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Improving the Delamination Resistance in Basalt Fibre Epoxy Composite Laminates by Stitching

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***Abstract:-* In recent years, fibre reinforced laminates are finding huge applications in various engineering fields such as aeronautical, marine and automotive applications due to its low specific weight and good mechanical properties. Basalt fibre epoxy composite laminates are one of the composites with good mechanical properties and high thermal, chemical resistance. The use of layered/laminated composites is increasing rapidly and hence failure prediction of those structures becoming necessary task.**

Delamination is one of the most frequently encountered damage modes in multi-layered structures. It is a crack between the two layers and can initiate a structural failure. The main objective of the present work is to manufacture the stitched and un-stitched basalt fibre epoxy laminates by through thickness reinforcement and to improve the de-lamination resistance of laminates by stitching the laminate plies with the help of sewing machine and thread. Stitched and un-stitched specimens are prepared and various tests are conducted. From the experimental work we can find tensile strength, impact strength, delamination resistance for both stitched and un-stitched specimens.

Keywords: Basalt fibre, Stitched and Unstitched laminates, Delamination resistance

I.INTRODUCTION:

Now-a-days, a significant growth is observed in the manufacture of composite materials. Intensively developed polymer composite materials (PCM) are used in different sectors of industry and technology. They are going to successfully replace traditional construction materials and also permit the conditions that exclude use of metals. The significant among them is their response to impact loading. A structure is subjected to an impact force when an external objects hits it such as the loads imparted by dropped tool on bonnet cover of car body, runway debris and bird hit on an aircraft engine are typical examples of impact loads.

One of the basic reinforcing elements of composite materials is fibres. Glass fibres are commonly used for making composites; carbon fibres are among the most effective and promising reinforcing fibres for creating PCM used in conditions of high loads. By producing of glass fibre especially scarce component are used - oxide boron (B_2O_3). Carbon fibres at their high cost have no prospects of mass application. In present time a several work is executed on development of modern continuous fibres from basalt stones. By industrial production of basalt fibres on the basis of new technologies their cost is equal and even less than cost of glass fibre. Thus basalt fibres and materials on their basis have the most superior parameter a ratio of quality and the price in comparison with glass & carbon fibres, and other types of fibres.

i. Basalt fibre:

Basalt fibre is a material made from extremely fine fibres of basalt rocks, which is composed of minerals pyroxene, olivine and plagioclase. Basalt rocks originates from volcanic magma and flood volcanoes, a very hot fluid or semifluid material under the earth's crust, solidified in the open air. Basalt is a common term used for a variety of volcanic rocks, which are grey, dark in colour, formed from the molten lava after solidification. Basalt rock-beds with a thickness of as high as 200 m have been found in the East Asian countries. Russia has unlimited basalt reserves. In India basalt reserves are found in Deccan traps.

Key properties of basalt fibres

- Good mechanical strength
- High chemical resistance
- Ecological friendliness
- Thermal resistance
- Fire resistance

Table-1: Comparison of physical/mechanical properties of basalt fibre with E-glass, S-glass fibres

Physical/Mechanical properties	units	Basalt	E-glass	S-glass
Density	g/cm^3	2.66	2.60	2.46
Tensile Strength	MPa	4500	3450	4890
Compressive Strength	MPa	3790	3030	-
Elastic Modulus	GPa	85-91	72-77	85-87
Linear expansion coefficient	1/K	5.5	5.0	1.6
Elongation at break	%	4.0	4.70	5.7
Sound absorption coefficient	%	0.9-0.99	0.8-0.93	-

Figure-1: Basalt cut fibres and basalt fibre fabric

ii. Delamination:

Delamination is a mode of failure where a material/laminate fractures into layers. A large variety of materials including composite laminates and concrete structures will fail by delamination. Processing/Manufacturing can create layers in materials such as steel formed by rolling and metals, plastics from 3D printing which can fail from layer separation. Also surface coatings such as paints and films can delaminate from the coated substance.

