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SCALING EFFECT OF CRACK DENSITY IN GFRP LAMINATES: INTRODUCTION TO A MULTISCALE FATIGUE TESTING SCHEME AND FINDING AN APPROPRIATE BIAXIAL ZONE SHAPE OF THE CRUCIFORM SPECIMEN

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Abstract

The number of off-axis cracks in a multidirectional laminate or crack density has been identified as an important fatigue parameter for laminate composites and it is related to its stiffness degradation. But for implementing crack density as a fatigue parameter in a multi-scale modelling scheme, it is important to investigate its sensitivity to scale effects. In this research, rectangular coupon and cruciform specimens with variation in the in-plane dimensions are loaded in tension-tension fatigue where the crack density evolution is monitored with white light imaging. But the design of a cruciform specimen is not straightforward and is heavily dependent on the research goal. This particular work focuses on the design of the cruciform specimen through finite element simulations by comparing 4 biaxial zone geometries – circle, square, rhombus and curved square, investigating the uniformity of the induced strain state in the biaxial zone. A circular biaxial zone is found to be appropriate. The multi-scale fatigue testing and modelling scheme of the CASMaT Initiation Project at the Technical University of Denmark is presented as well.

1 Introduction

Fiber reinforced polymers (FRP) are widely used in the fields of aerospace, automotive and wind energy due to its strength to weight ratio. But with these applications comes the necessity of studying FRP's for its behavior against fatigue loading. Fatigue damage in composite is a complicated process and has not been well understood. In multidirectional laminates, fatigue loading leads to a number of matrix cracks which initiate and coalesce to form a tunneling crack propagating along the fiber length. Unlike in metals which are isotropic in nature, the anisotropic nature of the FRP's makes the study and determination of well-established fatigue laws even more difficult. Thus the same isotropic fatigue laws built for metals cannot be implemented for composite laminates.

The matrix cracks are also known as off-axis cracks, as they tend to appear in the off axis plies to the loading direction and can be attributed to the stiffness degradation of multi-directional laminates [1]. It is also known that matrix cracking further leads to the initiation of other damage modes such as delamination and fiber breakage eventually causing a catastrophic failure of the structure [1].

There are numerous references in literature where researchers have tried predicting the stiffness degradation of the multidirectional composite laminates due to fatigue loading with good results [2], but the understanding of fatigue failure in composite laminates is generally derived from experimental tests carried out on coupon specimens such as a rectangular uniaxial tensile specimen. Even though the usage of such coupon specimens is economically favorable, but in most cases the damage mechanisms observed and the damage models thus developed with these specimens tend not to be representative of the damage induced by a similar material system at the structural length scale, e.g. influence of the free edge on the initiation of the matrix cracks in the rectangular uniaxial tensile specimen [1]. The solution here is to introduce better test specimens such as a cruciform specimen which do not have free edges in the biaxial zone. Such specimens are expected to be representative of the defects observed in the structural length scale.

For utilizing crack density as a fatigue parameter in a multi-scale modelling scheme, it is quite imperative to check for its sensitivity to scale effects as well as to the type of testing specimen. For this case, a testing program is being designed where differently sized rectangular and cruciform specimens are both subjected to in-plane fatigue loading. For the rectangular specimens, existing standards such as the ASTM standard D3039/D3039M-17 can be utilized for manufacturing the specimens, but no such standards exists for composite cruciform specimens. Thus the selection of an appropriate cruciform specimen is an equally challenging task and needs to be addressed first which is the primary focus of this paper.

2 A multi-scale fatigue testing scheme

The Technical University of Denmark (DTU) launched a new research infrastructure called the Villum Centre for Advanced Structural and Material Testing (CASMaT) which comprises of three advanced laboratories - the Material Laboratory, the Structural Laboratory and the Large Scale Facility. A CASMaT Initiation Project has been realized in an attempt to try solve the problem of having more established fatigue laws in composite laminates by multi-scale testing and modelling. The project consists of 3 PhD students from the Department of Wind Energy, Mechanical and Civil Engineering looking at the problem at 3 different length scales - micro, macro and structural respectively.

