COMPORTAREA REGIUNII DE INTERFAȚĂ DINTRE OȚEL ȘI LAMELELE COMPOZITE POLIMERICE ARMATE CU FIBRE DE CARBON LA ÎMBINĂRILE ADEZIVE

BEHAVIOUR OF CFRP-TO-STEEL INTERFACES IN ADHESIVELY BONDED JOINTS

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The interface behaviour of carbon fibre reinforced polymer composite (CFRP) strips bonded to steel surfaces is a key aspect in assuring an efficient strengthening solution for structural or non-structural steel elements.

The experimental program which is presented in this paper was developed at the Faculty of Civil Engineering and Building Services from Iasi, and it focused on the investigation of the behaviour of the CFRP-to-steel bonded interfaces. A number of 25 single lap shear specimens were prepared and tested up to failure. The parameters considered in this study were: the type of the CFRP composite strip, the type of the adhesives and their thicknesses. In addition, the influence of the surface preparation was analysed by comparing the results obtained for specimens with grit-blasted steel surfaces and for untreated ones. The specific failure modes were identified and commented on the basis of the performed tests; the load-displacement curves were plotted and the strain distributions along the bond lengths were investigated at different load stages.

Comportarea regiunii de interfață dintre lamelele compozite polimerice armate cu fibre din carbon (CPAFC) lipite cu adezivi de suprafețele din oțel, reprezintă un factor important în asigurarea unei soluții eficiente de consolidare a elementelor din oțel.

Programul experimental care este prezentat în această lucrare a fost realizat la Facultatea de Construcții și Instalații din Iași și a constat în investigarea comportării regiunilor de interfață dintre oțel și lamelele compozite îmbinate cu adezivi. In acest sens, au fost realizate 25 de probe prin suprapunere simplă și testate până la cedare. Parametrii variabili care au fost analizați în acest studiu sunt tipul lamelei CPAFC precum și tipul și grosimea adezivilor. De asemenea, influența tratării suprafeței de oțel a fost analizată prin compararea rezultatelor obținute pentru suprafețele sablate cu alice și pentru cele netratate. Pe baza testelor efectuate au fost identificate și comentate modurile specifice de cedare; au fost trasate curbele forță-deplasare și s-a studiat distribuția deformațiilor specifice în lungul zonei de îmbinare.

Keywords: *CFRP composite strips, steel, interface behaviour, bonded single lap shear joints*

1. Introduction

Fibre reinforced polymer (FRP) composites are extensively used as strengthening materials for elements made of traditional materials (concrete [1], masonry [2] and timber) as they exhibit superior properties when compared to the classical, long-established rehabilitation or strengthening methods. Some of the most important advantages that are triggered by the use of these materials are: superior strength over specific weight ratio, great durability, superior handling and ease in application. As the industry of FRP composites has recorded substantial growth and developments in the last two decades, new types of materials becoming available on the market, the strengthening solutions of metallic elements based on FRP composite materials have become an attractive option, rising considerable interest from both research communities and field application companies.

Externally bonded FRP hybrid structural systems for steel elements can be divided into two main categories [3], depending on the function of the adhesive layer: bond critical applications where the adhesive layer transfers shear stresses between the steel and the FRP composites, like in the case of flexural strengthened steel beams, and contact critical applications where the adhesive layer is responsible for keeping the steel and the FRP composite elements in contact for an effective transfer of the normal stresses, like in the case of passive steel columns confinement.

A considerable number of research programs have been conducted for bond critical applications of FRP-to-steel systems [3-10], aiming to identify their specific particularities. The experimental analysis of the bonding mechanism and of the

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interfacial behaviour between the adherents has been carried out by applying different specimen configurations and testing methods. The most common ones consist in single or double shear lap tests where the loads are applied directly, to the FRP, or indirectly, to the steel elements [11]. Nevertheless, it has been concluded [12] that the most appropriate method to characterize the bond behaviour of FRP-to-steel interfaces is the single shear pull-off tests, which is also applicable to fatigue tests [13]. The main key parameters that describe the behaviour of such bonded joints are the bond strength and the bond-slip model.

