Cruciform Specimen Designs for Planar Biaxial Fatigue Testing in Composites

Moncy, A.; Castro, Oscar; Berggreen, C.

Published in:
Proceedings of 22nd International Conference on Composite Materials

Publication date:
2019

Document Version
Peer reviewed version

CRUCIFORM SPECIMEN DESIGNS FOR PLANAR BIAXIAL FATIGUE TESTING IN COMPOSITES

A. Moncy[1*], O. Castro[2] and C. Berggreen[1]

[1] Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, *amonc@mek.dtu.dk
[2] Department of Wind Energy, Technical University of Denmark, Risø Campus, Denmark.

Keywords: *Biaxial fatigue, Composite materials, Cruciform, Finite element analysis*

ABSTRACT

The usage of cruciform specimen for planar biaxial coupon testing is evaluated using finite element analysis. Nine cruciform designs made up of a multidirectional laminate are simulated under a biaxial loading state to test the uniformity of the local stress state and the global strain state in the off-axis layer and on the surface of the biaxial zone respectively. The learnings from this analysis though valid for the current loading condition is a step towards finding a possible 'one for all material configuration' cruciform specimen design in the future, which in turn can simplify the task of sizing of the cruciform specimens made up of composite materials.

1 INTRODUCTION

Currently, uniaxial rectangular specimens are majorly used to characterize the fatigue properties of composite materials [1]. Even though these specimens prove to be a cheap and fast method for fatigue characterization, the experimental results obtained from them need to be taken with a certain amount of reservation due to the inherent drawbacks of these specimens, such as the free edge effects [2]. It has been shown, for example, that the free edges in the uniaxial rectangular specimens act as initiators for matrix cracking [2], which in turn speed up the initiation and propagation of other damage mechanisms, such as delaminations [3]. Such a damage initiation and propagation from the edges may cause a reduction in the specimen lifetime which may not be representative to the lifetime of large structures or components made up of the same material system under the same loading conditions. Consequently, test specimens in which the damage evolution and the fatigue lifetime better represent reality are needed.

Additionally, the loads applied to uniaxial rectangular specimens during fatigue tests do not necessarily generate a realistic local state of stress if compared with the one that a structure might experience during operational loading conditions. Furthermore, in structures made of multidirectional composite laminates, the local stress states are always multiaxial due to the intrinsic anisotropy of the material (internal multiaxiality); however, more complex local multiaxial stress states can also be created by the externally applied multiaxial loading (external multiaxiality) as well [4]. Nevertheless, when testing uniaxial rectangular specimens, the multiaxiality in the laminate stress state is only caused by material anisotropy as the test loads are applied in a single direction. Hence, in order to study the fatigue behaviour of composite structures with the help of experiments at the coupon scale, it is necessary to design specimens to which it is also possible to apply multiaxial external loads.

So far, two types of specimens have been developed with which external multiaxiality can be induced. These are cruciform-shaped specimens and tubular specimens [4]. In tubular specimens, multiaxiality can be induced by either a combination of internal/external pressure and axial tension/compression or torsion and axial tension/compression [4]. The fundamental challenges with the tubular specimens are the premature failure due to the end tabbing [5] and the limitation on the allowable thickness of the specimens due to the increase in the variation of the through-the-thickness radial stresses with the increase in the laminate thickness [6]. Cruciform specimens, on the other hand, have a constant through-the-thickness strains in addition to offering a more straightforward way of inducing an in-plane biaxial stress state. But designing an appropriate cruciform specimen on its own is a very challenging task due to premature failure caused by stress concentrations (e.g. damage initiation from the corners

where adjacent arms meet) and the generation of a fairly uniform stress/strain field in the biaxial zone [8]. Hence, there is a need to find a cruciform specimen design made of composite laminates in which the stress concentrations are minimized and the uniformity in the strain/stress fields in the biaxial zone is maximized. The lack of a standard for planar biaxial fatigue testing of composite materials using cruciform specimens further emphasis the challenge.

