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Anisotropic effects on ultrasonic guided waves propagation in composite bends

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ABSTRACT

Ultrasonic guided waves have 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 waves propagation is needed to evaluate their suitability for the non-destructive testing (NDT) of such complex structures. This paper reports the Semi-Analytical Finite Element (SAFE) simulations revealing the capability of energy confinement carried by two types of guided modes in 90° carbon fiber/epoxy (CF/EP) bends. Existence of the phenomenon is cross-validated by both 3D Finite Element (FE) modeling and experimental measurements. The physics of such energy trapping effect is explained in view of geometric variation and anisotropic properties, and the frequency effect on the extent of energy concentration is discussed. Finally, the feasibility of using such confined guided waves for rapid inspection of bent composite plate structures is also discussed.

1. Introduction

Fiber reinforced composites are increasingly utilized in high-performance structural applications in aerospace, naval, and automotive industries, because of their high specific strength and stiffness, lightweight, and inherent corrosion resistance. This brings new challenges in the manufacturing of components as well as in the non-destructive testing (NDT) of the structure throughout its service life. Composite laminated structures are sensitive to impacts and thus prone to damages, such as matrix cracking, delamination, and fiber failure, which can severely degrade their mechanical properties and compromise the structural integrity [1–3]. Moreover, such damages may be barely visible from the surface of the structure, but can propagate deep underneath, therefore making them difficult to detect.

Among available NDT techniques to inspect composites, ultrasonic testing methods have been the most widely applied, because they are easy to implement, and have high penetration depth and good sensitivity to small defects [4–8]. The conventional bulk wave testing may be carried out either with a single transducer in pulse-echo mode or with two transducers in through-transmission mode. Both cases however, involve point-by-point local inspection, which require scanning with the transducer over the whole region of interest, and are thus time consuming and tedious. Ultrasonic guided wave testing can be an attractive alternative [9–14] as it potentially allows for rapid screening of large areas with a fixed transducer position and remote inspection of structures with difficult access, such as composite fuselages on airplanes and the inner surface of laminated pressure vessels. Guided waves are capable of interrogating the entire cross sectional area of the inspected structure and have high sensitivity to various defects [15,16]. However, guided wave based inspection of composites is challenging due to the complicated wave propagation in anisotropic viscoelastic media [17–19]. Multiple modes usually exist, and their dispersive behavior is critically influenced by anisotropic properties of each lamina and also by the stacking sequence of the laminate [20–22]. Moreover, guided waves in composites yield unique effects such as steering effect, mode coupling, and multiple energy velocities [23,24]. In addition, attenuation of guided waves is much higher than that in most metallic materials, mainly resulting from viscoelastic properties of matrix phases and often influenced by the operational frequency, which significantly limits their use at higher frequencies [25,26]. In recent aerospace structural applications, fiber reinforced composites have been molded into complex shapes, such as bends, spars, stiffeners, and ribs. Apart from the influence of anisotropy, wave propagation in such structures is also

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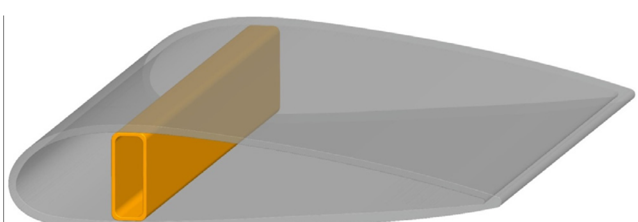
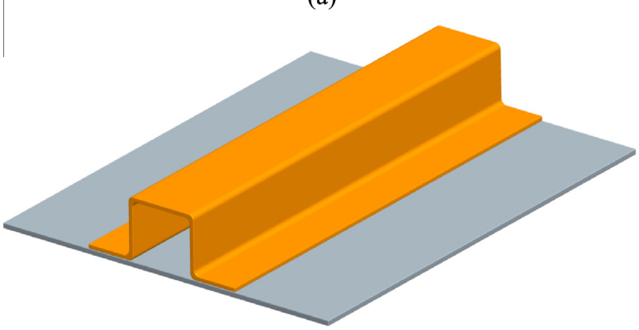
affected by the geometric variation, which adds complexity to the guided wave based NDT.

