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Impact velocity effect on the delamination of woven carbon–epoxy plates subjected to low-velocity equienergetic impact loads

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ABSTRACT

The low velocity impact behaviour of a woven carbon fibre/epoxy composite has been analysed in this work. The study has been divided in two experimental phases performed in a drop-weight machine. Firstly, an impact has been carried out to determine the main damage mechanisms appearing over the structure for impact energies between 1 and 20 J. Force time curve patterns and three different damage inspection techniques have been employed to define an incident impact energy range (between 1.75 and 8.8 J) where delamination is the main damage mode over the structure. Secondly, two impact energy levels within this range have been chosen to analyse the impact velocity effect on the generated delamination. Equienergetic impact loads, achieved with different mass and velocity combinations, have been carried out for this analysis. Results show how delaminated area can increase in a 45% while increasing impact velocity, and how this delamination growth, can lead to a 20% reduction of the residual stiffness of the structure within the analysed energy and velocity ranges.

1. Introduction

The impact performance of composite structures is commonly characterised by means of energy and force parameters (Critical Energy, Dissipated Energy, Damage Threshold Force, Peak Force) as a function of impact energy [1–4]. Most the experimental studies on this field are based on constant mass testing procedures, such as ASTM D 7136, without taking into account how this impact energy is achieved (mass and velocity combination). However, impact velocity can influence the impact response and damage evolution in composite structures in two ways: One through an inertial effect in the structural response and the other through the strain rate dependency of the material response [5]. It has already been demonstrated how the damaged area of a certain structure can be twice for a given incident impact energy, if this energy is applied by a large mass and low velocity instead of by small mass and high velocity impact [6]. This phenomenon has been shown to be produced principally by an inertial effect, which changes the structural response of the target, from quasi-static to a stress wave governed response [7]. Within the range of low velocity impacts, different studies, based either on experimental work or finite element models, have concluded that neglecting both inertial and strain rate effect can seriously underestimate the damaged area of a composite plate [5,8–10]. However, a change in the structural response of the target due to the inertial effect of the mass can be dismissed if a minimum striker to target mass ratio is achieved [11]. In large mass and low velocity impacts, the impact duration is sufficiently large to consider the structural response of the target to be quasi static and neglect that inertial effect [7,12]. In this study, large mass and low velocity impacts have been studied, neglecting the inertial effect of the mass. This way, the impact velocity effect over the structure can be related to the strain rate dependency of the composite material.

Strain rate dependency of composite materials can be attributed to the fact that the mechanical behaviour of both matrix and reinforcement have been found to be strain rate dependent [13,14]. However, composites are generally considered to be strain rate insensitive when tested in fibre-dominated modes. Furthermore, the global impact response of composite structures has been assumed to be insensitive to the strain rate dependency of the reinforcement [15,16]. The mechanical behaviour of the matrix affects the overall response of the composite structure principally through the interlaminar behaviour of the material [17,18]. Impact damage threshold is associated to the interlaminar strength of the composite, while the delamination evolution is associated to the interlaminar fracture toughness of the composite [19]. Several authors have concluded that interlaminar fracture toughness of composite materials is rate dependent [20–22], however, a lack of consensus has been reported about how this effect is [23,24].

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Delamination is one of the most critical damage mechanisms appearing on composite structures when subjected to a transversal low velocity impact due to two main reasons [11,25,26]: It is the first damage mechanism affecting the bearing capacity of the structure and is not detectable by the naked eye. It is well known, how complex the impact behaviour of composite structures can be, since it involves different and combined failure mechanisms. However, the same damage evolution sequence has been described in different studies where unidirectional and woven composites have been subjected to transversal low velocity impact loads: First of all, ply level matrix cracking is introduced. Matrix cracking does not affect the impact response of the structure [27], but facilitates the subsequent appearance of delamination [18,19,28]. Secondly, delamination damage mechanism is developed [11,25,29], where the local decohesion of adjacent plies leads to a reduction of the bearing capacity of the structure. Lastly, fibre fracture appears in the impact zone due to the local stress concentration and indentation phenomenon [29] and leads to a ply level failure. In this damage process, delamination damage mode has significant effect not only when appears as the main damage over the structure; but also when fibre fracture is achieved, since it has already been developed and coexists with this ply level failure mode.

In summary, this review leads to the conclusion that composite plates under large mass and low velocity impact show an impact velocity dependency, principally due to the fact that delamination is strain rate sensitive. This study aims to: first, characterise the impact behaviour of a carbon fibre epoxy structure to identify delamination damage mode; and second, analyse the impact velocity effect on the delamination and the residual stiffness of the structure when subjected to equienergetic impact loads.

