scan along the bend direction. As for the transverse or axial crack in the bend, reflected waves from the defect can always be used for its localization, which potentially only requires a single transducer position in the pulse-echo configuration. The severity of defects can also be inferred from the reflection coefficient spectrum.

In the other case, intended for screening of the adhesive composite joint, the SH(3) mode was chosen among multiple existing FGW modes due to its attractive characteristics mentioned above. More importantly, this mode possesses sufficient out-of-plane power flow in the bond layer, which indicates more efficient energy transfer between the bonded components. Consequently, the defects occurred in the bond layer will be more likely to change the propagation of the SH(3) mode, and it is therefore more sensitive to adhesive defects in the bond line. This finding can provide a generic guideline for selecting guided modes for inspecting bond line between assembled components. In the investigated composite assembly, the adhesive defect can be identified either through the reflection behaviour of the SH(3) wave or by the wave energy approach demonstrated above. Parametric studies have shown the influence of the variation in defect size and bond thickness on the reflection coefficient of the SH(3) mode, shedding light on its practical employment.

Additionally, there are some new implementations of the Semi-Analytical Finite Element (SAFE) method in the thesis. This approach has been well documented in literature for the modal study of isotropic waveguides with arbitrary cross section. It has also been reported to study guided waves in flat composite laminated plates or beams, which were previously investigated by applying the matrix techniques [210]. In this thesis, to the best of the author's knowledge at the time of writing, it is the first time to account for spatially-varying anisotropy in the SAFE method, by imple-

menting a curvature based rotation of the stiffness matrix at each nodal position, in Cartesian coordinates. This potentially enables the SAFE modelling of anisotropic waveguides of arbitrary cross section.

Also, Perfectly Matched Layers (PML) have been incorporated into the SAFE approach, implemented in a commercially available software package, without the expense and complexity of maintaining homegrown source codes. The exploitation of PMLs can significantly reduce the computational cost and get rid of more spurious modes in the eigensolutions as compared with the use of absorbing regions which, however, are easier to implement.

In summary, the identified FGWs can be used as a screening tool to rapidly interrogate the long-range composite bends and adhesive composite joints. The interaction of these FGW modes with different types of defects in the feature area has been investigated, and their NDT capabilities have been well demonstrated. Meanwhile, the generic numerical tools developed in the thesis can be used for investigating guided waves in viscoelastic anisotropic composite components with arbitrary geometry and in even more complex assembled structures, not limited to the cases investigated here.

8.2.2 Development of FGW based SHM strategy

The thesis has extended the study of FGWs to SHM applications, mainly concerned with the detection of unexpected localized damage. This work was driven by the strong diffraction observed in the SH(3) waves scattering with adhesive defects, as demonstrated in Chapter 6. The FGWs were used as a screening tool to interrogate the feature area, and an array of sensors permanently attached to the base plate captured the diffracted waves from the localized damage. This technique was combined with the synthetic focusing method for the damage reconstruction. The defects were identified by the indications with coherently enhanced intensity in the reconstructed image. Information about the location and severity of defects can thus be obtained.

Such SHM scheme can be generalized to evaluate the health state of features in other composite structures. Also, the sensors used in the array can be either permanently attached (e.g. piezoelectric wafers) to the surface of the structure or embedded (e.g. fibre Bragg gratings) in the laminates, integrated with the existing composite structures. This can be very attractive to the *in-situ* maintenance and to the scenarios where small defect reflectivity is encountered. Additionally, the FGW based SHM approach intended for feature monitoring can be combined with the conventional guided wave SHM system that is mainly responsible for monitoring the plate or shell elements. Thus, richer information about the entire structure can be obtained. Furthermore, under optimal sensor configuration, the proposed SHM scheme can even share the reception sensors and associated hardware that originally used for plate monitoring, without incorporating additional sensors to the existing structure. This will be favourable to the practical employment in aircraft composite components.

Some important conclusions and practical implications arising from the work will make contributions to the relevant research and development of ultrasonics-based NDT/SHM for a broad range of complex structures (not even limited to composite components) in the aerospace industry.

8.3 Future Work

In the context of this thesis, there are several future avenues which can be pursued.

FGW based SHM via a time-reversal technique

One of the possible research directions is to improve the robustness of the SHM strategy proposed in Chapter 7, by adopting other imaging techniques such as time reversal approach in the reconstruction phase. This method originates from time reversal acoustics [211,212], where an input wave signal can be focused at the source, as the response signal measured at a distinct location is reversed in the time domain and re-emitted back to the original excitation location. Such time reversibility is due to the spatial reciprocity and time-reversal invariance of linear wave equations [213].

The time reversal process has subsequently been extended to guided waves based NDT for compensating the dispersion effect of guided modes and for the damage detection [184, 214–217].

In the current SHM scheme using the synthetic focusing approach, a quantitative study of the scattered waves has to be performed in order to figure out all the wave components contained in the packet. It may be difficult to accurately reconstruct the localized damage if multiple time-overlapping diffracted waveforms are caused or the diffraction guided modes are highly dispersive. Hereby the time reversal approach can be used for the post-processing, as it can potentially deal with dispersive guided modes and multi-modal propagation contained in the scattered wave field. The reconstruction process is achievable without physically re-emitting the received signals, and the Green's function can be applied among all the sensor locations to produce the image of the entire feature area. The focused indications obtained in the image correspond to the defect that originally causes scattered waves in the forward time propagation.

Anisotropic viscoelasticity in 3D FE simulation

Another potential methodology improvement is the definition of anisotropic viscoelasticity in 3D FE simulations, although it has been well defined in the SAFE approach implemented by COMSOL. In the thesis, isotropic viscoelasticity has been well implemented in Abaqus FE package, which enables the absorbing region to damp the waves entering it. To the author's knowledge at the time of writing, there is not a straightforward way to define the anisotropic viscoelasticity in Abaqus, some subroutines have to be developed for such material constitution. With such improvement, the wave attenuation can be predicted more accurately in the 3D FE modelling, and a better comparison can be offered with SAFE results.

Appendix A

Effective Elastic Constants of Anisotropic Layered Structures

The thesis estimates the overall equivalent homogeneous properties of layered composites by the *Backus averaging method*, which was developed in the context of seismological studies by Postma [218] and Backus [160], and was subsequently applied to the characterization of composite laminated materials, as reported in the Refs. [161, 162, 219, 220].

The Backus averaging method for homogenization relies on the assumption of constant or slowly varying normal stress and in-plane strain components through the laminate thickness. In principle, these components are continuous at each layer interface (stress continuity and no-slip condition), and according to classical lamination theory, are also constant through each layer (Backus only assumes that they are slowly varying through the thickness of the structure). The constitutive equation can then be rearranged into a form where rapidly varying coefficients multiply slowly varying stresses or strains. A thickness-weighted averaging through the thickness direction thus leads to the averaged stiffness matrix properties. Rearrangement back to the constitutive equation format allows the effective stiffness values to be identified. Derivation of the generalized Backus equations and suggested programming formulation are given in this appendix.

A.1 Derivation of the effective stiffness matrix

The reference coordinate system is set such that the layer interfaces are normal to the x (or 1) axis, the fibres are parallel to the z (or 3) axis, and the y (or 2) axis is normal to the fibres but in the plane of the layers. Such coordinate system has been adopted throughout the thesis to define the fibrous materials.

The *Voigt notation* is used for stiffness (C_{ijkl}), stress (σ_{ij}), and strain (ϵ_{ij}) tensors. The stress and strain become one-dimensional tensors, in the form of

$$\sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{bmatrix}, \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} = \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ 2\epsilon_{23} \\ 2\epsilon_{31} \\ 2\epsilon_{12} \end{bmatrix}. \quad (\text{A.1})$$

The stress-strain relation can then be written as

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ & & C_{33} & C_{34} & C_{35} & C_{36} \\ \text{sym.} & & & C_{44} & C_{45} & C_{46} \\ & & & & C_{55} & C_{56} \\ & & & & & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}, \quad (\text{A.2})$$

where the stiffness tensor C_{ij} is symmetric, and has 21 independent elements for general anisotropic media.