A suitable cruciform design should (i) achieve a fairly uniform stress state in the biaxial zone, (ii) prevent premature failure of the specimens such as breakage of the arms due to stress concentrations, (iii) maximize the biaxial zone size and (iv) reduce the load transfer between the adjacent arms and the biaxial zone. The presented work will mainly address requirements (i), (iii) and (iv) by comparing nine cruciform designs while evaluating (ii) but not addressing it. This work is a part of a multi-departmental collaborative effort at the Technical University of Denmark (DTU) to study fatigue damage at 3 length scales – structural, macro and micro scale. The cruciform specimen is primarily used in the macro length scale.

2 METHODS

In this study, nine cruciform designs are analysed considering three types of external features and three biaxial zone shapes, see Fig. 1. The cruciform designs are compared to each other by using a finite element analysis in order to evaluate their usage for multiscale modelling and fatigue testing of composite materials under a planar biaxial global strain state.

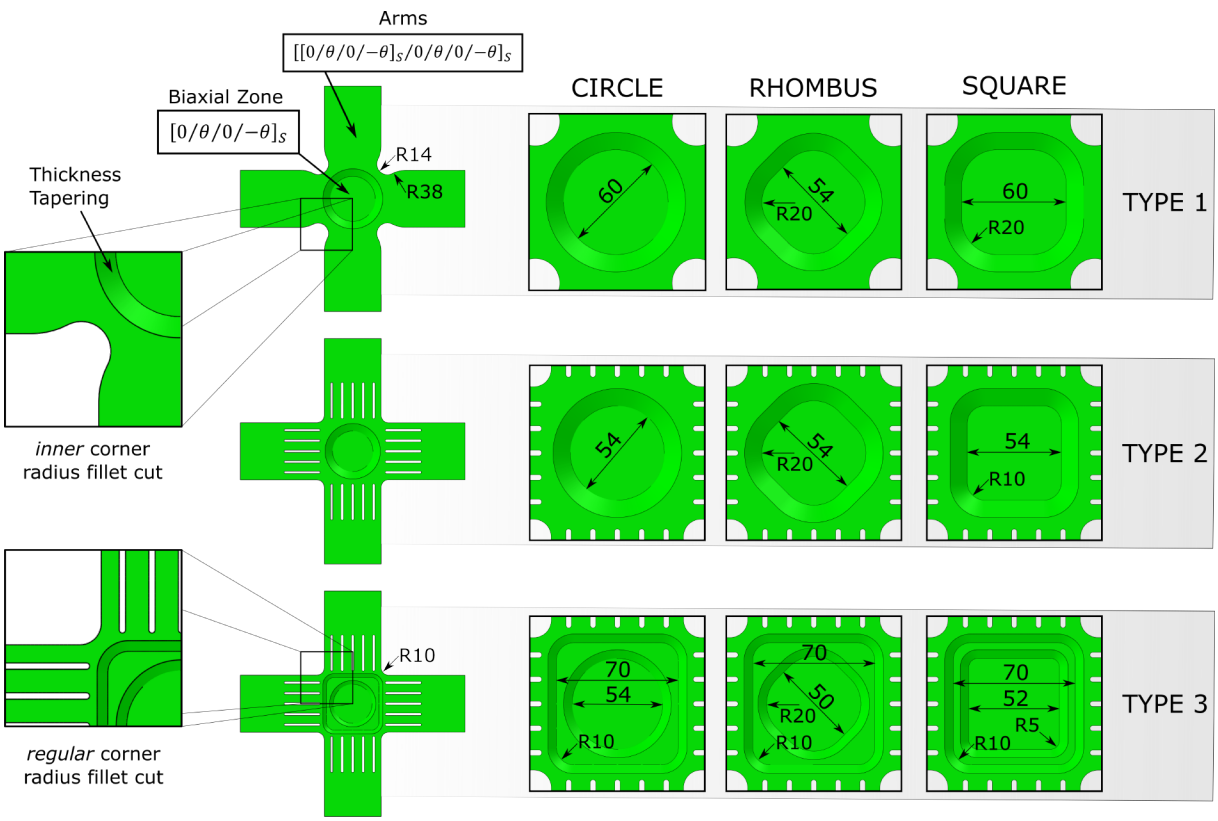

Figure 1: Nine cruciform specimens considered in this study. Dimensions in mm.

