SUITABILITY OF CRUCIFORM SPECIMENS FOR CHARACTERISING BIAXIAL BEHAVIOUR OF COMPOSITE LAMINATES

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Keywords: Biaxial testing, Cruciform specimen, Chopped Strand Mat (CSM)

Abstract

A parametric study is carried out to establish the effect of different geometric parameters on the design of cruciform specimen and a suitable geometry is proposed for studying the biaxial behaviour of glass CSM reinforced polyester composites. Cruciform specimens are fabricated and subjected to equi-biaxial loading using an inplane biaxial test rig. The experimental observations confirmed the predictions of numerical analysis that the failure is governed by raised stresses near the transition zone rather than the biaxial stresses in the gauge area.

1 Introduction

The potential of composite material systems is widely accepted in industries such as aircraft, automobiles, pressure vessels and piping etc [1]. Most structural components in these systems are subjected to complex service loads, where more than a single non-zero principal stress may exist. For safe and reliable design of such components and thus of the system, it is of much importance to characterize the mechanical response and fracture behaviour of composite laminates under multi-axial stress-states [1-8]. Several experimental and corresponding computational studies have been undertaken which simplify complex multi-axial loads to various combinations of controlled bi-axial loading conditions on usually tubular or cruciform specimens. Among these, cruciform specimens find wide acceptance as most of the industrial structures are flat or gently curved [2].

Important aspect of the cruciform specimen based studies is the design of optimal cruciform specimen, which produces the maximum, uniform and pure biaxial state of stress in the gauge area [1-8]. Finite element analysis has been used for the optimization of the specimen geometry. Common features of the various cruciform specimen geometries proposed in the last few years are (i) gauge area with a lesser thickness compared to arms – to increase the stresses (ii) shape of the gauge – for a uniformly stressed region and (iii) a rounding radius at the intersection of the arms – to minimize the stress concentration [4]. The studies carried out on the cruciform specimens have proved their ability to obtain the failure data in the tension-tension [2, 3], tension-compression [3] and even the complete biaxial failure envelope [8]. These studies arrive at final specimen dimensions without providing the details of the parametric study or quantifying the effect of different geometric parameters. Influences of different geometric parameters on the strain distribution in the gauge area were first coined by Lamkanfi et al. [6]. The study describes that geometric discontinuities are the main source of failure and they have also explained the importance of 3D finite element analysis in capturing the information at these geometric discontinuities [7].

In the present work, the primary focus is to evaluate the effect of key geometric parameters on the suitability of the cruciform specimen in characterizing the mechanical response and the fracture behaviour under a complete biaxial state of stress. The specimen is developed for the biaxial stress analysis under tension-tension case. The material in consideration is a chopped-strand-mat (CSM) reinforced glass-polyester composite laminate. CSM type fibre reinforcement sheet consists of short fibres oriented in random directions. Due to nearly inplane-isotropic properties of the materials, these are mainly used in chemical transportation and construction industries [1]. For this a systematic 3 dimensional Finite Element Analysis is performed in ANSYS 10 and finally arrived at cruciform specimen geometry with best possible dimensions. Using these dimensions bi-axial specimens are fabricated using hand layup technique and subjected to equi-biaxial loading on an inplane biaxial loading machine. The test facility used has four hydraulic loading arms (each) of load capacity 250 kN.

2 Cruciform specimen design using ANSYS

To achieve bi-axial state of stress, cruciform specimen has four loading arms. The intersection area that is common to both the loading directions develops a bi-axial state of stress and thus is referred as the gauge area of a cruciform specimen as shown in Fig.1.

Figure 1. CSM glass/polyester cruciform specimen.

However, to use the cruciform specimen for characterizing the biaxial response of the composite laminate several issues needed to be addressed. Due to the intersecting arms, stress concentrations occur at the corner and the gauge area becomes the strongest part of the specimen as a result of larger area for load distribution. Introduction of corner shape at the intersection of arms can reduce the stress concentration but cannot completely avoid. It is possible to improve the stress state in the gauge by reducing its thickness. In addition to that the shape of the thickness reduction also plays an important role in attaining a uniform stress region in the gauge. Hence, for the suitable design of a cruciform specimen for the biaxial study of composite materials it is very important to study the influence of these geometric parameters. In the present study, to address the influence of each of these parameters a numerical analysis is carried out by decoupling the parameters into two groups as: cruciform shape parameters and gauge area parameters. The cruciform shape parameters are (i) the radius of the corner *(r)* and (ii) the shortest distance of the circular edge from the centre of the specimen *(l)* as shown in Fig. 2. The gauge shape parameters are (i) non-dimensional thickness transition ratio (t_g/t_{arm}), (ii) radius of the gauge area corner (r_g) and (iii) the radius of the thickness transition (r_f) as shown in Fig. 3. In the analysis of results all these parameters (except t_g/t_{arm}) are made non-dimensional by normalizing with the width of the arm (w). Effect of each of these parameters is investigated in detail, by considering allowable range of values.

