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EXPERIMENTAL PROGRAM REGARDING THE BEHAVIOUR OF COMPOSITE MATERIALS JOINTS

BY

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Abstract. An experimental investigation regarding the behaviour of composite materials joints manufactured from glass fibre reinforced polymers (GFRP) is presented. The study is concerned with analysing several types of single and double lap joints: adhesively bonded connection; mechanical joints with one, two and four steel bolts; hybrid joints – combined adhesively bonded and mechanical methods; steel bolts mechanical connections with aluminium inserts consolidated holes. Behaviour of composite materials joints, failure modes, failure strength and bearing strength may be determined and observed with this experimental configuration.

Key words: bolted joints; adhesively bonded joints; hybrid joints; composites.

1. Introduction

The joining of composite materials represents a major interest considering the use on a large scale of these materials in industry and in civil

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engineering. The most popular methods to join two or more composite materials are adhesive bonding, mechanical fasteners, brazing, welding and combinations of these methods. Adhesive bonding method is the most common and a wide variety of materials can be assembled using this solution. The mechanical joining is easy to prepare, reliable, can be disassembled and it is easy to inspect. Brazing and welding requires a rather complex process for execution of these joints.

Important factors as structural and architectural requirements, technological process, nature of materials, application speed, environment advantages and disadvantages, as well as the total cost, need to be considered when the type of connection is chosen. In structural applications, adhesively bonded and mechanical joining methods or a combination of these two are the main ways of joining composite materials.

2. Literature Review

The main experimental studies carried out by various international research teams on the behaviour of composite materials joints with different connecting systems are described in this section.

The tensile response and failure of composite riveted joints were studied experimentally by Li *et. al.* (2001). Experimental results have identified new failure modes, bending-induced cross-section failure and rivet cap penetration failure. It was also shown that the rivet rotation is significant in some joint designs, which could damage the laminate and thus reducing the joint strength.

Starikov and Schon (2001) studied quasi-static behaviour of composite joints with countersunk composite and metal fasteners and joints with protruding-head. Results have shown that the highest quasi-static strength was obtained for specimens with titanium fasteners. Composite bolts demonstrated lower mechanical strength under shear loading, which led to bolt failure. The obtained results showed that specimens joined by six bolts in either single or double lap configuration displayed the highest quasi-static tensile and compressive strengths.

Failure characteristics of laminated composites with a single fastener were investigated by Okutan and Karakuzu (2002). The general behaviour of the composite was obtained from the load-displacement curves. $[\pm 45]_{2S}$ laminates failed in a more sudden fashion than $[90,0]_{2S}$ ones. Nonlinearity affects material failure upon the laminate's mechanical response in a pin-loaded configuration.

Aktas and Dirikolu (2003) carried out an experimental study regarding the determination of the safe as well as the maximum bearing strengths of pinned-joint carbon epoxy composite laminate with $[0°/45°\text{-}45°/90°]_s$ and $[90°/45°\text{-}45°/0°]_s$ stacking sequences. The $[90°/45°\text{-}45°/0°]_s$ sequence was found to be stronger when compared to the [0°/45°-45°/90°]$_s$ by up to 2% and 20% in terms of safe and maximum bearing strengths. The optimum geometry was obtained with $E/D \geq 4$ and $W/D \geq 4$. The geometric parameters *E, D, W, K* are described in Fig. 1.

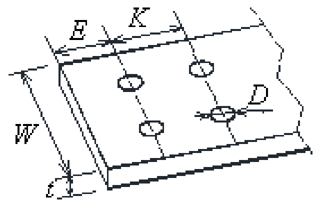


Fig. 1 – Geometric parameters description.

The relationship between laminate architecture, macroscopic damage and bearing response were investigated by Vangrimde and Boukhili (2003). True damage tolerant behaviour was observed for laminates with sufficient off-axis reinforcement. The bearing behaviour changed from a catastrophic failure with relatively low strength to a progressive high strength failure.

An experimental study of bolt-hole clearance effects in double-lap, multi bolt composite joints was made by Lawlor *et al.* (2005). The obtained results indicate that variable clearances in multi-bolt joints significantly influence the load distribution. Load is transferred to the neat-fit bolt(s). At the higher loads the distribution tends to even out, but this process may be interrupted by failure.