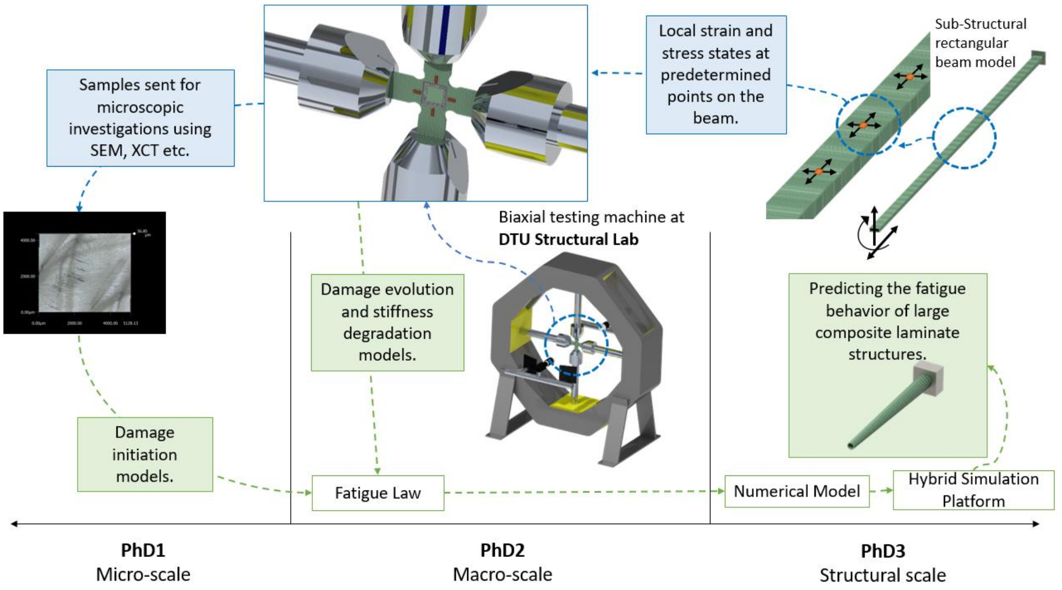


Figure 1. Multi-scale testing and modelling approach.

The preliminary multiscale testing approach has been outlined in Figure 1 where PhD3 carries out tests at the structural length scale of specimens such as a cantilever hollow beam with a rectangular section or a T-Pylon structure attached to a strong wall under a complex load at the DTU Structural Lab. The knowledge of the stress and the strain state in places of interest of the structure is passed one scale down to PhD2 where a cruciform specimen is used to recreate the stress state in the biaxial zone with the help of a 100kN planar biaxial testing machine at the DTU Structural Lab and monitor the resulting damage evolution. Along with PhD1 who would be looking into the initiation and growth of damage at the microscale, a biaxial fatigue damage evolution law would be proposed and would be tested at the structural length scale following which it would be implement by PhD3 as a numerical model. The work presented in this conference paper is relating to the findings from the PhD 2 (macro-scale) study.

3 Recreating a strain state in the biaxial zone of the cruciform specimen

A good cruciform specimen design is crucial for studying the damage evolution due to biaxial loads. Previous experience from literature [3] has put forward the conclusion that a perfect cruciform specimen is yet to be designed but certain measures can be taken to make sure the characteristics of (i) achieving a fairly uniform stress state in the biaxial zone (ii) preventing immature failure of the specimen such as breakage of the arms (iii) maximization of the biaxial zone size and (iv) reduction in the load transfer between adjacent arms, are achieved.

