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Mechanical Properties and Failure Mechanism of the Polymer Composite with 3-Dimensionally Stitched Woven Fabric

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Abstract: The mechanical properties and failure mechanisms of through-the-thickness stitched plain weave glass fabric/polyurethane foam/epoxy composites were studied. Hybrid composites were fabricated using resin infusion process (RIP). Stitched sandwich composite increased drastically the flexural properties as compared with the unstitched fabrics. The breaking of stitching yarns was observed during the flexural test and this failure mode yielded relatively high flexural properties. Composites with stitched sandwich structure improved the mechanical properties with increasing the number of stitching yarns. From this study, it was concluded that proper combination of stitching density and types of stitching fiber is important factor for through-the-thickness stitched composite panels.

Keywords: polymer composite, mechanical property, failure mechanism, stitching, woven fabric, sandwich structure.

Introduction

The delamination behavior of sandwich composites have restricted their applications in many lightweight structures for supporting out-of-plane loads.[1,2] Therefore, forming technology such as weaving, stitching, braiding, knitting has been employed to fabricate advanced composites with higher mechanical properties.[3-5] Traditional laminated sandwich structures generally exhibit poor interlaminar fracture toughness and thus are susceptible to delamination when subjected to interlaminar stress.[6] One of the objectives for using stitching fiber is to enhance interlaminar strength and stiffness in thickness direction. Stitching, however, requires at least one additional step where the fibers are introduced to the through-the-thickness direction of composites after the lay-up of the laminate and the sewing process follows. This step causes in-plane damage of lamination. This damage can decrease the in-plain mechanical properties, including tensile and compressive strength. It has been studied that stitching can improve or seriously degrade or leave unchanged the in-plane properties, depending upon the type of composite, the stitching method, and the loading condition.[7,8]

The resin infusion process (RIP) was originally developed for modifying the autoclave process using a vacuum bag/tooling combination for shaping parts. Due to a quite low viscosity of thermosets at elevated temperature before curing, resin infusion into a dry fibrous preform becomes an attractive manufacturing technique especially for 3-D composite structures. In addition, RIP is easily adaptable to the fabrication of honeycomb sandwich structures with various types of core materials and stitching fibers.[9-11] The resin flows in the stitched structure composed of woven fabric skins, urethane foam core and transversely stitched glass bundles.[10]

In this study, the stitched composites with hybrid sandwich structure were manufactured by using RIP on the basis of previous modeling.[10] The objective of this research was to study the relationship between the preform structure, mechanical properties, and the failure modes for various stitching method. Significant attention was focused on the bending response of the PU foam inserted in the sandwich composites.

Experimental

Materials. As a matrix, DGEBA (diglycidyl ether of bisphenol A) epoxy resin was used in the form of film. The formulation of the resin system was same amounts of liquid YD-128 and solid YD-011 epoxy resin (both from Kuk Do Chem. Co.). As a curing agent, 10 phr of dicyandiamide (DICY) were mixed for the resin system. As a reinforcement, WR580A (Hankook Fiber Co.) which is E-glass woven fabric with 6.3×6.3 tow/inch of woven density was used. A mixed fiber yarn, G55 (Hankook Fiber Co.) containing 45 wt% polyester yarn and 55 wt% E-glass fiber was used as a stitching fiber which connected the plain weave fabric layers and polyurethane (PU) foam in the thickness direction.

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Table I. The Basic Properties of Matrix Resin

	Resin System		
	YD-128	YD-011	DICY
E.E.W.(g/eq)	185~192	450~500	21
Viscosity at 25 °C (Pa.s)	12.5	solid	solid
Specific Gravity at 20 °C	1.16	1.18	-
Melting Temp. (°C)	-	60	202
	resin system		

Table II. The Basic Properties of Glass Woven Fabric and Stitching Fiber

	WR580A	G55
Product Type	Roving Cloth (plain)	Yarn (stitching)
Filament Diameter (μm)	22	11
Roving Tex (g/km)	1150	92.
Cloth Density (tow/inch)	6.3 × 6.3	-
Surface Density (g/m²)	580	-

