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Low-Velocity Impact Response of Braided Carbon/Epoxy Composites

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Summary

In this paper, low-velocity impact response of braided composites is presented. Three types of braided fabrics were used. They were: ±45, 0/±45, and 0/±60. Laminates with 7 layers of ±45 and 4 layers of 0/±45, and 0/±60 were fabricated by vacuum assisted resin infusion molding process to get an average thickness ranging from 2.25 to 2.4 mm. Samples of size 10 × 10 cm were then cut from the panels and impacted at 10, 20 and 30 J. Impact parameters like peak load and absorbed energy were calculated and normalized for thickness. All the samples were then subjected to ultrasonic c-scan testing to determine the damage size. From the results it was seen that laminates sustained the load without any damage at 10J, a little damage at 20 J and more damage at 30J. Triaxial laminates carried more load than the biaxial laminates. From ultrasonic tests it was seen that the 0/±45 laminates had the highest damage.

Introduction

Fiber Reinforced Plastic (FRP) composites exhibit high specific strength and stiffness as compared to conventional metallic components. Of different types of FRP composites, carbon/epoxy laminates are most used in weight sensitive aerospace industry as they offer highest specific strength and stiffness. However, the increased use of carbon/epoxy (CFRP) composites in many applications has been hindered due to concerns of the complex failure modes intrinsic to composite materials. The primary concern with the current conventional CFRP materials is premature failure due to delamination under transverse loading. Conventional composite materials, which consist of laminated layers of unidirectional fibers embedded in matrix, are very strong in the direction of fibers, but much weaker in the direction perpendicular to the fibers. Out-of-plane properties of a unidirectional composite laminate are matrix dominated. Delaminations are usually initiated in one of the three ways: by means of mechanical defects in the composite, damage due to impact, or out-of-plane loads. In all the cases development of through-the-thickness stress is the primary cause of delamination. When subjected to impact loading, inelastic energy in composites is absorbed in the form of creation of new surfaces. The failure mechanisms include matrix cracking, delamination and ply splitting [1-2], which reduce the residual mechanical properties of the laminate considerably. The worst scenario occurs when the damage is at subsurface levels. It is well known that the residual compressive strength, which is the most affected

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mechanical property, is reduced up to 50% [3]. Hence, in past couple of decades material science researchers have invested their efforts to address the delamination issues. Methods of reducing inter-ply delamination include the use of tougher matrix systems, woven fabrics and through-thickness reinforcement. Of more recent origin are the braided fabrics. Braided fiber architecture resembles a hybrid of filament winding and weaving. Like woven materials, braided fibers are mechanically interlocked with one another. The combination, however, is quite extraordinary. When functioning as a composite reinforcement, braid exhibits remarkable properties because it is highly efficient in distributing loads. Because all the fibers within a braided structure are continuous and mechanically locked, braid has a natural mechanism that evenly distributes load throughout the structure.

With regard to strength and stiffness, properly molded biaxial braided composites exhibit properties that are essentially identical to unidirectional tape laminates of the same orientation and fiber volume. Because of the load distributing feature inherent in braided reinforcement, there is no knock down due to fiber crimp. This phenomenon is limited to triaxial constructions that have significant fiber volume in the axial direction. The laid in axial yarns force added crimp in the bias yarns, causing the biases to lose in-plane properties. The axial fibers also tend to inhibit the distribution of loads within the laminate, yielding lower breaking strength. However, triaxial constructions are very cost effective in a myriad of applications because the automated formation of complex net shape preforms frequently affords more savings than the additional cost associated with the fiber needed to meet design loads. Braid is commonly used in composites simply because it enables lower finished composite costs. Braided reinforcements present composite fabricators a variety of opportunities to be more cost effective because of its unique combination of attributes. These fabrics can be produced with a biaxial architecture such as $\pm 45°$ or a triaxial architecture, such as $0°/\pm 45°$ or $0°/\pm 60°$ within one layer. The biaxial form is the most common form of braid and is often chosen by composite manufacturers since it allows for predictable, consistent lay-up and conforms to any shape. This typical braid construction is most often a basket weave with two yarns crossing over and under each other. The triaxial form involves adding a third set of yarns in the axial direction. This multi-directional braid achieves unidirectional and off-axis reinforcement within one layer.

