BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi" din Iaşi
Volumul 69 (73), Numărul 2, 2023
Secţia
CONSTRUCŢII DE MAŞINI
DOI:10.2478/bipcm-2023-0020

FEA OF CARBON FIBER REINFORCED POLYMER SUBJECTED TO TENSILE AND SHEAR

BY

IONUȚ MITITELU* and PAUL DORU BÂRSĂNESCU

"Gheorghe Asachi" Technical University of Iaşi,
Faculty of Mechanical Engineering, Iaşi, Romania

Received: July 22, 2023
Accepted for publication: July 31, 2023

Abstract. Composites occupy an important place in high-end industries due to their superior characteristics compared to traditional materials or individual constituent materials.

The work focuses on the FEA analysis of composite materials with CFRP carbon fibers with polymer matrix subjected to tensile and shear loads, an important subject of study in the field of engineering. The analysis using the finite element method is a real help by simulating the materials in different conditions. Due to their advanced properties, composite materials can be tested and optimized before being used in production. This can reduce the need to make prototypes and testing multiple times. The aim is to increase productivity and eliminate excess waste, an important process that is the basis of all industries today.

Modified butterfly-type specimens were used in these research studies to be tested on the Arcan device. The simulation conditions were similar to a tensile and shear test conducted in the laboratory, considering a material without cracks

*Corresponding author; *e-mail*: ionut.mititelu@student.tuiasi.ro

or other impurities in its structure and utilizing mechanical properties provided by software Ansys for unidirectional carbon fiber and epoxy-reinforced matrix.

Keywords: CFRP, Arcan device, FEM, DMA, tensile, shear.

1. Introduction

In the trend of preserving raw materials, composites were developed to replace, in a significant proportion, traditional materials, reaching themselves to be marked by shortcomings related to performance, structural complexity and, last but not least, costs. Originally developed in the aerospace and sports industries, today composite materials can be found in practically all fields. Parallel to this expansion of use, there appeared the need to evaluate the quality and improve their properties, the discovery of new procedures and methods of analysis and testing without losing sight of the requirements of environmental protection (Autar, 2006).

Among these composites, those based on carbon and those with natural fibers claim first place. Carbon fiber reinforced composites (CFRP) continue to be widely used, they have evolved both as reinforcement and matrix, epoxy resin being the most common matrix for CFRP (Autar, 2006). If initially they replaced traditional materials in a significant percentage, today they themselves are faced with some shortcomings in terms of performance, obtaining and processing procedures, structural complexity and costs (Hübner *et al*., 2019; Lei *et al*., 2022; Savin *et al*., 2020). The growing demand for CFRP structures is accompanied by the increase in eco-efficient production performance. CFRP performance becomes critical in engineering applications when temperature changes, impact with low energies or high humidity can produce changes in mechanical characteristics. Ecological, economic and operational safety aspects are involved in this approach (Petrakli *et al*., 2020).

There is a tendency to use CFRP in dynamic loading applications where the cyclic loads and working environments to which they are exposed result in material wear and fatigue (Kim *et al*., 2010). The tensions inside the materials that appear during their lifetime must be constantly monitored, in order to find out the moment when a part, structure or assembly can no longer fulfill its performance characteristics. The evolution of technologies today offers the possibility of monitoring a structure from the design phase of the material. A special emphasis is placed on the analysis of degradations produced by impact with various energies (Garnier *et al*., 2013), or overloading the structure (Petrakli *et al*., 2020). Modeling in conditions similar to those for which the composite is designed, using finite element analysis (FEA), provides useful information right from the design phase. The damage mechanism and the action of inhomogeneities are much more complex in the case of composites compared to metals, due to the heterogeneous nature of composites (Elmarakbi *et al*., 2013). The quantitative-qualitative analysis (using FEA and experimental results) of the composite structures that go into the construction of complex components can limit unwanted effects.

Thus experimental methods using the Arcan device (Arcan *et al.*, 1978) can be used in the case of subjecting composites to uniaxial loads (Maragoni *et al.*, 2020) and respectively biaxial.

The distribution of stresses in the maximum stress area depends on a series of parameters as well as the method of obtaining, the properties of the material, the number of layers and their orientation, etc.

