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Damage modes in 3D glass fiber epoxy woven composites under high rate of impact loading

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ABSTRACT

A qualitative analysis of experimental results from small caliber ballistic impact and dynamic indentation on a 3D glass fiber reinforced composite are presented. Microscopic analysis of the damaged specimens revealed that the current 3D weaving scheme creates inherently two weak planes which act as potential sites for delamination in the above experiments. It is concluded that while the z-yarns may be effective in limiting the delamination damage at low loads and at low rates of impact, at high loads and high loading rates delamination continues to be the dominant failure mode in 3D woven composites. It is shown that dynamic indentation can be used to capture the progression of damage during impact of 3D woven composites.

1. Introduction

The use of composites in aerospace, military and marine industries has grown steadily over the last few decades. Despite their increased use and improvements in properties, delamination continues to be a common problem, especially under impact loading. One effective approach to enhance the delamination resistance and damage tolerance is 3D stitching or weaving. While 3D composites have been around for some time, their use has often been limited due to high cost of manufacturing. Also, manufacture of parts from such composites with repeatable properties is nontrivial. Recently, there has been an increased interest in these materials as the cost of their manufacture has decreased dramatically and the demand for strong and damage-tolerant lightweight materials has increased.

Compared to 2D woven composites, laminated composites may have much greater stiffness and strength [1]. The lower strength in woven composites is attributed to warping of fiber bundles as well as a higher volume content of the matrix phase [1]. However, both composites suffer from delamination between the individual lamina. To prevent this failure mode, 3D woven composites with z-yarns that weave multiple laminas are used [2]. The lamina tows warp during the weaving process and create large spaces to form. These spaces are then filled with matrix material during consolidation resulting in a high volume fraction of matrix. The warping and low fiber volume fraction result in degraded in-plane material properties similar to 2D woven composites [3]. Therefore, it is important to understand the effect of through-thickness reinforcement on the strength and stiffness of fiber reinforced composites.

A number of studies have been conducted to determine the tensile properties of 3D reinforced composites. Tensile tests at low loads revealed crack initiation even in the elastic regime [4]. The crack formation was associated with the resin rich areas near the z-yarn reinforcement [5]. Compressive tests performed on both stitched and woven 3D composites revealed that the geometric flaws created by the weaving process significantly reduce the yield strength when compared to stitched composites [6]. However, the woven composites showed larger strain to failure whereas the stitched composites failed catastrophically at low levels of strain. A significant increase in the mode-I fracture toughness and a moderate increase in the mode-II fracture toughness was noted in these composites [7–9]. Fatigue test on various types of composites revealed that reinforcements, in general, decrease the fatigue life [10–12]. The major benefit of through-thickness reinforcement in a composite is its increase in impact damage resistance. Transverse impact tests performed [13] on a 3D woven composite, revealed that the damage mechanisms were dependant on the loading rate. Under low loading rates failure of the composite occurred due to excessive tensile and compressive stresses created by the bending moment. At higher loads the damage manifested in terms of matrix

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failure, fiber failure, and fiber pullout. It was noted that the z-reinforcement prevented delamination. Mouritz [8] studied a 3D woven composite subjected to high velocity ballistic impact and shock loading. While the z-yarn weaving did not prevent delamination during high velocity ballistic loading, it did reduce the damage during shock loading. It was inferred that ballistic loading at rates much higher then the ballistic limit was the cause of severe delamination regardless of the level of z-reinforcement.

Indentation or ''punch'' test is another type of test method for determining the mechanical response of composite materials. This method is particularly effective in examining the delamination strength of the composite as well as for understanding the evolution of damage mechanisms during low velocity impact. A variety of methods are used to perform this test including static indentation using universal testing machine [14], low velocity impact with instrumented drop tower [15,16] and dynamic indentation using the split Hopkinson pressure bar (SHPB) technique [17,18]. In these studies, 3D woven composites were found to absorb more energy and survive more repeated impacts before perforation compared to 2D woven composites. Low velocity drop tests on 2D plain woven, 3D stitched, and 3D pinned composites revealed that at low energy impacts, both pinned and stitched composites enhanced the inter-laminar shear strength [19]. However, at higher loads the 3D pinned composite did not show any improvement over the 2D woven specimen, while the 3D stitched composite revealed much better strength. On the other hand, experimental studies by Grogan et al. [20] have also clearly shown that 3D woven composites provide better resistance to delamination under ballistic conditions then 2D woven composites. Clearly, all these results point to the fact that 3D stitching and weaving may not always be beneficial.