A numerical and experimental investigation on the use of bonded metallic inserts to increase the strength and the efficiency of single-shear composite bonded joints was performed by Camanho *et al.* (2005). The experimental results show that using tapered end inserts, the onset of damage in the composite is delayed. Furthermore, the maximum load sustained by single-shear joints and the joint efficiency are increased due to the creation of new regions of load transfer.

Khashaba *et al.* (2006) studied the effect of washer size and tightening torque on the performance of bolted joints in composite structures. The experimental results show that under the same tightening torque, the slope of load–displacement diagrams of bolted joints increases with decreasing washer size.

The effect of joint configuration, adhesive layer thickness, defects, humidity, spew fillet and adherend stiffness were investigated in 2006 by Abdelaziz *et al.* The failure load and displacement were found to decrease dramatically when the adhesive layer thickness was increased or when the joint was aged in a hot humid environment. Most of the joints made from $(0/90)_n$ laminates failed at the adherend joggle knee and all the joints made from $(\pm 45)_n$ laminates failed in the interface at lower load.

Karakuzu *et al.* (2008) investigated failure mode, failure load and bearing strength in a laminate woven glass–vinylester composite plate with two parallel holes and two serial circular holes. For specimens with two parallel holes, experimental results shown that the shear out failure modes are directly related to E/D ratio. For $E/D = 1$, failure mode is shear out and for specimens with $E/D > 1$ and $M/D > 2$ is bearing failure. For specimens with two serial holes, net tension failure is directly related to the width of the specimens. The failure load values are highly depending on the ratio E/D. The failure load increases with increasing ratios M/D, W/D; critical ratio is $W/D = 3$ and failure load does not change for ratio $W/D \geq 3$.

Khalili *et al*. (2008) made an experimental study on the influence of adhesive reinforcement in single lap joints subjected to mechanical loads such as tensile, bending, impact and fatigue. The results shown that except for the 90^0 unidirectional orientation, reinforcing the adhesive with glass fibre or powder increases the joint strength. The use of a volume fraction of 30% of micro-glass powder gave the best performance in the above loading conditions.

An experimental failure analysis was performed by Sen *et al.* (2008), to determine the failure modes and bearing strength of mechanically fastened bolted joints in glass fibre reinforced epoxy laminated composite plates. Results shown that failure modes and bearing strengths were considerable affected by increasing of preloads. The material and geometrical parameters of composite bolted joints influence the failure behaviour and the values of bearing strengths.

Lee *et al.* (2009) conducted an experimental investigation to characterize the joint strengths, peel stresses and failure modes in adhesively bonded double-strap and supported single-lap glass fibre-reinforced polymer joints. Experimental results have shown that the joint strength of double-strap joints decreases with the adhesive layer thickness. An approximate adhesive layer thickness between 0.2 and 0.5 mm maximizes the joint strength. Peel stresses exist in both double strap and supported single-lap joints. The peeling effect is crucial to the failure behaviour of adhesively bonded joints.

An experimental and numerical study of the mechanical response of bolted joints using new hybrid composite laminates based on the substitution of carbon fibre reinforced polymer (CFRP) plies with titanium ones was made by Camanho *et al.*(2009). The specific bearing strength of a hybrid joint with 50% titanium content at the bearing region was with 29% higher than that of a monolithic CFRP joint.

Atas (2009) has examined experimentally the bearing strength of pinned joints in woven fabric composites with small weaving angles. It was concluded that using layers with identical orientation may result in undesirable damages modes and the small load carrying capacities in mechanically fastened joints with small weaving angles.

A comparative study on different drill points geometries and feed rate for composite laminates drillings was made by Miguel *et al.* (2010). Low feed rate seemed appropriate for laminate drilling, as it reduced the axial thrust force and, consequently, the risk of delamination onset. The use of higher feed rates is possible, as long as there is knowledge about the effects on thrust force and delamination for each tool. The most adequate tool for higher feed rates is the twist drill with a 120^o point angle. A 120^o twist drill should be used for minimal delamination.

Kapti *et al.* (2010) conducted an investigation on the effects of preload moment, moisture and interference-fit on bearing strength and failure modes in pin–jointed and bolted carbon–epoxy plates. The test results showed that the ultimate failure loads were directly affected by the geometrical parameters, preload moments and interference-fit. The bearing strengths reached higher values in preloaded specimens than non-preloaded ones (155% and 176% for M = 3 N.m and M = 6 N.m).

