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Structural health monitoring of a composite skin-stringer assembly using within-the-bond strategy of guided wave propagation

Mohammad H. Sherafat [a], Robin Guitel [b], Nicolas Quaegebeur [b], Pascal Hubert [a], Larry Lessard [a,*], Patrice Masson [b]

[a] Department of Mechanical Engineering, McGill University, Macdonald Engineering Building, 817 Sherbrooke West, Montreal, QC H3A 0C3, Canada
[b] GAUS, Department of Mechanical Engineering, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada

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ABSTRACT

The objective of this paper is to investigate the within-the-bond guided wave propagation in a composite skin-stringer joint. The structure of interest is composed of three carbon fibre reinforced polymer (CFRP) plates bonded together by adhesive film. This bonded joint is prone to disbond when submitted to extreme loads or fatigue. Therefore, two bonding conditions are investigated, namely undamaged and damaged (with disbond). The artificial disbond is introduced into the joint using a circular Teflon tape during manufacturing. Two co-localized slender rectangular piezoceramics are used to generate plane guided waves within-the-bondlines and non-contact measurement is performed using a 3-D laser Doppler vibrometer (LDV) to extract the required information for evaluation of the bonding conditions. The results include reflection, transmission and also scattering of the guided waves at the joint as a function of frequency, propagating mode and presence of artificial damage. It was found that the amplitude of the reflection, transmission coefficients and directivity patterns of scattered waves are affected by the presence of damage, such that Structural Health Monitoring (SHM) design guidelines can be derived for efficient damage detection in the composite assemblies using a within-the-bond inspection strategy.

1. Introduction

Composite skin-stiffener assemblies are extensively employed in Principle Structural Elements (PSE) of aerospace structures (i.e. aircraft wings, control surfaces and fuselage skins). This structural feature mostly consists of either co-cured or adhesively bonded stringers at regular intervals. The bonded composite joints are also being increasingly used to extend the operational life in aerospace and maritime industries as well as in civil infrastructure [1]. The major advantages of adhesive bonding include higher fatigue resistance, light weight, ability to join thin and dissimilar components, good sealing, low manufacturing cost, and good vibration and damping properties [2]. However, the joint area is known as a zone of potential weakness, because of load transferring phenomena taking place that may induce possible disbonds. Moreover, the adhesive is prone to degradation over time, harsh environment or improper installation, resulting in local disbond or porosity.

These types of damage can significantly jeopardize the performance and safety of a structure with little advanced warning, and since they cannot be easily detected by visual inspection, Non-Destructive Testing (NDT) methods are being employed for detailed inspection of the structures. Conventional NDT approaches have attained maturity in engineering applications during the last decades, but since they are usually conducted at regular scheduled intervals during the part's lifetime, they cannot provide descriptive information about structural integrity in a real-time manner. Moreover, most of the existing NDT methods require extremely time-consuming point-by-point inspection. Structural Health Monitoring (SHM) has been proposed as an improved and retrofitted version of traditional NDT for continuous inspection of the structural features including composite joints to evaluate health and integrity of the assemblies. SHM systems replace scheduled maintenance with condition-based maintenance, thus saving the cost of unnecessary maintenance as well as improving the level of safety through the consideration of working condition updates [3]. It has been shown that an effective SHM could reduce the total maintenance cost compared to traditional NDT approaches by more than 30% for an aircraft fleet [4]. Among the different approaches of SHM, ultrasonic guided (Lamb) wave propagation with piezoelectric transducers has been proposed for effective monitoring of composite structures [5] since it is quick, repeatable, sensitive to small-sized damage and cost effective [3]. Guided

* Corresponding author.
E-mail addresses: mohammad.sherafat@mail.mcgill.ca (M.H. Sherafat), robin.guitel@USherbrooke.ca (R. Guitel), nicolas.quaegebeur@Usherbrooke.ca (N. Quaegebeur), pascal.hubert@mcgill.ca (P. Hubert), larry.lessard@mcgill.ca (L. Lessard), patrice.masson@USherbrooke.ca (P. Masson).

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Table 1
Material properties from manufacturer of woven CFRP (CYCOM 5320) and adhesive film (Cytec FM-300-2).

Material	$E_{11} = E_{22}$ (GPa)	E_{33} (GPa)	$\nu_{12} = \nu_{13} = \nu_{23}$	$G_{12} = G_{13} = G_{23}$ (GPa)	ρ (kg/m^3)
CFRP	64.6	14	0.042	4.13	1300
Adhesive	1.0	1.0	0.3	0.38	1420

wave propagation has been successfully employed in the past for damage detection in repaired composites and bonded joints as well [6–10].

