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Statistical Investigation of Parameters Influence on Fracture Toughness of the Glass Fiber Reinforced Composites

Ganga Reddy C[1], Dr. Shantharaja M[2]

[1,2]*Department of Mechanical Engineering, University Visvesvaraya College of Engineering, Bangalore 560001, India*

***Abstract*— The objective of the work was to investigate statistical analysis of fracture toughness of the glass fiber reinforced composites at different stacking sequences, strain rate and crack length. The glass reinforced vinylester composites prepared by hand layup technique with stacking sequences of 0/90, 45/-45 and chopped strand orientations. 3-point bending for fracture toughness test for various notch depth ratio's as per linear elastic fracture mechanics concept was conducted. Further the initial notch depth method was adopted to find the critical stress intensity factor KIC for the given notch depth ratio. Design of experiment using Taguchi L9 array was formulated to understand the influence of parameters on fracture toughness. The result of surface methodology showed the stacking sequence of [45/-45/0/90/Chopped]3s, with strain rate of 0.5 mm/min and without notch having the highest fracture toughness of 81.36 Mpa $\sqrt{m}$, when compared to Al 6061 alloy which has the fracture toughness of 33.09 Mpa $\sqrt{m}$. The specimens failed due to fiber pull out, de-bonding and also fiber breakage during the loading conditions, which was evident by SEM.**

***Keywords*—Notch, stacking sequence, fracture toughness, glass fiber composites**

I. INTRODUCTION

Fiber reinforced Composite materials having the advantage of higher strength to weight ratio, resistance to corrosion, acids and to impact loads are replacing the metal alloys in spacecraft and automobile industries[1]. Many components of industrial applications are subjected to fluctuating loads during their life time and they may fail through fatigue due to stress intensity factor. Fracture toughness is a fracture mechanics parameter that measures the load carrying ability of pre-cracked component [3-5]. Fatigue failure is the degradation of the mechanical properties of a component due to the repeated load. It is understood from the past experience that the component will fail even if the stress acting on it is well below the yield strength of the material [6,7].

Fatigue is the cause of crack and final fracture in a mechanical component, it is important to assess the performance of composite structures under the basis of S-N data [8, 9]. For composite materials multiple transverse cracks may initiate at free edges and subsequently moves into the laminate which will degrade the stiffness while providing the site for de-lamination [10]. It was found both flexural strength and flexural modulus of composites increased with increase in resin content between 13 % to 19 % and fiber content between 1 % - 1.5 %. The critical stress intensity factor also increased with increase in glass fiber ratio but did not alter for varying notch depth (a/b) ratio. Applicability of S-N data to different lay-ups made of the same composite has provided difficulties, considering the laminate stress as the similitude parameter which does not account for differences in damage mechanics produced by change in lay-up [11]. The behavior of composite made of unidirectional, woven and chopped fiber arrangements on impact, tensile and fracture toughness were studied [12] and the results showed strength improvement on increase in fiber volume fraction. Subsequent de-lamination is initiated at interface which grows along unidirectional plies aligned with loading direction, propagates until the remaining material is unable to carry the load [13-14].

Many research works related to effect of fiber/matrix volume fraction, fiber orientation and notch depth ratio on KIC have been reported in the past. By taking one variable parameter at a time the fracture behavior was studied but effect of all the three parameters and interaction between them was not studied and was a concern. In this context, the present work was focused on finding the fracture toughness of fiber reinforced composite for variable test parameters under combined experimental and statistical analysis tool using Taguchi L_9 array of design.

II. EXPERIMENTAL STUDIES

The materials used in this project work are listed in Table 1 with their specific properties.