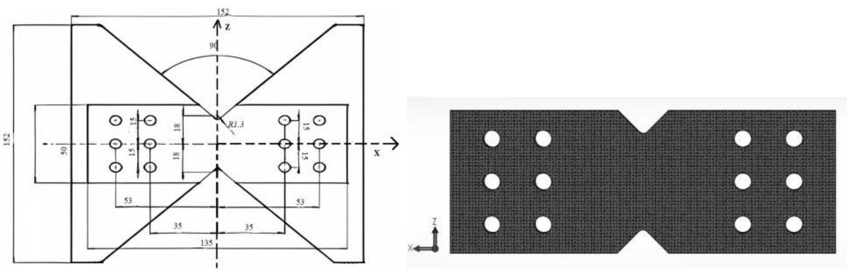
The paper proposes the analysis of the behavior of composites in traction and shear followed by simulations with finite elements. The use of FEA has proven to be a productive tool for improving structures with composite-composite or composite-metal joints, bringing additions and validations to the experimental analysis data regarding the performance of composite materials.

2. Material and methods

Composite materials are made up of two phases, the matrix and the reinforcement. Their properties are influenced by the nature of the fiber, its geometry and adhesion to the matrix being clearly superior when loaded in the direction of the fibers. In the case of CFRP, the matrix is polymeric, the adhesion between the fibers and the matrix gives the material an integrity that makes them resistant to fiber breakage.

The studied materials were developed at the Faculty of Mechanical Engineering, University of Ljubljana, Slovenia through autoclaves with different fiber placement sequences $[0/90]_8$ and $[+45/-45]_8$ (Bergant *et al.*, 2018).

The tested specimens of these materials are modified butterfly type, made according to the Iosipescu model (Iosipescu, 1967). The geometry has been optimized by achieving a notch angle of 90º and the radius at its tip of 1.3 mm according to the standard ASTM D 7078, obtained by cutting plates with dimensions of 210x297 mm and thickness of 2 and 2.8 mm.



a) b)

Fig. 1 – Specimen: a) scheme; b) photo; (Mititelu *et al.*, 2022).

The Dynamic Mechanical Analyzer (DMA 242C-Netzsch Germany) was used to evaluate the viscoelastic properties and the effects of manufacturing technologies, with 3-point bending using Protheus software v.4.8.5. (Bergant *et al*., 2018).

The tests were performed with a constant rate of temperature increase inside the test chamber at different frequencies. The response of the sample being measured with a variable displacement linear transducer. For viscoelastic composite materials, the response is out of phase with the original sinusoidal input (Bergant *et al*., 2018).

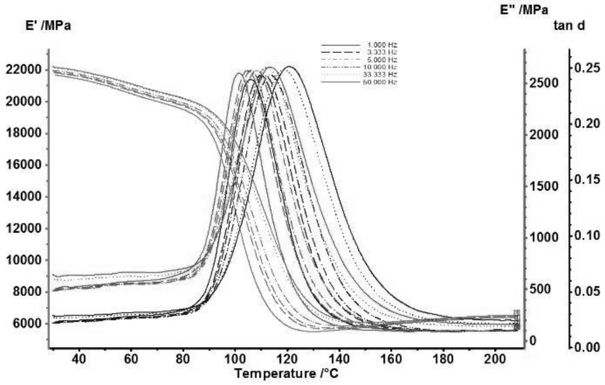


Fig. 2 – The mechanical properties determined with DMA (Bergant *et al*., 2018).

Another non-destructive examination method used for CFRP testing is ultrasound (US). The method involves the use of a Phasor XS device with a network of 32 sensors and a central frequency of 5MHz, for which the presence of material porosities and the propagation speed of US (longitudinal and transverse) through the material is determined. The average values of the US propagation speed obtained are C_l=2754±20m/s and C_t=1945±20m/s for samples with layers $[0]_8$ and C_l=2840±20m/s and C_t=1970±20m/s for those at $[(45/0)_2]_s$ (Savin *et al*., 2020).

The obtained results are used for the calculation of Poisson's ratio, Young's modulus and shear modulus necessary for finite element analysis (FEA).

3. Finite model analysis

The FEA analysis was performed for the case of an ideal composite material without cracks. The sample made in 3D model with the CAD software SolidWorks Fig. 3 then imported into Ansys software version R17.0 where the analysis with finite elements was performed (Li *et al*., 2015).

