Study of Composite Laminate Behavior with different ply sequence under Biaxial loading

Sambamurty Saravakota[1] and R Velmurugan[2]

[1] Department of Aerospace Engineering, IIT Madras, Chennai, Tamilnadu, 600036, India. E-Mail: sambaiitm@gmail.com.

[2] Professor, Department of Aerospace Engineering, IIT Madras, Chennai, Tamilnadu, 600036, India. E-Mail: ramanv@iitm.ac.in

ABSTRACT:

Composites are increasingly used in engineering applications due to their superior strength-to-weight ratio and ability to manufacture them as per the design. The composites might be subject to complex combined loading in critical components like pressure bottles, wind blades etc. Hence conducting biaxial studies is crucial because multiaxial characterization of composites will improve our understanding of their mechanical behavior and characterization. This study mainly focused on the development of the bi-axial test specimen for study of several composite laminates with the aim of achieving the pure bi-axial stress field in the gage area itself. Also, developed the bi-axial test set-up to load the materials under different bi-axial loading conditions to test their behavior and tested glass/epoxy composite laminate with quasi-isotropic lay-up [0^0/-60^0/60^0]. The study is further extended in performing finite element simulations with different ply sequence to understand the material bi-axial stress behavior which will enable the better design of composite laminates under multi-axial loading conditions. Based on the bi-axial stress-strain behavior [0^0/-60^0/60^0] laminate configuration is more promising compared to other layup configurations for bi-axial loading conditions.

Keywords: Composite Laminates, Glass/Epoxy, Ply sequence sensitivity, Bi-axial Loading, Stress Analysis.

1. INTRODUCTION:

Conventionally the design of any structural component is based on uni-axial stress-strain curve of the material. But in practical engineering applications, most of the components such as pressure vessels, wind blades etc. are subjected to complex stress state. The design based on uni-axial properties will not predict the actual behavior of the material. Recently, there has been a resurgence of interest in the creation of devices or systems that can execute biaxial loading to replicate real-world stress circumstances.

For biaxial testing there are no standard test procedures available in literature as in uni-axial testing and hence there is no standard specimen geometry to ensure the pure biaxial stress state. Different specimen geometries have been tried by earlier investigators to predict the exact mechanical behavior under biaxial loading. The behavior of composite materials under biaxial loading has been studied by many researchers. Hart-Smith[1] described the role of biaxial stresses in failure theories of composite materials. Swanson and Smith[2] conducted a series of biaxial tests to measure the strength of 2-D braided carbon/epoxy specimens and compared the measured strength with that of laminations constructed with similar materials and fiber orientations. Khondker et al.[3] studied the effects of biaxial deformation of the knitted glass preform on the in-plane mechanical properties of the glass/vinyl-ester composite. They found that the tensile modulus, strength, and strain-to-failure were all affected, whereas the compression properties were relatively insensitive to fabric biaxial deformation. Kaddoura et al.[4] described the behavior of glass/epoxy filament wound composite tubes under quasi-static equi-biaxial tension-compression loading.

Smits et al.[5] investigated the behavior of fiber reinforced composites subjected to biaxial loading. Cruciform specimen was developed by performing finite element simulations in combination with experiments on different geometries of cruciform specimens. Welsh et. al.[6] conducted 2-D biaxial testing and described the failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates. Mohamad et al.[7] developed the biaxial loading frame to study the behavior of fiber reinforced composite laminates under in-plane biaxial loading. Specimen geometry with a reduced thickness at test section, in combination with fillet at the intersection of loading arms are proposed in their investigation. Carla Ramault[8] developed guidelines for biaxial testing of fiber reinforced composites using a cruciform specimen. Several strain measuring techniques are compared to obtain correct strain results in the center of the specimen for both quasi-static tests and dynamic tests. Srinivasan et al.[9] studied biaxial behavior of commercially pure Titanium using cruciform specimen geometry and employed non-contact digital image correlation technique to measure the failure strain. The decrease in ductility with an increase in strength is observed under biaxial conditions. Zhanwen et al.[10] studied macro/micro multi-scale analysis based on the efficient implementation of the generalized method of cells coupled with Classical Lamination Theory (CLT) was conducted to predict the biaxial failure of composite laminates by applying failure criteria at the constituent level, including fiber, matrix and interface.

Wen-Pin Lin et al.[11] developed a numerical constitutive model for a single layer of fiber reinforced composite laminates, including nonlinear stress-strain relations, mixed failure criterion and post failure response to predict the ultimate strengths of the composite laminates under biaxial tension test loads. D V Hemelrijck et al.[12] developed mixed numerical/experimental method to determine the in-plane stiffness parameters from testing a single cruciform test specimen. They used the material system glass fiber-reinforced epoxy with a lay-up typically used in wind turbine blades for experimental validation. Lecompte et al.[13] developed the numerical-experimental technique for the identification of four in-plane orthotropic engineering constants of composite plate materials. Biaxial tests are performed on cruciform test specimen and displacement field is measured by digital image correlation technique, which in turn validated against finite element model. Xiaowen et al.[14] investigated the biaxial properties of CFRP with cruciform specimens with Hashin criterion. The embedded continuous laying method (ECLM) was proposed to achieve the desired thickness of the cruciform specimen.

2. MATERIALS AND METHODS:

For experimental investigations under biaxial stress state, different specimen geometries and compatible loading systems have been proposed in the above-described literature. But all the proposed models have either stress concentrations outside the gage area or they are complex, which are difficult to manufacture. In biaxial testing, specimen geometry is indeed crucial and must be carefully designed to match the capabilities and objectives of the loading system. Hence high-fidelity finite element analysis is carried out to obtain suitable specimen geometry so that we get maximum homogeneous stress field in the gage area and is comparatively simple and suitable experimental test facility is established for performing experiments.

Since there is no standard universal bi-axial testing set-up is available, the bi-axial testing machine is developed which can carry out both uni-axial and bi-axial loading in both tension and compression type of loading of equal and variable magnitude. The equi bi-axial tensile test is performed on quasi-isotropic lay-up [0^0/-60^0/60^0] configuration and compared against finite element simulation results. Once the finite element models are calibrated against the real test data, various laminates with different ply sequences are studied to understand the influence of different laminate stack up with bi-axial loading conditions.

2.1 Bi-axial Test Specimen Design:

The most realistic experimental technique to create a biaxial stress state in materials is applying the in-plane loads along two perpendicular directions to the arms of the biaxial specimen. To ensure the failure inside the gage area, two step thickness reductions with straight taper transition is incorporated to achieve the pure biaxial stress state under biaxial loading. The analysis of the biaxial test specimen is important to produce the homogeneous biaxial stress state. The primary step in the analysis is to select overall specimen dimensions. Consideration is given here to a number of test system features and characteristics including loading capacity at specimen grips, the size of the envelope available within a loading frame for specimen installation and gripping, gripping arrangement, size restrictions imposed by the specimen grips, necessary specimen test section required to fulfill strain measurement requirements and the overall load capacity requirements to strain the test section of the specimen up to its tensile strength.