2. Material and experimental methods

2.1. Materials and manufacturing process

Woven composite plates have been obtained by infusion from a high strength plain carbon fibre fabric (Hexcel's Ref. 43199) and an epoxy matrix system (SiComin's SR 8100/SD 8822). 10 plies symmetric layups have been manufactured in a 20 min infusion with a 20 m^3/h vacuum pump (Busch R5 021C). After the infusion, plates have been cured for 24 h at room temperature and another 24 h up to 40 °C. Plates of 250 × 250 mm and a nominal thickness of 2.3 mm have been obtained. Manufactured plates have been cut by water jet process into circular specimens of 60 mm diameter.

2.2. Properties of the manufactured laminates

Density (1.42 ± 0.01 g/cm^3), fibre volume fraction (49 ± 1%) and void content (3.2 ± 0.1%) of each plate have been measured according to ASTM 792, ASTM D 3171 and ASTM D-2734 respectively. A quasi-static mechanical characterisation of the resulting material has also been carried out according to ASTM standards [ASTM D 3039; ASTM D 3518]. Tensile and shear modulus (57 ± 4 and 2.9 ± 0.3 GPa) and strengths (784 ± 12 and 81 ± 3 MPa) have been obtained by these methods.

2.3. Impact characterisation of the structure

Low-velocity impact tests with incident impact energies between 1 and 20 J have been carried out using a drop-weight testing machine. The Fractovis-Plus (Ceast) machine has been equipped with a striker instrumented with a 20 kN load cell, to register the contact force history, and an anti-rebound device, to avoid multiple collisions. The recorded force time history has been converted into impact parameters, such as acceleration, velocity, displacement and energy histories, based on Newton's second law and assuming the striker is a free falling rigid body [30]. A 2 kg mass striker with a 20 mm diameter hemispherical head has been used. The striker releasing height, and so the impact velocity, has been changed to achieve all the impact energies with the same striker mass. Specimens have been simply supported over an annular ring with an inner and outer diameter of 40 mm and 60 mm respectively. At least three specimens have been tested for each impact condition.

The structure has been characterised according to the Composite Structure Impact Performance Assessment Program (CSIPAP) proposed by Feraboli and Kedward [26] for the incident impact energy range described above. A multi parameter plot characterisation method has been carried out: peak force, total contact duration and residual stiffness evolution have been analysed. This multi parameter approach fully characterises the impact behaviour of a particular structure, allowing the detection of the different failure modes. Peak force and total contact duration have been obtained directly from the test instrumentation data of the impact inducing event, while residual stiffness of each specimen has been obtained by a three-test characterisation method defined in [31]. Specimens have been subjected to subcritical impacts before and after the damage inducing impact event. The ratio of pristine to damaged contact duration has been used to obtain the relative residual stiffness of the specimen. This relationship has been used to build a normalised CAI-type curve [26].

Incident impact energies have been classified in three energy ranges divided according to the dominant damage mode induced to the specimen: subcritical impacts, delamination generating impacts and delamination and fibre fracture generating impacts. This classification has been carried out according to the three different patterns detected when analysing force time curves; and afterwards, validated by the described CSIPAP methodology and three different damage inspection methodologies.

2.4. Delamination inducing equienergetic impact tests

Two impact energy levels (4 and 8 J) have been chosen within the delamination impact range to analyse the impact velocity effect. The striker mass has been increased by additional masses to achieve different impact velocities for a same impact energy. Five incident impact velocities (between 0.98 and 2.8 m/s) have been achieved for each impact energy level employing five striker masses (9, 7, 5, 3, and 2 kg).

Force time and force displacement curves, damaged areas and residual relative stiffness have been analysed for these equienergetic impacts. Damaged areas have been obtained by a non-destructive ultrasonic inspection, while the residual stiffness of each specimen has been analysed employing the three-test characterisation method described in Section 2.3.

2.5. Impact induced damage inspection

Impact tests have been followed by a three stage damage inspection of the specimens. Firstly, an ultrasonic non-destructive inspection has been carried out to examine the size and shape of the damaged areas of the specimens. The portable sound encoder OmniScan® MXU M, a broadband phase array probe of 5 MHz and a two axes encoded scanner have been used to perform the non-destructive ultrasonic measurements. C-Scanning images have been analysed using an image processing software (TomoViewer 2.10) developed by Olympus. All the impact specimens have been submitted to an ultrasonic analysis before and after the impact loading; the projection of the damaged area over each specimen has been detected and measured by comparing both images.