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Damage detection in quasi-isotropic composite bends using ultrasonic feature guided waves

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Abstract

Complex-shaped composite components have been extensively incorporated as reinforcing structures in the aerospace industry. Various types of damages can be initiated in these structures due to the stress concentration and out-of-plane impacts during the in-service use, which have to be detected timely in case they propagate at subsurface laminae and ultimately lead to catastrophic failure. This paper explores the feasibility of using ultrasonic feature guided waves (FGW) for rapid screening of typical 90° bends made of quasi-isotropic composite laminates. Such FGWs are capable of focusing the propagation energy along the feature, with limited leakage to the adjacent plate. Modal studies of the composite bent plate are carried out by applying the Semi-Analytical Finite Element (SAFE) method, revealing properties of the FGWs that exist in the structure. A shear horizontal type bend-guided mode has been identified as a promising candidate. 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 study the interaction of the identified FGW mode with different defects occurred in the bend region such as the interlaminar delamination and the transverse crack, showing good agreement. The wave-defect resonance phenomenon and the reflection behavior are investigated for localizing these two types of defects, and the potential of the FGW for efficient damage detection in composite bends is well demonstrated.

Keywords: Ultrasonic guided waves, 90° quasi-isotropic bends, Rapid screening

1. Introduction

Fiber reinforced composites are increasingly utilized in the aerospace industry because of their high specific strength and stiffness, lightweight, and corrosion resistance as compared with traditional metallic materials. Serving as reinforcing elements, such composites are often molded into complex

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5 shapes such as bends, spars and stiffeners, owing to the advancement in manufacturing techniques. However, these structures are susceptible to various types of damages during the in-service use, including matrix cracking, delamination and fiber breakage, consequently degrading the structural integrity and reliability. Evidence has been provided to account for the vulnerability of the curvature or the junction region of such composite structures [1, 2]. It has been found that the stress/strain concentration is induced in the bend region of a L-shaped composite beam subjected to quasi-static tensile loading, where the first failure always occurs perpendicular to the radius direction as delamination [1]. It has also been reported that the web-flange junction of the T-shaped stiffener (fabricated either by laying up plies of unidirectional tap or 2D woven fabric or even by 3D-braid process) is prone to cracking and delamination under impact or out-of-plane loads [3]. This is caused by local strain concentrations, stemming from the seriously twisted or non-uniformly distributed fibers in the curved zones. Therefore, the feature areas of the composite structures are critical regions to be inspected during the service life to ensure their safe operation.

The present paper 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, as shown in Fig. 1 (a). 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. 1(b), which is time consuming and tedious. Furthermore, different wedges are needed for different bend radius, and they are worn easily during the measurement. Although some water-immersed phased array techniques [4] can be applied for the inspection free of wedges, sophisticated delay laws are required to adapt to the complex surface geometry and to compensate for the probe misalignment, which is expensive and complicated for the long-range testing. Ultrasonic guided wave testing can be an effective alternative 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 - feature guided waves (FGW) have received much attention and been discussed in the literature extensively [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Guided waves not only exists in the regular waveguides (e.g. plates and cylinders), but also exist in the complex-shaped structures, such as metal welds, bends and stiffeners. Owing to the influence of geometric variation, the topographical feature can be a special ‘local’ waveguide, and the energy of proper guided waves can be highly concentrated in the feature. The physics of such energy trapping effect can be explained that the guided modes in the separate feature have similar mode shapes to the adjacent plate but possess slower phase velocities, causing the wave energy to be constrained in the ‘slower medium’, arising from the total internal reflection [5, 16]. Recent studies by the authors on FGWs in structural bends started from guided waves in the metallic plate structures with 90° transverse bends, and a shear horizontal type bend-guided mode [10] was discovered to be attractive

for rapid screening of long-range bends due to its little-dispersive and low-attenuative characteristics. The mode strongly retaining its wave energy in the bend region can propagate long distances and is also capable of particularly interrogating such feature rather than the entire structure. Its interaction with transverse and longitudinal defects in the bend region was then investigated, and the capability of this bend-guided mode for NDT applications has been well demonstrated [11]. Similar FGW phenomena have been found in unidirectional composite bends for the S_0 -like and SH_0 -like bend-guided modes. The influence of fiber orientation on the energy trapping effect was studied, and the results indicate that the energy concentration is caused by both the geometric variation and the anisotropic properties, laying a foundation for the investigation of multidirectional composite bends.

In this study, we explore 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 [17, 18] 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 [19, 20, 21, 22]. As to the composite bend, both the geometrical variation and anisotropic material properties would influence the propagation of guided waves, thus adding complexity to the FGW based damage detection.

The paper starts with the modal analysis of FGW modes existing in the composite bent plate by applying the Semi-Analytical Finite Element (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, and good agreement can be observed. Finally the paper concludes with the direction for future work.