The analysis of biaxial test specimen needs to consider the following constraints: (1) maximize the region of homogeneous biaxial stress field in the test section, (2) minimize the shear strain in the test section, (3) minimize the stress concentration outside the test section, (4) size the specimen to obtain yielding in the test section itself, and (5) specimen failure in the gage area of the test specimen. However, analyzing composite structures indeed presents significant complexity due to their intrinsic characteristics and multitude of parameters such as directional mechanical properties, fiber orientation, number of layers and lay-up sequences that affect their performance. The present work describes the characterization of composite laminates with different layup configurations after calibrating the finite element models with the tested sample data.

2.2 Bi-axial Test Specimen Analysis:

The bi-axial test specimen analysis is carried out through finite element analysis package ANSYS. The biaxial test specimen is analyzed using 3-Dimensional finite element analysis to meet the biaxial test requirements. The biaxial test specimen for composite materials is usually analyzed using layered elements with orthotropic material properties[7]. To ensure the pure biaxial stress field within the gage area, two step thickness reduction with optimal fillet radii at loading arms is developed by performing the design of iterations using finite element simulations. SOLID185 is used for modeling composite laminates. It is defined by 8 nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions. The glass/epoxy laminate is used for the study.

The bi-axial test specimen of 250mm x 250mm with central gage area of 60mm x 60mm is designed with 2-step thickness reduction from 6.3 to 2.1mm with intermediate step thickness of 4.2mm. The design of experiments is performed by varying the parameter of fillet corner radius at intersection of the loading arms and compared the stress field at both corner fillet region and region of interest i.e. tested gage area. The corner fillet radius (R) of 26mm is achieved during optimization (as shown in Figure 2) to achieve the pure biaxial stress field within the gage area itself. 50kg/cm^2 pressure load is applied along the four loading arms in tension to simulate the in-plane tensile bi-axial stress field as shown in Figure 1. The symmetric boundary conditions about X and Y-axes are imposed in the finite element model to reduce the computational time of the simulations significantly.

Figure 1: Finite Element Meshing of 1/4th bi-axial test specimen.

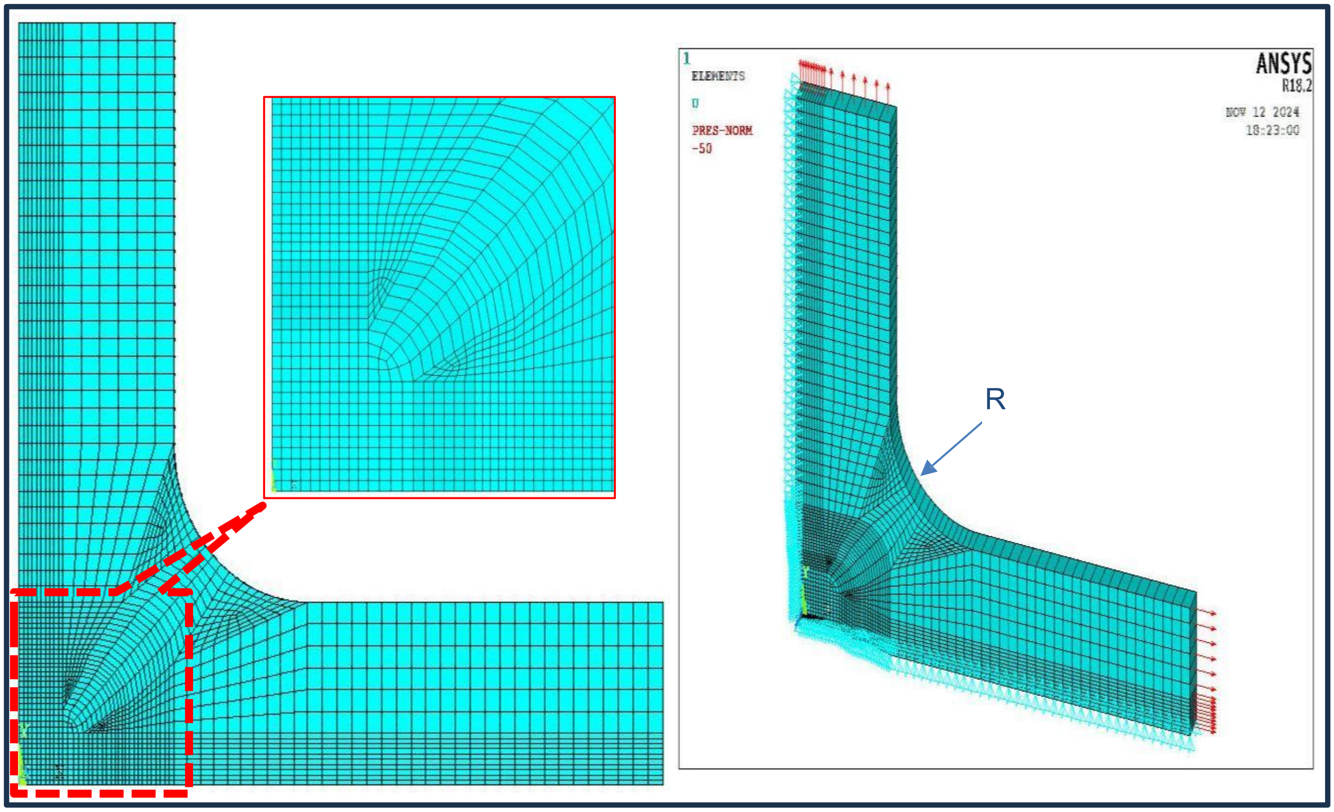
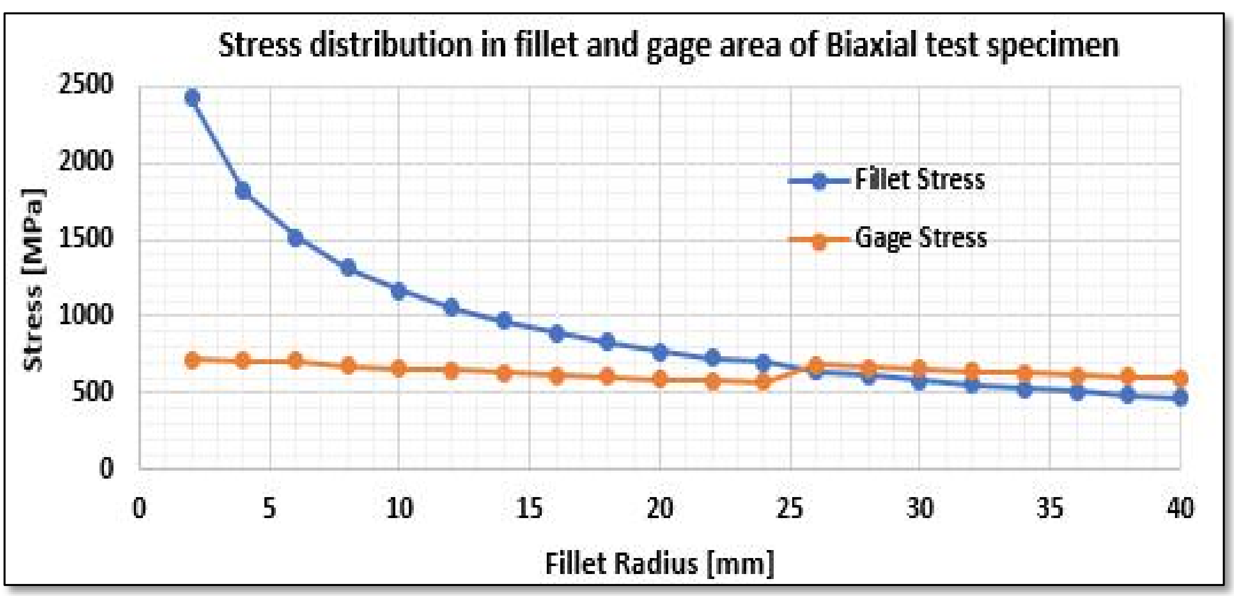


Figure 2: Stress distribution in corner fillet & gage area of test specimen



The unidirectional glass/epoxy lamina properties are used to model the specimen[9], which are given in Table 1.