There are many studies on the impact response of unidirectional and more recently woven carbon/epoxy composites [4-19]. However, there are very limited studies on the low-velocity impact response of braided composites. Hence, in this study response of braided carbon/epoxy composite laminates is investigated. Both biaxial ($\pm 45°$) and triaxial braided ($0°/\pm 45°$ and $0°/\pm 60°$) are considered and compared. Laminates were fabricated using vacuum assisted resin infusion molding process. Impact response at 10, 20 and 30 J was recorded and analyzed in terms of peak load and absorbed energy. Damage was evaluated through ultrasonic c-scan testing.

Experimental Work

Three different carbon fabric architectures were used. They were biaxial (±45°) and triaxial braided (0°/±45° and 0°/±60°) supplied by A & P Technology. The off-axis angle fiber tows were 12K whereas the longitudinal fiber tow was 24K. Hence, 7 layers of biaxial and 4 layers of triaxial fabrics were used for the fabrication of the laminates to obtain more or less similar thickness (varying between 2.25-2.40 mm). The epoxy resin system was a toughened room temperature curing SC-15 supplied by Applied Polyremic Inc. The laminates were fabricated through vacuum assisted resin infusion molding (VARIM) process. VARIM is a simplified and environmentally responsible method of processing. The process uses one-sided low-cost tooling and vacuum bag technology.

For fabricating the laminate (size 30 × 30 cm), a release film was applied to the mold. Seven layers were carefully placed on the mold. Then a sealant tape was tacked on the surface of the mold about 50 mm from the perimeter of the fabric layers. Resin supply tubes were connected to the system with the mold end of the tube connected to a spiral wrap, which distributed the resin through the laminate when vacuum was applied. Tubes linking the vacuum pump and the spiral wrap were also connected. A resin trap was placed between the vacuum pump and the mold to collect any excess resin. Finally, vacuum bag was placed on the mold pressed firmly against the sealant tape to provide an airtight system. The preform was left to debulk under vacuum to remove any entrapped air within the dry fabric. After debulking, the SC-15 resin system was infused. The inlet valve was closed when resin completely wetted the preform and reached the suction side. The wet laminate was left to cure at room temperature. Vacuum was maintained until the end of cure to remove any volatiles generated during the polymerization, and also to maintain the pressure.

All the impact tests in this study were conducted using an impact drop tower device- DYNATUP Model 8210 manufactured by GRC Instruments. DYNATUP equipped with Impulse data acquisition system, version 3. Impulse, v.3 can acquire 8192 data points. Using this machine, impact energy and velocity can be varied by changing the mass and height of the dropping weight. During the test, specimen is held with clamped edge conditions in the fixture placed at the bottom of the drop tower, which provides a clamped circular support span of 75 mm in diameter. The weight of cross head was maintained at 6.62 kg and it was guided through two smooth guide columns. Transient response of the samples includes velocity, deflection, load and energy as function of time. For each type of laminates, at least three samples were subjected to impact at 10, 20, 30 J. The data is analyzed in terms of peak load and absorbed energy. The absorbed energy is calculated as the difference of total energy (at the end of the event) and the energy at peak load. The impact energy is, in general, mainly absorbed in the form of elastic deformation, plastic deformation and through various damage modes. As composite materials have no plastic deformation, all the energy is absorbed through elastic deformation and through different failure modes. Hence, in the current study, absorbed energy is attributed to the energy spent in creating damage.

Ultrasonic inspection of the laminates was conducted using an ultrasonic pulse-receiver unit by Sonix Inc. with FlexSCAN-C™ software. The scanning was done in pulse- echo immersion mode using 2.25 MHz 50 mm-focus transducer. Scanning was done with the impacted surface facing the sensor to obtain the projected damage. Gate was set on the back surface echo. All the laminates were subjected to ultrasonic nondestructive evaluation both before and after impact testing. The ultrasonic testing before impact loading was carried out to ensure that there was no fabrication defect in the sample. Post impact ultrasonic testing was conducted to evaluate the extent of damage in the sample. From the c-scan images, the damage area as projected onto a plane was measured.

