Thin-Walled Structures 104 (2016) 82–105

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

# Finite element simulation of damage and failure predictions of relatively thick carbon fibre-reinforced laminated composite panels subjected to flat and round noses low velocity drop-weight impact

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ARTICLE INFO

*Article history:*
Received 6 October 2015
Received in revised form
21 February 2016
Accepted 8 March 2016
Available online 12 March 2016

*Keywords:*
Fibrous composites
Low velocity impact
Drop-weight impact
Mode based failure

ABSTRACT

This work is concerned with the dynamic computational modelling of fibre-reinforced laminated composite panels subjected to low velocity drop-weight impacts. Wings and fuselage of aircraft structures are prone to tool (box) drop impacts during normal shipping and handling of component assembly and maintenance services. Flat nose impacts inflict localised barely visible internal damage that severely reduce compressive residual strength and might result in catastrophic failure during future operations. Hence it is important to have a better understanding of the impact response of composites to mitigate the damage and avert the unexpected failures. Many reported works on the topic are experimental, based on quasi-static indentations that take longer than contact time, and produce global deformations of thin panel where short time effects and through-thickness stresses are neglected. Hence dynamic model is needed to investigate impact behaviour of thick panels for detailed information. The present computational model includes short time effects and utilise through-thickness stresses in mode-based failure criteria to differentiate ply-by-ply failure modes. Cases of laminates up to 7.6 mm thick impacted with flat and round (for comparisons) nose impactors were simulated using ABAQUS™/Explicit dynamic routine. High stress concentration regions were meshed with adaptive meshing techniques using reduced integration elements. Selected simulation results were compared against experimental, intra-simulation results, and the data available in the literature and found to be in acceptable agreement.

## 1. Introduction

Carbon fibre-reinforced laminated composites are being increasingly used in the aerospace industry due to their high strength and stiffness coupled with lightweight properties. Modern commercial airliners Boeing 787 Dreamliner and Airbus A350 and A380 series have increased weight of composites usage over 50%. Some modern military aircraft components contain over 70% composites by weight. Applications of composites make existing systems stronger, lighter, and cheaper [1]. For example, the total weight of 45.4 kg of a missile launcher that the soldier must hold and aim in battle consists of a hardback component of 18.6 kg and rails of 5.7 kg weight. The new launcher system designed using a carbon fibre materials hardback of 13.2 kg and the rails of 3.2 kg [2] is a significant example of weight saving. However, composites lack at fibre reinforcement in the out-of-plane direction, vulnerable to the low velocity impact that could reduce residual strength up to 60% [3,4]. Investigations are needed to address adverse effects of the low velocity impact induced damage in order to design more reliable components.

Extensive experimental (empirical), engineering models (analytical and phenomenological), and numerical studies have been conducted on different aspects of the topic. Since one procedure cannot always provide all the desired information, a combination of the methods is often resorted [5]. It has been reported in [6–9] that the experimental studies have formed the basis for analytical and finite element analyses. Greszczuk [10] proposed an analytical approach for impact response that determined impact-induced surface pressure distribution, internal stresses in the target caused by surface pressure, and failure modes. It was reported in [5,7] that numerical modelling can be used to supplement experimental testing and analytical analyses to provide insight into the damage mechanisms. As such, finite element analysis based numerical modelling has become a widely adopted approach in both industrial and research environments. Researchers can choose a commercially available finite element code that has the capability to deal with a wide range of contact-impact problems and can be

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http://dx.doi.org/10.1016/j.tws.2016.03.011
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customised for various applications [11]. Davies and Ankersen [12] studied the feasibility of relying on simulations in great detail to test composite structures to failure. They concluded that simulations are rapidly evolving into viable design tools. Nguyen et al carried out a review [13] on the capability of finite element software on their ability to model the damage arising from the impact of composites. Results of the review established that the commercial software is capable of creating, solving, and post-processing an impact damage event with ability to evaluate the damage in each individual ply. Finn et al. [14] performed a parametric study in which effects of plate thickness, impactor mass, and thickness of the ply were investigated. Studies in [15] established that major cause of delamination is bending-induced stresses and showed that the composites tend to bend concave in the fibre direction and convex in the transverse direction. The studies attribute formation of delamination to the mismatch of bending stiffness between adjacent layers. Moreover, different fibre orientations between layers have direct relationship between the bending stiffness mismatch and the size of delamination. Studies on interaction between delamination cracks and transverse matrix cracks damage modes can be found in [16] while Malvern et al performed microscopic observations of impacted cross-ply laminates [17]. They compiled detailed interactions between delaminations and matrix cracks for various layups of composite laminates. According to Olsson [18], the different failure modes depend on: material properties, impact velocity, mass and geometry of impactor and target, impactor nose profile, and support conditions, etc. Although one of the failure modes may dominate, the target may fail by a combination of failure modes. Lopes et al in [19] reported analysis using ABAQUS/Explicit software based on continuum damage mechanics to predict the quasi-brittle process of failure of composites. Tsartaris et al in [20] reported that internal damage caused by low velocity impact can be examined in two categories: inter-laminar delamination; and intra-laminar transverse ply cracking. Detailed study was performed by Finn et al. [14] and Noh [21] that measured locations and geometries of the delaminations induced by an impact load. Failure initiation (the first-ply failure) can be predicted by means of an appropriate failure criterion [22,23]. Finite element based models capable of accurately predicting the impact damage and failure sequences are reported in [24]. The previous researches predicted damage sequences as observed in experiments on impact damages using Chang-Chang [25] and Hashin's criteria [26]. For the sharper impactor tips, there is a clear relationship between the delamination areas and the depth of the dents [27]. However, these relationships are dependent on the radius of the impactor tip, and for the blunter impact tips no strong correlation could be determined between the delamination area and the depth of the dents [28]. Attempts have been made to use depths of surface dents as a metric to indicate internal damage [29,30]. The other relevant work was found in [31–36]. Although, progressive failure model comparisons and non-destructive evaluations are extensively presented in the literature; however, no theory is able to perform in an acceptable manner in all the impact induced damage cases [30]. The literature search revealed that most of the studies on the topic lack at considering rotary inertia dynamic effects and contributions of through-thickness shear stresses (major source of delamination).

