2D woven/ 3D orthogonal Woven Non-crimp E-glass Fabric as Reinforcement in Epoxy Composites using Vacuum Assisted Resin Infusion Molding

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ABSTRACT
E-glass/Epoxy composites were fabricated using Vacuum Assisted Resin Infusion Moulding (VARIM) in fiber weight fractions of 40%, 45%, 50% and 55 percent. E-glass fiber in the form of 2D plain woven fabric of 320 gsm and 3D orthogonal woven non-crimp fabric with 1830 gsm were considered for reinforcement. Mechanical properties including tensile strength, flexural strength, impact strength and inter-laminar shear strength (ILSS) of both the composites were evaluated and compared to explore the possibility of 3D fabric as an alternative over the plain weave fabric. Improvement in mechanical properties was seen with increase in fiber content in both the composites. Results support the view that 3D orthogonal weave fabric can be used in lieu of plain weave fabric as it exhibited improved mechanical properties. Morphological studies were used to analyze the fracture mechanisms.

Keywords: 2D Plain woven fabric, 3D orthogonal woven non-crimp fabric, Epoxy, VARIM, Mechanical properties.

INTRODUCTION
In recent years there has been an increase in demand for composite materials because of numerous advantages that they possess [1]. Composites are fast replacing materials that have been traditionally used and the rate at which they are replacing them is increasing exponentially [2]. Though the area of composite materials is very vast, polymer matrix composites is an area which is garnering more interest. One factor potentially limiting this growth is the lack of an organized database documenting the mechanical properties of composite materials, as there are for conventional materials [3]. Moreover, the properties of composites depend on several factors which include properties of the matrix, properties of the reinforcing elements, its geometry and form, the amount of reinforcing elements (fiber weight fraction), fabrication technique, etc. Hence, determining the properties through experimentation is the best way to suggest the suitability of composite materials. Though numerical methods have been used for characterization they have to be validated by carrying out experiments [4, 5].

Glass fibers are one of the most widely used synthetic fibers for composite materials. This is mainly because they are inexpensive [6] but at the same time possesses many advantages such as good resistance to chemical attack, excellent insulating properties, no moisture absorption and high tensile strength [6-9]. Glass fibers come in form of yarns, short fibers, mat, etc. In the form of mat, chopped strand mat (CSM) is quite common [10] and several types of woven fabric are used, including unidirectional (UD), plain weave (PW), twill weave (TW), basket weave (BW) and satin weave (SW) mats [8]. Other than UD mat, the performance of all others is affected to various levels because of the presence of crimp [11]. This can be resolved by the use of UD mat or a new class of glass fiber mat known as 3D woven mats. While, strength of composite made with UD mat is direction specific, 3D mats can be woven in such a way that the composite can have more or less the same strength in at least two directions, namely warp and weft. Also, since 3D mats are much thicker than the others, less number of mats will be required during fabrication thereby reducing the chances of delamination, which is a common reason for failure among the composites fabricated using bi-directional woven mats [11].

Suresha et al. [12] concluded that 3D E-glass fiber reinforced vinyl ester composites could bear greater load when compared to composites with 2D E-glass as reinforcements. Aktas et al. [13] did modifications by increasing the number of layers in the plain weave E-glass fabric to check its effect on impact energy absorption capability in epoxy composites. They observed increase in perforation threshold in composites with plain weave fabric having more than one layer when compared with plain weave fabric having a single layer. The later though could resist compressive loads better when subjected to lower impact energy. Zhang et al. [14] proved that three-dimensional woven fabric reinforced composites can absorb more impact load when compared to unidirectional and plain weave fabric composites. Fiber yarns are interlaced in the case of plain weave fabrics. This causes reduced in-plane stiffness, resulting in poor shock load absorbing capacity.

Behera and Dash [15] investigated and compared mechanical properties of composites fabricated with 3D E-glass fabric of different yarn architecture with UD and plain weave fabric reinforced composites. Results suggested that 3D fabric with angle interlocked z yarn were more capable of bearing loads than warp interlocked and orthogonal weave in that order. However, 2D plain woven fabric reinforced composites and UD fabric reinforced composites showed better stress bearing capacity when tested in the warp direction than all the other variety of 3D composites. Li et al. [16] extensively studied the tension – tension characteristics of 3D multi-axial warp knitted epoxy composites. Bilisik and Yolacan [17] carried out experiments to study the low velocity impact energy absorption mechanism of unstitched and stitched multi-layer plain weave fabrics. The stitching was done using yarns of aramid, E-glass, Carbon and Nylon. They concluded that multistitching suppressed the impact energy to a smaller area. Kevlar stitched E-glass reinforced polyester composites showed improved better damage tolerance.

