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Statistical Analysis of Effects of Some Essential Parameters on Impact Properties of Fabric-Based Hybrid Composites

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Abstract – In this study, hybrid composite structures were manufactured by vacuum assisted resin transfer molding method using three different woven fabrics (jute, E-glass and carbon) as the reinforcing material and polyester resin as the matrix material. All composite structures comprise four layers of fabric. Four factors (yarn –material- type, fabric direction, fabric stacking sequences and MWCNT type) were specified and their effects on impact strength results were examined by full factorial analysis method and it was observed that the four selected factors had statistically significant effects on the impact strengths of the fabric-based hybrid composite samples.

Keywords – *textiles, composites, impact properties, carbon nanotubes, statistical analysis.*

I. Introduction

During the last four decades, polymer matrix composites are gaining importance in both conventional and high technology application areas due to their high specific stiffness and strength, low cost, corrosive resistance and high dimensional stability properties [1]. Using low-cost, light-weight polymers with high strength and high modulus fibers provides good combination of mechanical and technological properties to composites [2-4].

The bonding strength between the matrix and the reinforcement material is the most important factor that affects the mechanical properties of a composite structure because the reinforcement is the phase that can resist the applied load and load is transferred from the matrix to the reinforcement material from the interface [5-7]. The bonding strength has a huge effect on the failure mode of the composite, which is directly related to the impact properties of the material [6].

Full-factorial experiments are the experiments in which the effects of more than one factor on response are investigated. Factorial designs are mostly used to examine the effects of experimental factors and the interactions between those factors, that is, how the effect of one factor varies with the level of the other factors in a response. Also, the number of experiments geometrically increases with the increasing number of factors and levels [8, 9].

In the present study, the effects of yarn type, fabric direction, fabric stacking sequences and MWCNT type on the impact strengths of fabric-based hybrid composite structures were evaluated and the statistical significance of the results were verified by utilizing full-factorial experimental method.

II. Materials and Method

A. Materials

Jute, E-glass and carbon plain weave fabrics, which have areal densities of 200 g /m2, were used as the reinforcement materials, while unsaturated orthophthalic polyester resin, cobalt (accelerator) and methyl ethyl ketone peroxide (hardener) were utilized as the resin system.

Three different types of MWCNTs (MWCNT, MWCNT-OH and MWCNT-COOH) were added to the matrix material as nanofiller.

B. Methods

Composite Production

Vacuum assisted resin transfer molding technique was used for the manufacturing of composite specimens. Mixing of the MWCNT and polyester resin was performed by ultrasonic mixer.

Devotrans Charpy Impact Test Machine was utilized to evaluate the impact resistance of the composite samples according to BS EN ISO 179:1997 standard. The energy that was applied to the sample was 12 J.

Statistical Analysis

The statistical analysis of the results was performed by using Minitab 18 software program. The full factorial experimental layout was designed in order to examine the main factors and their interactions on the impact properties of hybrid composite samples. One factor with two levels two factors with three levels and one factor with four levels were chosen to design the experimental study. The factors and levels are given in Table 1.

Table 1. Example of a table

Factors	Level 1	Level 2	Level 3	Level 4
Yarn (Material) Type	Jute/ E-glass	Jute/ carbon	E-glass/ carbon	-
Fabric Direction	Warp	Weft	-	-
Stacking Sequence	High strength inside	High strength outside	Alternately	-
MWCNT Type	None	MWCNT	MWCNT-OH	MWCNT -COOH

Table 2. Full-factorial experimental design layout.