Results and Discussion

Figures 1-3 illustrate typical impact response plots in the form of load-time and load-energy response of the laminates at 10, 20 and 30 J respectively. Under the impact load, laminates respond elastically at low energy levels. As long as the energy is well within a certain threshold value, the response will continue to be elastic and is well captured in the impact response plots as seen in Fig. 1. The loading and unloading curves are smooth and symmetric about the peak load. So, at 10 J all the three types of fabric configurations studied here show elastic response without any damage. When the energy values exceed the threshold energy, the laminates absorb the energy through elastic deformation as well as through creation of damage since composites are inherently brittle in nature. The initiation and growth of damage causes the local stiffness to decrease and is indicated in the load-time plots by the drop in the load as seen in Fig. 2. When the damage initiates there will be drop in load which again picks up as the load gets distributed to the neighboring fibers. The level of load drop also indicates qualitatively the severity of the damage as seen in Fig. 3. In this study, energy absorbed by the braided laminates was calculated as the difference in the energy at the end of impact event and that corresponding to the peak load. It was assumed that the energy up to the peak load is absorbed in the form of elastic deformation. Since the laminates varied slightly in thickness, impact parameters like peak load and absorbed energy were normalized for thickness. The normalized load at 10 J for $\pm$ 45° biaxial laminates was 1.12 kN/mm

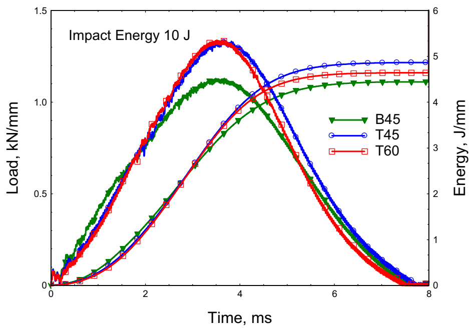

Figure 1: Impact response of braided composites at 10 J

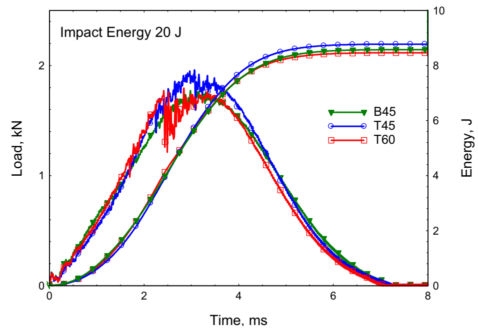

Figure 2: Impact response of braided composites at 20 J

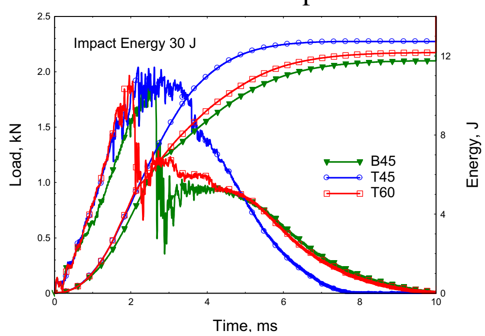

Figure 3: Impact response of braided composites at 30 J

and was 1.33 kN/mm for 0°/±45° and 0°/±60° laminates. The absorbed energy was 1.30, 1.32 and 1.29 J/mm respectively. The normalized load at 20 J was 1.78, 1.98 and 1.79 kN/mm for ± 45°, 0°/±45°, and 0°/±60° laminates respectively. The absorbed energy was 2.66, 2.63 and 3.84 J/mm respectively. The normalized load at 30 J was 1.90, 2.02 and 1.95 kN/mm respectively for ± 45°, 0°/±45°, and 0°/±60° laminates. The absorbed energy was 5.91, 6.17 and 7.26 J/mm respectively. Form these values, it is inferred that triaxial laminates absorb more energy and also sustain relatively higher loads that the biaxial laminates. The increased energy absorption and the load carrying capability can be attributed to the presence of 24k fiber tow along the longitudinal direction. Though, the presence of extra tow makes the in-plane properties lower for triaxial fabrics than that of the biaxial, the mere presence of the longitudinal fiber tow allows them to carry extra flexural tensile stresses resulting from the impact event. Among the triaxial fabrics, ±45° tows offer higher in-plane properties when compared with ±60° tows, although ±60° tows offer a quasi-isotropic in-plane conditions.

