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RESEARCH ON EVALUATING MECHANICAL PERFORMANCES OF CFRP MATERIALS

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Abstract: *The studies investigate the mechanical loading tests of laminated composites manufactured by two methods as vacuum-packed wet coating and autoclave processing method and were performed using two types of epoxy / carbon laminates. The stacking sequence is imposed on the eight-layer laminate* $[0]_8$ *and* $[(45/0)_2]s$*. The orientation of the fibers, the stacking sequences and the production methods influence the response of the composite structure. Starting from estimating the response of the composite structure to mechanical loads, an optimized Arcan device for testing thin composite plates was used. A finite element analysis of the Iosipescu type test piece in a biaxial state of stress was made using ANSYS 17.0 software.*

Key words: *CFRP, tensile strength, compressive tests, Arcan device.*

1. INTRODUCTION

The composite materials are in full use in automotive industry [1], marine applications [2] and aerospace [3] and beginning to gain interest in applications where tribological features are needed. Although they are considered light structures, these composites require rigidity, resistance to thermal damage mechanisms [4], durability requirements. There is a trend of using CFRP in dynamic loading applications, where cyclic loads and work environments lead to material wear and fatigue [5]. Carbon fibers reinforced plastics CFRP are manufactured by different methods, depending on the properties expected for each category of use [6]. Today, different manufacturing methods of CFRP are developed and applied, such as by casting or compression or autoclave casting [7], but autoclave processing is one of the efficient methods for strengthening thermoset prepregs. In wet lay-up process, a two-component epoxy resin is mixed, and a primer layer is first applied on the mold, shaped upon requirements of the structure. Depending on available equipment, the fibers woven are placed over the primer then the resin is pouring over it. Vacuum bagging improves the wet lay-up/vacuum bag (WLVB) methods avoiding the apparition of pores and voids.

The physics properties of CFRP structures are in connection on the strength of the fibers, the matrix but also on the adhesion between the two. There are methods to improve the interfacial bond between the polymer matrix and the carbon fibers through treatments [8] or [9]. CFRP laminates show a reduction in stress concentration, although, separated, the matrix and the fibers have a fragile behavior. CFRP performance is investigated with mechanical testing using standard samples cropped out from large plates. The tests are necessary for the basic research of CFRP, applying uniaxial [10] or biaxial [11] loads and establishing in laboratory conditions in order to see their fit to other potential applications. The distribution of stresses in area of maximum effort is largely dependent on a multitude of parameters, including the material properties, laminated lay-up, ply orientation, etc. The mode and working environment under load are defining for the structure and therefore it is important to analyze them according to the manufacturing processes. These studies investigates the mechanical loading tests of laminated composites manufactured by two methods as vacuum-packed wet coating and autoclave processing method and were performed using two types of epoxy/carbon laminates. The stacking sequence on the eight-layer laminate $[0]_8$ and $[(45/0)_2]_s$ is taken into consideration. The orientation of the fibers, the stacking sequences and the production methods influence the response of the composite structure. Starting from estimating the response of the composite structure to mechanical loads, an optimized Arcan device for testing thin composite plates was used. The Arcan device, originally designed to test an S-shaped specimen, was later transformed to test a butterfly specimen [12]. The present study aims to use a modified Arcan device for an Iosipescu specimen [13] that allows combinations of loading directions ranging from plane at 0° load to 90° shear and other combinations [14]. Although is a powerful device for mixed loads, it will be used for the experimental characterization of the shear traction combinations according to the theoretical models for the prediction of failures in loading conditions. With this device, the specimen's behavior in pure normal, pure-shear and mixed modes respectively is investigated. Starting from the estimation of the response of the composite structure to mechanical loads, it is following the simulations with finite elements and the experimental results during the tests, thus data completion the analysis regarding the performances of the composites processed with autoclaves and justifying high investment for improvement of material properties. Thus, the analysis of the behavior of the composites under load, apart from the adjusting plan, is helpful for the improvement of composite-to-composite or composite-to-metal structures.

