Materials & Design 83 (2015) 848–857

Contents lists available at ScienceDirect

Materials & Design

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

The influence of preload and boundary conditions on pre-damaged composite plates subject to soft-body impact

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A R T I C L E I N F O

Article history:
Received 10 March 2015
Revised 28 April 2015
Accepted 30 May 2015
Available online 20 June 2015

Keywords:
Carbon fibre
Impact
Delamination
Mechanical testing
Simulation

A B S T R A C T

This research investigates the influence of preload and boundary condition compliance on low-velocity impact damaged CFRP T800S/3900-2B plates subject to secondary higher-velocity soft-body impact (50 J, 75 J, 100 J). A bilinear cohesive element based delamination model combined with ply-based composite material failure was developed using LS-DYNA 971. Double Cantilever Beam (DCB), 3-point End-Notched Flexure (ENF), and Fixed Ratio Mixed Mode Bending (FRMMB) simulations validate the accuracy of the delamination model when compared with theory. The low-velocity impact simulations were shown to compare well with the results of drop-tower impact experiments and ultrasonic inspection data in terms of maximum impact force and projected delamination area. An investigation of boundary condition compliance in the direction of impact showed a reduction in peak impact force, interlaminar delamination and intralaminar failure with increasing coupon translation. High-velocity impact simulations based on the model with initial damage showed a reduction in interlaminar delamination damage with tensile preload when compared to compressive preload and unloaded cases for all impact energies.

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1. Introduction

Commercial aircraft such as the Boeing 777 and 787 Dreamliner currently apply advanced composite materials including Carbon-Fibre Reinforced Polymer (CFRP) in both primary and secondary structures [1]. A recent market report by the Boeing aircraft company has forecast this trend in advanced composite material usage to continue with an annual growth in world aircraft fleet of 3.6% up to 2032 with 5.2% of growth occurring within the Asia Pacific region [2]. Advanced composite materials continue to be recognized as a key enabling technology to assist the reduction of aircraft weight and meet increasing green-house and aircraft-engine emissions legislation [3]. In relation to structural properties, CFRP materials have a number of advantages relative to other aerospace materials including: high specific strength, stiffness, improved fatigue life and the ability to tailor the mechanical properties of a structure. However laminated CFRP materials are susceptible to impact from low-velocity and low-energy impact damage often requiring expensive inspection and repair [4,5]. The damage from such impacts often occurs during take-off or landing while the aircraft is in a loaded stress state and may be characterized by a small indentation with sub-surface damage including matrix cracking, fibre breakage and/or delamination.

The influence of low-velocity impact onto CFRP has been widely studied [6]. Despite the extensive literature in this area there is almost no research which highlights the role of higher velocity impact onto damaged panels subject to preload a situation more consistent with real flight conditions. The lack of literature in this area has been highlighted in recent work by Amaro et al. [7] who investigated the influence of multiple impacts on GFRP coupons with a quasi-isotropic layup. Three different sequences of impacts with the same total impact energy were investigated, (1 + 1 + 1) J, (1 + 2) J and 3 J. The test data showed that a single impact of 3 J was more detrimental than multiple lower energy impacts, however all testing was performed at low impact energy levels (<3 J) and no preload was applied. A similar observation was made by Wyrick and Adams [8] in CFRP laminates where the primary damage from multiple impact events of the same impact energy was initiated during the first impact. A further investigation by Amaro et al. [9] also considered the influence of low velocity impact on quasi-isotropic GFRP with open-holes. In this case test and simulation results showed that the presence of the holes increased the energy absorbed by damage as well as the damage size. Morais et al. [10] investigated the influence of stacking sequence and laminate thickness on structural performance under

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http://dx.doi.org/10.1016/j.matdes.2015.05.080
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multiple impacts. In particular cross-ply and non-symmetric laminates were shown to have a better performance against low impact energy events than unidirectional laminates.

The influence of initial preload on the response of CFRP has been investigated by a small number of researchers. Whittingham et al. [11] conducted impact testing at low and high impact energy levels under uniaxial and biaxial preload at ±1500 με. The results showed that penetration depth, peak load and absorbed energy were largely independent of pre-stress at low levels of impact energy (6 J) becoming more significant at higher levels (10 J). A number of analytical studies have confirmed the application of tensile preload increases the contact force and the deflection of plates under impact [12]. In separate work Heimbs et al. [13] investigated the influence of tensile and compressive preload on CFRP panels with dimensions of 300 mm × 200 mm up to a maximum impact energy of 40 J. Tensile preload (0.25% strain) was found to reduce the extent of delaminations, while compressive preload (28 kN) led to an increase resulting from higher levels of plate deflection during impact. Saghafi et al. [14] investigated the influence of impacts onto curved GFRP panels 3.1 mm thick, representative of a fuselage skin, for three different impact energies (6 J, 12 J and 24 J) and two preloads (3000 με, 5000 με). The results showed that the curvature had more influence on the damaged area than preload. In the case of curved aero-engine components, Vignjevic et al. [15] referring to the work of Miyachi et al. [16] highlighted the importance of including pre-stress in fan-blades subject to impact noting that the final deformed shape of a fan-blade is sensitive to the magnitude of centrifugal force.

