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Biaxial Cruciform Testing of Fiber Composite Materials

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Abstract: The biaxial cruciform testing method was adopted to validate the failure criteria results obtained through numerical simulations. A biaxial testing machine was developed, and carbon fiber-epoxy laminate specimens were tested. Failure strains were evaluated in the central area of the specimens. Specimens without tabs failed in the arm section, while specimens with glass-fiber tabs failed in the central section. However, both failed prematurely, as confirmed by numerical simulations with a progressive damage model. The first ply failures for the matrix and fibers were evaluated using simulations. The values of the first ply failure strain in the simulation were much lower than the measured ultimate failure strains. This demonstrates that the use of biaxial tests can be advantageous for determining the ultimate failure of components in combination with simulations, even in cases where the specimens fail prematurely.

Keywords: biaxial; cruciform; composite; failure; validation.

1 Introduction

The design process of a composite structural part comprises several stages, as depicted in Fig. 1. Initially, conceptual ideas are sketched, and the concept of the part is developed. This is followed by the part's design using CAD software. Numerical simulations play a pivotal role in optimizing the component and conducting failure analysis. The accuracy of the numerical model heavily relies on precise input data. However, not all material parameters can be directly measured, leading to the need for determination through various means. For instance, to fully define the stiffness matrix of an orthotropic linearly elastic material, nine constants are required, including three Young's moduli, three shear moduli, and three Poisson's ratios. Additionally, determining the material's strengths is critical for accurate failure analysis. This process typically involves a combination of mechanical tests, micromechanical models and educated guesses, which introduces uncertainty into the outcomes of numerical models. To simulate fracture behavior, a progressive damage model can be utilized. Furthermore, in the case of thin laminates, a plane stress simplification is applied, reducing the number of independent material parameters to five [3].

Various failure theories (Max stress. Max strain, Hoffman, Tsai-Wu, Hashin, Puck, LaRC04, etc.) can be used to evaluate failure based on computed stresses and strains in simulations [1]. Each failure criterion predicts failure in a distinct manner. That is the reason why failure prediction of composites is not so straightforward as in the case of isotropic materials.

Different approaches can be employed to validate safety limits of parts from fiber composites obtained from numerical simulations. Uniaxial mechanical test data alone may not be adequate for conducting reliable failure analysis under complex stress conditions [4]. Traditionally, validation of simulations involves prototyping and performing experiments to simulate real-world conditions. Alternatively, biaxial tests can be employed. Two common methods are used to conduct biaxial tests on fiber-reinforced composites. The first involves applying a combination of axial (tensile/compressive), torsional, and internal or external pressure loading to tubular specimens, which creates a biaxial stress state. Tubular specimens were utilized in the World Wide Failure Exercise [5]. The second approach uses planar cruciform specimens, where the desired biaxial stress state is achieved through a combination of tension and compression applied independently along two axes. Validation of simulations can be performed following these steps:

1. Evaluate the critical stress state in the simulation.
2. Manufacture a cruciform specimen using same material and layup as is in a critical area determined by simulation.
3. Induce the critical stress state in the specimen by biaxial test machine.
4. Compare failure stresses and strains obtained from both, the test and simulations.

The advantage of performing biaxial tests is that specimens are made from flat laminates, resulting in a relatively fast preparation compared to prototype experiments. The same instrumentation, measurement technique and evaluation method is used for all biaxial tests. On the other hand, in case of prototype testing, the prototype part has to be manufactured to be able perform experiment simulating conditions in real environment. In case of fiber composite part, this includes production of molds, which is usually the most expensive stage of manufacturing process. Additionally, specialized test rigs with comprehensive measurement instrumentation are required. The significant advantage of this approach is the robust validation of simulations, leading to trustworthy results. However, it comes at the expense of high costs.