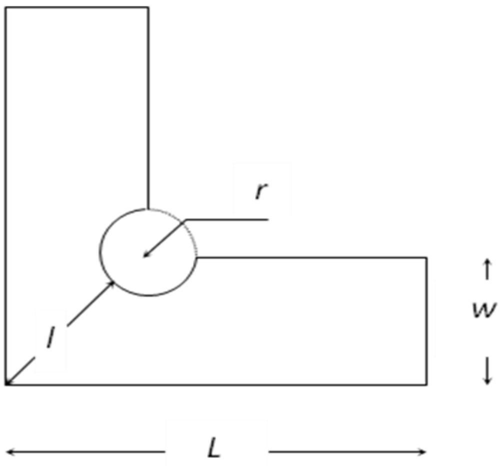


Figure 2. Corner shape parameters.

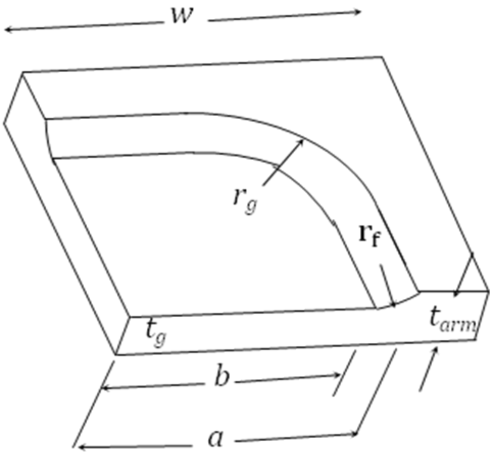


Figure 3. Gauge area parameters.

Numerical simulations are carried out in ANSYS using Solid45 elements. It is a 3D element defined by 8 nodes and having 3 degrees of freedom at each node: translation in x, y and z directions. The analysis is carried out by giving the inplane elastic properties of the glass CSM/polyester composite as input. A specimen of size $2w\times 2w\times t_{arm}$ (280×280×16) mm is used in the analysis by taking the envelop available in the biaxial test setup into consideration. Length and width of the each arm are X (100) mm and $2w$ (80) mm respectively and the size of the gauge area is $2w\times 2w$ (80×80) mm. By taking the advantage of the geometric symmetry of the cruciform specimen, only a quarter of the specimen is considered in the analysis for reducing the computational time. Entire model is meshed with the hexahedral elements. Symmetric boundary conditions are applied at the planes of symmetry. All the arms are subjected to equal amount of tensile loading and the displacements in the thickness direction are also constrained.

3 Biaxial testing machine

The test rig (shown in Fig. 4) mainly consists of loading frame, hydraulic power pack and a data acquisition system. The loading frame consists of four hydraulic cylinders (double-acting), rigidly fixed on an I-sectional base frame, and thus the centre of the test specimen remains in the same position during the test. The hydraulic loading system is used to load the specimen with negligible mechanical losses. The fluid pressure in each pair of hydraulic cylinders is controlled independently. All the four hydraulic cylinders are connected to the power pack consisting of hydraulic pump and solenoid valves. Load cells are used in each loading direction to measure the load values directly. The data acquisition system ("system 5000") is connected to the test facility to extract the strain gauge and load cell readings by using “strain smart” software. The system has an accessible loading area to fix the specimen and visible test section to observe the crack propagation.

Figure 4. Biaxial loading frame.

4 Results and discussion

The cruciform specimen geometry is obtained through the numerical simulations and its suitability for studying the bi-axial behaviour of CSM glass/polyester laminates is verified experimentally. The attributes of an ideal bi-axial specimen are:

- The highest stresses are in the gauge area.
- The stresses should be purely bi-axial in nature.
- The pure biaxiality should be uniform and as wide spread as possible.
- The location of critical stresses and the parameters that can help in minimizing them
- The gauge area with uniform thickness is reasonably large.