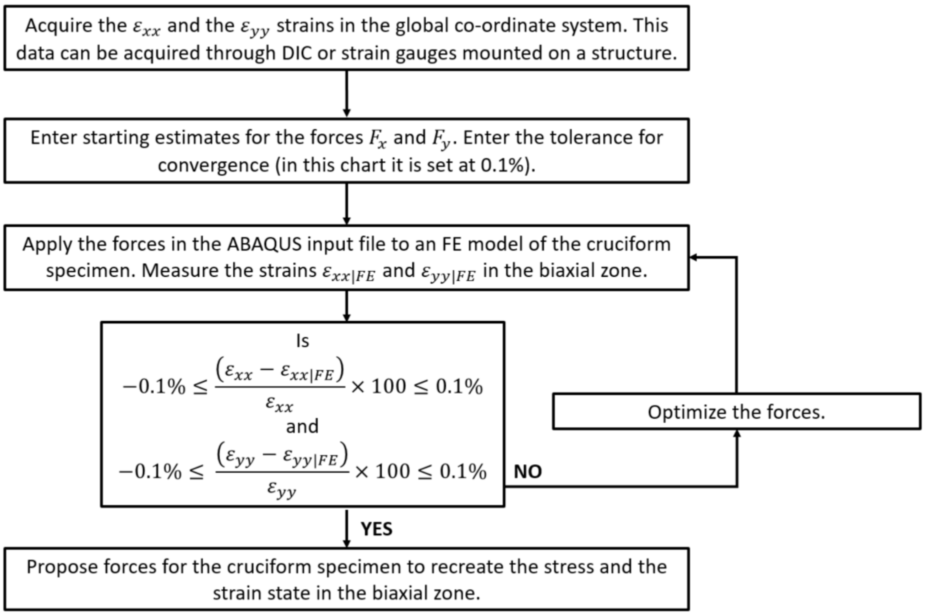


Figure 2. MATLAB – ABAQUS interaction algorithm for calculating the forces required to recreate a stress and a strain state in the biaxial zone of the cruciform specimen.

For the case of the cruciform specimen, due to the restriction in the testing machine, only the size of the biaxial zone will be scaled up in-plane without the proportionate scaling of the arms and the length of the specimen. Thus, it is imperative that the biaxial zones of the different specimen for the scaling effect study must be subjected to the same state of stress and accordingly the forces needs to be applied by the testing machine. But, the production of a state of stress and the application of load is not very intuitive due to a stress and a strain field which are highly dependent on the geometrical features of the cruciform specimen. Thus, a MATLAB – ABAQUS interaction algorithm has been realized which helps in determining the loads required to be applied for reproducing a certain state of stress. Such a tool also helps in a multi-scale modelling scheme where the global strains recorded with DIC or strain gauges from a structure can be taken as input to the algorithm for which it would compute the corresponding biaxial forces needed to recreate the global strain state in the biaxial zone. The algorithm used for predicting the loads is presented in Figure 2.

4 Investigating the shape of the biaxial zone in the cruciform specimen

Having realized an appropriate tool for strain recreation in the biaxial zone, it is also necessary to investigate the effect of the geometrical features of the biaxial zone on the uniformity of the stress and the strain state. The 4 biaxial zone geometries as seen in Figure 3 are being studied. The interaction algorithm developed ensures that the biaxial zones in all the four cases are under the same state of stress for a valid comparison. The FE simulations for these geometries have been conducted on ABAQUS by creating 3D numerical models with 8 node brick type of elements. The boundary condition applied to one such geometry is shown in Figure 4. The material properties applied were E_{11} = 39.10 GPa, E_{22} = 14.44 GPa, E_{33} = 14.44 GPa, ν_{12} = 0.294, ν_{13} = 0.294, ν_{23} = 0.294, G_{12} = 5.39 GPa, G_{13} = 5.39 GPa and G_{23} = 5.39 GPa [4].

