

FINAL REPORT

Cover Page

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Design and Manufacture of Stitch Bonded Textile Composites

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ACTIVITIES

We have conducted research in design, fabrication, testing and analysis of stitch bonded laminar composites. We produced three dimensional (3D) composites by machine stitching to improve properties in through-the-thickness direction. The specific objectives were to improve interlaminar shear strength and increase fracture toughness. The effects of through-the-thickness yarn distribution and density on the mechanical properties of composites were examined. Damage resistance, flexural and shear strength were investigated as a function of distribution of the third direction yarns. Properly stitched 3D composites were found to reduce the degree of delamination and to increase shear strength and impact energy.

The research included hybrid composite development to obtain better material properties. Hybrid composites are susceptible to accidental low energy impacts from hazards such as tools dropping during maintenance, transportation debris and hailstones. These impacts can cause significant strength reduction and localized damage which is potentially a source of mechanical weakness especially for graphite composites. For this purpose, several hybrid orders with three different ply angles were used.

Dr. Adanur visited the Egyptian counterpart Dr. Samy E. Shalaby at the National Research Center in Cairo, Egypt in February 2000.

Dr. Samy E. Shalaby of the National Research Center in Cairo visited Auburn University in September 2000.

Dr. Mohamed Abdalla Saad of the National Research Center in Cairo visited Auburn University in February 2002.

Materials Used

We used glass fiber woven fabrics to make textile reinforcement structures. Kevlar® aramid yarns were used as stitch yarns to bind numerous fabric layers together to produce 3D composite preforms.

E-glass fiber was used in plain weave from PPG industries. AS4 carbon plain fabric was supplied from Hexcel Corporation with an areal density of 1925 g/m². The stitching process provides through-the-thickness strength and integrity. Stitched yarn for through the thickness application was Kevlar® 49 aramid from E.I. Dupont de Nemours. Matrix for the composite production was Shell EPON 828 multi purpose epoxy type resin. EPICURE 3140 from Shell Chemicals was used as hardener. In order to reduce the amount of air bubbles, and therefore to decrease the void content inside the composites, BDK555 air release agent was added to the matrix. Physical properties of fibers are given in Table 1.

Table 1. Physical properties of fibers

Fiber	Density (g/cm ³)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Strain at failure (%)
Carbon (AS4)	1.78	4000	235	1.6
E-glass	2.58	3331	72.5	4.59
Kevlar49	1.44	3620	124	2.9

First, 0.2 m by 0.2 m fabric specimens were cut from the glass woven roving. Depending on the resulting composite thickness, certain number of specimen layers were stacked until the desired thickness was obtained. Kevlar® aramid yarns were introduced as the third direction fibers through the fabric layers in stack using an industrial stitching machine (Durkopp Adler Model 205-370). The sewing needle size was 200 with a round tip which was chosen to minimize the fiber damage during stitching. The stitch yarn tension was kept constant for all the samples at 175 grams. A stitch length of 7 mm was chosen. The interlock type of stitch was used to bind the plies together.

All of the samples were prepared with the same volume fraction ratio (V_f) of 0.41 ± 0.02 . Volume fraction ratio was calculated both theoretically and experimentally. Theoretical V_f

calculation was done using the rule of mixture. Experimental procedure was done by the application of ASTM standard of D 2584-68. Approximately 5 g specimens with the size of 2.5 x 2.5 cm are cut from the composite plate. These pieces are initially burnt at higher temperatures until only ash and carbon remain in the porcelain crucible. After measuring these traces, the residue is heated again until all carbonaceous material has disappeared. The remaining is cooled to room temperature and is measured. The ignition loss, which is considered as resin content, is calculated with the following equation.

$$\text{Ignition loss, weight \%} = [(W_1 - W_2) / W_1] \times 100 \quad (1)$$

where, W_1 is weight of specimen (g) and W_2 is weight of residue (g).

