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FINITE ELEMENT ANALYSIS OF DISCONTINUITY INDUCED CFRP LAMINATE BY USING NASTRAN SOFTWARE

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Abstract

A numerical model based on the finite element method has been constructed with the aim to examine the Linear and shear stress induced in continuous as well as discontinuous specimens in different layers. The first stage of modeling was designed to analyse the problem of continuous tensile CFRP prepreg specimen, in second stage of modeling was designed to analyze the problem of discontinuous specimens like gap, overlap specimens. Each layer tensile stress strain is calculated because of induced discontinuities. This model had many assumptions and was also solved with the use of NASTRAN software. The coupons assumed in the Nastran are based on ASTM standards and were built using CFRP Prepreg with desired thickness by using layered method in NASTRAN. The NASTRAN results were verified experimentally for tensile specimen to measure strength, breaking point, and how crack propagates. The computed values appeared to be in good agreement with those obtained experimentally.

Index Terms – Fabrication, fem, discontinuities, CFRP prepreg

1. INTRODUCTION

Since olden times, human beings have been intrigued by materials that are stiff, durable, and lightweight, particularly for their practical uses. The concept of melding disparate metals and non-metals to create unique material with amplified properties has captivated interest, especially in advanced societies. A composite material is formed from combining two or more different materials with significantly different properties. The characteristic properties of composites will be different from the individual materials. Each material component remains separate and distinct within the finished structure. [1]. In today's present time the requirement for more efficient material is very significant for the event of latest products [2], [3].

Composite materials, particularly different fiber reinforced polymeric composites are a broad and versatile class of materials for automotive, aerospace and marine applications due to their higher strength [7]. Composites made of such materials not only retain high strength, stiffness and thermal resistance but also show enhanced impact strength, fatigue Strength. Carbon based materials/laminates are gaining popularity because of environmentally friendly nature and its low cost [8], [9].

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Carbon fiber-reinforced plastic (CFRP) composites are a main material for aeronautical applications because of their specifically high strength and stiffness. To use this material safely in aeronautical , satellite applications, the establishment of its strength prediction is essential. The strength of unidirectional fiber composites is especially important when failure occurs in the direction normal to the fiber axis, since it directly affects the strength of the entire composite structure. Therefore, many studies predicting the strength of unidirectional fiber-reinforced composites have been documented in the literature [1–7]. These survey studies have shown that both estimating the fiber strength statistics and the constitutive law of the matrix and using the full 3D numerical model are important in predicting composite tensile strength.

The main purpose of the present investigation is to calculate the strength and stiffness of CFRP specimen with induced gaps (discontinuities) using finite element analysis software NASTRAN. The results from the present investigation are compared and verified with experimental results [8]. If the results are validated, then we can use this FEA steps to analyze any laminate with induced discontinuities. Moreover, a number of parametric studies with induced discontinuities layer wise in tensile sample were carried out in order to discuss the importance of material selection and ply orientation in CFRP laminates.

Figure 1: CFRP Laminate

2. LITERATURE SURVEY

The literature review highlights various approaches and methodologies employed by researchers in studying carbon composites, particularly CFRP (Carbon Fiber Reinforced Polymer) materials. The papers [1-7] delve into the reliability of tensile strength predictions by using Monte Carlo simulations within a shear-lag model, exploring the impact of local fiber geometry and establishing upper and lower bounds for composite strength. Additionally, different models, including a 3D shear-lag model considering micro-damage and statistical strength prediction, are discussed. Mayank Nirbhay's work [8] focuses on developing a numerical tool using ABAQUS® for efficient design of multidirectional CFRP materials. A 3D model is created to simulate tensile tests, providing insights into mechanical strength and failure strain of composite materials. Meanwhile, [9] concentrates on the different mechanical properties of carbon fiber reinforced epoxy composites, conducting tensile testing according to ASTM 3039 standards and using the obtained data in finite element models to analyze stress and strain distributions. Bathala Surendra's study [10] involves modeling a Glass Fiber/Epoxy resin composite laminate using CATIA software and conducting Finite Element Linear Analysis (FEA) to study flexural strength. The papers [11-13] explains the failure of composite

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laminates is a gradual deterioration process. Local failure will cause load redistribution, and different failure modes will continue to accumulate, which degrades the stiffness of the laminated composite material, reduces the load-bearing capacity, and eventually causes the overall failure. For theoretical and numerical studies of composite laminates, progressive damage analysis (PDA) is often used to calculate damage initiation and damage evolution in composite structures. However, a significant gap in the literature data is identified regarding the comparison between FEA studies and experimental analyses of carbon composites. And also, the absence of an efficient FEA model for analyzing induced composite laminates in NASTRAN software is noted. Based upon these observations, the objectives of the current work are outlined for addressing these gaps and developing a standardized approach for analyzing composite laminates.