Boundary conditions applied in the lamination require that the stresses normal to all the interfaces are continuous, and therefore equal along the through-thickness direction. Also, the no-slip condition assumes that the strains in the plane of the layers are also equal throughout the structure. Thus, the stress components $\sigma_1, \sigma_5, \sigma_6$ and the strain components $\epsilon_2, \epsilon_3, \epsilon_4$ are constant.

Hereby, the matrix equation Eq. (A.2) can be split into two sets, namely the constant $(\sigma_1, \sigma_5, \sigma_6, \epsilon_2, \epsilon_3, \epsilon_4)$ and varying $(\sigma_2, \sigma_3, \sigma_4, \epsilon_1, \epsilon_5, \epsilon_6)$ terms.

$$\begin{aligned} \begin{bmatrix} \sigma_2 \\ \sigma_3 \\ \sigma_4 \end{bmatrix} &= \begin{bmatrix} C_{21} & C_{25} & C_{26} \\ C_{31} & C_{35} & C_{36} \\ C_{41} & C_{45} & C_{46} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} + \begin{bmatrix} C_{22} & C_{23} & C_{24} \\ C_{32} & C_{33} & C_{34} \\ C_{42} & C_{43} & C_{44} \end{bmatrix} \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} \\ &= A \begin{bmatrix} \epsilon_1 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} + B \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} ; \end{aligned} \quad (\text{A.3})$$

$$\begin{aligned} \begin{bmatrix} \sigma_1 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} &= \begin{bmatrix} C_{11} & C_{15} & C_{16} \\ C_{51} & C_{55} & C_{56} \\ C_{61} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} + \begin{bmatrix} C_{12} & C_{13} & C_{14} \\ C_{52} & C_{53} & C_{54} \\ C_{62} & C_{63} & C_{64} \end{bmatrix} \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} \\ &= E \begin{bmatrix} \epsilon_1 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} + D \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} , \end{aligned} \quad (\text{A.4})$$

where matrix D is the transpose of matrix A , i.e. $D = A^T$. Then solve the Eqs. (A.4) and (A.3) for varying terms $\{\epsilon_1, \epsilon_5, \epsilon_6\}$ and $\{\sigma_2, \sigma_3, \sigma_4\}$, respectively. Eq. (A.4) can be rewritten as

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} = E^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} - E^{-1} D \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} . \quad (\text{A.5})$$

Substituting Eq. (A.5) into Eq. (A.3), the relation becomes

$$\begin{bmatrix} \sigma_2 \\ \sigma_3 \\ \sigma_4 \end{bmatrix} = AE^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} + (B - AE^{-1}D) \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} . \quad (\text{A.6})$$

Combine Eqs. (A.5) and (A.6) into a single equation

$$\begin{bmatrix} \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \epsilon_1 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} = \begin{bmatrix} AE^{-1} & B - AE^{-1}D \\ E^{-1} & -E^{-1}D \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_5 \\ \sigma_6 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} \quad (\text{A.7})$$

Upon rearrangement of the constitutive equation, the stress/strain components on the right-hand side are constant, so that Eq. (A.7) can be averaged (denoted by $\langle \cdot \rangle$) directly:

$$\begin{bmatrix} \langle \sigma_2 \rangle \\ \langle \sigma_3 \rangle \\ \langle \sigma_4 \rangle \\ \langle \epsilon_1 \rangle \\ \langle \epsilon_5 \rangle \\ \langle \epsilon_6 \rangle \end{bmatrix} = \begin{bmatrix} \langle AE^{-1} \rangle & \langle B - AE^{-1}D \rangle \\ \langle E^{-1} \rangle & -\langle E^{-1}D \rangle \end{bmatrix} \begin{bmatrix} \langle \sigma_1 \rangle \\ \langle \sigma_5 \rangle \\ \langle \sigma_6 \rangle \\ \langle \epsilon_2 \rangle \\ \langle \epsilon_3 \rangle \\ \langle \epsilon_4 \rangle \end{bmatrix} \quad (\text{A.8})$$

The averaged stress-strain relation is resulted from the average of modified stiffness matrix. In order to obtain the effective elastic properties of the layered system, Eq. (A.8) has to be related back to its original format. The same technique demonstrated above are needed to invert these equations.

The bottom half of Eq. (A.8) can be rewritten as

$$\begin{bmatrix} \sigma_1 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \langle E^{-1} \rangle^{-1} \begin{bmatrix} \langle \epsilon_1 \rangle \\ \langle \epsilon_5 \rangle \\ \langle \epsilon_6 \rangle \end{bmatrix} + \langle E^{-1} \rangle^{-1} \langle E^{-1}D \rangle \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix} \quad (\text{A.9})$$

Then substitute this into the top half of Eq. (A.8) to obtain

$$\begin{aligned}
 \begin{bmatrix} \langle \sigma_2 \rangle \\ \langle \sigma_3 \rangle \\ \langle \sigma_4 \rangle \end{bmatrix} &= \langle AE^{-1} \rangle \langle E^{-1} \rangle^{-1} \begin{bmatrix} \langle \epsilon_1 \rangle \\ \langle \epsilon_5 \rangle \\ \langle \epsilon_6 \rangle \end{bmatrix} \\
 &+ \left[\langle AE^{-1} \rangle \langle E^{-1} \rangle^{-1} \langle E^{-1} D \rangle + \langle B - AE^{-1} D \rangle \right] \begin{bmatrix} \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \end{bmatrix}
 \end{aligned} \tag{A.10}$$

By comparing these averaged stress-strain relations with Eqs. (A.3) and (A.4), the following blocks associated with the effective stiffness C^* can be obtained:

$$\begin{aligned}
 A^* &= \langle AE^{-1} \rangle \langle E^{-1} \rangle^{-1}; \\
 B^* &= \langle AE^{-1} \rangle \langle E^{-1} \rangle^{-1} \langle E^{-1} D \rangle + \langle B - AE^{-1} D \rangle; \\
 E^* &= \langle E^{-1} \rangle^{-1}; \\
 D^* &= \langle E^{-1} \rangle^{-1} \langle E^{-1} D \rangle = A^{*T},
 \end{aligned} \tag{A.11}$$

where only four matrices in total require averaging over all the laminated layers, namely E^{-1} , AE^{-1} , $E^{-1}D$, and $B - AE^{-1}D$.

By relating these blocks to the stiffness matrix defined in Eqs. (A.3) and (A.4), the effective stiffness of the layered system takes the form

$$C^* = \begin{bmatrix} E_{11}^* & D_{11}^* & D_{12}^* & D_{13}^* & E_{12}^* & E_{13}^* \\ A_{11}^* & B_{11}^* & B_{12}^* & B_{13}^* & A_{12}^* & A_{13}^* \\ A_{21}^* & B_{21}^* & B_{22}^* & B_{23}^* & A_{22}^* & A_{23}^* \\ A_{31}^* & B_{31}^* & B_{32}^* & B_{33}^* & A_{32}^* & A_{33}^* \\ E_{21}^* & D_{21}^* & D_{22}^* & D_{23}^* & E_{22}^* & E_{23}^* \\ E_{31}^* & D_{31}^* & D_{32}^* & D_{33}^* & E_{32}^* & E_{33}^* \end{bmatrix} \tag{A.12}$$

A.2 Programming formulation

Since the implementation will involve high memory storage for the layer matrices, it may be advisable to average layer by layer, rather than storing the sub-matrices for all layers. The formulation is presented as follows.

