NUMERICAL ANALYSIS OF CARBON FIBRE/EPOXY STITCHED LAMINATES WITH VARIED THROUGH THICKNESS STITCHED DENSITY

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Abstract

Carbon-fibre/epoxy T800SC-24kf laminates with stitch thread of vectran 200d with different stitch density (0.11mm^{-2} and 0.028mm^{-2}) has been analyzed for deformation behavior under in-plane tensile loading based on continuum mechanics. Laminates have been modeled on lamina wise basis to obtain macroscopic damage and stress-strain distribution. During this numerical analysis stitch and lamina are modeled separately and bonded together with contact capability. Discretization procedures for the principle of virtual work and in addition with discretizing the contact traction have been utilized. While progressive failure analysis, has been carried out to characterize failure behavior of the laminate. Post-failure analysis has been carried out for transverse crack densities quantization. This analysis showed strength, stiffness and crack propagation depends upon reinforcement density or locations of stitch. Average transverse crack density has been calculated with an experimental calibration of crack onset stress value. This finite element method result has been validated with experimental result.

1. Introduction

Through-thickness reinforcement (TTR) helps to enhance interlaminar toughness and suppress damage in composite laminates. TTR is commonly performed by two methods. The first method includes reinforcement process performed on dry performs followed by resin infiltration and curing. This reinforcement process avoids severe fiber breakage than reinforcing in pre-preg tape [1],[2]. The second method includes z-pinning reinforcement process which is carried out before curing laminates [3]. A new approach for TTR was proposed recently by drilling circular holes through-thickness and inserting fibrous carbon rods into the host laminates after it was cured. The bonding between rod and laminate was done by liquid resin [4].

Tanzawa, et al [5] performed 2D finite element analysis for 3D-orthogonal interlocked fabric composite introducing slack absorption, tuning with frictional force. This research gives the fracture phenomena of z-fiber yarn in which z-yarn was perfectly bonded initially. Some of

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the major parameters that influence stitched laminate mechanical properties are ply thickness, laminate streaking sequence, stitching thread properties, stitch row spacing and stitch pitch. Cox [6] reports that TTR is not strongly influenced by volume content or diameter of reinforced stitch or 3D weaving tows. Moreover, it has been reported that there is contradicting conclusion on in-plane properties improvement [3],[6],[7],[8] degradation[9],[10],[11] due to reinforcement. Findings, that report reduction on mechanical properties on stitching tend to correlate the reduction is the result of fibre waviness or misalignment (in-plane and out-of-plane), breakage of in-plane fibre and resin rich region.

On most of the aerospace grade, composite materials strain has been found to be large as compared to stress due to matrix failure. Transverse crack is most common crack arrested at initial phase loading on laminates. This transverse crack has been followed by oblique crack and interlaminates delamination. It has often been observed that delamination starts at that point where a macroscopic inter-fibre crack i.e. matrix crack meets the interface between two laminae. This inter-fibre crack develops and allows delamination to different interfaces [12].

This paper presents the evaluation of stitch laminates at the macroscopic structural level, in which stitched and lamina are discretized with contact capability. While progressive failure analysis have been carried out to characterize failure behaviour of the laminates. Post-failure analysis has been carried out for transverse crack densities on multi-axial laminates. This finite element method (FEM) result has been validated with the experimental result [13]. Using this formulation, stitched laminate of T800SC-24kf were analysed under tensile loading with laminate staking sequence of $[+45/90/-45/02/+45/902/-45/0]_s$. Vectran 200d thread have been employed for stitching on the composite specimen: moderately stitching has stitched density of 0.11mm^{-2} and highly stitching has stitch density of 0.028mm^{-2}

2. EXPERIMENTAL ANALYSIS

Coupon test was prepared following SACMA SRM 4R94 standard instructions titled “Tensile properties of oriented fiber-resin composites”. Specimen of 250 mm x 25mm x 4 mm, T800SC-24f, XNR/X6813 manufactured by Toray Industries was cut from a mother plate. Instron 8802 with maximum load capacity of 100kN was used for tensile loading at the rate of 1mm/min. Moreover, single element strain gauges from Kyowa were used for strain measurement using Kyowa DB-120T8 bridge box for connecting strain gauge, amplification and signal conditioning.

