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Investigation of the quasi static penetration resistance behavior of carbon fiber reinforced laminate HDPE composites

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ABSTRACT

In this paper, a study on the quasi-static penetration resistance behaviour of unidirectional carbon fiber fabric/High Density Polyethylene (HDPE) composite with two different thicknesses which are laminated 4L and 12L (4 layers & 12 layers), i.e., $H_C = 3.1$ mm and 9.3 mm, is presented using the quasi-static punch shear test (QS-PST) methodology for the experiments. The penetration resistance is usually shown by a load–displacement graph, integral of which is the energy dissipated by the composite during penetration. The penetration energy varies with the diameter of the support span which can be equal or higher than the punch diameter. During tests, a flat punch of diameter 7.6 mm with a range of support spans 8.89 mm–50.8 mm has been used and QS-PST experiments are carried out for varying support span to punch diameter ratios (i.e., SPR = 1.16, 1.33, 1.67, 2.00, 2.33, 2.67, etc.). Their damage mechanisms for different SPRs and thickness are documented. Stiffness, peak force, deflection, damage area, and energy dissipation results are presented in detailed form.

1. Introduction

Fiber reinforced thermoplastic composites are now gaining popularity in manufacturing of some parts due to their superior reinforcing properties, ease of handling and well established textile technologies [1]. They are lighter, tougher, stiffer, more sustainable and can be produced in high volumes. These advantages result in a wide range of applications, i.e., structural members in aerospace, automotive, and other industries. Some experimental studies on the forming of thermoplastic composites can be found in the literature. In addition to their excellent quasi-static properties such as high specific stiffness and strength, fracture toughness and impact resistance are among the most important properties of polymers and their modified systems [2,3].

The impact capabilities and other properties of most composites has been studied and investigated extensively in recent years and many technical articles, books, and reviews about impact on composites, are available. Main goal in optimizing these materials for use in ballistic applications is to understand their characteristic properties and to evaluate their energy dissipating ballistic damage mechanisms. One of them, quasi-static penetration resistance of a composite structure represents the energy dissipating capacity of the structure under transverse loading without dynamic and rate effects. Erkendirci and Gama [11,12] studied quasi-static penetration resistance of glass and Carbon fiber reinforced composites. They reported dissipated energy capacity of these composite laminates. Gama et al. [4,10] investigated the punch shear behavior of thick-section composites under quasi-static, low velocity, and ballistic impact loading and identified the energy dissipating damage mechanisms during quasi-static punch shear of thick-section composites. John and Naidu [13] observed no significant improvement in impact strength of the sisal/glass hybrid composites. However, they noticed a marginal increase in compressive strength of these hybrid composites.

Furthermore, understanding the causes of the formation of such damage and improving the damage resistance characteristics of composites are very important. When subjected to impact loading, the energy is dissipated in the form of creation of new surfaces. The failure mechanisms include indentation, matrix cracking, delamination, ply splitting, and fiber fracture [14]. Ross and Sierakowski [15] studied the influence of the filament orientation, volume fraction and various combinations of filaments by impact tests. They observed that the geometrical arrangement of fibers is extremely important in the resultant type fracture pattern obtained: that is, either a very localized penetration or large interlaminar failure can occur based on ply geometry. Also Rilo and Ferreira [16] investigated low velocity impacts on glass-epoxy

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laminated composite plates and compared the results then developed several relevant ideas. Belongardi and Vadori [17] examined the characterization of composite material suitable for constructing structural parts devoted to dissipate kinetic energy during impacts on the glass–fiber/epoxy composite laminate plates. B Alcock et al. [18] analyzed the impact performance of all-PP composite materials through penetrating and non-penetrating impact by falling weight test which is performed on a similar Ceast falling weight impact machine with an identical striker, but also equipped with a mechanism to catch the striker on rebound from initial impact, and prevent further strikes which occur following rebound from non-penetrating impact. They reported the impact properties of all-PP composite plates.

Alves et al. [19] studied the effects of environmental agents on polyolefin materials, virgin and recycled, utilized accelerated tests, short exposures to weather and gamma radiation, and also studied the influence of aging agents in the mechanical and ballistic performance of a UHMWPE composite armor. Rasool et al. [20] observed the flexural properties of glass fiber reinforced polymer composites with metal mesh layers. And they used two thermoplastic polymers, polyetherimide (PEI) and polyphenylene sulfide (PPS) as the matrix. Zivkovic et al. [21] manufactured poly (p-phenyleneterephthalamide) reinforced laminar thermoplastic composite material to improve for penetration of ballistic projectiles. They obtained optimal shaping parameters and optimal resin content for thermoplastic composite material. The subject of their experiment was the analysis of aramid fibers-PVB ballistic composite materials with embedded optical fibers as intensity sensors for detection of real time mechanical damage and deformations. Their experimental results confirmed the possibility to apply optical fibers as intensity sensors for health monitoring of thermoplastic composite laminate (Aramid-PVB composite materials), under real-time conditions of static loading. Erkendirci et al. [22] are investigated the effect of inclined cracks on the fatigue and fracture behavior of woven steel/reinforced polyethylene composite. However, penetration resistance behavior of fiber reinforced thermoplastic composite system is not available in the literature, and is the motivation for the present research.