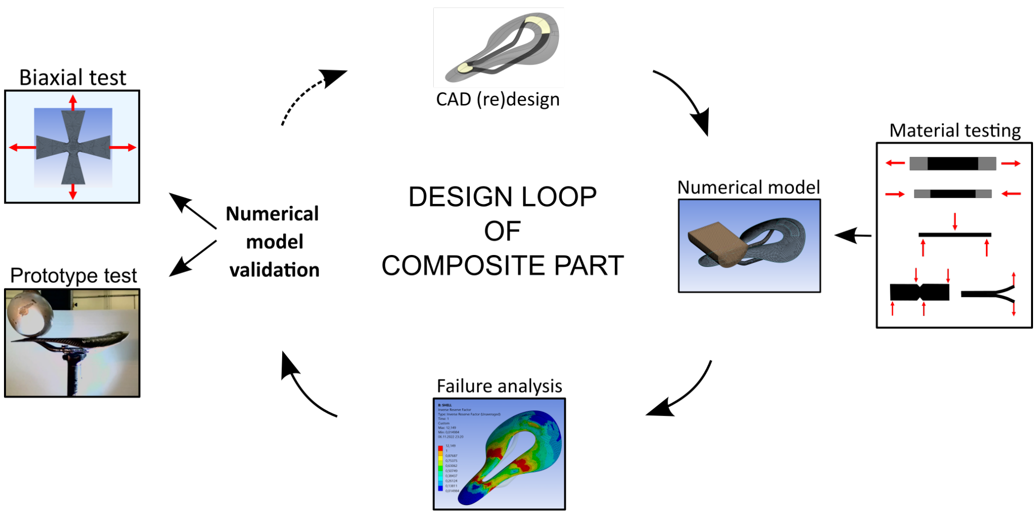

Fig. 1: Design loop of composite part.

Cruciform specimens must meet several criteria: i) failure should occur in the central region, ii) the area with a uniform biaxial stress state must be sufficiently large, iii) global shear stress in the central section should be minimized, and iv) the results must be repeatable [6]. A commonly used specimen type, as designed in [7], features a reduced thickness in the central region to promote failure at that location and includes double fillet corners at the junctions of the specimen arms.

The development of specimen type is still ongoing, as challenges remain with premature failures occurring outside the central section. Factors such as specimen geometry, tab types and materials, and the method of tab application (e.g., bonding or milling) can significantly influence the failure behavior. An ideal specimen should fully utilize the material's potential to provide accurate and reliable data for validation purposes.

2 Biaxial cruciform tests

Biaxial cruciform test machine was developed at VUTS, a.s. Test machine consists of 4 independent actuators with maximal load capacity of 10 kN. The stroke of the machine is 350 mm, which allows composite and elastomer testing. Tests can be performed in both displacement and load control mode. Displacements and strains are measured by Digital Image Correlation system Monet 3D. Detailed scheme of the biaxial testing setup is shown in Fig. 2.