A novel reinforcing method for glass fibre reinforced composites, which consists of interadherend glass fibre (IAF) that get through the composite adherent like a pin, was investigated experimentally and numerically by Bertan *et al.*(2011). The experimental results reveal that the ultimate strength and failure limit were increased by 80.7% and 60%, respectively. It is also noticed that fibres reduce stress values in the overlap region.

Ozen and Sayman (2011) made an experimental and numerical study to investigate the first failure load and the bearing strength behaviour of pinned joints of glass fibre reinforced woven epoxy composite prepregs with two serial holes. Results showed that increasing the preload moment, the high values of K/D, W/D and E/D ratios caused an increase of the failure load. Net tension and bearing modes were observed for M = 0. However only the net-tension mode was observed under M = 3 N.m and M = 6 N.m preload moments.

The stress analysis of multi-bolted joints for FRP pultruded composite structures was examinated by Feo *et al.* (2012). The results of this study showed that in multi-bolt joints, the load was not distributed equally due to varying bolt position, bolt–hole clearance, bolt torque or tightening of the bolt, friction between member plates and at washers–plate interface. The results also indicated that the presence of washers influence the stress distributions around the holes.

Chishti *et al.* (2012) performed an experimental investigation on damage progression and strength of countersunk composite joints. Experimental tests showed that introduction of the countersunk holes causes an offset of the local bearing damage region such that it remains parallel to hole edge and can also cause delamination. Increasing h/t ratio reduces the extent of bearing damage and promotes bending.

3. Specimens Preparation and Experiment Setup

3.1. Specimens Preparation

Five series of joints have been conceived for the experimental program. Series A, B, C, D are single lap joints and E series are double lap joints and all contain four subseries as follows:

a) A_1, B_1, C_1, D_1 – single lap adhesively bonded joints.

b) E_1 – double lap adhesively bonded joints.

c) A_2, B_2, C_2, D_2 – single lap bolted joints with one, two and four steel bolts.

d) E_2 – double lap bolted joints with four steel bolts.

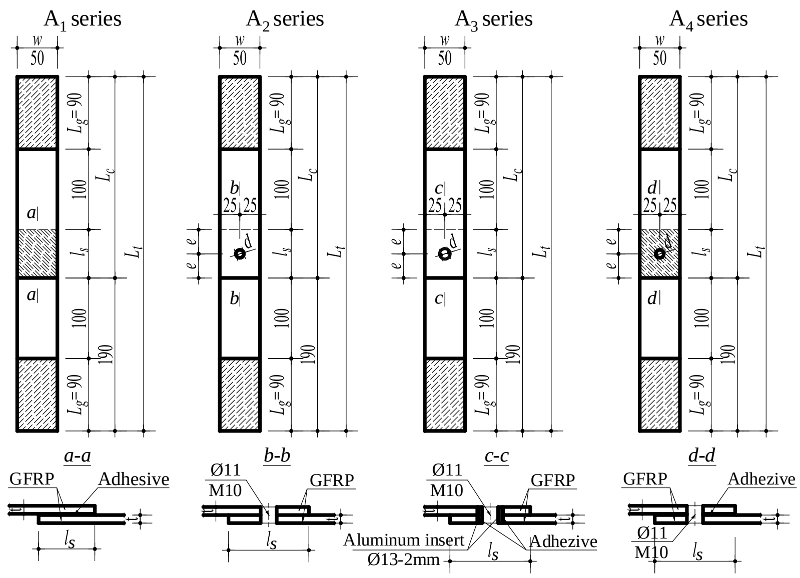
e) A_3, B_3, C_3, D_3 – single lap bolted joints with one, two and four steel bolts and aluminium inserts in holes.

f) E_3 – double lap bolted joints with four steel bolts with aluminium inserts in holes.

g) A_4, B_4, C_4, D_4 – single lap bonded-bolted joints with one, two and four steel bolts.