Shivamurthy et al. [18] studied the effect of graphite particles on the mechanical properties of bi-directionally woven E-glass fabric reinforced epoxy composites. Increases in tensile, flexural, ILSS and impact strength were reported with the addition of 3% by weight graphite particles. Further increase of graphite reduced the strength. Siddhartha and Gupta [19] observed that bi-directional E-glass composites possessed better tensile, flexural, ILSS and impact strength when compared to chopped E-glass epoxy composites for all fiber content.

This study evaluates and compares the tensile, flexural, impact and ILSS of multi-layer 2D plain woven and single layer 3D orthogonal woven non crimp E-glass epoxy composites fabricated by vacuum assisted resin infusion molding (VARIM) to explore the possibility of use of 3D E-glass fabric in place of 2D plain woven fabric. Scanning Electron Microscopy is used to study the failure mechanism of the composites.

MATERIALS AND METHODS

Materials

2D plain woven and 3D orthogonal woven non crimp E-glass fabric were selected as reinforcements. The areal density of 2D plain woven E-glass fabric was 320 gsm with five threads per cm in both the warp and weft direction, while in the case of the 3D fabric it was 1830 gsm with 8 threads per cm in warp and 11.4 threads per cm in the weft. The thicknesses of 2D plain woven fabric and 3D fabric were 0.3 mm and 1.7 mm respectively. Both fabrics were supplied by Fibermax Composites, Greece. Epoxy Bisphenol-12 (Lapox – L12) and Triethylene Tetro Amine (Lapox K6) supplied by Atul Ltd. India was chosen as the resin and hardener respectively.

Fabrication of Composites

The composite panels were fabricated by VARIM process. Six plies of fabric made up the 2D plain woven reinforced epoxy composite panels (PW composites) while only one ply of 3D orthogonal woven fabric was used in fabrication of 3D epoxy composite panels (3D composites). Since the aim of this study is to compare the mechanical properties of the composites having reinforcement as a glass fabric with two different forms of weaving, the areal densities of the fabrics in both the composites must be equal. The areal density of six plies of 2D plain woven fabric is approximately equal to a single ply of 3D fabric. Moreover, the thickness of six plies of 2D plain woven fabric together comes close to the thickness of a single ply of 3D fabric. Both the panels were fabricated to dimensions of 300 x 300 x 2.5 mm. Composites with four fiber contents by weight were fabricated viz. 40%, 45%, 50% and 55 percent. Resin content was reduced in order to increase the fiber weight fraction. Fabrication and curing was done at room temperature. The curing duration was 24 h.

Characterization of Composites

Tensile and flexural properties were determined on a Zwick Roell UTM. The tensile test specimen dimension was 250 mm x 25 mm and the gauge length was fixed to 150 mm. Testing was done at a constant cross head speed of 2 mm/min as per ASTM D3039 [20]. A tensile test was considered valid when the fracture took place in the gauge length zone. In order to prevent slippage between the jaws and the test specimen, emery cloth was used for better gripping. For flexural testing, a span to thickness ratio of 32:1 was used and the width of the specimens was 13 mm. The overall length was taken as 20% more than the span length. ASTM D7264 [21] was followed and the testing was done at a cross head speed of 1 mm/min. Three-point bending procedure was adopted.

Izod impact testing was done on a Zwick Roell impact tester. Notched specimens were subjected to energy of 5.5 J and the tests were conducted at a theoretical velocity of 3.458 m/s. The tests were conducted according to ASTM D256 [22] and the specimen dimension was 63.5 mm x 12.7 mm x 2.5mm. ILSS tests were conducted on an Instron UTM according to ASTM D2344 [23] at a cross head speed of 1 mm/min. The setup was similar to flexural testing. The specimen dimension was 15 mm x 10 mm x 2.5 mm. The span length was 10 mm.

All tests were conducted on conditioned specimens and in a controlled environment at a temperature of 22 °C. The test specimens were cut from the panels by abrasive water jet cutting at Bangalore. The 3D composite specimens were cut in the warp direction (the direction of the z-yarn) since the number of fibers in this direction is less than in the weft. Results are expressed as averages of 5 individual tests. All the specimens were inspected visually for any kind of defects on the edges before selecting them for testing.

