COMPUTATIONAL MECHANICS 2022
37th conference with international participation
Srní
November 7 - 9, 2022

Cruciform biaxial tests of FRP: Influence of tabs thickness

V. Vomáčko, M. Šulc

Computations and Modeling Department, VÚTS, a.s., Svárovská 619, 46001, Liberec, Czech Republic

1. 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 [2]. 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 [1]. Consequently, biaxial mechanical tests can be performed to failure criteria validation.

Two types of biaxial tests for fiber reinforced composites are commonly used. Combination of axial (tensile/compression), torsional and pressure loading (internal/external) can induce biaxial stress state in tube specimens. Tube specimens were used World Wide Failure Exercise [4]. Second commonly used approach are planar cruciform specimens. Desired biaxial stress state is induced by combination of tension and compression in two independent axes. The advantage of using cruciform specimens is relatively easy and repeatable manufacturing compared to the tubular specimens. On the other hand, cruciform biaxial test requires special test equipment. Also stress computation is not straightforward due to difficult determination of loaded area [2]. Next issue is proper design of cruciform specimen to be able perform a reliable test.

Biaxial test machine was developed for purpose of biaxial cruciform testing at VÚTS, a.s. 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. Detail scheme of the equipment is shown in Fig. 1.

Biaxial testing machines with servomotor and ball screw loading system are much cheaper, than the one with hydraulic loading. On the other hand they are limited by maximal loading force. Wider application of biaxial cruciform tests could be adopted if testing machines with small force range could be applied to perform biaxial test on composite materials. For this purpose it is important to assess influence of tab thickness on specimen strength. Numerical simulations with progressive damage and experimental test are performed in this work. Two types of specimen are tested i) CFRP cross-ply specimen with no tabs, ii) CFRP cross-ply specimen with bonded tabs of 2 plies of woven GFRP.

2. Biaxial cruciform tests

Equibiaxial tests with strain ratio $R = 1/1$ are performed in displacement control mode. Type of cruciform specimen geometry is double corner fillet with reduced thickness in the central

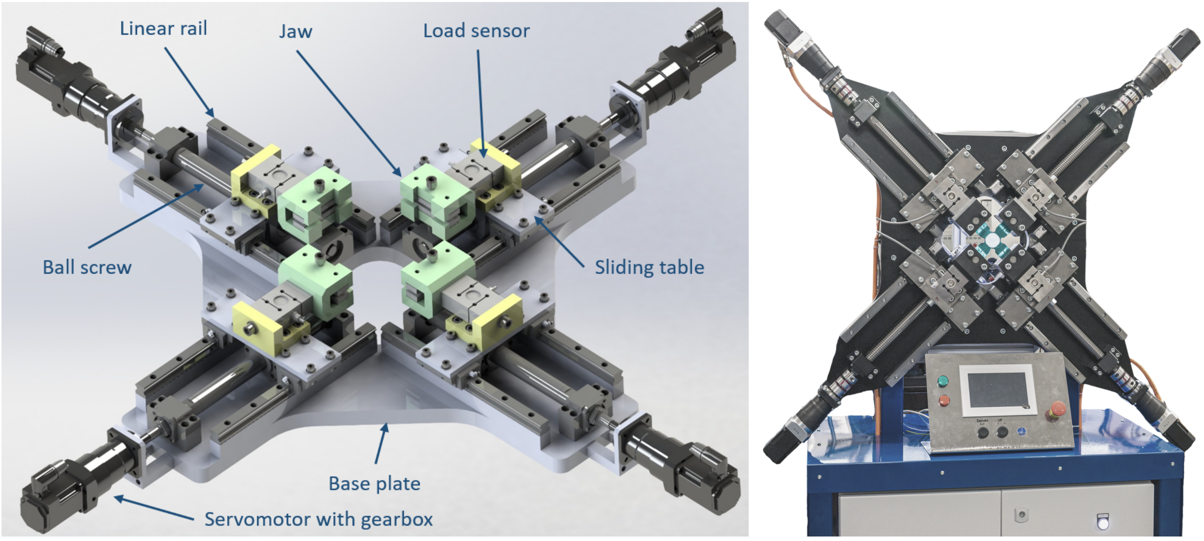

Fig. 1. Biaxial testing machine: CAD model scheme and real machine

area. The geometry arose from the geometry C developed in [3] and several adjustments were made. The specimen is $0.7\times$ 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 can not 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 ortotropic material using measured strains [2]. 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.

3. Numerical model

Numerical simulation of biaxial cruciform test is performed to be able validate failure criteria results. Finite element software Ansys 2021R1 with composite module ACP is used. The material model is ortoropic elasticity with progressive damage. The progressive damage model uses Puck failure criterion - when the failure criteria is met, the mechanical properties in the element are degraded. Degradation factor 1 means 100 $\%$ reduction and 0 means no reduction of mechanical propertie. 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). Mechanical properties of specimen and tabs are summarized in Table 1. The boundary conditions are $u = 0.5$ mm in the end of the tabs.

4. Results and discussion

Strains at failure are evaluated as average strain in the 9×9 mm square in the central area of the specimen. Measured values of strain at failure and computed strengths are summarized in Table 2. Specimens with GF tabs achieved higher strains at failure, 0.2 $\%$ higher compared to the specimens without tabs.

