Robustness of a Structural Health Monitoring System under Drop-weight Impact Loading in Composites

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ABSTRACT

In this study, the robustness of a structural health monitoring system is tested on fiber glass composite coupons under impact testing using a drop-weight impact. The composite coupons are fitted with lead-zirconate-titanate (PZT) transducers to induce Lamb waves into the specimens. Robustness of the structural health monitoring system is assessed. The electrical admittance defined by the inverse of the impedance is chosen as the robustness metric and is measured using an LCR analyzer prior to, and following an impact event. Detachment of the PZT transducer is monitored through comparison of the measured electrical admittances. An average minimum composite coupon thickness of 7 mm is defined for impacting fiber glass composite coupons with pre-attached PZT transducers. A 1.5 % drop of electrical admittance was observed for that thickness for one impact. The chosen metric is related to the capability of the structural health monitoring system to provide accurate damage detection results following an impact.*

1 INTRODUCTION

With the evolution of nondestructive testing techniques (NDT), the mechanical and aerospace fields are now considering Structural Health Monitoring (SHM). SHM implies using an *in-situ* on-line monitoring system to detect damage whereas conventional NDT is conducted during periodic offline maintenance routines (Mickens *et al.*, 2003). These maintenance routines currently constitute 27% of an aircraft's life cycle cost (Kessler *et al.*, 2002). On the other hand, aerospace structures have also increasingly begun to shift away from metals towards composite laminates. Impact loading tests on composite laminates have therefore more increasingly become the focus of research for some time (Saravanos & Heyliger, 1995).

Current successful NDT techniques for composite laminates include: X-radiographic detection (penetrant-enhanced X-ray), and hydro-ultrasonics (C-scan). These techniques are generally used for small laboratory specimens and are impractical for in-service inspection. They therefore oppose SHM's criteria to be implemented for *in-situ* damage detection within large components or integrated vehicles (Kessler *et al.*, 2002).

Ultrasonic Lamb waves have shown to be promising candidates in SHM in that they can both detect material damage and can be induced into a solid media remotely (Ercsey-Ravasz, 2007). Lamb waves have been induced and measured in several materials for SHM using various techniques described, among others, by: Saravanos & Heyliger, Monkhouse *et al.* and Valdez & Soutis. Recent literature has shifted towards the use of lead-zirconate-titanate (PZT) transducers to both induce and capture Lamb waves.

In conventional SHM using PZT transducers, there are three methods that are used to detect damage within a material specimen: pitch and catch or pulse-echo, and phased arrays. The pitch and catch technique is the most popular technique in which two PZT transducers are used. One of the PZT transducers induces a Lamb wave into the material specimen whereas the other transducer placed at a distance is used to receive the transmitted signal. Variations in the transmitted and received signal amplitudes can indicate damage within the material specimen (Lin & Giurgiutiu, 2006). In an effort to reduce noise, there exists a non-contact approach using a laser vibrometer to measure the received signal (Murase *et al.*, 2001).

The placement of PZT transducers onto the surface of a material specimen between impact tests causes large variations in results due to the fashion in which they are installed. The PZT transducers are attached by hand in a roughly measured location using a resin. Due to their small and lightweight nature, PZT transducers can detach and break from the material specimen in the event of an impact and are therefore not usually attached prior to impact tests except in the case of Sung *et al*.

According to Park *et al.,* by measuring the electrical admittance before and after an impact into a material specimen fitted with PZT transducers, sensor functionality can be assessed. A drop in the electrical admittance curve following an impact event could signify a faulty transducer in a SHM system. The electrical admittance (γ) is defined as the inverse of the impedance as in Equation 1 where ω is the excitation frequency and C is the capacitance. The impedance of a PZT transducer can be measured using an LCR analyzer. The LCR analyzer can provide accurate impedance measurements across a sweep of frequencies.

$$\gamma = \omega C \tag{1}$$

2 METHODOLOGY

The work presented in this paper examines the effect of impacting a material specimen with PZT transducers attached prior to impact testing on fiber glass composite coupons using a drop-weight impact system.

Table 1 - Characteristics of the fiber glass composite coupons

#	# of plies	Ply orientation	Average coupon thickness (mm)	Coupon length (cm)	Coupon width (cm)
1	16	$[-45\ 0\ 45\ 90]_s$	7.1±0.1	15.2±0.1	10.2±0.1
2	16	$[-45\ 0\ 45\ 90]_s$	5.8±0.1	15.2±0.1	10.2±0.1
3	16	$[-45\ 0\ 45\ 90]_s$	5.1±0.1	15.2±0.1	10.2±0.1
4	8	$[-45\ 0\ 45\ 90]_s$	3±0.1	15.2±0.1	10.2±0.1

The lay-up of the fiber glass coupons is shown in Table 1. Each layer was cut from a fiber glass role, coated with epoxy resin, and stacked into a steel mold. The mold was inserted into a press pre-heated to 250 ^{o}C and loaded with 200 MPa of pressure for one hour. The result was a 30cm x 30cm plate with a measured resin to fiber fraction of 1.22:1.

Following fabrication, several tests were performed where the coupon thicknesses and plies count were varied. The objective of each trial was to determine the minimum thickness of a fiber glass composite coupon where the PZT transducers would not detach from their surface following an impact event. The characteristics of the fiber glass composite coupons are provided in Table 1.

PZT (5 mm) transducers were attached manually by hand using cyanoacrylate glue at a measured location on the composite coupon specimens. The location of the PZT transducer was chosen to ensure that the transducer was centered in the composite coupon specimen's width and was placed at a specific distance from the impact location with substantial clearance from the impact head of the drop-weight impact system, i.e. at a distance of 2 cm. Following attachment of the PZT transducers, initial (baseline) impedance readings were collected from the fiber glass coupons before impact using an HP 4263B LCR analyzer.