From layer 1-N:

- Transform the stiffness matrix of the layer in local principal axes to that in the global coordinate system, according to the required fibre orientation;
- Define matrices A , B , D , E (without asterisks) as that used in Eqs. (A.3) and (A.4);
- Define matrix combinations E^{-1} , AE^{-1} , $E^{-1}D$, $B - AE^{-1}D$;
- Calculate the average of these matrix combinations up to the n^{th} layer:
 $\langle M \rangle_n = \frac{1}{n} [(n-1) \langle M \rangle_{n-1} + M_n]$, where M denotes arbitrary matrix combination indicated above;

End of loop

- Determine the effective matrices for the required set of layers A^* , B^* , D^* , E^* using Eq. (A.11) from the averages $\langle M \rangle_n$;
- Determine the effective matrix using Eq. (A.12).

Such implementation implies that different parts of the stiffness matrix need to be averaged in different ways, so that it is not possible to simply average the entire stiffness matrix directly. Also, it should be noted that these effective elastic constants are the static properties of the laminate, and the results keep reasonably good accuracy when the wavelength of the propagating elastic waves is much larger than the layer thickness.

References

- [1] G. A. Matzkanin and H. T. Yolken. Techniques for the nondestructive evaluation of polymer matrix composites. *AMMTIAC Quarterly*, 2(4):3–7, 2007.
- [2] G. L. Dillingham. Aviation Safety: Status of FAA’s actions to oversee the safety of composite airplanes. Report to Congressional Requesters GAO-11-849, US Government Accountability Office, September 2011.
- [3] R. Selzer and K. Friedrich. Mechanical properties and failure behaviour of carbon fibre-reinforced polymer composites under the influence of moisture. *Composites Part A*, 28(6):595–604, 1997.
- [4] R. D. Adams and P. Cawley. A review of defect types and nondestructive testing techniques for composites and bonded joints. *NDT Int.*, 21(4):208–222, 1988.
- [5] S. Abrate. Impact on laminated composite materials. *Applied Mechanics Reviews*, 44(4):155–190, 1991.
- [6] D. Hull and Y. B. Shi. Damage mechanism characterization in composite damage tolerance investigations. *Compos. Struct.*, 23(2):99–120, 1993.
- [7] K. B. Katnam, L. F. M. Da Silva, and T. M. Young. Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities. *Prog. Aerosp. Sci.*, 61:26–42, 2013.
- [8] P. D. Soden, A. S. Kaddour, and M. J. Hinton. Recommendations for designers and researchers resulting from the world-wide failure exercise. *Compos. Sci. Technol.*, 64(3):589–604, 2004.

- [9] K. Mason. Nondestructive testing broadens its scope. *High Performance Composites*, May 2006.
- [10] K. wood. In-situ composite repair builds on basics. *High Performance Composites*, October 2008.
- [11] C. Soutis. Fibre reinforced composites in aircraft construction. *Prog. Aerosp. Sci.*, 41(2):143–151, 2005.
- [12] C. Niu. *Airframe structural design: practical design information and data on aircraft structures*. Connilit Press, 1988.
- [13] EASA. Certification specifications and acceptable means of compliance for large aeroplanes. CS-25 Amendment 14, European Aviation Safety Agency, December 2013.
- [14] M. D. Banea and L. F. da Silva. Adhesively bonded joints in composite materials: an overview. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications*, 223(1):1–18, 2009.
- [15] W. Hufenbach, A. Hornig, B. Zhou, A. Langkamp, and M. Gude. Determination of strain rate dependent through-thickness tensile properties of textile reinforced thermoplastic composites using L-shaped beam specimens. *Compos. Sci. Technol.*, 71(8):1110–1116, 2011.
- [16] L. D. Zhou and Z. Zhuang. Strength analysis of three-dimensional braided T-shaped composite structures. *Compos. Struct.*, 104:162–168, 2013.
- [17] Q. D. Yang, K. L. Rugg, B. N. Cox, and M. C. Shaw. Failure in the junction region of T-stiffeners: 3D-braided vs. 2D tape laminate stiffeners. *Int. J. Solids Struct.*, 40(7):1653–1668, 2003.
- [18] M. I. Naji and S. V. Hoa. Curing of thick angle-bend thermoset composite part: curing cycle effect on thickness variation and fiber volume fraction. *J. Reinf. Plast. Compos.*, 18(8):702–723, 1999.

- [19] Y. Li, M. Li, Y. Gu, and Z. Zhang. Numerical and experimental study on the effect of lay-up type and structural elements on thickness uniformity of L-shaped laminates. *Appl. Compos. Mater.*, 16(2):101–115, 2009.
- [20] P. Hubert and A. Poursartip. Aspects of the compaction of composite angle laminates: an experimental investigation. *J. Compos. Mater.*, 35(1):2–26, 2001.
- [21] X. Wang, Z. Zhang, F. Xie, M. Li, D. I. Dai, and F. Wang. Correlated rules between complex structure of composite components and manufacturing defects in autoclave molding technology. *J. Reinf. Plast. Compos.*, 28(22):2791–2803, 2009.
- [22] S. Feih and H. R. Shercliff. Quality assessment of curved composite components in peel joint structures. *Composites Part A*, 36(3):97–408, 2005.
- [23] K. Çınar and N. Ersoy. Effect of fibre wrinkling to the spring-in behaviour of L-shaped composite materials. *Composites Part A*, 69:105–114, 2015.
- [24] B. Gözlüklü. *Modeling of Intersonic Delamination in Curved-Thick Composite Laminates under Quasi-static Loading*. PhD thesis, Middle East Technical University, 2014.
- [25] G. Wimmer, W. Kitzmüller, G. Pinter, T. Wettemann, and H. E. Pettermann. Computational and experimental investigation of delamination in L-shaped laminated composite components. *Engineering Fracture Mechanics*, 76(18):2810–2820, 2009.
- [26] T. Matsuo, T. Goto, and J. Takahashi. Investigation about the fracture behavior and strength in a curved section of CF/PP composite by a thin-curved beam specimen. *Adv. Compos. Mater.*, 24(3):249–268, 2015.
- [27] J. F. Owens and P. Lee-Sullivan. Stiffness behaviour due to fracture in adhesively bonded composite-to-aluminum joints II. experimental. *Int. J. Adhes. Adhes.*, 20(1):47–58, 2000.

- [28] E. E. Theotokoglou and T. Moan. Experimental and numerical study of composite T-joints. *J. Compos. Mater.*, 30(2):190–209, 1996.
- [29] B. M. Parker. The strength of bonded carbon fibre composite joints exposed to high humidity. *Int. J. Adhes. Adhes.*, 10(3):187–191, 1990.
- [30] C. C. H. Guyott and P. Cawley. Evaluation of the cohesive properties of adhesive joints using ultrasonic spectroscopy. *NDT Int.*, 21(4):233–240, 1988.
- [31] P. B. Nagy and L. Adler. Nondestructive evaluation of adhesive joints by guided waves. *J. Appl. Phys.*, 66(10):4658–4663, 1989.
- [32] M. J. S. Lowe and P. Cawley. The applicability of plate wave techniques for the inspection of adhesive and diffusion bonded joints. *J. Nondestr. Eval.*, 13(4):185–200, 1994.
- [33] J. M. Allin. *Disbond detection in adhesive joints using low frequency ultrasound*. PhD thesis, University of London, 2002.
- [34] F. L. di Scalea and P. Rizzo. Propagation of ultrasonic guided waves in lap-shear adhesive joints: Case of incident a_0 Lamb wave. *J. Acoust. Soc. Am.*, 115(1):146–156, 2004.
- [35] F. L. di Scalea, H. Matt, I. Bartoli, S. Coccia, G. Park, and C. Farrar. Health monitoring of uav wing skin-to-spar joints using guided waves and macro fiber composite transducers. *J. Intell. Mater. Syst. Struct.*, 18(4):373–388, 2007.
- [36] B. Le Crom and M. Castaings. Shear horizontal guided wave modes to infer the shear stiffness of adhesive bond layers. *J. Acoust. Soc. Am.*, 127(4):2220–2230, 2010.
- [37] I. G. Scott and C. M. Scala. A review of non-destructive testing of composite materials. *NDT Int.*, 15(2):75–86, 1982.
- [38] K. V. Steiner, R. F. Eduljee, X. Huang, and J. W. Gillespie. Ultrasonic nde techniques for the evaluation of matrix cracking in composite laminates. *Compos. Sci. Technol.*, 53(2):193–198, 1995.