Table 1. Moduli & Strength parameters of unidirectional glass/epoxy laminate

Moduli parameters	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)	υ_{12}	υ_{23}	υ_{13}
E-Glass/ epoxy	44	10.5	10.5	3.74	3.50	3.74	0.36	0.50	0.36

Strength parameters	X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	Z_t (MPa)	Z_c (MPa)	S_{12} (MPa)	S_{23} (MPa)	S_{13} (MPa)
E-Glass/ epoxy	800	350	50	125	50	125	120	40	120

Total five laminate stack-ups are studied under same loading and boundary conditions to make relative performance comparison of the desired bi-axial stress field. The laminate sequences are of 1) Uni-directional laminate [0^0]; 2) Quasi-isotropic laminate [0^0/-60^0/60^0]; 3) Quasi-isotropic laminate [0^0/-45^0/45^0/90^0]; 4) Symmetric cross-ply laminate [0^0/90^0/90^0/0^0]; and 5) Symmetric angle-ply laminate [45^0/-45^0/-45^0/45^0].

The smeared material elastic properties of the composite laminate configurations are calculated by using the uni-directional lamina properties using Classical Lamination Theory (CLT), which involves transforming the individual lamina stiffness matrices to a global coordinate system, then summing up across all layers in the laminate to obtain the effective laminate stiffness matrix, essentially smearing the properties of each lamina into a single set of properties representing the entire laminate. The calculated smeared properties to each laminate stack-up are shown in Table 2 and assigned to the corresponding laminate FE models to study the bi-axial loading behavior.

Table 2: Smeared elastic properties of different layup stack laminates.

Smeared Elastic parameters	E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	G_{12} (MPa)	G_{23} (MPa)	G_{13} (MPa)	n_{12}	n_{23}	n_{13}
0^0	44000	10500	10500	3740	3500	3740	0.36	0.50	0.36
$[0^0/-60^0/60^0]$	21204	21204	11953	7925	3620	3620	0.34	0.36	0.36
$[0^0/-45^0/45^0/90^0]$	21204	21204	11953	7925	3620	3620	0.34	0.36	0.36
$[0^0/90^0/90^0/0^0]$	27579	27579	11953	3740	3620	3620	0.14	0.47	0.47
$[45^0/-45^0/-45^0/45^0]$	12127	12127	11953	12109	3620	3620	0.62	0.21	0.21

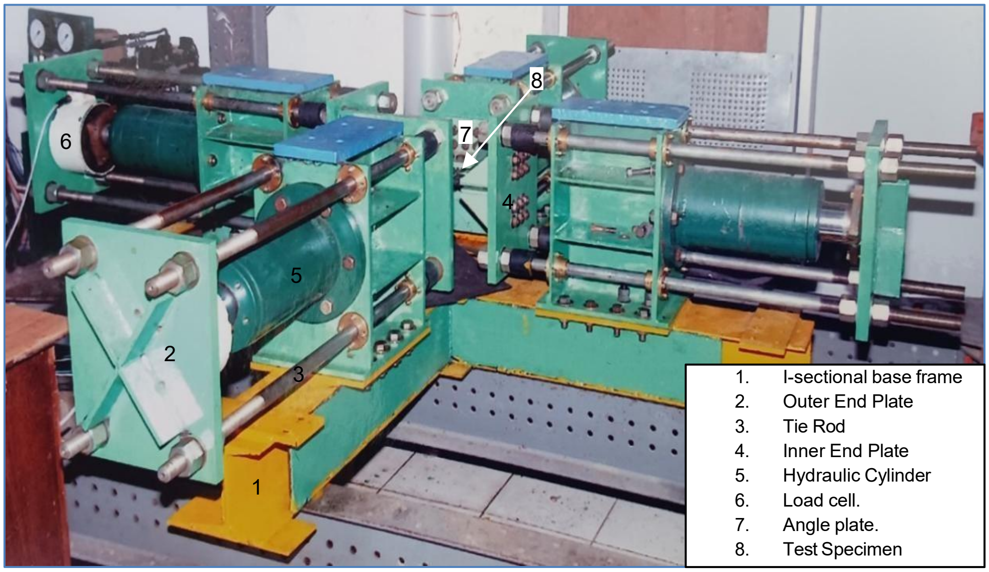
2.3 Bi-axial Testing Set-Up:

The in-plane bi-axial testing machine with 25-ton loading capacity is designed and established at relatively low cost. The most realistic experimental technique to develop the biaxial stress state in the materials is, applying the in-plane loads along two mutually perpendicular directions. The developed test set-up has flexibility in characterizing the material under different loading conditions like bi-axial tension, compression and shear loading, and uni-axial loading by activating one set of loading system. In-plane biaxial testing enables better predictions to be made on the material subjected to complex stress state. The test rig mainly consists of loading frame, hydraulic power pack and Windows based 'System 5000' Data Acquisition System to capture test measurement data accurately as shown in Figure 3.

Figure 3: In-plane Bi-axial test facility

The loading frame consists of four double-acting hydraulic cylinders, rigidly fixed with an I-sectional base frame, and thus the center of the test specimen remains in the same position during the test. This loading frame can apply tensile, compressive or shear loads on the test specimen. One hydraulic cylinder is placed at each side on the base frame. The hydraulic loading system is used to load the test specimen with negligible mechanical losses. The fluid pressure in each pair of hydraulic cylinders placed opposite each other is servo controlled, independently. All the four hydraulic cylinders are connected to the power pack, which primarily consists of hydraulic pump and solenoid valves. Loadcells are used in each loading direction to measure the load values directly as shown in Figure 4. The data acquisition system is connected to the test facility to extract the strain gage and loadcell readings.

Figure 4: Loading frame components details



2.3.1 Biaxial Loading Frame:

The load frame is primarily coupled with four independent loading points, each consisting of hydraulic cylinder, end plates and tie rods. The hydraulic cylinder is fixed to the I-Section rigid frame structure to withstand the reaction forces exerted by the hydraulic piston. The I-section rigid frame is intern connect to the base frame. The inner and outer end plates are designed to withstand the bending at the center of the plate, while loading the specimen. The biaxial test specimen is fixed to the inner end plate with the help of angle plates as shown in Figure 4. Each side of the specimen is firmly gripped between the angle plates. While loading the specimen, initially the bottom angle plate on each direction is tightly fixed to the inner end plates with M12 bolts. Then the biaxial test specimen is placed on the fixed bottom angle plates. Then the top angle plates are placed on the biaxial test specimen and bolted tightly between the angle plates by using M14 high strength bolts. The holes which are used to fix the top angle plate to the inner end plates, are made elliptical for testing the biaxial test specimens of different thicknesses. Rubber bushes are provided between the inner end plates and the I-section carrying the hydraulic cylinder to avoid the jam of the inner end plates with the hydraulic cylinder.