This paper presents results obtained in evaluated mechanical performances of CFRP materials during the mechanical loading tests. Thin composite plates having the layout of laminas $[0]_8$ and $[(45/0)_2]$s were obtained by vacuum-packed wet coating and autoclave processing method. For testing thin composite plates, an optimized Arcan device was used. Also, a finite element analysis of the Iosipescu type test piece in a biaxial state of stress was made using ANSYS 17.0 software. Ansys Mechanical software [15] offers superior capabilities for solving complex engineering problems and supports making efficient and fast design decisions. The Ansys software advanced technology in the analysis of composite structures allows engineers to perform strength analysis, stiffness and in-service behavior assessment. It also offers the ability to simulate layered composites, fabrics or other complex types of composite materials, allowing full performance evaluation in a variety of applications.

2. ARCHITECTURE SENSOR; THEORETICAL PRINCIPLES AND CONSTRUCTION

2.1 Estimation of mechanical and elastic features of the composite

From a constructive point of view, composite materials contain two phases, the matrix itself, which represents the continuous phase and the reinforcement defined as the continuous phase. In the case of CFRP, the matrix is polymeric, the adhesion between the fibers and the matrix offers the material an integrity that resists to the breaking of the fibers, characteristic of TENCATE composites [16]. All types of fabrics have been simulated for studies in literature [17], practically interest presenting only six types of fabrics with geometric pattern of idealized generated fabric architectures. The matrix is the plastic and deformable component of the composite, with lower mechanical strength than the embedded reinforcement material. However, its mechanical properties cannot be neglected; they have a great influence on the behavior at static and dynamic stresses. The thermoset polymer matrix is most often used in fiber-reinforced composites, being known as epoxy resin. It has a good thermal stability, corrosion resistance and low contraction, thus being resistant to severe conditions.

The properties of composites are influenced by the nature of the fiber, its geometry and its adhesion to the matrix. Carbon fibers with a content of over 80% carbon, have a tensile strength of about 7GPa with a modulus of elasticity of 230GPa (compared to steels that have 210GPa). However, the most well-known are those with graphite fibers. The properties of carbon fiber reinforced composites are clearly superior when they are loaded in the direction of the fibers. The mechanism of damage in composite materials compared to that of steel or aluminum is much more complicated. In addition to the working conditions and the degree of loading of the composite architecture, the polymeric matrix and the fiber structure can cause microstructural accumulations in the general mechanism of damage.

Matrix cracking, fiber detachment from the matrix, fiber rupture or delamination are damages to the CFRP that leads to failure of the composite. The micro cracks of the composite are difficult to notice, but their presence can significantly affect the material, becoming dangerous as the load applied to the composite increases. For composites subdued to tensile loading, crack initiation begins with transverse cracking of the fiber bundle whose direction does not coincide with the loading direction. The microstructure of composite materials is more complicated than classical materials; however their behavior is governed by the same general equations of elasticity theory as the equilibrium equation (Cauchy), geometric equations (displacement deformation relation), constitutive equations (Hooke's law).

The studied manufacturing methods [18] have shown that the properties of the composite depend on the applied technology [19]. WLVB technology is a traditional one still used a lot to obtain composites with low costs but which is often affected by voids that can reach a concentration of up to 10% (maximum allowed being 2.5%) and porosities that reduce the resistance and deformations to traction, compression and shear [20] or [21]. The replacement of low-cost wet lay-up and vacuum bagging technology with that of more expensive autoclave processing technology should be done in relation to the evaluation of CFRP performance depending on the type of manufacturing. The proposed model for the study of CFRP performances involves a simple iterative optimization procedure, in which the analysis is made for two types of samples obtained through the two manufacturing processes and the identification of the optimal mechanical parameters.

The workflow presented in Figure 1 includes CFRP manufacturing, by wet lay-up and vacuum bagging and autoclave processing method following fiber matrix stacking, finite element analysis to validate experimental results using Arcan device. Consequently, the predictions of these FEM models as mechanical properties are used to evaluate the mechanical performance of CFRP. At the same time other relationships between the pressure variation in the autoclave and the mechanical properties can also be established.