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TABLE 1
MATERIAL SPECIFICATIONS

Materials	Specifications
E-Glass Fibre	Density: 2.55 g/cc, UTS: 3400 MPa E: 70-75 Gpa
Vinylester resin (Polyflex GR 200-65 superior)	Density: 1.05 g/cc, UTS: 60Mpa FS: 130 Mpa
Di-Methyl acetamide as promoter	Density: 0.94 g/cm3
Cobalt naphthalate as accelerator	Density: 0.98 g/cm3
Methyl Ethyl Ketone peroxide (MEKP) as catalyst.	Density: 1.17 g/cm3

Hydraulically operated Hot Press of 2 ton capacity was used for curing of the laminate stacked in the mould to ensure uniform distribution of resin throughout the laminate. The pressure application was carried out at room temperature then in hot press of temperature of 120 °C. The pressure applied in the hot press machine improves the uniform wetting of the fiber in the laminate. The uniform wetting of fiber and bonding of the fiber and matrix improves the fiber / matrix interphase and curing process of the composite. The pressing also reduces the number of imperfections and voids present in the laminate and control the thickness of the laminate. Laminate is cured under the hot press for 24 hours for the proper adhesion between the fiber and matrix interface to form strong bond. A Universal Testing Machine (UTM) is a standard testing machine used for measuring flexural strength of materials by using digitally controlled load cell and displacement. There exist different fixtures for holding samples depending on the type of test conducted. The laminates removed from hot press were cut into required specimen size as per ASTM E399 three point bending fracture test standards

III. DESIGN OF EXPERIMENT

The three basic principles of experimental design are replication, randomization and blocking.

In this project the stacking sequence (A), strain rate (B) and notch depth ratio (C) are taken as three levels with each having three factors. The factor A contains three levels of 0/90, 45/-45 and chopped strand glass fibers stacked together having notches of 0, 5.7 and 7.5 depth. And the tests were conducted for three strain rates of 0.5, 1.5, 2.5 mm/min.

The latest version Minitab V16 was used to create the experimental layout in this project. For this investigation, the orthogonal array had to be selected which could accommodate three factors, each at three variability levels. This accommodation was possible in the feature “Three Level Design” in Minitab where it was decided to select a L9 array with three factors at each level. Table 2 shows experimental layout obtained through Minitab statistical software. The combinations of factors are shown in 1st column and two responses namely Fracture toughness and critical load are shown in 2nd column respectively.

TABLE 2
EXPERIMENTAL PLANNING BY L9 ORTHOGONAL ARRAY

Sl No	Experimental variable parameters			Fracture toughness Mpa $\sqrt{m}$	Critical Load N
	A	B	C		
1	0/90	0.5	0.00	58.37	8724
2	0/90	1.5	0.38	23.04	3126
3	0/90	2.5	0.50	22.06	3175
4	45/-45	0.5	0.38	27.12	4375
5	45/-45	1.5	0.50	26.47	3905
6	45/-45	2.5	0.00	41.47	6426
7	Chop	0.5	0.50	12.4	1516
8	Chop	1.5	0.00	49.97	7284
9	Chop	2.5	0.38	16.5	2406

It was observed form Fig 1 that fracture toughness decreased as fiber orientation changes from 0/90 to 45/-45 to chopped strand glass fiber. The fracture toughness decreased with increase in strain rate from 0.5 to 2.5. It was inferred that strain rate had a negative effect on the fracture toughness, with the increase in the strain rate the fracture toughness decreases indicating that materials become less tough thereby decreasing their ability to resist fracture.

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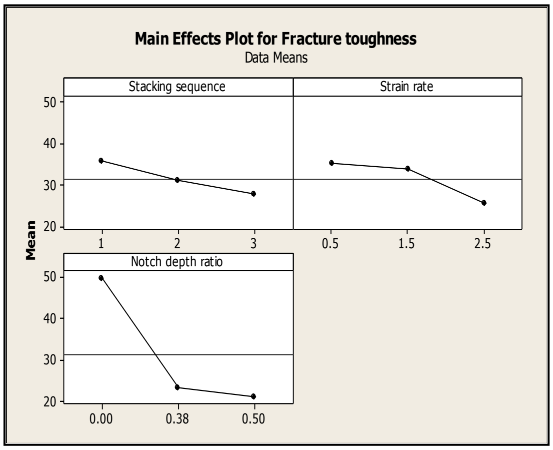