4.1 Numerical results

Keeping the ideal attributes in mind, the process of arriving at the appropriate dimensions for the cruciform specimen has been decoupled into 3 stages:

- ➢ Overall dimensions of the cruciform specimen: *r/w* and *l/w* ratios (minimizing the corner stresses) – reduces the stress concentration at the intersection of the arms.
- ➢ Gauge area parameters – improves the stress state in the gauge area and also ensures uniform stresses in the gauge area.
- ➢ Interaction between gauge and cruciform parameters – ensures that the objectives of the shape and gauge parameter optimization are not compromised in the final geometry.

4.1.1 Cruciform shape parameters

The critical cruciform shape parameters are the non-dimensional radius of the corner (*r/w*) and the normalised distance of the circular edge from the center of the specimen (*l/w*) where the edges of the orthogonal arms meet. As these parameters primarily control the corner stresses, a wide range of cruciform geometries with uniform thickness were modeled and analyzed to quantify the effect. The effect of the location parameter observed in Fig. 5 is that the lowest stress concentration occurs when the circular edge is tangential to both the arms i.e, it is the fillet between the edges. Any further reduction in distance from the center leads to build up of stress concentration and is therefore avoidable. As shown in Fig. 6, it is observed that starting from the infinite stresses expected at a sharp corner ($r/w=0$), as the non-dimensional radius of the corner increases the maximum principal stress at the corner decreases sharply and for *r/w* greater than *0.25*, it gradually saturates.

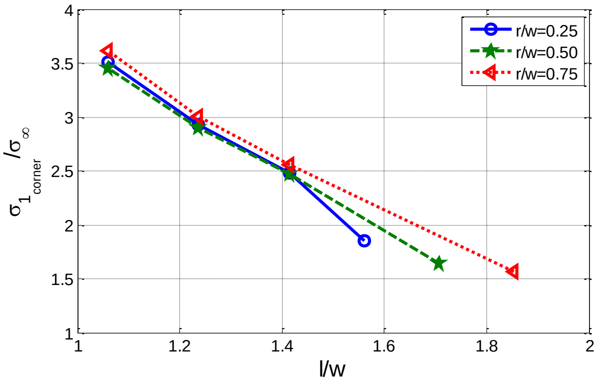


Figure 5. Effect of location of shape parameter, *l/w* on the normalized corner stress.

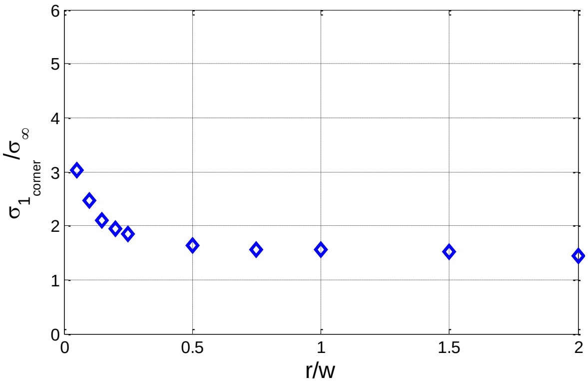


Figure 6. Effect of radius of shape parameter, *r/w* on the normalized corner stress.

The other effect of the radius of the corner is to influence the uniformity of the stress state in the central area. The extent to which the principal stresses are within *5%* of the stresses at the center, *X/w*, is shown to decrease with increasing radius of the corner in Fig.7. Here *X* is the length of the uniform region. Based on these figures it can be argued that an appropriate choice for the radius at the corner would be of *0.25w* and located such that the shape is a fillet and not a notch, not only this results in the stress concentration being close enough to the saturation value but also ensures uniformity of stresses in a larger area around the center.

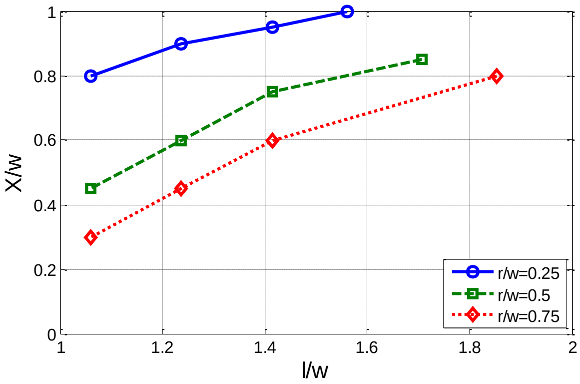


Figure 7. Effect of location of shape parameter, *l/w* on the uniform stress region in the gauge area.