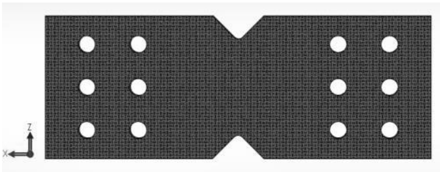
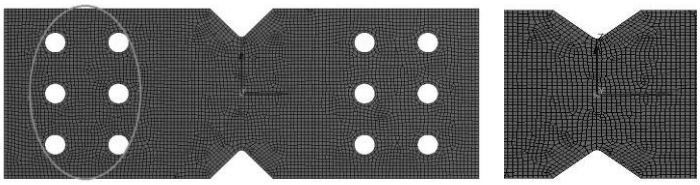


Fig. 3 – Model 3D SolidWorks.

For the FEA simulation, the quadrilateral discretization method with uniform size function and fine center relevance was used. Transition fast and smoothing High, were used for uniformity of the table. A function of the size of the elements of 1mm was introduced to ensure a higher accuracy of the results and the geometry of the section Fig. 4 was obtained. which contains 109,429 nodes and 24,762 elements.

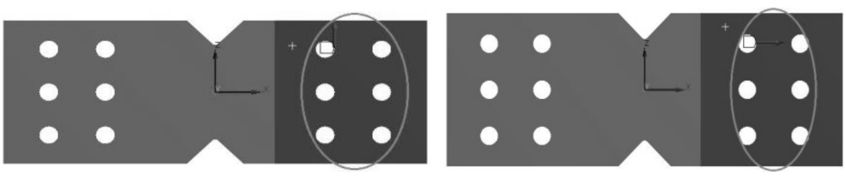


a) b)

Fig. 4 – a) The sample with the mesh structure; b) the analyzed section.

It was considered fitting in the 6 holes in Fig. 4a in the circled area, applying a fixed support. Embedding is the clamping of the specimen in the Arcan device (Arcan *et al*., 1978) using screws, respectively in the bins of the car to be tested.

In Fig. 5 in the circled area, a uniformly distributed force was applied on the 6 holes corresponding to the test direction and on the surface of the sample because it was considered that it is fixed between the 2 plates of the Arcan device (Arcan *et al*., 1978) by tightening with screws. The forces were applied identically in the two cases studied, the only difference being the direction of its loading.

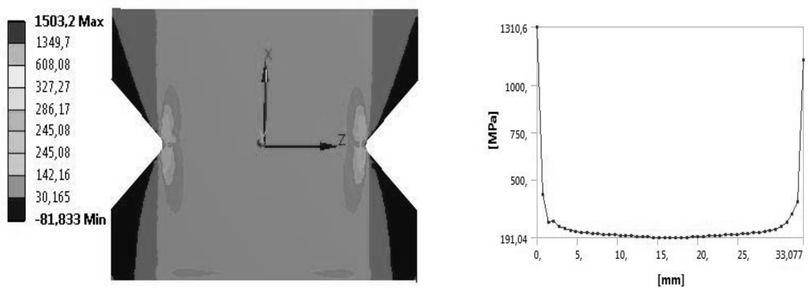


a) b)

Fig. 5 – a) The force applied for the tensile test in the X direction; b) The force applied for the shear test in the Z direction.

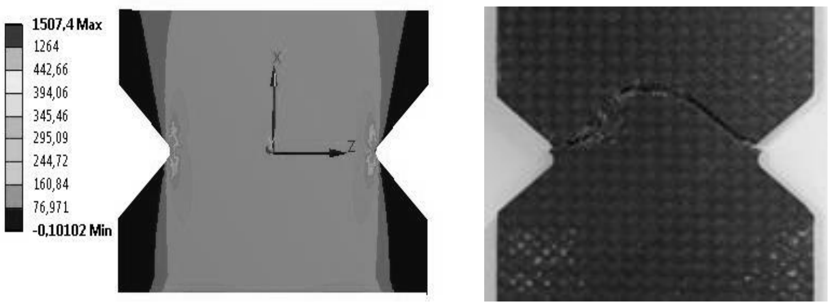
4. Results and discution

For the tensile test Fig. 5a a force of 10 kN was applied in the direction of the X axis. A uniform distribution of stresses in the breaking section was observed, see Fig. 6. with the beginning of the crack in the central area of the sample around the stress concentrator created by the radius at the tip with a value of 1.3 mm, according to ASTM D 7078. The stress graph Fig. 6b indicates an area with approximately constant stresses on the central area of the sample with a minimum of 191 MPa in the central area and a maximum of 1310 MPa at the top of the crack.



a) b)

Fig. 6 – Normal stress in the X direction; b) Normal stress graph on X direction.



a) b)

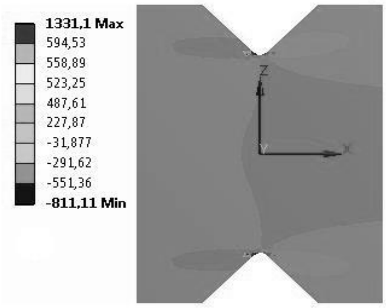
Fig. 7 – a) Maximum principal stress; b) Specimen broken in the tensile test in the X direction.

