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BEHAVIOUR OF COMPOSITE-TO-COMPOSITE INTERFACE FOR ADHESIVELY BONDED JOINTS
EXPERIMENTAL SET-UP

BY

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Abstract. This paper presents the set-up needed for an experimental study regarding the behaviour of adhesively bonded joints manufactured from glass fibre reinforced polymer (GFRP) composites and structural epoxy adhesives. Two types of single lap shear pull-off specimens were designed and assembled for the experimental study. Twelve series of adhesively bonded joints have been conceived for the experimental program. Each series consists in combinations between GFRP composite structural flat profiles bonded with two types of adhesives which are applied in three thicknesses (1 mm, 2 mm and 3 mm). For each combination between the type and the thickness of adhesives, three overlap lengths have been applied (5 cm, 7 cm and 10 cm). By performing this experimental program, several important aspects related to the behaviour of adhesively bonded composite elements such as: characterization of the bond-slip behaviour, characterization of the failure modes, identification of the ultimate loads and evaluation the effective bond lengths are analysed.

Keywords: adhesively bonded joints; single lap shear pull-off specimens; GFRP.

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1. Introduction

The most common methods currently utilised in connecting two or more parts made of fibre reinforced polymer (FRP) composites are the mechanical fastening and the adhesive bonding or a combination of these two methods. The mechanical fastening is easy to manufacture but it requires drilling the pieces that are assembled which may lead to localized damages of the composite element and significant stress concentrations.

An adhesively bonded joint is defined as a permanent link of two adherents which are connected by an adhesive. The adhesively bonded joint enables the stress transmission through constituents more uniformly than a mechanical joint.

For most of the structural applications of FRP composite materials that include adhesively bonded connections, the adhesive layer has a critical function, being the component of the system which is responsible for shear stresses transfer between the adherents. Since the bond behaviour is of major importance in achieving appropriate performances for all types of applications, there is a special need for a comprehensive characterization of the bonding phenomena.

The bonding process and the bond behaviour are complex issues that are influenced by many parameters referring to the quality of the components preparation and to the quality of execution (*i.e.* surface treatment of the composite elements, proper mixing of the adhesive, appropriate handling of the elements, proper application of the adhesive, etc.). After the execution phase is finished, other parameters that are related to the mechanical properties of the constituents and to the geometrical configuration of the bond can be highlighted, such as: the effective thickness of the adhesive layer (t_a), the effective overlap length (L_o), the ultimate load that is carried out by the joint (P_{ult}), the influence of the elastic and strength properties of the constitutive materials and the specific failure modes.

The experimental program presented in this paper refers to two types of single lap shear pull-of tests, the single lap joints (SLJ) tests and the thick adherents joints (TAJ) tests. The main objective of the program is to describe the parameters that influence the bond mechanism and the behaviour of glass fibre reinforced polymer (GFRP) composite elements adhesively bonded joints.

2. Literature Review

The most relevant experimental studies carried out by various research teams regarding the behaviour of the joints of FRP composite materials adhesively bonded are described in this section. Most of the studies that are presented were prepared and carried out for two main reasons: firstly, to identify the most appropriates surface preparation techniques for common FRP composites adherents and secondly, to develop valid models which can characterize the behaviour of FRP composite adhesively bonded joints.

Hart-Smith (1973) studied the analysis procedures of composites adhesively bonded double lap joints. Based on several experimental tests results, the author modified the theoretical Volkersen analysis and extended it to account for the adhesive plasticity and the adherents' thermal mismatches. Three important characteristics of composite double lap joints were deduced both through experimental testing and by applying the analytical procedures: there is a definite overlap length for specified adherents and particular adhesive and the maximum bond shear strength is determined by the adhesive strain energy in shear per unit area of bond. The third factor relates to the maximum thickness of the adherents for which the variation of the peel stresses does not exceed the safety limit.

Brinson and Grant (1986) studied the influence of time dependent adhesive mechanical properties on lap shear stress distribution and interfacial stresses. Several laboratory test methods that were developed in order to provide aging and durability predictions on various FRP adhesively bonded joints configurations have been discussed. The authors proposed several new geometrical configurations of composite adhesively bonded joints for which a single failure mechanism may be related to a single (main) stress.