The primary task of this work is to categorize the external cruciform features into three types, see Fig. 1. 'Type 1' is a thickness tapered cruciform specimen with an *inner* corner radius cut at the intersection of the adjacent arms. The thickness tapering joins the arms to the biaxial zone with a certain taper angle. This is one of the most extensively studied cruciform specimen designs both numerically and experimentally [7-13]. The *inner* corner radius is hypothesized to reduce the load sharing between the adjacent arms and the biaxial zone or decouple them but generally the cruciform specimen suffers

from stress concentrations at this location. 'Type 2' is also a thickness tapered cruciform specimen but instead of the *inner* corner radius cut, slots are used in the arms to achieve the same goal of decoupling of the adjacent arms with the biaxial zone[14]. Such a type of specimen is commonly used for metals but their usage is limited in composites due to the manufacturing challenges to have the slots. Finally, 'Type 3' specimens are quite similar to 'Type 2' specimens but the thickness tapering is achieved in two steps rather than a single [15].

Moreover, along with the three external cruciform features, three of the most common biaxial zone shapes are also analysed: rhombus [16, 17], circle [11, 15] and square [7-10, 12-14], see Fig. 1. The square-shaped gauge zone has the largest biaxial zone size with the rhombus-shaped gauge zone being the smallest. A large biaxial zone according to requirement (iii) for a suitable cruciform specimen is desirable; in turn making the square-shaped biaxial zone instantly a good candidate. But the selection would also depend on the uniformity of the stress/strain state in the biaxial zone.

On the other hand, the layup configuration evaluated in the biaxial zone of the cruciform specimens is $[0/\theta/0/-\theta]_s$, see Fig. 1. Such a layup configuration was chosen to study the growth of transverse matrix cracking for different off-axis ply angles, θ. For the current study, $\theta = 60°$. A symmetric layup is necessary to make sure that the laminate response to the extension forces in the biaxial zone is in-plane. In addition, the arms are assumed to be three times thicker than the biaxial zone and the tapering from the arms to the biaxial zone is achieved with a taper angle of 20°. Moreover, a GFRP material property is used, whose material properties are presented in Table 1.

E_{11} GPa	E_{22} GPa	E_{33} GPa	G_{12} GPa	G_{23} GPa	G_{13} GPa	υ_{12}	υ_{23}	υ_{13}
39	14	14	5.4	5.4	5.4	0.3	0.3	0.3

Table 1. Material properties used in the FE analysis

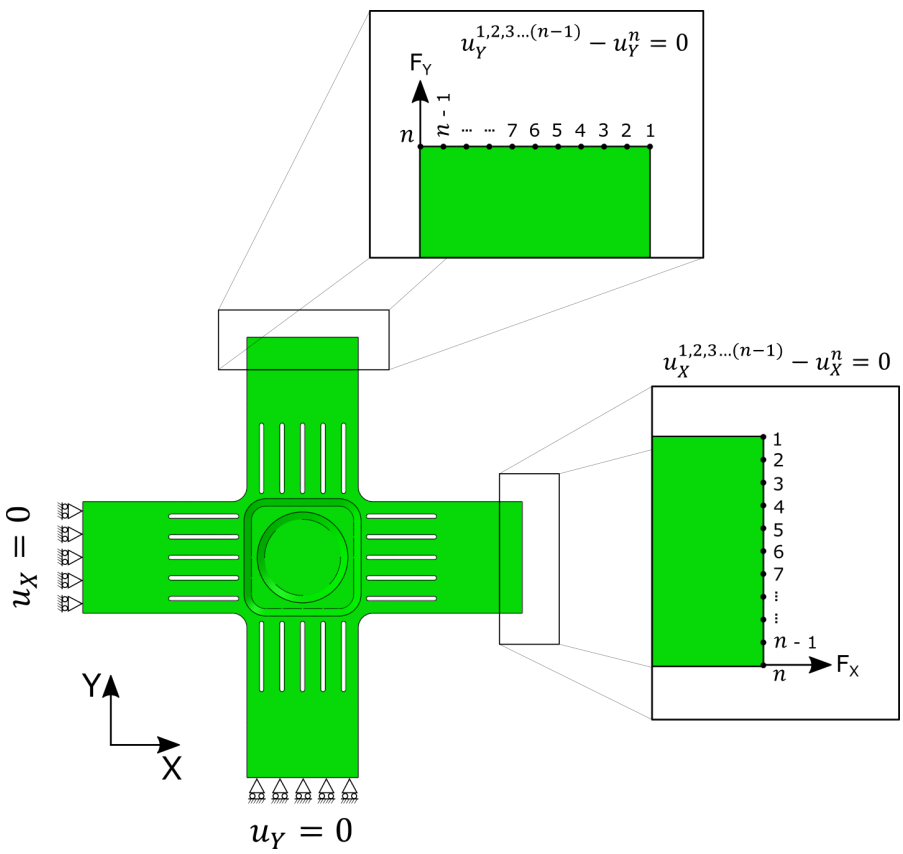

Figure 2: Boundary and loading conditions.