The development of inter-laminar stresses is the primary cause of delamination in laminated fibrous composites. Delamination occurs when the inter-laminar stress level exceeds the inter-laminar strength. The inter-laminar stress level is associated with the specimen geometry and loading parameters while the inter-laminar strength is related to the material properties. It is the inter-laminar strength which is the weak link for composite laminates as it relies on the brittle matrix properties and the bonding strength of the fibre/matrix interface. To achieve the optimum delamination resistance in the composite structure it is necessary to choose an optimum combination of the parameters to obtain a lower inter-laminar stress level with higher inter-laminar strengths.

Numerous reinforcing techniques have been developed to combat the problem of delamination. These reinforcing concepts can be classified either as improvement of the materials or modification of the fibre architecture. Materials improvement requires increasing the fracture toughness of the composite laminate resulting in improved inter-laminar strength. Recognition of the importance of inter-laminar fracture toughness to composite damage tolerance has led to the development of interfacial coatings to control the interfacial strength, to toughened thermoset or thermoplastic resins and to the hybridization of the fibres in the composite structure. Placing the fibre where it is needed by the efficient use of fibre architecture is a more direct method to achieve significant improvements in the inter-laminar and intra-laminar strength. Through-thickness reinforcing can provide improved inter-laminar strength and delamination resistance while producing a more integrated composite structure. There are two basic categories of fibre architecture for through-thickness reinforcing: fully integrated (3D) systems produced by textile processing and systems manufactured from planar lamina with selective through-thickness reinforcing. Neither of these solutions is particularly straightforward. To produce 3D composites such as weaves or braids, some special techniques have been developed; however, their complexity, limited shape-ability and processability minimizes their use to special applications where highly tri-axial stress states are predominant while the manufacturing of through-thickness reinforced composites from 2D constructions, stitching or interleaving, normally require at least one additional production step.

With the increasing demand for larger allowable design strains and reliability of aerospace structural components it is suspected that the improvement of the fracture toughness using improved materials alone will not be sufficient. Thus, the concept of third direction fibres to provide through-thickness reinforcing is promising.