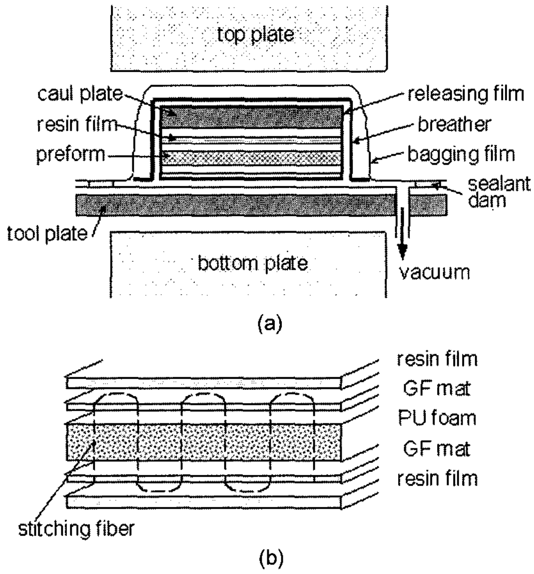

Figure 1. The scheme of composite manufacturing by resin infusion process. (a) autoclave modified RIP and (b) stitched hybrid composite.

One layer of PU foam with closed pore structure was inserted in the sandwich structure and they were stitched by stitching yarns. The properties of materials used in this work are listed in Table I and II.

Sample Preparation. The following procedures for the preparation of sandwich panel were used in this study. Three layers of plain weave fabrics were placed at upper and lower layer, PU foam was inserted in middle of the woven fabrics. Specially, PU foam was sandwiched with glass woven fabrics and this sandwich structure was stitched with yarn in order to bind together. The PU foam used in this work has closed-cell structure, which protects the resin to impregnate into the foam inside. Therefore, stitching fibers could induce resin flow through the stitching hole and improve mechanical properties. The resin films with various thickness were placed in upper and lower layer of the preform. An autoclave modified RIP as shown in Figure 1(a) was used for manufacturing the specimens. The lay-up procedure was similar to a conventional autoclave process, except that a resin layer and a fibrous preform were placed separately instead of using prepreg layers. The preform was placed in the vacuum bag molding. Impregnation time and cure cycle were determined in the previous study.[10] The mold was heated to 115 °C and the preform was simultaneously impregnated with epoxy resin. The specimen was cured at 115 °C for 2 hrs. Vacuum in the autoclave modified RIP was used at the initial stage in order to reduce the void. Dimension of the final specimen was 150 mm× 150 mm× 30 mm.

The 3-D sandwich panels composed of glass fabric, stitching fiber and PU foam, as shown in Figure 1(b), were prepared. Specially, PU foam was sandwiched with glass woven fabrics and this sandwich structure was stitched with yarn in order to bind together. To investigate the effect of stitching density, two strands of the stitching yarns were used and the distance between the stitching holes was 10, 20 and 30 mm. The number of stitching holes was used by 0, 16 (4×4, 30 mm spaces), 49 (7×7, 20 mm spaces), 196 (14×4, 10 mm spaces) in each specimens area (150 mm× 150 mm). To investigate the effect of stitching yarns, the stitching density with 16 (4×4, 30 mm spaces) was used and the stitching yarns with 0, 2, 4, 8 strands were used. Finally, by comparing the stitching methods, it is intended to reveal the design rules in manufacturing of 3-D sandwich panels.

Mechanical Test. The stitched and unstitched sandwich panels were used for flexural test. The flexural test was performed according to the ASTM D 790-91 as a three-point flexural test, and ASTM D 6272 as a four-point flexural test. The three-point and four-point loading schemes were selected, and the test was performed using Instron 4201 universal testing machine. The sample dimensions were 150 mm× 70 mm× 30 mm, and the span length was 100 mm at a three-point bending test and 120 mm at a four-point bending test.

Results and Discussion

Effect of Stitching Density. Sandwich structured composites were prepared by RIP. PU foam with 3 cm of thickness was inserted between the layer of glass woven fabric. They were stitched through the thickness direction. Two strings of stitching fiber bundle were used. Sufficient impregnation was carried out at low viscosity range, and it was pressurized to get