3.OBJECTIVES OF THE STUDIES

1. The objective is to develop a FEM model for continuous laminate of carbon fiber reinforced polymer matrix composite and analyze its behavior under tensile loading.

2. The objective is to develop a discontinuous laminate, such as specimens with gaps and overlaps, of carbon fiber reinforced polymer(CFRP) matrix composite and investigate its behavior under tensile loading.

3. A method to calculate Finite element analysis (FEA) of prepreg laminates/laminates with induced gaps, overlap discontinuities for tensile using NASTRAN.

4. Conducting a comparison between the experimental findings and Finite Element Analysis (FEA) outputs.

4. EXPERIMENTAL APPROACH

In this study, Specimen of ASTM standards or full-scale models are considered for testing. Coupons were fabricated using CFRP prepreg to make the laminate we used ASTM3090 Standards. The CFRP lamina properties are given in Table 1 and the epoxy properties are given in Table 2.

Table 1: Properties of CFRP lamina

Lamina attributes	Values
E_T (longitudinal)	282 GPa
E_T (transverse)	7.2 GPa
μ	0.22
G_{LT}	3.86 GPa

Table 2: Properties of Epoxy

Lamina attributes	Values
E^T	4 GPa
μ	0.42
G	1.4 GPa

In this research, In order to confirm availability of repeatable results, it was decided to go for more than 20 coupons per type of specimen. Two types of coupons like continuous tensile specimens and with gap specimens were planned. The laminates are prepared then, vacuum

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bagged according to instruction, then autoclaved according to specified temperatures, and then cut according to ASTM3039 dimensions standards and verified for the measurements. In our project, the laminate with gaps and overlaps were fabricated according to ASTM D3039 for tensile. These laminates were tested in a universal testing machine. The strain gauzes are attached to get the stress, strain of failure load, were directly read from the machine. Collation and evaluation of results were completed using MS-Excel and Mat lab.

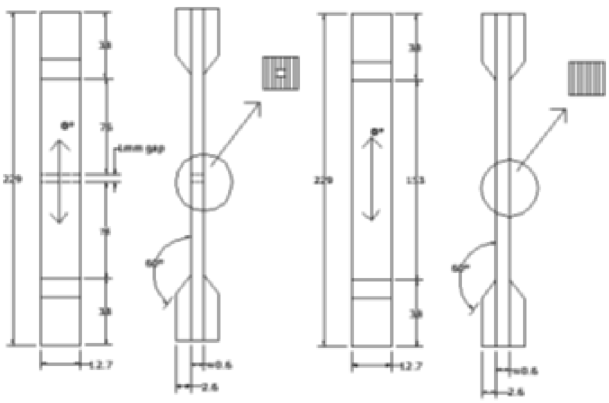

Figure 2: Tensile test specimen (with gap and no gap)

Figure 3: UTM testing machine

5. FEM APPROACH

With advancement in the computers, technology-based software's; finite element analysis has come up as one of the powerful tool available to engineers for the use in design and multi analysis of complex problems. It is designed to solve advanced numerical calculations and originates from the theories of continuum mechanics, which studied equilibrium, motion and deformation of physical solids. FEM involves the approximation of all geometries by using nodes or the continuum functions by a discrete model where the body to be examined is discretized into large number of small parts, called elements. This meshed model is composed by different types of FEA elements like quad, triangle, tetrahedron etc that are continuous over each separate element. These function elements are connected by nodes. Numerical values at a large number of nodes are compiled to ensure the element functions accurately approximate the global function. By increasing the number of nodes or dividing the structure into finer parts, the efficiency and accuracy of the analysis improve. Various loads are then applied based on our research, resulting in different types of analysis, such as linear analysis, thermal analysis, and more.