Surface Morphology of Fractured Surfaces

Fractured surfaces of both the types of composites were analyzed to understand the failure mechanism with the help of a scanning electron microscope (Make: Zeiss EVO 18). The specimens were coated with a very thin layer of silver by ion sputtering. An accelerating voltage of 15kV was used during the analysis.

RESULTS AND DISCUSSION

Tensile Strength

The variation in tensile strength versus fiber content is presented in *Figure 1*. It is evident the tensile strength increases with increasing fiber content for the both the types of composites. For PW composites the increase in strength when the lowest and highest fiber content is considered is about 51% whereas for 3D composites, the increase is about 49 percent. The tensile strength of PW composites increases by about 30% initially when the fiber content is increased from 40 to 45%. Further increase in fiber content by the same amount led to increase in tensile strength by about 8% and 6%. This is an indication that 40% fiber weight fraction is far away from the optimum fiber content while the reduction in percentage increase in strength with increase in fiber content suggests that the optimum fiber content is close to 55%. Similar variations in 3D composites led to the following observations. Initial increase in tensile strength was about 14 percent. When the fiber content was increased from 50 to 55%, the increase was on the order of 8%. The 3D composites have better tensile strength than the PW composites at all fiber add levels considered and when the best tensile strengths of the two composites are compared, strength of 3D composite is about 32% higher. The higher tensile strength of the 3D composite is attributed to higher fiber packing than the plain woven fabric in the direction of loading. Also, the fiber yarns in the 3D fabric have no crimp and hence are not pre-stressed.

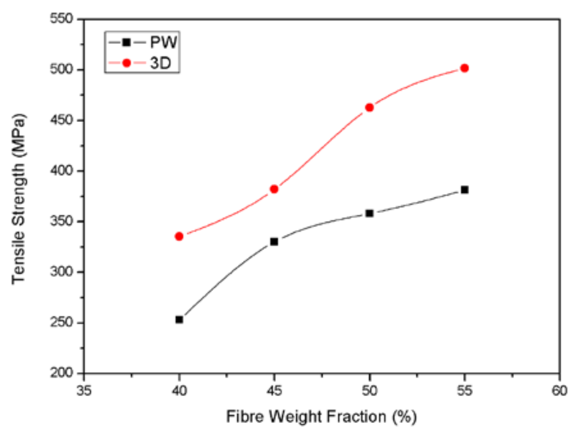

FIGURE 1. Variation in average tensile strength.

Flexural Strength

Flexural strength is an indication of how strongly the composites resist to bending. Results of the flexural tests (*Figure 2*) are comparable to the trends observed with the tensile strength. For all fiber weight fractions, 3D composites show higher flexural strength. Flexural loading results in failure of the material due to tension, compression, delamination or combination of these. Tensile forces are experienced by the material on the outermost layer while the innermost layer experiences compressive forces. Delamination results in the separation of layers. The most common failure mode is due to tensile failure [15] and the same was observed in all the specimens. As reported by Behera and Dash [15], the main reason for tensile failure of specimen is that the specimens are subjected to stretching on the outer layer resulting in initiation of crack which then propagates towards the inner surface. Since delamination is eliminated in 3D composites by the virtue of the weave of the fabric and due to better resistance to propagation of cracks through the fabric thickness, the strength of 3D composite is much higher than that of the PW composites. The 3D composites with 55% fiber content could take up about 58% more stress than the PW composites before undergoing failure.

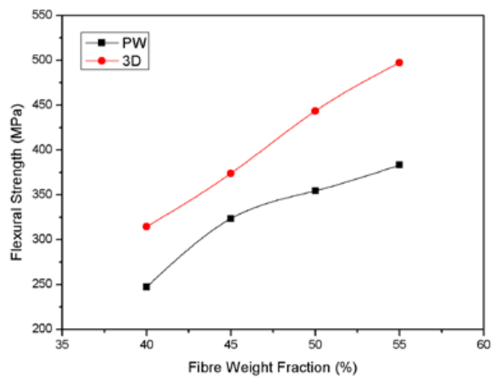

FIGURE 2. Variation in average flexural strength.