Taib *et al.* (2006) studied the effects of the joint configuration, the adhesive layer thickness, the adherents' stiffness, defects and humidity for various bonded joints between composite laminates. This experimental program has been conducted on four joint configurations: single lap joints, joggle lap joints, double strap joints and L-section joints, respectively. Considering the tensile tests results, the authors concluded that the joints strengths were mainly influenced by the edge conditions and by the relative ductility of the adhesive compared to that of the adherents'.

Lee *et al.* (2009) carried out an experimental study regarding the characterization of the joint strength, failure modes and peel stresses variations for adhesively bonded straps and supported single lap GFRP composite joints. Based on the experimental results it has been concluded that the strength of double strap joints decreases with the adhesive layer thickness. The authors suggested that the optimum adhesive layer thickness should be chosen between 0.2 mm and 0.5 mm, values for which the joint strength is maximized. A major issue for both of the proposed joints configurations was the peel stresses variation. It has been concluded that the peeling effect was crucial for the failure behaviour of the specimens.

Palmieri *et al.* (2013) investigated the effect of laser surface preparation techniques on carbon fibre reinforced polymers (CFRP) composite lap shear specimens. Three series of specimens have been prepared, instrumented and tensile tested: specimens using a peel ply surface treatment, specimens having a laser ablation pattern on the surface and specimens that were laser ablated and aged in a desiccator. The authors concluded that using a laser ablation pre-bonding treatment provides a precise and reproducible surface topography that is suitable in a production environment.

Girolamo *et al.* (2015) carried out both experimental and numerical studies aiming to predict the strength of composite adhesively bonded splice joints under tensile loads. The results that have been obtained through the experimental testing of the specimens were in good agreement with the ones obtained through the numerical analysis of the finite element models and with the ones provided by applying the progressive damage analysis (PDA) method. The authors concluded that the numerical analysis of composite adhesively bonded joints can provide consistent results and reliable predictions on failure loads, displacements and sequence of failure events only if it is correlated with the specimens corresponding modes of failure.

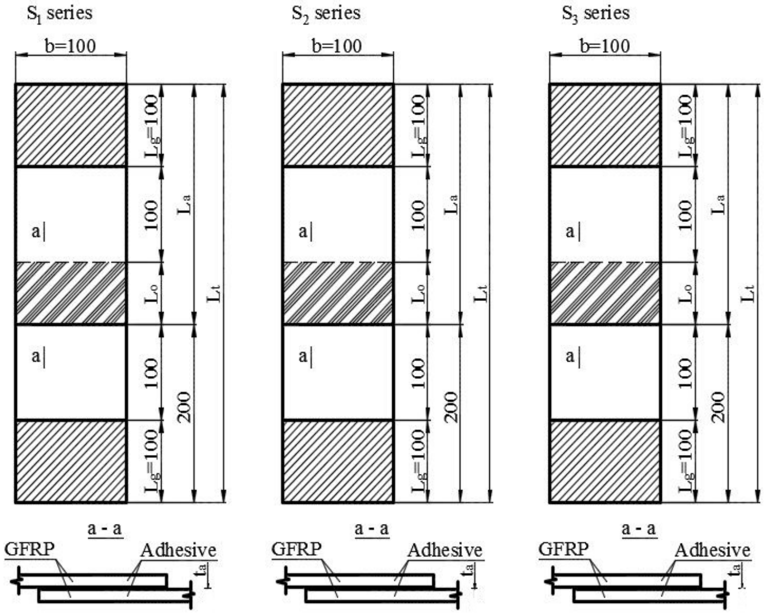
3. Description of the Experimental Program

The proposed experimental program aims to describe the bond mechanisms and the behaviour of GFRP composite elements adhesively bonded joints. Thus, twelve series of adhesively bonded joints have been conceived. Series S_1-S_6 are single lap joints and series S_7-S_{12} are thick adherents lap joints. The geometric characteristics of each series are presented in Figs. 1,...,4.