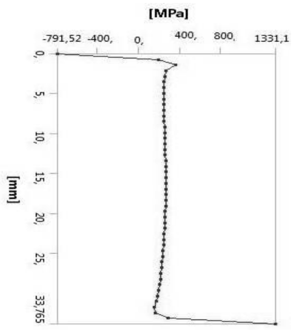
We notice the stress distribution obtained in the analysis with finite elements that corresponds to the mode of breaking the sample tried in the laboratory Fig. 7b.

The shear test Fig. 5b was performed in the XYZ coordinate system applying a force of 10 kN in the direction of the Z axis.

We note the fact that in Fig. 8a the stresses appear in the area of the notch and extend towards the inside of the analyzed sample. In the lower part of

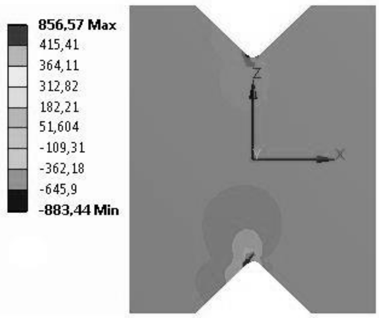
Fig. 9a, there are tensile stresses (positive) with a maximum value of 856 MPa, which are correlated with the beginning of the crack, and in the upper part, negative stresses of 883 MPa, which represent compression in the analyzed area.

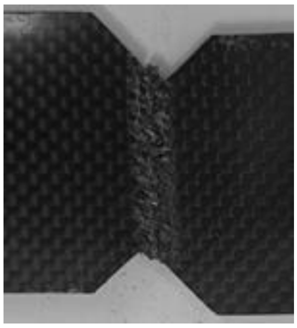




a) b)

Fig. 8 – a) Shear stress in XZ plane; b) Shear stress graph in XZ plane.





a) b)

Fig. 9 – a) Normal stress in the Z direction; b)the sample tested for shearing in the Z direction.

5. Conclusions

Simulations were carried out using the finite element method and tensile and shear tests that validated the obtained results.

The Arcan device was used for tensile and shear tests with a modified butterfly test, following that the tensile results were compared with the tensile test according to the ASTM D3039 standard. We notice that the areas with the critical stresses obtained in the simulations correspond to the areas of breaking the samples in the two cases.

It is desired to find a material that can also be used in places where there are traction and shearing demands, so using the finite element method, the materials can be analyzed before they are made according to the requirements that must be met. Thus, the structure of the material is analyzed and modified in the design phase. Changes can be made to the orientation of the layers at different angles, more layers or a more resistant epoxy matrix. A predominance of layers distributed in the direction of the X axis corresponding to the angle of 0 degrees will form a material that will resist much better in traction in the direction of the fibers.

The studies carried out with the Arcan device for testing traction and shear represent a starting point for future analyses. Specially designed to test samples under compound stress, it represents one of its main advantages. The testing involves the simultaneous application of several forces or loads on the sample allowing the evaluation of the performance of the components in realistic and relevant conditions that occur in composite materials with carbon fibers or other materials such as basalt, flax or glass fiber.

REFERENCES

Arcan M., Hashin Z.A., Voloshin A., *Experimental mechanics*, 18 (4), 141 (1978).

ASTM D 7078, *Standard Test Method for Shear Properties of Composite Materials by the V-Notched Rail Shear Method*, ASTM International, West Conshohocken, PA, 2005.

ASTM D3039/D3039M, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials* (astm.org).

Autar K.K., *Mechanics of compozite materials*, Ed. Taylor & Francis Group, LLC, U.S.A., ISBN 0-8493-1343-0 (2006).

Bergant Z., Savin A., Grum J., Polymers and Polymer Composites, 26(5-6), 358, 2018.