The number of plies was varied from four to seven. Specimens were produced in terms of five different ply sequence and three different angle order. Hybrid sequence of plies and angle order are given in Table 2 where G denotes glass fabric and C denotes carbon fabric.

Table 2. Hybrid sequence of plies and in-plane angle order.

Sample ID	Ply Order
a	G ₄₅ G ₉₀ G ₄₅ G ₉₀ *
	G ₊₇₅ G ₉₀ G ₋₇₅ G ₉₀
	G ₉₀ G ₉₀ G ₉₀ G ₉₀
b	C ₄₅ C ₉₀ G ₄₅ C ₉₀ G ₄₅ C ₉₀ C ₄₅
	C ₊₇₅ C ₉₀ G ₋₇₅ C ₉₀ G ₊₇₅ C ₉₀ C ₋₇₅
	C ₉₀ C ₉₀ G ₉₀ C ₉₀ G ₉₀ C ₉₀ C ₉₀
c	C ₄₅ G ₉₀ C ₄₅ C ₉₀ C ₄₅ G ₉₀ C ₄₅
	C ₊₇₅ G ₉₀ C ₋₇₅ C ₉₀ C ₊₇₅ G ₉₀ C ₋₇₅
	C ₉₀ G ₉₀ C ₉₀ C ₉₀ C ₉₀ G ₉₀ C ₉₀
d	G ₄₅ C ₉₀ C ₄₅ C ₉₀ C ₄₅ C ₉₀ G ₄₅
	G ₊₇₅ C ₉₀ C ₋₇₅ C ₉₀ C ₊₇₅ C ₉₀ G ₋₇₅
	G ₉₀ C ₉₀ C ₉₀ C ₉₀ C _{90v} C ₉₀ G ₉₀
e	G ₄₅ C ₉₀ G ₄₅ C ₉₀ G ₄₅
	G ₊₇₅ C ₉₀ G ₋₇₅ C ₉₀ G ₊₇₅
	G ₉₀ C ₉₀ G ₉₀ C ₉₀ G ₉₀

* Subscripts denote ply angle to the composite axis. (+) gives right slope and (-) gives left slope with composite axis.

After laminates were placed in correct order, they were stitched at both longitudinal and transverse directions using an industrial stitching machine with a modified lock stitch with Kevlar® 49 aramid thread at a stitched distance of 1cm.

According to our former studies on production parameters of hybrid composites, 77/33 (epoxy/hardener) combination was adopted. Air releaser was added as %1 of matrix weight. Delamination caused by lack of matrix impregnation was reduced by heating the laminates at 85°C in an oven for ten minutes. For the same purpose, matrix was subjected to microwave energy for better ingredient mixing and better air release. The resin was exposed to microwave energy at 300 W for 50 seconds. Finally, matrix was poured on heated preform. Fifteen minutes was enough for air release.

Stitched composites were fabricated in compression molding machine. Our earlier study led us to fabricate under 85° C heat, 116 MPa clamp pressure and 70 minutes exposure time for better mechanical properties. Void content of the composites was calculated according to the ASTM standard of D2734-91. The following equations were employed.

$$T = 100/(R/D + r/d) \quad (2)$$

where T is theoretical density; R is resin in composite as weight percentage; D is density of resin; r is reinforcement in composite as weight percentage; d is density of reinforcement. Therefore, void content can be calculated with the formula below:

$$V = 100(T_d - M_d)/T_d \quad (3)$$

where M_d is the measured composite density. It could be found either from the ASTM standards or from the manufacturer data.

After consolidation, composite samples were cut to the dimensions suggested by the ASTM standards.

Both 2D and 3D preforms were prepared. The difference between 2D and 3D samples was the inclusion of through-the-thickness yarns in 3D preforms. Apart from this fact, 2D and 3D samples had the same thickness.

Polyester and aramid fibers were used in the form of stitchbonded nonwoven fabrics. Specific properties of each fabric are given in Table 3. Several layers of nonwoven plies were stitched with Kevlar® 49 aramid yarn using the Durkopp Adler industrial stitching machine.

