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## Effect of Mode I Interlaminar Fracture Toughness of Stitched Composites by DCB Test

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**ABSTRACT:** Aim of this paper is to study the effect of mode I interlaminar fracture toughness of stitched composites, plain stitching has been made by untwisted glass fibre roving of various Tex. The traditional fibre reinforced plastics (FRP) laminated composites have poor interlaminar fracture resistance and suffer extensive damage by delamination cracking when subjected to out-of-plane loading. Through-the-thickness reinforcement is done by stitching with untwisted glass fibre roving of various Tex to increase the delamination resistance. In this work glass woven roving mats (WRM), glass unidirectional mats (UDM) are stitched in the thickness direction with untwisted glass roving of various Tex as 140 g/km, 280 g/km and 420 g/km by the plain stitch at the stitch density (number of stitches per unit area) of 0.033 stitches/mm<sup>2</sup>, the specimen having same stitch density but different stitch distributions. Effect of stitching on mode I interlaminar fracture toughness ( $G_I$ ) of glass/polyester laminates has been investigated by performing double cantilever beam (DCB) test. Double cantilever beam tests are carried out on Instron testing machine of model INSTRON 3382 with BluehillInstron software, the  $G_{IC}$  is determined using modified beam theory (MBT) method and delamination resistance curves (R-Curves) are plotted.

**KEYWORDS:** Interlaminar fracture toughness, Stitching, Delamination, DCB test.

### I. INTRODUCTION

Fibre reinforced plastics (FRP) composites are widely used in structural applications due to their high strength to weight ratio. These FRP composite structures are often subjected to out-of-plane loads during manufacturing and service conditions. In such cases, layered composites suffer severely by delamination cracking because of poor interlaminar fracture resistance. On further loading, the interlaminar crack propagates and thus weakens the structure. By introducing small amount of fibres in the thickness direction of the laminate, the damage tolerance and suppression of delamination crack initiation or rate of interlaminar crack growth can be enhanced [14]. The simplest method for this is, stitching the laminate together in the thickness direction. So, it is necessary to study the resistance offered against delamination propagation, which is much useful in the design and analysis of composites structures. Delamination resistance is measured as fracture toughness (kJ/m<sup>2</sup>). So for many researcher have tried to improve the delamination fracture toughness through different techniques. In some investigations, delamination fracture toughness has been improved by toughening the matrix material through addition of nanoclay [8] and short fibres [1] with matrix material. In some other investigations, improvements in delamination fracture toughness have been performed through 3D fibre architecture (stitching, knitting and braiding). Through thickness stitching is a promising reinforcing technique to

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improve interlaminar strength and delamination resistance [4-6]. The improvement in delamination resistance is primarily due to suppression of the delamination crack growth by stitches. Stitch fibres are stiff when compared with resin matrix and provide an alternative load path for an approaching delamination crack front. Earlier studies have shown that through thickness reinforcement done by stitching delays delamination propagation and improve the interlaminar fracture toughness by providing more integrated composites. In the present work glass woven roving mats (WRM), glass unidirectional mats (UDM) stitching is done manually by plain stitch using untwisted fibre roving of various Tex with different stitch distribution and various lay-up sequences.

## II. MATERIALS AND METHODS

### 2.1 Experimental Design

Taguchi techniques have been used widely in engineering design [2]. The main trust of the Taguchi techniques is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation. The Parameters are as shown in Table 1.

Table 1: Parameters and Levels of Experiments

S. No	Parameters	Levels		
1	Stitch Tex	140 g/km (A)	280 g/km (B)	420 g/km (C)
2	Stitch Distribution	6 mm – 5 mm (D)	7.5 mm – 4 mm (E)	9.6 mm – 3.125 mm (F)
3	Lay-up Sequence	WRM/ (UDM)  /WRM (G)	WRM/ (UDM ) <sub>2</sub> /WRM (H)	WRM/ (WRM)  /WRM (I)

Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design requires the use of a strategically designed experiment which exposes the process to various levels of design parameters. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization; some of the previous work listed [10].