3 RESULTS

The following three sub-sections provide a brief comparative overview on the strain state uniformity (in the global co-ordinate system), the stress state uniformity (in the material co-ordinate system) and the load sharing experienced by the nine cruciform specimens with their biaxial zones subjected to the same global strain state using the methods described in the previous section.

3.1 Comparing the global strain state on the surface of the biaxial zone.

The strains obtained from finite element analysis in the biaxial zone were normalized by the required strain, see Fig. 3, according to the following equation:

$$\varepsilon_{NN}^{*} = \frac{\varepsilon_{NN|FE}}{\varepsilon_{NN|REQ}} \tag{1}$$

where $NN = XX$ or YY represents the global directions, $\varepsilon_{NN|FE}$ are the strains obtained from the finite element model and $\varepsilon_{NN|REQ}$ are the required global strains (i.e., $\varepsilon_{XX} = 5000\mu$strain and $\varepsilon_{YY} = 2500\mu$strain in the present case). The normalization of the numerically obtained strains provides a more in-depth knowledge on the areas of the biaxial zone where the required strain state is achieved. Thus, ideally, ε_{NN}^{*} at the center of the specimen should be one. In order to have a common legend for the nine contour plots, the normalized strain field was limited to the range of 0.8 to 1.2 (see Fig. 3) for an unbiased comparison of the strain field in the biaxial zone.

As seen in Fig. 3, the square-shaped biaxial zone has in general the worst strain field uniformity of the required strain state among the three shapes; whereas, the rhombus (Type 1) and circle (Type 1) shapes have the best strain field uniformity. Moreover, within the external feature types, Type 1 has, in general, a better strain field uniformity of the required strain state than the Type 2 and Type 3.

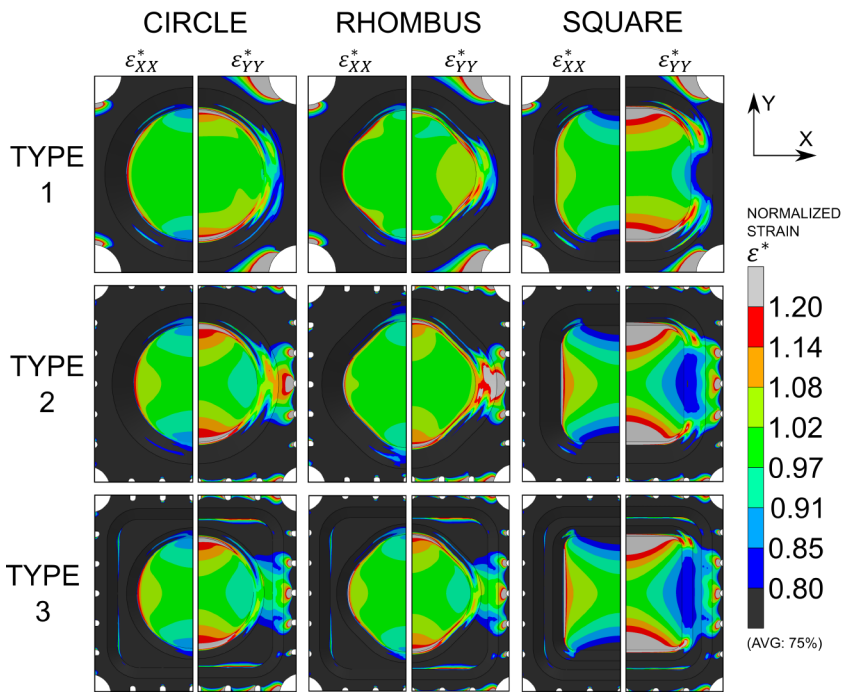

Figure 3. ε_{XX}^{*} and ε_{YY}^{*} distribution on the surface of the nine evaluated cruciform specimens.