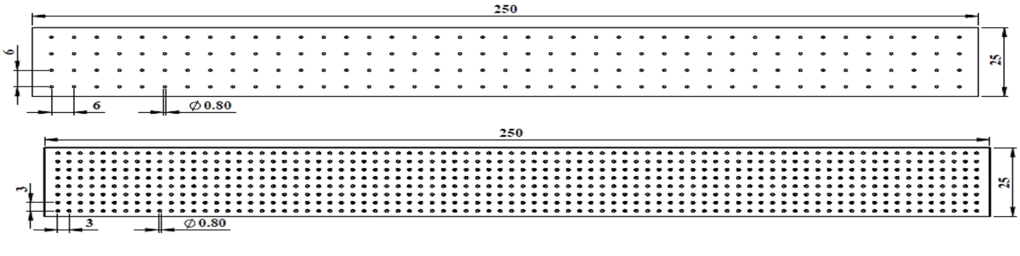

Fig1. Schematic of 6x6 Stitched and 3x3 Stitched Laminates

3. FINITE ELEMENT ANALYSIS (MACROSCALE)

3D structural modeling fig. 2(a) & (b) has been carried out for stitched laminates because of its capability to realistic physical representation and in-plane, out-of-plane laminates behavior. Finite element model of stitched composite coupon of 6x6 and 3x3 with stitch density 0.028mm^2 and 0.111mm^2 has been analyzed with total element size of 131840 and 637608

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respectively. Moreover, modeling with stitch has been given importance in this analysis to study the effect of the stitch on laminates. Interfaces between matrix and stitch yarns are modeled by contact. Together with 3D modeling, Puck's failure theory can incorporate post-failure analysis. In this analysis, post failure analysis has been carried out for quantization of transverse crack density.

During this analysis, single element per lamina has been employed in contrast to define laminate staking sequence in single element through the thickness. In this formulation, lamina properties have been assigned separately with layer-by-layer. Multi-layered laminates have been modelled with orthotropic material definitions for each lamina on table 1 and table 2. This approach transfers laminate definition based on material properties to lamina geometric orientation defined by stacking sequence. While, nodes in between lamina has been shared. Solid element has been generated for composite laminate and stitches individually. Staking sequence of [+45/90/-45/02/+45/902/-45/0]s has been defined on an individual layer of the laminate.

For the modeling of stitch, emphasis has been taken for stitching process as well. Stitching process consists of inserting a needle, carrying stitch thread through a stack of fabric layers. Fibers are arranged along two axial lines and series of stitch yarn with predefined pitch are thrusted into fiber layers [1]. Henceforth stitch and laminates have been disintegrated while modeling.

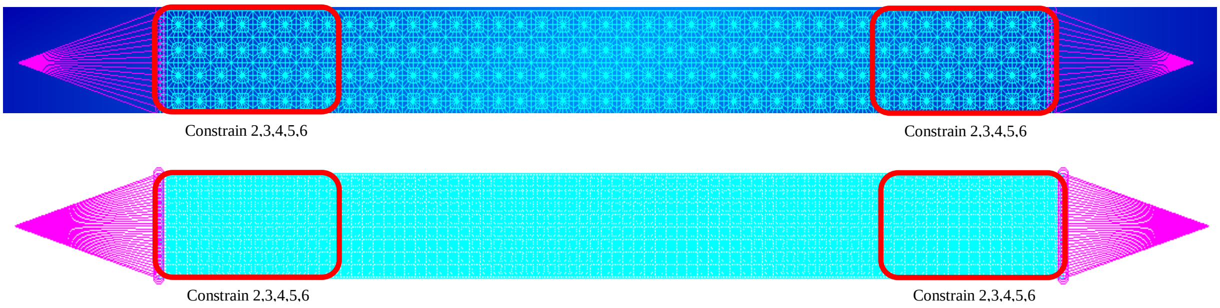

Fig 2. Loading and boundary condition for stitched laminate (a) 6x6 stitched laminate (b) 3x3 stitched laminate

Table1. Material PropertiesT800SC-24k	Unstitched	6x6 Stitched	3x3 Stitched	Vectran 200d
Longitudinal Modulus (GPa) E_x	133.9	140.1	146.2	75
Transverse Modulus (GPa) E_y	8.389	8.356	8.322	3
Out-of-plane Modulus (GPa) E_z	8.431	8.298	8.165	3
In-plane Shear Modulus (GPa) G_{xy}	9.879	9.935	9.991	5
Out-of-plane Shear Modulus (GPa) G_{xz}	9.902	9.995	10.09	5
Out-of-plane Shear Modulus (GPa) G_{yz}	4.790	4.852	4.913	5
Poisson's ratio ϑ_{xy}	0.347	0.348	0.348	0.3
Poisson's ratio ϑ_{xz}	0.329	0.338	0.348	0.012
Poisson's ratio ϑ_{yz}	0.472	0.464	0.455	0.3