Table 3. Properties of nonwoven fabric samples

Code	Material	No. of Layers	Weight g/m ²	Thickness (under 20kN/m ²) mm
1	Polyester	Two	659	3.228
2	Polyester	Three	1031	4.340
3	Polyester	Four	1430	6.398
4	Polyester	Five	1564	6.585
5	Kevlar®/ Polyester	Two	811	5.082
6	Kevlar®	One	713	5.748
7	Nomex®	Three	920	5.720

TESTING

Three mechanical tests, flexural test, short beam shear test and impact test were performed. The flexural test was conducted according to ASTM D790-81, Method I which is the three point loading system utilizing center loading on a simply supported beam. The Instron cross head speed was 0.00127 m/min. Short beam tests were performed according to ASTM D2344-84 shear test method. The span-to-depth ratio was between 16:1 and 19:1 for flexural tests and 5:1 for shear and impact tests. ASTM D3029-84 test method was used for instrumented drop weight impact testing using Dynatup Model 8250.

Test specimens were conditioned in the standard laboratory conditions for 40 hours prior to testing. Five tests were done on each specimen and the average was calculated.

Flexural Tests

Flexural properties of the composites were measured using the three-point bending method using Instron 4505 Universal Testing Machine. Specimen thickness is the major criteria to determine the sample dimension. Based on sample thickness, the load-span length, which is the distance between two beam support, is selected from the table in ASTM standard D790. Rectangular specimens are cut from the composite plate with

proper dimensions. It is important that fabric surface be flat and notchless to keep stress concentrations low. Cross-head speed is selected from the same table as well.

Five samples were tested and their average is reported with standard deviation and coefficient of variation (CV). Maximum tensile stress and strain, tensile modulus of elasticity and toughness are reported. 0.2% yield stress, breaking stress and strain can be added as well for the sake of clarity

It is possible to calculate the needed data from the equations given in the ASTM standards. The maximum tensile stress, σ_{\max} , for a three point bending is determined from the following equation:

$$\sigma_{\max} = \frac{3PL}{2bh^2} \quad (4)$$

where σ_{\max} = bending stress (MPa), P = load (N), L = loading span (mm), b = beam width (mm) and h = beam thickness (mm). The maximum strain (ϵ) in the outer fibers occurs at midspan and is calculated as follows:

$$\epsilon = \frac{6Dd}{L^2} \quad (5)$$

where ϵ = maximum strain, D = maximum deflection of the center of the beam (mm), L = loading span (mm) and d = beam thickness (mm). The tangent modulus of elasticity within the elastic limit is calculated as follows:

$$E = \frac{L^3 m}{4bd} \quad (6)$$

where E = modulus of elasticity in bending (MPa), L = loading span (mm), b = width of beam (mm), d = beam thickness (mm), m = slope of the tangent to the initial straight line portion of the load deflection curve (N/mm).

Shear Tests

Short-beam shear test was performed according to the ASTM D2344. This test method determines the apparent interlaminar shear strength of reinforced plastics. The same set up for flexural test and software is utilized in shear test as well. Five samples were tested on Instron 4505 Universal Testing Machine with a crosshead speed of 1.3 mm/min. The maximum shear strength (τ) in the mid plane of composites was estimated by using the Euler-Bernoulli beam theory equation:

$$\tau = \frac{3P}{4bd} \quad (7)$$

FINDINGS

The impact resistance of a material is determined by the amount of absorbed energy inside material prior to contact of impactor. High correlation of determination (R^2) showed that total energy absorption of composite decreased as glass percentage increased (Figure 1).