Sample Code	Yarn Type	Fabric Direction	Stacking Sequence	MWCNT Type	Impact Strength (kJ/m^2)
JGGJ-warp	1	1	1	1	98.94
JGGJ-MWCNT-warp	1	1	1	2	122.11
JGGJ-MWCNT-OH-warp	1	1	1	3	106.70
JGGJ-MWCNT-COOH-warp	1	1	1	4	110.98
GJJG-warp	1	1	2	1	205.42
GJJG-MWCNT-warp	1	1	2	2	227.86
GJJG-MWCNT-OH-warp	1	1	2	3	216.70
GJJG-MWCNT-COOH-warp	1	1	2	4	229.17
JGJG-warp	1	1	3	1	130.00
JGJG-MWCNT-warp	1	1	3	2	152.89
JGJG-MWCNT-OH-warp	1	1	3	3	136.78
JGJG-MWCNT-COOH-warp	1	1	3	4	141.99
JGGJ-weft	1	2	1	1	82.74
JGGJ-MWCNT-weft	1	2	1	2	95.57
JGGJ-MWCNT-OH-weft	1	2	1	3	85.84
JGGJ-MWCNT-COOH-weft	1	2	1	4	89.17
GJJG-weft	1	2	2	1	182.53
GJJG-MWCNT-weft	1	2	2	2	197.35
GJJG-MWCNT-OH-weft	1	2	2	3	183.57
GJJG-MWCNT-COOH-weft	1	2	2	4	194.91
JGJG-weft	1	2	3	1	110.43
JGJG-MWCNT-weft	1	2	3	2	132.03
JGJG-MWCNT-OH-weft	1	2	3	3	116.97
JGJG-MWCNT-COOH-weft	1	2	3	4	117.14
JCCJ-warp	2	1	1	1	90.40
JCCJ-MWCNT-warp	2	1	1	2	109.48
JCCJ-MWCNT-OH-warp	2	1	1	3	95.75
JCCJ-MWCNT-COOH-warp	2	1	1	4	97.27
CJJC-warp	2	1	2	1	115.34
CJJC-MWCNT-warp	2	1	2	2	133.94
CJJC-MWCNT-OH-warp	2	1	2	3	118.46
CJJC-MWCNT-COOH-warp	2	1	2	4	134.26
JCJC-warp	2	1	3	1	98.94
JCJC-MWCNT-warp	2	1	3	2	104.80
JCJC-MWCNT-OH-warp	2	1	3	3	102.98
JCJC-MWCNT-COOH-warp	2	1	3	4	106.47
JCCJ-weft	2	2	1	1	79.84
JCCJ-MWCNT-weft	2	2	1	2	93.24
JCCJ-MWCNT-OH-weft	2	2	1	3	81.76
JCCJ-MWCNT-COOH-weft	2	2	1	4	84.01
CJJC-weft	2	2	2	1	104.79
CJJC-MWCNT-weft	2	2	2	2	116.80
CJJC-MWCNT-OH-weft	2	2	2	3	106.04
CJJC-MWCNT-COOH-weft	2	2	2	4	112.70
JCJC-weft	2	2	3	1	88.91
JCJC-MWCNT-weft	2	2	3	2	92.76

JCJC-MWCNT-OH-weft	2	2	3	3	89.98
JCJC-MWCNT-COOH-weft	2	2	3	4	91.84
CGGC-warp	3	1	1	1	246.92
CGGC-MWCNT-warp	3	1	1	2	262.99
CGGC-MWCNT-OH-warp	3	1	1	3	259.05
CGGC-MWCNT-COOH-warp	3	1	1	4	255.76
GCCG-warp	3	1	2	1	231.08
GCCG-MWCNT-warp	3	1	2	2	252.76
GCCG-MWCNT-OH-warp	3	1	2	3	241.92
GCCG-MWCNT-COOH-warp	3	1	2	4	246.17
GCGC-warp	3	1	3	1	176.36
GCGC-MWCNT-warp	3	1	3	2	198.47
GCGC-MWCNT-OH-warp	3	1	3	3	179.98
GCGC-MWCNT-COOH-warp	3	1	3	4	187.17
CGGC-weft	3	2	1	1	193.76
CGGC-MWCNT-weft	3	2	1	2	205.17
CGGC-MWCNT-OH-weft	3	2	1	3	203.96
CGGC-MWCNT-COOH-weft	3	2	1	4	202.83
GCCG-weft	3	2	2	1	214.74
GCCG-MWCNT-weft	3	2	2	2	221.78
GCCG-MWCNT-OH-weft	3	2	2	3	218.26
GCCG-MWCNT-COOH-weft	3	2	2	4	246.01
GCGC-weft	3	2	3	1	155.70
GCGC-MWCNT-weft	3	2	3	2	163.77
GCGC-MWCNT-OH-weft	3	2	3	3	156.71
GCGC-MWCNT-COOH-weft	3	2	3	4	159.96
CJJC-MWCNT-OH-weft	2	2	2	3	106.04
CJJC-MWCNT-COOH-weft	2	2	2	4	112.70
JCJC-weft	2	2	3	1	88.91
JCJC-MWCNT-weft	2	2	3	2	92.76
JCJC-MWCNT-OH-weft	2	2	3	3	89.98
JCJC-MWCNT-COOH-weft	2	2	3	4	91.84
CGGC-warp	3	1	1	1	246.92
CGGC-MWCNT-warp	3	1	1	2	262.99
CGGC-MWCNT-OH-warp	3	1	1	3	259.05
CGGC-MWCNT-COOH-warp	3	1	1	4	255.76
GCCG-warp	3	1	2	1	231.08
GCCG-MWCNT-warp	3	1	2	2	252.76

