Mechanical Systems and Signal Processing 76-77 (2016) 497–517

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Evaluation of barely visible indentation damage (BVID) in CF/EP sandwich composites using guided wave signals

Samir Mustapha [a,b,*], Lin Ye [b], Xingjian Dong [c], Mehrisadat Makki Alamdari [d]

[a] *Department of Mechanical Engineering, American University of Beirut, Lebanon*
[b] *Laboratory of Smart Materials and Structures, Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering, the University of Sydney, NSW 2006, Australia*
[c] *School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[d] *DATA61, CSIRO, Level 5, 13 Garden Street, Eveleigh, NSW, Australia*

A R T I C L E I N F O

Article history:
Received 6 March 2015
Received in revised form
27 January 2016
Accepted 30 January 2016
Available online 15 February 2016

Keywords:
CF/EP sandwich composites
Barely visible indentation damage
Finite element simulation
Guided waves
Damage assessment
Time reversal

A B S T R A C T

Barely visible indentation damage after quasi-static indentation in sandwich CF/EP composites was assessed using ultrasonic guided wave signals. Finite element analyses were conducted to investigate the interaction between guided waves and damage, further to assist in the selection process of the Lamb wave sensitive modes for debonding identification. Composite sandwich beams and panels structures were investigated. Using the beam structure, a damage index was defined based on the change in the peak magnitude of the captured wave signals before and after the indentation, and the damage index was correlated with the residual deformation (defined as the depth of the dent), that was further correlated with the amount of crushing within the core. Both A_0 and S_0 Lamb wave modes showed high sensitivity to the presence of barely visible indentation damage with residual deformation of 0.2 mm. Furthermore, barely visible indentation damage was assessed in composite sandwich panels after indenting to 3 and 5 mm, and the damage index was defined, based on (a) the peak magnitude of the wave signals before and after indentation or (b) the mismatch between the original and reconstructed wave signals based on a time-reversal algorithm, and was subsequently applied to locate the position of indentation.

1. Introduction

A sandwich structure consists of two strong panels separated by a lightweight core such as honeycomb or foam. The separation between the panels increases the moment of inertia, with only a slight increase in weight, producing an efficient structure for resisting bending and buckling loads. Composite sandwich structures are used in primary components in aerospace structures and are therefore susceptible to incurring impact damage that creates a major concern for structural integrity [1,2].

In that context, low-velocity impacts are caused by various sources such as bird strikes (while an aircraft is parked or during taxiing) [3], tools dropped on parts during manufacture and servicing, or runway debris encountered during take-off. Such impacts can easily crush the core and create a dent on the surface of a panel [2,4]. A low-velocity impact can produce

---

[*] Corresponding author at: Department of Mechanical Engineering, American University of Beirut, Lebanon. Tel.: +961 350000x3445.
E-mail address: sm154@aub.edu.lb (S. Mustapha).

http://dx.doi.org/10.1016/j.ymssp.2016.01.023
0888-3270/© 2016 Elsevier Ltd. All rights reserved.

extensive core damage that is capable of significantly reducing residual strength, due to deterioration in the mechanical properties of both skin and the core [4]. Such impact loading usually produces hidden damage, known as barely visible indentation damage (BVID). If a structure with existing damage remains in service, the severity of the damage may increase, leading to catastrophic failure [1].

Damage resulting from impact loading is dependent on both the velocity and the energy of the impact, which have been defined to be in the range of 4–8 m/s for velocity and 50 J for energy [5]. Gower, Shaw and Sims [6] used a laser profilometer to obtain a dent measurement that was mainly defined as the depth of the damage induced. They found no direct relationship between dent depth and area damaged. However, the delaminated area has been linearly correlated with the kinetic energy of the impact beyond a specific threshold value [7]. There is no firm definition of the residual indentation resulting from BVID, and various values have been reported. The National Physical Laboratory in the U.K. defined BVID as damage causing a 0.5 mm dent [6], whereas a NASA report defined BVID as a 1.27–2.54 mm dent [8].