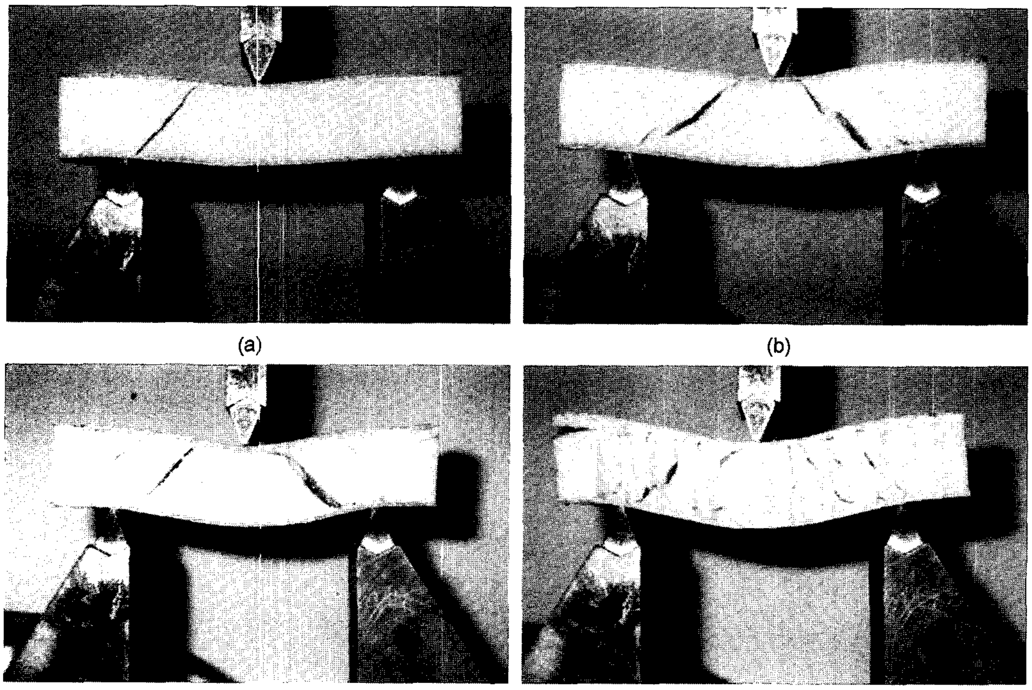

Figure 2. The photographs of three-point bending failure. (a) unstitched panel, (b) stitching distance 3 cm apart, (c) stitching distance 2 cm apart, and (d) stitching distance 1 cm apart laminated composite.

void-free products. From the process proposed by previous study,[10] the processing variables such as applied pressure and temperature were controlled in manufacturing the stitched sandwich structure. This sandwich form can be used in building structure such as container wall parts, whose properties should be light and stiff.

Initially we tried to determine the effect of stitching density using the bending test. In this study, stitching density was defined as a ratio of number of stitching hole to unit area. The testing specimens and propagation of cracks or delaminations are shown in Figure 2. Split in the PU foams of the composite took place during the testing of three-point bending specimens. Cracks and delaminations occurred more especially for the stitched specimens. However, these fractures were introduced at a final stage of the test which the higher load was applied than the case of unstitched specimen. In general, stitching adversely affect the bending behavior, and higher stitching density lowers the bending strength.[7,8] However, in this study, flexural strength increases with stitching density. It is explained that dense stitching systems exhibit "bridge" effect for the sandwich structure with brittle core of PU foam. A close observation of the composite failure showed that there was some visible damage on the foam area. As loading is increased, the crack is initially developed in the middle foam-plain of the specimens. Three-point bending load versus displacement curves for the unstitched and stitched samples were showed in Figure 3. As shown in

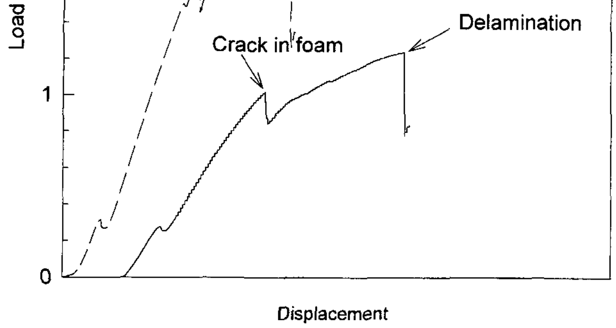

Figure 3. Load-deflection curves for stitched and unstitched sandwich panel in three-point bending test.

figure, initial cracks take place in foam area then stitching yarn fracture follows and finally interface of woven fabric and PU foam is delaminated as increasing of loading. Figures 4 and 5 show the three-point and four-point bending properties of sandwich composite panels. The flexural strength and modulus are increased as the stitching density is increased. Increasing ratio of bending strength is very high at lower stitching density then that decreases with the increasing of stitching density. It is explained that the stitching hole acts as defect for composites with higher stitching density during the testing of specimens. It was concluded that stitching increases bending properties and dense stitching is more complicated in the aspect of fracture.