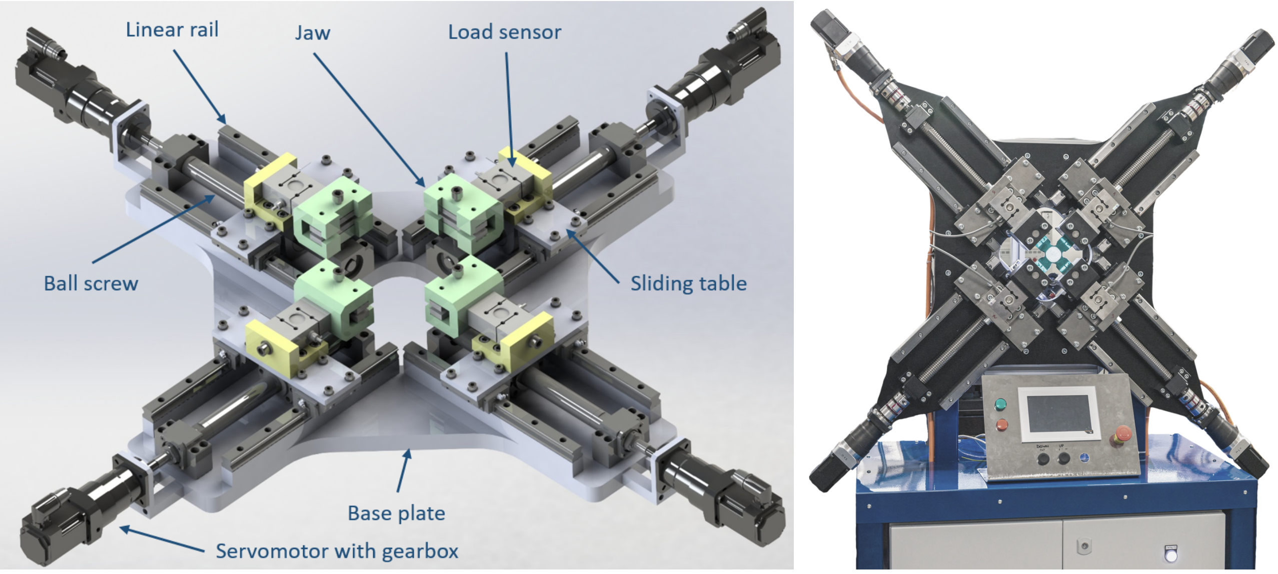

Fig. 2: Biaxial testing machine: CAD model scheme and real machine.

2.1 Analysed specimens

Equibiaxial tensile tests were performed in the displacement control mode. The cruciform specimen geometry features a double corner fillet with reduced thickness in the central area. The geometry arose from the geometry C developed in [7] and several adjustments were made (see Fig. 3). Original dimensions of this specimen are $0.7\times$ scaled down to be able to perform measurement on a test machine with maximal load 10 kN. The arms are not straight but towards the clamps they are wider to ensure good grip in the clamps. Laminates were produced by vacuum infusion process using LH385 epoxy system. Specimen were milled to final shapes by CNC machine and GF tabs were bonded to the CF laminate using Letoxit PL20 (see Fig. 3). Carbon-fiber laminate of interest featuring cross-ply layup $[0/90]_S$ and three different tab types are examined:

- no tabs,
- glass-fiber laminate tabs $[\pm 45F]_3$,
- glass-fiber laminate tabs $[0F]_3$.

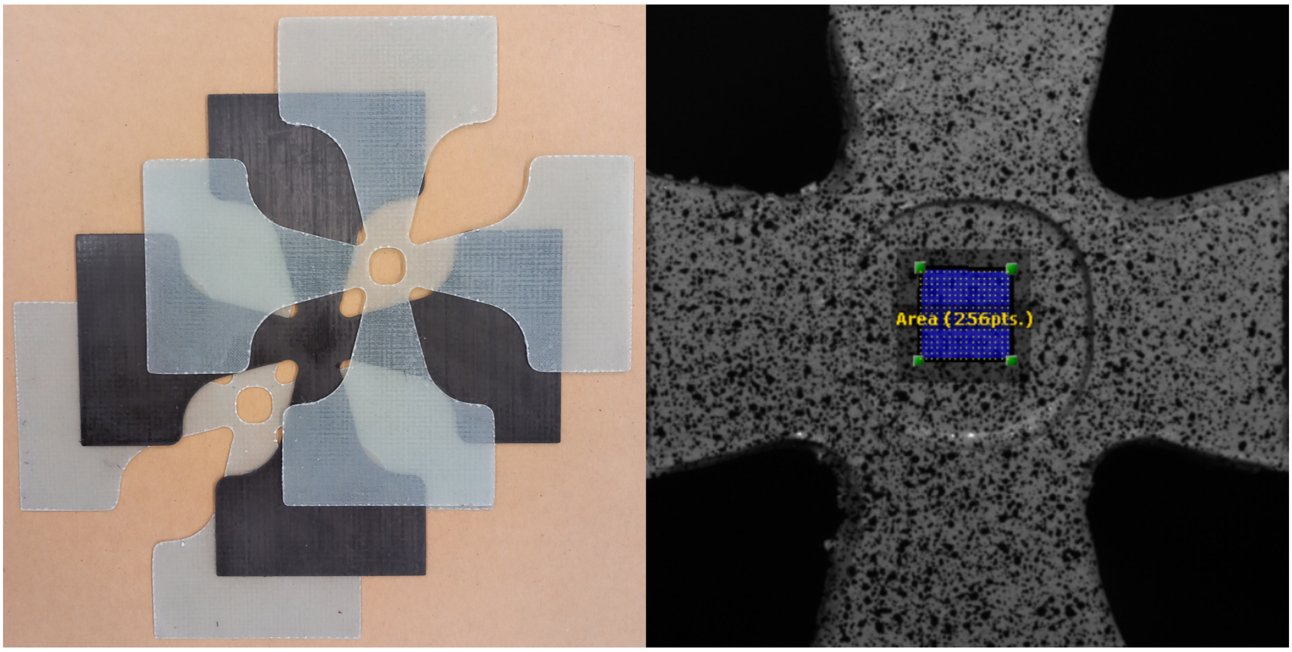

Fig. 3: Specimen with GF tabs before bonding (left) and speckle pattern for DIC (right).