4.1.2 Gauge shape parameters

To establish the effect of the gauge parameters in isolation from the overall cruciform shape, an idealized square shaped geometry ($2w \times 2w \times t_{arm}$) with uniform bi-axial stress applied at the edges and a gauge area at the center ($1.2w \times 1.2w \times t_{gauge}$) is modeled for a range of the involved geometric parameters. Initially, to determine effect of the radius of the gauge area (r_g), keeping $t_g/t_{arm}=0.25$ and $r_f/t_g=4.5$, the stress field is obtained for a range of gauge corner radius. As shown in Fig. 8, as the gauge corner radius is increased the maximum principal stress decreases and reaches very close to the gauge stresses (within *5%*) at the maximum radius possible which is the case when the shape of the gauge is a circle. Next with a circular gauge shape and the gauge size parameter, $a/w=0.6$, a range of thickness ratios were investigated with the objective of maximizing the amplification. The key role of the thickness ratio, t_g/t_{arm} is to achieve amplification of stresses in the gauge area such that they are significantly higher than the corner stresses that may develop in the cruciform specimen. As shown in Fig. 9, as the thickness ratio is reduced from *1* corresponding to the uniform thickness case, the stresses get amplified in the gauge area. Since the lowest stress concentration factor achievable in the cruciform geometry is around *1.5*, the gauge thickness ratio must therefore be lower than *0.4* for which the amplification is approximately *2.5*.

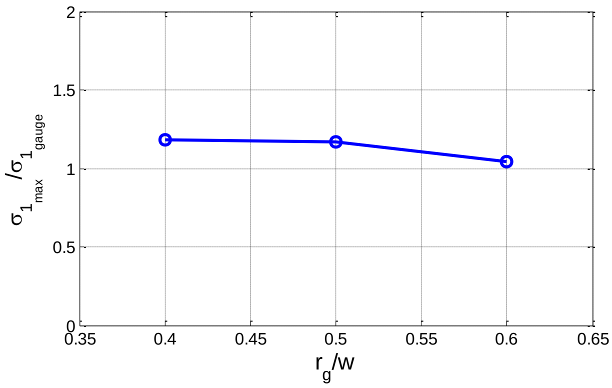


Figure 8. Effect of corner radius parameter, r_g on the normalized maximum principal stress.

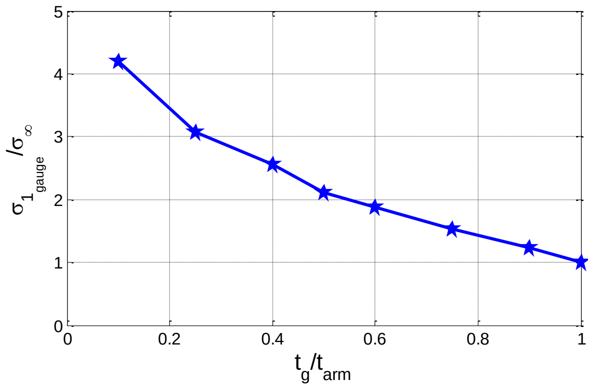


Figure 9. Effect of transition parameter, t_g/t_{arm} on the normalized gauge area stress.

However, reducing the gauge thickness ratio also leads to build up of stresses at the transition zone and therefore to find an appropriate thickness ratio the maximum principal stress due to thickness transition are normalized with the gauge stress as illustrated in the Fig. 10. The transition radius (r_f) is taken to be the largest radius possible such that the gauge area has uniform thickness up to a distance of *0.5a* from the center. As observed in the figure for the range $t_g/t_{arm}<0.4$ which produces useful amplification, the transition stress to gauge stress ratio keeps decreasing with decrease in thickness ratio. Therefore, a circular gauge area with a thickness transition ratio (t_g/t_{arm}) of 0.1 and the largest transition radius (r_f) is found to give good outcome.