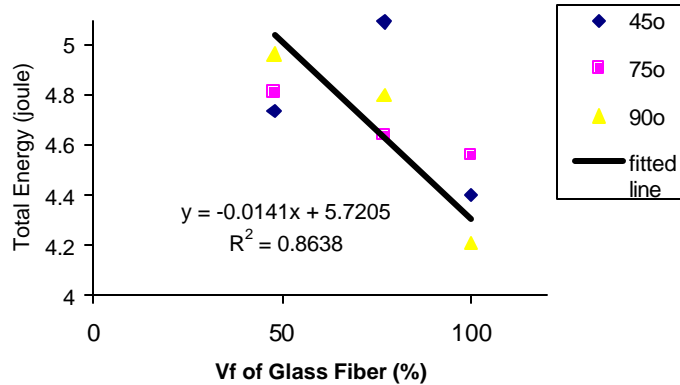


Figure 1. Effect of fiber content on total energy.

The breakage during tensile tests started after debonding and followed by delamination. The variation of tensile strength for the same fiber volume fraction (order b, c, d) may be attributed to the location of delamination and debonding inside the composite. Central placement of glass plies may split the carbon interaction and may increase the amount of debonding and delamination so that tensile strength declined with the rate of splitting. That is why, as the glass ply came closer to specimen surface, tensile strength improved (Figure 2).

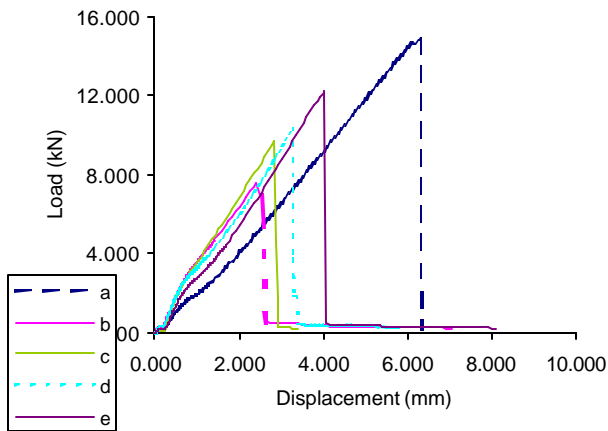


Figure 2. Tensile load versus displacement.

Hybridization seemed to be ineffective for undamaged specimens, whereas high glass content resulted in better shear strength to damaged laminates. Higher tow count and tow diameter in glass plies compared to carbon plies may improve the interlaminar properties, because more matrix can be located between layers and this increases the interactions within the plies. In general 90° plied samples had slightly higher shear strength than the other angles (Figure 3).

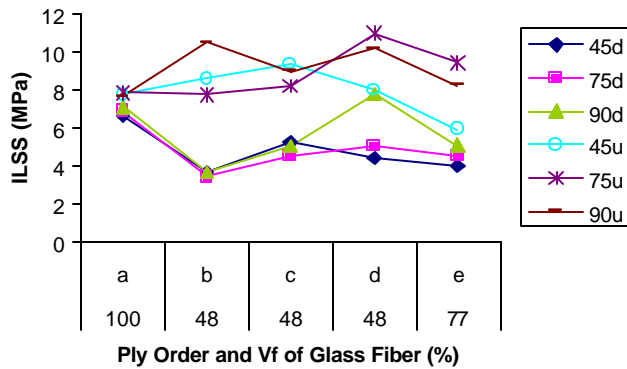


Figure 3. Shear strength versus ply order and V_f of glass fiber. “d” represents damaged strength and “u” represents undamaged strength.

Carbon fibers have higher modulus and strength but lower strain to fracture ratio, while glass fibers have moderate strength, and relatively higher strain. However, it was observed that the strength of damaged samples reinforced with carbon plies exhibited

lower endurance. Within the same carbon volume fraction, as glass plies came closer to composite surface flexural resistance increased for both damaged and undamaged specimens. The result was attributed to better energy absorption capability of glass fiber (Figure 4). As a general perspective, higher glass fiber content resulted in better flexural strength and energy absorption.