2.2 Experimental results

Strains are evaluated in central square 8x8 mm of specimen (see Fig. 3). Average values of measured failure strains, forces and computed strengths are summarized in Tab. 1. Strengths are computed using plane stress equations and mechanical properties noted in Tab. 2. The specimens set without tabs demonstrate consistent results with minimal measured value $\epsilon_f = 0.95$ % and maximal measured value $\epsilon_f = 1.15$ %. Both specimen sets with GF tabs show similar behavior reaching higher failure strains from $\epsilon_f = 1.27$ % to $\epsilon_f = 1.6$ % and strengths compared to the specimens with no tabs. The value of the highest reached failure strain $\epsilon_f = 1.6$ % is close to the value $\epsilon_{funiaxial} = 1.65$ % obtained by uniaxial tests on coupon specimens of same layup and material. The use of tabs significantly enhances the values of failure strain and strength.

Tab. 1: Measured average values of failure strain, computed strength and force at ultimate failure of different specimen tab types and number of tests performed per specimen type.

Experiment	ϵ_{fx} [%]	ϵ_{fy} [%]	X_t $[MPa]$	Y_t $[MPa]$	F_x $[N]$	F_y $[N]$	N
No tabs	1.08	1.06	651	640	5294	5263	10
GF $[45F]_3$	1.35	1.44	815	870	9089	9099	5
GF $[0F]_3$	1.37	1.51	831	908	9618	9523	3

3 Numerical model

A quarter numerical model was employed to simulate biaxial testing of cruciform specimens. The simulations were performed using the finite element software Ansys 2022R2. The boundary conditions were $u = 0.5$ mm in the end of the tabs, see Fig. 4. The computational mesh consists of 62000 elements of type SOLID185. The material model utilized in this study was orthotropic elasticity with a progressive damage approach. The progressive damage model incorporates the Puck failure criterion, which triggers a reduction in mechanical properties within the element when the failure criteria are met. The degradation factor, denoted as 1, corresponds to a 100 % reduction of stiffness, while a factor of 0 implies no reduction. Values of degradation factors were set to $E^*_{ft} = 0.99$ (Fiber tensile damage) and $E^*_{mt} = 0.85$ (Matrix tensile damage).

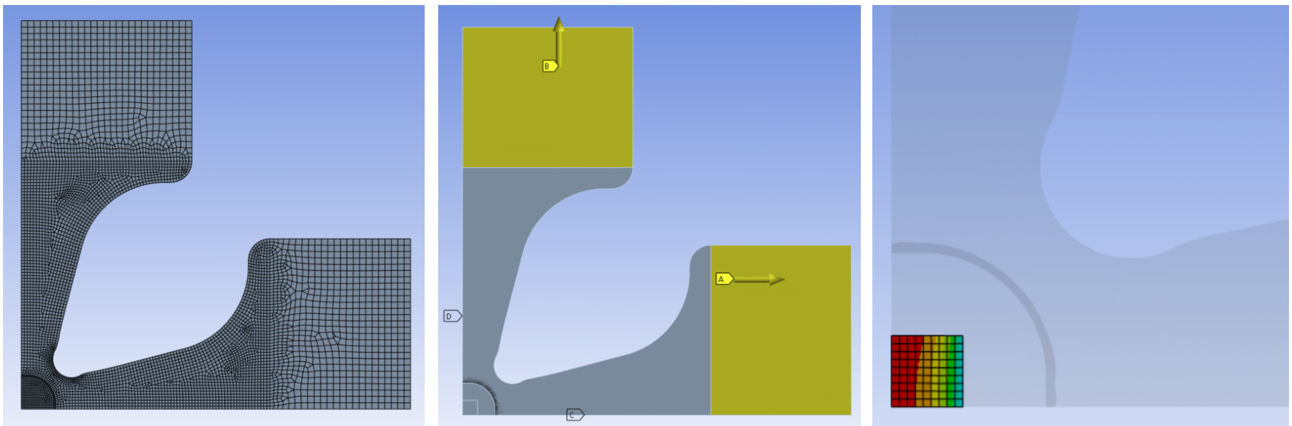

Fig. 4: Mesh, boundary conditions and observed area.