The aim of this paper is to investigate both anisotropic and geometric effects on guided waves propagation in complex-shaped composite structures, which is intended to lay a foundation for identifying proper guided wave modes and choosing operational frequency for the inspection of such structures. In this connection, there is much interest in a class of guided wave modes confined in plate bends, similar to feature guided wave (FGW) phenomena in isotropic structures, discussed in the literature extensively in recent years [27–31]. Guided wave propagation characteristics in composites can be predicted by using the matrix techniques such as the Transfer Matrix method and the Global Matrix method [32], or by exploiting the Semi-Analytical Finite Element (SAFE) method [33–35], which allows for solving problems for waveguides with arbitrary cross section. In this study, to understand the anisotropic effects in regular structures, fundamental guided modes at low frequencies are investigated in highly anisotropic, unidirectional carbon fiber/epoxy (CF/EP) laminates. Then the laminates are formed into 90° transverse bends being typical elements to compose the wing spars and stiffeners in the aerospace industry, as shown in Fig. 1. Due to stress concentration the bends are prone to failure during the in-service use, hence critical regions to be inspected, in which the characteristics of guided waves are essential to be understood. The SAFE method is adopted for modal studies, evaluating the performance of different guided wave modes in the anisotropic bends.

Two special types of modes have been identified as their propagation energy strongly confined to the bend region, indicating that the topographical feature created by geometric variation can be a special, 'local' waveguide for the transport of guided wave energy. This property can be very promising to the long-range testing of composite bends since it offers the possibility of using guided waves to particularly interrogate such structural features. As noted above, this is related to FGW phenomena discussed in the literature [27,36,28,29,31]. The existence of the energy concentration phenomena in bent composite plates, is supported by the three-dimensional (3D) Finite Element (FE) simulations and validated by experiments. Finally, the influences of the fiber orientation and the frequency on such energy trapping effect are discussed, after which the paper concludes with directions for future work.



(a)



(b)

Fig. 1. Illustration of the (a) wing spar and (b) stiffener.

2. Guided waves in flat laminates

The composite material used in the present study is T700/340 CF/EP lamina. A 14-ply unidirectional laminate was manufactured with stacking thickness of 2.28 mm, and its mass density is 1480 kg/m^3. The laminated plate is considered to be elastic (undamped) and in transversely isotropic symmetry. As in much of the literature the reference coordinate system used to defined fibrous materials is set such that the fibers are aligned in the x_1 direction, as shown in Fig. 2(a). The elastic properties were determined by ultrasonic bulk wave and guided wave measurements [37], and are given in Table 1.

Fig. 2(b) shows the dispersion curves for guided wave modes propagating along the fiber direction ($\theta = 0^\circ$), which represents the dependence of phase velocity with the frequency. In practical NDT/SHM applications it may be preferable to choose the frequencies below the higher order cut-off frequency where only fundamental guided modes exist, and to select a non-dispersive region since the detected signals will be simpler to interpret. Also, in viscoelastic media, the attenuation of guided modes is frequency dependent and strongly related to the dispersion, and it is normally low at such lower frequencies [25]. Thus the frequency range from 100 to 500 kHz has been chosen for our investigations. For propagation in the principal directions, parallel and normal to the fibers, the Lamb and the shear horizontal (SH) type modes are de-coupled and behave similarly to the equivalent modes in regular isotropic materials. However, due to anisotropy the wave propagation in non-principal directions is no longer this case, and these modes are effectively coupled, having displacement components in all three orthogonal directions. Therefore, guided wave characteristics in such laminates are directionally dependent.

To illustrate this, the phase slownesses (inverse velocity) of fundamental Lamb modes (the symmetric mode S_0 and the antisymmetric mode A_0) and the SH mode with respect to propagation angles were calculated by the SAFE method at 300 kHz, and the results are presented in Fig. 3(a). It can be seen that the velocity of the modes changes with the propagation direction, and the shape of the slowness surface varies with modes. The directional dependency of guided waves can also be expressed by their 3D dispersion surfaces, as shown in Fig. 3(b)–(d), where the dispersion curves for all propagation angles are plotted. It can be seen that the velocity of the S_0 mode is more affected by anisotropy than the A_0 mode, decreasing as the propagation angle increases. The SH_0 mode is non-dispersive in the 0° and 90° directions, but has different degrees of dispersion at other angles.

Besides the angular dispersion, another propagation phenomenon caused by the anisotropy in composites is steering effect, which leads to the difference between the energy and phase velocity directions. As shown in Fig. 4(a), at a fixed phase front direction θ, the energy velocity (i.e. group velocity in lossless media) is in the normal direction to the slowness curve, 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. 4(b) shows their relationship for fundamental guided wave modes at 300 kHz for the investigated CF/EP laminate. We can see that the direction of energy transport coincides with the wave front (phase front) only in 0° and 90° directions, where there is no occurrence of steering effect. The energy direction of the S_0 mode and the A_0 mode is biased towards the fibers, thus resulting in the energy being focused in the vicinity of fiber orientation. As the modes are polarized in different directions relative to the fibers, the S_0 mode shows much stronger beam steering than the A_0 mode, which firmly limits the wave energy propagation within