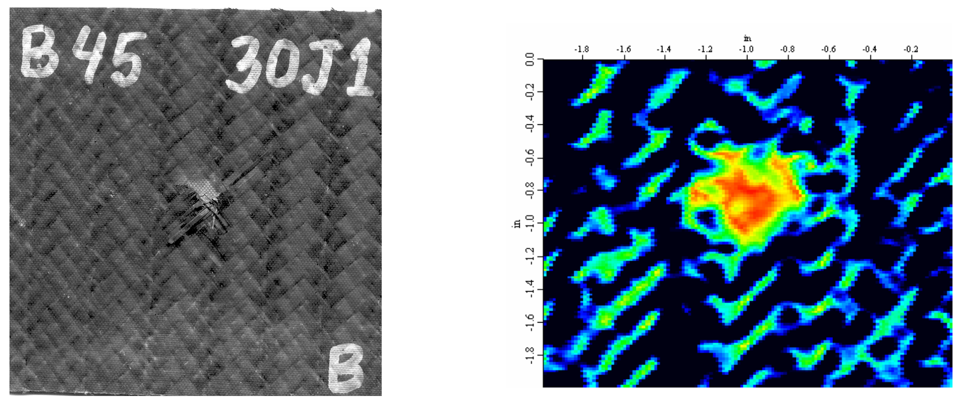

Figure 4: Images of back face (left) and Ultrasonic c-scan (right) of biaxial (±45°) braided composite laminate impacted at 30 J

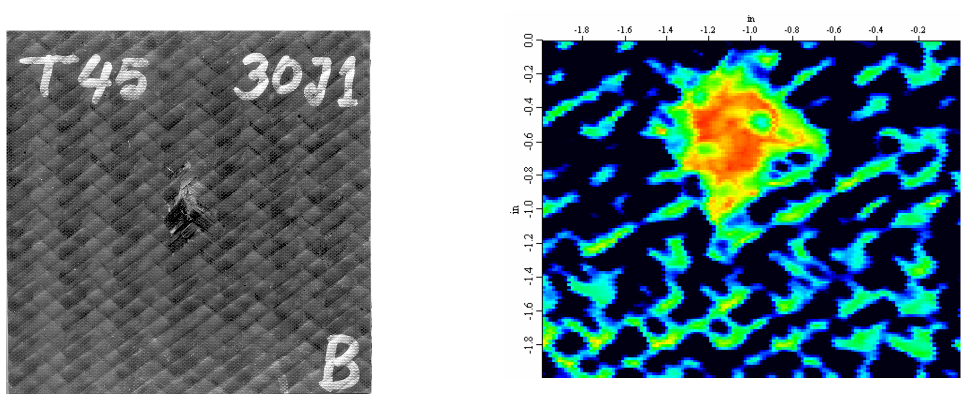

Figure 5: Images of back face (top) and ultrasonic c-scan (bottom) of triaxial (0°/±45°) braided composite laminate impacted at 30 J

From the ultrasonic c-scan studies it was seen that the laminates did not show any damage at 10 J. Some of the laminates showed damage at 20 J. Of the three samples tested only two laminates showed damage at 20 J for the ±45° and 0°/±45° layups, whereas all three samples of 0°/±60° layups showed damage. The damage for the biaxial layup laminates was 5.81 and 11.61 mm^2. For the 0°/±45° layups, the damage was 9.16 and 6.45 mm^2, whereas the damage for the 0°/±60° laminates was 6.45, 9.68 and 32.36 mm^2. The variation in the damage size is attributed to the quality of the laminate local to the point of impact. Any presence of microvoids or local misalignment of fiber tows could lead to lower local stiffness value leading to slightly higher damage. When impacted at 30 J, all three types of laminates exhibited considerable damage at the back surface. On the impact face, there was indentation damage. However, the laminates were not completely penetrated. The