Mechanical properties (considered as mechanical properties at lamina level) of specimen and tabs are summarized in Tab. 2. Note that using linear elasticity model for glass-fiber laminate is simplification as its stress-strain curve is not linear, therefore secant tensile modulus is used.

3.1 Validation of numerical model

Firstly, simulations were performed using uniaxially measured value of tensile strength in fiber direction $X_t = 1620$ MPa. Force-strain curves from both simulation and experiment are compared in left section of

Tab. 2: Mechanical properties and stress limits of unidirectional CF laminate $[0]_4$ 125 gsm and woven GF laminate $[0]_4$ 200 gsm. E, G, X, Y and S in [MPa] and ν in [1].

	E_x	E_y	ν_{xy}	G_{xy}	X_t	Y_t	S_{xy}
CF UD	126 000	4700	0.365	4700	1620	29	60
GF fabric	13 800	13800	0.143	3300	392	392	120

Fig. 6. The experimental curves represent averaged data from the specimen set. Additionally, the figure illustrates the first ply failure in the matrix (marked with a black circle) and in the fibers (marked with a black square) obtained through the Puck failure criteria in simulations. The values of failure strains from experiments consistently exceed those from simulations. Tensile strength in fiber direction X_t determined by uniaxial test is the mechanical property of highest influence on failure strain ϵ_f.

Secondly, the force-strain curves from simulations were fitted by adjusting tensile strength in fiber direction X_t to align with experimental results. The force-strain curves exhibited the closest fit for tensile strength $X_{tfit} = 2087$ MPa, see right part of Fig. 6. The observed discrepancy underscores the need for a reassessment of the methodology employed in experimentally determining the tensile strength for application in the progressive damage model.

The comparison of strain maps obtained using experiment and simulations are depicted in Fig. 5.

