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FAILURE PREDICTION OF FIBER COMPOSITE MATERIALS

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Structural design of parts made from long-fiber composite materials is complicated due to their anisotropy. Data only from uniaxial mechanical tests are insufficient to perform reliable failure analysis. Therefore, results of failure criteria provided by computer simulations should be validated by multiaxial mechanical tests. For this purpose, biaxial 10 kN test machine was designed and constructed. Biaxial testing methodology was adopted and numerical model with progressive damage of this test was developed to assess simulation failure prediction limits.

Key words: composite, biaxial, cruciform , mechanical test, simulation

INTRODUCTION

Structural design of parts made of long-fiber composite materials is complicated due to their anisotropy. Data only from uniaxial mechanical tests are insufficient to perform reliable failure analysis for complex stress states [1]. Therefore, results of failure criteria provided by FEM simulations should be validated by multiaxial mechanical tests. Fiber reinforced composites are commonly characterized by small thickness (out-of-plane stresses are negligible) and simplified approach in form of plane stress is possible [2]. Consequently, biaxial mechanical tests can be performed to failure criteria validation. For this purpose, biaxial testing machine was designed, testing methodology was adopted and initial mechanical tests were performed.

TESTING MACHINE

Biaxial test machine was developed for purpose of biaxial cruciform testing at VUTS, see Fig. 1. Test machine consists of 4 independent actuators with maximal load capacity 10 kN. The stroke of the machine is 350 mm, which allows both composite and elastomer testing. Tests can be performed in displacement or load control mode. Displacements and strains are measured by Digital Image Correlation system Monet 3D.

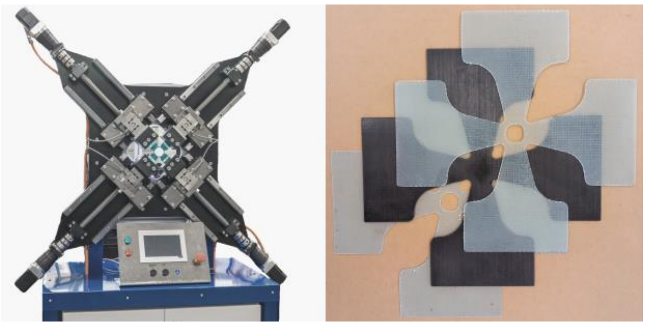

Figure 1: Biaxial testing machine and cruciform specimen with glass-fiber laminate pads.

BIAXIAL TESTING

Equibiaxial tests with strain ratio R = 1/1 are performed in displacement control mode. Chosen type of cruciform specimen geometry is double corner fillet with reduced thickness in the central area. The geometry arose from the geometry C developed in [3] and several adjustments were made. The specimen is 0,7x scaled down to be able perform measurement at test machine with maximal load 10 kN. And the arms are not straight but towards the clamps they are wider to ensure good grip in the clamps. Cross-ply laminate $[0, 90]_s$ is measured. The material is unidirectional carbon fiber 50K 125 gsm with epoxy resin LH385 manufactured by vacuum infusion process. Glass fiber 200 gsm woven laminate pads are bonded to the CF laminate using Letoxit PL20. The stress in the central section of the specimen cannot be evaluated directly from the area as in the case of uniaxial tests. For linearly elastic materials (carbon fiber laminates) is possible compute stress from equation for plane stress for orthotropic material using measured strains [1]. This approach requires values of E_x, E_y, ν_{xy} and ν_{yx} obtained from uniaxial tests or estimation based on micro-mechanical models. Specimens with four pad variants are examined: no pads, glass fiber pads $[45]_2$, $[45]_3$ and $[0]_3$.