Impact Strength

The highest impact strength value was observed for 3D composites with 55% fiber weight fraction. When compared with PW composites, 3D composites could absorb 70 to 85% more energy. This an important observation. It proves that 3D fabrics are superior to plain weave fabrics in shock loading. This is an important advantage in applications which experience sudden impact loads at low velocity. Lower energy absorption in the case of the PW composite is due to its susceptibility to delamination. This results in easy propagation of cracks, leading to premature failure of the material. Zhang et al. [14] also observed a similar weakness which they attributed to lower in-plane stiffness as a result of interlaced fiber yarns. When compared to PW composites, 3D composites will require a lower number of plies, resulting in lower delamination and increased impact resistance. The variation in impact strength can be seen in *Figure 3*.

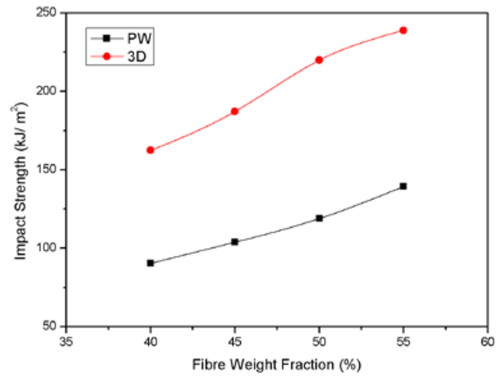

FIGURE 3. Variation in average impact strength.

Inter-laminar Shear Strength (ILSS)

The interfacial stress between two adjacent lamina is referred to as inter-laminar stress. Such stresses result in localized deformation between the lamina, leading to failure mid-plane [24]. To evaluate ILSS it is necessary to induce sufficient stress between lamina so that the specimen is forced to fail in shear. Specimens with small span to thickness ratios are tested in order to prevent maximum normal stress and to promote failure due to inter-laminar stresses. Variation in ILSS is presented in *Figure 4*. It can be seen that the ILSS increases with increase in fiber content. Also, 3D composites show higher ILSS than PW composites, mainly due to the fact that these composites are made up of a single ply and interfacial stresses are only between stacked layers of fibers within the fabric.

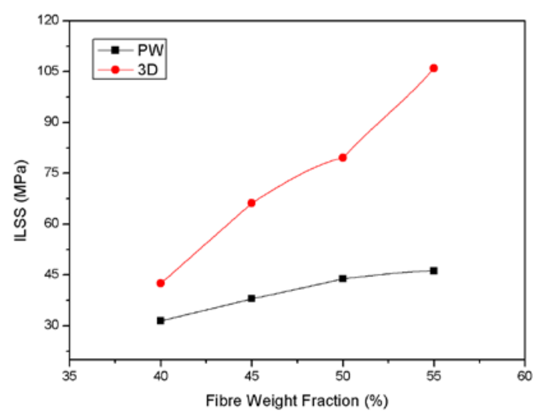

FIGURE 4. Variation in average ILSS.

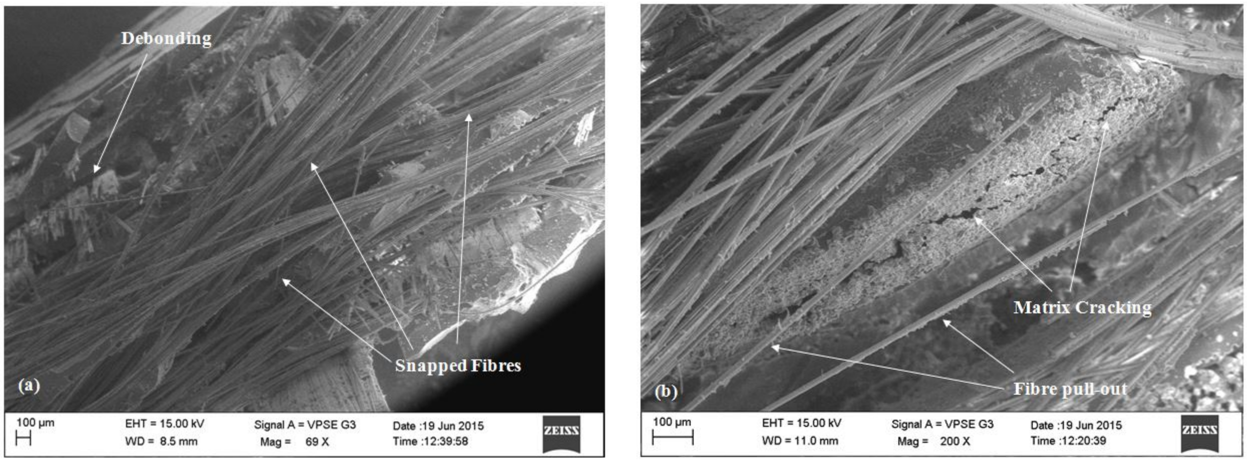

FIGURE 5. SEM image of a) PW composite tensile specimen b) PW composite flexural specimen.