Typical laboratory tests such as compression testing are useful for evaluation of fundamental damage modes but they may not truly reflect the conditions that prevail during a realistic service condition such as ballistic impact. Therefore, by conducting actual ballistic impact tests it may be possible to evaluate how the damage recorded in laboratory tests compares to induced damage during ballistic tests. Also, identification of the damage or failure modes in such ballistic tests allows determination of possible strengths and/or weaknesses in our composite material. In this manuscript the damage induced due to ballistic impact and dynamic indentation on a 3D glass fiber reinforced composite is presented. The microstructural features responsible for the observed damage modes are discussed.

2. Experimental methods

2.1. Materials and microstructure

A 3D glass fiber reinforced epoxy composite of thickness 16.5 mm was used in this study. The composite specimen was supplied by the US Army Research Laboratory, Aberdeen Proving Grounds, MD. The composite was made of 27 layers of tows stacked in a cross-ply sequence, with 13 layers in the 0° direction (x-tows) and 14 layers in the 90° direction (y-tows). Z-yarns are then used to weave the y-tow layers together, i.e., the z-yarn runs parallel to the x-tows. To analyze the microstructure, each specimen surface was polished using traditional metallographic techniques and then a final polish using a 0.05-μm colloidal silicon/alumina mixture. A 3D view of the composite microstructure and a schematic of the composite architecture are shown in Fig. 1. It is shown that the z-yarns do not fully stitch all 27 layers of tows. Instead, two z-yarns are used: one weaves 9 of the y-tow layers and 8 intermediate x-tow layers, while the other weaves the remaining 5 y-tow layers and 4 x-tow layers. This weaving scheme leaves one layer of x-tows unstitched between the two stacks of woven tows as seen in Fig. 1b. Since this layer is not woven, it is susceptible to delamination. To minimize this weakness, the above weaving scheme is alternated in each adjacent row (i.e., on a given row one z-yarn weaves the top 17 layers together while the other weaves the bottom 9 layers. In the adjacent row one z-yarn weaves the top 9 layers and the other z-yarn weaves the bottom 17 layers). While this scheme marginally strengthens the weak x-tow layer, it does create two layers which have half the number of z-yarns running through them. The schematic in Fig. 1 illustrates these concepts.

Using an optical microscope equipped with a digital camera and image analysis software, we have measured various dimensions of the tows and yarns of the 3D composite. As can be seen in Fig. 2, the x- and y-tows are approximately rectangular in shape. They measure approximately 2.5 mm in width and 0.6–0.7 mm in height. The y-tows near the turn of the z-yarns are crimped into a semicircular shape. The z-yarns are more elliptical with major and minor dimensions around 1.3 and 0.5 mm, respectively. At high magnification (Fig. 2c) the dimensions of the individual fibers within a tow can be measured. The average diameter was found to be around 10 μm. By counting the number of fibers within a given area of the tow, and using the average fiber diameter (10 μm), the fiber volume fraction was determined to be approximately 65%