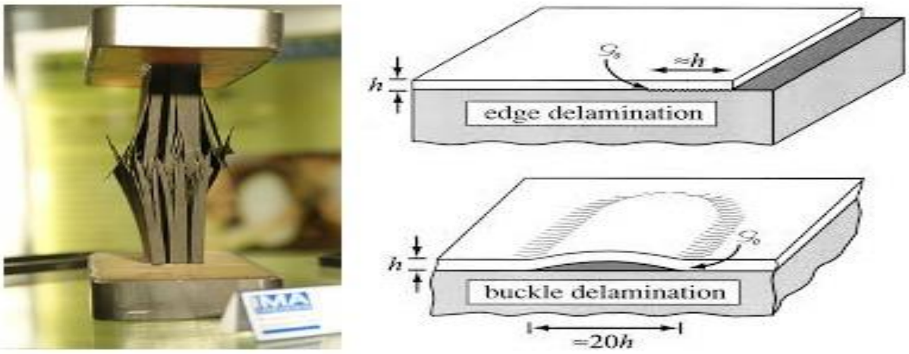

Figure-2: Different types of delamination

II. LITERATURE SURVEY:

1. Kimberley Dransfield, Caroline Baillie & Yiu-Wing Mai (1993) in their work "IMPROVING THE DELAMINATION RESISTANCE OF CFRP BY STITCHING – A REVIEW" carried out a study on the delamination resistance in carbon fibre reinforced polymers and the manufacturing process of them. They also carried out a research on the effect of micromechanics in the delamination resistance and also discussed on the stitching parameters and how they affect the delamination resistance. They also mentioned the advantages and limitations with explanation.
2. Kunal Singha (2012) in his work "A SHORT REVIEW ON BASALT FIBER" has carried out a research on the physical and chemical properties of basalt fibres, their chemical composition and how the basalt fibres are spinned. In addition to this he also mentioned the manufacturing of basalt fibre laminates and the modifications required to the manufacturing line. He also mentioned various fields where basalt fibres have huge applications.
3. S.M.SPEARING, A.G.EVANS (1992) in their work "THE ROLE OF FIBER BRIDGING IN THE DELAMINATION RESIUSTANCE OF FIBER-REINFORCED COMPOSITES" has carried out experimental works on laminated brittle matrix composites reinforced with Nicalon fibres. They considered both the linear and non-linear behaviour of the composites during testing. They found that the bridged fibres resisted the crack growth and graphs like normalized resistance v_s crack growth and load v_s displacement curves were plotted
4. R Muruganadham, Velamurali (2016) in their work "Low Velocity Impact Analysis on Stitched and Unstitched Laminates" worked on how the low velocity impact loads can cause damage to the laminates. In their work they manufactured both the stitched and unstitched laminates and conducted impact tests with the help of drop weight impact test machine by varying the fibre orientations. They also analysed the damage incurred at the outlet and inlet, graphs like load v_s displacement, damage area v_s impact energy, damage area Vs stitch density are plotted.
5. V Nanthagopal, T Senthilram, VR Giri Dev(2013) in their work "Flexural and impact studies on stitched self-reinforced polypropylene composites" have manufactured the self-reinforced composites from woven polypropylene tapes and stitched by lockstitch. They conducted the flexural and impact tests on the stitched laminates by varying the stitching parameters such as Stitch density, sewing yarn count and the direction of stitching and found that there is a significant effect on the mechanical properties than the normal one.
6. J.Dasa Prakash, G.Sai Krishnan, P.Sethu Ramalingam, C.Murugan (2018) in their work "PERFORMANCE ANALYSIS OF STITCHED AND UNSTITCHED GLASS FIBER WITH JUTE MATERIAL USING EPOXY LAMINATES" manufactured the glass fibre and jute fibre mixed epoxy composite laminates, conducted the tensile and compression shear tests on both stitched and unstitched laminates and the stress-strain curves are plotted for both the stitched and unstitched specimens.
7. Zongwen Li, Jianxun Ma, Hongmin Ma, Xin Xu (2018) in their work "Properties and Applications of Basalt Fiber and Its Composites" have mentioned the manufacturing processes of the basalt fibres in continuous form, short cut form, fabric cloth form. They also mentioned the physical and chemical properties of the basalt fibres and compared the important mechanical and physical properties with its commercially competitive neighbours.

III.MANUFACTURING PROCESSES:

i. Stitching:

In the stitching process, a stack of plies consisting of in-plane fibres is penetrated and bound together by means of needle and bobbin threads. The drive shaft has a vertical crank attached to it, going down under the base plate. Again, by a series of levers, this connects to a hook ring. The hook ring picks up the upper thread and guides it round the bobbin holding the lower thread. Using the up and down movement of the needle and the rotation of the hook ring, the two threads are looped together to form the stitch.

The various types of stitching patterns are

1.Lock stitch
2 .Plain stitch
3. Chain stitch
4 .Modified lock stitch

➢ Stitching can be done by industrial sewing machines for faster work by using polyester and cotton yarn threads

➢ In order to reduce the distortion in interior of the laminate, modified lock stitch is adopted for stitching by easing the tension of needle thread.

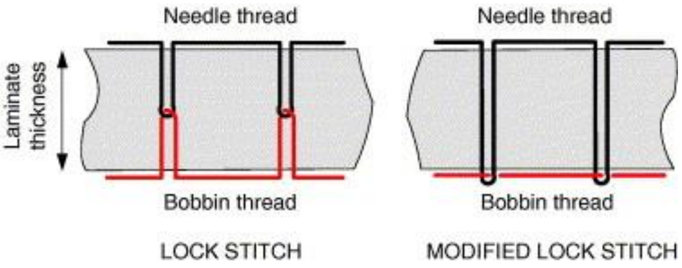

Figure-3: Difference between lock stitch and modified lock stitch *ii. Resin preparation:*

