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Finite element simulation of core inspection in helicopter rotor blades using guided waves

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ABSTRACT

This paper extends the work presented earlier on inspection of helicopter rotor blades using guided Lamb modes by focusing on inspecting the spar-core bond. In particular, this research focuses on structures which employ high stiffness, high density core materials. Wave propagation in such structures deviate from the generic Lamb wave propagation in sandwich panels. To understand the various mode conversions, finite element models of a generalized helicopter rotor blade were created and subjected to transient analysis using a commercial finite element code; ANSYS. Numerical simulations showed that a Lamb wave excited in the spar section of the blade gets converted into Rayleigh wave which travels across the spar-core section and mode converts back into Lamb wave. Dispersion of Rayleigh waves in multi-layered half-space was also explored. Damage was modeled in the form of a notch in the core section to simulate a cracked core, and delamination was modeled between the spar and core material to simulate spar-core disbond. Mode conversions under these damaged conditions were examined numerically. The numerical models help in assessing the difficulty of using nondestructive evaluation for complex structures and also highlight the physics behind the mode conversions which occur at various discontinuities.

1. Introduction

The use of sandwich composite materials increased tremendously with the increase use of composite materials in the aircraft industry. Due to their light-weight nature, sandwich composite structures are highly sought after. Based on the application, sandwich structures utilize either high density or low density core materials. An ideal place where both types of cores are used is in the helicopter rotor blade. The complexity of the rotor blade lies in its construction; the low density core is used near the trailing edge of the blade, while the high density, high stiffness core is used in the leading edge or nose section of the blade. Typically high density high stiffness cores include glass–epoxy or polyester based materials. Typical cross section of a rotor blade is shown in Fig. 1. The spar/core or "web" section forms an I-beam. Traditional nondestructive evaluation (NDE) techniques such as tap testing, ultrasonic inspection, [1–3] etc. have been used to detect skin-core disbond. But applying these techniques to detect damage inside the web portion of an I-beam becomes very difficult. The use of guided Lamb modes for NDE is well documented in the literature [4–10]. Ramadas et al. [7] studied Lamb wave propagation in T-Joints and showed that new Lamb modes were generated at structural discontinuities referring to some these as "turning modes". The authors proposed that these back-propagating modes could be used for inspecting T-Joints. Turning Lamb modes were used to inspect damage in web section of a helicopter rotor blade by Chakrapani et al. [11]. Inspection was carried out by generating Lamb modes in the spar section, which mode converted into other Lamb modes upon interaction with discontinuities, and was received in the 2nd spar section. Finite element modeling was used to capture the mode conversions numerically, and the various mode conversions occurring at geometrical discontinuities were well documented both numerically and experimentally.

Although Lamb modes can be used to inspect low density core section, it is difficult for Lamb waves to propagate in thick multi-layered structures such as a high density core bonded to the spar. In such cases the Lamb wave, mode converts into a Rayleigh wave traveling across the thick multi-layered structure, which acts as a half-space. The wavelength is the relative measure to determine if the spar-core is a half-space. This type of mode conversion from Rayleigh waves to Lamb waves and vice versa has been documented both numerically and experimentally [13,14].

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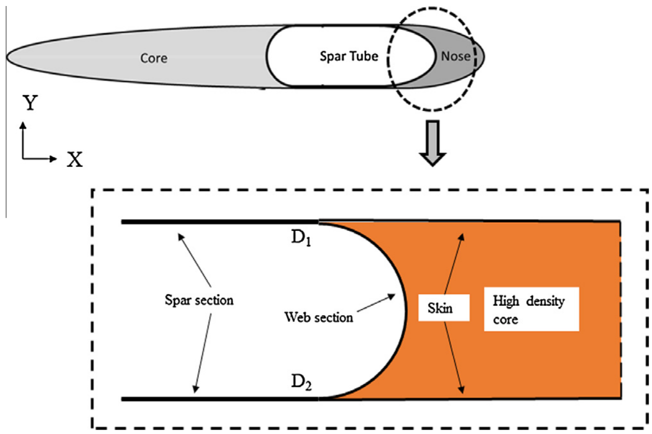

Fig. 1. Schematic of the sample construction. The circled region of interest has been shown in detail. The web section bounded by high stiffness core acts as the half-space. Discontinuities D_1 and D_2 give rise to mode conversions.

Rayleigh wave interaction with surface and sub-surface defects is well documented in the literature [15–18]. Achenbach and Brind [15] performed a study of the scattering of surface waves by sub-surface cracks. Angel and Achenbach [16] studied the reflection and transmission of Rayleigh waves by a surface breaking crack. Hirao et al. [17] performed a similar study of the scattering of Rayleigh waves by edge cracks using finite difference technique accompanied by experimental work. They showed that at each discontinuity the Rayleigh wave undergoes reflection and transmission and bulk mode conversion. Reflection and transmission coefficients were measured and the estimated crack depth was compared to actual crack depth.