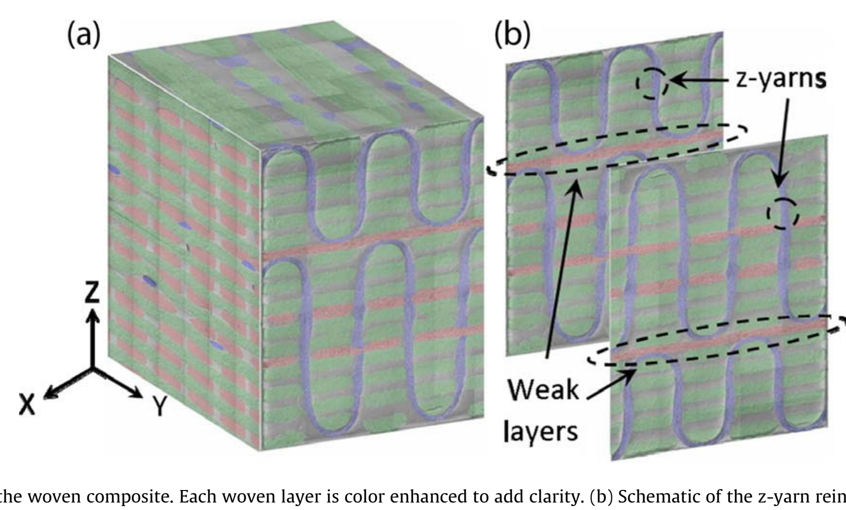

Fig. 1. (a) 3D representation of the woven composite. Each woven layer is color enhanced to add clarity. (b) Schematic of the z-yarn reinforcement scheme in two adjacent planes revealing the position of the weak layer.

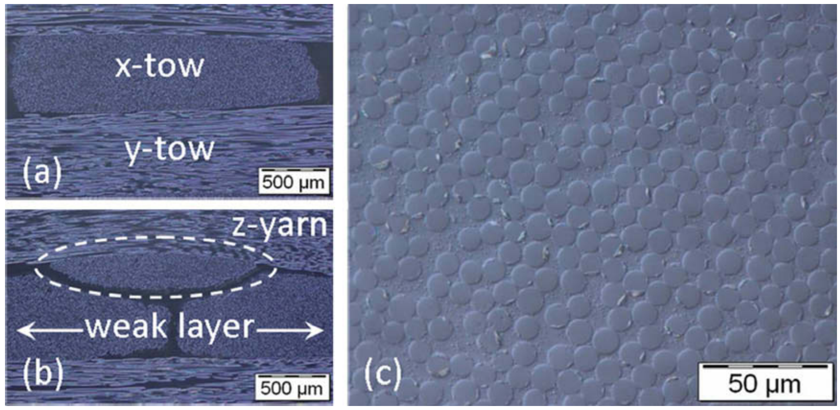

Fig. 2. Microscopy images of a specimen sectioned along *y—z* plane (a) x tows showing rectangular cross-section, (b) cross-section of a z yarn and the weak layer, and (c) high magnification image showing individual glass fibers.

within the tows. The overall fiber volume would be much less than this value, due to the presence of large pockets of epoxy caused by the weaving of z-yarns.

2.2. Ballistic impact

Small caliber ballistic impact tests were performed on specimens of size 40 mm × 40 mm cut from the 3D woven composite tiles. The specimens were held against a 9.5-mm thick sheet of oriented strand board (OSB). The OSB board served both as a support structure as well as a witness plate to record penetration of the target. A model AR-15 rifle was used to fire a standard projectile at the specimen located approximately 18 m away. Two projectiles were used: A 5.56x45 NATO 55 grain (M193) projectile with a lead core and full metal (copper) jacket, and 5.56x45 NATO 62 grain (M855) projectile with a steel tip ahead of the lead core in a full metal (copper) jacket. Typical bullet velocities were around 940 m/s.

2.3. Indentation experiments

Using a modified SHPB [21], dynamic indentation tests were performed on specimens cut from the 3D woven composite sample. In this method, momentum trapping technique [22] on the incident bar of a SHPB is used, see Fig. 3. A striker bar (50.8 mm diameter and 600 mm long) launched from a gas gun impacts the incident bar (50.8 mm diameter and 2.5 m long) creating one-dimensional stress waves within the incident bar. At the opposite end, a hardened steel conical indenter (with a cone angle of 45° and tip radius of 1 mm) is attached to the incident bar. The composite specimen is held against a rigid steel anvil. The stress waves travel towards the indenter and cause an indentation into the specimen. The momentum-trap ensures that only a single indentation is imparted onto the specimen. The duration of the impact was approximately 240 μs. Typical indenter velocities during the penetration were around 5–10 m/s. Using this velocity and the damage zone size (5–10 mm) on the surface an estimate of average strain rate during the indentation [21] was determined to be around 1000/s. More details of the dynamic indentation process are provided in [21–23].