Table 2. Material Properties T800SC-24kf and Epoxy XNR

Fiber Tensile Strength (GPa)	5.49
Fiber Compressive Strength (GPa)	2.6
Matrix Tensile Strength (MPa)	80
Matrix Compressive Strength (MPa)	50

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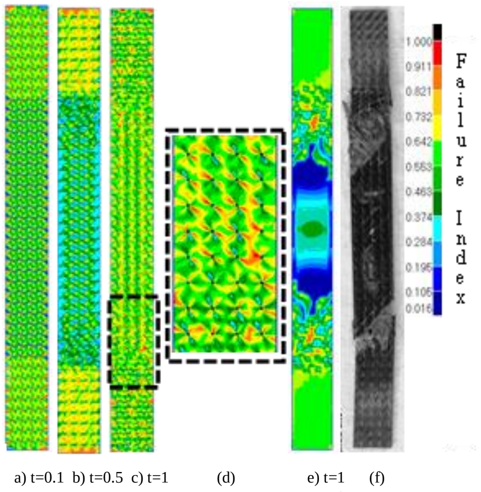
4. Results and Discussions

4.1. Progressive Damage Analysis

Progressive damage analysis in fig. 3(a-c) and fig. 4(a-c) shows 6x6 stitched laminate and 3x3 stitched laminates with stitched thread. While fig. 3(e) and fig. 4(e) depicts 6x6 stitched and 3x3 stitched laminates with homogeneous material properties. FEM result shows initiation of damage has occurred at the edges as shown in fig. 3(a) and fig. 4(a). With the increase in load, these damages are prominent in between the stitch as shown in fig. 3 (b) and fig. 4 (b). Stitch had suppressed crack propagation to some extent, as 3x3 stitched laminates are capable of holding more stress than 6x6 stitched laminates.

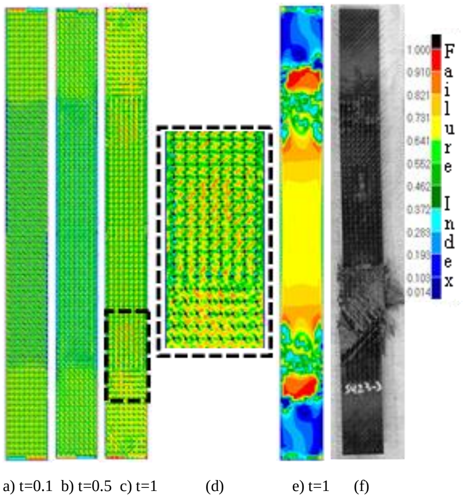
Damage analysis at stage fig. 3-4(c) showed that damage occurred at contact region which signifies matrix debonding at resin rich region which eventually lead to stitch fibre breakage. This phenomenon has also been observed in 2D orthogonal stitched laminates[5]. Thus, simultaneous matrix-crack and fibre-matrix debonding finally lead to catastrophic failure of the laminate. Fig. 3 (c-d) and fig. 4(c-d) (fig. d showed magnified counter near grip area) showed that both laminate finally failed at the vicinity of grip area which flowed towards the center. In both cases for 6x6 and 3x3 stitched laminates FEM analysis were able to predict damage effectively. It is to be noted that in fig. 3(e) and fig. 4(e) homogeneous idealization could predict final failure of the laminates but unable to correlate the effect of stitching in laminates. Thus, modelling with stich will help designers to know the behaviour of laminates in detail.

In a layer-wise failure analysis defined by Puck a macroscopic crack through the entire lamina causes failure of a lamina. Damaged portion of lamina no longer transmit any load but neighboring laminae still induce load into the sound sections of the damaging lamina. This result in multiplication of cracks if more loads is applied. Hence, with an increasing crack density, the load which is carried by the damaging lamina reduces and the load is redistributed to the neighboring laminae itself. At a saturated crack density, the sound sections of the damaging lamina have become so small that the induced load is no longer sufficient for producing further cracks. At this point the damage development in the considered lamina is completed, even if more loads is applied. This saturated crack has been employed to calculate transverse crack density in correlation with experimental crack onset stress in section 4.3



a) t=0.1 b) t=0.5 c) t=1 (d) e) t=1 (f)

Fig 3. Damage Propagation of 6x6 stitched laminate



a) t=0.1 b) t=0.5 c) t=1 (d) e) t=1 (f)

