DYNAMIC RESPONSE AND SPALL STRENGTH OF S2 GLASS FIBER REINFORCED POLYMER COMPOSITE

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ABSTRACT

In the present paper results of plate impact experiments conducted to understand the dynamic response of glass fiber reinforced plastics (GRP) are presented. The shock compression response of GRP was investigated because of its promising potential for use in future combat vehicle defense systems. The GRP laminates were provided by ARL, MD, and were made from S2 glass woven roving in Cycom 4102 polyester resin matrix with resin content 32+/-2% by weight. The laminate plies were 0.68 mm thick. A multi-beam VALYN VISAR was used to obtain the particle velocity history at the rear surface of the target plate. These measured profiles were used to understand (a) dispersion and attenuation of shock-waves in GRP, (b) conditions under which dynamic deformation in GRP is reversible, and (c) the spall (delamination) strength of the GRP composite under compression and pressure-shear shock wave loading conditions. The experimental results indicate that the GRP deforms elastically up to 1.3 GPa. The shock front indicates an initial sharp rise in particle velocity followed by a distinct knee. The rise-time associated with the initial sharp rise is observed to decrease with an increase in impact velocity. The slope of the wave profile, following the knee, is observed to increase with an increase in impact speed. Moreover, the results indicate that the GRP shows almost no attenuation with propagation distance. This result is in contrast to the previous work reported in the literature on GRP that was conducted employing embedded PVDF gages. The results of the spall experiments indicate that even when the deformation of the GRP proceeds in an elastic manner, the decohesion strength of the plies under pure tensile loading can be very small. Also, it is observed that the presence of shear strain is detrimental to the delamination strength of the GRP.

1 INTRODUCTION

Ballistic threats and multifunctional survivability requirements (e.g., overhead indirect fire fragments, direct fire tank munitions, and increasingly potent infantry weaponry) encouraged the evolution of ground fighting vehicles to their present 70+ ton status. However, in order to optimize deploy-ability and war-fighting capability in various remote locations, good mobility and ballistic impact resistance ground combat force in any environment becomes essential for future combat vehicles [1]. This has placed renewed demands on new and improved lightweight, highly damage-tolerant armor materials.

The utilization of heterogeneous material systems in the development of armor provides a potential for a quantum leap in ballistic performance in a variety of lightweight armor applications. Such systems are envisioned to exploit synergistic effects resulting from a combination of dissimilar materials, such as polymers and ceramics, thereby developing unique property combinations not possible via other means. Some of the notable recent examples demonstrating the success of synthetic heterogeneous material systems include the use of composite materials with organic matrices reinforced by glass fibers to achieve lightweight and enhanced ballistic resistance [2-4]. The US Army is contemplating to use these material systems for future combat vehicles, platforms and structures.

The development of armor utilizing such heterogeneous material systems is a complex process that requires performance of ballistic experiments as well as computer simulations of ballistic events in order to fully understand the performance of armor material. Simulations are conducted using wave propagation/finite-element codes; such codes require dynamic properties of materials for carrying out analysis of ballistic events. While the dynamic response of homogeneous materials, such as metals and ceramics/glasses has been well documented, the ballistic response of heterogeneous material systems is poorly understood. This is partly due to the very nature of these composites, which is a conglomerate of matrix, fibers, and interfaces between fiber and matrix and between different laminae, various lay-up sequences with different ply orientations and different forms of fiber arrangements within the matrix (particulate, planar, 2D/3D woven). The very heterogeneity that allows an engineer to alter the stiffness and strength response to meet the design needs makes it challenging to predict the overall structural and acoustic properties from the details of the construction. Thus, knowledge of the response of GRP under dynamic loading is essential to develop a better understanding of its performance as a structural armor material.

In view of the technological importance of GRP to the army and the current lack of understanding of the dynamic behavior of these composites, an experimental study was undertaken at CWRU to investigate the compression and rarefaction induced tension response of GRP under shock wave loading conditions. Using these experiments the shock response of the GRP is investigated as a function of impact speed (8.5 m/s to 333 m/s) and as a function of distance of propagation of shock wave. The results of the experiments are used to understand (a) the structure of the shock waves (dispersion and attenuation) in the GRP, and (b) the effects of shock compression and combined shock compression and shear on the delamination strength of GRP.