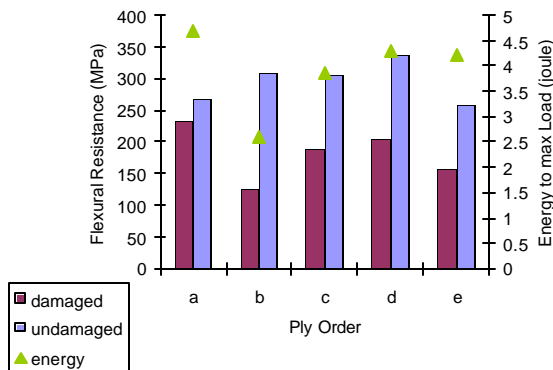


Figure 4. The effect of ply order on flexural resistance and energy to max load after and before impact testing

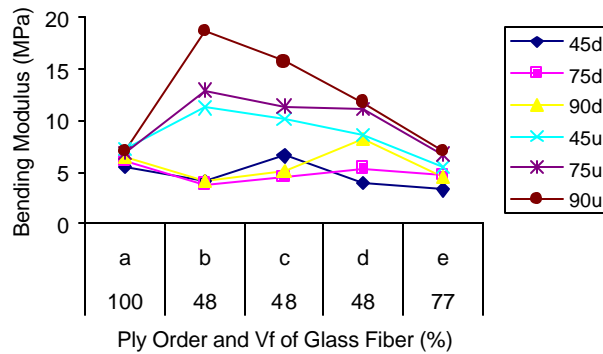


Figure 5. The effect of ply angle on bending modulus vs ply order and glass volume fraction

As the ply axis got closer to composite axis, the bending modulus became higher for carbon dominant undamaged hybrid structures (Figure 5). Fiber distribution inside the composite structure was thought to be effective. While the ply axis and composite axis

were closer or exactly the same, the bending modulus of the damaged samples seemed to decrease.

The shear test results for nonwoven composite samples are given in the following table.

Nonwoven composite test results

Code	Displacement	Strain	Load	Stress	Modulus	Shear
	mm	%	kN	kN	Mpa	Mpa
1A	6.417	2.464	0.2051	57.78	2955	1.84
1B	9.04	3.471	0.2257	63.58	2722	2.03
1C	7.549	2.899	0.1798	50.65	2776	1.62
1D	7.329	2.815	0.2502	70.48	2611	2.25
1E	7.004	2.689	0.1607	45.27	2820	1.44
2A	6.395	2.456	0.2293	64.59	2797	2.06
2B	7.594	2.916	0.1891	53.27	2573	1.7
2C	7.495	2.878	0.2117	59.64	2652	1.9
2D	6.481	2.489	0.2175	61.27	2755	1.96
2E	9.534	3.661	0.213	60	2209	1.92
3A	10.09	3.873	0.1902	53.58	2457	1.71
3B	9.33	3.584	0.2023	56.99	2442	1.82
3C	9.49	3.646	0.1865	52.54	2376	1.68
3D	9.58	3.678	0.2003	56.42	2424	1.8
4A	15.88	6.098	0.1539	43.35	1507	1.38
4B	13.04	5.008	0.1886	53.13	1878	1.7
4C	12.58	4.83	0.1855	52.26	1837	1.67
4D	11.75	4.514	0.1751	49.33	1753	1.57
5A	9.302	3.572	0.1997	56.26	1806	1.8
5B	12.62	4.847	0.2534	71.38	1973	2.28
5C	11.43	4.387	0.2318	65.3	2003	2.09
5D	12.7	4.877	0.269	75.78	2055	2.42
5E	9.527	3.658	0.2028	57.13	2040	1.82
6A	14.78	5.674	0.572	44.28	1130	1.41
6B	15.77	6.056	0.1211	34.11	817	1.09
6C	13.88	5.331	0.1544	43.49	1147	1.39
6D	19.09	7.332	0.1263	35.58	733	1.13
7A	14.87	5.711	0.1354	38.14	939	1.22
7B	14.68	5.638	0.1197	33.72	825.1	1.07
7C	14.14	5.43	0.1403	39.52	947	1.26

Conclusions

Stitching can provide higher efficiency and productivity in multi-layer preform manufacturing compared to 3D weaving and braiding methods. The stitched preforms have the advantages of high density, control of yarn orientation and an integrated 3D structure made of various yarn and fabric layers. However, yarns can be damaged at the needle penetration points during stitching and strength and structural integrity of the composite may be reduced. Thus, it is of importance to properly control the stitching parameters in terms of stitch patterns and stitch density.