Previous studies demonstrate that two strategies can be employed for inspection of bonded joints using guided waves [9], namely "across-the-bond" and "within-the-bond". The "across-the-bond" method has been mostly employed in previous studies for inspection of metallic assemblies [11,12]. With this method, the degree of disbond in adhesive joints can be estimated by measuring the attenuation level of the A0 mode [13]. The second approach examined in the literature is the "within-the-bond" method by which the bond-line is used as a waveguide hence the influence of complex geometrical features on wave behaviour is minimized [14]. It has been shown that using this approach, a primary anti-symmetric mode (A0) below a frequency of 200 kHz is a good candidate for effective inspection of hybrid bonded structures [15]. Within-the-bond inspection allows detecting damage by monitoring changes in the phase velocity of the anti-symmetric mode [16], in the wavenumber versus frequency [17] using spatial Fourier transformation or also by monitoring the attenuation level of guided waves [18]. A study including the effect of joint geometry has been presented [9] using a within-the-bond approach in the pitch-and-catch configuration. Measurement of the RMS signal amplitude exhibits a strong sensitivity to the bonding condition, such that attenuation of the A1 and S0 modes appears as a potential candidate for bond inspection within-the-bond [15]. Although there are several studies that have investigated Lamb wave scattering due to a hole and rivet in metallic structures [19,20], the scattering of guided wave through a composite adhesive bonded joint has not been addressed so far.

In this paper, using the reflection, transmission and scattering of guided waves, the state of integrity of a composite skin-to-stringer is studied. The main idea is to define the inspection characteristics in terms of mode, frequency and transducer location (reflection, transmission or scattering) for a within-the-bond strategy, for which the excitation is performed along the joint. For this purpose, the whole assembly is manufactured and instrumented in order to include the complex geometry, bondlines' reflection and joint edge scattering. The guided waves are generated by a co-localized piezoceramic device, and non-contact measurement of the in-plane and out-of-plane velocity is performed using a 3-D Laser Doppler Vibrometer (3D-LDV) over a circular grid of points. Using the circular scanning grid, and by estimating the amplitude ratio of the reflected, transmitted and scattered waves to the incident wave, the behaviour of the guided waves is investigated. By comparing the sensitivity of the scattering with respect to bonding condition, frequency and mode of propagation, SHM design guidelines are extracted justifying the guided wave method's ability for disbond detection.

2. Structure description

Composite bonded joints are selected as a simplified representative of hybrid or composite assemblies, co-cured stiffened panels or repairs in the aerospace industry. The structure of interest in this paper is a skin-stringer bonded joint commonly used in aircraft structures. The material used is an out-of-autoclave plain weave prepreg (CYCOM 5320) with the same properties in the warp and weft directions. The layup is $[0/45/90/-45]_s$, where each ply represents a woven layer and the 0-degree direction is the warp direction. The assembly is composed of three quasi-isotropic panels bonded together using Cytec FM® 300-2 M adhesive. The elastic material properties of the material used in this research are given in Table 1. The skin dimensions are 12″ × 36″ (304 mm × 914 mm) and the two stringers are 3″ × 12″ each (76 mm × 304mm) bonded using the adhesive as depicted in Fig. 1.

The thickness of each lamina is 0.0834″ (0.212 mm). Since each individual part is made of 8 plies, thickness of stringers and skin become 0.067″ (1.7 mm) each, and that of the stiffened region of the skin is 0.1343″ (3.409 mm), which includes the thickness of the adhesive, 0.0035″ (0.09 mm). A circular disbond (with 25.4 mm diameter) is introduced into the joint using two pieces of Teflon tape, as a reliable way to model a defect of a known initial size. However the disbond should ideally be an interlaminar crack to model a real case. In a "co-bonding" strategy, the skin is cured and the stringer is laminated onto the skin (with the help of the adhesive) and then cured; while in a "secondary bonding" strategy both parts are cured separately and then glued together using an adhesive. In this study the three components of the assembly are laid up, vacuumed bagged simultaneously and cured in one step using the "co-curing" strategy.

3. Experimental methodology

Two basic configurations are usually employed in guided wave techniques for damage detection: "pulse-echo" and "pitch-and-catch". In the former, both transmitter and receiver are located on the same side of the targeted zone, and the sensor receives the echoed wave signals from the defect or structural feature; therefore, the sensitivity is mainly governed by the magnitude of the wave back-scattered (reflected) from the damage. In the latter method, waves are emitted from an actuator to

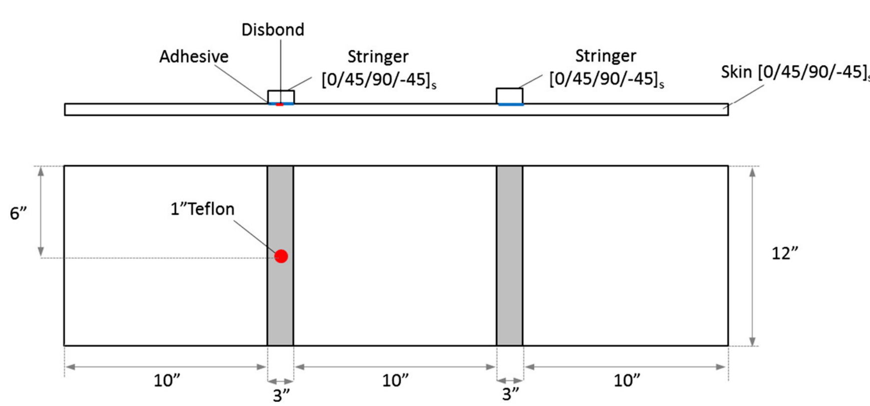

Fig. 1. Schematic view of the skin-stringer bonded joint configuration; undamaged (right) and damaged joint (left).