3. Discussion and results

3.1. Ballistic impact

In these experiments, the projectiles penetrated both the specimen and the OSB. The specimens sustained significant damage as seen in Fig. 4. In both cases, fiber breakage and bulging were present on both the front (impact) surface as well as the back (exit) surface; see Fig. 4a. The M193 projectile resulted in a large hole (approximately 25 mm) in the OSB indicating a significant amount of expansion of the projectile upon impact, whereas the M855 projectile resulted in a much smaller hole (approximately 13 mm). The specimens impacted by the M193 projectile generated considerable delamination (Fig. 4c). Extensive delamination damage was clearly visible towards the back surface of the specimens impacted with the M855 projectile (Fig. 4b). These specimens were sectioned to assess the level of damage on the interior of the material. Bulk failure of the material in terms of fiber brakeage (tensile or shear failure), delamination, and matrix failure was clearly visible in the path of the projectile (Fig. 4a). Surrounding this damaged region is a zone of extended delamination. Copper and lead fragments of the projectile were found in these regions. To enhance the contrast of the damaged regions, especially the small delamination regions away from the projectile path, a stain was intro-

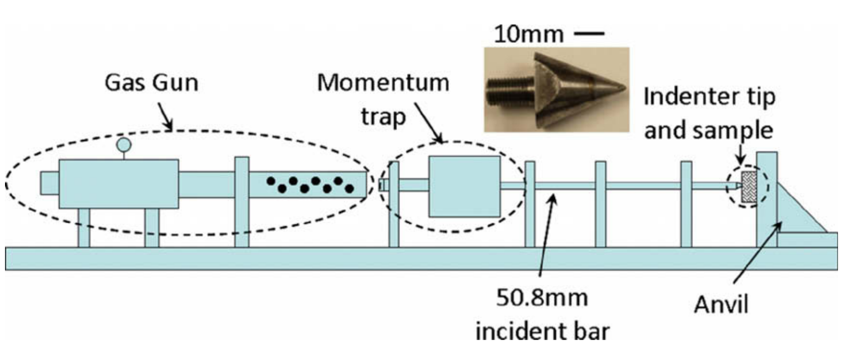

Fig. 3. Schematic of the dynamic indentation test set up. The inset shows a photograph of the steel indenter.

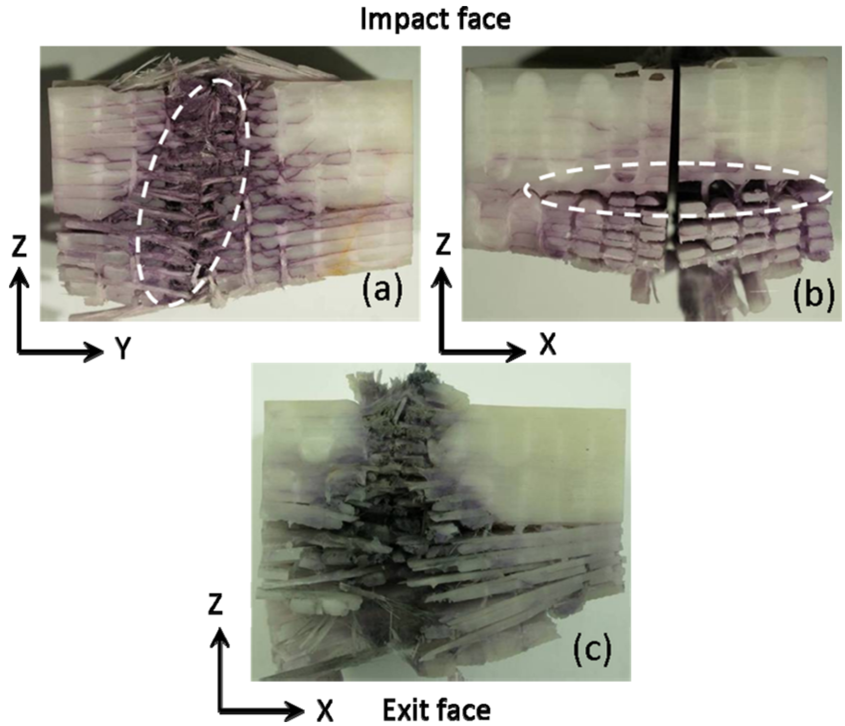

Fig. 4. Cross-sectional images of the induced-damage due to projectile impact on 3D woven composite. (a) Cross-section on *y*—*z* plane revealing fiber breakage and delamination due to M855 projectile, (b) severe delamination along the weak plane, and (c) *x*—*z* plane of specimen showing extensive delamination due to M193 projectile.