- Resin is used to transfer the stress between the reinforcement fibres and acts as a glue to hold the fibres together in the laminate preparation. Some of the commonly used resins are epoxy, polyester and vinyl ester
- Epoxy is one of the most commercially used resin which belongs to a class of reactive pre-polymers and polymers which contain epoxide groups.
- Epoxy resins may be reacted both with themselves through catalytic homo-polymerisation or with a wide range of co-reactants to form a thermosetting polymers.
- These co-reactants are commonly referred as hardeners or curatives and the cross-linking reaction is commonly referred to as curing.
- Some of the commonly used hardeners at different temperatures are mentioned below:
    - HY951 – at room temperature.
    - HT927 – temperature ranging from 80˚C - 130˚C
    - HT974 - temperature ranging from 70˚C - 80˚C
    - HZ978 - temperature ranging from above 100˚C
- Resin is prepared by mixing the Epoxy LY556 with the hardener HY951 in the ratio of 10:1.
- Resin is stirred frequently otherwise it will be hardened.

Figure-4: Epoxy resin, hardener and resin preparation jar with stirrer

iii. Moulding preparation

- Two rectangular hard-boards with smooth and flat surface of dimensions 400mm x 400mm is taken.
- Two rectangular plastic sheets of 400mm x 400 mm dimensions are taken and placed over the hard-boards which can be held firmly with the help of stick tapes and clamps.
- Now release gel such as wax or paraffin is applied over the plastic sheet uniformly with brush which avoids the sticking of laminates while removing from the mould.

Figure-5: Flat hard board with plastic sheets, release gel and release gel coating on moulding surface

iv. Laminate preparation

1. Un-stitched laminate

- Initially the basalt fibre fabric is taken and marked with 300*300 dimension lines with the help of marker and cut down into laminate plies with the help of scissors.
- Now resin is poured on the wax coated sheet and is applied uniformly with the help of brush and laminate ply is placed over it.
- Now again pour some resin and is thoroughly impregnated into the pores of the laminate with the help of brush.
- Now another ply is taken and placed exactly over the previous laminate and the above process is repeated up to eight layers.
- Now the second wax coated sheet is taken and placed over the laminate.
- Now with the help of roller, force is applied on the laminate in order to force the resin to move into the voids and the laminate plies are sticked firmly one over another.
- Now another flat plate is placed over the laminate and a uniform weight of 10 kg is applied over it and allowed for 12 hours to cure.
- After curing the laminate is taken out and extra material attached to it is cut down.

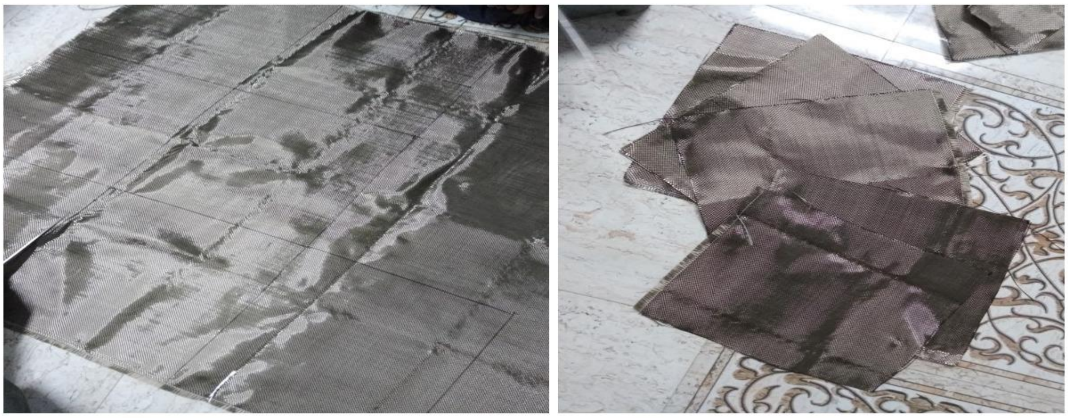

Figure-6: Basalt fabric with markings cutted down into plies of required dimensions

Figure-7: Layer by layer preparation of laminate through impregnation of resin with brush

2. Stitched laminate

- In this laminate, initially plies are placed over one another and stitched with the help of sewing machine with cotton yarn as thread.
- The stitches are made in cross direction (45◦) with 2.5mm between each stitch and 1cm distance between each line of stitch such that on average of 4 stitches/cm^2 .
- Now the sewed pre-peg is placed over the release gel coated sheet and resin is poured and impregnated forcedly such that it reaches into small voids such that resin is applied uniformly.
- Now the laminate is kept under uniform load and allowed for curing same as unstitched laminate.

