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FEM Evaluations and Fabrication of Carbon Fiber Reinforced Polymer Laminates with Induced Discontinuities

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Article Info
Volume 83
Page Number: 5190 - 5196
Publication Issue:
March - April 2020

Article History
***Article Received**: 24 July 2019*
***Revised**: 12 September 2019*
***Accepted**: 15 February 2020*
***Publication**: 27 March 2020*

Abstract

The paper aims to study the possible discontinuities in the laminates resulting due to fiber extension and the influential behavior of the CFRP. The standard pattern of discontinuities is induced initially in the laminates prepared using CFRP prepreg with its impact on the strength is quantified experimentally. Experimental and Numerical studies are proposed to quantify the behavior of CFRP with induced continuities.

I. INTRODUCTION

Since the early dawn of civilization, the stiff, durable, and light material has always fascinated humankind for typical applications. The idea of combining two or more different materials resulting in a new material with improved properties. Composites bestowed with unique advantages like lightweight, high stiffness to weight, and high strength to weight ratio drew attention from the developed world towards novel application. Composite, the wonder material with lightweight, high stiffness to weight and high strength to weight ratio, and stiffness properties has come a long way in replacing conventional materials like metals, especially aluminium alloys.

Composite materials are heterogeneous materials, having two or more physically distinct components when combined, they become stronger and stiffer and perform superior to each of the different components. In general, a composite consists of a continuous phase known as matrix and the intermittent phase known as reinforcement. In a composite, fibers are principal load-carrying members, while the surrounding matrix keeps them intact in the desired position and acts as a load transfer medium between them. From the theoretical point of view, the fibers having excellent strength modulus, along with perfect bonding with the matrix is supposed to yield a quality composite material.

II. OBJECTIVES OF THE PROPOSED RESEARCH WORK

Study of the discontinuities in the fabrication of large composite laminates are as follows:

- Fabrication & characterization of CFRP with induced discontinuities for tensile & flexure behavior
- Finite element analysis (FEA) of CFRP with induced discontinuities for tensile & flexure behavior using NASTRAN.
- Comparing the experimental results with

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FEA outputs.

III. EXPERIMENTAL APPROACH

In this method, representative or full-scale models are considered for testing. Experimentation is costly, both in terms of test facilities, the model instrumentation, and the actual test, but yields realistic results.

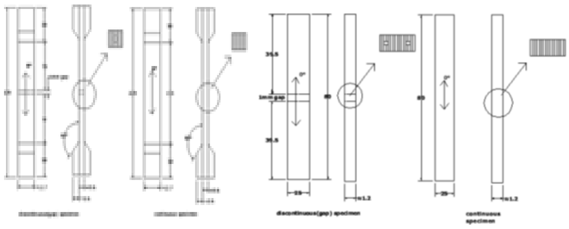
In this method, representative or full-scale models of CFRP composite can be tested. There are many standards like ASTM standards and DIN standards, which give procedures to check the laminates and composites to get the required properties of composites. Experimental Standards contain standard procedure of geometry requirements, load and boundary conditions, fixtures, testing machines, loading parameters, and formulae, etc.

In our project, the laminate with gaps and overlaps were fabricated according to ASTM D3039 for tensile and M790 for flexure. These laminates were tested in a universal testing machine. The failure load, stress, strain were directly read from the machine. Collation and analysis of results were carried out using MS-Excel and Mat lab.

Finished specimens

The laminates were cut according to respective drawings, which provided additional cutting allowances, edge allowances, etc. As a precaution, 2 mm of each edge of the laminates was trimmed as edges are prone to contain defects. Laminates were cut using markers, verniercalipers, and cutting tools. Corresponding drawings are shown in Fig 5.1, 5.2, and 5.3. Cut laminates having gap and overlap, were adequately identified and stored.

The coupons prepared, as explained earlier, were deburred using emery paper and cleaned using acetylene. Finally, the coupons were subjected to dimensional inspection to verify compliance with ASTM standard test specimen drawings, as shown in Fig 5.7, 5.8, and 5.9.



Experimental set-up

The objective of the experiment set up is to support the testing of laminates under tensile and flexure loads to evaluate the stress-strain relationships as well as failure loads.

Test procedure:

Strain gauge bonding

Strain gauges are bonding on the surface of the top or bottom of the coupon to get longitudinal and transverse strains. The strain gauge properties are shown in Table 5.6.

Manufacturer: Tokyo SukkiKenkyujo co. LTD.