2 EXPERIMENTAL WORK

2.1 Material

The S2 Glass Fiber Reinforced Polymer (GRP) were made from S-2 glass woven roving in Cycom 4102 polyester resin matrix with resin content of 32% by weight. The laminate plies were 0.68 mm thick. Desired number of laminates were stacked in ± 90 degrees sequences between two steel caul plates with release films. The whole assembly was vacuum bagged and subjected to the following heat cycle:

(i) Initially heated to 339 K for 45 min.
(ii) Temperature raised to 353 K for 2 hours.
(iii) Temperature raised to 398 K and held for 2 hours.
(iv) Cooled to 312K at the rate of 7 K per min.

The mean density of the composite was measured to be 1.949±0.30 mg/M^3.

2.2 Configuration of the plate impact experiment to investigate the structure of shock waves during shock compression of GRP

The plate impact experiments were conducted using the 83 mm single-stage gas gun at CWRU. The GRP target plates were impacted by employing a 7075-T6 Al flyer plate, as shown in Figure 1. A multi-beam VALYN VISAR was used to measure the particle velocity at the free surface of the target plate. The experiments were conducted using 54 mm × 54 mm square GRP plates of four different plate thicknesses, i.e. 3 mm, 7 mm, 13.5 mm and 20 mm. The GRP targets were held in aluminum target holders, and are carefully aligned to be parallel to the Al 7075-T6 flyer plate within 2×10^{-5} radians by using an optical alignment scheme. The fiberglass projectiles were accelerated through the 5.6 m gun barrel by compressed Helium up to speeds of 450 m/s, which generates approximately 2.5 GPa of normal compression on the GRP composites. In the present study the structure of the shock wave was investigated by (a) varying the impact velocity from 8.5 to 450 m/s, and (b) by varying the plate thickness from 3 to 20 mm.

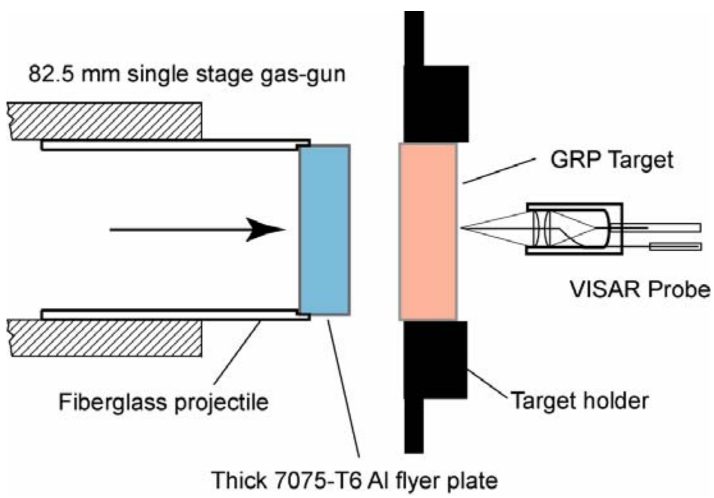

Figure 1: Schematic of plate impact experiment used to study structure of shock waves during shock compression.

2.3 Configuration of the plate impact experiment employed to investigate the effect of shock compression and combined pressure and shear loading on the delamination strength of GRP

In the present study the spall strength was determined by conducting plate impact shock compression and combined shock compression and shear experiments. The advantage of using a shock-wave technique to determine delamination strength of GRP composite comes from the fact that the tensile loading in the composite is generated through the interaction of plane wave propagation. Consequently, the tensile loading is homogeneous over the whole surface of the composite and the spall strength determined by performing shock-wave experiments is thus the pure tensile stress necessary to pull the GRP apart. Hence, in the present study, in order to conduct the spall experiments, the thickness of the Al flyer is carefully controlled so that the unloading wave and the tensile wave from the free surface of the target plate meet at the center of the GRP to induce delamination.