Most studies report that stitching degrades the flexural properties, with the magnitude of the reduction being influenced by the type and thickness of the composite as well as by the type, yarn size, number, density and orientation of stitching.[12-15] The degradation of the flexural properties has been attributed to fiber damage suffered during the stitching process, such as fiber breakage and misalignment, together with stress concentration effects at the stitches.[12,13] However, in this study, it was observed that delaminations formed in the unstitched panel at a lower flexural stress than in the stitched panel. These delaminations are due to the weakness of PU foam which is inserted in middle position of the composite panel. As a result, the flexural strength and modulus in three-point bending test was increased by about 50% to 150% due to stitching depending on stitch density. The different flexural properties of the composites with various stitching density can be reflected in the failure mode. Figure 6 shows the predicted fracture modes (initiation and propaga-

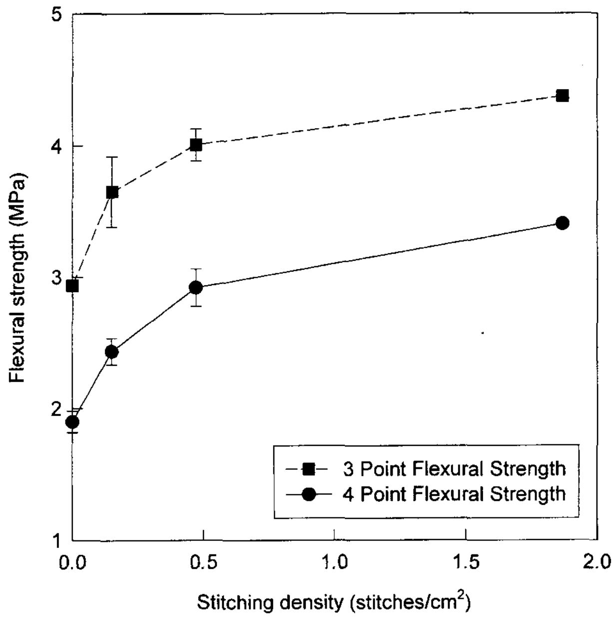

Figure 4. The effect of stitching density on the three-point and four-point flexural strength of sandwich composite panels.

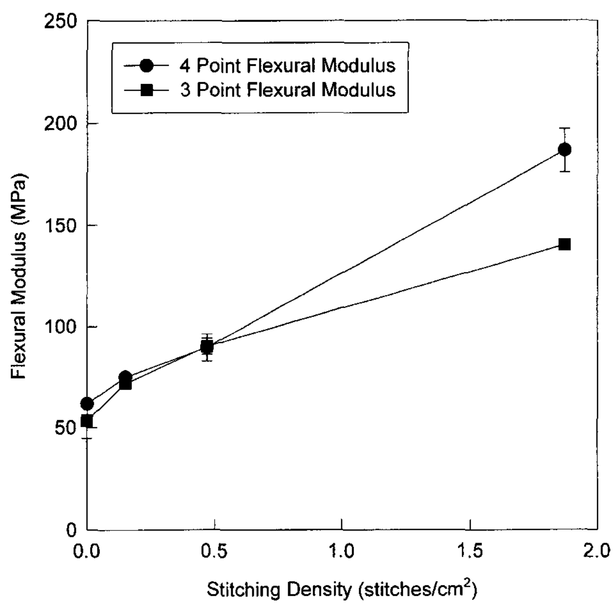

Figure 5. The effect of stitching density on the three-point and four-point flexural modulus of sandwich composite panels.