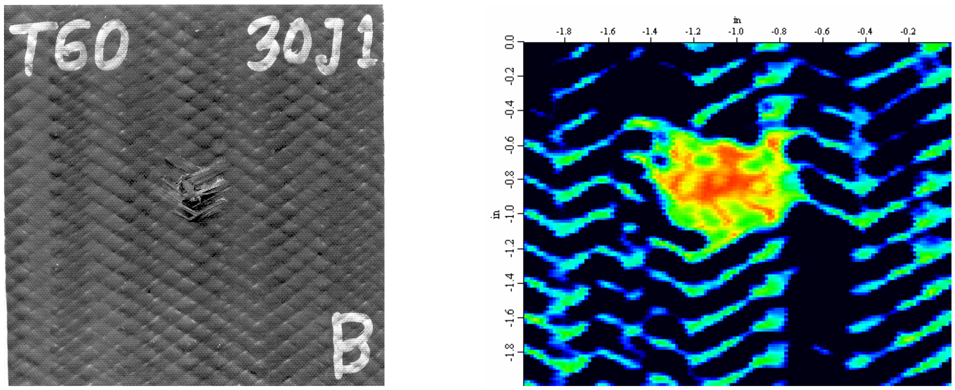

Figure 6: Images of the back face (left) and ultrasonic c-scan (right) of triaxial (0°/±60°) braided composite laminate impacted at 30 J

three biaxial samples impacted at 30 J had 58.06, 58.06, and 64.52 mm^2 damage. The three 0°/±45° triaxial laminates had damage of 80.65, 85.16 and 100.19 mm^2 whereas three 0°/±60° triaxial laminates had damage of 51.61, 51.61, and 66.65 mm^2. Representative images of back surface and c-scan of the three types of braided composites are shown in Fig. 5-6. The damage resulting from the impact is depicted in the middle of the images. As the damage was localized, only 50 × 50 mm area of the samples was scanned. The damage was localized due to the fact that the interlacing fiber tows do not allow the damage to propagate across the fiber tows. The damage is initiated by the tensile fracture of the off-axis fiber tows which makes the laminate locally compliant allowing increased deformation. Once the fiber tow is completely cut through, it will no longer carry any load. The load carried by that tow will be transferred to the fiber tow running in the other direction. Because of the interlacing of the fiber tows in the two directions, the damage does not propagate across the width of the laminate as in the case of unidirectional laminates, but will spread through the thickness. This will result in a much localized damage to the laminate which is good as far as the residual mechanical properties are concerned. The amount of damage is also influenced by the in-plane properties of the laminate. If the in-plane properties of a particular laminate are higher, then that will sustain less damage as compared with those laminates that have lower in-plane properties. Biaxial braids, in general have higher in-plane properties due to the fact that there are only two fiber tows involved in the weave which reduces the crimping of the fabric. On the other hand, triaxial braided fabrics due to the presence of fiber tows in three directions will have more crimp and hence lower in-plane properties. On careful observation of the back surface damages, it was seen that the 0°/±45° triaxial laminates had more off-axis tows damaged than 0°/±60° triaxial laminates. The damage seems to spread along the longitudinal direction, once the off axis tows were fractured. The shape of damage in case of the 0°/±45° triaxial laminates was elliptical with the major axis along the longitudinal direction. On the other hand for the other two laminates, the damage was circular. It is also possible that the additional load carried by the 0°/±45° triaxial laminates induced increased damage.

Conclusions

In this study, impact response of three braided carbon/epoxy composites was studied. The laminates were impacted at 10, 20 and 30 J using an instrumented impact test setup. Due to the interlacing of fibers, the laminates were able to absorb the impact loads with little or no damage at 10 and 20 J and localized damage at 30 J. Among the different laminates, triaxial laminates sustained higher load at 20 and 30 J with 0°/±45° triaxial laminate carrying the highest loads. As a consequence it also had more damage at 30 J.

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