FIG. 1 MAIN EFFECT PLOT FOR AVERAGE FRACTURE TOUGHNESS

High loading rates will make the material more brittle resulting in reduced ability to plastic deformation and thus lowers the fracture toughness. Thus loading is one of the important parameter to be observed during fracture tests. And the notch depth ratio adversely affected the fracture toughness as it increased from without notch to notch ratio 0.38 to 0.5. The maximum fracture toughness achieved from experiments is 62.03 MPa $\sqrt{m}$.

Normal probability plots for the fracture toughness which is obtained from MINITAB V-16 are shown in Fig.2. The S/N ratios for experimental response are found to be equally distributed along the trend line of a normal probability, Hence the process is said to be stable.

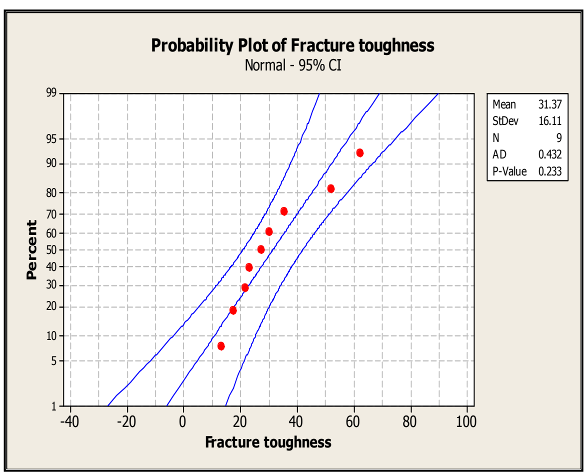

FIG. 2 NORMAL PROBABILITY PLOT FOR FRACTURE TOUGHNESS MPA $\sqrt{m}$

The goal set used for optimization was upper limit used, lower limit used, weights used and importance of the factors is presented in Table.3

TABLE.3
CONDITIONS USED TO GET OPTIMIZATION PLOTS IN MINITAB SOFTWARE

Response	Goal Set	Lower limit	Target	Weight	Importance
Fracture toughness	Maximize	13.12	100	1	1

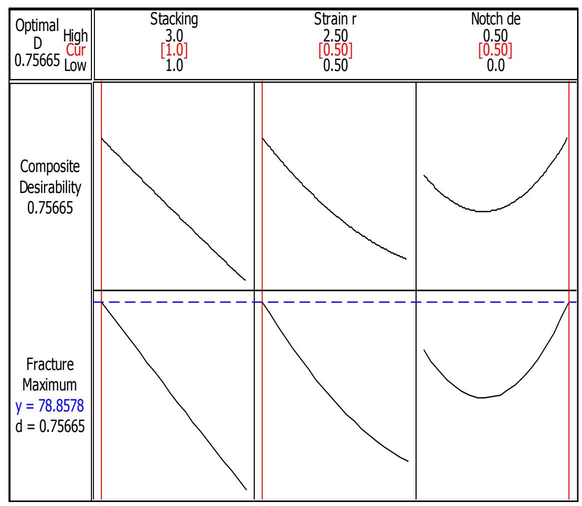

FIG. 3 RESPONSE SURFACE OPTIMIZATION PLOT

From the response surface optimization shown in Fig 3 it was inferred that the laminate with stacking sequence 0/90 with strain rate 0.5 mm/min and notch depth ratio 0.5 would give out the largest possible fracture toughness of 78.8578Mpa $\sqrt{m}$ with desirability of 0.75665. The solution of optimized parameters shown in Table.4