Two load cells are provided in the loading frame, one in the X-direction and the other in the Y-direction to measure the loads directly by applying the hydraulic pressure. Loadcells of 25ton capacity supplied by HBM are used. These are calibrated as full-bridge Wheatstone bridge sensors to connect the data acquisition system.

Though there is provision for testing all types of loads, the present study is focused on equi tensile loading in all four directions. A stacked rectangular strain gauge rosette is mounted on the center of the test specimen gage area. The specimen is fixed in the loading frame with bolts. After ensuring that the specimen is properly mounted on the loading frame, the load is applied with regular increments until the specimen failed under bi-axial loading. The strain and load data are collected through the data acquisition system.

2.3.2 Hydraulic Power Pack:

A 25-ton capacity hydraulic power pack is used in the present study to load the test specimen. The double acting hydraulic cylinders are used in the test facility to apply the tensile and compressive loads by allowing the hydraulic piston to move in the forward and backward direction respectively. Opposite hydraulic cylinders in each loading direction are connected to common flow control valves so that the loads exerted by them are equal and opposite. These hydraulic cylinders have a maximum capacity of 25 ton in both forward and backward strokes. The pressure developing system is packed inside the hydraulic fluid tank. It is mainly coupled with 2.2kW electric motor and gear pump. The level gauge is provided outside the tank, to indicate the fluid level in the tank. The fluid level should be always more than half to operate the system safely.

2.4 Test specimen preparation:

The glass fiber reinforced with epoxy is used and prepared using hand lay-up process. The composite laminate is made by using unidirectional fibers (UD-750gsm) and epoxy resin by hand lap up technique. For the matrix material, epoxy (Araldite LY 556) is mixed with hardener (HY 951) in the ratio of 10:1 by weight. Absence of voids has been ensured by proper mixing of epoxy and hardener. A hand roller is used to compact the composite plies and to remove any entrapped air as this is a manual process, traces of voids may still be present. Laminates are prepared by hand lay-up process on this mould using uni-directional glass fibre/epoxy comprising eight layers with fibre orientation of $[0^0/-60^0/60^0]$ layup. Mylar film is glued to the mold before fibers are laid on to it. Wax is applied on the film for easy removal of the laminate after curing. The volume fraction of the fibers in the laminate is determined. It is approximately 0.4.

Total 'five' composite specimens each with $[0^0/-60^0/60^0]$ layup sequence is prepared to test under both uniaxial and equi bi-axial loading conditions. To prepare the uniaxial test specimens, 195mm x 385mm laminate is prepared with quasi-isotropic $[0^0/-60^0/60^0]$ layup configuration. After the room temperature curing for 24hours, the laminate is post-cured at 80^0C for 3 hours. As per ASTM D638 standards, five uni-axial test specimens of 320mm x 25mm are cut from the base laminate. Similarly, a mould is prepared with plexi-glass material to form the desired thickness gradients with fillet radii for the bi-axial testing cruciform specimens. The composite layers of the cruciform specimen are initially made available with necessary pre-cut to achieve the central gage area of having 2.1mm thickness build with quasi iso tropic layup of $[0^0/-60^0/60^0]$ layers and having 6.3mm thickness at loading arms with $[0^0/-60^0/60^0]_3$ layers with intermediate step thickness of 4.2mm having $[0^0/-60^0/60^0]_2$ layers.

2.5 Experimental Test validation:

The uni-axial test specimen is fixed on the bi-axial testing machine and only activated one set of loading arm to which the specimen is fixed for uni-axial loading. The uni-directional strain gage is mounted at the gage area of the uni-axial test specimen and connected to the data acquisition system. The strain data and loads are monitored during the experiment by connecting the data acquisition system to the personal computer. The hydraulic pressure is applied at the rate of 1 kg/cm^2 per 30 seconds. The stress-strain curves of all the uni-axial test specimens with quasi iso tropic layup of [0^0/-60^0/60^0] are shown in Figure 4. The average specimen failure load of 5.49kN is observed with the standard deviation of 0.12kN. The cross-sectional area of the uni-axial test specimen is 25mm x 3mm at the gage area. The stress values are calculated based on initial cross-sectional area. The average failure stress of 73.16MPa is observed with the standard deviation of 1.6MPa. The average failure strain of 5662 με is observed in the test specimen at gage area with the standard deviation of 82με as shown in Table 3.

Figure 4: Uni-axial stress-strain curve of [0^0/-60^0/60^0] configuration

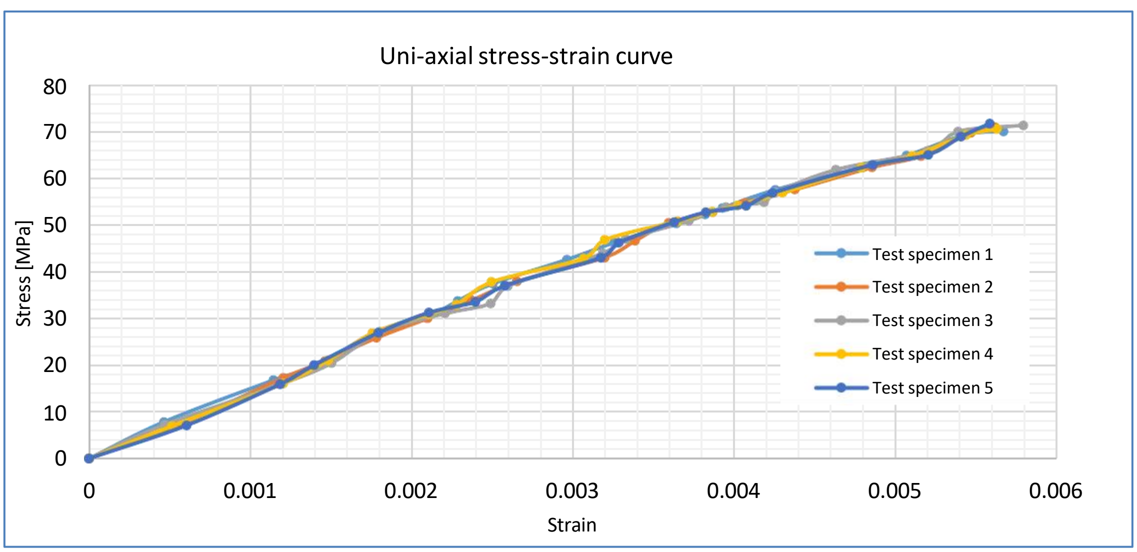
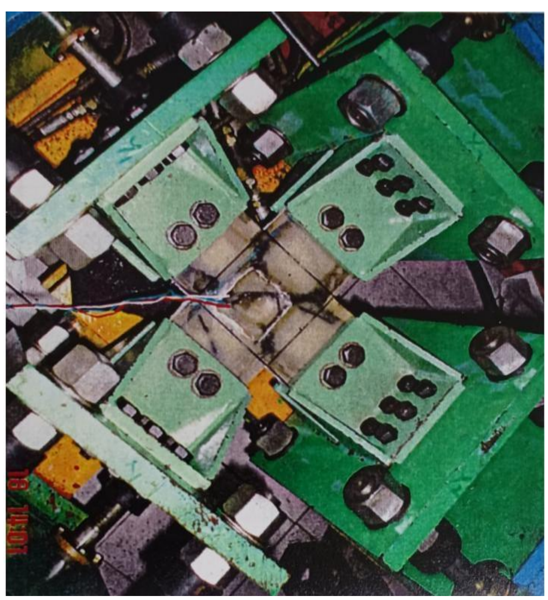