The specimens from S_4-S_6 series have been prepared using the same geometrical characteristics as for the specimens belonging to S_1-S_3 series. The parameter which differentiates them is the type of the epoxy adhesive: Sikadur 30 for the specimens belonging to S_1-S_3 series and Sikadur 330 for the specimens belonging to S_4-S_6 series.

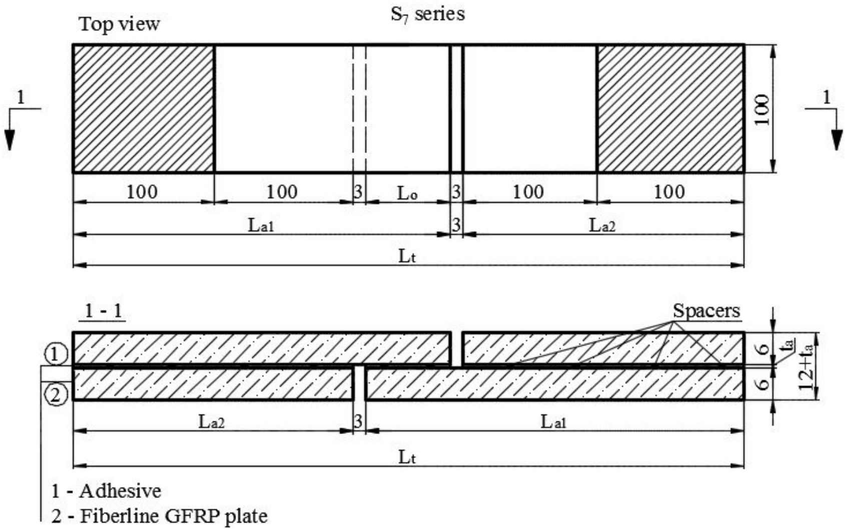
By performing single lap shear pull-of tests on specimens prepared with different types of adhesives and identical geometrical configurations, the influence of the elastic and strength properties of the adhesive on the joint strength can be observed and analysed.

For the same purpose, the specimens from S_{10}-S_{12} series have been designed using the same geometrical characteristics as for the specimens belonging to S_7-S_9 series, but they were prepared using a different type of epoxy adhesive, Sikadur 330.



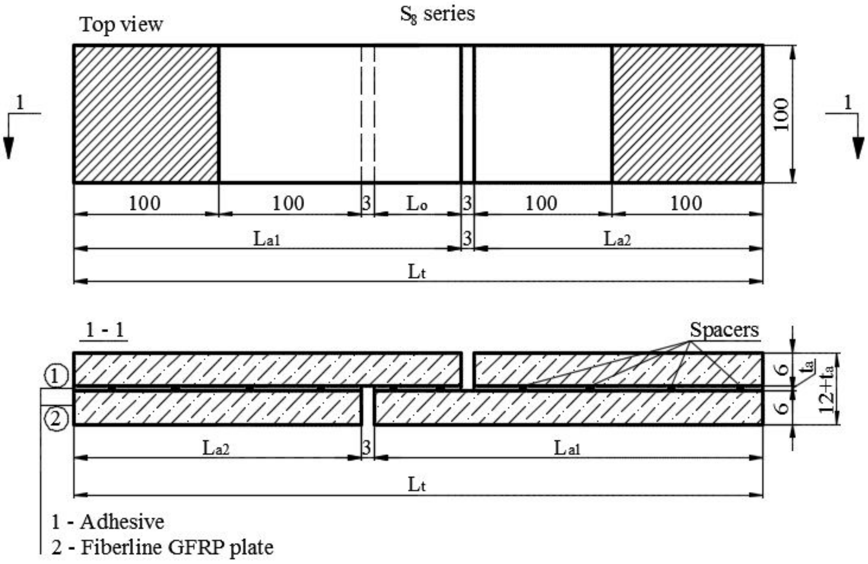
t_a = 1, 2, 3 mm; L_o = 50, 70, 100 mm; L_a = 250, 270, 300 mm;
L_t = 450, 470, 500 mm; Adhesive type: Sikadur 30;

Fig. 1 – Specimens geometry for $S_{1\text{-}3}$ series.



