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Thickness-dependent energy dissipation characteristics of laminated composites subjected to low velocity impact

Celal Evci [*]

Turkish Military Academy, Defense Sciences Institute, Ankara, Turkey

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ABSTRACT

This study investigates the low velocity impact properties such as damage thresholds, critical energy thresholds and damage process of laminated composites. Damage thresholds of Hertzian failure and main failure corresponding to woven and unidirectional Glass Fiber Reinforced Polymer laminates in varying thicknesses from 2 mm to 8 mm are determined through impact tests with nominal impact energies of 4, 6, and 8 J/layer. Hertzian failure and main failure thresholds of a composite laminate with a particular thickness remain substantially constant with the nominal and incipient impact energies. Energy profile and normalized energy profile diagrams are used to find out the penetration and perforation thresholds as well as explaining the correlation between the threshold energies and damage process of the laminates. Dissipated energy by a laminate is determined using a second order polynomial regression based on the relationship between energy dissipation and impact energy of data points before penetration. Penetration and perforation energies increase non-linearly with the thickness and thickness dependence is expressed using a power regression. Test results related to damage thresholds, threshold energies and effective damage area reveal that unidirectional laminates possess lower impact damage resistance and hence are more sensitive to impact damage.

1. Introduction

The nature of the mechanisms governing failure in fiber reinforced polymer (FRP) composites is substantially different from that in metals. Failure in metallic materials is either based on brittle fracture or ductile fracture. Although brittle fracture in metals is more catastrophic, ductile fracture involves an extensive amount of plastic deformation. On the other hand, fiber reinforced composites with thermosetting matrix material are brittle. Since polymers do not have crystallographic planes, grain boundaries and dislocations, yield in FRP composites does not exhibit the same behavior as yield in metallic materials which is controlled by the mechanism of dislocation motion. FRP composites have orthotropic mechanical properties which lead to complex damage modes such as delamination and microbuckling. Impact damage on FRP composites has proved to be far complicated and multiple forms of damage mechanisms such as matrix cracking, delamination and fiber breakage can occur at different stages of loading in such a way that failure mechanisms may interact among themselves with one or two being dominant [1].

Low velocity impact event, which is either defined in terms of striking velocity (according to Cantwell and Morton [2]: velocities up to $10\,\mathrm{m\,s^{-1}}$ as simulated by falling weight impact testing, according to Abrate [3]: impact speeds of less than $100\,\mathrm{m\,s^{-1}}$) or the extent of damage on the material (as suggested by Liu and Malvern [4]), may arise from many sources including tool drops, foreign object hits, hailstone impact, maintenance and in-service impacts. Stresses induced on most metallic materials as a result of low velocity impact may not be considered to be threatening due to the ductile nature of the material and their high energy absorption potential. Unlike the damage behavior encountered in metallic materials, low velocity impact may induce significant damages in composite materials at the micro-scale level, resulting in a considerable reduction on the strength and stiffness of the material, without any visible signs of damage on the impacted surface [3,5–13].

Extensive research on low velocity impact damage of FRP composites has been conducted to study the complex nature of damage phenomenon in composite materials. Impact loading in FRP composites, can give rise to different damage modes simultaneously which are closely dependent on the properties of both the impactor and impacted material [14,15]. Major damage modes encountered in composite materials subjected to low velocity impact are

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[*] Tel.: +90 312 4175190; mobile: +90 505 8868048.
E-mail addresses: celalevci@yahoo.com, cevci@kho.edu.tr

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matrix mode, delamination mode, fiber mode and penetration [16]. Incipient impact energy, impact velocity, fiber/matrix configuration, impactor shape and composite plate thickness are the foremost parameters to determine the type of damage mode. Interaction between failure modes is also effective in damage progress and energy dissipation properties of composite materials. Force/energy–time and force/energy–deflection graphs obtained using the impact software of instrumented drop-weight testing are considerably useful to relate the impact response of composite materials, in terms of damage force thresholds and energy thresholds, to the damage mechanisms and damage growth within the material.

A typical force history of low velocity impact on the composite material reveals two critical threshold forces (Hertzian failure load and maximum impact load) and two critical threshold energies (penetration energy and perforation energy). Delamination is the first sign of significant damage mode in laminated composites subjected to low velocity impact. Delamination failure in a composite may be recognized with a damage threshold which is called Hertzian failure force [17,18]. Delaminations take place due to the poor contribution of fibers to overall strength in the thickness direction when the composite laminate is subjected to out of plane stresses generated by impact loading. Delaminations occur at the interfaces between plies in such a way that debonding of the individual laminas occurs due to the mismatch in the bending deformations of adjacent plies.

