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Influence of fiber orientation and thickness on the response of glass/epoxy composites subjected to impact loading

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ABSTRACT

Composite laminates, made of glass/epoxy using compression molding technique, were subjected to impact loading. The ballistic limit and energy absorption capacity of the laminates were obtained. Experiments were carried out to study the effect of fiber orientation and thicknesses on ballistic limit and energy absorption of the laminates, by using a rigid conical bullet having 9.5 mm diameter and mass of 7.5 g in an air gun. Analytical expressions were obtained to find the ballistic limit, residual velocity and energy absorption capacity of the laminates. The expressions obtained by considering the various damage modes, which were involved in penetration, when laminates subjected to impact loading. The values obtained from analysis were compared with experimental results and good agreement was found. The strain rate sensitivity of the glass/epoxy composites was considered for analysis.

1. Introduction

Ballistic study of laminated plates is important in the fields of protective armour, aircraft and spacecraft. For designing of these structures, ballistic limit and energy absorption capacity are most important factors. Ballistic limit is defined as the velocity required for the projectile to penetrate the armor plate completely without any residual velocity. It is usually determined by experiments. Large numbers of papers have been reported on impact analysis of laminates for velocities, which are beyond the ballistic limit and some are on analytical formulations for finding ballistic limit of the composite laminates. Zhu et al. [1,2] presented an analytical model based on the laminate plate theory for a cylindrical projectile with conical tip. In the model energy dissipative mechanisms, which included indentation at the front face of the plate, bulging of the plate on the back side, delamination, fiber failure, and friction were taken into account. Experiments on the kevlar/polyster composite laminates were also carried out and the ballistic limits of laminates were obtained for various thickness values. It was observed that there was a good comparison of ballistic limit obtained from experiments with analytical results. Sun and Potti [3] used static punch curve with Mindlin plate model to predict the penetration phenomenon of laminates in the dynamic case. Series of impact tests were performed on the graphite/epoxy, quasi isotropic composite plates. The predicted residual velocities and ballistic limits showed good agreement with experimental values. Goldsmith et al. [4] carried out experimental and analytical study of woven carbon fiber laminated plates. Analytical model was based on the energy absorption by considering the global plate deflection, fiber breakage, delamination, bending of petals, hole enlargement and friction between the striker and sample. Predicted ballistic limits showed good agreement with experimental values. Jenq et al. [5] conducted a series of experiments to predict the ballistic limits of woven glass/epoxy composite plates. Quasi-static punch tests were performed to understand the progressive damage modes of targets. The major damage modes found to be delamination and fiber breakage. A dynamic version of the finite element program was incorporated with a penetration model to analyze the impact responses of target and projectile. Good agreement between experimental and numerical results were obtained by considering the dynamic elastic properties in FE analysis. Buitrago et al. [6] performed impact experiments on laminates made of E-glass/polyester woven laminates in which, three monolithic laminates with thicknesses of 3, 6 and12 mm and two multiplate laminates, namely, the sandwich type with face-sheets of 3 mm thick and a 30 mm PVC-foam core, and another designed as spaced plates, consisting of two 3 mm laminates separated 30 mm apart were considered. It was observed that thicker monolithic laminates showed higher ballistic limit and higher damage area. The ballistic limit in a multi plate laminate was similar to that of a single laminate of equivalent thickness. Nevertheless, the amount of damage area on the back side of the sandwich plate was more than the spaced plates. Sevkat et al. [7] also studied S2 glass-toughened epoxy composite beams, impacted at different velocities, experimentally and numerically. They developed a user defined