Property	**Value**
Gauge type	FCA-2-11(tensile specimens) FLA-2-11(flexure specimens)
Gauge factor and gauge length	2.11 and 2mm
Adhesive	P-2
Gauge resistance	120±0.5Ω
Coefficient of thermal expansion	11.8*10-6/ºC
Temperature coefficient of gauge factor	+0.1± 0.05%/10ºC

Table 1 Strain gauge properties

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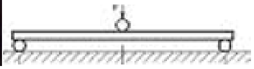

Fig 2: Tensile loading   Fig 3: Three-point bending test

Universal testing machine (UTM)

The tensile test is carried out using UTM and schematic diagram of the three-point bending test for the flexure loading of coupons, as shown in Fig 5.10 and 5.11. The appropriate tensile and flexure fixtures were selected. For flexure, the three-point bending test was carried out. The strain gauges are bonded, and longitudinal tensile load, as well as flexure bending load, was applied on the specimen at a speed of 1mm/min.

Test commands are set on the display screen. The machine automatically acquires the test data after the start command is executed. The specimen's maximum load during the test and the extension at specimen rupture are recorded.

FEM APPROACH

ANSYS: Is one of the FEM packages used to analyze composites material. For a composite material, ANSYS provides a wide choice of state-of-the-art failure, depth-investigation of product, design iteration, efficient engineering of layered composite structures, more flexibility, wrap-up capability, etc. Some of the advantages are it is easier to use, and minimal user inputs are required.

ABACUS: It provides all the qualities which are given by ANSYS. Better model cohesive elements, and creation of one part and make multiple instances of it are a few advantages. ABACUS has better nonlinear capabilities; specific algorithms are more robust and accurate. The powerful solver has a relatively underdeveloped GUI. It looks like any CAD package and features all of their advantages by manipulating 3D objects naturally, efficiently, and robustly.

PATRAN/NASTRAN: It has similar qualities which are given by ANSYS, like nonlinear capabilities, analysis of particulates composites, composite failure theories, etc. Some of the advantages are its user-friendliness, uniqueness in the modeling of laminates, cracks, gaps, discontinuities in composites, etc.

MSC NASTRAN is a general-purpose FEA tool used in the field of static dynamics, nonlinear, thermal, optimization, and a FORTRAN program containing over one million lines of code. NASTRAN software has been used for the analysis of CFRP laminates in this project. A small description of NASTRAN`S menu features is provided below:

FE modelling steps

The 2-dimensional surface was modeled according to geometrical dimensions. Surface geometry modeled has been meshed with 4-noded quadrilateral elements, represented as quad 4 in MSC/PATRAN.

Quad 4 element

Quad 4 element assumes that:

- Element is thin
- Nodal thickness may vary
- The response is limited to XY-plane

Essential features of the Quad 4 element are:

1. This element obeys the plane stress assumptions. It is appropriate for modeling thin, flat structures subjected to inplane loading only. Plane stress elements cannot bend out of their plane.

2. Plane stress elements must lie in the global XY-plane. If any nodes in the model have a local

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coordinate system, the Z-axis of that local system must be parallel to the global Z-axis.

3. The 2D Plane Stress Quadrilateral (4 nodes) is a first-order isoperimetric quadrilateral. The four standard linear shape functions are used, as well as two "incompatible nodes," which are quadratic polynomials associated with internal nodes. The incompatible modes improve the performance of the element markedly, without penalizing accuracy or convergence. After creating the element stiffness matrix, static condensation is used to eliminate degrees-of-freedom associated with the internal nodes, so that the element appears to the user as a 4-noded element with eight degrees-of-freedom.

4. This element is numerically integrated using a 2x2 grid of Gauss points. It has no "mechanisms" (spurious rigid body modes) and passes the patch test.

5. The 2D Plane Stress Quadrilateral (4 nodes) can be loaded with two kinds of distributed loads, which are edge pressure and edge shears. Pressure is in units of force per unit length and may be constant along the element edge, or linearly varying and interpolated from values at the corner nodes. Pressure loads are converted to equivalent nodal forces.

The discontinuities in the model are shown in Fig 6.3 6.5 and 6.6, which are meshed with quad elements with less respect ratio, to have a better understanding of stress variation as the discontinuous region is more relevant in this work. The aspect ratio, no of nodes and elements for six types of the specimen are tabulated in Table 6.1.

Type of specimen	no of nodes	no of elements	no of elements
G_1	820	691	Quad 4
G_2	1535	1351	Quad4
G_3 and	617	520	Quad4
G_5			
G_4	1020	800	Quad4
G_6	1450	1250	Quad4

Table 2: FE model properties

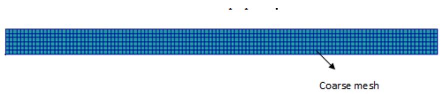

Fig 6.2: FE model for the continuous tensile specimen(G_1)

Load and boundary conditions

After meshing the specimens, the load and boundary conditions are applied as per respective ASTM standards. Strength degradation and failure loads in the specimen are analyzed by gradually increasing the loads and observing for failure.