### 2.2 Design of Experiments

The orthogonal array for three factors at three levels was used for the elaboration of the plan of experiments the array L9 was selected [15]. The first row was assigned to the stitch Tex, second row was assigned to the stitch distribution and third row was assigned to lay-up sequence. The possible input parameters were shown in Table 2. The input parameters by L9 orthogonal array was shown in Table 3.

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The parameters responses are stitch Tex, stitch distribution and lay-up sequence. By using the taguchi's methods of design of experimental to analyse the response for maximum interlaminar fracture toughness. The contributions of each parameter for each test were examined.

Table 2: Possible Input Parameters

ADG	BDG	CDG
ADH	BDH	CDH
ADI	BDI	CDI
AEG	BEG	CEG
AEH	BEH	CEH
AEI	BEI	CEI
AFG	BFG	CFG
AFH	BFH	CFH
AFI	BFI	CFI

Table 3: Input Parameters by L9 Orthogonal Array

S. No	Lay-up Sequence	Stitch Tex	Stitch Distribution
1	G	A	D
2	G	B	E
3	G	C	F
4	H	A	E
5	H	B	F
6	H	C	D
7	I	A	F
8	I	B	D
9	I	C	E

### III. EXPERIMENTAL WORK

#### 3.1 Double Cantilever Beam (DCB) Test Laminate Fabrication

Stitched six layered planar laminates of dimension 200 mm x 200 mm were made with glass woven roving mats (WRM) of density 610 g/m<sup>2</sup> and glass unidirectional mats (UDM) of density 1000 g/m<sup>2</sup>. The test laminates must contain an even number of plies. A nonadhesive insert shall be inserted at the midplane of the laminate during layup to form an initiation site for the delamination. The film thickness shall be no greater than 13 μm (0.0005 in.). A polymer film is recommended for the insert to avoid problems with folding or crimping at the cut end of the insert. The matrix material used was isophthalic polyester resin. Stitching was done by glass fibre roving of Tex 140 g/km respectively, and represented as type A, is shown in Table 1, glass fibre roving of Tex 280 g/km respectively, and represented as type B, is shown in Table 1, and glass fibre roving of Tex420 g/km respectively, and represented as type C, is shown in Table 1, in plain stitch manually. Specimens were stitched with stitch density (number of stitches per unit area) of

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0.033stitches/mm<sup>2</sup>, and the distance between adjacent stitches along warp and weft directions is 6 mm and 5 mm, respectively, and represented as type D, is shown in Table 1. In the type E, the distance between adjacent stitches along warp and weft directions is 7.5 mm and 4 mm, respectively, is shown in Table 1. In the type F, the distance between adjacent stitches along warp and weft directions is 9.6 mm and 3.125 mm, respectively, is shown in Table 1. The top and bottom layers were made of WRM mats and the UDM mats were kept in-between as [WRM/(UDM)<sub>4</sub>/WRM] are represented as type G is shown in Table 1. In the type H, the top and bottom layers were made of WRM mats and the UDM, WRM mats were kept in-between as [WRM/(UDM/WRM)<sub>2</sub>/WRM] respectively, is shown in Table 1. In the type I, the top and bottom layers were made of WRM mats and the WRM mats were kept in-between as [WRM/(WRM)<sub>4</sub>/WRM] respectively, is shown in Table 1. Accelerator used as Cobalt Naphthenate, 1.5-2% and Catalyst used as Methyl Ethyl Ketone Peroxide, 1.5-2%. Dry fabrics were stitched together and the resin was applied after stitching by hand lay-up. Stitch bridging traction distribution area as forward distribution scheme. Specimens with fibre weight fraction of 0.5 were prepared and cured at room temperature.

### 3.2 Double Cantilever Beam (DCB) Test Specimen Fabrication

Double cantilever beam test specimens having dimension 140 mm, 25 mm and 5 mm as per ASTM D5528 – 01 (Reapproved 2007)<sup>e3</sup> [9], were cut from the planar laminates to determine the mode I interlaminar fracture toughness,  $G_{IC}$ . Specimens should not be precracked before testing. The nominal thickness of laminates was around 5.0 mm. A non-adhesive Teflon film was inserted in the mid-plane of the laminate during fabrication which acted as delamination initiator. The loading hinges (Steel Safety-1.5 Inches) were mounted on the top and the bottom surfaces of the end of DCB specimen arms by using Araldite (Epoxy) resin as shown in Fig 1.