3.2 Comparing the local stress state in the off-axis 60° ply.

Due to the anisotropic nature of composite materials and the complex shape of the cruciform specimen, it is important to evaluate the stress distribution in the off-axis layers (which in the current

layup configuration are the 60° and −60° plies). Features like the fillet corners and the slot tips can act as stress raisers, potentially leading to the premature failure of the specimen.

The local stress state of a particular layer obtained from the finite element analysis was normalized by the expected local stress of the same layer calculated from the required global strain state using Classical Laminate Theory (CLT). The normalization is as follows:

$$\sigma_{nn}^{*} = \frac{\sigma_{nn|FE}}{\sigma_{nn|CLT}} \tag{2}$$

where $nn = 11$ or 22 represents the local coordinate system directions, $\sigma_{nn|FE}$ are the finite element determined stresses and $\sigma_{nn|CLT}$ are the CLT determined stresses. It is expected that σ_{nn}^{*} should be one at the center of the biaxial zone, which is also observed in Fig. 4. The normalized stress for all the nine designs was plotted again in the same range of 0.8 to 1.2 for providing an unbiased comparison in their stress state.

As shown in Fig. 4, the distribution in the local stress state is more uniform with the circular and the rhombus-shaped biaxial zones; whereas, the square-shaped biaxial zone proved to have the poorest uniformity in its local stress state. It is observed from the finite element analysis that the nature of the stress state uniformity in the biaxial zone can be attributed to its proximity to geometrically induced stress raisers to a large extent, if not completely. As an example, the square-shaped biaxial zone, due to its larger size, is much closer to the cruciform specimen corners (where the adjacent arms meet) as compared to the circular and the rhombus-shaped gauge zone with the latter being the farthest. These corners which act as stress raisers contribute to the non-uniformity of the square-shaped biaxial zone more when compared with the other two biaxial zone shapes. In general, the Type 1 specimens have their stress concentrations at the *inner* corner radius; whereas in Type 2 and Type 3 specimens, the stress concentration shifted to the tip of the slots.

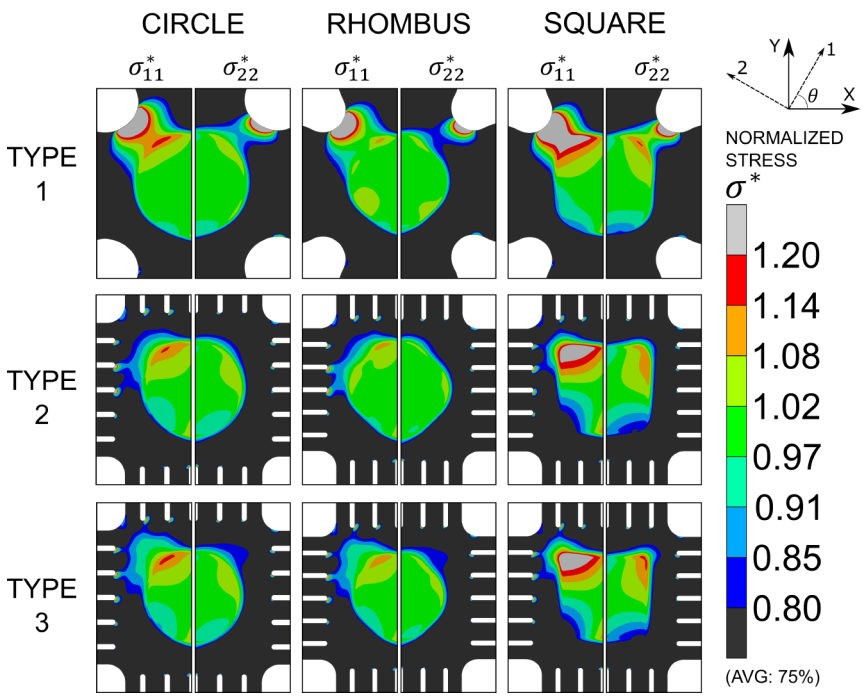

Figure 4. σ_{11}^{*} and σ_{22}^{*} distribution in the $\theta = 60°$ ply of the nine cruciform specimen designs.