- [39] F. Aymerich and S. Meili. Ultrasonic evaluation of matrix damage in impacted composite laminate. *Composites Part B*, 31(1):1–6, 2000.
- [40] M. E. Ibrahim. Nondestructive evaluation of thick-section composites and sandwich structures: A review. *Composites Part A*, 64:36–48, 2014.
- [41] W. A. Grandia and C. M. Fortunko. Nde applications of air-coupled ultrasonic transducers. *Proc. IEEE Ultrason. Symp.*, 1:697–709, 1995.
- [42] M. Castaings and P. Cawley. The generation, propagation, and detection of lamb waves in plates using air-coupled ultrasonic transducers. *J. Acoust. Soc. Am.*, 100(5):3070–3077, 1996.
- [43] P. Cawley. The rapid non-destructive inspection of large composite structures. *Composites*, 25(5):351–357, 1994.
- [44] E. A. Birt. Damage detection in carbon-fibre composites using ultrasonic Lamb waves. *Insight*, 40(5):335–339, 1998.
- [45] S. S. Kessler, S. M. Spearing, and C. Soutis. Damage detection in composite materials using Lamb wave methods., 11(2), 269. *Smart Mater. Struct.*, 11(2):269–278, 2002.
- [46] C. H. Wang and L. R. F. Rose. Wave reflection and transmission in beams containing delamination and inhomogeneity. *J. Sound Vib.*, 264(4):851–872, 2003.
- [47] H. Matt, I. Bartoli, and F. L. di Scalea. Ultrasonic guided wave monitoring of composite wing skin-to-spar bonded joints in aerospace structures. *J. Acoust. Soc. Am.*, 118(4):2240–2252, 2005.
- [48] Z. Su and L. Ye. Lamb wave-based quantitative identification of delamination in CE/EP composite structures using artificial neural algorithm. *Compos. Struct.*, 66(1):627–637, 2004.
- [49] Z. Su, L. Ye, and Y. Lu. Guided Lamb waves for identification of damage in composite structures: A review. *J. Sound Vib.*, 295(3):753–780, 2006.

- [50] S. Yashiro, J. Takatsubo, and N. Toyama. An ndt technique for composite structures using visualized Lamb-wave propagation. *Compos. Sci. Technol.*, 67(15):3202–3208, 2007.
- [51] M. Castaings and B. Hosten. Ultrasonic guided waves for health monitoring of high-pressure composite tanks. *NDT & E Int.*, 41(8):648–655, 2008.
- [52] M. Castaings, D. Singh, and P. Viot. Sizing of impact damages in composite materials using ultrasonic guided waves. *NDT & E Int.*, 46:22–31, 2012.
- [53] J. P. Sargent. Corrosion detection in welds and heat affected zones using ultrasonic Lamb waves. *Insight*, 48(3):160–167, 2006.
- [54] N. Juluri, M. J. S. Lowe, and P. Cawley. The guiding of ultrasound by a welded joint in a plate. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 26, pages 1079–1086. American Institute of Physics, New York, 2007.
- [55] Z. Fan and M. J. Lowe. Elastic waves guided by a welded joint in a plate. *Proc. R. Soc. A*, 465:2053–2068, 2009.
- [56] Z. Fan. *Applications of guided wave propagation on waveguides with irregular cross-section*. PhD thesis, Imperial College London, 2010.
- [57] Z. Fan, M. Castaings, M. J. Lowe, C. Biateau, and P. Fromme. Feature-guided waves for monitoring adhesive shear modulus in bonded stiffeners. *NDT & E Int.*, 54:96–102, 2013.
- [58] A. Ramdhas, R. K. Pattanayak, K. Balasubramaniam, and P. Rajagopal. Antisymmetric feature-guided ultrasonic waves in thin plates with small radius transverse bends from low-frequency symmetric axial excitation. *J. Acoust. Soc. Am.*, 134(3):1886–1898, 2013.
- [59] A. Ramdhas, R. K. Pattanayak, K. Balasubramaniam, and P. Rajagopal. Symmetric low-frequency feature-guided ultrasonic waves in thin plates with transverse bends. *Ultrasonics*, 56:232–242, 2015.

- [60] C Aristegui, M. J. Lowe, and P. Cawley. Guided waves in fluid-filled pipes surrounded by different fluids. *Ultrasonics*, 39:367–375, 2001.
- [61] D. N. Alleyne, B. Pavlakovic, M. J. S. Lowe, and P. Cawley. Rapid, long range inspection of chemical plant pipework using guided waves. *Insight*, 43(2):93–96,101, 2001.
- [62] J. L. Rose, M. J. Avioli, and W. J. Song. Application and potential of guided wave rail inspection. *Insight*, 44(6):353–358, 2002.
- [63] P. Fromme and M. B. Sayir. Detection of cracks at rivet holes using guided waves. *Ultrasonics*, 40(1):199–203, 2002.
- [64] P. Cawley, M. J. S. Lowe, D. N. Alleyne, B. Pavlakovic, and P. Wilcox. Practical long range guided wave testing: application to pipes and rail. *Mater. Eval.*, 61(1):66–74, 2003.
- [65] I. Bartoli, F. L. di Scalea, and E. Fateh, M. and Viola. Modeling guided wave propagation with application to the long-range defect detection in railroad tracks. *NDT & E Int.*, 38(5):325–334, 2005.
- [66] M. J. S. Lowe. *Plate waves for the NDT of diffusion bonded titanium*. PhD thesis, University of London, 1992.
- [67] H. Lamb. On waves in an elastic plate. *Proceedings Royal Society*, 93:114–128, 1916-1917.
- [68] A. E. H. Love. *Some problems of geodynamics*. Cambridge University Press, London, 1911.
- [69] B. N. Pavlakovic, M. J. S. Lowe, D. N. Alleyne, and P. Cawley. Disperse: A general purpose program for creating dispersion curves. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 16, pages 185–192. Plenum Press, New York, 1997.
- [70] P. Wilcox. A rapid signal processing technique to remove the effect of dispersion from guided wave signals. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 50(4):419–427, 2003.

- [71] P. Roux, B. Roman, and M. Fink. Time-reversal in an ultrasonic waveguide. *Appl. Phys. Lett.*, 70(14):1811–1813, 1997.
- [72] L. Adler, M. de Billy, G. Quentin, M. Talmant, and P. B. Nagy. Evaluation of friction-welded aluminum-steel bonds using dispersive guided modes of a layered substrate. *J. Appl. Phys.*, 68(12):6072–6076, 1990.
- [73] P. Huthwaite and F. Simonetti. High-resolution guided wave tomography. *Wave Motion*, 50(5):979–993, 2013.
- [74] M. Mazzotti, A. Marzani, I. Bartoli, and E. Viola. Guided waves dispersion analysis for prestressed viscoelastic waveguides by means of the safe method. *Int. J. Solids Struct.*, 49(18):2359–2372, 2012.
- [75] P. Wilcox. Modeling the excitation of Lamb and sh waves by point and line sources. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 23, pages 206–213. American Institute of Physics, New York, 2004.
- [76] Lord Rayleigh. On waves propagated along the plane surface of an elastic solid. *Proc. London Math. Soc.*, 1(1):4–11, 1885.
- [77] P. Cawley and D. Alleyne. The use of lamb waves for the long range inspection of large structures. *Ultrasonics*, 34:287–290, 1996.
- [78] N. Guo and P. Cawley. The interaction of Lamb waves with delaminations in laminates. *J. Acoust. Soc. Am.*, 94(4):2240–2246, 1993.
- [79] M. J. S. Lowe and O. Diligent. Low-frequency reflection characteristics of the s_0 Lamb wave from a rectangular notch in a plate. *J. Acoust. Soc. Am.*, 111(1):64–74, 2002.
- [80] M. J. Lowe, P. Cawley, J. Y. Kao, and 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(6):2612–2622, 2002.
- [81] R. S. Lakes. *Viscoelastic solids*, volume 9. CRC press, 1998.