The main damage in the form of fiber fracture and laminate failure occurs as the maximum force threshold is reached and develops further until the maximum energy level is attained [17,19,20]. Although matrix cracking which occurs under fairly low impact energies does not cause a significant degradation of mechanical properties, delaminations may affect the laminate performance seriously. Fiber damage, on the other hand, results in the main damage (laminate failure) in the composite.

Shyr and Pan [17] investigated the low velocity impact damage characteristics of different reinforced fabric structures with various laminate thicknesses. Their study implies that the layer number is very important to determine the energy absorbing mechanism in composite laminates. Fiber fracture was the dominating failure mode for thick laminates while delaminations were more influential in the failure of thin laminates. They also stated that the threshold load for the major damage was independent of the incipient impact energy (the same conclusion as it was reached by Belingardi and Vadori [19]), but it was highly dependent on the laminate thickness.

Yang and Cantwel [21] conducted a series of low velocity impact tests on (0°, 90°) glass/epoxy laminated composites in order to investigate the influence of varying key impact parameters on the damage initiation threshold for test temperatures between 23 and 90 °C. They concluded that damage initiation threshold force followed a $t^{3/2}$ dependency, where t is the thickness of the composite, at elevated temperatures as well as at room temperature.

Penetration and perforation energy thresholds which can be determined by using the energy profiling technique are among the major characteristic properties of FRP composites subjected to low velocity impact. A correlation between the major damage modes and characteristic impact properties can be developed by using the energy profiling technique [22].

Quaresimin et al. [23], investigated the effects of stacking sequence and laminate thickness on the energy absorption capability of woven carbon–epoxy composite laminates under low velocity impact. They concluded that delamination threshold load and threshold energy for the onset of damage are insensitive to impact energy and laminate lay-up while the maximum contact force slightly increased with impact energy such that it was quite independent on laminate lay-up. On the other hand, delamination threshold load and threshold energy for the onset of damage as well as the maximum contact force were found to be closely dependent on the laminate thickness. They also proposed an original model to determine the energy absorption capability of composite laminates. The model which was based on a parabolic function which described the absorption coefficient (ratio of absorbed to penetration energy) as a function of the impact intensity coefficient (ratio of impact to penetration energy) predicted the energy absorption in composite laminates, independently of constituents, fibers architecture, laminate thickness and stacking sequences.

The main objective of this study is to make a useful contribution to the research in low velocity impact response and damage behavior of FRP laminates by providing a comprehensive understanding of primary damage mechanisms based on damage force thresholds and threshold energies. Thickness-dependent impact properties and energy dissipation characteristics of polyester resin polymers reinforced with woven and unidirectional glass fibers (GFRP) are investigated through instrumented drop-weight impact tests with nominal impact energies of 4, 6, and 8 J/layer. Penetration and perforation energy thresholds of the laminates are determined using energy profile and normalized energy profile diagrams. Normalized energy profile diagrams are modified from energy profile diagrams to investigate the energy dissipation characteristics of the laminates. The correlation of impact damage thresholds (Hertzian failure force and maximum impact force) and critical energy thresholds (penetration and perforation energies) with damage process is analyzed depending on the thickness of the laminate.

2. Material and method

Glass Fiber Reinforced Polymer (GFRP) laminates were fabricated using polyester resin reinforced with E-Glass fiber. Woven (plain weave) and unidirectional E-Glass fiber fabrics with areal densities of 800 g/m^2 and 500 g/m^2 were used as the reinforcement material. Composite plates made of unidirectional fiber fabrics were configured in [0/90] lay-out. Hand lay-up method was used to manufacture the composites in the form of plates, under a pressure of 1.96 MPa at a temperature of 140 °C. Test samples with dimensions of 100 mm by 100 mm were extracted from composite plates fabricated in a mould with dimensions of 400 mm by 400 mm. The number of fabric layers in each composite plate is properly adjusted so that final thicknesses of plates varied approximately from 2 mm to 8 mm. Material properties of woven and unidirectional E-Glass composite plates are listed in Table 1.

Mechanical properties of woven and unidirectional GFRP composites are determined using three-point bending tests according to EN ISO 178 Standard (Plastics-Determination of flexural properties). Stress–strain curves corresponding to quasi-static three-point bending tests are given in Fig. 1. Average values of elastic modulus and bending strength of composite test pieces obtained from five successive tests are displayed in Table 2.

Impact behavior of composite materials is determined according to standard EN ISO 6603-2 (Plastics-Determination of puncture impact behavior of rigid plastics- Part 2: Instrumented impact testing). Low velocity impact tests are performed using an instrumented drop weight impact tower, Instron Dynatup 9250. A spherical tup insert of 10 mm diameter was used as the striker. Composite plates with dimensions of 100 mm by 100 mm were clamped securely on the pneumatic clamping fixture. Composite plates were impacted with different nominal impact energies.