In addition to preload, a further area of concern is the importance of structural constraints or boundary conditions on impact damage. For example, during scaled testing it is customary to perform impact testing on smaller less-expensive structures which are representative of the actual component. In such situations however one must consider how to constrain or fasten the scaled component without affecting the components structural stiffness/compliance and the test result. Minak et al. [17] investigated the influence of clamped and simple support boundary conditions on circular CFRP laminates subject to low velocity impact at impact energy values of 6 J, 12 J and 18 J. The results showed that the clamped boundary condition type increased target stiffness leading to increased energy absorption and delamination. Guida et al. [18] also highlighted the influence of structural compliance during bird-strike testing and simulations based on a single bay section of a leading-edge fin tailcone. During the development of the simulations the authors included the supporting frame due to its potential influence on the impact measurements. Caputo et al. [19] highlighted the importance of boundary condition setup on the energy absorption of CFRP panels. The authors identified discrepancies between test and simulation results at an impact energy level of 50 J attributing the variation to difficulties in modelling the semi-compliant rubber material used in the clamping system. In applications relevant to the automotive industry Ekstrand and Asnafi [20] investigated the role of structural compliance during impact testing onto autobody panel materials. The result showed that the boundary conditions had a significant effect on stiffness and dent resistance measurements. In the majority of the above cases the influence of preload has been assessed independent of investigations into structural compliance.

The aim of the current research is to assess the influence of preload and structural compliance on low-velocity impact damaged CFRP T800S/3900-2B plates subject to secondary higher-velocity soft-body impact. Numerical simulations are performed in two key stages involving separate low- and high-velocity impacts using full-restart and stress-initialization features in LS-DYNA 971. The simulations are based on a bilinear cohesive element delamination model combined with ply-based composite material failure. Double Cantilever Beam, 3-point End-Notched Flexure and Fixed Ratio Mixed Mode Bending simulations are developed and compared with corrected beam theory to validate the accuracy of the delamination model. The first stage impact simulations are validated with comparison to drop-tower experiments and ultrasonic test data in terms of maximum impact force and projected delamination area. This model is also used as the basis for investigating the influence of structural compliance during impact. The second stage simulations which incorporate damage from the first stage are then compared to highlight the influence of tensile and compressive preload under soft-body impact.

2. Theory

2.1. Analysis of impact

The results of the experiments and simulations in Section 5 are presented in terms of impact force, energy absorbed, plate deflection, delamination area and effective delamination diameter. The energy absorbed $E(t)$ by the composite laminate during impact is calculated from the following equation [21]:

$$E(t) = E_k(t_0) - \frac{1}{2}m[v(t_0) + \Delta v(t)]^2 \quad (1)$$

where $E_k(t_0)$ is the kinetic energy at time $t = 0$, m is the mass of the impactor, and v is the velocity. The change in velocity as a function of time is given as:

$$\Delta v(t) = g \cdot t - \frac{1}{m}\int_0^t F(t)dt. \quad (2)$$

where g is the acceleration due to gravity and F is the impact force.

3. Experiments

3.1. Materials

CFRP T800S/3900-2B coupons measuring 180 mm × 50 mm × 3.04 mm in dimension were used during impact testing. Each coupon consisted of 16 plies with a fibre volume fraction $v_f = 0.6$ arranged in a quasi-isotropic lay-up sequence $[45°/0°/-45°/90°]_{2s}$, Fig. 1. The unidirectional material property data for CFRP T800S/3900-2B obtained from [22–25] and used in subsequent simulations is summarised in Table 1.

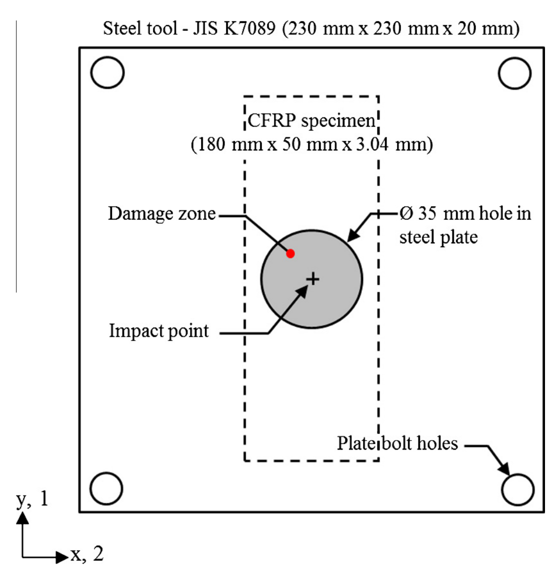

Fig. 1. Impact test setup showing CFRP specimen dimensions and JIS K7089 tool.

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