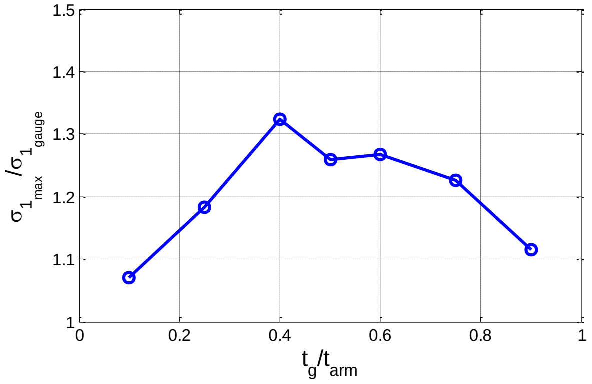
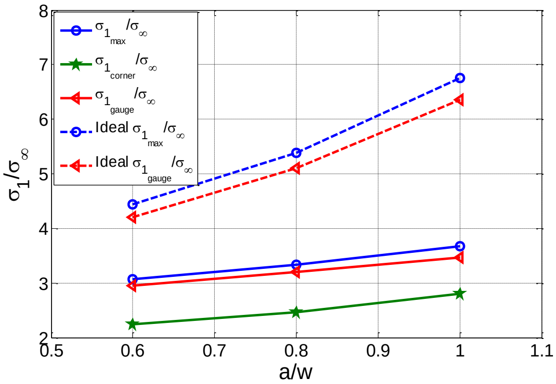


Figure 10. Effect of transition parameter, t_g/t_{arm} on the normalized maximum principal stress.

4.1.3 Coupled Analysis

Optimum values obtained from the analyses of the corner shape parameters and gauge area parameters are coupled together for suitable cruciform specimen geometry. Interaction between these parameters is studied by varying the gauge area size (*a*) such that *a/w=0.6, 0.8* and *1* respectively. The effect of *a/w* on the stresses at different locations (i.e. at the centre of the gauge area, transition region and corner) is presented in the Fig. 11, for an ideal (square specimen) and cruciform geometries. It is observed that with increase in a/w, the stresses at all the locations increase. This increase is dramatic for ideal geometry and it is not as pronounced for a cruciform geometry. For all the *a/w* ratios, as the r_f value is taken to be the largest radius possible such that the size of the area inside the gauge (*b)* is *0.5a*. This is the region (*b*) which is subjected to biaxial state of stress. From the Fig. 12 it is observed that the extent of uniformity (*X/a*) for all the *a/w* ratios is found to be 0.5, which represents that the stresses in the entire *b* region are within the 5% of the stress at the centre. It signifies that for a circular shaped gauge the stress uniformity (*X/a*) is not dependent on the gauge area size.



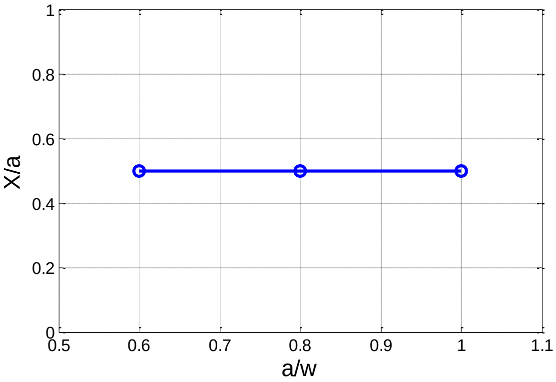
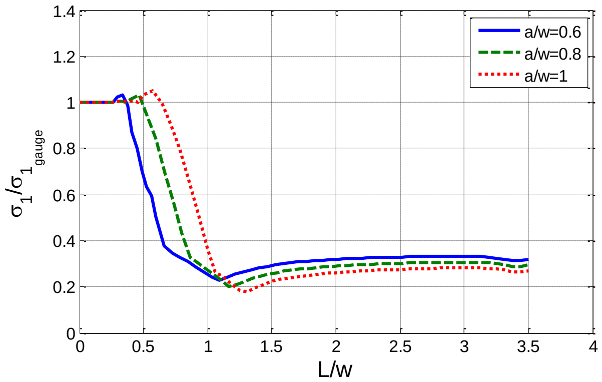


Figure 11. Effect of gauge size parameter, *a/w* on the normalized stresses at different locations.

Figure 12. Effect of gauge size parameter, *a/w* on the uniform gauge region.

Distribution of normalized principal stresses along the length of the arm starting from the centre of the specimen is shown in Fig.13. This stress distribution is uniform in the gauge area, it reaches a peak value at the transition region then starts decreasing and finally becomes stable along the arm. It can also be observed that peak stresses are unavoidable at the transition region and the value of peak stresses increase with increase in *a/w*. Hence, a cruciform specimen with a fillet *of* $r/w=0.25$, $t_g/t_{arm}=0.1$ and with a circular gauge area of $a/w=0.6$, is the optimal geometry obtained from the numerical analysis. Principal stress contour of this geometry is shown in Fig.14.