TABLE 4
SOLUTIONS OF OPTIMIZATION BASED ON DESIRABILITY VALUE OF RESPONSE

Response	Solution	Desirability
Fracture toughness	78.85 Mpa $\sqrt{m}$	0.75665

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LEFM technique was again applied to find the fracture toughness of Al alloy with the same sample size as used for GFRP. The plane stress fracture mechanics was adopted since the fracture toughness depends on thickness of sample used. By comparing the fracture toughness of both aluminium and GFRP it was inferred that GFRP had the highest KIC value of 81.36 when compared to aluminium with 33.09 Mpa $\sqrt{m}$ by considering LEFM. And hence fiber reinforced composites are better to use in the area where weight is of concern.

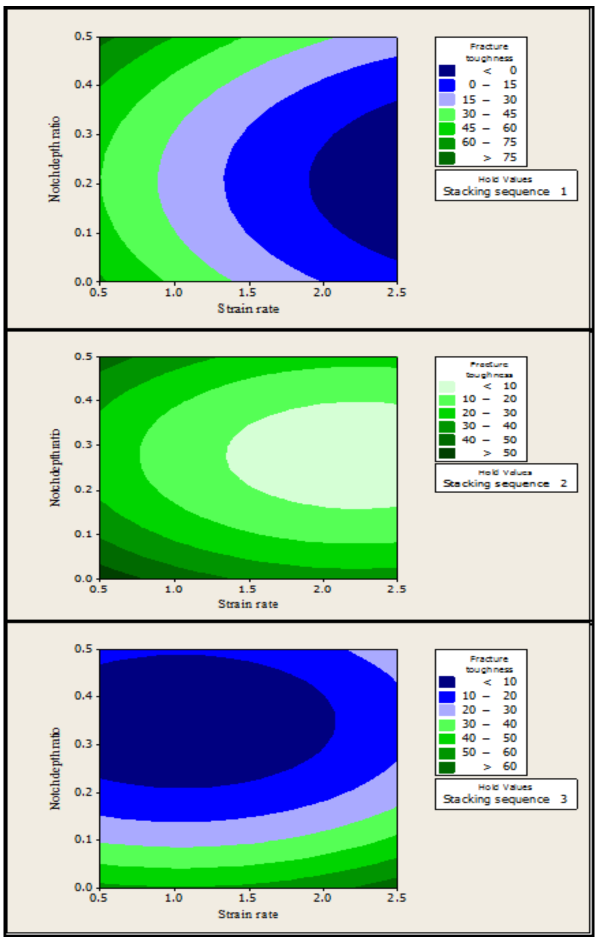

FIG.4 CONTOUR PLOTS BY HOLDING STACKING SEQUENCE AT 0/90, 45/-45 AND CHOPPED

By holding the stacking sequence at three levels, response surface was obtained as shown in Fig 4. It was inferred that stacking sequence of 0/90 among all the plain laminates with strain rate 0.5mm/min and at notch depth ratio 0 gave the best fracture toughness value of more than 70 Mpa .