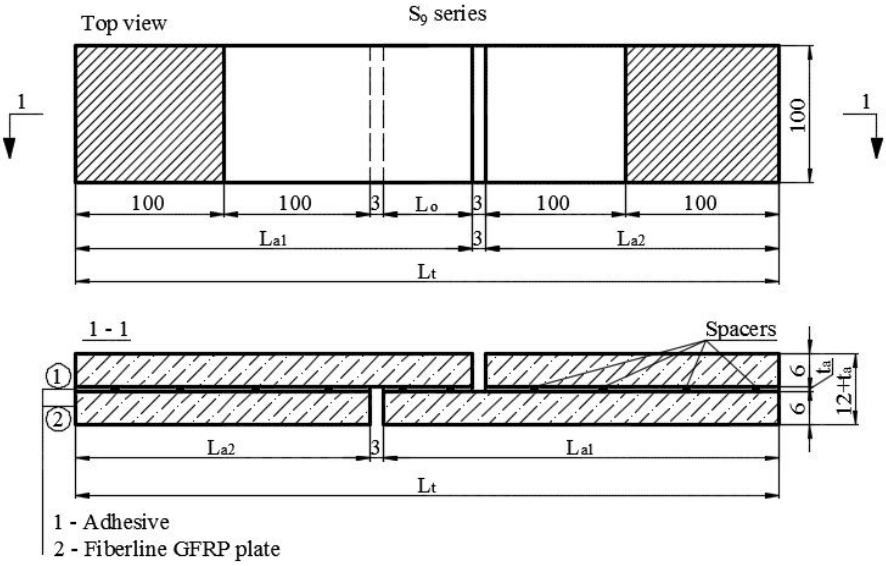
L_o = 50, 70, 100 mm; L_{a1} = 253, 273, 303 mm; L_{a2} = 200 mm;
L_t = 453, 473, 503 mm; t_a = 1mm; Adhesive type: Sikadur 30;

Fig. 2 – Specimens geometry for S_7 series.



L_o = 50, 70, 100 mm; L_{a1} = 253, 273, 303 mm; L_{a2} = 200 mm;
L_t = 453, 473, 503 mm; t_a = 2mm; Adhesive type: Sikadur 30;

Fig. 3 − Specimens geometry for S_8 series.



L_o = 50, 70, 100 mm; L_{a1} = 253, 273, 303 mm; L_{a2} = 200 mm;
L_t = 453, 473, 503 mm; t_a = 3mm; Adhesive type: Sikadur 30.

Fig. 4 − Specimens geometry for S_9 series.

3.1. Materials Properties

The adherents are made of GFRP composite plates from Fiberline (Fig. 5), being 6 mm thick and 100 mm wide. The Fiberline composite profiles are reinforced with E-glass roving with woven and complex mattings. The properties of the GFRP composites plates are presented in Table 1 (for notations Fig. 6).

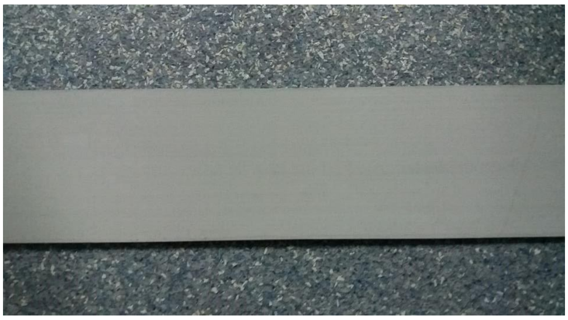


Fig. 5 – GFRP composite plate profile.