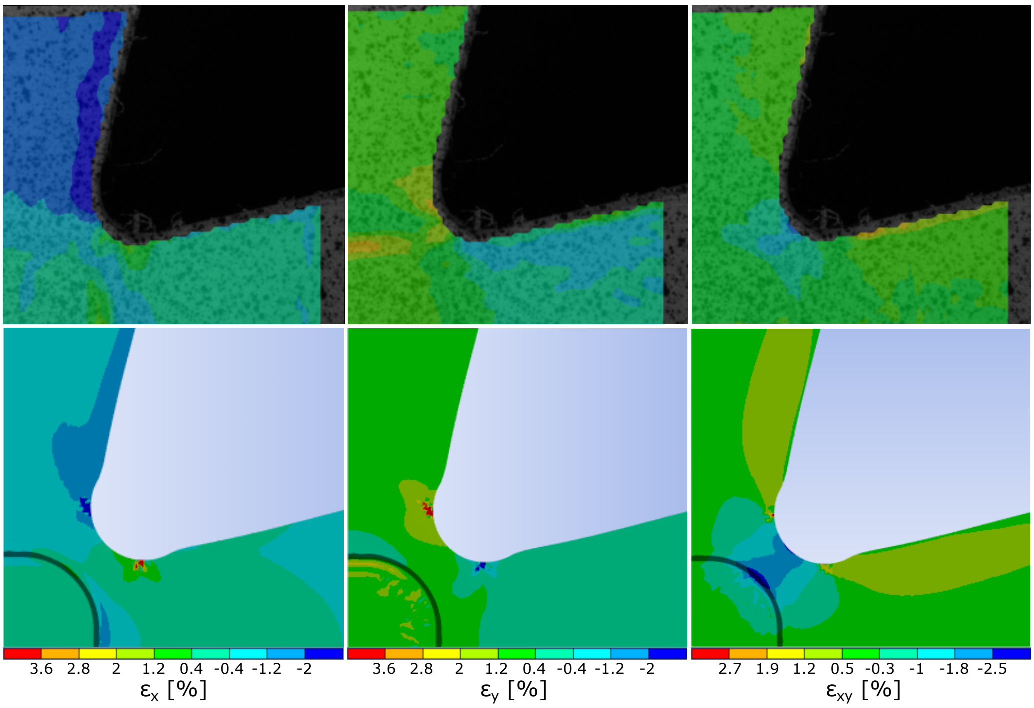

Fig. 5: Comparison of strain maps from experiment and simulation for specimen with GF $[45F]_3$ tabs at force 8000 N.

3.2 Observed failure

The failure observed in specimens, as depicted in Fig. 7, indicates successful biaxial tests for specimens with GF tabs. In contrast to specimens with no tabs, where failure occurs in a single arm.

However, the area of failure near transition between tabs and central section corresponds with maxima of Puck failure criteria observed in simulations. According to the simulations, the failure initiates in 0 fiber direction (see Fig. 7). It can be explained by stiffness change and therefore stress concentration in transition from tabs to central area, where the outer plies carrying load are more loaded than inner plies in second direction (which are protected by outer plies and load transition is smoother). This observation implies that the failures are still occurring prematurely.