3.3 Load sharing between adjacent arms.

Not all the applied forces are directed towards the biaxial zone as some are also 'shared' by the

adjacent arms. This sharing implies that the application of extension loads on two opposite arms lead to an extension in the direction of the force not only in the biaxial zone, but also in the immediate area around the biaxial zone towards the adjacent arms. Cruciform designs with the least amount of load sharing is a requirement for testing systems limited on loading capacities as it provides us with the flexibility of testing different multiaxial loading ratios and material systems (with various different fiber orientations) on the same testing system. A lower load sharing also ensures that most of the loads are used to generate the required strain state in the biaxial zone and higher stresses are not observed in areas outside the biaxial zone, especially in the arms.

From the finite element analysis, it is seen that the load sharing between the adjacent arms was less in Type 3 specimens than in Type 1 and Type 2 specimens, see Fig. 5. In general it is inferred that the specimens with the slots required less forces to create the required global strain state in the biaxial zone as compared to the specimens with the *inner* corner radius fillet. The least force was required by the Type 3 specimen with square-shaped biaxial zone and the most force was required by the Type 1 specimen with rhombus-shaped biaxial zone.

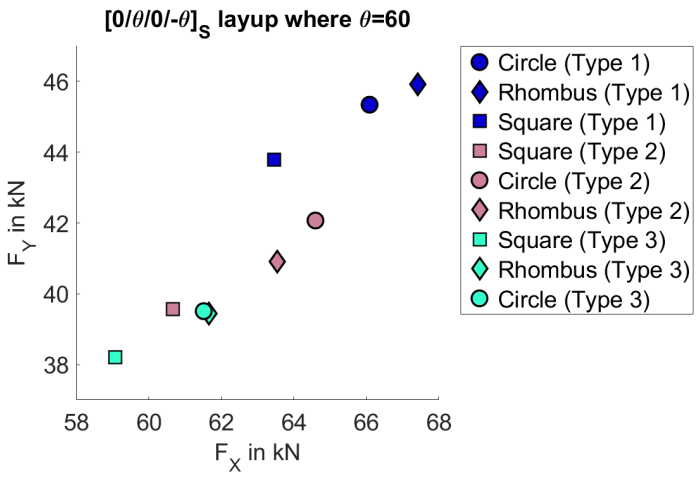

Figure 5. Forces required to recreate the global strain state of $\varepsilon_{XX} = 5000\mu$strain and $\varepsilon_{YY} = 2500\mu$strain in the biaxial zone.

4 CONCLUSIONS

For the required global multiaxial strain state of $\varepsilon_{XX} = 5000\mu$strain and $\varepsilon_{YY} = 2500\mu$strain, nine cruciform specimens with a biaxial zone made of a $[0/\theta/0/-\theta]_s$ laminate, where $\theta = 60°$, were compared using a linear elastic finite element analysis in order to evaluate their uniformity in the global strain state and the local stress state. Additionally, the complex shape of the cruciform geometry demanded that the areas of stress concentrations be looked upon as well.

It was found that the circular and the rhombus-shaped biaxial zones had a better uniformity in both the global strain state and the local stress state when compared with the square-shaped biaxial zone. Among these two best shapes, the rhombus-shaped biaxial zone requires much higher forces as compared to the circular-shaped biaxial zone to recreate the required strain state within the same type. The square-shaped biaxial zone required the least forces, implying that it has the least load sharing between the biaxial zone and the adjacent arms. However, even though the square-shaped biaxial zone has the largest biaxial zone size and requires the least forces to recreate a strain state, it still remains an unfavorable design due to the comparatively higher non-uniformity of the stress state in the biaxial zone as mentioned earlier.

Moreover, in general, the adjacent arm decoupling or reduction in load sharing was better in Type 2 and Type 3 specimens when compared with Type 1 specimens. However, the usage of slots in Type 2 and Type 3 specimens caused the highest stress concentration at the slot tips. The stress concentrations at the slot tips can be a potential sight for splitting cracks to originate under the application of a transverse load to the 0° fiber, thus limiting their usage for biaxial testing. In comparison, the Type 1 specimens

were found to have the highest stress concentrations at the *inner* corner radius fillet.