Extensive research has been conducted for the development of suitable bond-slip models, aiming to provide a consistent relation between the local interfacial shear stress and the relative slip between the steel block and the FRP element. The first bond slip model for the CFRP-to-steel bonded joints was developed by Xia and Teng [3] based on the full-range model that had been previously established by Yuan et al. [14] for FRP-to-concrete bonded joints. The simplified shear stress - slip curves have a bilinear shape and the proposed model delivered accurate predictions of the ultimate loads and of the effective bond lengths but only for adhesives with a linear behaviour and for specimens failing cohesively (debonding in the adhesive layer). Aiming to extend the work of Xia and Teng [3], Fernando [6, 15] slightly modified the bond-slip model for adhesives with a linear behaviour and proposed a new model for adhesives that exhibit non-linear behaviour. For the latter, the simplified shear stress – slip curves have a trapezoidal shape due to the plateau of constant shear stresses. To increase the accuracy of the formulas used to predict the key parameters of such bonded joints, other bond-slip and strength models have also been proposed; they have been developed based on the results of complex investigations and parametric studies (experimental, numerical and/or analytical) [16-19]. Even if a relatively large number of bond and strength models are available in the scientific literature, there is still no general acceptance regarding their full validity since the closed-form solutions which are provided for the key parameters are strongly influenced by the thickness and the mechanical properties of the adhesive and by the specific failure modes. Thus, further research and investigations are needed.

This paper describes part of an experimental study performed at the Faculty of Civil Engineering and Building Services of Iasi.

The study included 25 single lap specimens, each of them being composed of a steel element bonded with a CFRP strip. The single shear pull-off test was adopted for these specimens, since it confers good monitoring during the load applying phase and easy inspection of the failure pattern. Each specimen was instrumented so that, the load, the axial strains of the un-bounded part of the CFRP strip and the slip between the adherents could be measured during the tension tests. All specimens were tested up to failure using the load control procedure.

2. Experimental program

The experimental program consists in a series of single shear pull-off tests, aiming to investigate the bond mechanism and the behaviour of such bonded joints [20]. During the design and preparation of the specimens the following parameters were taken as variables: the axial stiffness of the CFRP composite strips, the moduli of elasticity and the thicknesses of the adhesives and the surface preparation method for the steel substrates. Thus, two types of CFRP composite strips were bonded to prepared and unprepared steel surfaces using two types of adhesives, under two different thicknesses. For each combination, at least two identical specimens were prepared (see Table 4).

2.1. Materials properties

The steel plates were made of common carbon steel elements, S235 JR, 10 mm thick, 500 mm long and 120 mm wide. The properties of the steel plates are presented in Table 1. The bonding surfaces of the steel plates for 21 out of a total of 25 specimens were mechanically abraded using 0.18 mm steel grit blasting, in order to avoid the premature adhesion failure of the test samples [21]. The bonding surface of the other 4 steel plates was not mechanically roughened, to identify the surface treatment effect.

Table 1

Properties of the steel plates [22] / *Proprietăţile platbandelor din oţel*

Thickness, t_s [mm]	Width, b_s [mm]	Yielding strength, $f_{y,s}$ [MPa]	Ultimate strength, $f_{u,s}$ [MPa]	Modulus of elasticity, E_s [GPa]	Shear modulus, G_s [GPa]	Poisson's ratio, ν_s
10	120	235	360	210	81	0.3

Table 2

Properties of the CFRP composite strips [23] / *Proprietăţile lamelelor CPAFC*

Type	Thickness, t_{CFRP} [mm]	Width, b_{CFRP} [mm]	Cross sectional area, A_{CFRP} [mm^2]	Longitudinal modulus of elasticity, E_{CFRP} [GPa]	Tensile strength, $f_{t,CFRP}$ [MPa]	Elongation at break, $\varepsilon_{u,CFRP}$ [%]
Sika Carbodur S512	1.2	50	60	165	3100	> 1.30%
Sika Carbodur M514	1.4	50	70	210	3200	> 1.35%

Table 3

Properties of the adhesives [25,26] / *Proprietăţile adezivilor*

Type	Density [kg/dm^3] (mixed)	Compressive strength, $f_{c,a}$ [MPa]	Tensile strength, $f_{t,a}$ [MPa]	Modulus of elasticity, E_a [GPa]	Elongation at break, $\varepsilon_{u,adh}$ [%]
Sikadur 30	1.65	70-80	25-28	12.8	1%
Sikadur 330	1.30	75-80	34	4.5	0,9%

Since the axial rigidity of the CFRP composite strip is an important parameter in this study, two types of strips were selected having different longitudinal moduli of elasticity. Their geometrical and mechanical properties are presented in Table 2. According to the provided technical sheet [23], the minimum carbon fibre volume fraction is 68% which is constantly distributed along the longitudinal direction of the composite element [24].