This study builds upon previous works on the development of a Quasi-Static Punch Shear Test (QS-PST) methodology in the research of the penetration mechanics of composite materials [4–9]. The QS-PST experimental methodology uses several support spans with a constant diameter punch (ratio of which is defined as the support span to punch diameter ratio, $SPR = D_S/D_P = 1.16-6.67$) to mimic ballistic impact damage mechanisms and is also able to quantify the QS-penetration energy. Present research utilizes fiber reinforced thermoplastic composite system made from one directional carbon fabric, and HDPE films using hot press compression molding method. Penetration mechanics behavior of the composite material is quantified in terms of energy dissipation, perforation stiffness and energy dissipating damage mechanisms.

2. Experimental

2.1. Material and material processing

Carbon/HDPE composites are made using one or unidirectional carbon fabric cut into 305-mm by 305-mm sheets of two layers (4L and 12L) by compression molding method. During production processing, commercial HDPE films, which are supplied from market bag (product of Lianhong Plastic), are sandwiched among one directional carbon fabrics (product of Cytec and linear density = 0.32-g/m). The top and bottom HDPE films are four pieces and others are eight pieces that are placed among carbon fibers. After stacking sequence HDPE films and carbon fabric sheets are centered on the hot press (Fig. 1a). During compression molding, commercial HDPE films (Thickness = 0.07-mm) are laid on top, bottom, and between each carbon layers following the stacking sequence presented in Table 1.

The platens are closed and the hot press plates are heated to 356 °F and the compression pressure is set to 2.69 MPa. Once the temperature of the platens reached 356 °F, the compression pressure is increased to 13.44 MPa and held constant for 5-min for the first Carbon layer and additional 3-min for each additional carbon layers. After this first compression cycle (Fig. 1b), the platen temperature is reduced to 302 °F while the pressure is maintained at 13.44 MPa until the temperature reach 302 °F. At 302 °F platen temperature, the pressure is increased to 40.33 MPa and held for a total of 5-min (for all layers) followed by cooling to room temperature (75 °F). Once the platen temperature reached 75 °F, the Carbon/HDPE composite laminate is taken out of the compression molding frame.

The density and areal-density of the laminates are calculated by using of thickness, dimensions, and mass of Carbon/HDPE composite material. Additionally, density is calculated from a separate mass and volume measurement according to ASTM standard D792-00. Furthermore, fiber volume fractions (V_f) of the composite materials, which are determined by the resin burn-off method following ASTM standard ASTM D2584. The areal-density is the function of measured density and thickness of the composite panels and calculated from Eq. (1) [11].

$$AD = \rho_C H_C \tag{1}$$

where, ρ_C is the average density and H_C is the average thickness of the composite panels. Mass and geometric properties of all composite laminates are shown in Table 2.

2.2. Quasi-static punch shear testing (QS-PST)

A quasi-static punch shear test (QS-PST) use for determination of the penetration resistance behavior and energy dissipating damage mechanisms of thick section composites [3–5]. Furthermore, QS-PS tests have many advantages, in comparison to drop weight test and other impact tests. They are more accessible, easier to conduct, and (possibly more important) provide consistent and controlled data acquisition of damaged and undamaged structures, which is unavailable or inaccessible in impact tests. Therefore, if equivalence can be demonstrated, quasi-static testing can facilitate an enhanced understanding of the damage mechanics of composite structures. Quasi-static simulation of impact can also provide more consistent and informative damage information, which would be particularly useful in comparative damage-tolerance studies [11].

Two types of steel fixture which consist of a square bottom support plate, a matching top cover plate, a punch guide, and a punch (Fig. 2) are used for QS-PS tests. First one of them, the 'Small' QS-PST fixture has a bottom support plate of dimension 101.6-mm × 101.4-mm × 38.1-mm with a centered hole of diameter 76.2-mm bored 25.4-mm deep. It is capable of housing many support rings of various diameters and a 25.4-mm diameter hole in the support plate which provides access from the rear side of the support plate. 'Medium' fixture dimension is 152.4-mm × 152.4-mm × 50.8-mm with a centered hole of diameter 101.6-mm bored 25.4-mm deep, and is very similar to the 'Small' fixture. They have concentric rings (thickness 25.4-mm) of different inner and outer diameters can be assembled to cover a wide range of support span diameter in the range, 7.7-mm $< D_S <$ 101.6-mm. The ratio between the support span diameter and the punch head diameter is termed as 'SPR,' value of which can vary in the range, $1.01 < SPR = D_S/D_P < 13.33$ for the 7.62-mm punch head [11].