Table 3: Uni-axial Testing Data

Uni-axial Test specimen	Ultimate Failure Load	Ultimate stress	Ultimate Failure strain
[#]	[kN]	[MPa]	[με]
1	5.663	75.50	5671
2	5.473	72.97	5620
3	5.542	73.89	5800
4	5.373	71.64	5630
5	5.385	71.80	5590
Mean	**5.49**	**73.16**	**5662**
Standard Deviation	0.12	1.60	82

Similarly, the bi-axial test cruciform specimens are also tested by using the bi-axial testing machine. The cruciform specimen is fixed to all four loading arms as shown in Figure 5. The specimen position is aligned with the loading axis to avoid the undesirable out-of-plane loading on to the cruciform specimen. The post-yield rosette strain gages are mounted on the gage area to capture the bi-axial strain field. Initial load is applied and ensured that the equal in-plane loading among both loading directions.

Figure 5: Bi-axial testing of [0^0/-60^0/60^0] configuration



The equi bi-axial tensile load is applied among all loading arms. The pressure load is applied at the rate of 1 kg/cm^2 per 30 seconds. The load and strain data are extracted at the center of the gage area from the data acquisition system. The load vs. strain data for all five test specimens are captured in Figure 6. The average failure stress of 59.33MPa is observed with the standard deviation of 0.91MPa. The average failure strain of 2882με is observed in the test specimen at central gage area with the standard deviation of 92με as shown in Table 4.

Figure 6: Bi-axial load-strain curve of [0^0/-60^0/60^0] configuration

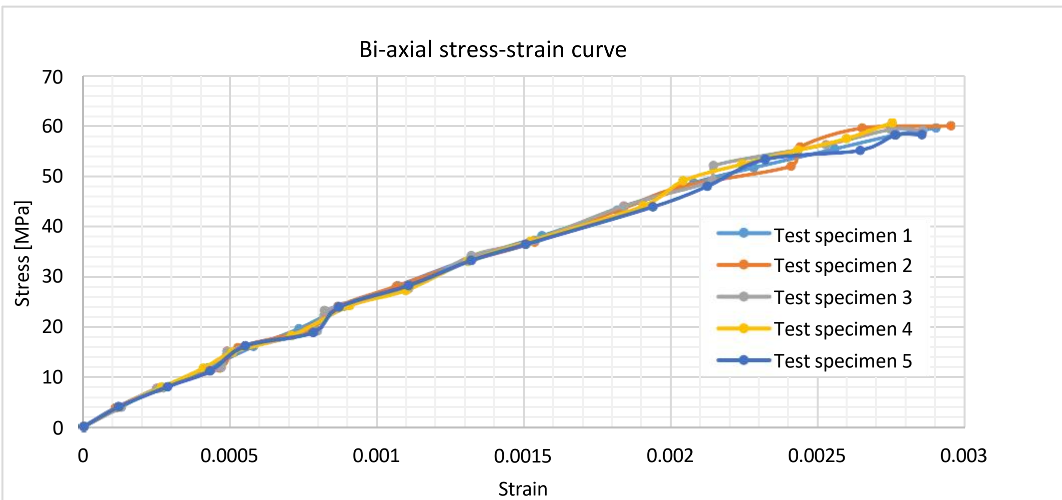
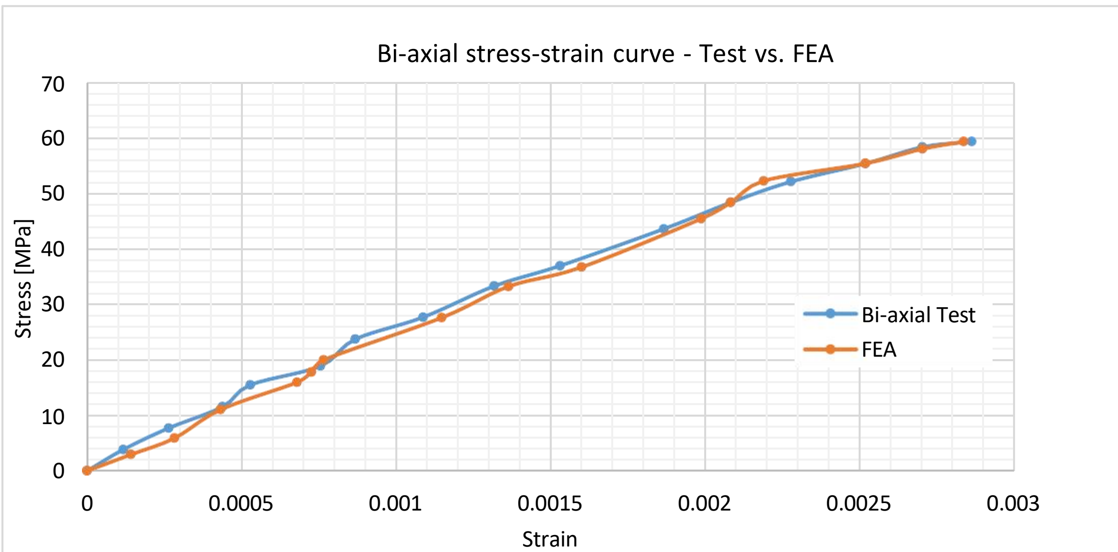


Table 4: Bi-axial Testing Data

Bi-axial Test specimen	Ultimate stress	Failure strain
[#]	[Mpa]	[με]
1	59.40	2980
2	59.80	2959
3	58.90	2868
4	60.47	2750
5	58.06	2852
Mean	59.33	2882
Standard Deviation	0.91	92

Non-linear static analysis is performed with activation of auto time stepping option to capture the specimen biaxial strain response with multiple load increments by applying the same failure load as observed in actual testing. The tested experimental data for bi-axial loading of quasi iso tropic layup of [0^0/-60^0/60^0] configuration is compared against the finite element simulation data as shown in Figure 7 to calibrate the finite element models under bi-axial loading.

Figure 7: Test vs FEA comparison of [0^0/-60^0/60^0] configuration



There is good agreement observed with finite element results compared with test data. The percentage difference between test and finite element results are within 5%. Due to the complexity of the specimen preparation for all different composite lay-up configurations, the above calibrated finite element models are utilized to study the bi-axial loading behavior of composite laminates with different ply configurations.

3. **RESULTS AND DISCUSSION**:

The bi-axial stress analysis is performed on all composite layup configurations. The displacement and strain field observed at test gage area region with various layup configurations under equi bi-axial load of 55kg/cm^2 is described in this section. The displacement field and bi-axial stress-strain distribution in gage area with $[0^0]_3$ layup configuration is shown in Figure 8 & Figure 9 respectively. Since the fibers are oriented in 0^0 direction, the displacements observed in X-direction are significantly smaller compared to Y-direction. Similar stress-strain behavior is observed as the fibers are offering more resistance in X-direction.