Boundary conditions for tensile specimens:

For the tensile specimen, the left side tab region is constrained as per ASTM 3039. At left tab region T_x, T_y, T_z, R_x, R_y. R_z is fully constrained. Tensile load is applied at rightmost regions in steps of 490.5N for every increment, from 6867 N to 11772 N successively. The load and boundary conditions for tensile specimens are shown in Fig 6.7.

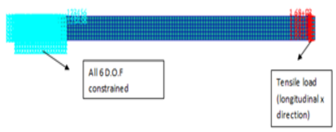

Fig 5: Load and boundary conditions for tensile specimens.

Boundary conditions for flexure specimens:

For flexure, a three-point bending test was done according to ASTM M790. For flexure specimens at support noses, the translational Tz and rotations R_x, and R_z are constrained, and all others are free. Flexure load is applied in z-direction for middle nodes in steps of 19.62N for each increment, from

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333.54 N to 706.32 N successively. The load and boundary conditions for flexure specimens are shown in Fig 6.8.

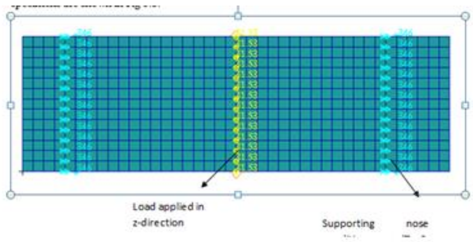

Fig 6: Load and boundary conditions for flexure specimens

IV. RESULTS AND DISCUSSIONS

For tensile continuous tensile specimen

In this case, as there are no fiber discontinuities in the specimens modeled, the stress, strain, and Tsai-Hill number for all layers are identical. The stress and Tsai-Hill number for critical layers are shown in Fig 7.7, 7.8.

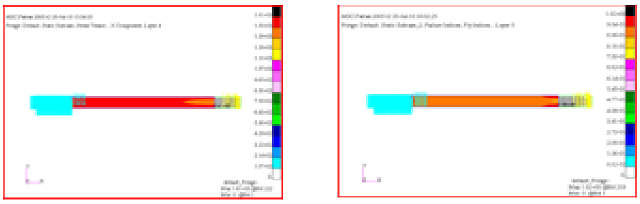

Fig 7: stress in the continuous tensile specimen for the 4th layer and Tsai-Hill index for a continuous tensile specimen for the 5th layer

For tensile discontinuous tensile specimen

In this case, there are fiber discontinuities in 4th and 5th layers. Stress withstanding capacity is less for these discontinues layers compare to continuous layers. The stress and TSAI-HILL number for critical layers are shown in Fig 7.9-7.12.

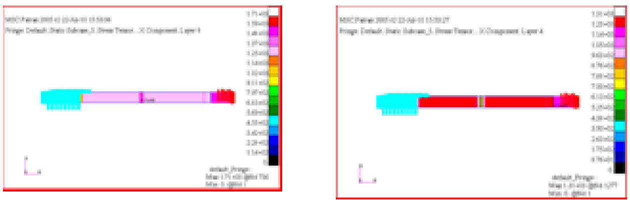

Fig 9: stress in the discontinuous tensile specimen for 8th layer and Stress in the discontinuous tensile specimen for the 4th layer

For continuous flexure specimen

In this case, as there are no fiber discontinuities in the specimens, the stress, strain, and Tsai-Hill number for all layers will vary according to the bending load applied and distance of lamina from the load point. The stress and Tsai-Hill number for critical layers are shown in Fig 7.13-7.16.

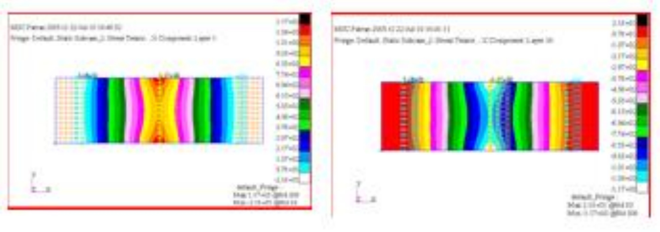

Fig 12, stress in continuous flexure specimen for 1st layer and Stress in continuous flexure specimen for 16th layer

For discontinuous flexure specimen

In this case, there are fiber discontinuities in 3rd, 4th, 13th, and 14th layers. Stress withstanding capacity is less for these discontinuous layers compared to continuous layers. All layers resist different loads in bending. Usually, the flexure specimens fail in compression only. The stress and Tsai-Hill number for critical layers are shown in Fig 7.17 and 7.18.