Figure-8: Impregnation of resin into stitched plies and application of uniform load over it

v. Specimen preparation

- After curing the laminate is taken and its outer edges are trimmed such that it has good edges without any fiber distortion.
- Now the obtained laminate is cut down into the specimens of sizes 80 mm x 10 mm and 250 mm x 25 mm.

Figure-9: Basalt fibre composite laminate specimens

IV. EXPERIMENTAL TESTS:

i. Tensile Test:

- Tensile testing is also known as tension testing, is a important materials science and engineering test in which a sample is subjected to a controlled tension until failure.
- Properties that are directly measured through tensile test are ultimate tensile strength, breaking strength, maximum elongation and reduction in area and by using these measurements properties such as Young’s modulus, Poisson’s ratio, yield strength and strain hardening characteristics are also determined.
- The most common testing machine used in tensile testing is the universal testing machine powered by hydraulic or electromagnetic with data acquisition.
- Now the specimens to be tested are fixed firmly in the upper and lower jaws and the tests are carried out for both the stitched and unstitched specimens and observed values are noted and stress-strain curves are drawn.
- The above process is repeated for another set of specimens as mentioned above.

Table-2: Tensile test of stitched and un-stitched specimens

Test Parameters	Units	Observed values			
		Basalt fibre With Unstitched One		Basalt fibre With Stitched One	
		T1	T2	T1	T2
Gauge Width	mm	24.11	24.53	26.55	24.74
Gauge Thickness	mm	2.27	2.34	2.01	2.00
Original Cross Sectional Area	mm^2	54.73	57.40	53.37	51.48
Ultimate Tensile Load	KN	12.63	13.09	19.02	18.56
Ultimate Tensile Strength	MPa	231.00	228.00	356.00	361.00

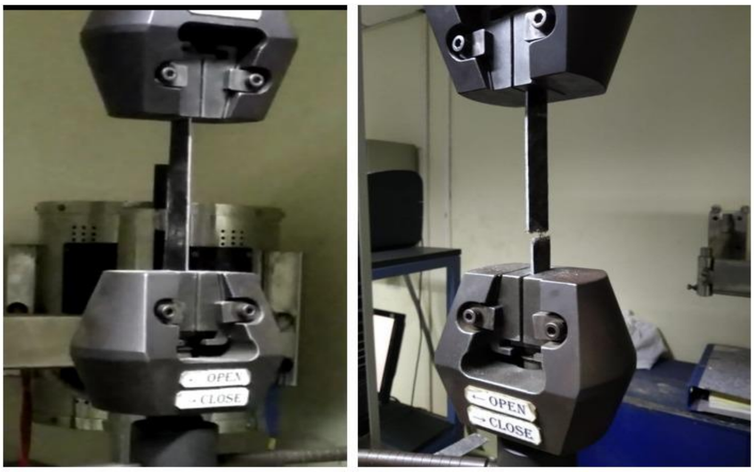

Figure-10: Tensile test (before testing and after testing)