METHODOLOGY:

In the present study the linear static analysis is carried by using PATRAN for drafting/NASTRAN for analysis purpose. The process steps for FE modeling of CFRP laminates with continuous and discontinuities are given below:

First, the initial 2-dimensional surface was modeled according to the geometrical dimensions specified in Figure 4, adhering to the tensile specimen standards of ASTM3090

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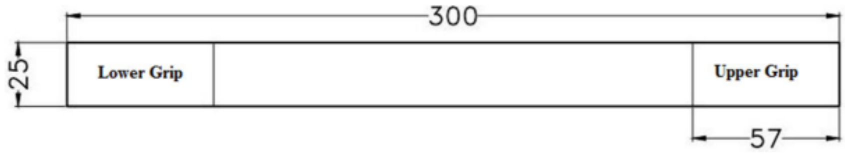

Figure 4: 2D model of the tensile specimen

.**Second,** the surface geometry has been meshed with 4-noded quadrilateral elements, represented as quad 4 in MSC/PATRAN. The schematic diagram of Quad 4 element is shown in Figure 5 and quad 4 element assumes that element is thin, nodal thickness may vary; Response is limited to xy-plane.

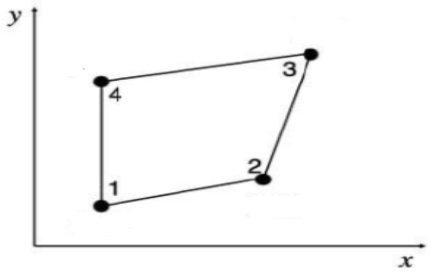

Figure 5: Quad 4 element

In third step the **discontinuities** in the model are added in the middle we can see this in Figure 6, which are meshed with quad elements with less respect ratio, to have a good understanding of stress variation as the discontinuous region is more relevant in our project work. The meshed models for continuous and discontinuous tensile specimens are given in Figure 6.

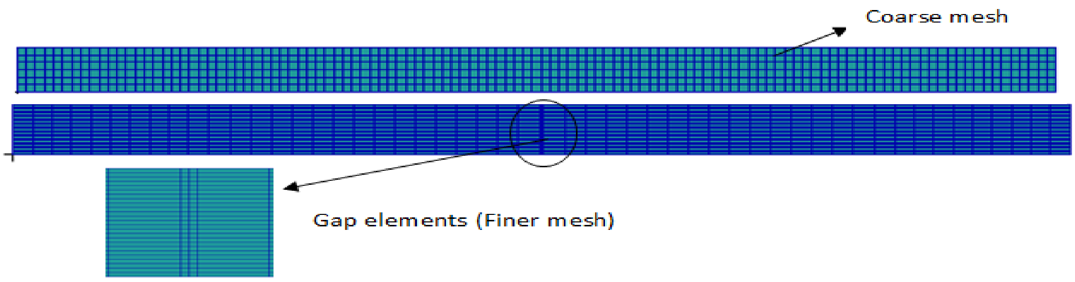

Figure 6: Meshed tensile continuous and discontinuous specimen

In fourth step, the **load and boundary conditions** are applied as per ASTM3090 for tensile specimen. Strength loss in laminates, Crack initiation, crack propagation and failure loads in specimen are taken by gradually increasing the loads and observing for failure analysis. For tensile specimen Left side tab region is constrained according to ASTM 3039.At left tab region Tx, Ty, Tz, Rx, Ry. Rz are fully constrained. The tensile load was applied starting at 6867 N. Each time, the load was increased by 490.5 N until the specimen failed, and the observed values were recorded. With load conditions fig is showed in Figure 7

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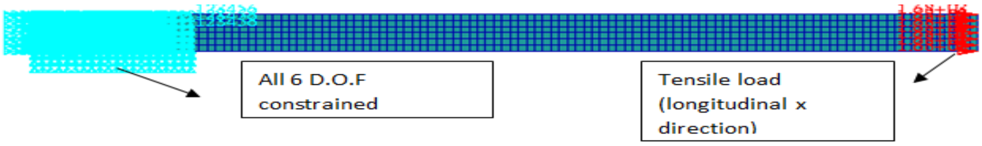

Figure 7: Load conditions and boundary restrictions for tensile specimens.

In the fifth step, laminate properties are specified in the material section of NASTRAN. The finite element model has been attributed to the properties listed in Tables 4, which were calculated from test data. To validate the methodology, these test-derived properties are used, and the experimental failure loads are compared with the analysis failure loads. The strength properties and material properties from test data for both continuous and discontinuous types of specimens are presented in Tables 4 and 5.

