Composites Part B 138 (2018) 168–180

Contents lists available at ScienceDirect

Composites Part B

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

# Damage characterization of composite plates under low velocity impact using ultrasonic guided waves

A. De Luca[a], F. Caputo[a,*], Z. Sharif Khodaei[b], M.H. Aliabadi[b]

[a] Department of Industrial and Information Engineering, University of Campania L. Vanvitelli, Via Roma 29, 81031 Aversa, Italy
[b] Department of Aeronautics, Imperial College London, South Kensington Campus, Exhibition Road, SW7 2AZ London, UK

## ARTICLE INFO

*Keywords:*
Laminates
Impact behaviour
Finite element analysis (FEA)
Non-destructive testing
Lamb waves

## ABSTRACT

In this work, two numerical procedures based on Finite Elements Method (FEM) have been developed in order to simulate the Lamb wave propagation in Low Velocity Impact (LVI) damaged CFRP (Carbon Fibre Reinforced Polymer) laminate. The former (softening representation), usually adopted in literature, consists of modelling LVI damages by lowering the elastic material properties which allowed investigating the Lamb wave propagation at different stages of LVI damages evolution. The latter, proposed in this paper, conversely to the first one and the most of techniques presented in literature, consists of simulating Lamb wave propagation in a plate characterized by an initial stress-strain state and the related failures carried out by a previous impact simulation involving the same model. Such technique allows a better damage modelling and, consequently, overcoming the damage modelling approximations introduced by the former strategy; the lowering of the elastic material properties leads to a bad damage modelling which does not allow reproducing accurately what happens in the reality. Such procedure allowed investigating the Lamb wave propagation at different impact energy levels.

The interaction between Lamb waves and damages has been investigated under three central frequencies of the actuation signal: 150 kHz, 200 kHz and 250 kHz which resulted in interesting observations to minimize the effect of the first lamina's fibres orientation on the wave propagation velocity. It is well known that different wave propagation velocities along fibres and matrix lead to different RMSD (Root Mean Square Deviation) damage index values, even if the sensors are mounted at the same distance from the damage location, resulting in wrong or less accurate information about the identification of both damage size and location during the post-processing phase. Moreover, the relationships between the RMSD damage index values, recorded at different instants of time of the impact history, and the impactor phases has been achieved. Finally a comparison between the results achieved by the two investigated strategies has been carried out and presented here.

## 1. Introduction

Experience with structural failures led to several changes in aircraft design practice, especially for conventional materials, such as steel, aluminium alloys and so on. The improvement of the design practice has allowed the modern structures better tolerating the presence of cracks and, in general, damages under the in-service loading conditions. Thanks to the predictive models, assessed and validated by experimental evidence, designers' forecast capability has been improved significantly. Thus, especially in the aerospace field, nowadays, the damage tolerance philosophy is the heart of the current design practice. Conversely to the conventional materials, composite ones, which have found increasing industrial applications in the last decades, especially in the aerospace and transport fields [1], cannot count on established predictive models in support to the damage tolerance approach. This results in the oversizing of the structures which must be enabled to tolerate damages as well as conventional materials.

Concerning composite materials, in particular Carbon Fibre Reinforced Polymers (CFRP) materials, several types of undetectable manufacturing defects and accidental damages could affect the residual strength of the structures [2–9]. Among the several accidental damages, Low Velocity Impact (LVI) [10–16] ones play a critical role during the current design practice. Following a LVI, such as tool drop or runway debris, the structure may return to its original shape without showing any detectable damages, whilst it has suffered internal massive damages [11] resulting in Barely Visible Impact Damage (BVID) [11]. To fulfil the damage tolerance design targets, several safety factors are applied during the design practice as a function of the damage size (Fig. 1). For civil aviation, according to the FAR25/CS25, the AMC 25.571–2.1.2 [17] allows the residual strength of a component in

---

[*] Corresponding author.
*E-mail address:* francesco.caputo@unicampania.it (F. Caputo).

https://doi.org/10.1016/j.compositesb.2017.11.042
Received 1 August 2017; Received in revised form 13 October 2017; Accepted 27 November 2017