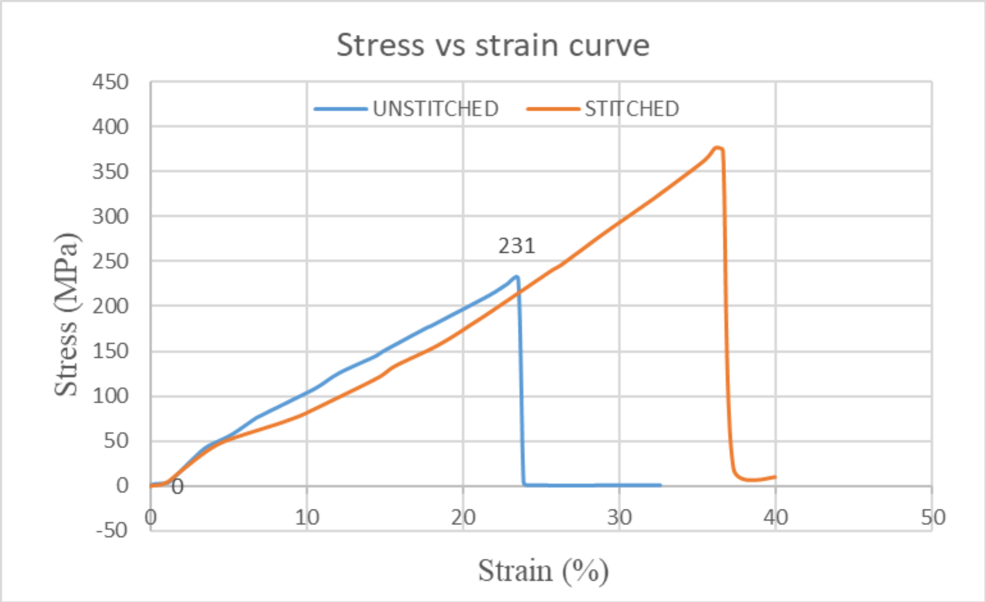

Figure-11: Stress vs strain curves of stitched and unstitched specimen during tensile test

ii. Impact test:

- Impact test is a method for evaluating the toughness and the notch sensitivity of engineering materials. It is usually used to test the toughness of the metals, but similar tests are used for polymers, ceramics and composites.
- The Charpy impact test is a standardised high strain-rate test which determines the amount of energy absorbed by a material during fracture.
- The absorbed energy is a measure of a given material's toughness and acts as a tool to study temperature-dependent ductile-brittle transition.
- It is convenient to use in industries, since it is easy to prepare and conduct and results can be obtained quickly and cheaply.
- Now the specimens prepared were placed in the position and tests are carried out for required no of stitched and unstitched specimens and the observed values are noted.

Table-3: Impact test of stitched and unstitched specimens

Sample Id	Specimen Size	Test Temperature	ID-1	ID-2	ID-3	Average
Basalt Fibre With Unstitched One	2 x 10 x 80	25^{0}C	02	04	02	2.67
Basalt Fibre With Stitched One	2 x 10 x 80	25^{0}C	06	08	06	6.67