Figure 2 shows the schematic of the plate impact pressure-shear experiment used to obtain the delamination strength of the GRP under combined pressure and shear loading. Experiments were conducted with skew angles 15 and 20 degrees and impact speed ranging from 35 m/s to 70 m/s. The thickness of the flyer plate and the GRP target was chosen to induce tension in the unloaded region behind the propagating shear wave.

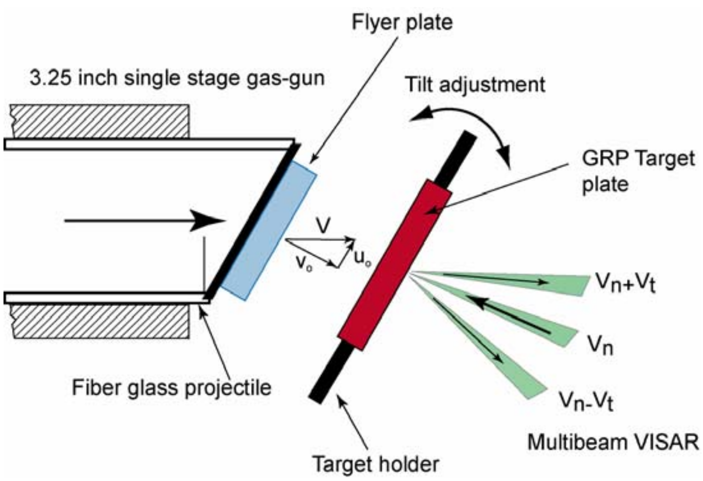

Figure 2: Schematic of the Gas Gun pressure-shear plate impact experiments.

2.4 Results and Discussions:

Figure 3 shows results of plate impact experiments conducted on GRP targets having a thickness of approximately 6.75 mm. Three different impact velocities were employed: 114 m/s, 181 m/s and 321 m/s. In all cases a 7075-T6 Al alloy plate was used as the flyer. Corresponding to the three impact velocities the stress levels were 519 MPa, 824 MPa and 1461 MPa, respectively. At all the three impact velocities the particle velocity versus time profiles showed similar features, i.e. a sharp rise in particle velocity followed by a distinct knee in the velocity time profiles. The time associated with the sharp rise in particle velocity is observed to decrease as the impact velocity was increased. Moreover, the slope of the wave profile following the knee is observed to increase with an increase in impact speed. This behavior is understood to be consistent with the viscoelastic response of the matrix material. The final level of the particle velocity at impact speeds corresponding to 114 m/s and 181 m/s correspond to prediction based on elastic-plastic behavior of Al flyer and elastic response of GRP. However, at an impact speed of 321 m/s, this level of the free surface particle velocity is lower than that predicted by wave analysis. This lower than predicted particle velocity level implies an increase in the acoustic impedance of the GRP at stress levels in excess of 1460 MPa. Also, these results suggest that the shock compression of the S2 glass composite has a much larger positive effect on acoustic impedance when compared to a decrease in impedance due to accumulation of damage.

Figure 4 shows the results of the plate impact experiments conducted on GRP targets having a thickness of approximately 13 mm. In this series of experiments, specimens were tested at impact speeds ranging from 8.6 m/s to 218 m/s. Features in free surface particle velocity similar to those observed for the 6.75 mm thick specimens were observed. The rise time was observed to decrease as the impact velocity was increased. Also, a distinct knee is observed in the velocity time profiles. Since in this series of experiments the maximum impact velocity was 218 m/s (stress ~ 1000 MPa), the levels of the free surface particle velocity correspond well to those predicted by the analysis.