Figure 8: Displacement field in gage area with $[0^0]$ layup configuration

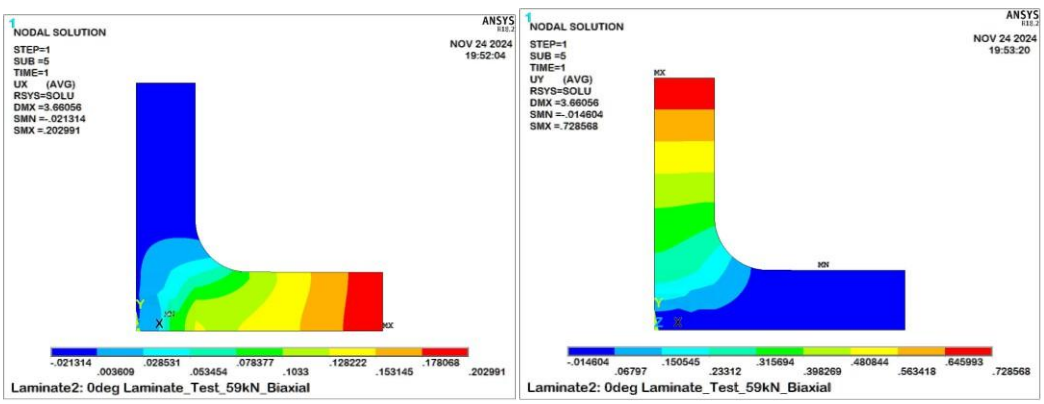
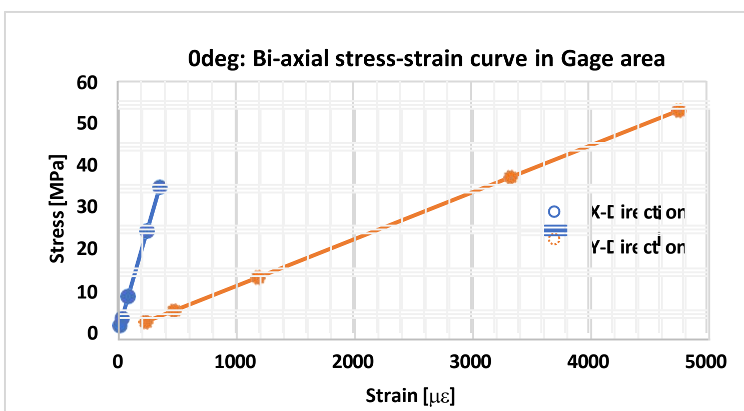


Figure 9: Bi-axial stress-strain in gage area with $[0^0]$ layup configuration



The displacement field in [0^0/-60^0/60^0] laminate is shown in Figure 10. Similarly, the bi-axial stress-strain distribution in gage area under equi-biaxial tensile loading is shown in Figure 11. Since the fibers are oriented in every 60^0 direction and leading quasi-isotropic configuration, the displacements observed in both X and Y directions are same. Similarly, equi bi-axial stress-strain behavior is observed in both X and Y directions.

Figure 10: Displacement field in gage area with [0^0/-60^0/60^0] layup configuration

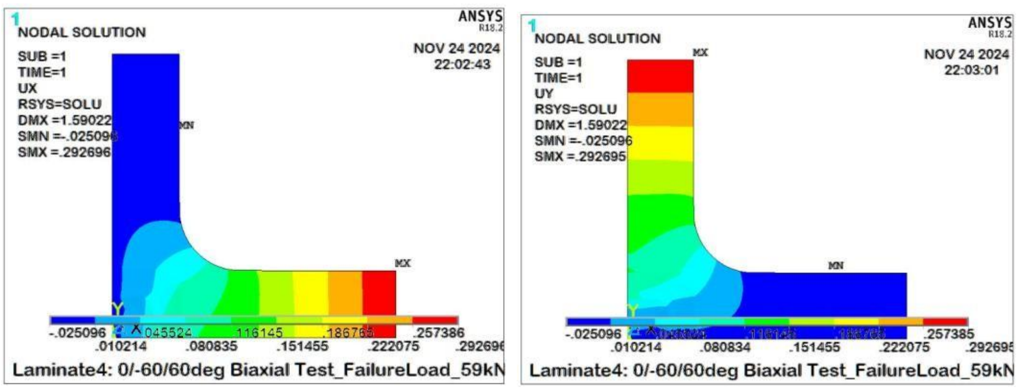
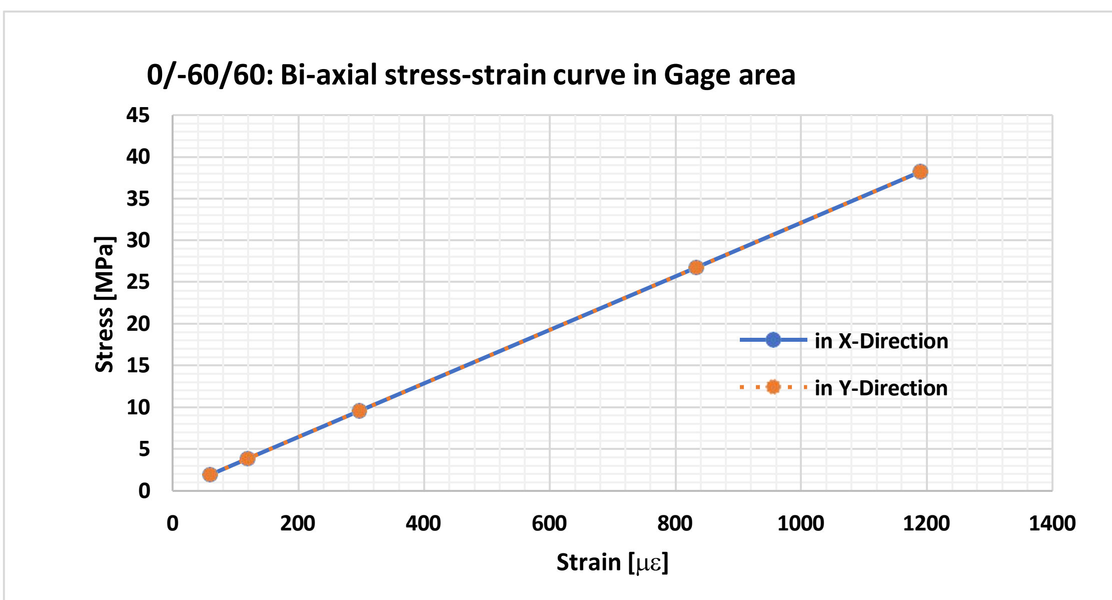


Figure 11: Bi-axial stress-strain distribution in gage area with [0^0/-60^0/60^0] layup



The displacement field in [0^0/-45^0/45^0/90^0] laminate configuration is shown in Figure 12 and the bi-axial stress-strain distribution in gage area under equi-biaxial tensile loading is shown in Figure 13. Since the fibers are oriented in every 45^0 direction and leading quasi-isotropic configuration, the displacements observed in both X and Y directions are the same. Equi bi-axial stress-strain behavior is observed in both X and Y directions.