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subroutine for LS-Dyna using a nonlinear orthotropic model to predict damage extent, residual velocity of the projectile and ballistic limit. Estimated values of ballistic limit showed good match with experimental results. Lim et al. [8] used DYNA-3D to predict ballistic limit, residual velocity, energy absorption and fabric displacement profiles of the ballistic tests conducted on twaron fabric. He et al. [9] employed ABAQUS/Explicit code to examine the perforation of the laminates impacted by different shapes of projectiles. A velocity dependent forcing function was applied at the surface of the projectile as boundary condition, in the numerical model to predict the penetration depth, residual velocity, ballistic limit, transient response and velocity of the projectile. Wu et al. [10] have carried out theoretical study on the perforation of fiber-reinforced plastic laminates, which were subjected to impact loading, by flat-nosed projectiles for a wide range of velocities. Different failure modes, which included global deformation, failure with local rupture as well as wave-dominated local failure, were given and a shear failure criterion was also employed to predict the perforation of laminates which failed in global deformation mode. By combining the wave-dominated local failure model and the concept of Von Karman's critical impact velocity, a criterion for the transition of the above mentioned two failure modes, was obtained. The model predictions were in good agreement with the available experimental results in terms of ballistic limits and failure modes. Hosur et al. [11] analyzed the stitched and unstitched woven carbon/epoxy laminates. Plane and satin weave woven fabric were used to fabricate the laminates. They found that stitching restricted the damage but the ballistic limit was high for unstitched laminates. Satin weave laminates showed higher ballistic limit compared to plane weave laminates. Iremonger and Went [12] conducted ballistic impact tests of chisel nose fragment-simulating projectile on nylon 6,6/ethylene vinyl acetate composite laminates. It was found that during penetration there was plug formation in laminates by shearing followed by delamination between fiber layers. Gellart et al. [13] conducted ballistic tests using steel cylindrical projectile on glass fiber reinforced plastic composite plates of different thickness values. They showed a bilinear relationship between energy absorption and target thickness. They also presented a simple analytical model to show this bilinear behavior of the composite plates for ballistic loading. Mines et al. [14] conducted experiments on glass/polyester composite laminates of different types of glass fabrics by varying the thickness, impactor geometry and mass. They investigated the different deformation mechanisms involved in energy absorption such as delamination energy, energy absorption due to friction, energy required to penetrate the upper skin, energy absorbed locally due to shear, energy absorbed locally due to tension and effect of strain rate on these deformation mechanisms. Wen et al. [15,16] presented a simple analytical model for the perforation of FRP plates by rigid projectiles of different shapes. The model was based on the assumption that deformations were localized and the resistive pressure applied on the projectile by target was because of the static elasto–plastic deformations of target material and dynamic pressure due to velocity effects. Analytical predictions showed good agreement with theoretical values for different projectile nose shapes and velocities. Barre et al. [18] showed that kevlar/epoxy laminates were not strain rate sensitive while glass/epoxy laminates were highly strain rate sensitive. Harding and Welsh [19] performed experiments for different strain rates of woven roving reinforced glass/epoxy laminates and uni-directionally reinforced carbon/epoxy laminates and obtained the effect of strain rates on tensile modulus, strength, failure strains and energy absorbed in fracturing. The strain rates considered for glass/epoxy laminates were in the range of quasi-static to 1000 s^{-1}. Though there have been experimental and theoretical studies on composite laminates subjected to impact loading, composites being brittle and heterogeneous, further studies are required to ensure that the deformation pattern and the behavior of the composites are well understood.

In the present study, experiments were performed on the glass/epoxy laminates to determine the ballistic limit, residual velocity and energy absorption capacity of the laminates. Analysis was carried out to predict the residual velocity and ballistic limit of the laminates for different fiber orientations and thicknesses. The analysis considered the energy absorbed in, tensile failure of the primary fibers, elastic deformation of the secondary fibers, delamination, matrix cracking and kinetic energy of the moving cone at the back face of the laminates, during perforation. The ballistic limit and residual velocities for higher incident velocities were predicted. The dynamic Young's modulii, which were strain rate sensitive, were used for the analysis. The analytical model was based on energy method, in which the ballistic limit was obtained by equating the kinetic energy of impacting projectile to the sum of energy absorbed by different damage mechanisms of the laminates, during perforation. For the velocities above ballistic limit, residual velocity of the projectile was used to predict the residual kinetic energy of the projectile.

2. Experimental investigation

Impact experiments were performed on the glass/epoxy laminates of different fiber orientations and thicknesses to determine the ballistic limit and energy absorption capacity. To study the influence of fiber orientations on impact resistance, laminate with orientations of (0/90), (0/90/30/−60), (0/90/45/−45) and (30/−60/60/−30) were considered. Laminates were prepared for four different thicknesses which included, 1.5 mm, 3 mm, 4 mm and 5 mm. These thicknesses were obtained by using 2 layers, 4 layers, 6 layers and 8 layers, respectively.

2.1. Specimen fabrication

The glass/epoxy laminates were fabricated by using glass fiber woven fabric and epoxy resin. Areal density of the fabric was 600 gm^{-2}. The epoxy resin used in fabrication of the laminates was LY556 and mixed with hardener HY951 of 10% by weight. The laminates were fabricated using hand-lay-up technique followed by compression molding and the sizes of the laminates were 300 mm × 300 mm.

To fabricate the laminates of different thicknesses and fiber orientations, glass fabrics of 350 mm × 350 mm were taken for different fiber orientations. The bottom steel plate of compression molding machine, which was first coated with a releasing agent, was wetted thoroughly with the epoxy resin before the first ply was placed on it. More resin was applied on the first ply with a brush until this layer was thoroughly wet with resin. Then steel roller was used to remove the excess resin and break the air bubbles. This operation was repeated for each layer of reinforcement in order to obtain the desired thickness of the laminates. Then the laminate was placed under the pressure of 20 bar at 80 °C in the compression molding machine. The curing time of 4 h was chosen to ensure complete cross linking. Specimens of different thicknesses and fiber orientations were prepared by this process. After curing, laminates were cut into 300 mm × 300 mm size using bend saw and the edges were finished by abrasive grinding. The laminates had the weight fraction of 0.5.

2.2. Material characterization

Glass/epoxy composite is strain rate sensitive hence Young's modulii change with strain rates. In the present analysis, velocity of impact was around 170 m/s at this velocity the strain rate was