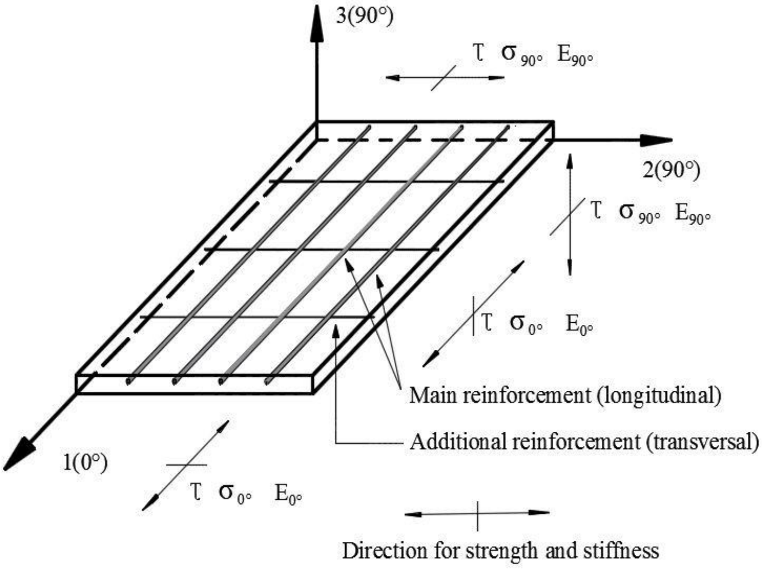


Fig. 6 – Indication of directions for strength and stiffness.

Table 1
The mechanical properties of GFRP composites plates (Fiberline, 2012)

Modulus of elasticity, $E_{0°}$ [MPa]	23000
Modulus of elasticity, $E_{90°}$ [MPa]	8500
Tensile strength, 0°, $f_{t,0°}$ [MPa]	240
Tensile strength, 90°,$f_{t,90°}$ [MPa]	50
Compressive strength, 0°,$f_{c,0°}$ [MPa]	240
Compressive strength, 0°,$f_{c,90°}$ [MPa]	70
Shear strength, f_τ [MPa]	25

The GFRP composites plates have been bonded using two different structural bi-components adhesives, Sikadur 30 and Sikadur 330. The adhesives are made from epoxy resin and the main parameter which differentiates them is the modulus of elasticity which is almost three times higher for the first one when compared to that of the second one. The properties of the adhesives are presented in Table 2.

Table 2
The physical and mechanical properties of the adhesives (Sikadur 30/330 adhesive – Technical sheet)

Adhesive	Density (mixed) [kg/dm^3]	Compressive strength, $f_{c,adh}$ [MPa]	Tensile strength, $f_{t,adh}$ [MPa]	Modulus of elasticity, E_{adh} [GPa]	Elongation at break, $\varepsilon_{u,adh}$ [%]
Sikadur30	1.65	70…80	25…28	12.8	>1.30%
Sikadur330	1.30	75…80	34	4.5	>1.35%

The mechanical properties of the GFRP composites plates and of the adhesives were taken according to the Technical data sheets provided by the local suppliers. The effective mechanical properties determined through the experimental program will be presented in a future work.

3.2. Specimen Preparation

The GFRP composites plates were cut to the specified dimensions using a universal cutting machine equipped with a diamond blade. Adhesively bonded joints required pre-treatment in the overlap region. Thus, prior to bonding, the surface of the GFRP plates was cleaned by solvent whipping, mechanically and hand abraded with sand paper until the fibres were visible and finally cleaned again by solvent whipping.

The bi-component epoxy adhesives were prepared according to the specifications provided in their technical data sheets. The components were mixed in clean and transparent recipients using a special drill at slow speeds (starting from 400 rpm and gradually increasing up to 700 rpm). For each series of specimens, the quantity of the adhesive components was carefully chosen according to the volumetric ratio (1:3 for Sikadur 30 and 1:4 Sikadur 330) and taken into account that the workability period of the adhesive is between 45 and 50 min.

A special attention has been paid to the application of the adhesive on the surface of the GFRP composites plates. For each group of specimens, three adhesive thicknesses were applied. The adhesive layer thicknesses were obtained by fixing spherical steel spacers of 1 mm, 2 mm and 3 mm on the top of the GFRP composites plates. Even if the maximum thickness of the adhesive layer is controlled by the spherical spacers, there still exists the possibility of applying the adhesive in an insufficient quantity. For this reason, a special jig with changeable and adjustable shims was designed. Each GFRP plate has been mounted into the jig fixture and the adhesive was applied in a quantity slightly higher than the nominal one. The excess material was removed by offsetting a linear shim over the bond line area. The bond line thickness of all specimens was nominally controlled both by the spherical spacers and by the changeable shims. After the application of the adhesive, the specimens were fixed with special clamps and stored for 14 days, until the adhesive cured. The jig fixture system is schematically shown in Fig. 7.