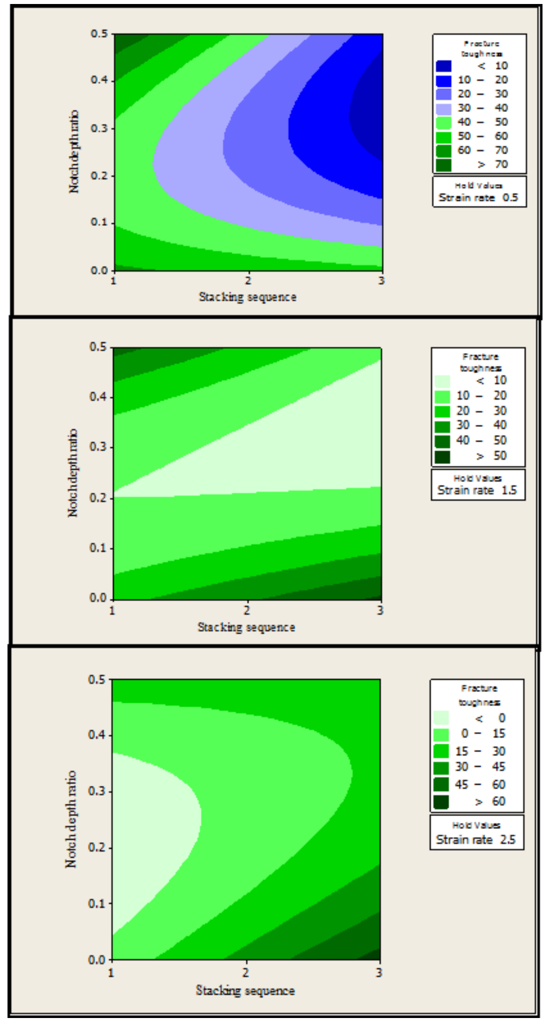

FIG.5 CONTOUR PLOTS BYHOLDING STRAIN RATE AT 0.5, 1.5, 5 MM/MIN

By holding the strain rates at 0.5, 1.5, 5 mm/min stacking sequence 0/90 plain laminate with notch depth 0.5 gives the best fracture toughness and in the range of notch depth ratio between 0.1 to 0.4 it is lowest as shown in Fig 5.

Holding notch depth ratios gave lowest fracture toughness of less than 20 Mpa for chopped strand laminate in the range of 0.5 to 5mm/min strain rate as shown in Fig 6.

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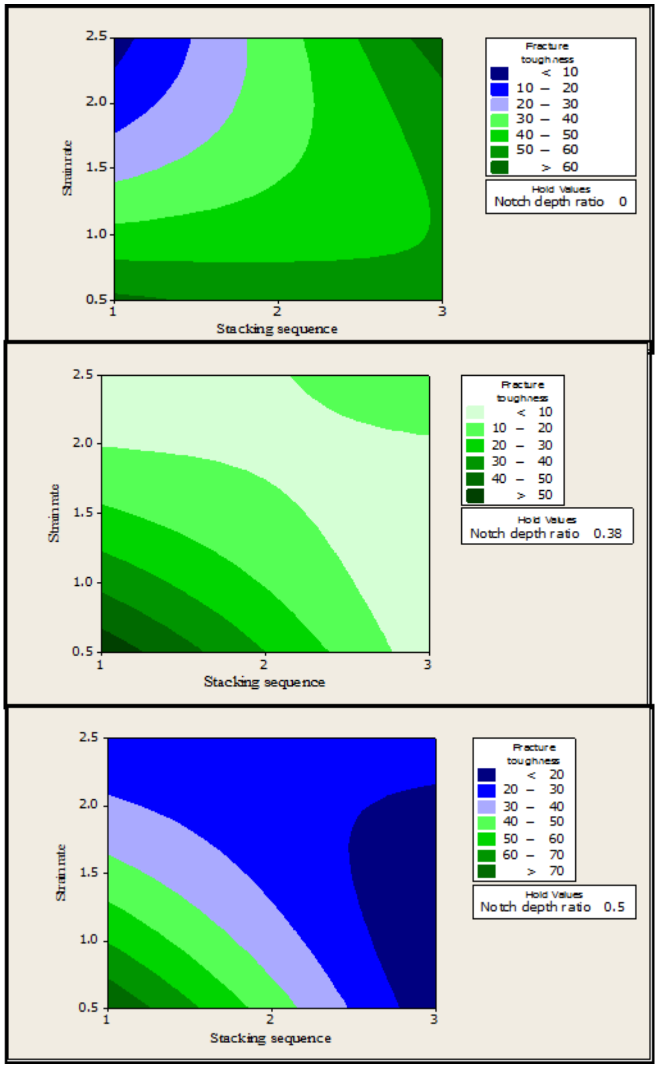

FIG.6 CONTOUR PLOTS BY HOLDING NOTCH DEPTH RATIO AT 0, 0.38, AND 0.5 RESPECTIVELY

From the SEM test as shown in Fig.7 it was observed that dominant failure modes were fiber breakage, fiber matrix de-bonding and fiber pull out. It was seen in fig b where fiber pull out was evident due to tensile stress acting on the lower portion of 3 point bending specimen.