In this work the dynamic effects of the drop-weight impact of relatively thick composite panels are considered and through-thickness stresses predicted from two-dimensional simulation were utilised to directly predict ply level damage and failure. Comparisons of the selected results against intra-simulation and available data demonstrated that the model is capable of efficiently predict ply level damage and failure.

## 2. Materials properties of fibre-reinforced laminated composite panels

The test specimens of 24-Ply laminates consisting of 150 mm × 120 mm average plane areas with 7.4 (±0.12) mm average thicknesses were considered. The symmetrical laminates of layups code [0/45/−45/90]ns where the subscript n varies from 1, 2, and 3 for sequence repetitions and s stands for symmetry. A schematic of symmetric 8-Ply panel with lay-up code $[0/90/45/\text{-}45]_S$ is shown in Fig. 1(a)–(c). In the configuration each fill fibre ply goes over four plies before going under fifth one. This configuration is called a 5-harness satin weave. The tests laminates are made of aerospace grade carbon fibre-reinforced toughened epoxy infused. Test laminates were provided by the industry [29], fabricated using fibre reinforcement: Fibre dux T300 914C-833-40 embedding fibre horns technique with material properties given in Table 1. The transversally isotropic fibre packing arrangement is assumed so that properties are nearly the same in any direction perpendicular to the fibres (along the *y* and *z* directions).

Since the material being tested is especially orthotropic and transversally isotropic; the constants are $G_{13}=G_{12}$; $E_2=E_3$; $\nu_{21}=\nu_{31,}$ and $\nu_{23}=\nu_{32.}$ In addition, the relationship among the isotropic engineering constants is valid associated with the 23 plane

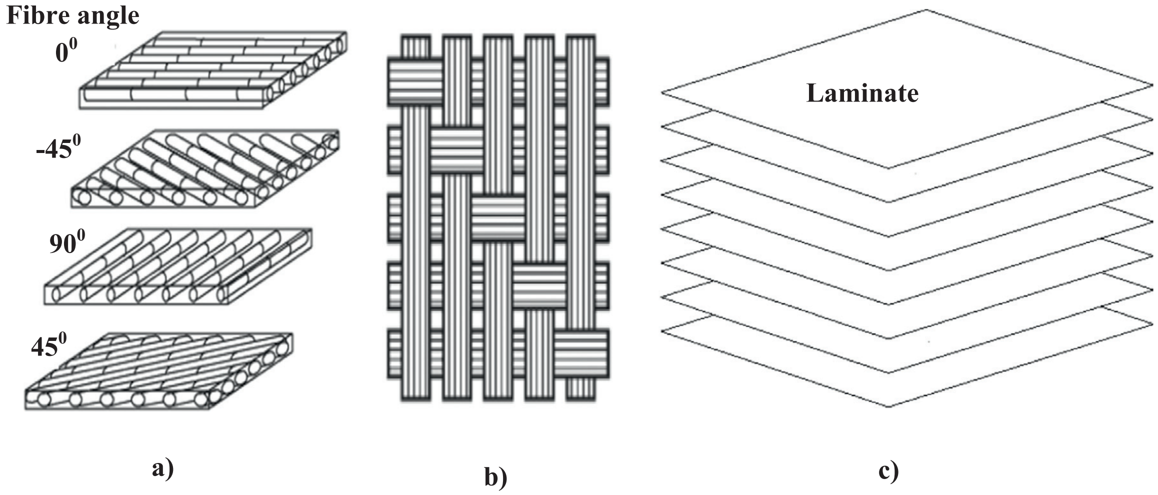

**Fig. 1.** Schematic of a) Ply orientation, b) Satin-weave, and c) 8-Ply laminate.