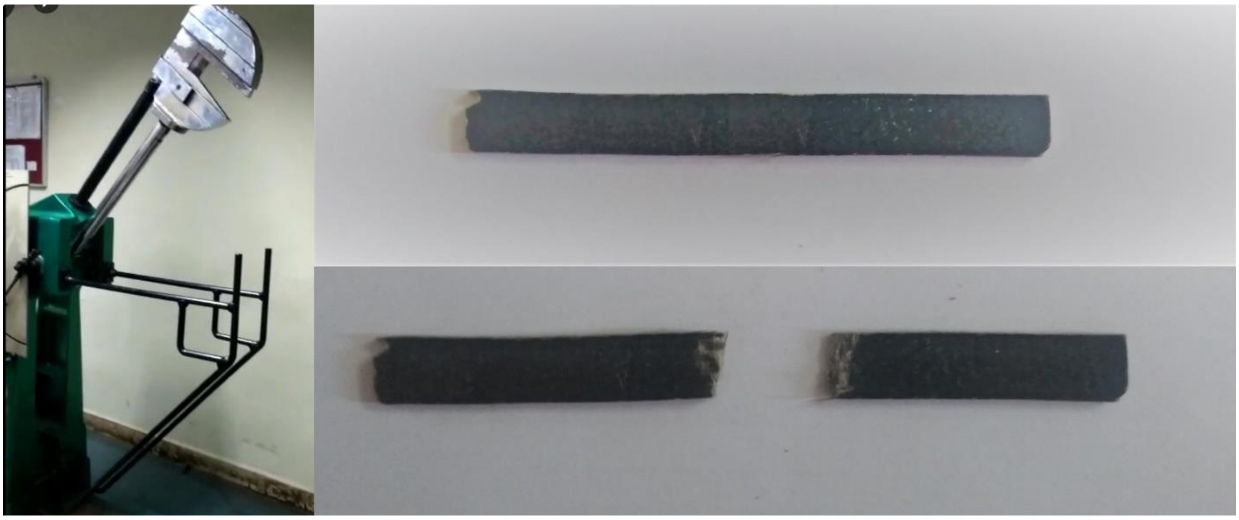

Figure-12: Charpy impact test machine, specimens before and after impact test

iii. Flexural test:

- Fracture toughness is a material property that describes resistance to fracture and delamination. It is denoted by critical stress intensity factor KC or critical strain energy release rate GC.
- For Unidirectional reinforced polymer laminate composites, ASTM provides two tests for inter-laminar fracture toughness i.e. Double cantilever beam test and Edge notch flexure test.
- We can select Edge notch flexure test i.e. Three point flexural test to determine the delamination resistance.
- Initially we induce some initial crick and specimen is placed in the position, tests are carried out and the obtained values are noted and load-displacement graphs were plotted.

Table-4: Flexural test of stitched and unstitched specimens

Test Parameters	Units	Observed values			
		Basalt fibre With Unstitched One		Basalt fibre With Stitched One	
		T1	T2	T1	T2
Gauge Width	mm	24.73	24.56	27.12	26.24
Gauge Thickness	mm	2.24	2.38	2.02	2.06
Original Cross Sectional Area	mm^2	55.40	58.45	54.78	54.05
Compressive load	KN	0.27	0.26	0.37	0.34
Compressive Strength	MPa	5.00	4.00	7.00	6.00

Figure-13: Flexural Test (before test and after test)

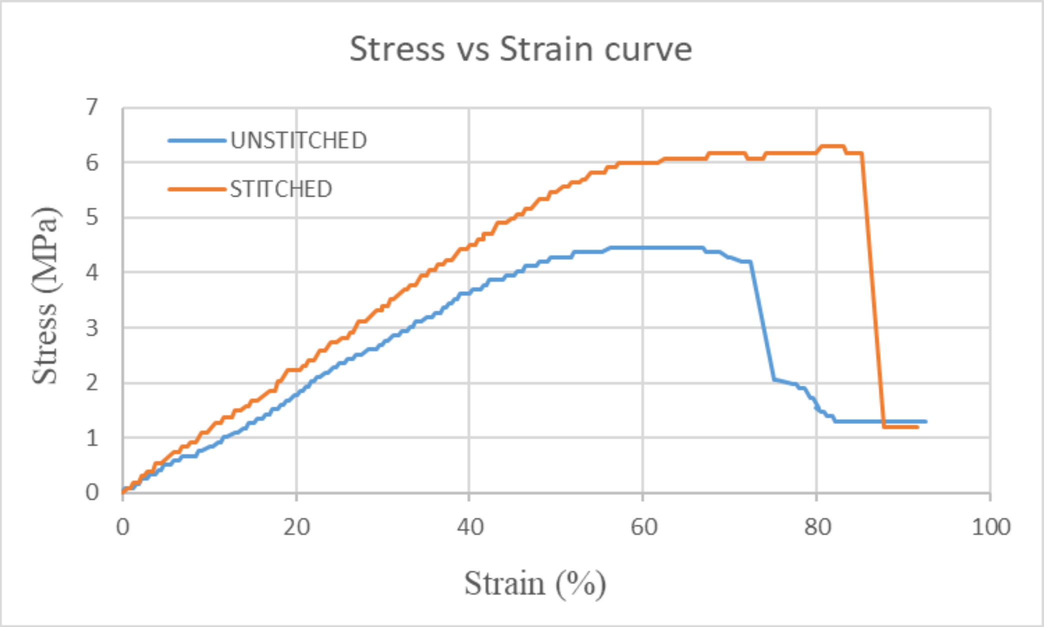

Figure-13: Stress vs strain curves of stitched and un-stitched specimens during flexural test