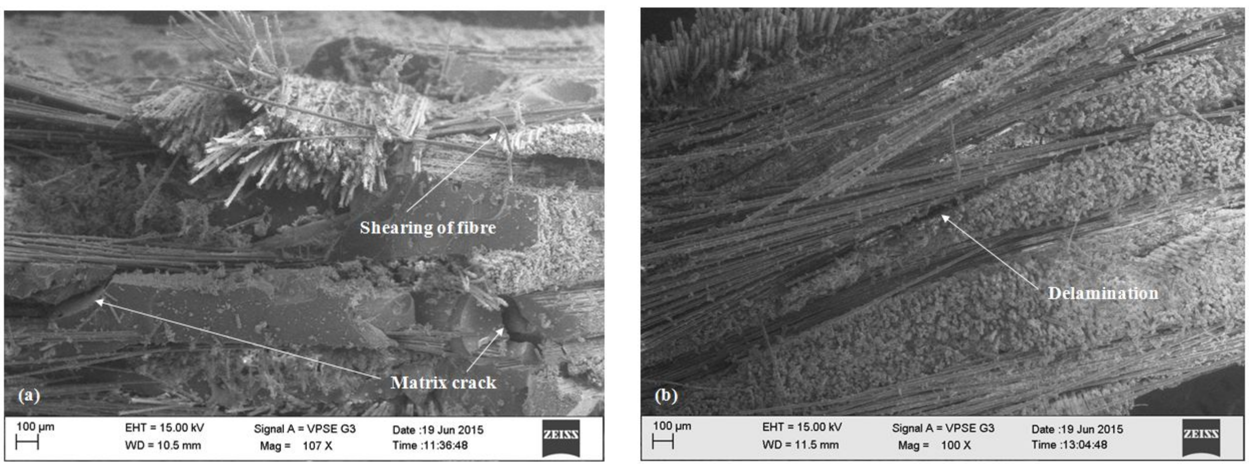

FIGURE 6. SEM image of a) PW composite impact specimen b) PW composite ILSS specimen.

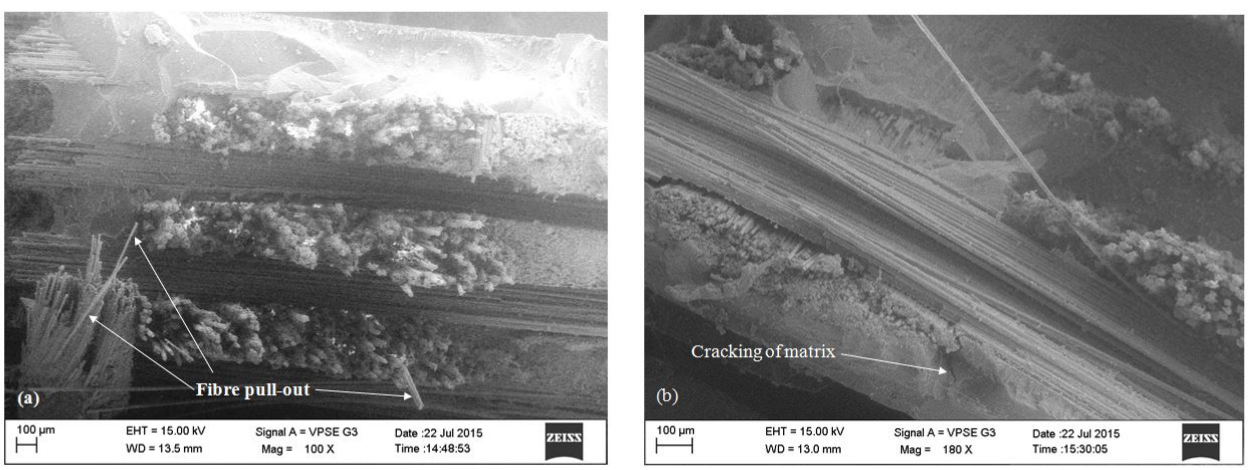

FIGURE 7. SEM image of a) 3D composite tensile specimen b) 3D composite flexural specimen.