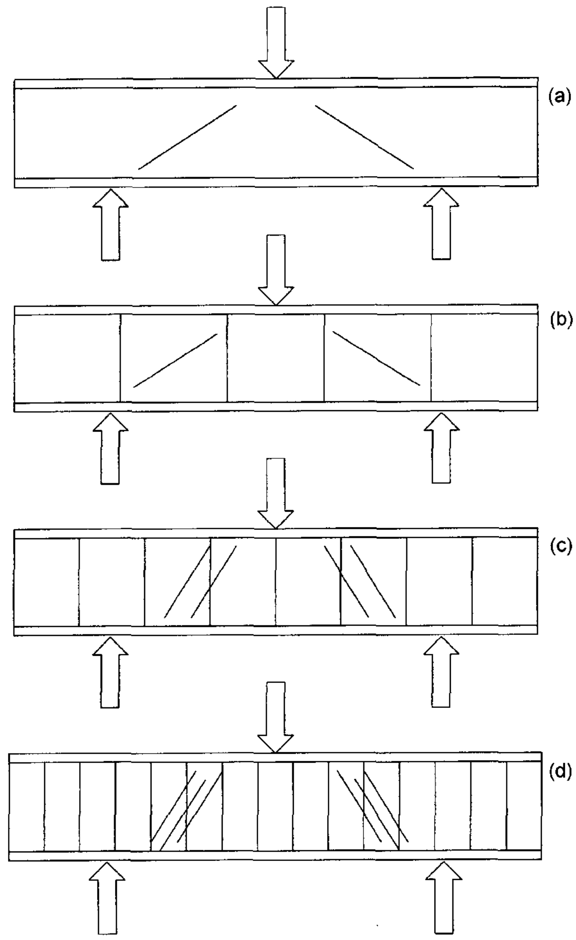

Figure 6. The schemes of the predicted failure modes in three-point bending test. (a) unstitched panel, (b) stitching distance 3 cm apart, (c) stitching distance 2 cm apart, and (d) stitching distance 1 cm apart laminated composite.

tion of cracks and delamination) of the three-point bending test according to the stitching density. Post-failure examination showed that crack propagation was at 45° angle and broad band to the loading direction at unstitched panel. However, the composites with dense stitching appeared to have different failure mode. As the stitching density is increased, failure band shows more shorten and steep behavior, then localized failure of stitching yarn can be seen in the crack propagation. The breaking of stitching yarn yielded relatively higher flexural strength.

Effect of Stitching Yarns. A gradual improvement was shown in the three-point flexural strength and modulus of the stitched sandwich panels with increasing number of stitching yarn, as shown in Figure 7. The tensile property of a stitching yarn is important for improving the flexural properties. In order to provide improvement in stiffness of a sandwich composite, the stitching yarn must also possess high tensile strength and stiffness. Therefore, increasing number of yarns represented the increased stiffness of the composites.

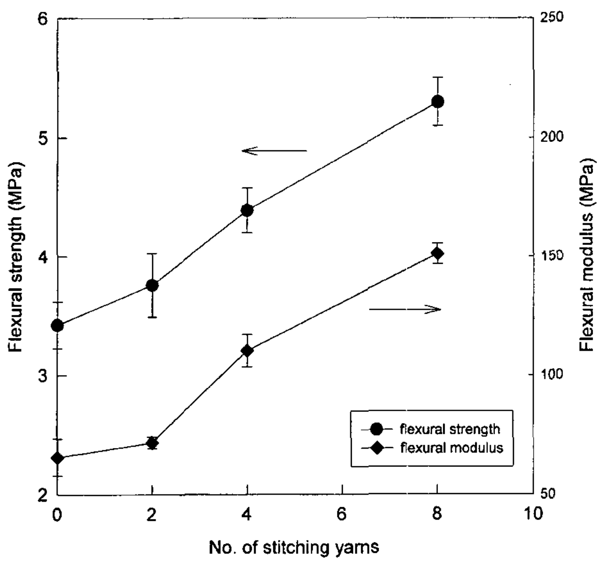

Figure 7. The effect of the number of stitching yarns on the flexural properties of sandwich composite panels.

Effect of Stitching Methods. The damage caused by stitching appears to be controlled to some extent by the type of stitch. By comparing the stitching methods, it is intended to propose the design rules in manufacturing process. Figure 8 illustrates the five types of stitching method. The stitching causes a local damage near the stitching position. This damage includes fiber breakage at the stitching hole and the fracture of resin/foam interface at the circumstance of stitching hole. Another problem resulting from stitching is the formation of the hole made by a needle. Stitching holes were filled with resin during impregnation, resulting in the formation of resin-rich regions. Three-point bending strength and modulus with the various stitching methods are shown in Figure 9. Significant differences of strength and modulus were not observed in the test. An interesting result is that increasing the stability of stitching are independent in the stiffness of composite with foam material. This independence in strength may result from the weakness of foam structure.