NUMERICAL MODEL

Biaxial cruciform test is numerically modelled to gain deeper understanding of the mechanical test and to identify any limitations in the failure criteria used in the simulation process. Finite element software Ansys 2021R1 with composite module ACP is used. The material model is orthotropic elasticity with progressive damage, which uses Puck failure criterion. Mechanical properties in the element are degraded when the failure criteria is met. Degradation factor 1 means 100 % reduction and 0 means no reduction of mechanical properties. Values of degradation factors are set to $E_{ft}^* = 0.99$ (Fiber tensile damage), $E_{fc}^* = 0.99$ (Fiber compression damage), $E_{mt}^* = 0.85$ (Matrix tensile damage) and $E_{mc}^* = 0.5$ (Matrix compression damage). The boundary conditions for displacement are u = 0.5 mm in the end of the specimen arms. Computational mesh, boundary conditions and evaluation area are depicted in Fig. 2.

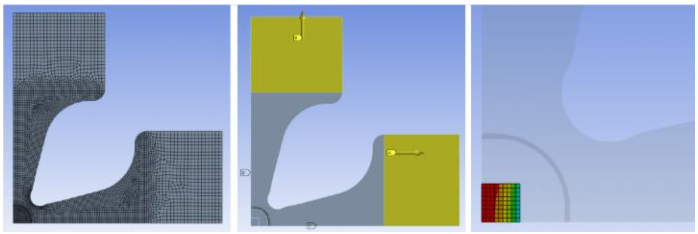

Figure 2: Mesh, boundary conditions and strain evaluation area of numerical model.

RESULTS AND DISCUSSION

Strains at failure are evaluated as average strain in the 9x9 mm square in the central area of the specimen. Complete failure of specimen in simulation is evaluated as first stiffness loss (force decrease).

Measured values of strain at failure and computed strengths are summarized in Tab. 1. Specimens without tabs failures prematurely - the failure is observed in the single arm not in the central area, which is not considered as a valid biaxial test. The higher number of plies of glass fiber pads, the higher are the reached strains at failure as well as strengths. The highest value of strain was achieved by specimen with pads layup $[0]_3$.

Table 1: Experimental results of strains, strengths and number of specimens of different pads types.

	ε_{rx} [%]	ε_{ry} [%]	X_t [MPa]	Y_t [MPa]	N
No pads	1.08	1.06	651	640	10
GF $[45]_2$	1.24	1.28	746	773	5
GF $[45]_3$	1.35	1.44	815	870	5
GF $[0]_3$	1.51	1.37	908	831	3

Comparison of simulation (black line) with experiment (red line) for selected specimen with tabs $[0]_3$ is shown in Fig. 3. Simulation predicts failure bit prematurely but captures well the slope of force – strain curve. Circle point show first matrix failure (FMF) and square point show first fiber failure (FFF) computed in simulation. This plot shows comparison of design approaches for failure prediction: i) failure criteria (FMF, FFF), ii) failure criteria with progressive damage model and iii) validation of failure criteria by mechanical testing. As the plot shows, cruciform biaxial tests can make failure prediction more precise and therefore accurate safety factor adjustment.

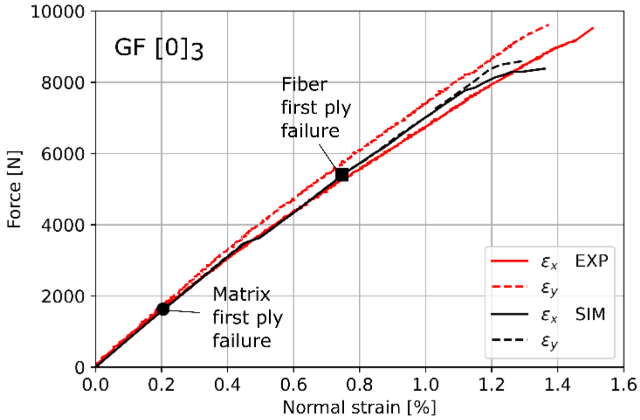

Figure 3: Comparison of force – strain curves from experiment and simulation of specimen with glass fiber pads $[0]_3$.

CONCLUSION

Biaxial testing machine was developed for cruciform testing of long-fiber composite materials. The adopted methodology includes specimen geometry modifications, strain and strength measurements, and numerical simulations using progressive damage modeling. The results showcased the significance of biaxial testing in refining failure predictions and validating failure criteria, offering an improved approach for assessing anisotropic composite materials mechanical behavior under complex stress states.

ACKNOWLEDGEMENT

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