2. Feature guided waves in composite bends

2.1. Semi-Analytical Finite Element modeling

Modal studies of the 90° composite bent plate were performed by applying the well-known SAFE approach. This approach solves an eigenvalue problem to find the wavenumbers along the propagation direction at the chosen frequency. The SAFE modeling only requires the discretization of the cross section of the waveguide, combined with an analytical description of the harmonic behavior along the waveguide, thus reducing a 3D problem to a 2D one. With the improved computational efficiency, this

method has gained its popularity to extract modal solutions for guided waves in irregularly shaped waveguides [5, 23, 24, 25, 26, 27] and in composite laminates [12, 28, 29, 30].

Considering a wave propagating in a solid with constant cross section, the displacement vector in the waveguide can be given by

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

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, as shown in Fig. 2. For general anisotropic materials, the equation of dynamic equilibrium associated with the elastic behavior law is given by:

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

where C_{ijkl} are the components of the stiffer tensor, and ρ is the mass density. Substituting Eq. (1) into Eq. (2), this differential equation of motion regarding an eigenvalue problem can be written as:

$$C_{ijkl} \frac{\partial^2 U_j}{\partial x_k \partial x_l} + I(C_{i3jk} + C_{ikj3}) \frac{\partial(kU_j)}{\partial x_k} - kC_{i3j3}(kU_j) + \rho \omega^2 \delta_{ij} U_j = 0, \quad (3)$$

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 [31], where the input formalism for eigenvalue problems is as follows:

$$\nabla \cdot (c \nabla \tilde{U} + \alpha \tilde{U} - \gamma) - \beta \nabla \tilde{U} - a \tilde{U} + \lambda d_a \tilde{U} - \lambda^2 e_a \tilde{U} = 0, \quad (4)$$

in which all matrix coefficients admit complex values, essential for viscoelastic materials, and $\tilde{U}$ represents the set of variables to be determined. Full implementation details for this method were given by Predoi *et al* [30].

The schematic of the SAFE model is shown in Fig. 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 [27]. The composite material used in the present study is a 16-ply carbon fiber/epoxy (CF/EP) laminate with a quasi-isotropic stacking sequence $[0/45/90/-45]_{2s}$. Its effective stiffness matrix was calculated from ply properties using the Backus averaging method [32, 33, 34] and is given in Table 1. The elastic properties of the unidirectional lamina of transversely isotropic symmetry were characterized by ultrasonic bulk wave and guided wave measurements [35]. The reference coordinate

system used to define fibrous materials is set such that the fibers lie along the x_3 axis and the layer interfaces are normal to the x_1 axis. 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 following transformation:

$$C'_{ijkl} = \omega_{im}\omega_{jn}\omega_{kr}\omega_{ls}C_{mnrs}, \quad (5)$$

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. Notably, as illustrated in Fig. 2, a curvature-based rotation about the x_3 axis ought to be implemented with $\varphi = g(x_1, x_2)$ being a function of nodal positions to account for the anisotropy across the bend region [12]. The problem was solved in the frequency range from 50 to 400 kHz with a step of 50 kHz.

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 our case), which can be identified in the SAFE calculation by examining the axial component of the time-averaged power flow (i.e. acoustic Poynting vector [16]) of modes over the cross section. Its quantity can be obtained by the following formula at each nodal position:

$$P_{x_3} = -Re[(\frac{I\omega}{2})(u_1^*\sigma_{31} + u_2^*\sigma_{32} + u_3^*\sigma_{33})], I = \sqrt{-1}, \quad (6)$$

where σ_{31} , σ_{32} and σ_{33} are components of the stress; u_1^* , u_2^* and u_3^* denote the complex conjugates of the horizontal, vertical, and axial displacements of the modes, respectively. Fig. 3(a) visualizes the axial power flow of the identified SH_B mode in the cross section at 300 kHz, with color 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. 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 occurred in the bend region. Fig. 3(c) and (d) depict the normalized through-thickness displacement and stress mode shapes, respectively. We can see 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 as the -6dB width [5] of the lobe

of axial power flow with respect to the bend arc, as graphically presented in Fig. 4(a) (i.e. Fig. 3(b) zoomed around the bend region). The narrower width indicates stronger energy concentration in the vicinity of the bend. Fig. 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.

Fig. 5 presents the calculated dispersion characteristics of the SH_B mode including the phase velocity and the attenuation. In practical NDT/SHM applications the favorable 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 [36], the operation of the SH_B mode is normally constrained in lower frequencies.

3. Validation of propagation characteristics

3.1. 3D Finite Element Simulation

To cross-verify the propagation of the FGW in the composite bent plate, three-dimensional time-marching FE simulations were carried out using the proprietary code ABAQUS Explicit [37]. 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. 6(b). Local coordinate systems were defined to assign anisotropic properties to the meshed elements.