The CFRP composite strips were bonded to the steel surfaces using two different bi-component, epoxy adhesives, with linear behaviour, Sikadur 30 and Sikadur 330. Table 3 presents the physical and mechanical properties of the adhesives [25, 26] utilized in the present study. It can be seen that the modulus of the elasticity of Sikadur 30 is almost three times higher than the one of Sikadur 330 while the tensile strengths and the ultimate strains have similar values.

2.2. Preparation of the specimens

Prior to the joining stage, the bonding surface of the steel plates was cleaned with solvents (acetone and alcohol), to remove any grease and pollutants, and sandblasted with 0.18 mm steel grit. After the sandblasting, the surface of the steel was vacuumed and wrapped in a plastic foil, to prevent future contamination. Only 4 steel plates were not sandblasted, aiming to identify the effect of this surface treatment method.

The CFRP composite strips were cut 550 mm in length, using a special diamond blade machine. Before bonding, the surface of the CFRP composite strips was cleaned with Sika ColmaCleaner solvent. Since the full range behaviour of the joints was to be analysed, the bond length was taken 350 mm, higher than the effective one (evaluated according to the strength models given by [3], [14], [15] and [27]).

24 hours after the surface preparation of the steel plates, the CFRP composite strips were bonded. The bi-component adhesives were mixed at 400-600 rpm, in clean recipients, according to the specifications presented in their technical data sheets, with volumetric ratios of 1:3 for Sikadur 30 and 1:4 for Sikadur 330. For each set of specimens, the quantity of mixed adhesive was chosen according to its optimum workability interval, which is about 45-50 minutes. For every combination of CFRP composite strip – adhesive type, two thicknesses of 1 mm and 2 mm have been assigned.

Usually, the obtaining of the designed adhesive thickness is a difficult stage in the preparation of the specimens. For this reason, a combined method has been applied for this study. Firstly, steel bearing balls of 1 mm and 2 mm, respectively, were fixed to the steel plate. Since the adhesive layer is initially spread on the CFRP composite strip and then attached to the steel plate, it is difficult to control the optimum quantity of the adhesive. Thus, if an insufficient quantity is applied, the bond might be inconsistent while if there is too much adhesive on the strip, the excess might squeeze during the roll-pressing stage and it would become difficult to be eliminated. For this reason, a special rig was designed, being composed of a rigid steel base on which steel strips are fixed at 50 mm clear distance (equal to the width of the CFRP strips). The thickness of the first set of steel strips was 1.3 mm and 1.5 mm, respectively, being only 0.1 mm thicker than the corresponding CFRP composite strips. The thickness of the second set of steel strips was 1 mm and 2 mm, being equal to the designed adhesive layer thickness. By using this method, when the adhesive was applied on the CFRP composite strip, its thickness was only 0.1 mm larger than the designed one, leading to an optimum fill of the bond surface and to a minimum quantity of excess during the roll pressing stage. The rig is presented in Figure 1.

