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Impact Damage Detection in Composite Sandwich Structures by Low Frequency Lamb Waves

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Summary

A cost and time effective inspection strategy for in-service health monitoring of composites is demonstrated using the fundamental anti-symmetric A_0 Lamb mode at frequencies of 15-20 kHz. In principle, this method involves analysis of the transmitted and/or reflected wave after interacting with the test-piece boundaries or discontinuities (defects). In the present work, the applicability of the technique to composite sandwich structures is explored.

Introduction

Composite materials are prime candidates for structural applications because of their high specific strength and stiffness but are expensive to maintain. The cost of inspection is approximately one third of the total cost of manufacturing and operating composite structures [1]. In order to realize their full potential it is essential that they are maintained in a safe and economical manner.

The evaluation of structural integrity using Lamb waves has long been acknowledged as a very promising technique [2-4]. Lamb waves are two-dimensional acoustic waves that can be generated in relatively thin solid plates with free boundaries and are also known as plate waves. They can be divided into symmetric S_n and anti-symmetric A_n modes according to their displacement pattern. Lamb waves excite the whole volume of the structure along the line between the transmitter and receiver and can propagate over considerably long distances. However, their dispersive nature and the existence of many modes simultaneously can complicate the interpretation of the acquired signal.

In this paper a cost and time effective inspection strategy using the anti-symmetric or flexural Lamb mode A_0, at low frequencies is applied to composite sandwich structures. The wave propagation characteristics in sandwich constructions are explored and it is shown that long-range inspection can be achieved. Defects of critical size are detected and located.

Experimental set-up

The sandwich beams examined in this study consisted of 2.25 mm thick quasi-isotropic skins $[+45^o/-45^o/0^o/90^o]_{2S}$ and approximately 10 mm thick foam core. The skins were manufactured from T700UD/SE84LV carbon fibre/epoxy pre-pregs. Two types of Rohacell foam R51 and R71 (higher density) from Emkay Plastics U.K. Ltd. were used. The skins and core were post cured to form the sandwich structure using an SA80 film adhesive by SP Systems U.K. Ltd. The specimens

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(sR51, sR71) were approximately 20 mm wide and 490 mm long. The sandwich beams were instrumented with 6 mm by 20 mm piezoceramic (PZT) elements.

The PZT elements were supplied by Maplin Electronics U.K. Plc and were used for the generation (transmitters) and reception (receivers) of low-frequency Lamb waves. The transmitter was placed on one skin (side 1) and the signal was captured from two receivers bonded on both skins (sides 1 and 2) of the beam at the same edge as the transmitter, Figure 1. The PZT transducers were bonded using instant glue at one edge of the composite specimens operating in pulse-echo mode. A 6.5-cycles sinusoidal pulse enclosed in a Hanning window with amplitude +/- 10 V was used to drive the transmitter. The signal was simultaneously captured from the two receivers at 1.25 MS/s sampling frequency.

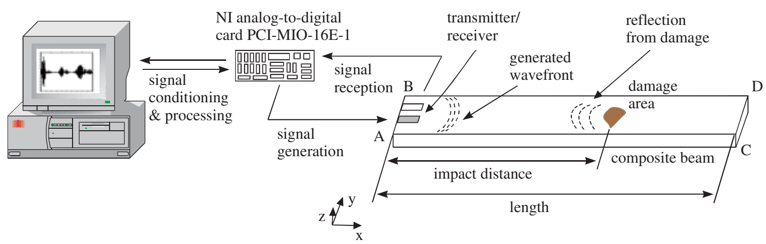

Figure 1: Schematic of the experimental set-up

A Pentium II personal computer and an analog-to-digital PCI-MIO-16E-1 card together with LabVIEW software by National Instruments U.K. Ltd. were used to generate the signal, excite the transmitter and subsequently acquire and process the data from the receiver. The inspection strategy described here is shown in Figure 1.

Analysis of lamb wave signals

A beam specimen was cut from the quasi-isotropic laminate for comparison of the wave propagation in the skin to the sandwich specimens. Figure 2 shows the signals acquired from the skin alone and from the sandwich beams (side 1) at different frequencies.

It can be observed that no significant changes in the shape or the arrival time of the pulse are introduced by the presence of the foam. However, significant attenuation is present due to energy being dissipated into the core. This allows us to assume that there is leaky Lamb wave propagation [5, 6]. Although attenuation is greater, the reflection from the far edge of the beam can still be detected, as can be seen in the time traces, after it has travelled twice the length of the beam, i.e. approximately 1 m. The A_0 mode at low frequencies could therefore be used for the long-range inspection of sandwich structures.

The resonant spectrum method [7] was used here to measure the phase velocity of the A_0 Lamb mode for the sandwich specimens. The group velocity was also

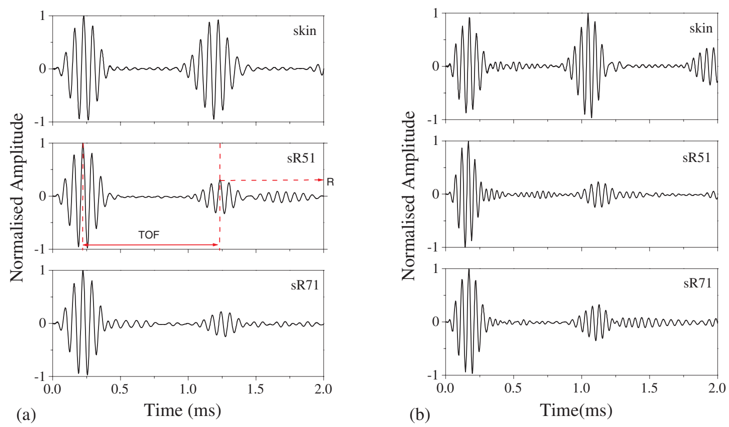

Figure 2: Signals received on the skin alone and the sandwich beams at 15 kHz (a) and 20 kHz (b)

calculated at various frequencies. The measurements were taken from the specimens having the transducer and receiver on the same side. The dispersion curves for the skin alone were also measured. The results are depicted in Figure 3.