5 ON-GOING AND FUTURE WORK

In order to conclude on a suitable cruciform designs which fits the 'one for all material configuration' requirement, much more investigations are required. The future work includes taking into consideration more possible cruciform shapes for analyzing the uniformity in their stress/strain states under more biaxial loading conditions and addressing the stress concentrations (e.g. at the *inner* corner radius fillet) presented in this work.

REFERENCES

[1] ASTM International, ASTM D3479/D3479M-19 Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials. West Conshohocken, PA; ASTM International, 2019.

[2] J. Glud, *Characterization and modelling of the multiaxial fatigue response of glass fibre reinforbed composite materials*, PhD Thesis, Aalborg University, 2017.

[3] P.A. Carraro, E. Novello, M. Quaresimin, M. Zappalorto, Delamination onset in symmetric cross-ply laminates under static loads: Theory, numerics and experiments, *Composite Structures*, **176**, 2017, pp. 420-432.

[4] M. Quaresimin, L. Susmel, R. Talreja, Fatigue behaviour and life assessment of composite laminates under multiaxial loadings, *International Journal of Fatigue,* **32**, 2010, pp. 2-16.

[5] M.M. Shokreih, A. Asadi, Design of Modified Tabs for Testing of Symmetric Composite Thin Walled Tubes Under Pure Torsional and Tensile Loadings, *Experimental Mechanics*, **50**, 2010, pp. 307-320.

[6] V.K.S. Choo, D. Hull, Influence of Radial Compressive Stress Owing to Pressure On the Failure Modes of Composite Tube Specimens, *Journal of Composite Materials*, **17(4)**, 1983, pp. 344-356.

[7] J. Welsh, D. Adams, An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens, *Composites - Part A: Applied Science and Manufacturing*, **33**, 2002, pp. 829-839.

[8] C. Ramault, *Guidelines for biaxial testing of fibre reinforced composites using a cruciform specimen,* PhD Thesis, Virje Universiteit Brussels, 2012.

[9] E. Lamkanfi, W. Paepegem, J. Degrieck, C. Ramault, A. Makris, D. Hemelrijck, Strain distribution in cruciform specimens subjected to biaxial loading conditions. Part 1: Two-dimensional versus three-dimensional finite element model, *Polymer Testing,* **29**, 2010, pp. 7-13.

[10] E. Lamkanfi, W. Paepegem, J. Degrieck, C. Ramault, A. Makris. D. Hemelrijck, Strain distribution in cruciform specimens subjected to biaxial loading conditions. Part 2: Influence of geometrical discontinuities, *Polymer Testing*, **29**, 2010, pp. 132-138.

[11] M. Gower, R. Shaw, Towards a Planar Cruciform Specimen for Biaxial Characterisation of Polymer Matrix Composites, *Applied Mechanics and Materials*, **24-25**, 2010, pp. 115-120.

[12] A. Smits, D. V. Hemelrijck, T. Philippidis, A.Cardon, Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates, *Composites Science and Technology,* **66**, 2006, pp. 964-975.

[13] A. Makris, C. Ramault, D. V. Hemelrijck, E. Lamkanfi, W. Paepegem, Biaxial fatigue testing using cruciform composite specimens, *Proceedings of the 13th European Conference on Composite Materials (ECCM-13), Stockholm, Sweden, 2008.*

[14] Y. Youssef S. Labonté C. Roy D. Lefebvre, Specimen Design, manufacturing and testing procedures for flat carbon fiber reinforced plastic laminates under biaxial loading, *Polymer Composites,* **19**, 2004 pp. 257-263.

[15] W. Jackson, J. Ratcliffe, Investigation of the leak response of a carbon-fiber laminate loaded in biaxial tension," in *Proceedings of the American Society for Composites - 28th Technical Conference, 9-11 Sep 2013.*

[16] D. Escárpita, *Experimental Investigation of textile composite strength subject to biaxial tensile loads*, PhD Thesis, Instituto Tecnológico y de Estudios Superiores de Monterrey, 2011.

[17] J. Gutiérrez, A. Lozano, A. Manzano, M. Flores, Numerical and Experimental Analysis for Shape Improvement of a Cruciform Composite Laminates Specimen, *Fibres & Textiles in Eastern Europe*, **2**, 2016, pp. 89-94.