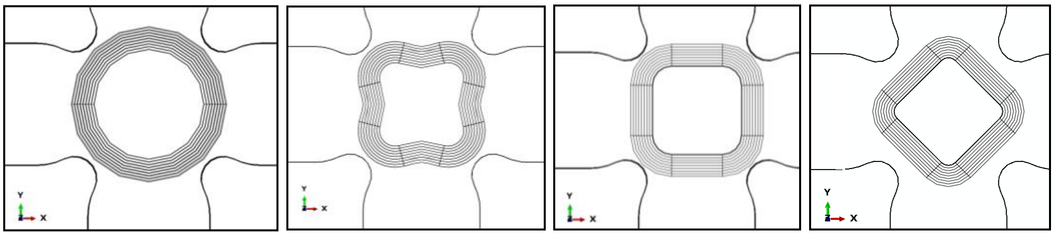


Figure 3. Biaxial zone shapes (left to right) – circle, curved square, square and rhombus. For all the geometries the profile of the cruciform remains the same for consistency. The angle of the transition zone from the arms to the biaxial zone is kept at 20 degrees with the x-y plane. The width of the arm is 60 mm, the radius for the outer curvature and the inner curvature at the intersection of adjacent arms are 11 mm and 30 mm respectively. The thickness of the arm is 12 mm and the thickness of the biaxial zone is 4 mm.

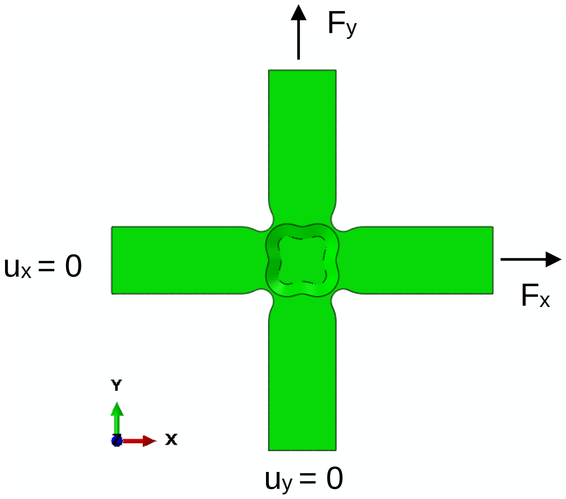
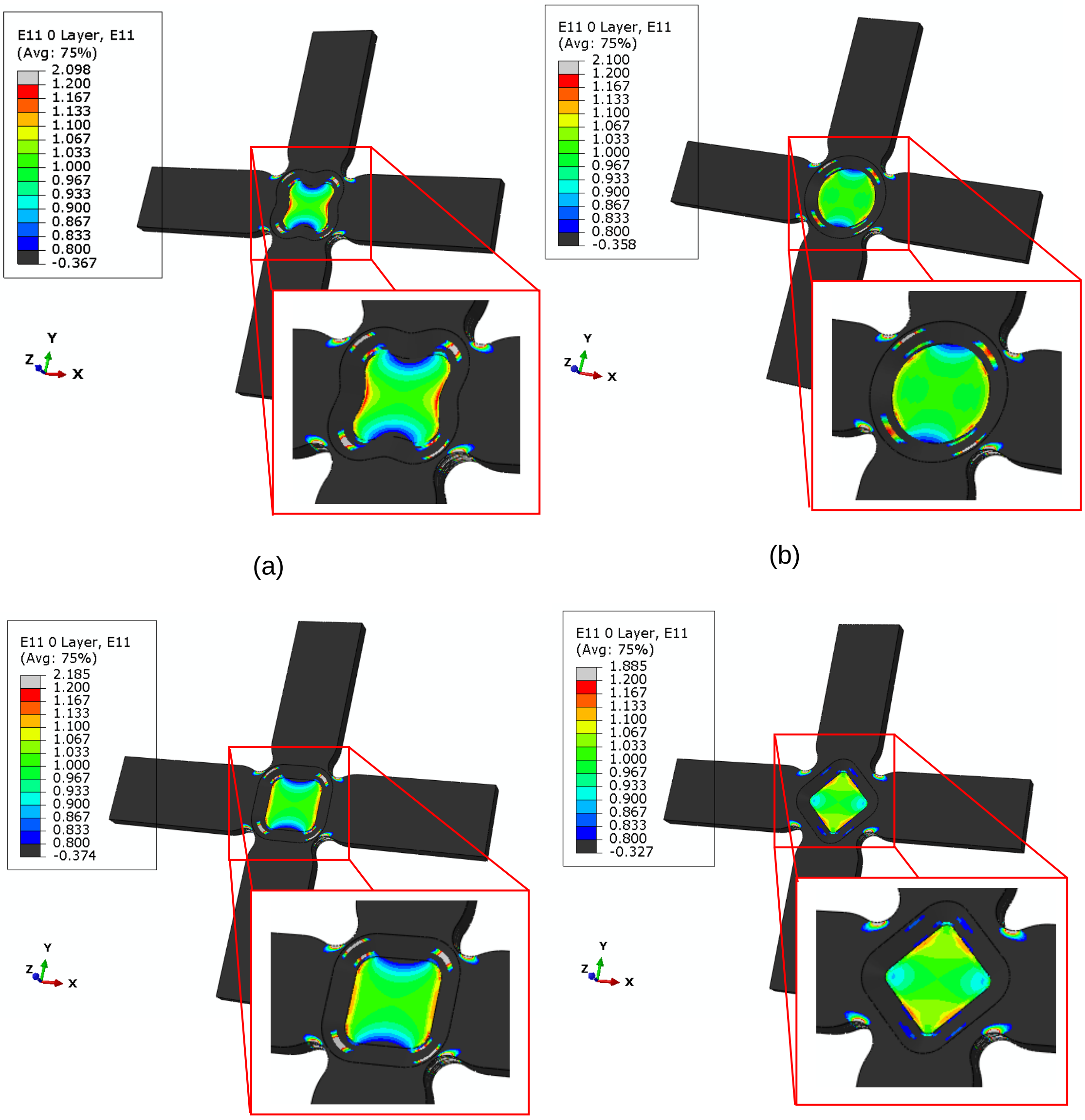