Table 3: Material properties for tensile continuous and discontinuous (gap) specimen

Material Properties (tensile mean)	**Continuous Tensile Specimen (GPa)**	**Discontinuous Specimen (GPa)**
E_T (longitudinal)	331.8	277.2
E_T (transverse)	7	7
μ	0.22	0.18
G_{LT}	3.87	3.87

Table 4: Tensile Strength of continuous and discontinuous (gap) specimen

Strength Properties (mean)	**Continuous Tensile Specimen (MPa)**	**Discontinuous Tensile Specimen (MPa)**
X_t	1569.6	1569.6
Y_t	16.7	16.7
X_c	493.24	493.24
Y_c	116.64	116.64
S_{12}	50.32	50.32
τ_{LZ}	65.23	65.23

In the sixth step, the lay-up sequence for the specimens is defined in NASTRAN. For continuous tensile specimens, the lay-up of 8 layer sequence is assigned using CFRP prepreg

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properties. In discontinuous specimen a gap is introduced in 4th and 5th layers. FE model is filled with epoxy resin properties, based on assumptions, while the continuous region is assigned with CFRP prepreg properties. In NASTRAN, the tabulated material properties for the FE model are assigned using the material option. The lay-up of layers is assigned using the composite option by adding the number of CFRP and epoxy layers. Figure 8 shows a typical NASTRAN window with the assigned lay-up sequence for a discontinuous tensile laminate.

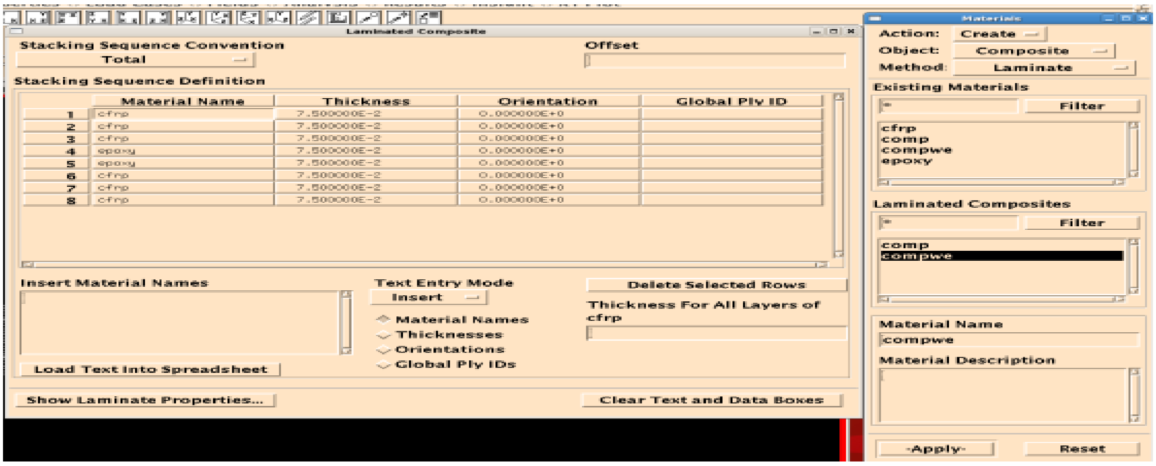

Figure 8: A typical NASTRAN window showing number of layers, thickness and orientations.

In seventh step the linear static analysis was carried out on the specimens based on experimental results. Here we used maximum ply failure theory for validation. Linear laminate analysis represents the behaviour of physical object or structure, which has forces applied to it and solves for the displacements, stresses etc, of the finite element model. The behaviour is characterized by its displacements, if the displacements of a structure are known; other important data can be calculated from it easily.

Here the stress, crack propagation, failure load in each layer for the different conditions, how it varies, in what load, in which layer it starts and fails everything will be analyzed layer wise. At the end, the solution is checked for errors, if any. Stresses and strains were evaluated for each layer of laminate and compared with the test results. First ply-failure theory is followed and Tsai-Hill ply failure indices were obtained for every layer. If the failure index is less than 1, the ply stress occurs inside the periphery of the ply and ply is safe. If the failure index is greater than 1, the ply stress falls outside the periphery of the ply and the ply fails.