- [82] J. L. Rose. *Ultrasonic Guided Waves in Solid Media*. Cambridge University Press, Cambridge, UK, 2014.
- [83] B. A. Auld. *Acoustic Fields and Waves in Solids*, volume 1. Krieger Publishing Company, Malabar, Florida, 1990.
- [84] B. Hosten, M. Deschamps, and B. R. Tittmann. Inhomogeneous wave generation and propagation in lossy anisotropic solids. application to the characterization of viscoelastic composite materials. *J. Acoust. Soc. Am.*, 82(5):1763–1770, 1987.
- [85] G. Neau. *Lamb waves in anisotropic viscoelastic plates. Study of the wave fronts and attenuation*. PhD thesis, University of Bordeaux, 2003.
- [86] A. H. Nayfeh, D. E. Chimenti, L. Adler, and R. L. Crane. Ultrasonic leaky waves in the presence of a thin layer. *J. Appl. Phys.*, 52(8):4985–4994, 1981.
- [87] R. Kumar. Dispersion of axially symmetric waves in empty and fluid-filled cylindrical shells. *Acta Acustica united with Acustica*, 27:317–329, 1972.
- [88] B. N. Pavlakovic. *Leaky guided ultrasonic waves in NDT*. PhD thesis, University of London, 1998.
- [89] L. M. Brekhovskikh. *Waves in layered media*. Academic Press, New York, 1980.
- [90] A. H. Nayfeh. *Wave propagation in layered anisotropic media with application to composites*. Elsevier, Amsterdam, 1995.
- [91] S. K. Datta and A. H. Shah. *Elastic waves in composite media and structures: with applications to ultrasonic nondestructive evaluation*. CRC Press, 2009.
- [92] S. Rokhlin, D. Chimenti, and P. Nagy. *Physical ultrasonics of composites*. Oxford University Press, 2011.
- [93] E. J. Barbero. *Introduction to composite materials design*. 2nd edition, CRC press, 2010.

- [94] W. J. Percival and E. A. Birt. A study of Lamb wave propagation in carbon-fibre composites. *Insight*, 39(10):728–735, 1997.
- [95] L. Wang and F. G Yuan. Group velocity and characteristic wave curves of Lamb waves in composites: Modeling and experiments. *Compos. Sci. Technol.*, 67(7):1370–1384, 2007.
- [96] O. Putkis, R. P. Dalton, and A. J. Croxford. The anisotropic propagation of ultrasonic guided waves in composite materials and implications for practical applications. *Ultrasonics*, 65:390–399, 2016.
- [97] S. G. Pierce, B. Culshaw, G. Manson, K. Worden, and W. J. Staszewski. Application of ultrasonic lamb wave techniques to the evaluation of advanced composite structures. In R. O. Claus and W. B. Spillman Jr., editors, *Proceedings of the SPIE*, volume 3986, pages 93–103, 2000.
- [98] Z. V. I. Hashin. Complex moduli of viscoelastic composites-II. fiber reinforced materials. *Int. J. Solids Struct.*, 6(6):797–807, 1970.
- [99] B. N. Pavlakovic and M. J. S. Lowe. Disperse user manual: a system for generating dispersion curves. *Copyright B. Pavlakovic, M. Lowe*, 2003.
- [100] Z. Su and L. Ye. *Identification of damage using Lamb waves: from fundamentals to applications*, volume 48. Springer Science & Business Media, 2009.
- [101] N. Toyama, J. Noda, and T. Okabe. Quantitative damage detection in cross-ply laminates using Lamb wave method. *Compos. Sci. Technol.*, 63(10):1473–1479, 2003.
- [102] Z. Su and L. Ye. Lamb wave propagation-based damage identification for quasi-isotropic CE/EP composite laminates using artificial neural algorithm: Part I-methodology and database development. *J. Intell. Mater. Syst. Struct.*, 16(2):97–111, 2005.
- [103] C. Ramadas, K. Balasubramaniam, M. Joshi, and C. V. Krishnamurthy. Interaction of guided Lamb waves with an asymmetrically located delamination in a laminated composite plate. *Smart Mater. Struct.*, 19(6):065009, 2010.

-
- [104] C. T. Ng and M. Veidt. Scattering of the fundamental anti-symmetric Lamb wave at delaminations in composite laminates. *J. Acoust. Soc. Am.*, 129(3):1288–1296, 2011.
- [105] C. A. Leckey, M. D. Rogge, and F. R. Parker. Guided waves in anisotropic and quasi-isotropic aerospace composites: Three-dimensional simulation and experiment. *Ultrasonics*, 54(1):385–394, 2014.
- [106] B. I. Murat, P. Khalili, and P. Fromme. Scattering of guided waves at delaminations in composite plates. *J. Acoust. Soc. Am.*, 139(6):3044–3052, 2016.
- [107] A. J. Croxford, P. D. Wilcox, B. W. Drinkwater, and G. Konstantinidis. Strategies for guided-wave structural health monitoring. *Proc. R. Soc. A*, 463:2961–2981, 2007.
- [108] M. J. Lowe, D. N. Alleyne, and P. Cawley. Defect detection in pipes using guided waves. *Ultrasonics*, 36(1-5):147–154, 1998.
- [109] R. S. Long, P. Cawley, and M. J. S. Lowe. Acoustic wave propagation in buried iron water pipes. *Proc. R. Soc. A*, 459:2749–2770, 2003.
- [110] P. Wilcox, B. Pavlakovic, M. Evans, K. Vine, P. Cawley, M. J. S. Lowe, and D. Alleyne. Long range inspection of rail using guided waves. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 22A, pages 236–249. American Institute of Physics, New York, 2003.
- [111] Z. Fan and M. J. Lowe. Interaction of weld-guided waves with defects. *NDT & E Int.*, 47:124–133, 2012.
- [112] R. K. Pattanayak, P. Manogharan, K. Balasubramaniam, and P. Rajagopal. Low frequency axisymmetric longitudinal guided waves in eccentric annular cylinders. *J. Acoust. Soc. Am.*, 137(6):3253–3262, 2015.
- [113] P. Rajagopal and R. K. Pattanayak. Ultrasonic guided waves in elliptical annular cylinders. *J. Acoust. Soc. Am.*, 138(3):EL336–EL341, 2015.
-

- [114] P. E. Lagasse. Higher-order finite element analysis of topographic guides supporting elastic surface waves. *J. Acoust. Soc. Am.*, 53(4):1116–1122, 1972.
- [115] B. Aalami. Waves in prismatic guides of arbitrary cross section. *J. Appl. Mech.*, 40(4), 1067-1072(4):1067–10072, 1973.
- [116] L. Gavrić. Computation of propagative waves in free rail using a finite element technique. *J. Sound Vib.*, 185:531–543, 1995.
- [117] T. Hayashi, W. J. Song, and J. L. Rose. Guided wave dispersion curves for a bar with an arbitrary cross-section, a rod and rail example. *Ultrasonics*, 41(3):175–183, 2003.
- [118] C. Tamayama Hayashi, T. and M. Murase. Wave structure analysis of guided waves in a bar with an arbitrary cross-section. *Ultrasonics*, 44(1):17–24, 2006.
- [119] S. Coccia, I. Bartoli, A. Marzani, F. L. di Scalea, S. Salamone, and M. Fateh. Numerical and experimental study of guided waves for detection of defects in the rail head. *NDT & E Int.*, 44(1):93–100, 2011.
- [120] P. Wilcox, M. Evans, M. J. S. Lowe, and P. Cawley. Dispersion and excitability of guided acoustic waves in isotropic beams with arbitrary cross-section. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 21A, pages 203–210. American Institute of Physics, New York, 2002.
- [121] U. Orrenius and S. Finnveden. Calculation of wave propagation in rib stiffened plate structures. *J. Sound Vib.*, 198(2):203–224, 1996.
- [122] I. Bartoli, A. Marzani, F. L. di Scalea, and E. Viola. Modeling wave propagation in damped waveguides of arbitrary cross-section. *J. Sound Vib.*, 295:685–707, 2006.
- [123] M. Castaings and M. J. S. Lowe. Finite element model for waves guided along solid systems of arbitrary section coupled to infinite solid media. *J. Acoust. Soc. Am.*, 123(2):696–708, 2008.