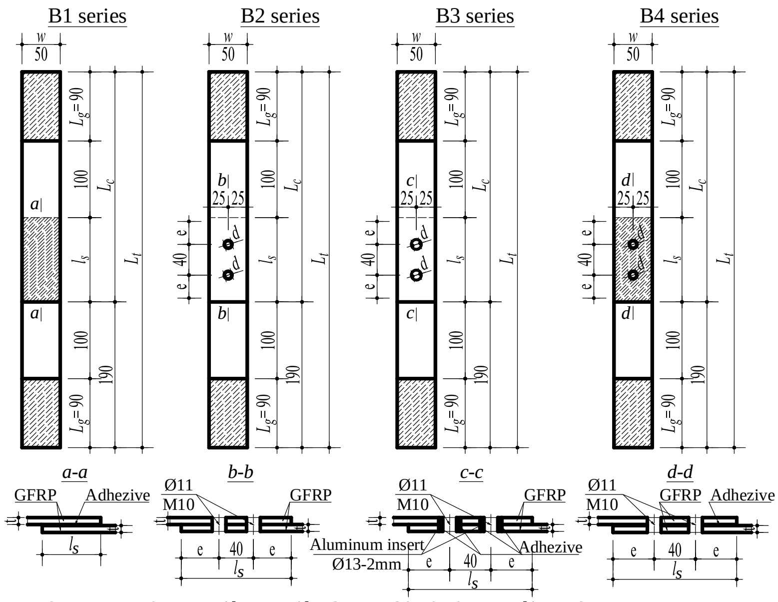
h) E_4 – double lap bonded-bolted joints with four steel bolts.

The geometric characteristics of each series are shown in Figs. 2,..., 6.



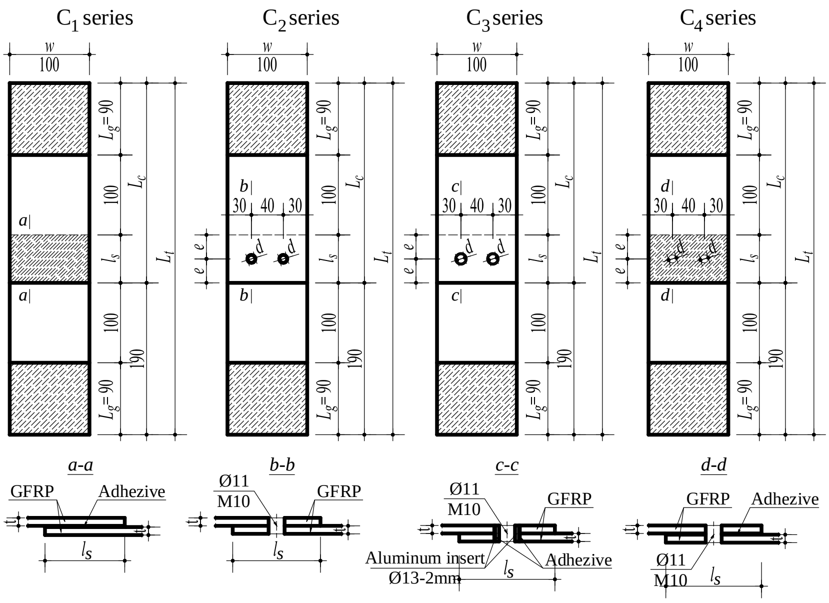
t = 6 mm; w = 50 mm; w/d = 5; e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67;
l_s = 60,80,100 mm; L_c = 250, 270, 300 mm; L_g = 90 mm; steel bolts M10 gr. 8.8

Fig. 2 – Specimens geometry for A joints series.



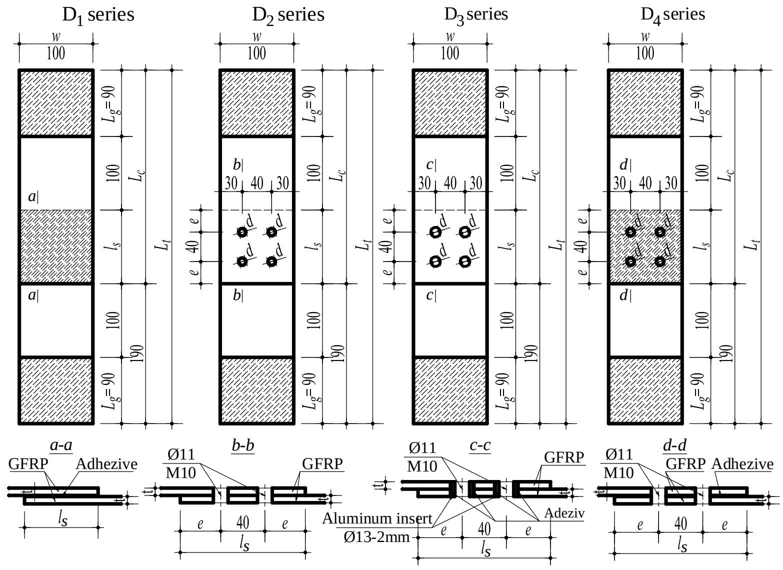
t = 6mm; w = 50mm; w/d = 5; e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67;
l_s = 100,120,140 mm; L_c = 290, 310, 330 mm; L_g= 90 mm; steel bolts M10 gr. 8.8;