The optimization method is proposed to perform biaxial tests for the specimen geometry. The literature presents numerous experimental devices and often a large number of specialized specimens for each type of industrial application depending on the intended use [22].

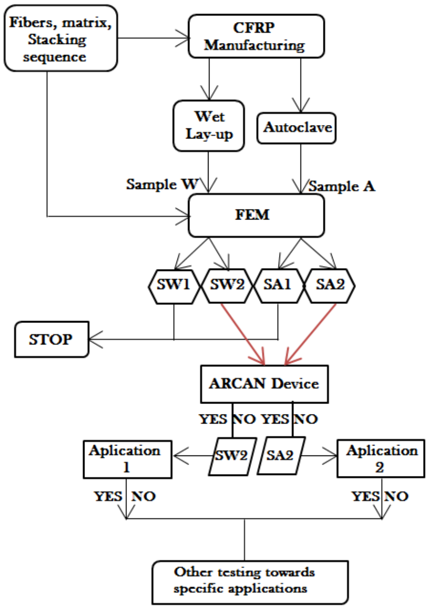


Fig.1. Flow chart of CFPR study

The optimization of the designs of the test device and specimen are carried out in FEM simulations. It is known that mechanical fixture often causes a reduction in the load-bearing capacity of composite structures due to stress around the clamping area. The stress distribution on holes edge depends on materials features, layers and plies configuration, etc. [23]. The Arcan device is used to determine the behavior of composites with the advantage of testing thin cross ply and quasi-isotropic symmetrical plain weave carbon-epoxy laminates for a specific set of epoxy/carbon fabric type.

The specimens were cut-out from 4 carbon-epoxy composite plates made at the Faculty of Mechanical Engineering, University of Ljubljana, Slovenia. Two type of laminates are manufactured by WLVB and autoclave processing method with different ply stacking sequences $[0]_8$ and $[(45/0)_2]s$ [24]. Dimensions of plates are 210x297mm with 2-2.8 mm thickness (the size of the specimen was given by the size of manufacturing form table). The laminates are obtained using CF fabrics, Sigrafil and Torayca. Woven fibers have a filament diameter of 7 µm, with 50k yarn filaments and 3K filaments) and an almost similar elastic modulus [25] or [26]. The epoxy system (MGS® 285, bisphenol diglycidyl ether type) and polyamide hardener (Epikure Curing Agent MGS LH 285) [26] were used for the matrix. Tests were performed to evaluate the mechanical properties and obtain additional information on the effects of manufacturing technologies.

Flexural stress was determined with equation [27]

$$\sigma_f = \frac{3}{2}\frac{F_{\max} L}{wh^2}. \tag{1}$$

were w is the width; h is thickness of the sample; L is length, F max is maximum force applied. For the flexural strain was used equation

$$\varepsilon_f = \frac{6sh}{L^2}. \tag{2}$$

where s is the deflection [27]. For this type of CFRP, the effects of manufacturing process and materials by testing DMA were analyzed [24] Figure 2. From the DMA analysis of the CFRP plates it is seen that the dynamic mode changes of the materials under the vibration load with temperature do not differ significantly. The loss modulus reflects the adhesion of the material. The storage modulus, i.e. the modulus of elasticity, reflects the stiffness of the material.

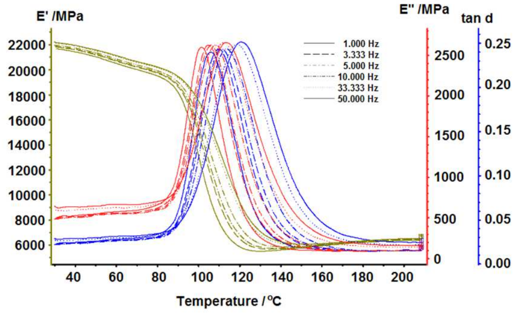


Fig.2. Mechanical properties determined by DMA

The microstructure of the composites was analyzed using an optical microscope Olympus Colorview integrated camera, image was post processed with Analysis Docu program which has allowed also the identification of voids content. The analyses showed that the materials have the established fiber orientation; they accomplish the integrity conditions and were selected for complementary tests.