duced into the damaged composite. It was noticed that in some cases the delamination was prevented from propagating to the edge of the sample due to the z-yarn reinforcement. However, severe delamination extending far into the specimen in the lateral direction was clearly visible along one of the weak planes discussed before; see Fig. 4b. This mode of delamination suggests that the current 3D weave architecture creates inherently weak planes which are susceptible to severe delamination due to impact loading. It was noted by Mouritz [8] that although 3D reinforcement can prevent delamination during impact events, when a composite is subjected to impact at much higher velocities than its ballistic limit, the delamination can still propagate through the specimen and the effect of z-fiber reinforcement is negligible.

3.2. Indentation experiments

In this study the striker bar was launched at three different velocities resulting in different depths of indentation in three specimens. Consequently, the level of damage was also different in each specimen. Immediately after each indentation, a strong smell of burnt epoxy was noted in each of the tests. This smell was also noted during ballistic testing. The goal of this experiment was simply to examine the level of damage and the damage propagation characteristics within the composite as depth of penetration was increased while the duration of the indentation was kept constant. The indenter penetrates the specimen and creates a zone of damage consisting of matrix failure and fiber breakage. The severity of damage increased with increase in indentation depth as shown in Figs. 5–7. At low-depths, the damage was mostly confined to a small zone surrounding the indentation and mostly consisted of delamination and matrix/fiber failure, see Fig. 5. Small cracks are also present in the pockets of epoxy created by the z-yarn. At higher depths of indentation the size of the zone consisting of matrix and fiber failure increased. Delamination cracks propagate away from the indentation region but are often arrested at the z-yarn. However, delamination is most severe along the weak planes (Fig. 1b) with less reinforcement and extends to the specimen edge as seen in Figs. 6 and 7. As the depth on indentation is further

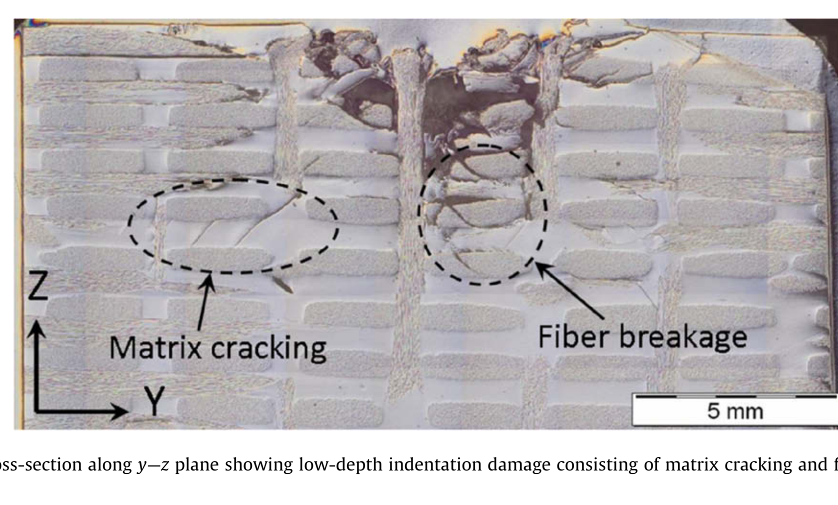

Fig. 5. Cross-section along *y*—*z* plane showing low-depth indentation damage consisting of matrix cracking and fiber breakage.