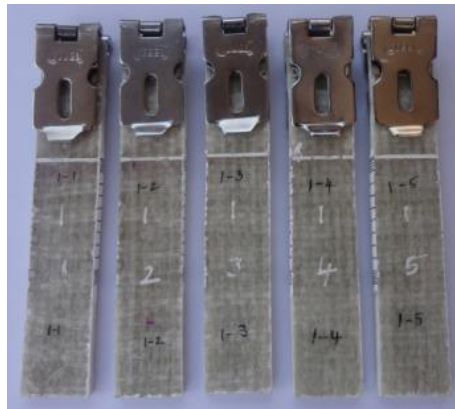


Fig 1. Photograph of Specimen with Hinges

### 3.3 Double Cantilever Beam (DCB) Testing

The Double Cantilever Beam tests were carried out in the Instron Tensile Machine of model INSTRON 3382 with BluehillInstron software. The pre-delaminated end of the DCB specimen was opened by quasi-static loading at a displacement control mode with a constant crosshead rate of 5 mm/min. The curve between load and load point displacement were drawn as shown in Fig 4, and the locations of instantaneous crack front were marked at intervals of delamination growth as shown in Fig 3. Delamination length was the distance between loading point and instantaneous delamination front. Five specimen samples were performed for each DCB test. Mode I interlaminar fracture toughness was determined from DCB test as per ASTM D5528 – 01 (Reapproved 2007)<sup>e3</sup> [18].

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## IV. RESULTS AND DISCUSSION

### 4.1 Mode I Interlaminar Fracture Toughness, ( $G_{IC}$ )

Mode I interlaminar fracture toughness was determined from double cantilever beam (DCB) test as per ASTM D5528 – 01 (Reapproved 2007) <sup>e3</sup> [18]. A non-adhesive Teflon film was inserted in the mid-plane of the laminate during layup to form an initiation site for the delamination. The loading hinges were mounted at the end of DCB specimen arms. The end of the DCB specimen was opened by controlling the crosshead rate of 5 mm/min. The Mode I crack opening loading setup in UTM as shown in Fig 2. The tested specimen as shown in Fig 3, and the values are given in Table 4.



Fig 2. Loading setup in UTM

The curve between load and load point displacement is drawn, and the locations of instantaneous crack front are marked for different intervals of delamination growth. It is understood from the Fig 3. The modified beam theory expression [18] used for calculating the mode I interlaminar fracture toughness of double cantilever beam is:

$$G_I = \frac{3P\delta}{2b(a+|\Delta|)} \quad (1)$$

Where P is load,  $\delta$  is load point displacement, b is specimen width, a is delamination length and  $|\Delta|$  is effective delamination length which is the correction factor for rotation of DCB arms in the delamination front. The delamination resistance curves (R-curves) between delamination length and mode I interlaminar fracture toughness ( $G_{IC}$ ) is drawn and as shown in Fig 5.

Table 4: Mode I Interlaminar Fracture Toughness

Sl. No.	Mode I interlaminar fracture toughness $G_{IC}$ [kJ/m <sup>2</sup> ]
1	1.19929068 ± 0.06005391
2	-
3	-
4	1.49558264 ± 0.02938451
5	-
6	-
7	1.59299836 ± 0.04008491
8	-
9	-

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## 4.2 Effect of Stitching on Mode I Interlaminar Fracture Toughness ( $G_{IC}$ )

It is observed from Table 4 that stitching improves the mode I interlaminar fracture toughness,  $G_{IC}$ . In the stitched specimens, in addition to matrix material, stitch fibres offer resistance to delamination crack propagation [12]. This is because during interlaminar mode I fracture propagation, the stitch fibres undergo tensile breakage and thus additional energy is required to break the stitch fibres.