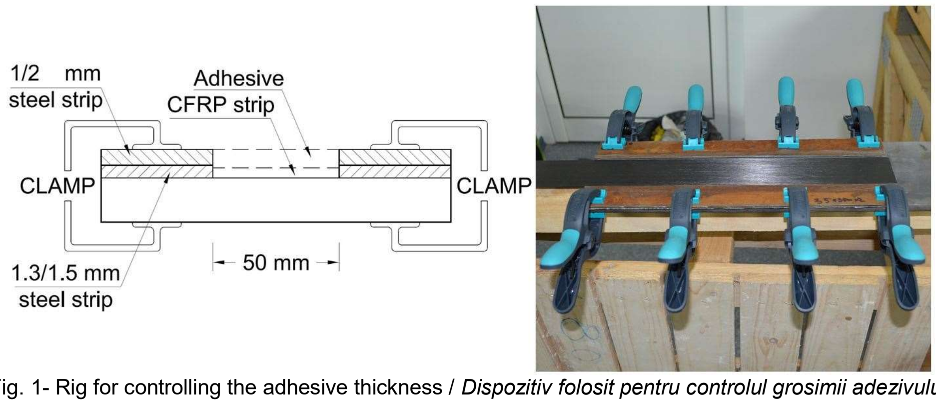


Fig. 1- Rig for controlling the adhesive thickness / *Dispozitiv folosit pentru controlul grosimii adezivului.*

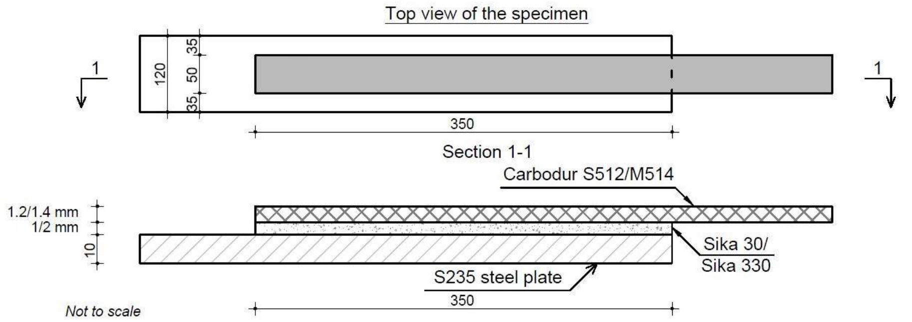


Fig. 2 - General configuration of the specimens / *Configurația generală a probelor.*

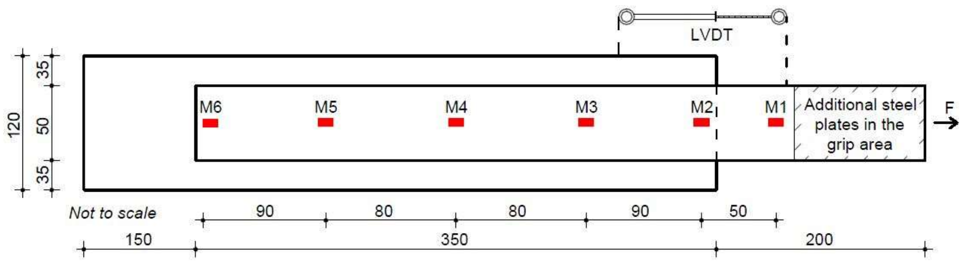


Fig. 3 - Specimen instrumentation with strain gauges and LVDT / *Instrumentarea probelor cu mărci tenometrice și traductori de deplasare.*

The CFRP composite strips have been attached to the steel plates, ensuring the 350 mm bond length, fixed with clamps and stored in laboratory conditions for 14 days until the adhesive cured completely.

Each specimen received a code (i.e. S1 – S512-30-1-I), indicating the type of CFRP composite strip, the type of adhesive and its thickness. The last term stands for identifying specimens with the same configuration. The general layout of the specimens is presented in Figure 2.

2.3. Instrumentation and loading procedure

Strain gauges were attached on the top surface of the CFRP composite strip since the state of stress in the mid-plane of the adhesive layer cannot be recorded. Five of them were glued above the bond length and one on the un-bounded region of the CFRP composite strip. The latter provided information regarding the state of stress outside the bonded area. The displacements between the adherents have been monitored using a LVDT installed at the loaded end of the specimen. The instrumented configuration of the specimens is presented in Figure 3.

The specimens were subjected to direct tension, applied at the free end of the CFRP composite strip, in a Zwick/Roell 1000 kN hydraulic test machine, located at the Faculty of Civil Engineering and Building Services, Iasi. The force controlled loading rate was set for 5 kN/min so that, the strain variations along the bond length could be accurately registered. During de application of the force, the following parameters were monitored and recorded, using a data acquisition system: the force, the relative displacement between the steel plate and the CFRP composite strip and the strain variation at the top surface of the composite strip. In order to improve the clamping in the grips of the testing machine, steel plates have been attached to the free end of the CFRP composite strip. Also, to compensate the offsets between the top and bottom parts of the specimens, which appeared as a result of the single lap joint configuration, metallic plates of various thickness were added in the grip area.