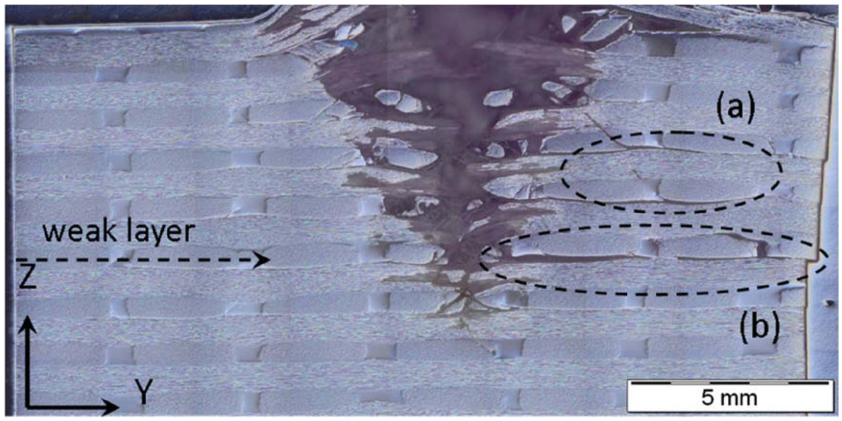

Fig. 6. Cross-section along y—z plane showing damage due to intermediate indentation depth. (a) Small delaminations arrested by z-yarn, and (b) large delamination along weak layer.

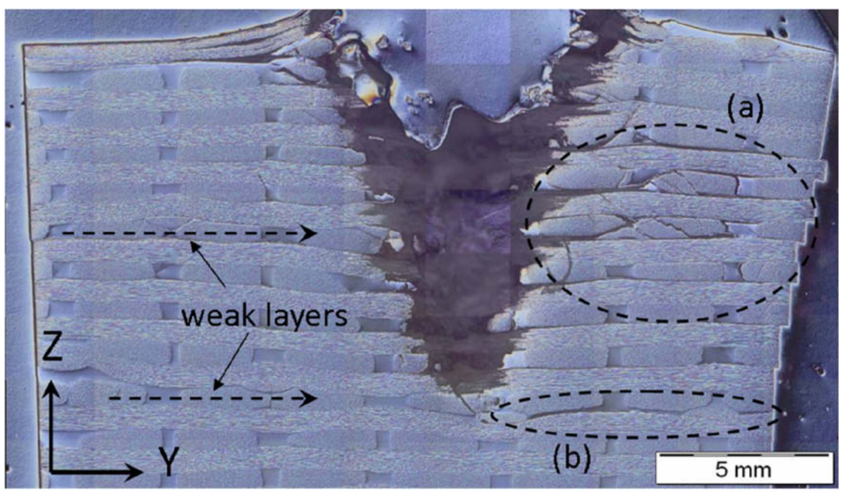

Fig. 7. Cross-section along y—z plane showing high amplitude indentation damage. (a) Several delaminated layers and crack formation within y-tows. (b) Delamination along weak layer of x-tows.

increased, delamination occurs consistently between all layers. At the highest depth the presence of "burnt" epoxy was detected indicating a significant rise in temperature during the dynamic indentation process.

Clearly, the above dynamic indentation experiments capture the initial stages of damage during the ballistic impact. The dissipation of energy due to impact event on a 3D woven composite seems to occur through a sequence of damage mechanisms. At low-depths damage manifests into matrix cracking and fiber breakage where as at high-penetration depths delamination dominates. The 3D stitching may be more effective in preventing delamination damage at low depths but at higher loads (depths) delamination continues to be a prominent damage mode in 3D composites.

4. Conclusions

Clearly in the tests described here, delamination along the weak layer seems to be the most severe weakness in the current 3D woven composite. It is also noticed that although z-yarns assist in reducing delamination during initial penetration, at high velocities as well as at large indentation depth, the 3D woven composites utilized in this study were susceptible to delamination damage. In ballistic tests it is noted that damage was highly dependent on the type of projectile used. Although both M855 and M193 projectiles have similar ballistic characteristics, the damage caused by their impact is very different most likely due to the deformation of the projectile. The above features are also consistent with the damage induced during dynamic indentation. While at low-depth indentation the damage was limited to matrix cracking and fiber breakage, at high depth indentation delamination continues to be the dominant damage mode.

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