Table 1. Mechanical properties of unidirectional CF laminate $[0]_4$ 125 gsm and woven GF laminate $[0]_4$ 200 gsm. E and G in [MPa] and ν in [1]

	E_x	E_y	E_z	ν_{xy}	ν_{yz}	ν_{zy}	G_{xy}	G_{yz}	G_{xz}
CF specimen	113 600	4700	4700	0.277	0.42	0.277	4700	3080	4700
GF tabs	22 400	22 400	7500	0.14	0.3	0.3	3300	2700	2700

Table 2. Measured values of strain at failure and computed strength of different specimens

		ϵ_{rx} [%]	ϵ_{ry} [%]	X_t [MPa]	Y_t [MPa]
No pads	Average	1.08	1.06	651	640
	St. Dev.	0.06	0.06	354	360
2 GF plies	Average	1.24	1.28	746	773
	St. Dev.	0.11	0.07	63	45

Measured representative force – strain curves are shown in the Fig. 2 on the left. On the right side of the same figure, there is comparison of experiment (full line) with FEM simulation (dash-dotted line). Complete failure of specimen in simulation is evaluated as first stiffness loss (force decrease). Simulations exhibits stiffer behavior of the specimen but failure is predicted earlier (lower strain and force results) than in experiment. 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.

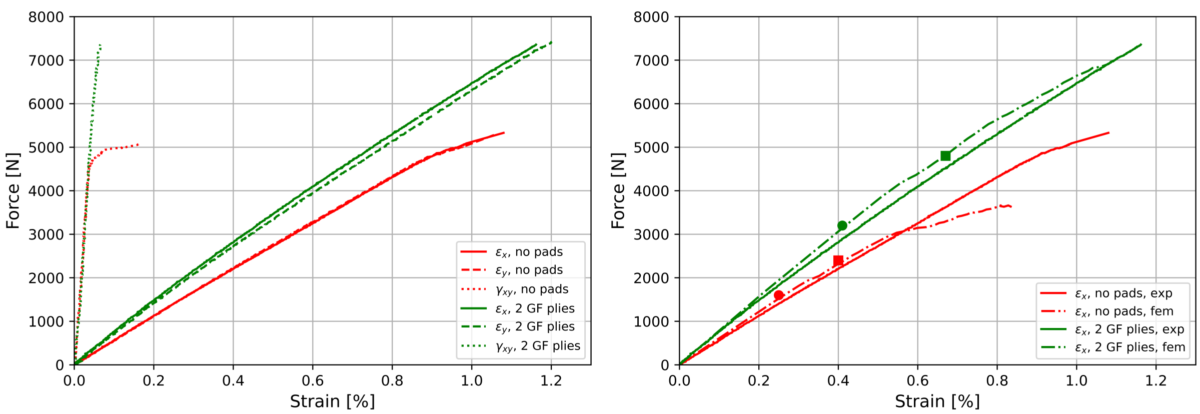

Fig. 2. (*Left*) Experimental results for specimens without tabs and with tabs from 2 GF layers. (*Right*) Comparison of strains in X axis of experiment (full line) with simulation (dash-dotted line)

Specimens without tabs failures prematurely – the failure is observed in the single arm and not in the central area. Typical failure of specimen with tabs of 2 is depicted in Fig. 3. The failure occurs in the central sections near the pads. No delamination between specimen and tabs is observed as reported in [2].

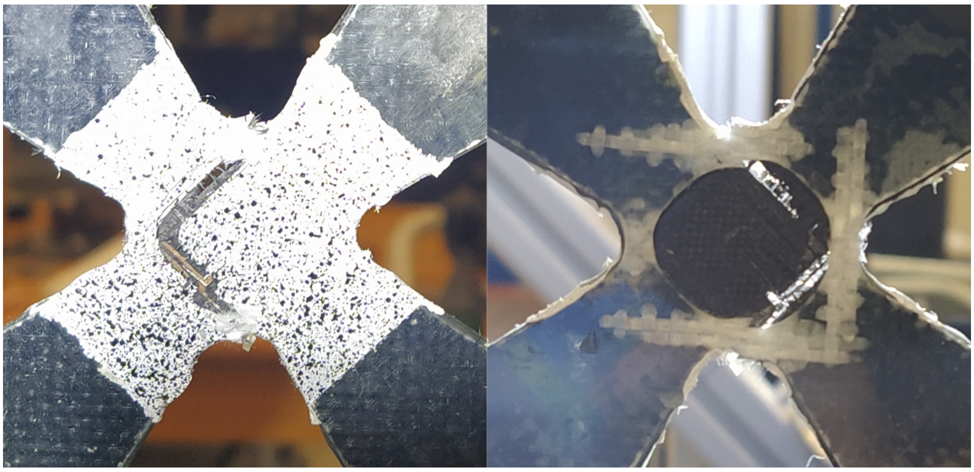

Fig. 3. Typical failure of specimen with tabs of 2 GF plies

Acknowledgement
This publication was supported by the Ministry of Industry and Trade (MPO) within the framework of institutional support for long-term strategic development of the research organization – provider MPO, recipient VÚTS, a. s.

References

[1] Muñoz, H., Moreno, M. del C. S., Advances in cruciform biaxial testing of fibre-reinforced polymers, Polymers 14 (4) (2022) No. 686.

[2] Ramault, C., Guidelines for biaxial testing of fibre reinforced composites using a cruciform specimen, Vrije Universiteit Brussel, 2012.

[3] Smits, A., Van Hemelrijck, D., Philippidis, T. P., Cardon, A., Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates, Composites Science and Technology 66 (2006) 964-975.

[4] Soden, P. D., Hinton, M. J., Kaddour, A. S., Biaxial test results for strength and deformation of a range of E-glass and carbon fibre reinforced composite laminates: Failure exercise benchmark data, Composites Science and Technology 62 (2002) 1489-1514.