Figure 12: Displacement field in gage area with [0^0/-45^0/45^0/90^0] layup configuration

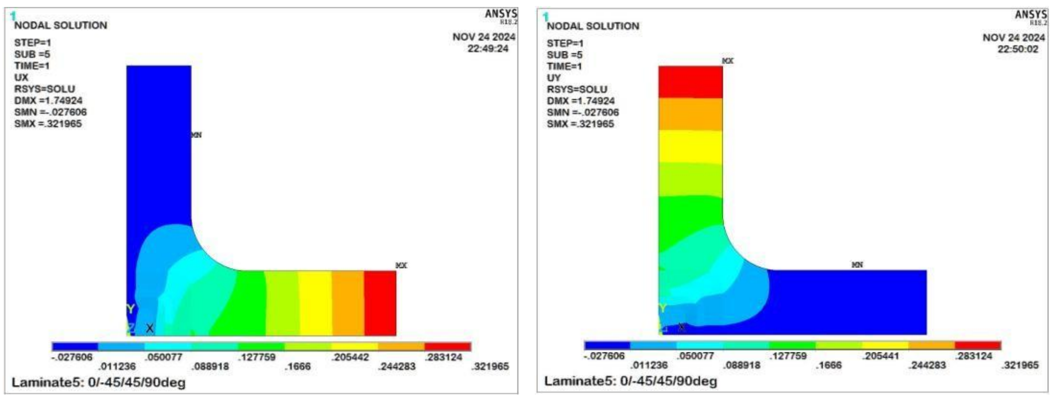
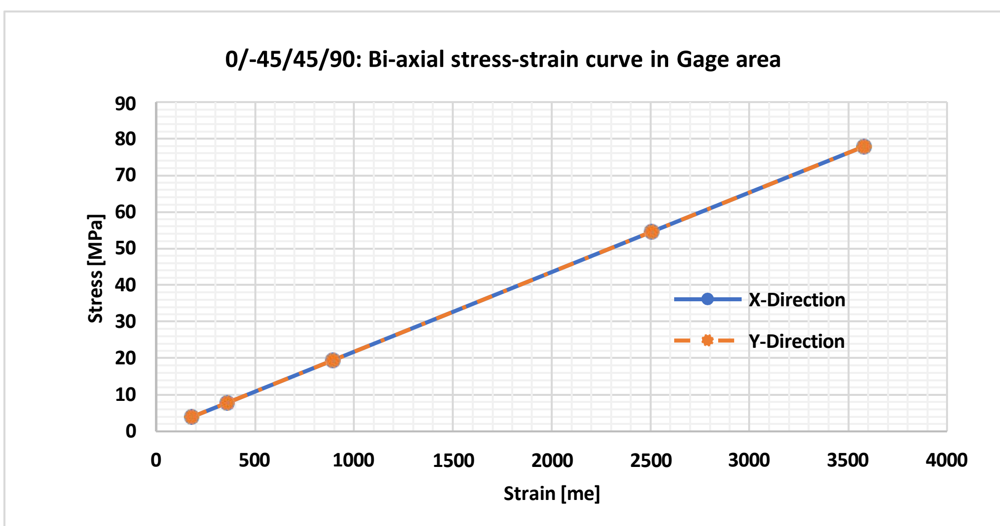


Figure 13: Bi-axial stress-strain distribution in gage area with [0^0/-45^0/45^0/90^0] layup



The displacement field in [$0^0/90^0/90^0/0^0$] laminate configuration is shown in Figure 14 and the bi-axial stress-strain distribution in gage area under equi-biaxial tensile loading is shown in Figure 15. Since the fibers are oriented only in X and Y direction, the displacements observed in both X and Y directions are same. Similarly, equi bi-axial stress-strain behavior is observed in both X and Y directions.

Figure 14: Displacement field in gage area with [$0^0/90^0/90^0/0^0$] layup configuration

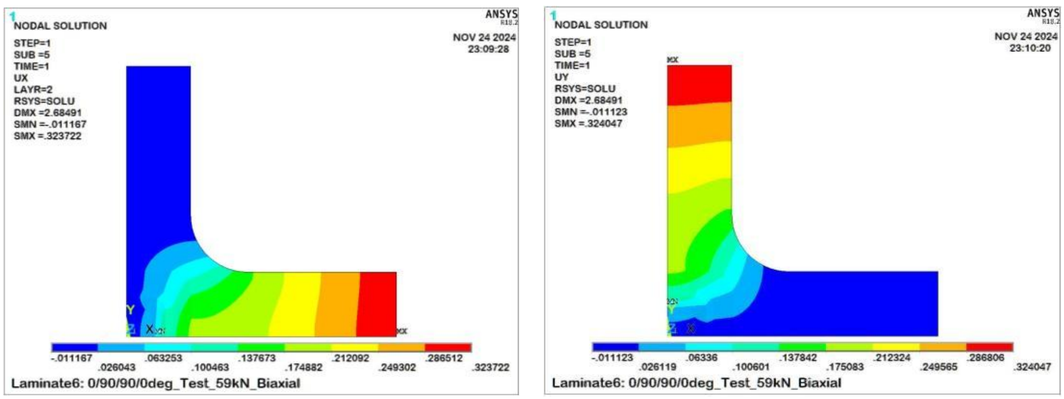
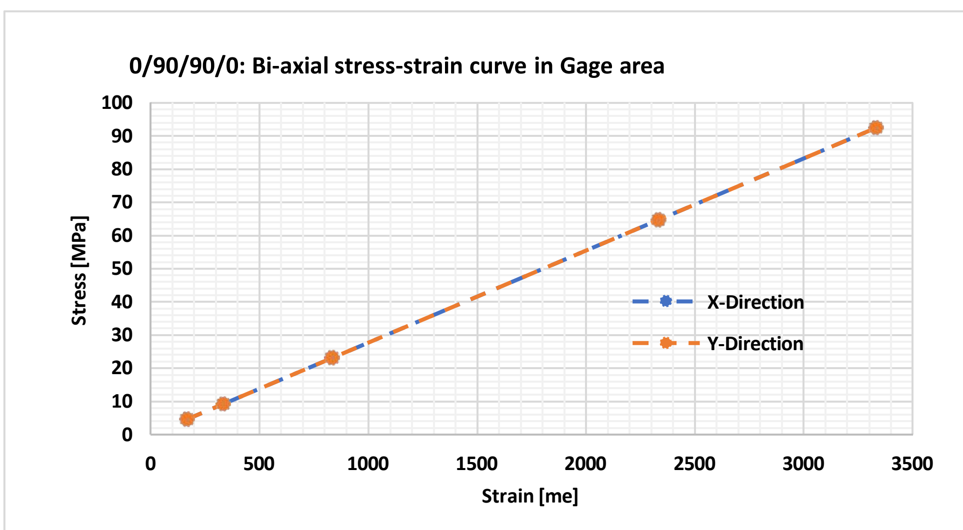


Figure 15: Bi-axial stress-strain distribution in gage area with [$0^0/90^0/90^0/0^0$] layup



The displacement field in [45^0/-45^0/-45^0/45^0] laminate configuration is shown in Figure 16. Similarly, the bi-axial stress-strain distribution in gage area under equi-biaxial tensile loading is shown in Figure 17. Since all the fibers are oriented only in 45degree direction, the displacements observed in both X and Y directions are same but significantly higher compared to previous quasi-isotropic configurations and equi bi-axial stress-strain behavior is observed in both X and Y directions.