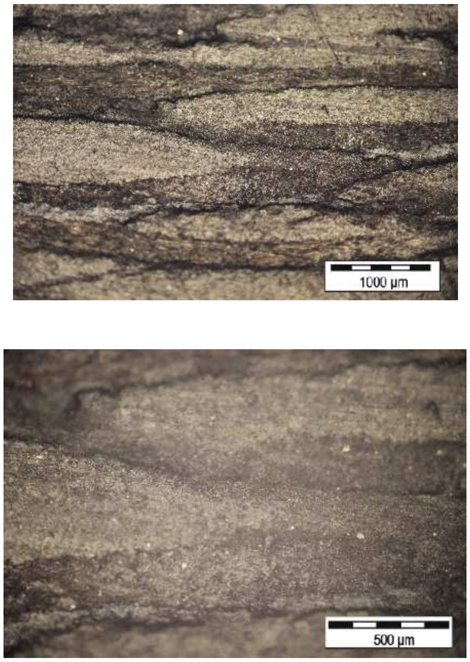


Fig.3. Microstructure of the cross-section of the composite

3. FINITE MODEL ANALYSIS

The principles of finite element analysis (FEM) were first developed by the German mathematician Richard Courant [28] and represent an effective method used in the study of the behavior of composite materials [30] or

[31]. The FEM analysis of the materials was developed starting from the ideal case of a composite without cracks. For the realized CFRP plates, longitudinal speed (C_l) and transverse speed (C_t) were determined using ultrasonic wave propagation, the average values of propagation velocity of US through the CFRP are C_l=2754±20m/s, C_t=1945±20m/s for sample $[0]_8$ and respectively C_l=2840±20m/s, C_t=1970±20m/s for sample $[(45/0)_2]_s$. The obtained values were used to determine the elastic constants as Poisson's ratio, Young modulus and shear modulus, required for Finite Element Analysis (FEA) simulations [32]. The simulations were performed with ANSYS software, version R17.0. The simulated specimen respects the Iosipescu model and was drawn in SolidWorks and then imported into ANSYS R17.0. The simulation was carried out as precisely as possible, applying the constraints and forces identical to those considered in the classic tests done in the laboratory. The test piece can be fixed in the Arcan device by 12 holes, each with a diameter of 6 mm, having an adequate arrangement for fastening in the device.

The total number of degrees of freedom for the mesh structure used in the specimen is 62172 and if we subtract from the total number of degrees of freedom the number of degrees of freedom corresponding to the elements where we applied fixed support, we will have a total of 59790 degrees of freedom. The used mesh is tetrahedral, with 10362 knots and 5940 elements. This type of discretization is common because it provides higher simulation accuracy (Figure 4).

The bearing conditions were considered in the left end on the 3 bolts and embedded inside the holes, like the fixing in the Arcan device (Figure 5).

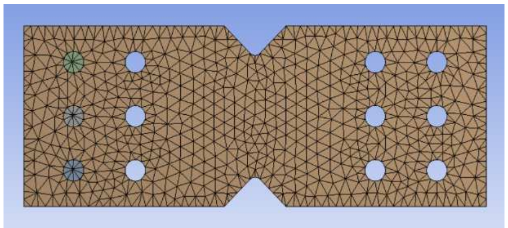


Fig.4. Mesh used for FEA

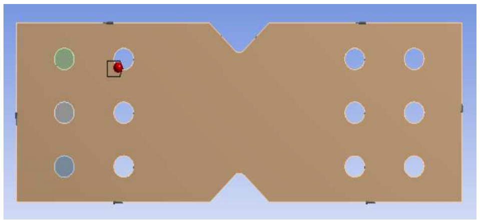


Fig.5. Fixing the specimen inside the holes on the left

The load on biaxial stress was applied with 250N force on the surface of each of the 6 holes on the right, at 45 ° from the directions of the X (horizontal) and Z (vertical) axes. The resultant of the force applied on a hole on the right side of the test piece, at 45 °, is 353.5 N (Figure 6) which corresponds to tests for mixed mode.