It can be observed that the dispersion curves obtained for the sandwich beams were very close to those calculated for the skin, in accordance with other studies [5-9]. The difference can be attributed to the adhesive because the skin with the adhesive has lower stiffness than the skin alone. The thicker the adhesive layer the bigger the difference [5].

In an earlier paper by the authors artificial debonds of the skin to the core, induced with a sharp knife, were detected using this experimental set-up [10]. Impact tests were undertaken here to introduce more realistic damage using a 1.54 kg, 12.5 mm in diameter, hemispherical impactor. The impact point was 200 mm from the edge of the beam on side 1. A 75 mm length of the specimen was clamped having the impact point in the centre. The impact tests were repeated with higher impact energy levels until a significant amount of damage had developed. The impact area, in generally, consisted of debonding of the skin from the core, crashed core and up to 25 mm long delaminations in the composite skin.

X-ray Radiography was used as an alternative damage inspection method. No damage was evident on the X-ray images after 5 J impact in the sR51 specimen. A debond between the skin 1 and the core appeared after a 10 J impact. Its location ranged from 170 mm to 240 mm from the edge of the beam. For the beam with the sR71 denser foam damage first appeared at higher impact energy level of 15 J. A debond immediately below the impact point was generated. Cracks developed

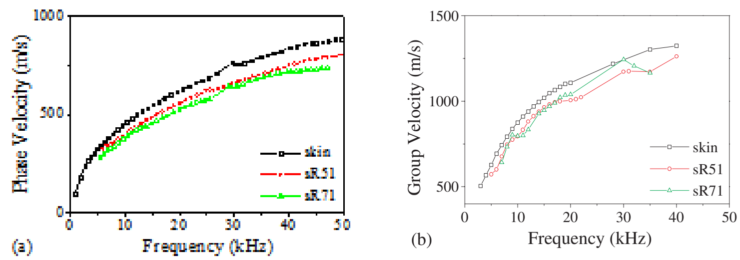

Figure 3: Experimental dispersion curves for the skin alone and the sandwich beams

at the edges of that debond in the core that propagated through the core and led to debonds on the opposite skin. Delaminated layers could also be seen at the surface of the top skin. The damage location ranged from 160 mm to 230 mm.

The response of the specimens from a 15 kHz excitation signal was captured by the two receivers. The transmitter and receiver 1 were in line with the impact point. The second receiver 2 was on the opposite skin. The reflection coefficient (R) of the transmitted signal and the time of flight (TOF) from the excitation are depicted in Figure 2. These parameters were monitored for the different stages of damage in Table 1 and Table 2. No consistent trend that relates to the size of damage has been found for the amplitude of the transmitted or reflected wave ($R=A_R/A_I$). However, it can be observed that the TOF increases as damage accumulates (by more than 30 μs for the specimen with a 15 J impact damage). This gives a clear indication of the extent of damage even for defects that was not detected by X-Ray radiography. It is also clear that detection is achieved by both receivers, due to the way the flexural wave propagates along the sandwich structures. It travels from one skin to the other through the core, thus carrying information for the whole structure. The location of damage was predicted closely to the true value for all the cases (4-12% difference).

Concluding remarks

The A_0 Lamb wave propagation in sandwich structures has been studied at low frequencies. No amplifiers were needed to detect the signals, which would be beneficial, if the technique is to be implemented for the continuous monitoring of aircrafts. At least 10 % of the amplitude of the excited signal was monitored after 1 m of propagation distance, which shows that the technique is applicable for the long-range inspection of sandwich structures. Changes in the response of the propagated pulses have been used to detect and locate impact damage. Moreover the relatively low sampling frequency required and the simple signal processing reduces the cost and time of the inspection. The technique could be used to inspect damage that is located in any position though the thickness even if only one side

Table 1: Effect of impact damage in the response of the sR51 sandwich specimen

Impact Energy (J)	Reflection Coeffi-cient	TOF (ms)	Damage Loca-tion (mm)	Reflection Coeffi-cient	TOF (ms)	Damage Loca-tion (mm)
	Receiver 1			Receiver 2		
0	0.243	0.938	-	0.278	0.997	-
5	0.305	0.943	-	0.287	1.002	-
10	0.137	0.996	226.7	0.455	1.026	213.0

Table 2: Effect of impact damage in the response of the sR71 sandwich specimen

Impact Energy (J)	Reflection Coeffi-cient	TOF (ms)	Damage Loca-tion (mm)	Reflection Coeffi-cient	TOF (ms)	Damage Loca-tion (mm)
	Receiver 1			Receiver 2		
0	0.279	1.020	-	0.270	1.028	-
5	0.283	1.026	-	0.252	1.034	-
10	0.294	1.034	-	0.268	1.042	-
15	0.239	1.053	207.0	0.297	1.056	217.5

is accessible for testing. However, in order to reveal small changes in the signals, the undamaged response is needed for comparison purposes. Also, closely spaced damage areas cannot be separately identified.

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