The experimental setup of the PZT transducer placed on the composite coupon is illustrated in Figure 1. An Instron Dynatup 8100 series drop-weight impact system was used with a 16 mm hemispherical impact head to induce approximately 47 ± 1.4 J impact into each fiber glass composite coupon.

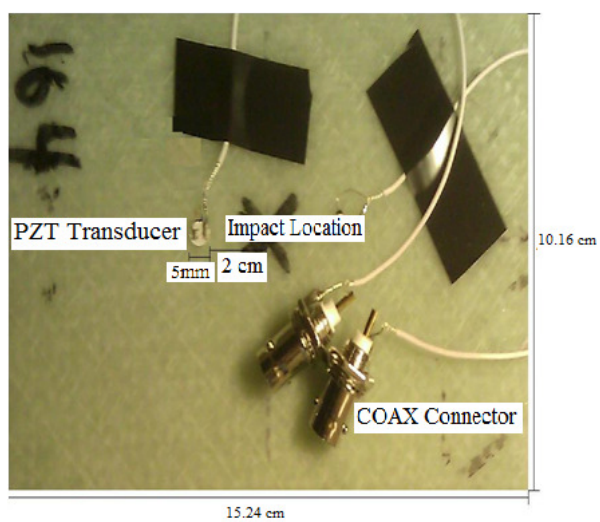

Figure 1 - Experimental apparatus illustrating the PZT transducer setup attached to the fiber glass composite coupons.

The impact energy (E) was calculated based on Equation 2 for the thickest composite coupon using

ASTM standard D7136 where C_E is the specified ratio of impact energy to specimen thickness (6.7 J/mm), and h is the nominal thickness of the composite coupon.

$$E = C_e h \tag{2}$$

All of the remaining composite samples were impacted with the same energy as that of the thickest composite coupon (~47 J). Following each impact, the impedance of the PZT transducers was measured and recorded.

3 RESULTS

Following each impact, the impedance of the PZT transducers was measured using the LCR analyzer and recorded for frequencies between 10 Hz – 100 KHz. The electrical admittance (the inverse of the impedance) was then plotted for each composite coupon thickness before and after each impact in Figure 2. The specimen numbers in Figure 2 correspond to those in Table 1.

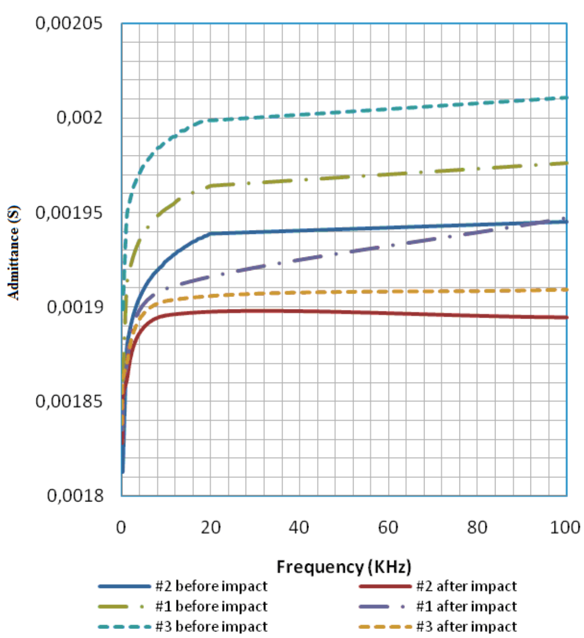

Figure 2 - Electrical admittance before and after a drop-weight impact onto composite coupons.

As observed by Park *et al.*, a drop in the electrical admittance of the PZT transducers was observed following an impact event to each material specimen. It can be observed in Figure 2 that the drop in electrical admittance is less severe as the thickness of the fiber glass composite coupons is increased. The increased thickness of the composite coupons allows for greater shock absorption and therefore a reduction in the shear stress applied to the PZT transducer attached to the surface of the composite coupon. The percentage drop of electrical admittance for each of the tested coupons at 100 kHz is summarized in Table 2. The PZT transducer of the 8 plies coupon detached completely from the surface of the composite coupon and broke into two pieces and therefore was not recorded in Figure 2 or Table 2. The percentage drop in electrical admittance for the thickest fiber glass coupon (specimen #1 ~ 7 mm) was as low as 1.5 %.

Table 2 - Percentage drop of electrical admittance for composite samples of varying thicknesses at 100 kHz

Average Specimen Thickness (mm)	Drop of electrical admittance (%)
7.1±0.1	1.5
5.8±0.1	2.7
5.1±0.1	3.5

4 CONCLUSION AND FUTURE WORK

In conclusion, the minimum thickness of fiber glass reinforced composite coupons has been characterized such that PZT transducers can be attached prior to a drop-weight impact event. For an average thickness of approximately 7 mm using 16 plies, a fiber glass composite coupon fabricated following ASTM standard D7136 can be impacted such that the previously attached PZT transducers will suffer a 1.5 % loss in electrical admittance. Future work will be needed to verify that this 1.5 % loss will not impede the performance of an SHM system for damage detection.

In future work, two PZT transducers will be attached in order to implement the pitch-catch method for damage detection on other composite material specimens. The signal acquisition error will be reduced as the position of the PZT transducers will not be varied prior to and following an impact event. Lamb waves will be inducted into the composite material specimens. Detachment of the PZT transducers will be monitored through comparison of the baseline Lamb wave signal acquired prior to impact and the captured Lamb wave signal following the impact. Furthermore, carbon fiber composite coupons will be characterized while fiber glass composite coupons were in this paper. An investigation into different adhesives for attaching the PZT transducers will be performed such that the minimal thickness of composite coupons can be reduced further.

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