Figure 4. Boundary conditions and applied forces to the cruciform specimen.

The layup sequence of the GFRP laminate from which the cruciform specimen is termed to be manufactured is $[0/+45/0/-45]_S$ with a nominal ply thickness of 0.5 mm. The ε_{11} and the ε_{22}

strains are plotted as both, a contour plot and a line plot across the biaxial zone in the global x and the y direction. The strains obtained from the finite element simulations are normalized with the strains required to be recreated in the biaxial zone. Naturally, the places where the normalized strains is close to 1 indicate that the required strain state has been achieved, thus ensuring the stress and the strain in the material co-ordinate system for each plies are recreated as well. The legend has been limited to 1.2 times and 0.8 times as the maximum and the minimum values of the normalized strains respectively for easy interpretation of the uniformity of the strain state. The contour plots for ε_{11} on the upper unidirectional ply for an induced biaxial strain state of $\varepsilon_{xx} = 0.005$ and $\varepsilon_{yy} = 0.0025$ can be found in Figure 5. The line plots in the biaxial zone along a path in the x and the y directions for the same induced biaxial strain ratio can be found in Figure 6.



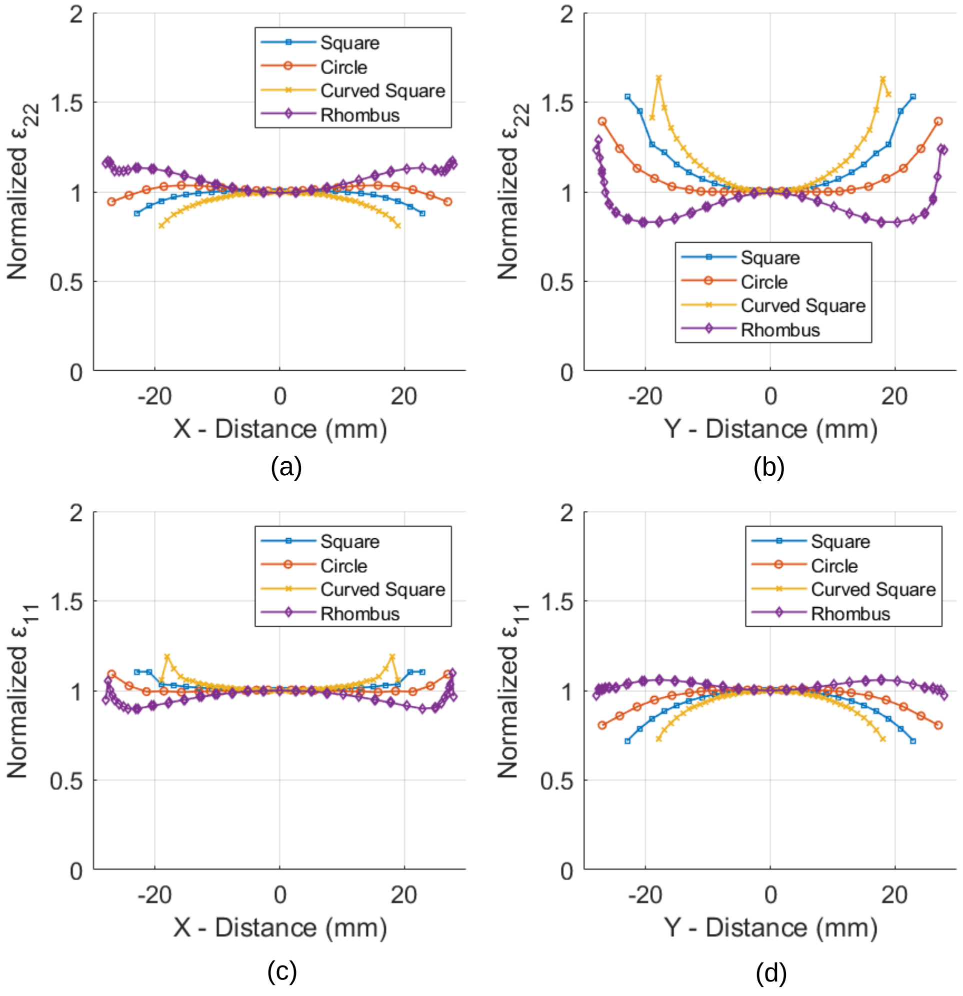
(a) (b)

(c) (d)

Figure 5. ε_{11} strains normalized with the expected strains in the biaxial zone are presented for (a) Curved Square (b) Circle (c) Square and (d) Rhombus geometries.

5 Conclusion

From the plots in Figure 6 it is observed that the circular biaxial gauge zone in general has a comparatively more uniform strain state. Similar results were obtained for induced biaxial strain ratio of $\varepsilon_{xx} = 0.0025$ and $\varepsilon_{yy} = 0.005$ as seen in Figure 7. The rhombus shape, though displayed good performance in Figure 6d and Figure 7a, it performs quite bad in the rest of plots, thus discarding the rhombus shape as a viable option. Stress concentrations were found at the end of the transition zone between the biaxial zone and the arms, but the magnitudes of these stress concentrations are clearly affected by the shape of the biaxial zone. The stress concentrations are reflected in the plots by the peaks in the strain at the opposite ends of the biaxial zone. The circular biaxial zone in many cases handles stress concentrations comparatively better than the other biaxial zone geometries.