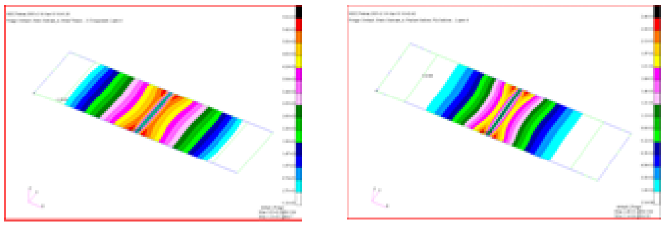

Fig 15: Stress in discontinuous flexure specimen for 4th layer and Tsai-Hill index for discontinuousflexure specimen for 4th layer

For overlap flexure specimen

In this case, an overlap of 20 mm in 1st, 2nd, 15th, and

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16th layers. Fiber overlap increases strength carrying capacity because of an increase in specimen thickness. The laminate fails in compression stress according to the bending theory. The stress and Tsai-Hill number for critical layers are shown in Fig 7.19-7.24.

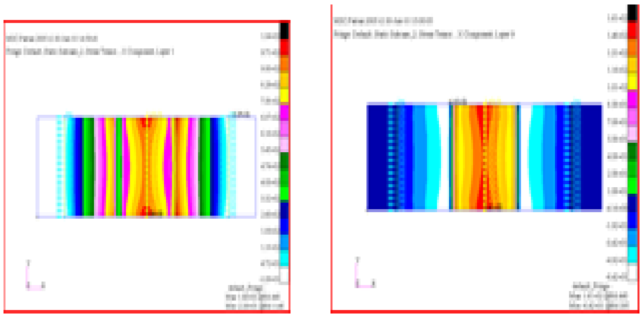

Fig 16: Stress in overlap flexure specimen for 1st layer and Stresses in overlap flexure specimen for 20th layer

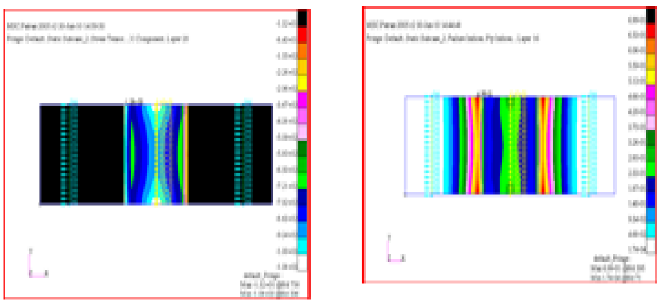

Fig 17: Stresses in overlap flexure specimen for 9th layer and

Tsai-hill index for overlap flexure specimen for 1st layer

V. COMPARISON OF EXPERIMENTAL RESULTS WITH NASTRAN RESULTS

In each case the results from tests are compared with NASTRAN results. The comparison of failure load in each case is tabulated in Table 7.9 and the comparison of stress, strain in each case is tabulated in Table7.10.

Type of specimen	Failure load from test (N)	Failure load from NASTRAN (N)
Tensile continuous	11960.35	11526 .75
Tensile Discontinuous	10544.09	10202.4
Flexure continuous	470.88	451.26
Flexure Discontinuous	402.21	382.59
Flexure(without overlap) continuous	451.26	431.64
Flexure Overlap discontinuous	676.89	647.46

Type of specimen	Failure stress from test (MPa)	Failure stress from NASTRAN (MPa)	Failure strain from test (%)	Failure strain from NASTRAN (%)
Tensile continuous	1569.6	1574	0.5	0.41
Tensile Discontinuous	1402.8	1560	0.57	0.45
Flexure continuous	1177.2	1120	0.38	0.33
Flexure Discontinuous	1000.6	1190	0.36	0.29
Flexure continuous	1108.5	1080	0.37	0.32
Flexure Overlap discontinuous	1079.1	1040	0.34	0.29

VI. CONCLUSIONS

A method has been developed to characterize CFRP laminates with induced discontinuities, which represent gap or overlap in fibers required to extend the fibres, to produce significant components.

Characterization of such CFRP laminates has been accomplished as follows:

1. By modeling and analyzing the stresses and strains through finite element methods.

2. By fabricating according to ASTM standards, load tests are carried out for standard tensile and flexure test coupons.

3. Comparing the FEM results with test data to understand the efficacy of predicting the failure modes by analytical means.

A comparison of analysis data with test results shows that fiber extension in the CFRP component either by overlap or gap can be satisfactorily analyzed using the Nastran FEM package. In particular, the following conclusions can be made.

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March - April 2020
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1. The strength variation or reduction of CFRP laminates due to gap or overlap can be satisfactorily modeled and analyzed using FEM packages.

2. The test results closely match the analysis results for the batch of CFRP material tested.

3. The methodology has been developed to generate design data for large CFRP parts that might need an extension of fibers.

This work also provides inputs to carry out repair work on damaged CFRP parts through the introduction of fibers by overlap

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