6. RESULTS AND DISCUSSIONS

6.1 Experimental results:

Two types of specimens like continuous and discontinuous tensile specimen with induced discontinuities were tested. Failure loads, young's modulus, ultimate stress and ultimate strain as well as coupon width and thickness have been averaged for a batch of coupons.

Table 5: Average experimental results

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SIno	Type of specimen	Failure load (N)	Width (mm)	Thickness (mm)	Young's modulus (GPa)	Ultimate Stress (MPa)	Ultimate strain (%)
1	Continuous tensile(G_1)	10438.8	12.8	0.51	332.8	1570.6	0.5
2	Discontinues tensile(G_2)	9330.3	13.4	0.49	278.2	1403.83	0.57

Stress strain curve for tested coupons

Stress-strain relationship curve for two batch samples were taken. They will yield approximately similar plot for a batch of specimens. Typical plot for one specimen from each batch is selected. The difference between failure stress, failure strain, and young's modulus for each type of specimen is evaluated. Stress-strain plot for tensile coupons were shown in Figure 9.

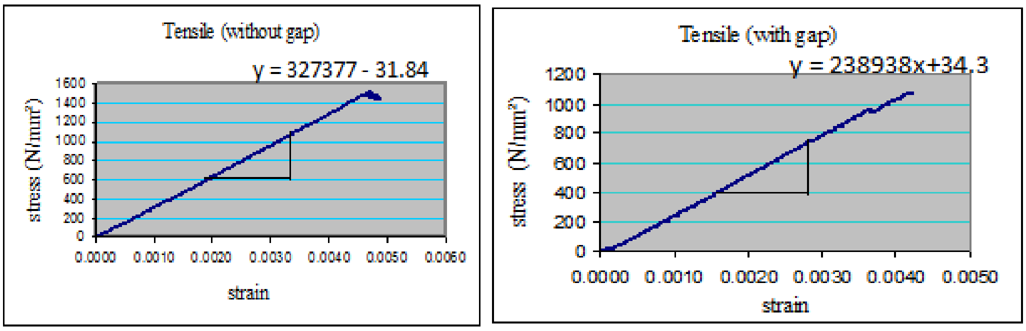

Figure 9: Stress-strain relationship for continuous (without gap) and discontinuous (with gap) tensile test specimen

Tested specimens before and after experiment

Figure 10: Tensile specimens before and after failure.

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6.2 Results from FE analysis

A results from NASTRAN analysis assumes dimensions of standard ASTM coupons. The induced stress is analyzed for the tensile load in steps of 491.5N from 6868N to 11771N progressively.

NASTRAN analysis has advantages of providing stress and strain for every layer, element and node. When there is a gap in a layer, the properties of the epoxy that fills the gap will be taken for analysis of stress locally. The specimens are also subjected to analysis for Tsai-Hill failure theory. When Tsai-Hill number is more than 1 it means failure for that particular load. For every case, the failure load, failure stress, Tsai-Hill numbers are shown in Table 6 and 7.

Table 6: Tensile continuous specimen

Load (N)	**Stress (MPa)**	**Displacement (mm)**	**Strain (%)**	**Tsai-hill number**
11526.75	1574	0.95	0.41	1.01

Table 7: Tensile discontinuons specimen (gap)

Load (N)	**Stress (MPa)**	**Displacement (mm)**	**Strain (%)**	**Tsai-hill number**
10202.4	1560 (1^{st} layer)	1.03	0.45	1.01 (1^{st} layer)
	1383.2(4^{th} layer)	1.03	0.45	0.80(4^{th} layer)

Layer stresses, Tsai-Hill number obtained from analysis

NASTRAN analysis has advantages of providing stress and strain for every layer, element and node. The stress, strain and Tsai-Hill number for critical layers for 2 types of specimens are given below.