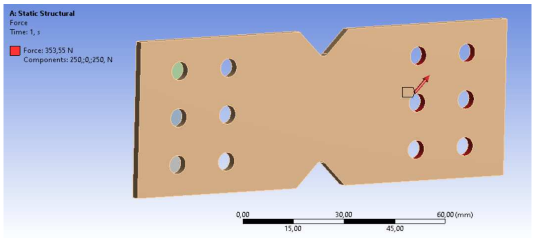


Fig.6. Loading of the specimen

It is known that for a biaxial state of stresses, the equivalent von Mises stress, which considers the shape-modifying energy (distortion energy), is determined by the relation:

$$\sigma_{eq} = \sqrt{\sigma^2 + 3\tau^2}\ . \tag{3}$$

where σ is normal stress and τ is shear stress. Under these conditions, the FEA provided the distribution of displacements (Figure 7) and von Mises stresses (Figure 8).

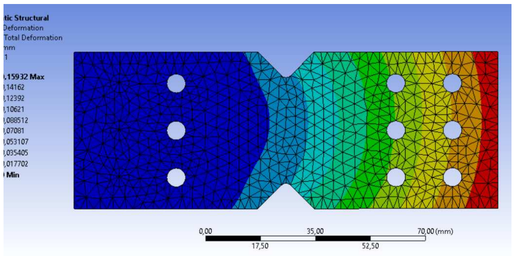


Fig.7. Total deformation of the specimen

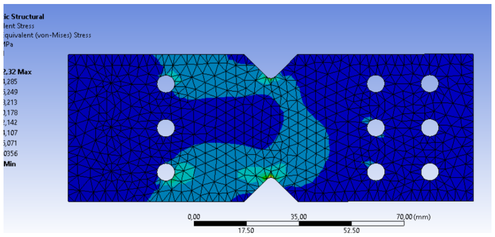


Fig.8. The map of von Mises stresses

It can be observed that the displacements are nulls in the embedded left part of the specimen and are maximum at the right end of the specimen. Figure 9 shows the distribution of von Mises stress in the area of the notches (detail of the Figure 8).

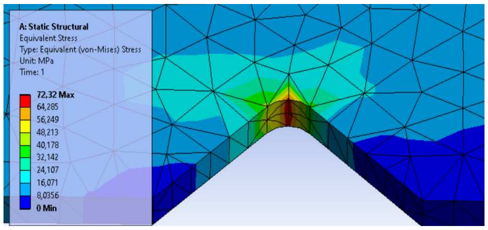


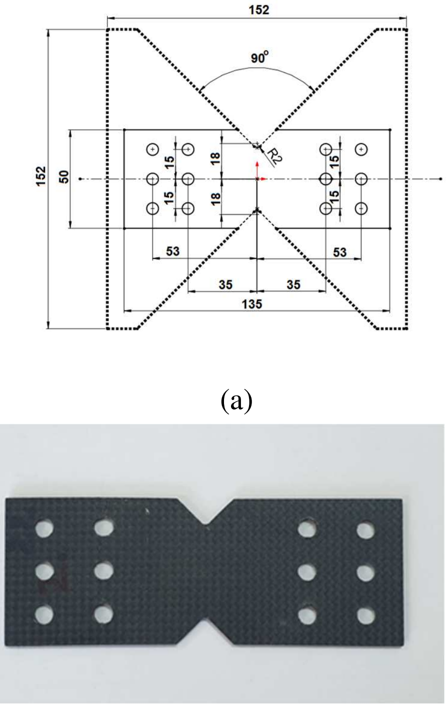
Fig.9. Distribution of von Mises stress in the area of the notches.

*in figures 6-9 the decimals are separated by commas

For this analysis, it can be observed that the maximum von Mises stresses are seen at the bottom of the notches and have the value 77.3MPa, for the analysis made. From these areas the failure of the specimen is initiated.

4. THE SPECIMEN AND TEST FIXTURE

The test procedure using the Arcan device consists in applying a tension in the direction of stress at a certain angle to the axis of the specimen, the difference lies in the ability of this device to be used in tensile, shear and compound stress tests. The specimen geometry has been optimized to analyze the uniformity of deformation in the required region and even more so if concentrated failure occurs in this region. A modified geometric butterfly type specimen was analyzed compared to the classic, Figure 10.