Fig 3. Tested Specimen

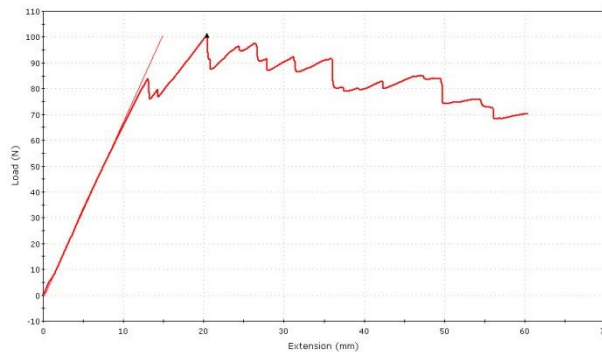


Fig4. Curve between load and load point displacement for specimen 1-3

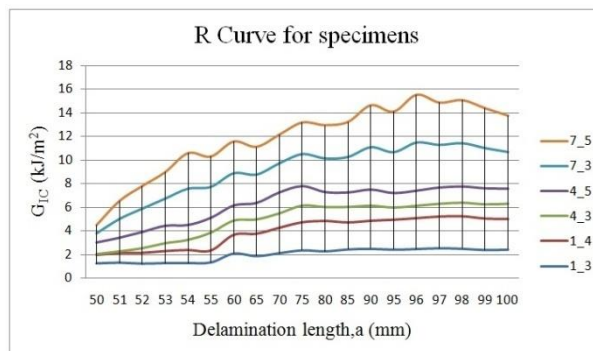


Fig5. Delamination Resistance curve for specimens



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## 4.3 In-Plane Fibre Misalignment due to Stitching

The in-plane fibre misalignment is observed in the fracture plane of stitched specimens. It is observed from the Fig6, that there is no restriction for fibre misalignment in the UD layers; whereas in the WRM layer, misalignment propagation in the warp directional fibres is arrested by weft directional fibres of the same layer and vice versa. The serve in-plane fibre misalignment leads to separation of fibres in the roving and causes resin rich region as shown in Fig6; this resin rich region leads to higher possibility of transverse crack initiation along the in-plane fibres.

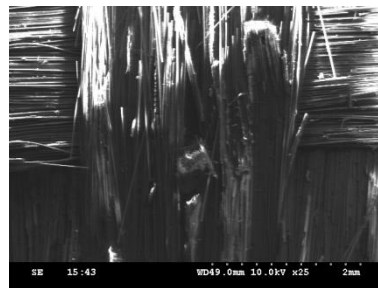


Fig 6. Scanning electron microscope (SEM) of mode I delamination interface in the stitched specimen

## V. CONCLUSION

It is clear that, plain stitch has no thread cross and thus no resin rich pockets. It causes lesser amount of fibre damage than that by lock stitch and modified lock stitch. When the untwisted fibre roving are used as stitch material, fibres are distributed uniformly in the stitches which result in better bonding between stitch fibres and matrix material and cause more integral structure. The Mode I interlaminar fracture toughness,  $G_{IC}$  of FRP composites depends on the stitch Tex, stitch distribution and lay-up sequence. It is understood that, stitching with glass fibre roving of Tex 140 g/km with stitch distribution of 9.6 mm and 3.125 mm and lay-up sequence as [WRM/(WRM)<sub>4</sub>/WRM] gives more delamination resistance when compared to stitching with glass fibre roving of Tex 140 g/km with stitch distribution of 7.5 mm and 4 mm and lay-up sequence as [WRM/(UDM/WRM)<sub>2</sub>/WRM] and stitching with glass fibre roving of Tex 140 g/km with stitch distribution of 6 mm and 5 mm and lay-up sequence as [WRM/(UDM)<sub>4</sub>/WRM]. For other six combinations of specimen loading hinges failed due to their bonding capacity, need to increase the loading hinges bonding strength. Then need to do the DCB test for required specimens to study the effect of mode I interlaminar fracture toughness of stitched composites.

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