- **For tensile continuous tensile specimen**

Here, as there are no fiber induced 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 displayed in Figure 11

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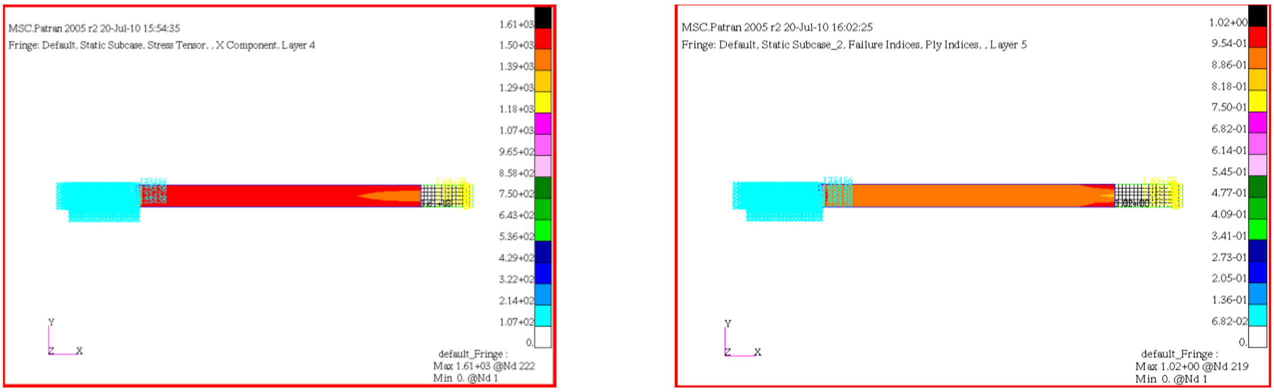

Figure 11: Distribution of stress in the fourth layer and Tsai-Hill index value of the 5th layer of continuous tensile specimen

- **For tensile discontinuous tensile specimen**

Here, we induced fiber discontinuities like 1mm gap in 4th & 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 displayed in Figure 12.

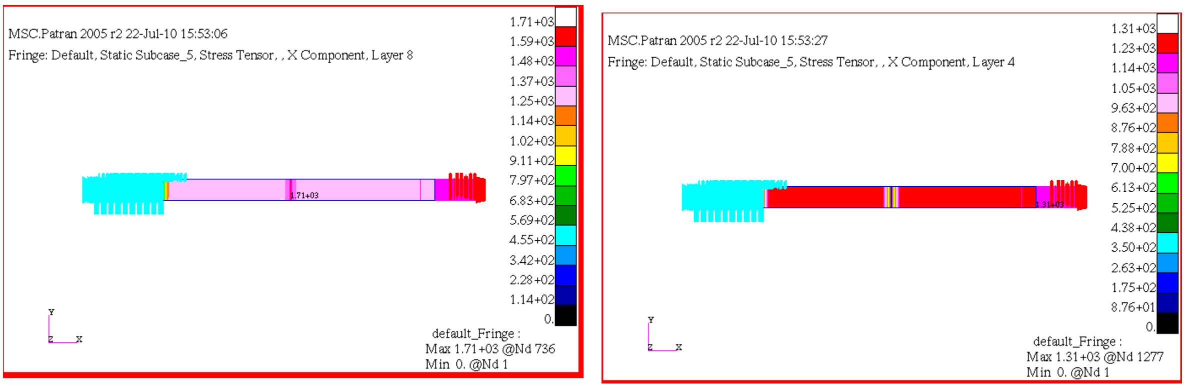

Figure 12: Stress distribution for gap induced specimen specifically examined for the 4th and 8th layers

6.3 Results from SEM analysis

We investigated crack orientation, failure surface analysis, lamina delamination, and crack propagation by using SEM analysis of 5 continuous and discontinuous coupons. The pictures are given below:

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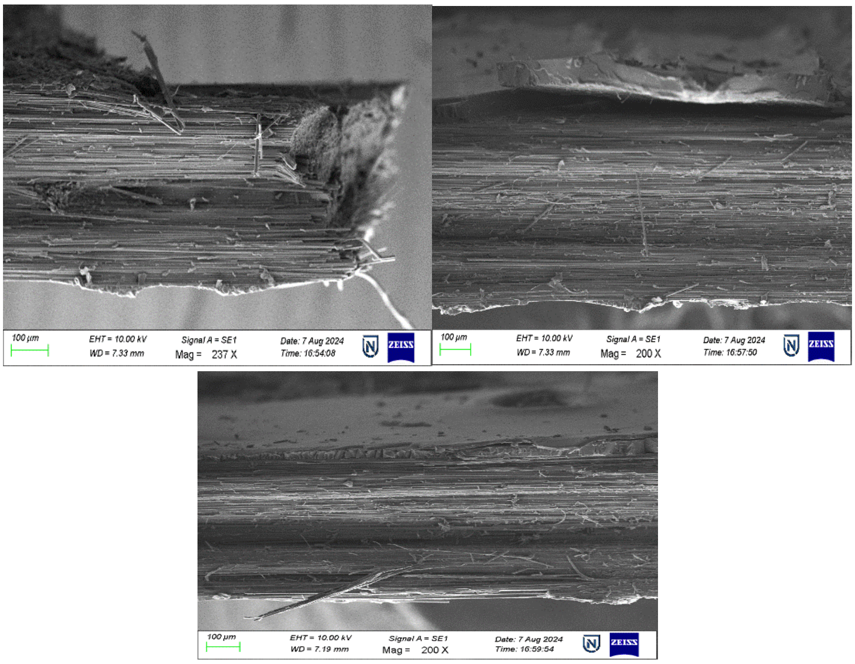