(a)

(b)

Fig.10. Specimen: (a) scheme; (b) photo

Commonly butterfly shaped specimens are mounted on the test fixture above, but these specimens consume a lot of material. The two types of specimens are presented overlapped in the Figure 10. Note that the central part (where is the minimum section, in which the rupture occurs) is identical for both specimens. FEA and IR thermography used in [33] have shown that the most uniform shear stress in specimen is achieved for the bottom notch of 2.54 mm radius. Different biaxial states of stress have been analyzed used a modified Arcan test fixture [33]. By varying the angle α (figure 11) the tensile or compression for α = 0° is achieved, respectively shear at 90° and different biaxial state of stress for angle between (0°-90°).

The four components of the testing device and the specimen are fixed together using a dozen of pins and eight screws. The analysis regarding the strength of the materials in traction, shear and in different biaxial stress states will be performed by fixing the Arcan device in Instron Tensile machine connected to a PC for data collection during the tests. Tests for thin CFRP materials using Iosipescu modified specimen [13] aim to obtain results that complement the classic tensile and shear tests, thus being able to determine the yield stresses for various states of biaxial stresses.

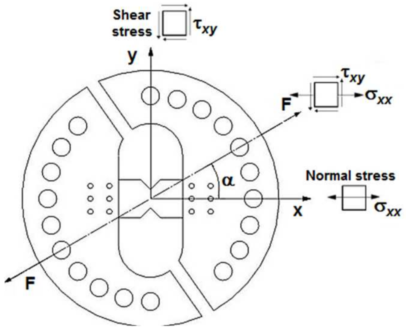


Fig.11. Arcan fixture for tension/shear test with different loading configuration

The tests on composite using the modified Arcan device mounted on the Instron machine showed that the areas, from which the crack, respectively the failure of the specimen is evident, validate the data obtained using FEA. Based on the tests and analyzes performed, we can make optimizations in the structure of the material to improve its resistance in the direction where maximum stresses appear by changing the orientation of the fibers or adding new layers, in the same or different directions. These optimizations can be carried out in the first stage in the FEA tests, eliminating possible additional costs in the material manufacturing processes.

4. CONCLUSIONS

The advantage of using autoclaves in CFRP production is well known, for the aeronautical industry, the autoclave casting process provides reliability, high strength and stable performance. It is also suitable for the manufacture of large cast products, with complex shapes contributing to weight reduction. The disadvantage is the need for post-processing where it is necessary to cut and drill the composite, knowing that these processes can lead to stresses/desbondings. A finite element analysis of the Iosipescu type test piece in a biaxial state of stress was made.

It was shown that the maximum von Mises stresses are seen at the bottom of the notches and as a result from these areas the rupture of the specimen is initiated.

Process modeling can facilitate optimization using autoclaves in CFRP production and can eventually lead to parts in complex structures with improved performance. FEA can provide reliable results for the case of composites subjected to mechanical processing required for fastening/adjustment. For future research, we will aim to change the orientation of the fibers and the use of other types of resins to make the materials in order to improve their resistance.

5. ACKNOWLEDGMENTS

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Cercetări privind evaluarea performantelor mecanice ale materialelor CFRP

Testele de încărcare mecanica se fac pe materiale compozite compozite laminate fabricate prin doua metode: acoperirea umeda ambalata in vid si metoda de prelucrare in autoclave. Încercările au fost efectuate folosind doua tipuri de material epoxidice/carbon laminate. Secvența de stivuire este impusa laminatului cu opt straturi $[0]_8$ si $[(45/0)_2]s$. Orientarea fibrelor, secvențele de stivuire si metodele de producție influențează răspunsul structurii compozite. Pornind de la estimarea răspunsului structurii compozite la sarcini mecanice, a fost utilizat un dispozitiv Arcan optimizat pentru testarea plăcilor compozite subțiri. Folosind software-ul ANSYS 17.0 s-a realizat o analiza cu element finit a piesei de încercare de tip Iosipescu in stare de efort biaxial.

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