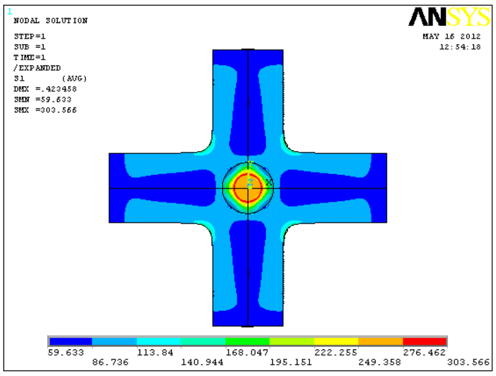


Figure 13. Distribution of normalized principal stresses along the length of the arm.

Figure 14. Final specimen geometry.

4.2 Experimental results

Using the dimensions obtained from the FE analysis, biaxial specimens are fabricated by a simple hand layup technique at room temperature. When all the arms of the cruciform specimen are subjected to equi-biaxial tension, the specimen found to fail along the line which makes an angle of 45^o with the principal loading axis. This failure is not initiated from the centre of the specimen. The peak stresses near the transition zone are the main source of failure initiation rather than the biaxial stresses in the gauge area as shown in the Fig. 15.

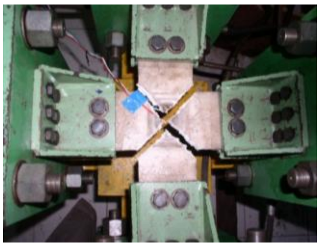


Figure 15. Failure profile of the CSM glass/polyester specimen.

5 Conclusions

A suitable cruciform specimen is proposed for studying the biaxial behaviour of CSM glass/ polyester composite laminates and the effect of different geometric parameters on the design is studied using a systematic numerical approach. Parameters influencing the design are decoupled into two groups (cruciform shape parameters and gauge area parameters) and analyzed. From the analysis of cruciform shape parameters, a fillet shaped corner with a radius of $0.25w$ is found be the optimal parameter as it provides a minimum stress concentration at the intersection of the arms. From the analysis of gauge area parameters, a circular shaped gauge area with a thickness ratio (t_g/t_{arm}) of 0.1 and with a largest possible transition radius (r_f) is found to be optimal as it improves the state of stress in the gauge area. Coupling of these optimum parameters found to have good interaction when the gauge area size (a) is equal to 0.6 times the width of the arm (w). Using these dimensions biaxial specimens are fabricated by a simple hand layup technique at room temperature and subjected to equi-biaxial loads using inplane biaxial test rig. These cruciform specimens are found to fail along the line which makes an angle of 45^o with the principal loading axis. It exactly confirms the prediction of simulations that the failure initiation is governed by raised stresses near the transition zone rather than the biaxial stresses in the gauge area.

References

[1] Arnold W.S., Robb M.D., Marshall I.H. Failure envelopes for notched CSM laminates under biaxial loading. *Composites*, **26**, pp. 739-747 (1995).

[2] Smits A., Hemelrijck V.D., Philppidis T.P., Cardon A. Design of cruciform specimen for biaxial testing of fiber reinforced composite laminates. *Composite Science and Technology*, **66**, pp. 964-975 (2006).

[3] Youssef Y., Labonte S., Roy C., Lefebvre D. Specimen design, manufacturing and testing procedure for flat carbon fiber reinforced plastic laminates under biaxial loading. *Polymer Composites*, **19(3)**, pp. 257-263 (1998).

[4] Makris A., Vandenbergh T., Ramault C., Hemelrijck V.D., Lamkanfi E., Paepegem V.W. Shape optimization of a biaxially loaded cruciform specimen. *Polymer Testing*, **29(2)**, pp. 216-223 (2010).

[5] Lebedev A.A., Muzyka N.R. Design of cruciform specimens for fracture toughness tests in biaxial tension (Review). *Strength of Materials*, **30(3)**, pp. 243-254, (1998).

[6] Lamkanfi E., Paepegem V.W., Degrieck J., Ramault C., Makris A., Hemelrijck V.D. Strain distribution in cruciform specimens subjected to biaxial loading conditions. Part 2: Influence of geometrical discontinuities. *Polymer Testing*, **29(1)**, pp. 132-138 (2010).

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

[8] Welsh J.S., Adams D.F. An experimental investigation of biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens. *Composite Part A*, **33**, pp. 829-839 (2002).