Figure 13: Tested tensile coupons Sem images

The coupons undergone SEM analysis to examine failure mechanisms by analyzing crack propagation and fracture surfaces.

After deep investigation we marked the largest crack area in the SEM images. The marked specimens are given below in figure 14 and 15.

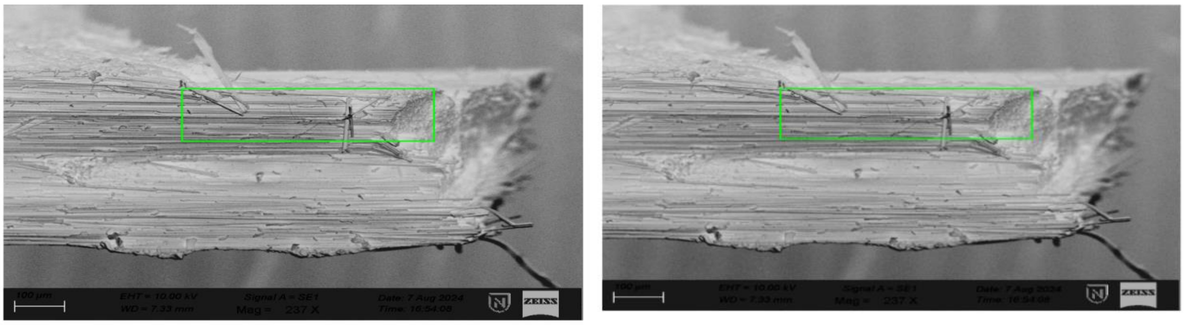

Figure 14: Tested tensile coupons Sem images of coupon 1,2

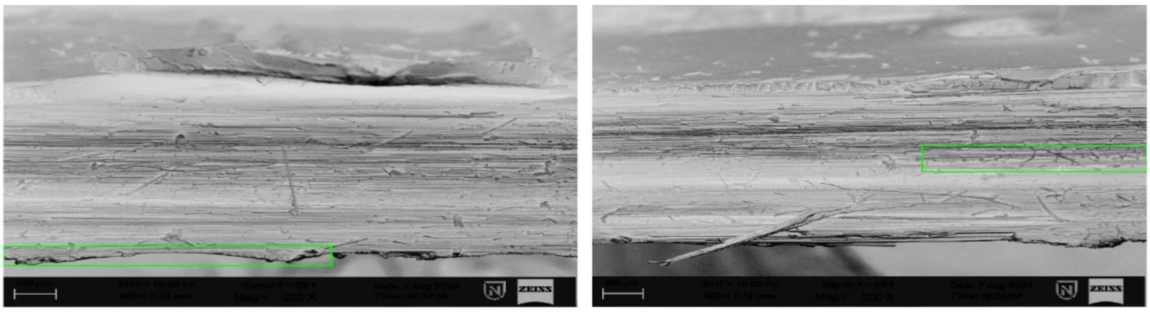

Figure 15: Tested tensile coupons Sem images of coupon 3,4

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Based on the largest crack region and the centroid tracking across the five images, the cracks seem to have initiated near the narrow end of the specimens, possibly at stress concentration points. This could be due to fiber breakage or matrix cracking, common in composite materials. The presence of delamination suggests that cracks started at weaker fiber-matrix interfaces where we given gap reason in the specimen.

The fractures exhibit progressive fiber breakage, indicating gradual failure under loading. Two specimens sem analysis exhibits a mixed or diagonal trajectory, suggesting a mixed-mode failure (tensile and shear). The cracks likely propagated along the fiber direction due to weaker matrix strength and interlaminar failure. The final break appears to be a combination of fiber pull-out, delamination, and catastrophic fiber rupture. And again the jagged fracture surface suggests brittle failure in some regions and fiber pull-out in others. And finally the SEM analysis indicates different crack distribution across the specimens.