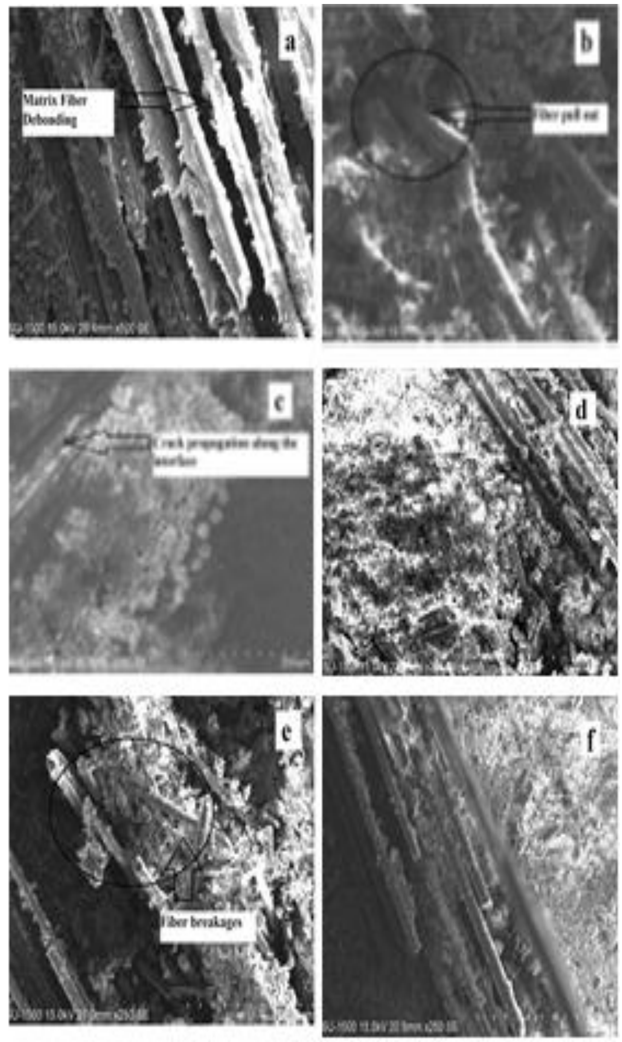

FIG.7 SEM OBSERVATIONS FOR A)[0/90] B) [45/-45], C) [CHOP], D) [0/90/45/-45/CHOP], E) [CHOP/45/-45/0/90], F) [45/-45/0/90/CHOP] LAMINATES.

IV. CONCLUSION

This work introduces the LEFM method to measure the stress intensity factor of GFRP adopting initial notch depth method and to determine the KIC value. Taguchi L9 array was used to design the experiments and to observe the effect of all the parameters on KIC. The following were arrived at:

- High loading rates will make the material more brittle resulting in reduced ability to plastic deformation and thus lower the fracture toughness.
- Fracture toughness depends on the stacking sequence of lamina, the one with [45/-45/0/90/Chopped]3s gave the highest KIC value of 81.3617Mpa $\sqrt{m}$.
- Lamina with 45/-45 woven glass fibers on top and bottom has better performance against fracture.
- Notch depth had the adverse effect for fracture toughness, and KIC decreased with the increase in notch depth ratio.
- Taguchi method of design gave out good results for interaction between the affecting parameters with less number of experiments and hence material and money can be saved to get utmost results.
- Al alloys could be replaced with GFRP from the fracture mechanics perspective where weight is of concern.
- From SEM it was evident that fracture had taken place by fiber breakage, matrix cracks and de-lamination.

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