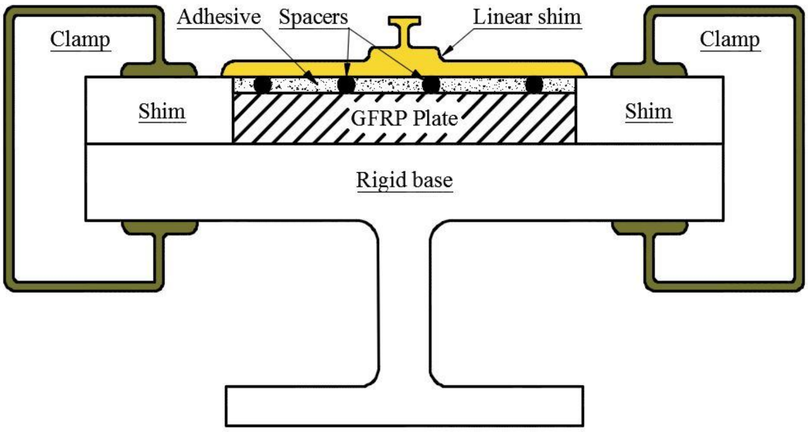


Fig. 7 – Schematic view of the jig and specimen.

For the ease of identification, a nominal code was assessed to each specimen. The code (*i.e.* S1-50-2-II) is referring to the series number, to the overlap length and to the adhesive thickness, respectively. The last digit (I or II), stands for the identification of identical specimens. For these experimental program, 72 specimens have been prepared, consisting in 2 identical specimens for each bonded joint configuration.

3.3. Experimental Procedure

After the adhesive cured, the specimens have been prepared for the loading stage. Strain gauges were installed on the upper side of the GFRP composites plates aiming to measure the strain variation in the overlap area. The application of the strain gauges was realized in laboratory conditions, respecting the specifications provided by the norms and producing company (ASTM D-3039). The wires of the strain gauges were welded and attached at the free end to electrical bridges fixed on the free surfaces of the GFRP composites plates. Using electrical bridges, the connection between the cables of the acquisition system and the cables of the strain gauges is obtained in a simple and easier way. The locations of the strain gauges corresponding to each series geometrical configuration are presented in Figs. 8,...,10.

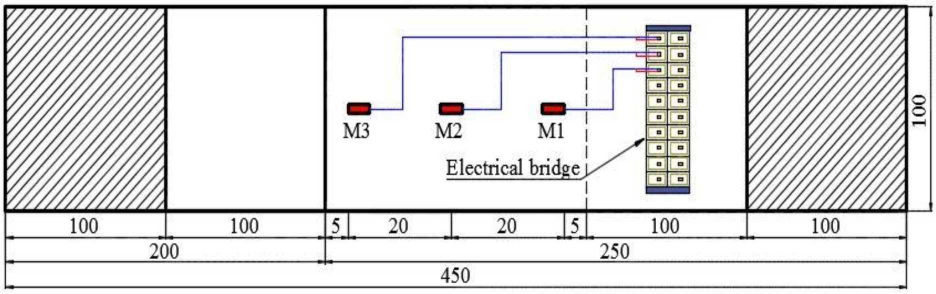


Fig. 8 – Location of the strain gauges for S_1 and S_4 specimens.