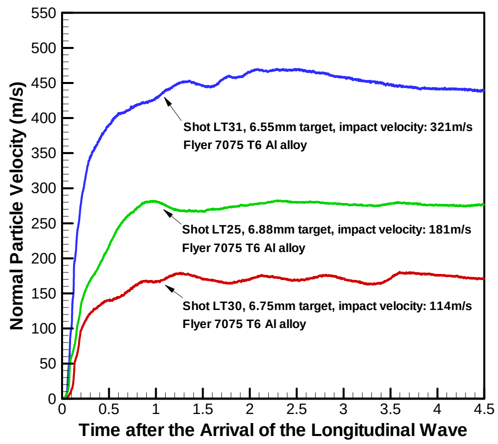

Figure 3: Structure of shock wave at three different impact speeds -- 114 m/s, 181 m/s and 321 m/s. The thicknesses of the GRP target plate for the three cases are 6.75 mm, 6.88 mm, and 6.55 mm, respectively.

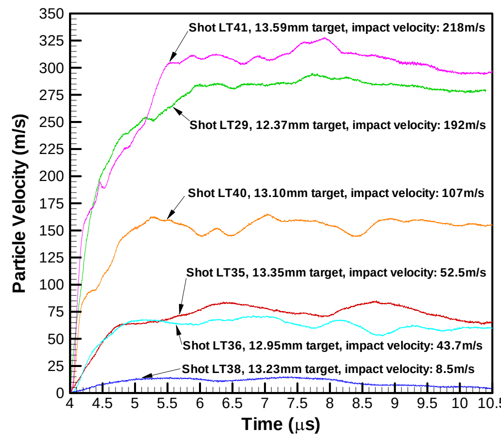

Figure 4: Structure of shock wave at five different impact speeds – 8.5 m/s, 43.7 m/s, 52.5 m/s, 107 m/s, 192 m/s, and 218 m/s. The thicknesses of the GRP target plate for the three cases are 13.23 mm, 12.95 mm, 13.35 mm, 13.10 mm, 12.37 mm, and 13.59 mm, respectively.

Figure 5 shows results of typical spall experiments in GRP conducted under normal compression (LT37) and combined pressure-shear loading (LT43) at a skew angle of 15 degrees. The abscissa represents the time after impact and the ordinate represents the normal particle velocity. The effect of shear stress (strain) on delamination strength during combined pressure shear impact loading is evident by comparing the results of the two experiments. From the figure a delamination strength of 25.8 MPa is inferred for Shot LT43 and 44.3 GPa for Shot LT37. For Shot LT37, the component of the stress normal to the impact plane is 178.7 MPa. This level is very similar to the normal stress of 177 MPa obtained for Shot LT43. Moreover, for Shot LT43, the component of shear stress is 47.9 MPa. It is interesting to note that at almost the same normal stress level, LT43 has considerably smaller spall strength when compared with LT37. This drop in delamination strength is understood to be because of the presence of shear strain in the GRP in the case of Shot LT43. There was no spall strength observed for pressure-shear experiments conducted at a skew angle of 20^o at normal stress in the range of 0.21~0.3GPa.

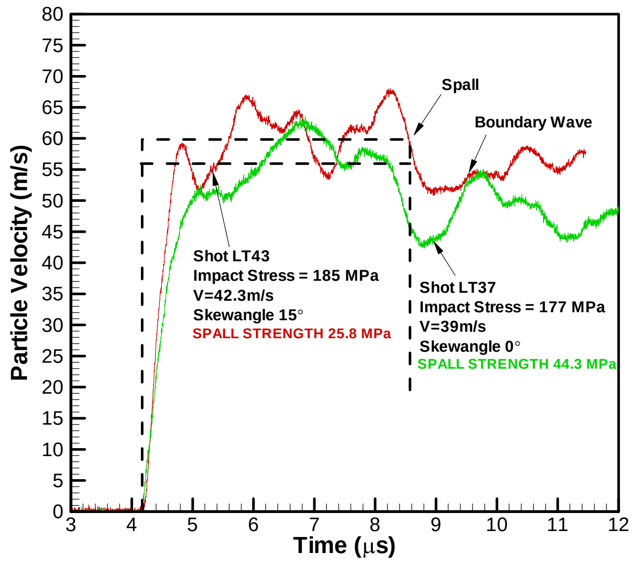

Figure 4: Spall Experiments for GRP composites under Normal Compression and 15 degree Pressure-Shear Shock Loading.

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