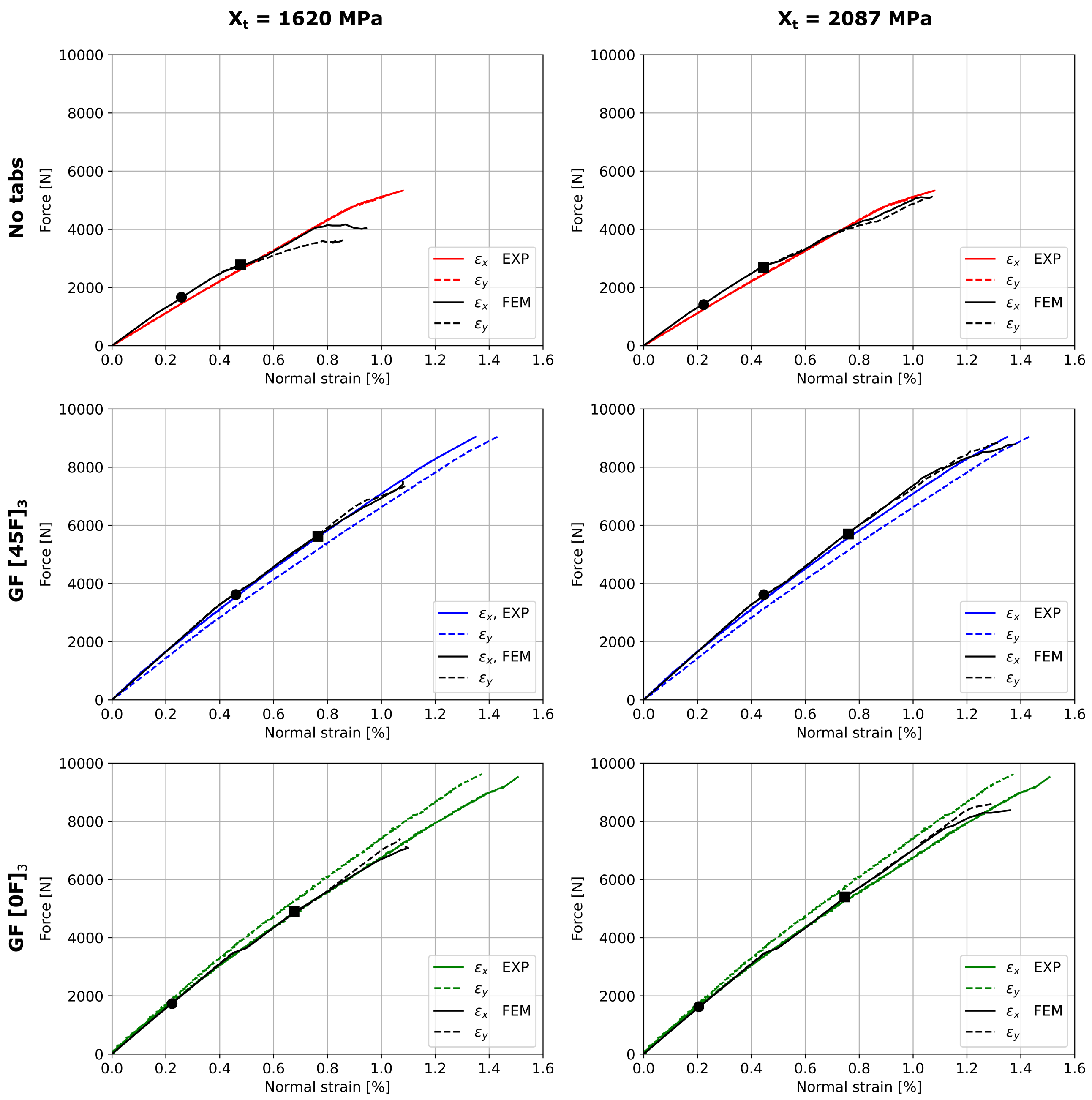

Fig. 6: Comparison of force-strain curves from simulation and averaged curves from experiment.

4 Conclusion

Biaxial cruciform tests can be used to validate failure criteria results obtained through numerical simulations, offering advantages over prototype testing in certain circumstances. A biaxial cruciform testing machine was developed and a testing methodology was adopted. Cruciform specimens were manufactured from carbon fiber - epoxy laminate without and with glass fiber tabs. Equibiaxial tension tests were performed, force and strain were measured and failure strains were evaluated.

Specimens with no tabs failed prematurely in arm section resulting in invalid biaxial test. In contrast, specimens with glass fiber tabs reached an average failure strain of approximately $\epsilon_f = 1.4$ %, still falling short of the uniaxially tested value $\epsilon_{funiaxial} = 1.65$ %. This indicates that the failure still might be premature, which is confirmed by numerical simulations with progressive damage model showing failure initiation in central section, but in the transition area between tabs and laminate of interest.

The comparison between experiments and simulations shows good agreement only in case when higher than uniaxially measured values of tensile strength were used as an input into progressive damage model. This

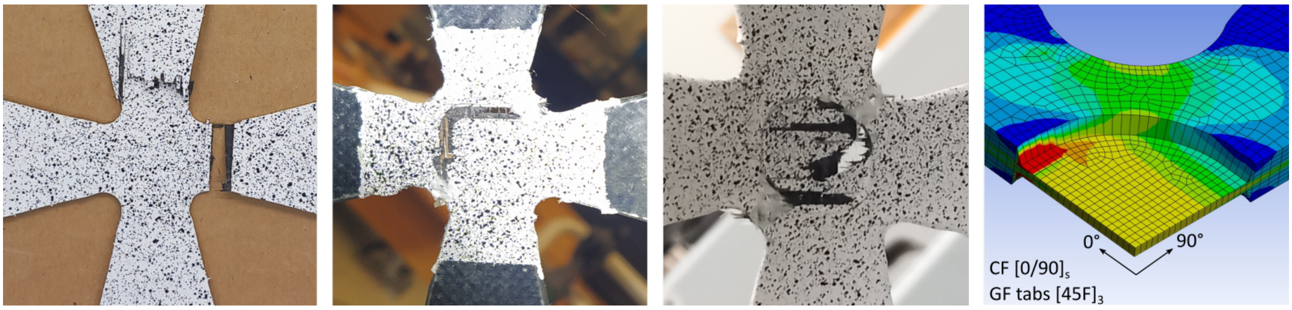

Fig. 7: Typical failure of specimens, from left 1) with no tabs 2) tabs GF$[45F]_3$, 3) tabs GF$[0F]_3$ and 4) maximum failure index near ultimate failure for tab types: GF $[45F]_3$

suggests that there may be a need to reconsider the method used to determine the uniaxial tensile strength for application in a progressive damage model.

The first ply failures for matrix and fibers were evaluated in simulations. The first ply failure strain values obtained in simulations are significantly lower than the ultimate failure strains measured experimentally, indicating that employing biaxial tests alongside simulations can be advantageous for determining the ultimate failure of components.

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