The first factor is the yarn (material) type. Three types of fabrics (jute, E-glass and carbon) were used in this study. Hybrid samples using two types of fabrics (jute/E-glass, jute/carbon and E-glass/carbon) were manufactured. The second factor is the fabric direction. The mechanical tests were done in two directions, those were; warp (longitudinal) and weft (transverse) directions. The third factor is the stacking sequence of fabric layers in the composite sample. Three levels were chosen for this factor. At level 1, fabric layers which have higher strength were placed between low strength fabric layers. At level 2, fabric layers which have lower strength were placed between high strength fabric layers while at level 3, fabric layers were aligned alternately. The last factor is the MWCNT type. The level 1 did not contain any MWCNT whereas levels 2, 3 and 4 comprised pristine MWCNT, MWCNT-OH and MWCNT-COOH, respectively.

III. Results

Table 2 demonstrates the full-factorial experimental design layout of the impact strength results given by Minitab 18 software program. In sample codes J, G and C refer to jute, E-glass and carbon fabric plies, respectively.

Table 3 displays the reduced ANOVA table of impact strength results. The F and p values could not be obtained from the ANOVA table due to the fact that DF of error was zero. By examining the Adj SS values, the interaction of fabric direction*stacking sequence*MWCNT type (Adj SS: 31) was sent to the error due to its low effect and so reduced ANOVA table was achieved.

Table 3. Reduced ANOVA table.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Linear	8	198326	24790.8	4759.83	0.000
Yarn (Material) Type	2	146630	73314.8	14076.45	0.000
Fabric Direction	1	10098	10098.3	1938.88	0.000
Stacking Sequence	2	39149	19574.4	3758.28	0.000
MWCNT Type	3	2450	816.5	156.77	0.000
2-Way Interactions	23	32049	1393.5	267.54	0.000
Yarn Type*Fabric Direction	2	1111	555.3	106.61	0.000
Yarn Type*Stacking Sequence	4	29991	7497.8	1439.57	0.000
Yarn Type*MWCNT Type	6	140	23.3	4.47	0.045
Fabric Direction*Stacking Sequence	2	348	173.9	33.40	0.001
Fabric Direction*MWCNT Type	3	125	41.6	7.99	0.016
Stacking Sequence*MWCNT Type	6	335	55.9	10.73	0.005
3-Way Interactions	22	1596	72.5	13.93	0.002
Yarn Type*Fabric Direction*Stacking Sequence	4	1261	315.3	60.54	0.000
Yarn Type*Fabric Direction*MWCNT Type	6	129	21.4	4.12	0.055
Yarn Type*Stacking Sequence*MWCNT Type	12	206	17.2	3.30	0.077
4-Way Interactions	12	166	13.8	2.65	0.120
Yarn Type*Fabric Direction*Stacking Sequence*MWCNT Type	12	166	13.8	2.65	0,120
Error	6	31	5.2		
Total	71	232168			