Elmarakbi A., Mollón V., Bonhomme J., Viña J., Argüelles A., *Ch. 10. Fracture and Failure Mechanisms for Different Loading Modes in Unidirectional Carbon Fibre/Epoxy Composites*, in Advanced Composite Materials for Automotive Applications: Structural Integrity and Crashworthiness, John Wiley & Sons Ltd (2013).

Garnier C., Pastor M.L., Lorrain B., Pantale O., *Fatigue behavior of impacted composite structures*, Composite Structures 100, 443-450 (2013).

Hübner M., Lepke D., Hardi E., Koerdt M., Herrmann A.S., Lang W., *Online Monitoring of Moisture Diffusion in Carbon Fiber Composites Using Miniaturized Flexible Material Integrated Sensors*, Sensors, 19(8), p. 1748, 2019.

Iosipescu N., *New Accurate Procedure for Single Shear Testing of Metals*, J. Mater., 2, 537-566 (1967).

Kim S.S., Yu H.N., Murayama H., Kageyama K., Composite structures, 92(5), 1039 (2010).

Lei Y., Kang Z., Zhang J., Sun Y., Zhang B., *Effect of freeze-thaw cycling on the mechanical properties of continuous carbon fiber-reinforced polyamide 6 composites*, Polymer Testing, 114, p. 107704, 2022.

Li D.S., Jiang N., Zhao C.Q., Jiang L., Tan Y., *Experimental study on the tension fatigue behavior and failure mechanism of 3D multi-axial warp knitted composites*, Composites Part B: Engineering, 68, pp. 126-135 (2015).

Maragoni L., Modenato G., De Rossi N., Vescovi L., Quaresimin M., Composites Part B Engineering 199, 108282 (2020).

Mititelu I., Petrișor S.M., Savin A., Šturm R., Bergant Z., Steigmann R., Stanciu M.D., Bârsănescu P.D., *Multi-Criteria Evaluation of the Failure of CFRP Laminates for Frames in the Automotive Industry*, Polymers, 2022, *14*, 4507, https://doi.org/10.3390/polym14214507.

Petrakli F., Gkika A., Bonou A., Karayannis P., Koumoulos E.P., Semitekolos D., Trompeta A.F., Rocha N., Santos R.M., Simmonds G., Monaghan G., *End-of-Life recycling options of (nano) enhanced CFRP composite prototypes waste a life cycle perspective*, Polymers, 12(9), p. 2129, 2020.

Savin A., Sturm R., Bergant Z., Stanciu M.D., Steigmann R., Dobrescu G.S., *Monitoring techniques for carbon fibers reinforced plastics used as complex structures*, IOP Conf. Series: Materials Science and Engineering, 916, 01210 (2020).

ANALIZA CU ELEMENTE FINITE A POLIMERILOR RANFORSAȚI CU FIBRE DE CARBON SUPUȘI LA TRACȚIUNE ȘI LA FORFECARE

(Rezumat)

Compozitele ocupă un loc important în industriile de vârf datorită caracteristicilor lor superioare în comparație cu materialele tradiționale sau materialele constitutive individuale. Înțelegerea comportamentului mecanic în diferite condiții de încărcare permite dezvoltarea de noi materiale inovatoare și optimizarea performanței acestora.

Lucrarea se concentrează pe analiza FEA a materialelor compozite cu fibre de carbon CFRP cu matrice polimerică supusă sarcinilor de tracțiune și forfecare, un subiect important de studiu în domeniul ingineriei. Analiza prin metoda elementelor finite este de un real ajutor prin simularea materialelor în diferite condiții. Datorită proprietăților lor avansate, materialele compozite pot fi testate și optimizate înainte de a fi utilizate în producție. Acest lucru poate reduce nevoia de a face prototipuri și de a testa de mai multe ori. Scopul este de a crește productivitatea și de a elimina excesul de deșeuri, un proces important care stă la baza tuturor industriilor de astăzi.

Specimenele modificate de tip fluture au fost folosite în acest studiu de cercetare pentru a fi testate pe dispozitivul Arcan. Condițiile de simulare au fost similare unui test de tracțiune și forfecare efectuat în laborator, luând în considerare un material fără fisuri sau alte impurități în structura sa și utilizând proprietățile mecanice furnizate de software-ul Ansys pentru ranforsantul fibră de carbon unidirecțională și matrice din rășină epoxi.