6.4 Comparison of experimental results with NASTRAN analysis results

The comparison of experimental results with NASTRAN analysis results for tensile testing on continuous and discontinuous specimens is shown in the table 8 & 9. It includes failure stress, failure strain, and failure load for both specimen types from both experimental testing and NASTRAN simulation.

Table 8: Failure load Comparison of test results obtained along with NASTRAN results.

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

Table 9: Stress-Strain Comparison of test results obtained along with NASTRAN results.

Type of specimen	**Failure load from Experiment (N)**	**Failure load from NASTRAN (N)**
Tensile continuous	11960.35	11526.75
Tensile Discontinuous	10544.09	10202.4

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For the analysis purpose we break down the comparison analysis. The difference shows in continuous specimen the results obtained from NASTRAN & test are almost identical, but in case of discontinuous specimen we got more deviation from the tested results..

The breakdown of the comparison analysis is given below:

- FailureStress (MPa)
- Tensile Continuous Specimen:
  - Experimental result: 1569.6 MPa ,NASTRAN result: 1574 MPa
  - Difference: 1574 - 1569.6 = 4.4 MPa
  - The failure stress predicted by NASTRAN is very close to the experimental value, with a minor discrepancy of 4.4 MPa.
- Tensile Discontinuous Specimen:
  - Experimental result: 1402.8 MPa, NASTRAN result: 1560 MPa
  - Difference: 1560 - 1402.8 = 157.2 MPa
  - There is a larger discrepancy of 157.2 MPa between the experimental and NASTRAN results for the discontinuous specimen, with NASTRAN predicting a higher failure stress.
- Failure Strain (%)
- Tensile Continuous Specimen:
  - Experimental result: 0.5%, NASTRAN result: 0.41%
  - Difference: 0.5% - 0.41% = 0.09%
  - There is a small difference of 0.09% in the failure strain, with NASTRAN predicting a slightly lower failure strain.
- Tensile Discontinuous Specimen:
  - Experimental result: 0.57%, NASTRAN result: 0.45%
  - Difference: 0.57% - 0.45% = 0.12%
  - NASTRAN shows a larger difference of 0.12% compared to the experimental result for the discontinuous specimen.
- Failure Load (N)
- Tensile Continuous Specimen:
  - Experimental result: 11960.35 N, NASTRAN result: 11526.75 N
  - Difference: 11960.35 - 11526.75 = 433.6 N
  - The failure load from NASTRAN is slightly lower than the experimental result, with a difference of 433.6 N.
- Tensile Discontinuous Specimen:

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- Experimental result: 10544.09 N, NASTRAN result: 10202.4 N
- Difference: 10544.09 - 10202.4 = 341.69 N
- NASTRAN shows a smaller difference of 341.69 N for the discontinuous specimen compared to the experimental result.

7. CONCLUSIONS

A different strategy has been formulated to measure Carbon Fiber Reinforced Plastic (CFRP) laminates with intentional fiber discontinuities, representing either gaps or overlaps, to create significant constituents. The characterization of these CFRP laminates was achieved through the following steps:

- Use of finite element software PATRAN/NASTRAN for design, modelling & analysis of stress-strain.
- Fabricating specimens in line with ASTM 3039 and 790 standards and conducting load tests for tensile and flexure evaluations.
- Comparing the FEA software analysis results with experimental data/theoretical data to gauge the accuracy of predicting failure modes through analytical means.

The comparison between the analysis data and test results proves that the continuous/discontinuous of fibers in the CFRP component, whether through overlap or gap, can be effectively analyzed using the Nastran/PATRAN FEM package. The study derived is as follows:

- Using FEM packages, the strength variation of CFRP laminates induced with gaps or overlaps were modelled and analysed.
- The validated results closely matched with the results of CFRP material under investigation.
- The developed methodology can generate design data for large CFRP parts that may require fiber extension.
- The result provides valuable insights for repairing damaged CFRP components by introducing fibers through overlapping.

In conclusion, this step-by-step process in NASTRAN offers a reliable means to illustrate CFRP laminates with intentional fiber discontinuities, enabling improved understanding and design for various applications in the field.

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