Preliminary analyses showed that for the considered geometry, Lamb wave excited on the 1st spar section mode converts into Rayleigh wave in the web section and converts back into a Lamb wave in the 2nd spar section. A finite element (FE) model was created to understand the various mode conversions and each mode was identified using displacement profiles and velocities. Effect of damage in the form of notch and delamination was investigated. Notch analysis was performed by varying the length of the notch and studying the reflection and transmission factors. The approach and FE modeling used in the current study is very similar to the approach used earlier by the authors [11,12,14] to observe good experiment-numerical correlation. Hence, the confidence in the numerical results is at the same level as that for the previous published works.

2. Numerical model

A schematic of the cross section of a typical rotor blade is shown in Fig. 1, with *X*–*Y* being the cross section plane and *Z* being the longitudinal axis. The cross section of a generic rotor blade has four components: trailing edge core, spar tube, leading edge nose core and skin. Fig. 1 shows each of these with the region of interest shown separately. The naming conventions used in this article is similar to the convention that was used earlier [11,12]. The spar is a carbon fiber reinforced polymer (CFRP) laminate tube bonded to the CFRP skin, each of equal thickness (1 mm). Where not bonded together, both the skin and spar are bonded to high density core material. Fig 1 refers to the region of spar/skin bonding as the "spar section", the region where the spar is bonded to core as the "web section", and where the skin is bonded to the core as the "skin section". Various sections of an actual rotor blade along with the type of guided wave inspections performed by the authors can be found elsewhere [12]. The web section and spar sections are the regions of interest in this study. The spar bonded to the core in the web section is termed as the "spar layer".

In a typical blade geometry, the web section acts as a curved I-beam as shown earlier [11]. Depending on the radius of curvature of the curved I-beam, dispersion effects can be observed for both Lamb wave and Rayleigh wave propagation. The radius of curvature of the web section changes to anywhere from 5 mm to 50 mm based on the location in the longitudinal direction of the blade. This value also varies between different blade geometries and constructions. Hence, to generalize this problem, a simplified structure was considered for this work. The web section seen in Fig. 1, was assumed to be a flat structure instead of a curved structure as shown in Fig. 2. This model is not intended to capture the dispersion of Rayleigh waves due to curvature. The generalized model can be extended for any curvature which will eventually give rise to dispersion. The current study only assumes direct wave propagation and no "turning mode" generation. Hence, only the web section and spar sections were modeled. The generation of turning modes in the skin section will be published elsewhere.

All numerical simulations were carried out on commercially available FEM code; ANSYS©. As shown earlier by the authors, the usage of commercial FE codes enables model assisted inspection of complex geometries. Developing FE codes for complex geometries modeled using commercial modeling software can be very challenging. Several researchers have shown that this shortcoming can be handled well by using a commercial FE code, especially for guided wave propagation [6,7,11,12,14]. 2D, 8 node quadrilateral elements with plane strain condition were used for modeling to reduce the 3D problem to 2D problem. The spar sections were modeled as 2 mm thick plates on either side of the stratified half-space attributed with CFRP properties. The stratified half space was modeled with a 1 mm thick layer of CFRP bonded to a 99 mm thick, high density polyester core. The thickness of the half-space (100 mm) was chosen based on the Rayleigh wave wavelength (~6 mm) and to ensure that reflections from the bottom side of the half-space were minimized. Depending on the capability, several people have used absorbing boundary layers, or infinite elements to simulate a half-space. But the approach used in the current work has been shown to work effectively for modeling Rayleigh wave propagation in a half-space [14]. CFRP is assumed to be transversely isotropic with fiber direction in the *Z* direction making it isotropic in the *XY* plane. The polyester core is assumed to be isotropic in nature, and the properties used to model the different materials have been listed in Table 1. To get a good convergence of the dynamic solution, the mesh size should have at least 10 elements per wavelength [19,20]. The element size in the current work was 0.3612 mm in the thickness direction, and 0.4662 mm in the length direction. Based on the Rayleigh wavelength of ~6 mm, there were about ~13 elements in the length

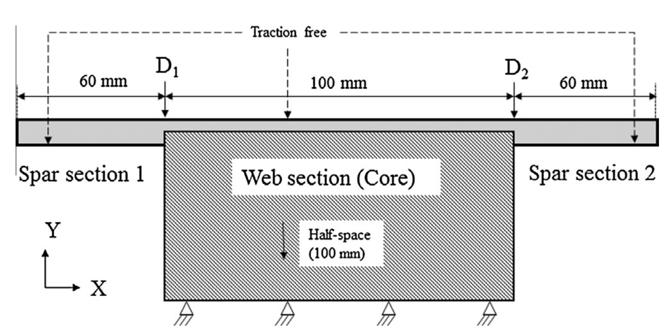

Fig. 2. A generalized geometry was modeled for the region of interest as shown in Fig. 1. The curvature has been discounted resulting in two straight spar sections on either side of the web section. This structure is equivalent to straitening the geometry of the region of interest as shown in Fig. 1.