This sandwich form can be used in building structure such as container wall parts, whose properties should be light and stiff. Specially this sandwich composites are very light due to the PU foam. Conclusively, enhanced mechanical properties can be achieved by using this sandwich structure with stitching in 3-D sandwich composites. In addition, stitched sandwich structure may be substituted with honeycomb

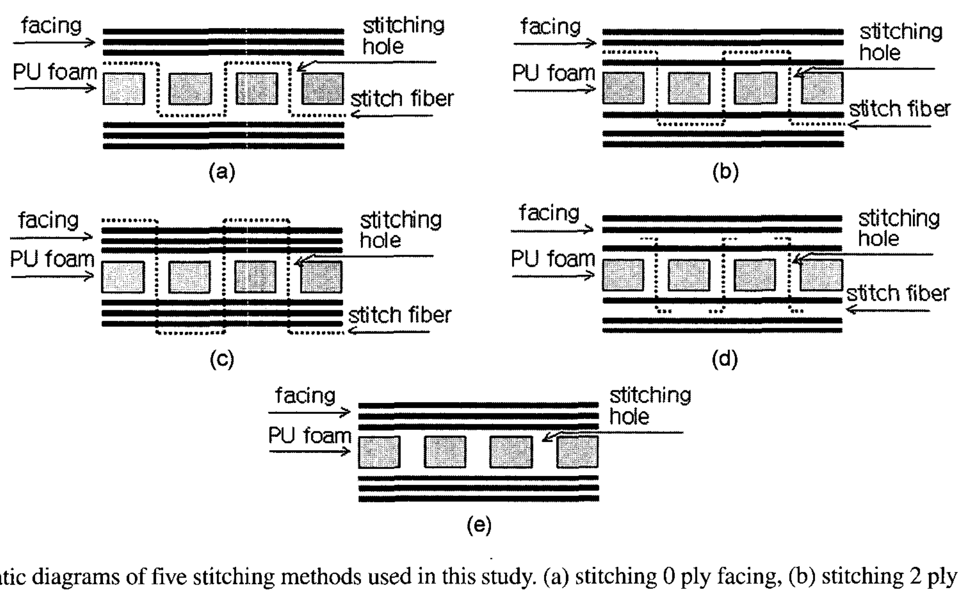

Figure 8. Schematic diagrams of five stitching methods used in this study. (a) stitching 0 ply facing, (b) stitching 2 ply facing, (c) stitching 6 ply facing, (d) cutting after stitching, and (e) only stitching hole without stitching yarn.

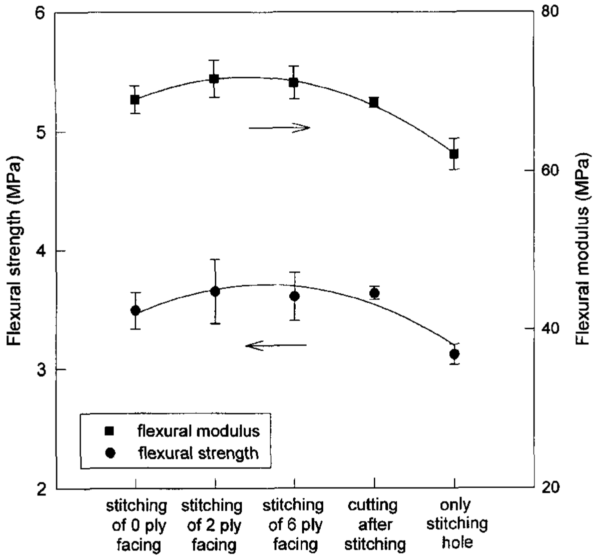

Figure 9. The effect of the stitching method on the flexural properties of sandwich composite panels.

structure.

Conclusions

Three-dimensional sandwich structured composites with plain weave glass fabric/polyurethane foam/epoxy resin were prepared by RIP. The preforms were stitched through the thickness direction using stitching yarns. The mechanical properties and failure mechanisms of stitched composites were studied for the various stitching density, stitching yarns and stitching methods. Stitched sandwich composites drastically increased the flexural properties as compared with unstitched composites. As the stitching density was increased, localized failure of stitching yarn could be seen in the crack propagation and this failure of stitching yarns yielded relatively high flexural strength. Composites with stitched sandwich structure improved the mechanical properties with increasing the number of stitching yarns. From this study it was concluded that proper combination of stitching density and types of stitching fiber are important factors for improving the mechanical properties of the through-the-thickness stitched composite panels. This stitched sandwich form can be used in building structure such as container wall parts, and so on. Conclusively, it is found that the required mechanical properties can be achieved by using stitching method in lightweight engineering sandwich structures.

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