Figure 16: Displacement field in gage area with [45^0/-45^0/-45^0/45^0] layup configuration

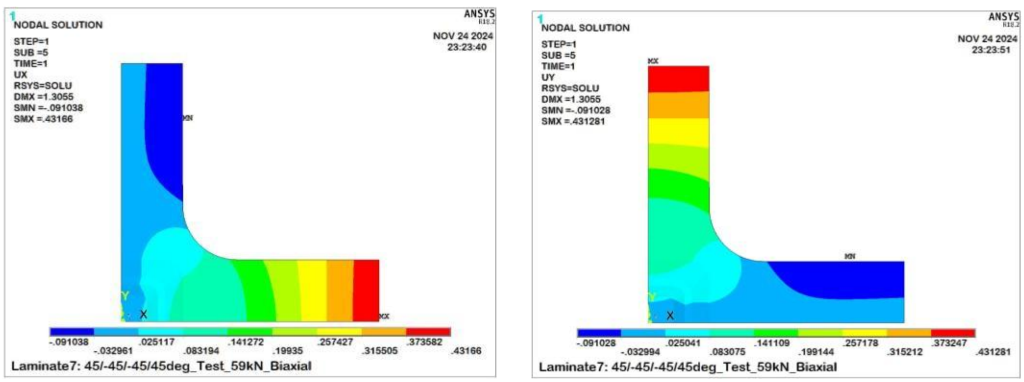
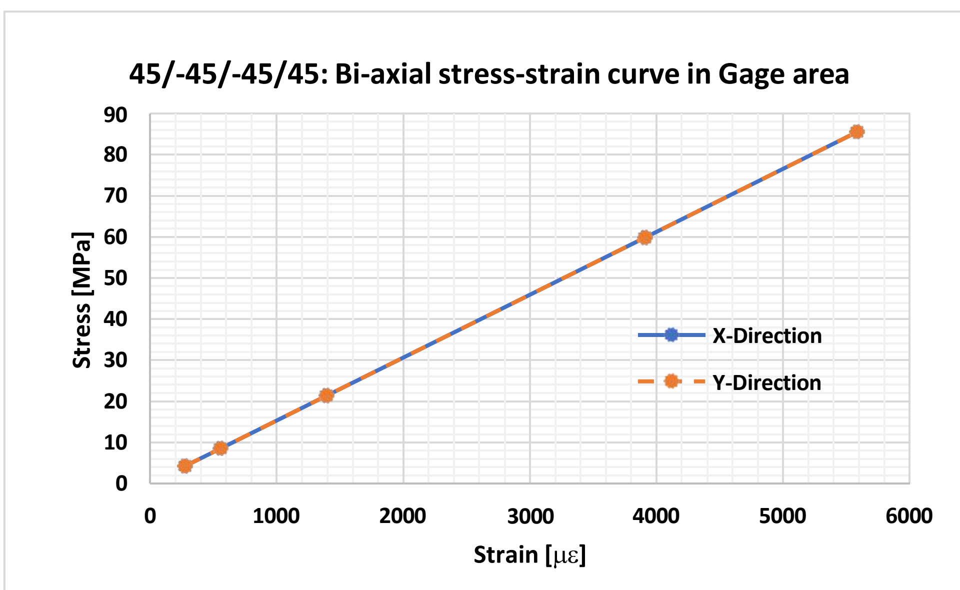


Figure 17: Bi-axial stress-strain distribution in gage area with [45^0/-45^0/-45^0/45^0] layup

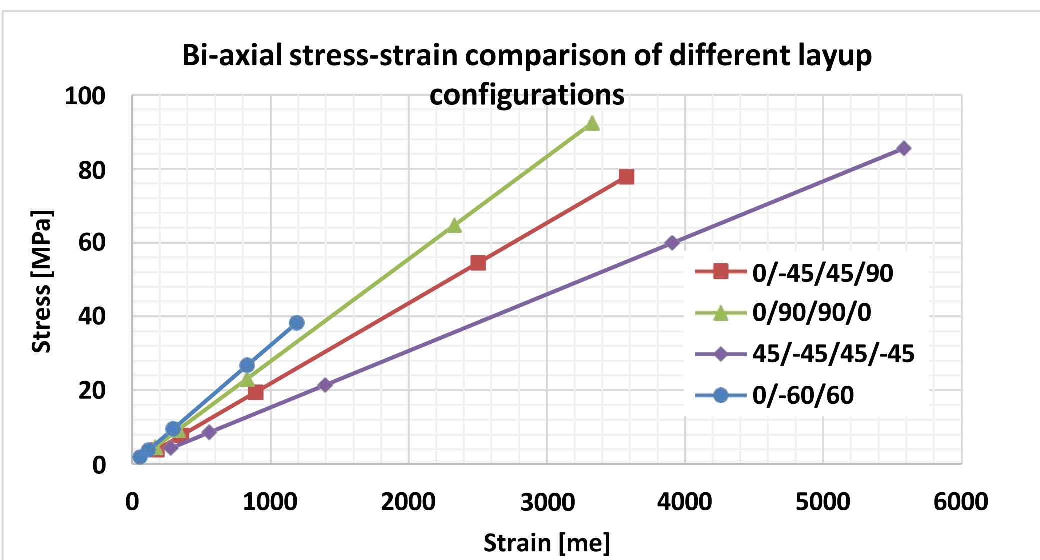


The displacements in X and Y direction are compared for all the laminate configurations as shown in Table 5 and observed that the displacement field in [0^0/-60^0/60^0] laminate configuration is better compared to other layup configurations. Similarly, the biaxial stress-strain distribution in tested gage area of all the composite layup configurations is compared as shown in Figure 18 and observed that the biaxial stress-strain behavior under [0^0/-60^0/60^0] laminate configuration is more promising compared to other layup configurations. Hence to achieve the more promising bi-axial stress-strain field [0^0/-60^0/60^0] configuration is better among the studied composite layup configurations.

Table 5: Displacement comparison among different layup configurations

Lay up	UX	UY
#	[mm]	[mm]
0^0	0.203	0.728
0^0/-60^0/60^0	0.293	0.293
0^0/-45^0/45^0/90^0	0.322	0.322
0^0/90^0/90^0/0^0	0.324	0.324
45^0/-45^0/45^0/-45^0	0.432	0.432

Figure 18: Bi-axial stress-strain comparison among different layup configurations



4. CONCLUSION:

- Based on the displacements mentioned in Table 5, except uni directional laminate, rest of the laminate configurations are yielding equi bi-axial displacement field in the desired gage area.
- The cross-ply laminate configuration [$0^0/90^0/90^0/0^0$] shows the same displacement field in primary X and Y directions, but the strains are slightly higher in X and Y directions compared to quasi-isotropic laminate configurations.
- [$0^0/-60^0/60^0$] laminate configuration is more promising compared to other layup configurations for bi-axial loading conditions. However, depending on the desired load ratios in X and Y directions, the layup stack-up can be modified based on the established stress-strain field using the finite element simulations with different configurations.

4.1 Future scope:

The present research work can be further extended to study the bi-axial behavior of different composite laminate configurations with different load ratios and tension/compression load combinations in the future. This proposed study will help in developing the material scaling factors to account in the design of the components subjected to bi-axial loading in real time application. This can eliminate the real time consuming and expensive bi-axial testing of each material configuration under the study.

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