Many attempts have been made to describe BVID phenomena and to develop methods to detect and assess different types of damage. Ruzek et al. [9] compared different detection methods including visual, C-scan, and shearography to inspect a composite sandwich structure after impact. C-Scan was not very suitable for BVID detection but shearography performed better and, as expected, the visual method was not efficient when dealing with BVID for low energy impact. Takeda et al. [10] demonstrated the capability of fiber Bragg grating sensors to detect BVID in composite wing structures during integrity tests after impact. They identified the damage by monitoring the change in signals of fiber Bragg grating sensors due to the presence of damage. Other studies [11,12] have been based on nonlinear elastic wave spectroscopy to identify BVID in CF/EP composites, as severe damage usually influences one of the dynamic characteristics of composites, for example, producing a shift in resonance frequency or the presence of harmonics and sidebands in the spectrum of the dynamic signals.

Guided waves (GWs) can propagate for relatively long distances, even in materials with high attenuation ratios. Lamb waves, as typical GWs, have high sensitivity to both surface and embedded structural damage and they have been widely

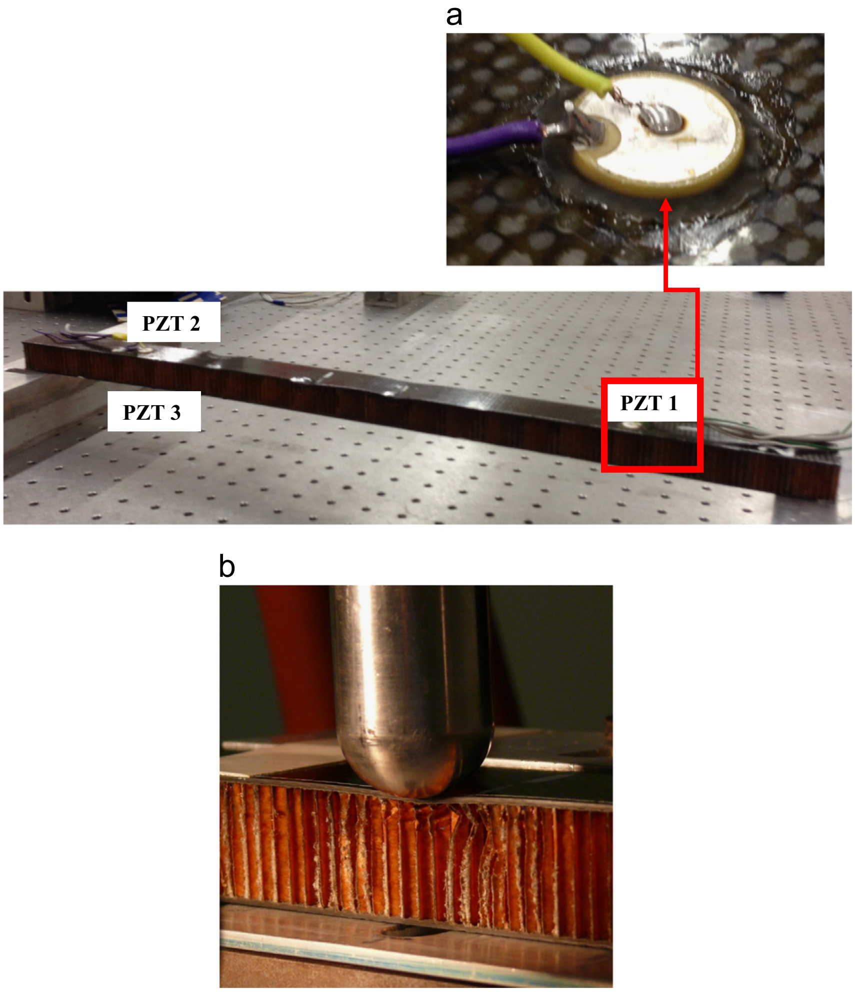

Fig. 1. CF/EP sandwich composite beam, (a) PZT elements and (b) indentation at edge of beam.