V. CALCULATIONS AND RESULTS:

- % Increase in impact strength = $\frac{\text{Energy absorbed by stitched specimen – Energy absorbed by unstitched specimen}}{\textit{Energy absorbed by unstitched specimen}}$

  $= \frac{\mathbf{6.67-2.67}}{\mathbf{2.67}}*100$

  $= 149.81 = 150\%$

- % Increase in tensile strength = $\frac{\text{Tensile strength of stitched specimen}-\text{Tensile strength of unstitched specimen}}{\text{Tensile strength of unstitched specimen}}$

  $= \frac{358.5-229.5}{229.5}*100$

  $= 56.21\%$

- % increase in delamination resistance = $[\,(\frac{G2}{G1}-1)*\ 100\,)$

Candidate fracture toughness / Delamination resistance $G_Q = \frac{3mPmax^2a0^2}{2B}$

Where, m = Fitting parameter determined by least squares method
Pmax = Maximum load
a = Crack length
B = Thickness of laminate

As two specimens have same thickness, initial and final crack lengths .Therefore,

B1 = B2, a1=a2, m1 = m2

i.e. $\frac{G2}{G1} = \frac{P2^2}{P1^2} = \frac{0.355^2}{0.265^2} = 1.7945$

% increase in delamination resistance = $[(\frac{G2}{G1}-1)*\ 100]$

$= [(1.7945 – 1) *100]$

$= 79.45\%$

VI. ADVANTAGES AND LIMITATIONS:

i. Advantages:

- Stitched laminates shows better mechanical properties i.e. impact, tensile and flexural strength than that of the unstitched laminates.
- Stitching is a simple process which adds just one additional step to the normal manufacturing process of laminates
- No heavy machinery required as it can be done with the normal or industrial sewing machines.
- The stitches holds the laminate plies which doesn’t let the layers to slip one over another and resists the shear loads very well.
- Stitching cost is very less and requires semi-skilled labour.

  - It avoids the usage of additional chemicals to increase the mechanical properties of a laminates.

ii. Limitations:

  - Stitching causes localised in-plane fibre damage due to the penetration of the needle.
  - There is a material discontinuity at the stitching point in the composite structure which can lead to high stress concentration.
  - The presence of the through-thickness reinforcing fibres creates resin rich pockets that reduces the volume fraction of in-plane fibres to the analogous composites

VII. AREAS OF APPLICATION:

- In Petro-chemical industry, basalt fibre stitched laminates are used for manufacturing of chemical, wear resistance tanks and for non-flammable fittings and pipe coverings.
- In Automobile industry, due to its good heat and sound insulation property, high impact and fracture toughness these are used for manufacturing of automobile mufflers, gaskets, insulation screens etc.,
- In Fire safety, they play a major role in fire safety equipment manufacturing such as fire-proof jackets and other fire safety components.

VIII. CONCLUSION:

The present experimental work involves the fabrication of stitched and unstitched basalt fibre epoxy composite laminates. The following conclusions were drawn from the response of the stitched and unstitched laminates to the above mentioned tests:

- Impact resistance of the stitched laminates is increased nearly 150% when compared to that of the unstitched laminates.
- Delamination resistance / Fracture toughness property of a stitched laminates increased by 79.45% than that of the unstitched laminates.
- Tensile strength of the Stitched laminates shown an increase of 56.21% to that of unstitched laminates.

From the above results we can conclude that Stitching to provide through-thickness reinforcement of basalt fibre composites is a promising concept. This technique significantly improves some mechanical properties. The extent to which the mechanical properties are affected by stitching is dependent on the stitching and testing parameters, and on the fabrication techniques. To maximize delamination resistance with minimal loss of in-plane mechanical properties, an optimal combination of the stitching and fabrication parameters will need to be identified.

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