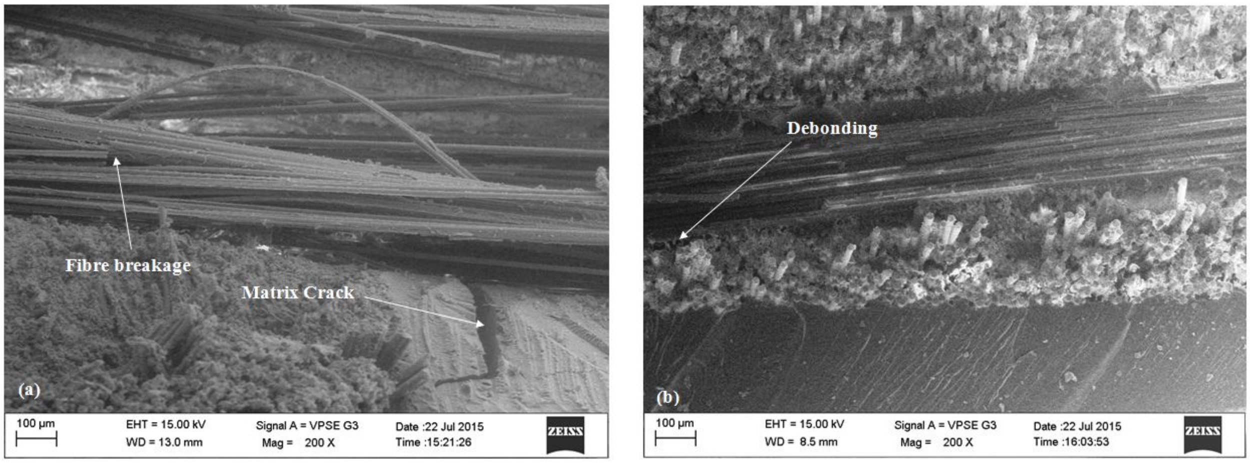

FIGURE 8. SEM image of a) 3D composite impact specimen b) 3D composite ILSS specimen.

Morphology of Fractured Surfaces

Figures 5 to 8 are micrographs of the fractured surface. Since composites fabricated with 55% fiber weight fraction gave the best results, the fractured surfaces of such specimens were selected for morphology study. *Figure 5a* shows the micrograph of the fractured surface of PW composite subjected to tensile loading. Significant lateral movement along with snapping of fibers can be seen. This is an indication of improper wetting of the fibers. Similar snapping with lateral movement can be observed in the flexural test specimen *(Figure 5b)*. In addition, fiber pull-out is evident. Matrix cracking is clearly visible and it propagates between two plies of plain weave fabric.

The micrograph of the impact test specimen of the PW composite is presented in *Figure 6a*. It is known that impact loading of notched a specimen results in initiation of cracks from the notch and propagation of the cracks through the specimen until it fractures. Resistance to propagation of the crack is indicated by the amount of energy absorbed by the specimen. Cracking of the matrix due to impact loading is evident. It propagates along the width of the specimen originating on the side of the notch. Shearing of fibers is also observed. Delamination at the mid plane which is typical in ILSS tests can be observed in *Figure 6b*. Matrix skin can be observed on the surface of fiber yarns. This is a sign of good interfacial adhesion between the matrix and the fiber.

Relatively less fiber pull out can be seen from micrographs of tensile test specimen of the 3D composite *(Figure 7a)*. Fiber yarns little disturbed and are also well stacked. Matrix skin can be seen on the fibers. From the micrograph of the flexural test specimen of the 3D composite *(Figure 7b)*, one can observe initiation and propagation of the crack from the bottom surface and through the fabric. The growth of the crack is not perpendicular to the thickness of the specimen which explains the improved flexural strength of the 3D composites. *Figure 8a* shows fiber breakage, which may be due to the growth of the crack through the ply when subjected to impact loading. Cracking of the matrix can also be observed. The ILSS test specimen micrograph *(Figure 8b)* shows minor debonding between the warp and weft layers of the 3D fabric.

CONCLUSION

An increase in mechanical properties was observed with increase in fiber weight fraction for both the types of composites. Significant improvement in properties was noted when the fiber content was increased from 40 to 45%. Composites fabricated with 55% fiber weight fraction showed the best results when compared to others. The 3D composites showed better mechanical properties than the PW composites. Reduced in-plane stiffness, lower pre-stressing of fiber yarns and increased resistance to propagation of cracks of 3D fabrics are the main reasons for improved the mechanical properties. Fiber pull out, snapping of fibers along with lateral movement, matrix cracking, delamination and shearing of fibers were the failure mechanisms observed by SEM analysis.

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