Fig 4. Damage Propagation of 3x3 stitched laminate

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4.2. Laminate Behavior

Fig. 5 depicts force-displacement curve of stitched laminates which describes the damage progression of stitch laminates. It shows that increased in stitching would improve laminate load carrying capacity under in-plane loading before first ply failure. Load drop signifies the point of damage initiation with first ply failure. At detailed modeling approach, it has been noticed that; immediately after the first ply failure 3x3 stitched laminates has lower strength than 6x6 laminates i.e. in-between 0.3-0.5mm displacement. This is due to sudden release of residual stress and multiplication of cracks after first ply failure. However at higher displacement highly densed stitched laminate is capable enough to suppress cracks propagation effectively than moderately densed stitched laminates. Thus highly densed stitched laminates had better in-plane tensile properties at global laminate fracture as well.

Moreover, analysis based on homogenized laminates; highly densed stitched laminates showed constantly higher strength than moderately stitched laminates even after first ply failure. Also, it showed higher strength than detailed laminate analysis. This is because it neglects detail simulation of the stitch. Hence, it can be concluded that idealizing model leads to overestimation of strength which was also reported on for 3D woven analysis [16]. Therefore, for the in-depth understanding of reinforced laminate structure, detail modeling is essential.

Fig. 6 depicts stress-strain distribution of 6x6 & 3x3 stitched laminate with finite element and experimental analysis, which shows that highly densed stitched laminate have slightly higher stiffness to moderately densed stitched laminate on in-plane tensile loading. It shows that failure has been initiated earlier in moderately densed stitch at 0.46% strain than highly densed stitch at 0.53% strain, which is 15.2% higher. Using this finite element (FE) technique, it showed a good agreement with the experimental result. During the analysis once the failure initiation has been detected, material stiffness coefficient degrades in a gradual manner given by[15]: $\Delta r_i = -(1 - e^{1-F})$

where r_i is stiffness reduction factor and F is failure index. Elastic modulus, shear modulus and poisons ratio are updated based on stiffness reduction factor as: $E^{new}=r_iE^{original}$, $G^{new}=r_iG^{original}$ $\vartheta^{new}=r_i\vartheta^{original}$. Final reduction facture has been found to be 0.027 and 0.089 for 6x6 stitched laminates detail modelling with stitch and homogeneous modeling respectively. Similarly, 0.022 and 0.088 for 3x3 stitched laminates detail modeling with stitch and homogeneous modeling respectively.