The stacking sequence was proved to be significant for all of the mechanical properties either individually or as an interaction with ply angle using ANOVA analysis. In particular, tensile behavior of sample had the strongest contribution from ply order for all samples. It played a significant role in determining the impact response. The location of glass fibers within the structure changed the material property in different ways. As glass ply was on the surface or came close to composite surface, tensile strength, bending toughness, impact energy absorption and flexural stress improved. However ductility index declined.

Volume fraction of glass fiber affected the material properties in different ways. Mechanical properties of composite were better under low velocity impact, as the percentage increased.

Apart from flexural strain, the contribution of ply angle of the composite material was related to stacking sequence. Besides, it donated the tensile failure mechanism of composite materials.

Tensile failure behavior of impacted reinforced plastics was thought to be affected by the interaction of reinforcement property, hybrid order and ply angle.

Even though materials were damaged with low velocity impact to approximate real life conditions, such small contacts led to significant strength reduction especially for carbon dominant samples.

PUBLICATIONS AND PRODUCTS

We have developed integrated, advanced fabric structures from laminar, single layer fabric structures with stitch bonding. Therefore, we obtained 3-D fabric structures with all the advantages of an advanced fabric system at a lower cost. This is because, stitching is less expensive than producing a 3D structure with special machines. The resulting stitch bonded fabric structures are suitable for flexible and rigid composites.

Publications and Presentations:

- Adanur, S., and Onal, L., “Experimental Analysis of Textile Composites”, Proceedings of the TechTextil North America Symposium, April 9-11, 2002, Atlanta, GA.

CONTRIBUTIONS

The cost factor has hindered the spread of composites into application areas and industries other than aerospace and defense. For this reason, limited information is available on their performance in areas other than aerospace and a few high-value sports and consumer applications. An important aspect of this research was to develop alternative low cost composite structures for applications in mechanical engineering, civil engineering, structural engineering and other areas such as automobiles and electronics. Great potential exists for the utilization of low cost composites in these areas as well as in aerospace applications.

The use of textile structural preforms in composites is increasing. Woven fabric composites provide more balanced properties in the fabric plane than unidirectional laminas. The bidirectional reinforcement in a single layer fabric provides excellent impact resistance. Fabric cost of 2-D preforms is relatively lower compared to fabrication of multi-directional preforms such as 3-D braided and 3-D woven constructions. The construction of the latter structures is still a tedious and expensive process.

An advantage of laminar composites is that if a flaw produces a failure in a layer, the failure will not propagate through the entire assemblage of structure. Traditional 2-D laminated structures, however, are known for weak interlaminar and thickness direction moduli and strength. Another purpose of this project was to eliminate or reduce this weakness by using thickness direction yarns to bond the layers together and add stiffness and strength in the third direction. These yarns reduce or eliminate interlaminar fracture and provide higher impact resistance and damage tolerance.

The findings of this research work will help the U.S. composite manufacturing companies to diversify into civilian applications. This work will help the private Egyptian textile companies to participate in design, development and manufacturing of textile structural composites.

Educational Contributions

Some of the composite manufacturing techniques established in this research have been integrated into several undergraduate courses: ENGR 1110 Introduction to Textile Engineering, TXEN 2250 Fabric Design and Engineering and TXEN 4250 Engineered Textile Structures. The manufacturing procedures developed with NSF funding is ideal for students to conduct their senior design projects.

Acknowledgement and Disclaimer

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