Fig. 3 – Specimens geometry for B joints series.



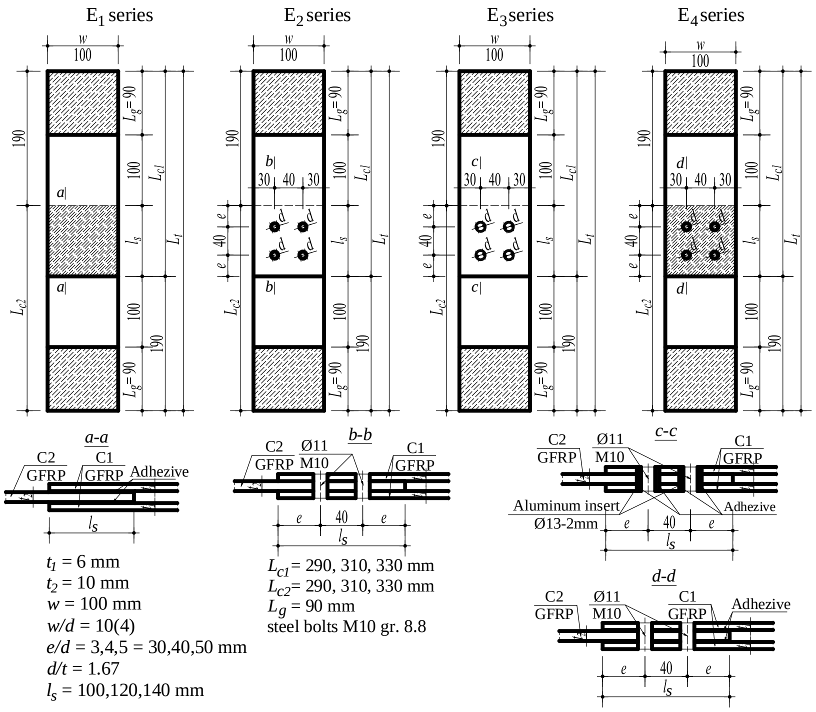
t = 6mm; w = 100mm; w/d = 10(2); e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67
l_s = 60,80,100 mm; L_c = 250, 270, 300 mm; L_g= 90 mm; steel bolts M10 gr. 8.8

Fig. 4 – Specimens geometry for C joints series.



t = 6 mm; w = 100 mm; w/d = 10(4); e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67
l_s = 100,120,140 mm; L_c = 290, 310, 330 mm; L_g = 90 mm; steel bolts M10 gr. 8.8

Fig. 5 – Specimens geometry for D joints series.



t_1 = 6 mm
t_2 = 10 mm
w = 100 mm
w/d = 10(4)
e/d = 3,4,5 = 30,40,50 mm
d/t = 1.67
l_s = 100,120,140 mm

L_{c1} = 290, 310, 330 mm
L_{c2} = 290, 310, 330 mm
L_g = 90 mm
steel bolts M10 gr. 8.8

Fig. 6 – Specimens geometry for E joints series.

Adherends are made of GFRP composite plates from Fiberline with longitudinal reinforcement and weave reinforcement on transverse direction. The adhesive used for bonded and hybrid joints is a bi-component adhesive Adesilex PG1 from MAPEI.

Adhesively bonded joints required additional treatment in the joint region. The surface was carefully cleaned with acetone, sanded with fine sandpaper until the fibres were visible and finally were cleaned again with acetone.