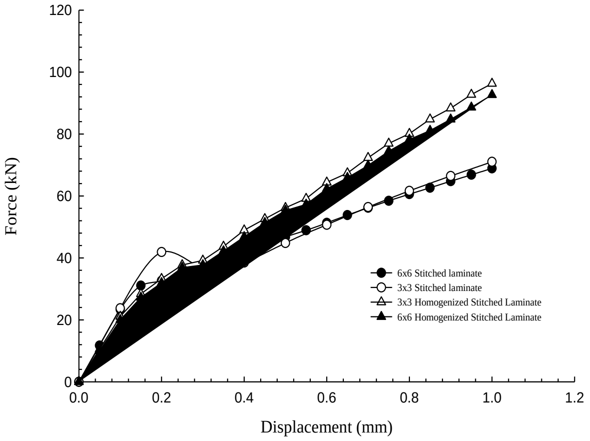

Fig 5. Load-deflection Distribution

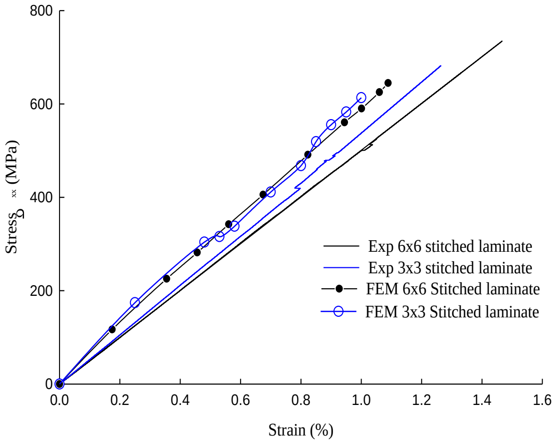

Fig 6. Stress-strain Distribution

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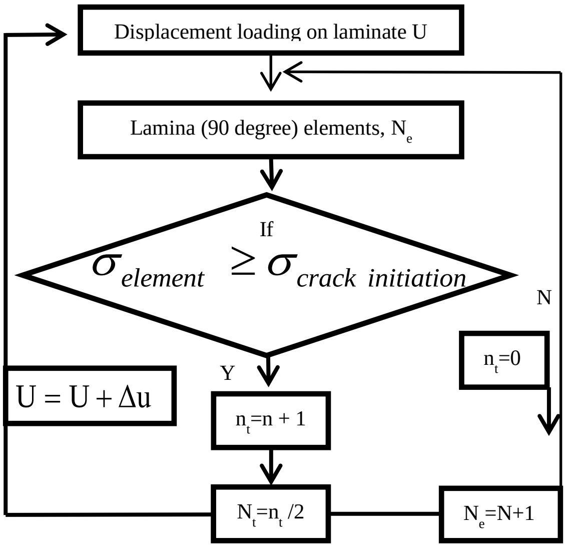
4.3. Post Failure Analysis

4.3.1. Average Transverse Crack Density Quantization



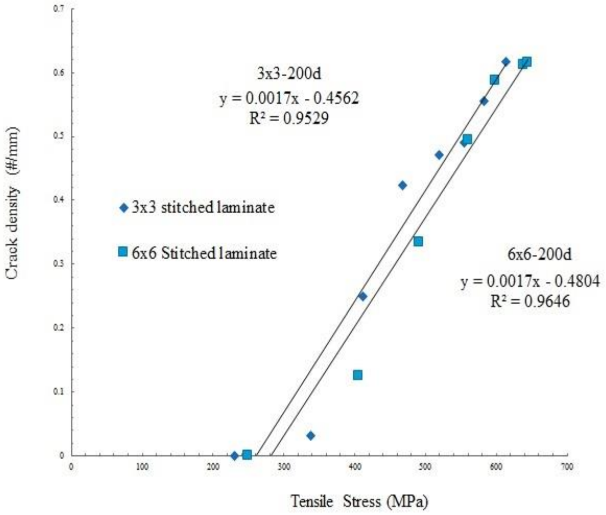


Fig 7.Transverse crack quantization methodology flowchart

Fig 8.Avg. Transverse crack density

For experimental damage characterization of transverse crack, interrupted test has been carried out at strain level of 0.5%, 0.6%, 0.7%, 0.8%, 1% and 1.2%[13][14]. For FEM transverse crack damage characterization post –failure analysis has been developed in which stress has been evaluated for every subcase. As transverse crack is developed on 90 degree laminas, a methodlogy has been developed as given by flowchart in fig. 7 for the quantization of transverse crack. Stress are has been evaluated for all integration points of each element from the 90 degree lamina excluding grip element. An evaluation is performed to predict damage initiation with the transverse crack onset stress. If it satisfies the condition i.e. element stress exceeds or equal to the experimental transverse crack onset stress, it is assumed that element develops a transverse crack.

Fig.7 depicting the methodology for the calculation of transvers crack density, where U= applied load, N_e= total number of element in lamina, n_t= number of transverse crack initiating point, N_t= total number of transverse crack. Transverse crack initiation stress has been determined from experiment [13][14] i.e. 6x6- 250 MPa & 3x3 – 231 MPa.

Further, it has been considered that there would be single crack if there are two such elements which exceed the crack stress. This process has been carried out with each load step until laminate catastrophic failure. Finally, these transverse cracks have been averaged between three 90 degree laminas. Then average transverse crack density per unit length has been calculated and illustrated as in fig. 8. Experimental linear regression curve fitting gives equation 6x6-200d: y = 0.0019x-0.4099 and 3x3-200d: y =0.0014x-0.2489 [13].

5. Conclusions

Numerical analysis of different stitch laminates at macroscopic structural level has been performed efficiently and accurately, which has been validated with the experimental results.

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This kind of detail analysis would be helpful for designers to understand stitched laminates fracture behavior in depth. Based on numerical simulation following points has been highlighted:

- Progressive failure analysis with puck's failure criterion has been capable of arresting fracture propagation along with the effect of stitching density. Also, x-ray radiography correlation shows that it could perfectly model crack propagation with detail modelling with stitch.
- TTR helps to enhance strength and stiffness of laminates. It showed that increase in stitched density would improve strength, stiffness by suppressing crack propagation on tensile loading.
- Stress-strain distribution has been validated with experiment. Also, this model is capable of obtaining the stress-strain distribution of through thickness throughout stitched structure which would be very important to understand structural behavior.
- Post-failure analysis has been carried out to quantize average transverse crack density. Algorithm develops and formulation to calculate average transverse crack has shown good correlation with experimental analysis.

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