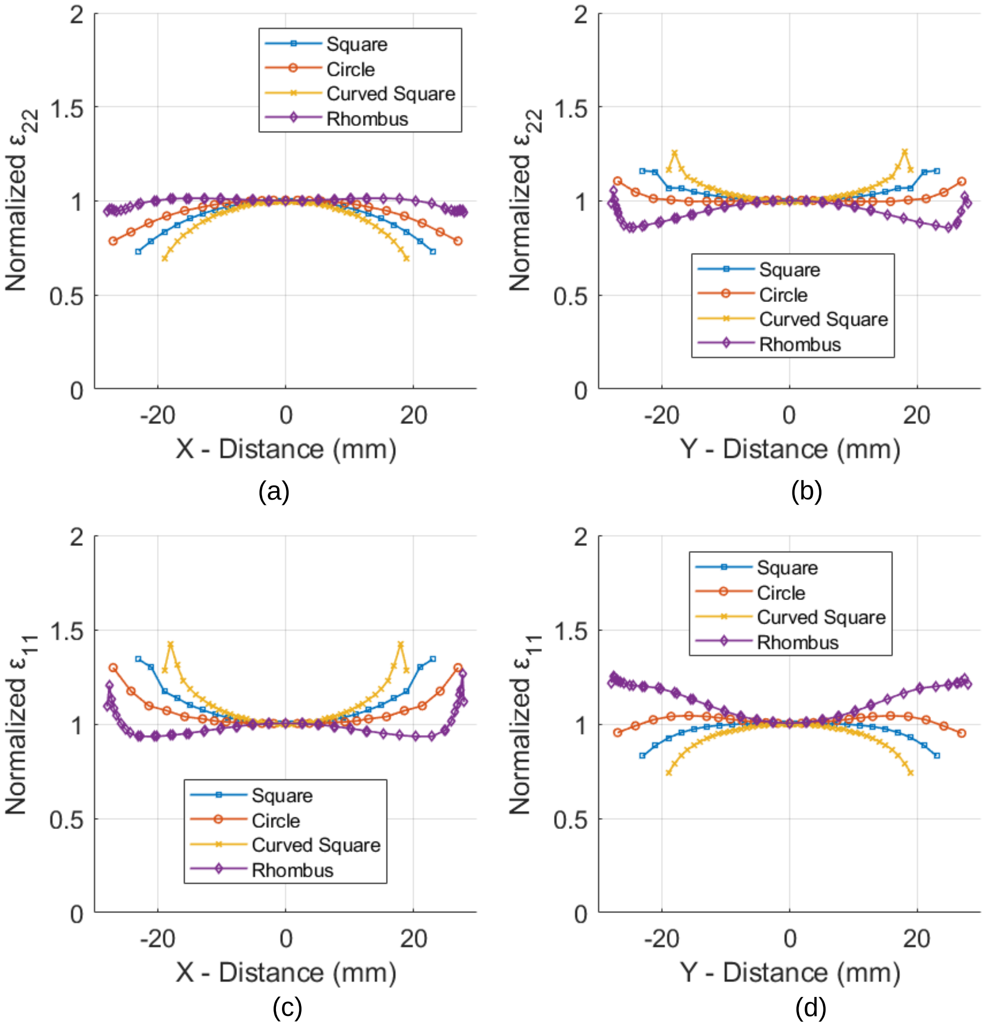


(a) (b)

(c) (d)

Figure 6. Plots for induced biaxial strain state of $\varepsilon_{xx} = 0.005$ and $\varepsilon_{yy} = 0.0025$ (a) Normalized ε_{22} strains along the X distance in the biaxial zone (b) Normalized ε_{22} strains along the Y distance in the biaxial zone (c) Normalized ε_{11} strains along the X distance in the biaxial zone and (d) Normalized ε_{11} strains along the Y distance in the biaxial zone.

Future work includes further optimization of the cruciform specimen to reduce the stress concentrations at the end of the transition zone. Design considerations such as the introduction of slits in the arms or the transition angle itself are being experimented with. On achieving a successful design for the cruciform specimen, the scaling effect study would be carried out.



(a) (b)

(c) (d)

Figure 7. Plots for induced biaxial strain state of $\varepsilon_{xx} = 0.0025$ and $\varepsilon_{yy} = 0.005$ (a) Normalized ε_{22} strains along the X distance in the biaxial zone (b) Normalized ε_{22} strains along the Y distance in the biaxial zone (c) Normalized ε_{11} strains along the X distance in the biaxial zone and (d) Normalized ε_{11} strains along the Y distance in the biaxial zone.

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