Fig. 6(a) presents a snapshot of the excited wave field of the SH_B mode, with the color contour denoting the amplitude of the resultant displacement. A 5-cycle Hanning windowed toneburst signal centered at 300 kHz was applied on the through-thickness nodes at the bend end (Fig. 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. 6(c)), the majority of the wave energy is concentrated towards the upper part of the bend region, which agrees with the SAFE predictions.

3.2. Experiments on simulated composite bends

The experimental setup is shown in Fig. 7. Similar 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 unidirectional SE84LV prepregs (Gurit Inc., USA) containing the T700 carbon fibers embedded in the #340 epoxy resin. A quasi-isotropic layup of $[0/45/90/-45]_{2s}$ was adopted with 0° fibers orientated along the bend direction. Upon stacking the unconsolidated prepregs on the mold of high temperature resistance, a molding 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 demolding 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. 7(c), which was driven by a RITEC RAM-5000 high power ultrasonics pulser (Ritec Inc., USA) producing Hanning windowed toneburst signals centered 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. 7(a) and (b), the two laser beams aligned at 60° [38] 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 [10]. The wave reception signals were processed by a digital storage oscilloscope (Teledyne LeCroy HDO 6054).

Fig. 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 source. The time traces were processed by the spatial two-dimensional Fast Fourier Transform (2D-FFT) [39], and the calculated phase velocity dispersion curve is shown in Fig. 9, where both the 3D FE results derived in a similar manner and the SAFE predictions obtained in Section 2.2 are compared. Excellent agreement can be found among the results, while the slight deviation from the experimental results is due to the accuracy in the estimation of material properties in the models.

4. Interaction of FGWs 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 the transverse crack has been investigated in this section by both experiments and 3D FE simulations.

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, and the created delamination is symmetric about the central axis with its front edge 200 mm away from the excitation location. In 3D FE simulations, the delamination was modeled by a volume split [17, 40, 41] at the same region in which 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.

Fig. 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 shape of the incident SH_B wave remains almost the same in the propagation, which confirms that the chosen FGW mode has little dispersion, contributing to its practical employment for rapid screening of the structure.

In principal, the localization of the delamination can be achieved by estimating the propagation speed and time of flight from the reflected signal [42, 43]. 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 [20]. 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 disfavoring the strong wave reflection.

Notably, as shown in the time traces monitored at defect center ($Z=205$ 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 [44], the total energy (E) of a signal can be obtained as follows:

$$E = \int_{-\infty}^{\infty} |s(t)|^2 dt = \int_{-\infty}^{\infty} |S(f)|^2 df, \quad (7)$$

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:

$$E = df \sum_{k=1}^{N_{FFT}} |S[k]|^2, \quad (8)$$

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. 11. Local peaks of the energy can be readily seen in the defect area in both cases, which 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 [21, 22]. Within the delamination region, the number of local maxima and minima of the wave energy is determined by the ratio of the wavelength of the standing wave to the length of the defect.

4.2. Transverse crack 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. 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 modeled in 3D FE simulations as well, by axially disconnecting adjacent elements having zero stress on the shared element faces. Fig. 12(b) shows the superposed two time 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 amplitudes remain almost constant in the propagation, suggesting the low leakage of the SH_B mode. Fig. 13 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.

To quantitatively study the reflection behavior 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. 13(b)). The resulting reflection spectrum as a function of frequency is shown in Fig. 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. Also, the SH_B mode is more sensitive to the defects occurred in the upper portion of the bend region because more energy concentrates towards the top surface, as predicted in Section 3.1. Nevertheless, the feasibility of using the reflection behavior for crack detection is well demonstrated.

5. Conclusions

In this paper, 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 confined to 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 the transverse crack. Close agreement has been observed between the numerical predictions and experimental measurements. To quantify the defect scattered wave field, both the wave energy along the propagation path and the reflection spectra are calculated for localizing the delamination and the crack, respectively. The capability of the FGW for damage detection in composite bends is well demonstrated. Noteworthy, the method proposed in this paper 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. The future work is planned to develop an on-site structural health monitoring system using FGWs based on integrated ultrasonic sensors.

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Table 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 CF/EP 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

Figure 1: (a) Illustration of a wing spar consisting of multiple composite bends; (b) schematic of the conventional technique used to inspect bends.

Figure 2: Schematic of the SAFE model of a quasi-isotropic CF/EP bent plate; global and local coordinates shown; absorbing region indicated.

Figure 3: (Color online) (a) Mode shape illustration of the feature guided wave propagating along the bend, derived by the SAFE method at 300 kHz; color 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 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.

Figure 5: SAFE predictions of (a) the phase velocity and (b) the attenuation dispersion curves of the identified feature guided mode.

Figure 6: (Color online) (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 color 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 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.

Figure 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 9: Phase velocity dispersion curves derived from the SAFE calculation (solid), the 3D FE simulation (diamonds) and the experiment (circles).

Figure 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.

Figure 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.

Figure 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 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.

Figure 14: Reflection coefficient spectra for the transverse crack, derived from the 3D FE simulation (solid) and the experiment (asterisk).