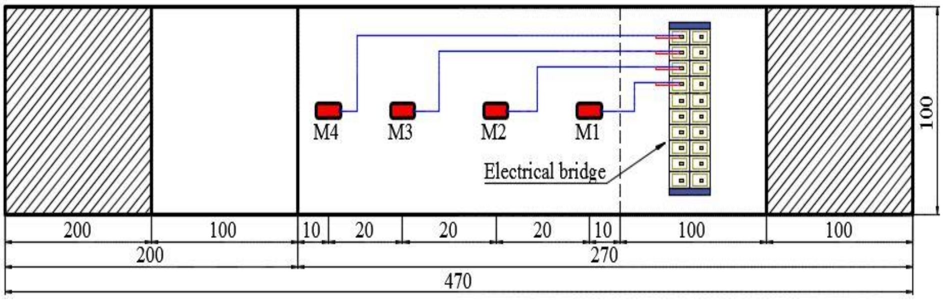


Fig. 9 – Location of the strain gauges for S_2 and S_5 specimens.

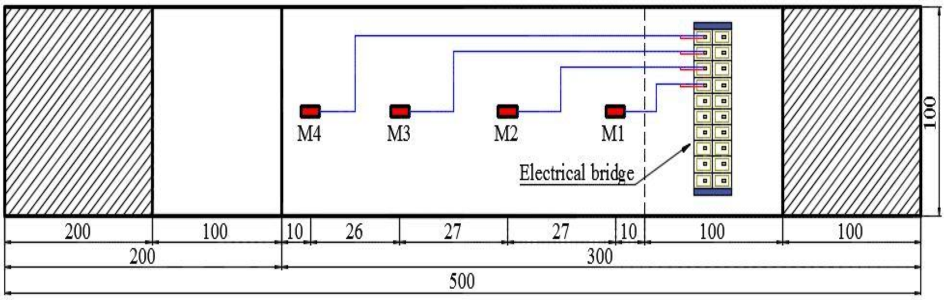


Fig. 10 – Location of the strain gauges for S_3 and S_6 specimens.

Since the thick adherents' joints specimens have been design with the same overlap lengths as the SLJ specimens, 50 mm, 70 mm and 100 mm, respectively, the locations of the strain gauges for S_7-S_{12} specimens are identical as for S_1-S_6 specimens.

The tensile tests on specimens were performed in a ZWICK/ROELL 100 kN test machine (Fig. 11). For monitoring the force applied, the testing machine is equipped with an acquisition board. The experimental tests were force controlled at a 5 kN/min loading speed. Several parameters were monitored during the application of the force: the relative displacement between the GFRP composites plates (measured with a linear variable differential transducer – LVDT), the variation of the applied force and the strain variations (measured by strain gauges).

Fig. 11 – ZWICK/ROELL 100 kN hydraulic test machine.

4. Conclusions

This paper presents the experimental set-up of a study aiming to describe the behaviour of adhesively bonded GFRP composite plates. The preparation and instrumentation of shear pull-off specimens (SLJ and thick adherents' joints) was extensively detailed. The experimental program focuses on the main parameters that characterize the bond behaviour of FRP composite elements: the effective overlap length, the effective adhesive thickness, the distribution of the shear stresses along the bond line, the ultimate load that is carried by the joint and the specific failure mode.

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⁂ *Sikadur 30 adhesive – Technical sheet.*

⁂ *Sikadur 330 adhesive – Technical sheet.*

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COMPORTAREA INTERFEŢEI LA DIFERITE ÎMBINĂRI ADEZIVE ALE MATERIALELOR COMPOZITE

Organizarea programului experimental

(Rezumat)

Se prezintă modul de organizare a programului experimental proiectat în scopul studierii conlucrării materialelor compozite polimerice armate cu fibre de sticlă

(CPAFS) îmbinate folosind adezivi structurali epoxidici. În acest sens, au fost proiectate şi asamblate două tipuri de epruvete. Pentru fiecare tip de epruvetă, s-au realizat câte şase serii de configurații distincte obținute prin selectarea tipului de adeziv, grosimii stratului de adeziv (1 mm, 2mm şi 3 mm) şi lungimii de conlucrare (5 cm, 7 cm şi 10 cm). Prin efectuarea acestui program experimental se pot analiza diferite aspecte specifice ale îmbinărilor adezive practicate materialelor compozite, cum ar fi: descrierea procesului de aderență-lunecare dintre interfețe, identificarea modurilor de cedare specifice, înregistrarea forței ultime la care se produce cedarea îmbinării şi determinarea/verificarea lungimii optime de conlucrare.