- [124] A. Marzani, E. Viola, I. Bartoli, F. L. di Scalea, and P. Rizzo. A semi-analytical finite element formulation for modeling stress wave propagation in axisymmetric damped waveguides. *J. Sound Vib.*, 318(3):488–505, 2008.
- [125] COMSOL. *COMSOL Multiphysics Reference Manual*. Version 5.1 by COMSOL MULTIPHYSICS, <http://www.comsol.com/>, 2015.
- [126] M. V. Predoi, M. Castaings, B. Hosten, and C. Bacon. Wave propagation along transversely periodic structures. *J. Acoust. Soc. Am.*, 121(4):1935–1944, 2007.
- [127] M. Drozd, L. Moreau, M. Castaings, M. J. S. Lowe, and P. Cawley. Efficient numerical modelling of absorbing regions for boundaries of guided waves problems. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 80, pages 126–133. American Institute of Physics, New York, 2006.
- [128] M. Castaings, C. Bacon, B. Hosten, and M. V. Predoi. Finite element predictions for the dynamic response of thermo-viscoelastic material structures. *J. Acoust. Soc. Am.*, 115(3):1125–1133, 2004.
- [129] F. Treyssède, K. L. Nguyen, A. S. Bonnet-BenDhia, and C. Hazard. Finite element computation of trapped and leaky elastic waves in open stratified waveguides. *Wave Motion*, 51(7):1093–1107, 2014.
- [130] K. L. Nguyen, F. Treyssède, and C. Hazard. Numerical modeling of three-dimensional open elastic waveguides combining semi-analytical finite element and perfectly matched layer methods. *J. Sound Vib.*, 344:158–178, 2015.
- [131] F. L. Teixeira and W. C. Chew. Complex space approach to perfectly matched layers: a review and some new developments. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, 13(5):441–455, 2000.
- [132] P. Zuo, X. Yu, and Z. Fan. Numerical modeling of embedded solid waveguides using safe-pml approach using a commercially available finite element package. *NDT & E Int.*, 90:11–23, 2017.

- [133] D. S. Jones. *Acoustic and electromagnetic waves*. Clarendon Press/Oxford University Press, Oxford/New York, 1986.
- [134] A. Bernard, M. J. S. Lowe, and M. Deschamps. Guided waves energy velocity in absorbing and non-absorbing plates. *J. Acoust. Soc. Am.*, 110(1):186–196, 2001.
- [135] X. Yu, P. Manogharan, Z. Fan, and P. Rajagopal. Shear horizontal feature guided ultrasonic waves in plate structures with 90° transverse bends. *Ultrasonics*, 65:370–379, 2016.
- [136] P. Manogharan, X. Yu, Z. Fan, and P. Rajagopal. Interaction of shear horizontal bend (SH_B) guided mode with defects. *NDT & E Int.*, 75:39–47, 2015.
- [137] Abaqus. *Abaqus Analysis User's Guide*. Version 6.14 by Dassault Systèmes, <http://www.3ds.com/>, 2014.
- [138] M. Castaings and C. Bacon. Finite element modelling of torsional wave modes along pipes with absorbing materials. *J. Acoust. Soc. Am.*, 119(6):3741–3751, 2006.
- [139] P. Rajagopal, M. Drozd, E. A. Skelton, M. J. Lowe, and R. V. Craster. On the use of absorbing layers to simulate the propagation of elastic waves in unbounded isotropic media using commercially available finite element packages. *NDT & E Int.*, 51:30–40, 2012.
- [140] E. Le Clézio, M. Valentin Predoi, M. Castaings, B. Hosten, and M. Rousseau. Numerical predictions and experiments on the free-plate edge mode. *Ultrasonics*, 41(1):25–40, 2003.
- [141] P. Rajagopal and 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):2895–2904, 2008.
- [142] B. A. Auld. *Acoustic Fields and Waves in Solids*, volume 2. 2nd edition, Krieger Publishing Company, Malabar, Florida, 1990.

- [143] P. E. Lagasse, I. M. Mason, and E. A. Ash. Acoustic surface waveguides—analysis and assessment. *IEEE Trans. Microwave Theory Tech.*, 21(4):225–236, 1973.
- [144] A. A Oliner. Waveguides for acoustic surface waves: a review. *Proceedings of IEEE*, 64(5):615–627, 1976.
- [145] A. Demma, P. Cawley, M. Lowe, and A. G Roosenbrand. The reflection of fundamental torsional mode from cracks and notches in pipes. *J. Acoust. Soc. Am.*, 114(3):611–625, 2003.
- [146] P. Rajagopal and 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):1527–1538, 2007.
- [147] M. Ratassepp, M. J. S. Lowe, P. Cawley, and 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):2873–2882, 2008.
- [148] P. Rajagopal and 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):2021–2030, 2008.
- [149] X. Yu, M. Ratassepp, P. Rajagopal, and Z. Fan. Anisotropic effects on ultrasonic guided waves propagation in composite bends. *Ultrasonics*, 72:95–105, 2016.
- [150] T. T. Wu and Y. H. Liu. On the measurement of anisotropic elastic constants of fiber-reinforced composite plate using ultrasonic bulk wave and laser generated Lamb wave. *Ultrasonics*, 37(6):405–412, 1999.
- [151] D. N. Alleyne and P. Cawley. A two-dimensional Fourier transform method for the measurement of propagating multimode signals. *J. Acoust. Soc. Am.*, 89(3):1159–1168, 1991.

- [152] D. L. Hopkins, M. Brassard, G. A. Neau, J. N. Noiret, W. V. Johnson, and L. Le Ber. Surface-adaptive ultrasound (SAUL) for phased-array inspection of composite specimens with curved edges and complex geometry. In D. O. Thompson, D. E. Chimenti, and Leonard J. B., editors, *Review of Progress in Quantitative NDE*, volume 32, pages 809–816. American Institute of Physics, New York, 2013.
- [153] S. Robert, O. Casula, O. Roy, and G. Neau. Real-time nondestructive testing of composite aeronautical structures with a self-adaptive ultrasonic technique. *Meas. Sci. Technol.*, 24(7):074011, 2013.
- [154] T. Hayashi and K. Kawashima. Multiple reflections of Lamb waves at a delamination. *Ultrasonics*, 40(1):193–197, 2002.
- [155] D. P. Willemann, P. Castellini, G. M. Revel, and E. P. Tomasini. Structural damage assessment in composite material using laser Doppler vibrometry. In *International Conference on Vibration Measurements by Laser Techniques: Advances and Applications*, pages 375–379. International Society for Optics and Photonics, 2004.
- [156] H. Sohn, D. Dutta, J. Y. Yang, H. J. Park, M. DeSimio, S. Olson, and E. Swenson. Delamination detection in composites through guided wave field image processing. *Compos. Sci. Technol.*, 71(9):1250–1256, 2011.
- [157] X. Yu, M. Ratassepp, and Z. Fan. Damage detection in quasi-isotropic composite bends using ultrasonic feature guided waves. *Compos. Sci. Technol.*, 141:120–129, 2017.
- [158] O. M. Mukdadi, Y. M. Desai, S. K. Datta, A. H. Shah, and A. J. Niklasson. Elastic guided waves in a layered plate with rectangular cross section. *J. Acoust. Soc. Am.*, 112(5):1766–1779, 2002.
- [159] C. C. Habeger, R. W. Mann, and G. A. Baum. Ultrasonic plate waves in paper. *Ultrasonics*, 17(2):57–62, 1979.