For bolted joints, holes and contact surfaces were carefully cleaned for a good contact. Holes were made considering specifications from norms, producing company and similar studies (Durão, 2010). Different preload moments are applied for some specimens to observe the failure modes under preload moment. The mechanical and technical characteristics of materials used are presented in Tables 1 and 2.

Table 1
GFRP Plates Mechanical Characteristics (Fiberline, 2012)

Characteristic	GFRP plates
Modulus of elasticity, [GPa]	23
Tensile modulus – longitudinal, [GPa]	23
Tensile modulus – transverse, [GPa]	7
Tensile strength – longitudinal, [MPa]	240
Tensile strength – transverse, [MPa]	50
Pin-bearing strength longitudinal, [MPa]	150
Pin-bearing strength transverse, [MPa]	70
Shear strength – longitudinal, [MPa]	25

Table 2
Adhesive Mechanical Characteristics (MAPEI 2010)

	ADESILEX PG1
Mixing ratio	Component A : Component B = 3 : 1
Complete hardening time, [days]	7
Compressive modulus of elasticity, [N/mm^2]	6,000
Compressive strength, [N/mm^2]	70
Shear strength, [N/mm^2]	25

3.2. Experimental Procedure

The tensile tests on specimens are made in a 100 kN hydraulic test machine (Fig. 7). For monitoring the force applied, the testing machine is equipped with an acquisition board.

The displacement is measured using linear variable differential transducers (LVDT). Strain gauges (SG) with two measuring grids (*T* – rosette) will be used to measure the strains in the composite plates. The application of the strain gauges is realized in laboratory conditions respecting the indications given by norms and producing company (ASTM D-3039, ASTM D-5961).

Fig. 7 – The universal testing machine for joint testing.

In Fig. 8 the positioning of the LVDTs and SGs for data acquisition is presented.

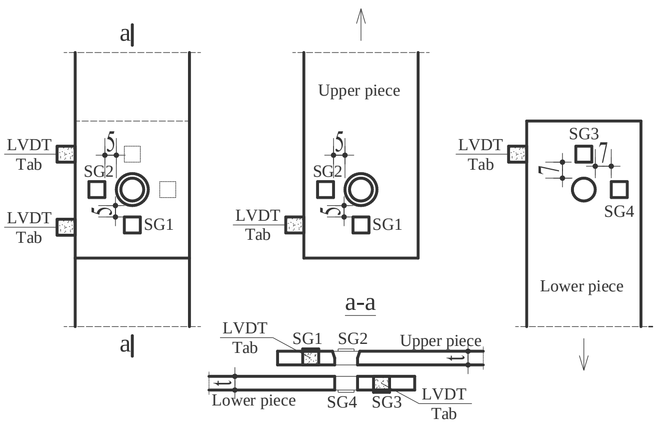


Fig. 8 – SG and LVDT positioning for a single lap bolted joint.

4. Conclusions

The aim of the performed experimental study is to obtain test results that can be used as a comparison for future work about composite materials joints manufactured from GFRP.

The study is focused especially on the behaviour and mechanical characteristics of hybrid joints and bolted joints with aluminium consolidated holes due to the limited publications on this subject.

The benefits of this experimental program are

a) Determining the failure strengths and bearing strengths for adhesively bonded joints, bolted joints, bolted joints with aluminium consolidated holes and hybrid joints.

b) Identifying defects that may occur in execution.

c) Identifying advantages and disadvantages of joining methods analysed in this study.

d) Identifying the failure modes.

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PROGRAM EXPERIMENTAL CU PRIVIRE LA MODUL DE COMPORTARE AL ÎMBINĂRILOR MATERIALELOR COMPOZITE

(Rezumat)

Se descrie programul experimental proiectat pentru evaluarea modului de comportare al îmbinărilor unor piese din materiale compozite realizate din poliesteri armaţi cu fibre de sticlă**.** Mai multe tipuri de îmbinări sunt analizate după cum urmează: îmbinări lipite cu adezivi; îmbinări mecanice cu unu, două şi patru şuruburi; îmbinări mecanice cu şuruburi cu găuri consolidate cu inserţii din aluminiu; îmbinări hibride realizate prin combinarea metodelor adezive şi mecanice. Prin acest program experimental se poate observa modul de comportare al acestor îmbinări, modurile de cedare şi se pot determina forţele de rupere şi forţele de strivire.