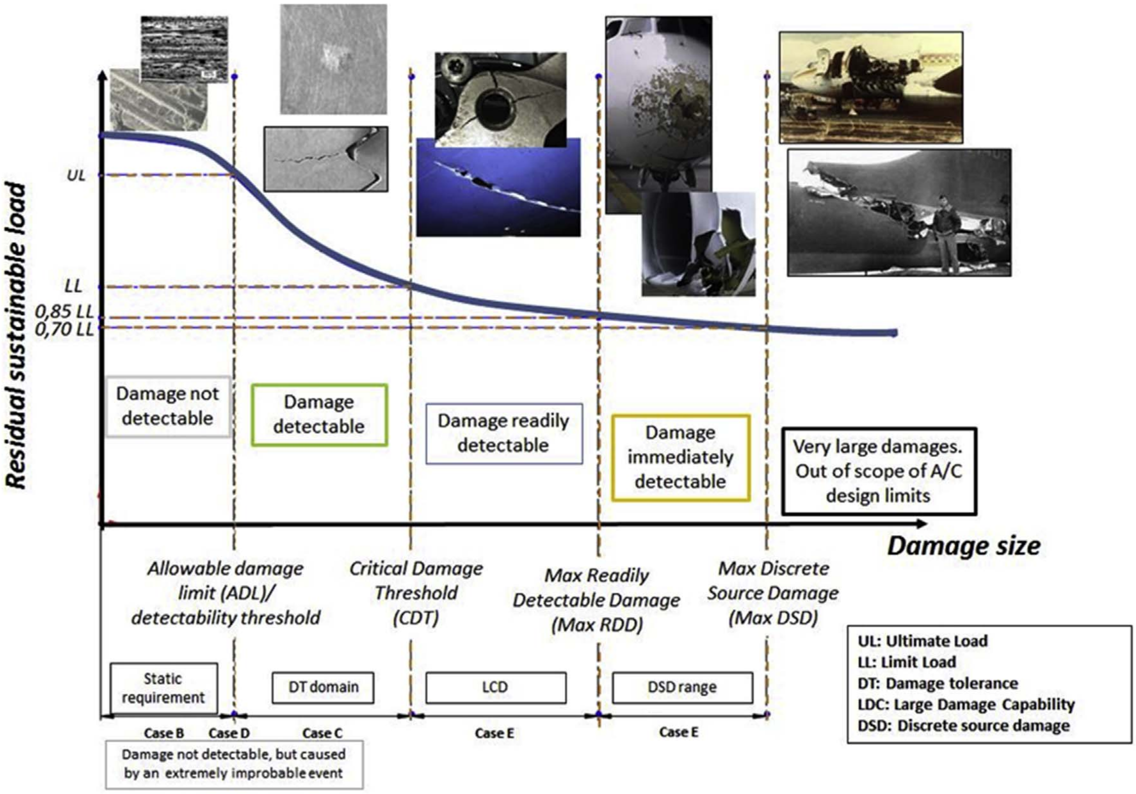

**Fig. 1.** Residual sustainable load vs. damage size.

presence of readily-detectable damages to be at load levels lower than the limit load (LL), specified in CS 25.571 (b) [17], and named 85% LL criteria [18]. For immediately detectable damages, where it is assumed that the crew will be aware of the damage and attempt to land as soon as possible after the event, lower residual strength loads criteria can be used (AMC 25.571–2.7.2 [17] named 70% LL criteria) [18].

According to Fig. 1, it can be noticed that BVIDs, contained in damage detectable domain, can be tolerated inside the structure as long as its residual strength does not decrease below the limit load. It means that, in order to tolerate damages with a lower detectability level, higher safety factors must be applied. So, nowadays, the interest of the research community is to lower the safety factors related to BVID, by being able to detect them during the in-service life. The main adopted research strategy consists of the development and application of Structural Health Monitoring (SHM) systems for damage detection purpose. The continuous assessment of structural health by means of non-destructive testing (NDT) methods [19] is an important task for the improvement of the damage tolerance philosophy [17,18]. Several authors investigated on the detection of LVI damages by means of SHM systems. Jang B-W et al. [20] investigated the potential of using high speed fibre Bragg grating (FBG) sensing system for detecting the delamination onset in thick CFRP laminates. In their study, the impact response signals and contact force histories for several LVI experiments, ranging between 1 J and 30 J, have been investigated. Shrestha P. et al. [21] used FBG sensors to achieve the LVI location on a composite wing structure. Among the several techniques, the SHM system based on the propagation of ultrasonic guided wave (Lamb waves), activated by piezoelectric sensors is increasingly being used, due to its durability, light weight and low power consumption [22]. Ochoa et al. [23] assessed the suitability of the two zero-order Lamb wave modes to detect multiple barely-visible impact damage in composite material. Three specimens were subjected to damage at three different low-energy levels and one was left as an undamaged reference sample. Ultrasonic Lamb wave modes were selectively generated by surface-bonded piezoelectric wafer transducers.

This paper focuses on the LVI damages detection capability of the Lamb wave SHM system in thin CFRP plates.

Such technique is based on the propagation of the guided waves, which are excited by one or more actuators. Once the waves are excited, they propagate through the plate and will be recorded by the sensors attached to the component. The propagation properties of the guided waves depend on the properties of the media they travel through. Therefore, once they interact with a damaged area, the wave reflects and refracts. The interaction of the propagated waves with the damage zone, not only depends on the properties of the damage zone, such as type and size of the damage, but also on the parameters of the excited wave, such as wave mode, shape and central frequency.

Moreover, whilst their propagation in homogenous and isotropic material is well established [22,24], further investigations are mandatory on non-isotropic materials, especially on dispersion [25], slowness and attenuation phenomena. In fact, in order to use Lamb waves for diagnostic purpose, they should be characterized by non-dispersion, low attenuation, high sensitivity to damage, easy excitability and good detectability. Also the choice of the right wave modes is important for damage detection purposes.

For such reason, experimental studies on this topic are not sufficient due to the high cost and time consumption of tests and the achievement of a prediction model to investigate on the right parameters which will drive the ultrasonic guided waves in real applications is still an ambitious task for the research community. As matter of the fact, several research activities and several investigation approaches can be found in literature. Such approach can be divided into analytical/semi-analytical, numerical, and experimental works. Numerical method, based on the Finite Element (FE) theory, is widely used in the literature because it allows the prediction of all propagation phenomena and the development of efficient damage detection algorithms. In more detail, both two-dimensional (2D) and three-dimensional (3D) approaches can be adopted. For example, Yelve et al. [26] used 2D FE simulation on Lamb