-
- [160] G. E. Backus. Long-wave elastic anisotropy produced by horizontal layering. *Journal of Geophysical Research*, 67(11):4427–4440, 1962.
- [161] G. W. Milton. *The Theory of Composites*. Cambridge University Press, Cambridge, UK, 2002.
- [162] Y. Humeida, V. J. Pinfield, R. E. Challis, P. D. Wilcox, and C. Li. Simulation of ultrasonic array imaging of composite materials with defects. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 60(9):1935–1948, 2013.
- [163] Z. Su, C. Yang, N. Pan, L. Ye, and L. M. Zhou. Assessment of delamination in composite beams using shear horizontal (SH) wave mode. *Compos. Sci. Technol.*, 67(2):244–251, 2007.
- [164] W. C. Chew. *Waves and fields in inhomogeneous media*, volume 522. IEEE Press, New York, 1995.
- [165] R. D. Adams and W. C. Wake. *Structural adhesive joints in engineering*. Elsevier Applied Science Publishers Ltd, New York, 1984.
- [166] A. J. Gunnion and I. Herszberg. Parametric study of scarf joints in composite structures. *Compos. Struct.*, 75(1):364–376, 2006.
- [167] C. H. Wang and A. J. Gunnion. On the design methodology of scarf repairs to composite laminates. *Compos. Sci. Technol.*, 68(1):35–46, 2008.
- [168] N. Rastogi, S. R. Soni, and A. Nagar. Thermal stresses in aluminum-to-composite double-lap bonded joints. *Advances in Engineering Software*, 29(3):273–281, 1998.
- [169] X. Yu, Z. Fan, M. Castaings, and C. Biateau. Feature guided wave inspection of bond line defects between a stiffener and a composite plate. *NDT & E Int.*, 89:44–55, 2017.
- [170] B. Hosten and M. Castaings. An acoustic method to predict the effective elastic constants of orthotropic and symmetric laminates. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 12, pages 1201–1207. Springer, Boston, 1993.
-

-
- [171] M. Castaings. Measurement of viscoelastic modules. In M. Bruneau and C. Potel, editors, *Materials and Acoustics Handbook*, pages 561–576. ISTE-WILEY, London, 2009.
- [172] J. Ma and P. Cawley. Low-frequency pulse echo reflection of the fundamental shear horizontal mode from part-thickness elliptical defects in plates. *J. Acoust. Soc. Am.*, 127(6):3485–3493, 2010.
- [173] C. R. Farrar and K. Worden. An introduction to structural health monitoring. *Phil. Trans. R. Soc. A*, 365:303–315, 2007.
- [174] C. Liu, J. Dobson, and P. Cawley. Efficient generation of receiver operating characteristics for the evaluation of damage detection in practical structural health monitoring applications. *Proc. R. Soc. A*, 473:20160736, 2017.
- [175] A. Raghavan and C. E. Cesnik. Review of guided-wave structural health monitoring. *Shock and Vibration Digest*, 39(2):91–116, 2007.
- [176] R. S. C. Monkhouse, P. D. Wilcox, and P. Cawley. Flexible interdigital pvdf transducers for the generation of lamb waves in structures. *Ultrasonics*, 35(7):489–498, 1997.
- [177] W. K. Wilkie, R. G. Bryant, J. W. High, R. L. Fox, R. F. Hellbaum, A. J. JALINK, B. D. Little, and P. H. Mirick. Low-cost piezocomposite actuator for structural control applications. In J. H. Jacobs., editor, *Proc. SPIE*, volume 3991, pages 323–334, 2000.
- [178] P. Wilcox, M. Lowe, and P. Cawley. Omnidirectional guided wave inspection of large metallic plate structures using an emat array. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 52(4):653–665, 2005.
- [179] N. Takeda, Y. Okabe, J. Kuwahara, and T. Kojima, S. and Ogisu. Development of smart composite structures with small-diameter fiber bragg grating sensors for damage detection: Quantitative evaluation of delamination length in CFRP laminates using lamb wave sensing. *Compos. Sci. Technol.*, 65(15):2575–2587, 2005.
-

- [180] X. Qing, A. Kumar, C. Zhang, I. F. Gonzalez, G. Guo, and F. K. Chang. A hybrid piezoelectric/fiber optic diagnostic system for structural health monitoring. *Smart Mater. Struct.*, 14(3):S98–S103, 2005.
- [181] P. Fromme, P. D. Wilcox, M. J. Lowe, and P. Cawley. On the development and testing of a guided ultrasonic wave array for structural integrity monitoring. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 53(4):777–785, 2006.
- [182] Z. Zeng, M. Liu, H. Xu, Y. Liao, F. Duan, L. M. Zhou, H. Jin, Z. Zhang, and Z. Su. Ultra-broadband frequency responsive sensor based on lightweight and flexible carbon nanostructured polymeric nanocomposites. *Carbon*, 121:490–501, 2017.
- [183] C. A. Paget, S. Grondel, K. Levin, and C. Delebarre. Damage assessment in composites by lamb waves and wavelet coefficients. *Smart Mater. Struct.*, 12(3):393–402, 2003.
- [184] C. H. Wang, J. T. Rose, and F. K. Chang. A synthetic time-reversal imaging method for structural health monitoring. *Smart Mater. Struct.*, 13(2):415–423, 2004.
- [185] H. W. Park, H. Sohn, K. H. Law, and C. R. Farrar. Time reversal active sensing for health monitoring of a composite plate. *J. Sound Vib.*, 302(1):50–66, 2007.
- [186] J. Moll, R. T. Schulte, B. Hartmann, C. P. Fritzen, and O. Nelles. Multi-site damage localization in anisotropic plate-like structures using an active guided wave structural health monitoring system. *Smart Mater. Struct.*, 19(4):045022, 2010.
- [187] Z. Su and L. Ye. An intelligent signal processing and pattern recognition technique for defect identification using an active sensor network. *Smart Mater. Struct.*, 13(4):957–969, 2004.

- [188] S. Legendre, D. Massicotte, J. Goyette, and T. K. Bose. Neural classification of lamb wave ultrasonic weld testing signals using wavelet coefficients. *IEEE Transactions on Instrumentation and Measurement*, 50(3):672–678, 2001.
- [189] G. Zhou and L. M. Sim. Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors-review. *Smart Mater. Struct.*, 11(6):925–939, 2002.
- [190] C. H. Zhong, A. J. Croxford, and P. D. Wilcox. Remote inspection system for impact damage in large composite structure. *Proc. R. Soc. A*, 471:20140631, 2015.
- [191] K. Worden, C. R. Farrar, G. Manson, and G. Park. The fundamental axioms of structural health monitoring. *Proc. R. Soc. A*, 463:1639–1664, 2007.
- [192] D. Wang, L. Ye, Y. Lu, and Z. Su. Probability of the presence of damage estimated from an active sensor network in a composite panel of multiple stiffeners. *Compos. Sci. Technol.*, 69(13):2054–2063, 2009.
- [193] T. Clarke, P. Cawley, P. D. Wilcox, and A. J. Croxford. Evaluation of the damage detection capability of a sparse-array guided-wave SHM system applied to a complex structure under varying thermal conditions. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 56(12):2666–2678, 2009.
- [194] T. E. Michaels, J. E. Michaels, and A. C. Cobb. Simultaneous ultrasonic monitoring of crack growth and dynamic loads during a full scale fatigue test of an aircraft wing. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 1096, pages 1458–1465. American Institute of Physics, New York, 2009.
- [195] R. L. Weaver and O. I. Lobkis. Temperature dependence of diffuse field phase. *Ultrasonics*, 38(1):491–494, 2000.
- [196] G. Konstantinidis, B. W. Drinkwater, and P. D. Wilcox. The temperature stability of guided wave structural health monitoring systems. *Smart Mater. Struct.*, 15(4):967–976, 2006.