Model summary: R-sq = 99.99%, R-sq(adj) = 99.84%, R-sq(pred) = 98.06%

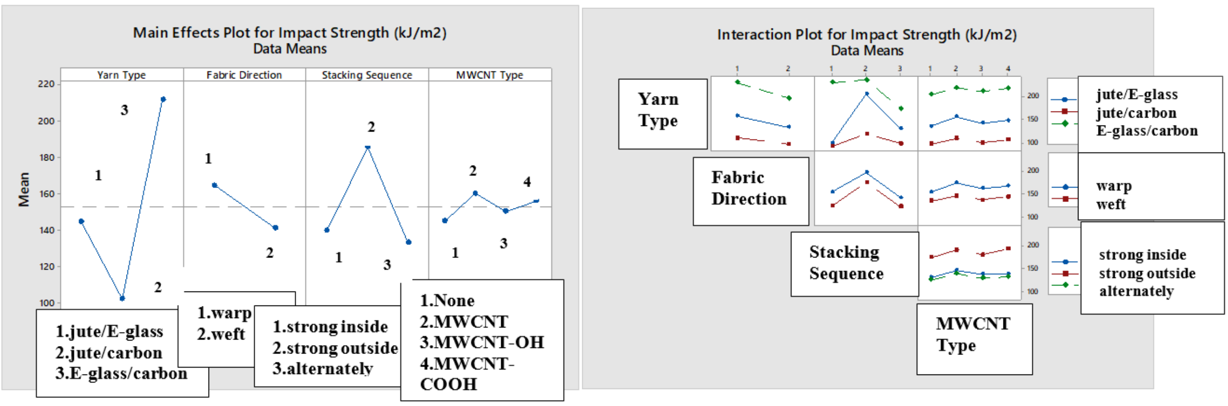

Fig. 1 (a) Main effects plot, (b)Interaction effects plot for impact strength.

When the linear factors were examined, it was noticed that all factors had statistically significant effect (p: 0.000) on impact strength of composite samples. While yarn (material) type had the highest effect (Adj SS: 146630), MWCNT type (Adj SS: 2450) had the least influence among linear factors. This fact was also seen from the main effects plot for impact strength (Figure 1). The difference between the levels of yarn (material) types was higher than the other factors. Taking into account that impact strengths of these three yarn (material) types (jute, E-glass and carbon) are so different from each other, it was not surprising that their binary combinations in hybrid composite structures also showed dissimilar impact strength results.

The fabric direction had lesser effect than yarn (material) type and stacking sequence. While the mean impact strength at warp direction was about 160 kJ/m2, it was about 145 kJ/m2 at weft direction samples (Figure 1). During testing, impact was given from lateral surface of the sample. So, both warp and weft yarns were exposed to a nearly same amount of impact. So, the less effect of fabric direction on the impact strength of samples could be due to this situation.

The highest impact strength was obtained by placing high strength fabrics to the outer layers (Mean impact strength: 180 kJ/m2) of the composite structures instead of placing inside (Mean impact strength: 140 kJ/m2).

When the effects of different levels of MWCNT types were considered, it was understood that the highest impact strength was obtained with pristine MWCNT treated sample. However, it was both seen from ANOVA table and main effects plot that type of MWCNT had the least influence on impact strength.

From Figure 1, it could be concluded that higher impact strength was achieved with the third level of yarn type (E-glass/carbon), the first level of fabric direction (warp), the second level of stacking sequence of fabric plies (low strength fabric inside) and the second level of MWCNT type (pristine MWCNT).

Moreover, it was revealed that the combined effect of yarn (material) type and stacking sequence had the highest statistically significant effect on the impact strength (Adj SS: 29991, p: 0.000). Considering the fact that by changing the stacking sequence of fabric plies, we were changing the places of the different yarn (material) types in composite structure. So, this also showed us that these two factors had really strong interaction between each other. Also, all two way interactions had statistically significant effect ($p<0.05$) on impact strength. The interaction of yarn type*MWCNT type had an Adj SS of 140 and p value of 0.045 which showed us that its effect was at borderline of statistically significance level. Moreover, the similar slopes of yarn type*MWCNT type curves in interaction plot promoted this result (Figure 1).

Among three way interactions, only the interaction of yarn type*fabric direction*MWCNT type had statistically significant effect on the impact strength. Moreover, the combined effect of these four factors had very low Adj SS value (166) and a high p value (0.120) which indicated its nearly no effect on tensile strength.

In this model, R-sq (0.9999), adjusted R-sq (0.9984) and predicted R-sq (0.9806) were in reasonable agreement, which indicated the adequacy of the model.

IV. Conclusion

Fabric-based hybrid composite structures were produced and their impact properties were quantified in this study. Their results were evaluated by full-factorial experimental design method and outcomes revealed that high impact fabric-based composites can be achieved by placing high strength fabrics to the outer layers. Moreover, addition of MWCNTs enhanced the impact strengths of the samples and the pristine MWCNT added samples give better results. Finally, results demonstrated that the fabric direction has a huge effect on the performance of the composite structure.

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