- [197] P. D. Wilcox, A. J. Croxford, J. E. Michaels, Y. Lu, and B. W. Drinkwater. A comparison of temperature compensation methods for guided wave structural health monitoring. In D. O. Thompson and D. E. Chimenti, editors, *Review of Progress in Quantitative NDE*, volume 975, pages 1453–1460. American Institute of Physics, New York, 2008.
- [198] Y. Lu and J. E. Michaels. A methodology for structural health monitoring with diffuse ultrasonic waves in the presence of temperature variations. *Ultrasonics*, 43(9):717–731, 2005.
- [199] T. Clarke, F. Simonetti, and P. Cawley. Guided wave health monitoring of complex structures by sparse array systems: Influence of temperature changes on performance. *J. Sound Vib.*, 329(12):2306–2322, 2010.
- [200] X. Yu, Z. Fan, S. Puliakote, and M. Castaings. Remote monitoring of bond line defects between a composite panel and a stiffener using distributed piezoelectric sensors. *Smart Mater. Struct.*, 27(3):035014, 2018.
- [201] E. B. Flynn, M. D. Todd, P. D. Wilcox, B. W. Drinkwater, and A. J. Croxford. Maximum-likelihood estimation of damage location in guided-wave structural health monitoring. *Proc. R. Soc. A*, 467:2575–2596, 2011.
- [202] P. D. Corl, G. S. Kino, C. S. DeSilets, and P. M. Grant. A digital synthetic focus acoustic imaging system. In *Acoustical Imaging*, pages 39–53. Springer, 1980.
- [203] M. Karaman, P.-C. Li, and M. O’Donnell. Synthetic aperture imaging for small scale systems. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 42(3):429–442, 1995.
- [204] J. T. Ylitalo and H. Ermert. Ultrasound synthetic aperture imaging: monostatic approach. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 41(3):333–339, 1994.
- [205] P. Fromme, P. Wilcox, and P. Cawley. Remote monitoring of plate-like structures using guided wave arrays. In D. O. Thompson and D. E. Chimenti,

- editors, *Review of Progress in Quantitative NDE*, volume 22A, pages 157–164. American Institute of Physics, New York, 2002.
- [206] R. Sicard, A. Chahbaz, and J. Goyette. Guided Lamb waves and L-SAFT processing technique for enhanced detection and imaging of corrosion defects in plates with small depth-to-wavelength ratio. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 51(10):1287–1297, 2004.
- [207] T. Hayashi and M. Murase. Defect imaging with guided waves in a pipe. *J. Acoust. Soc. Am.*, 117(4):2134–2140, 2005.
- [208] G. S. Kino. *Acoustic waves: devices, imaging, and analog signal processing*. Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1987.
- [209] J. S. Hall and J. E. Michaels. Minimum variance ultrasonic imaging applied to an in situ sparse guided wave array. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 57(10):2311–2323, 2010.
- [210] M. J. S. Lowe. Matrix techniques for modelling ultrasonic waves in multi-layered media. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 42:525–542, 1995.
- [211] M. Fink. Time reversal acoustics. *Phys. Today*, 50:34–40, 1997.
- [212] M. Fink and C. Prada. Acoustic time-reversal mirrors. , 17(1), r1. *Inverse problems*, 17(1):R1–R38, 2001.
- [213] M. Fink. Time reversal of ultrasonic fields. i. basic principles. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 39(5):555–566, 1992.
- [214] R. K. Ing and M. Fink. Time-reversed lamb waves. *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 45(4):1032–1043, 1998.
- [215] R. K. Ing and M. Fink. Self-focusing and time recompression of lamb waves using a time reversal mirror. *Ultrasonics*, 36:179–186, 1998.

- [216] C. Prada and M. Fink. Separation of interfering acoustic scattered signals using the invariants of the time-reversal operator. application to lamb waves characterization. *J. Acoust. Soc. Am.*, 104(2):801–807, 1998.
- [217] C. Prada and J. L. Thomas. Experimental subwavelength localization of scatterers by decomposition of the time reversal operator interpreted as a covariance matrix. *J. Acoust. Soc. Am.*, 114(1):235–243, 2003.
- [218] G. W. Postma. Wave propagation in a stratified medium. *Geophysics*, 20(4):780–806, 1955.
- [219] J. G. Berryman. Transversely isotropic poroelasticity arising from thin isotropic layers. In *Mathematics of Multiscale Materials*, pages 37–50. Springer, 1998.
- [220] W. J. Parnell. *Homogenization techniques for wave propagation in composite materials*. PhD thesis, University of Manchester, 2006.

List of Publications

- [P1] **X. Yu**, Z. Fan, S. Puliyakote, M. Castaings. Remote monitoring of bond line defects between a composite panel and a stiffener using distributed piezoelectric sensors. *Smart Materials and Structures*, 27(3):035014, 2018.
- [P2] **X. Yu**, Z. Fan, M. Castaings, C. Biateau. Feature guided wave inspection of bond line defects between a stiffener and a composite plate. *NDT&E International*, 89:44-55, 2017.
- [P3] **X. Yu**, M. Ratassepp, Z. Fan. Damage detection in quasi-isotropic composite bends using ultrasonic feature guided waves. *Composites Science and Technology*, 141:120-129, 2017.
- [P4] **X. Yu**, M. Ratassepp, P. Rajagopal, Z. Fan. Anisotropic effects on ultrasonic guided waves propagation in composite bends. *Ultrasonics*, 72:95-105, 2016.
- [P5] **X. Yu**, P. Manogharan, Z. Fan, P. Rajagopal. Shear horizontal feature guided ultrasonic waves in plate structures with 90° transverse bends. *Ultrasonics*, 65:370-379, 2016.
- [P6] P. Zuo, **X. Yu**, Z. Fan. Numerical modeling of embedded solid waveguides using SAFE-PML approach using a commercially available finite element package. *NDT&E International*, 90:11-23, 2017.
- [P7] P. Manogharan, **X. Yu**, Z. Fan, P. Rajagopal. Interaction of shear horizontal bend (SH_B) guided mode with defects. *NDT&E International*, 75:39-47, 2015.
- [P8] **X. Yu**, M Ratassepp, Z. Fan, P Manogharan, P. Rajagopal. Feature guided waves (FGW) in fiber reinforced composite plates with 90° transverse bends. In D. E. Chimenti and J. B. Leonard, editors, *Review of Progress in Quantitative NDE*, volume 1706, pages 030016. American Institute of Physics, New York, 2016.

- [P9] **X. Yu**, P. Manogharan, Z. Fan, P. Rajagopal. Feature-guided waves (FGW) in plate structures with 90° transverse bends. In D. E. Chimenti and J. B. Leonard, editors, *Review of Progress in Quantitative NDE*, volume 1650, pages 713-720. American Institute of Physics, New York, 2015.
- [P10] **X. Yu**, P. Manogharan, Z. Fan, P. Rajagopal. Investigation of ultrasonic feature guided waves for the monitoring of structural bends. In F. K. Chang and F. Kopsaftopoulos, editors, *Structural Health Monitoring 2015: System Reliability for Verification and Implementation*. DEStech Publications, Inc, United States, 2015.