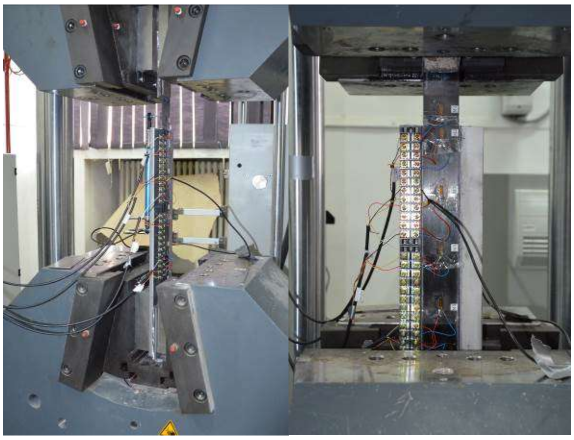


Fig. 4 - Specimens fixed in the testing machine / *Probele fixate în mașina de încercat.*

3. Experimental results

Table 4 summarizes the characteristics of the specimens, the ultimate loads and the failure modes.

The typical failure modes in an FRP bonded steel system that is subjected to tensile forces are illustrated in Figure 5. When compared to similar systems but with concrete substrates, the FRP

Table 4

Specimen details, ultimate loads and failure modes / *Detalierea probelor, forțele ultime și modurile de cedare*

Type	Adhesive Type	Adhesive thickness, t_a [mm]	CFRP elastic modulus, E_{CFRP} [GPa]	Adhesive tensile strength, $f_{t,a}$ [MPa] *mean value	Adhesive modulus of elast., E_a [GPa]	Ultimate load, P_{ult} [kN]	Failure mode
S1 – S512-30-1-I	Sika 30	1	165	26.5	12.8	42.10	C+D
S2 – S512-30-1-II	Sika 30	1	165	26.5	12.8	38.30	C+D
S3 – S512-30-1-III	Sika 30	1	165	26.5	12.8	39.40	C+D+SAI
S4 – S512-30-2-I	Sika 30	2	165	26.5	12.8	37.85	C+SAI+D
S5 – S512-30-2-II	Sika 30	2	165	26.5	12.8	38.65	C+D
S6 – S512-30-2-III	Sika 30	2	165	26.5	12.8	34.87	C+CAI+D
S7 – S512-330-1-I	Sika 330	1	165	34	4.5	74.80	CAI
S8 – S512-330-1-II	Sika 330	1	165	34	4.5	78.80	CAI
S9 – S512-330-1-III	Sika 330	1	165	34	4.5	48.00	D+CAI
S10 – S512-330-2-I	Sika 330	2	165	34	4.5	70.20	CAI
S11 – S512-330-2-II	Sika 330	2	165	34	4.5	61.25	CAI+SAI
S12 – M514-30-1-I	Sika 30	1	210	26.5	12.8	22.41	D+SAI
S13 – M514-30-1-II	Sika 30	1	210	26.5	12.8	51.06	C+CAI+D
S14 – M514-30-1-III	Sika 30	1	210	26.5	12.8	46.55	C+CAI+D
S15 – M514-30-2-I	Sika 30	2	210	26.5	12.8	10.00	D+C
S16 – M514-30-2-II	Sika 30	2	210	26.5	12.8	42.85	C+D
S17 – M514-330-1-I	Sika 330	1	210	34	4.5	80.80	SAI+CAI+D
S18 – M514-330-1-II	Sika 330	1	210	34	4.5	99.25	CAI
S19 – M514-330-1-III	Sika 330	1	210	34	4.5	85.00	CAI+SAI
S20 – M514-330-2-I	Sika 330	2	210	34	4.5	56.90	CAI+D
S21 – M514-330-2-II	Sika 330	2	210	34	4.5	53.35	CAI
S22NS – S512-30-1-I	Sika 30	1	165	26.5	12.8	32.10	SAI
S23NS – S512-30-1-II	Sika 30	1	165	26.5	12.8	31.50	SAI+CAI
S24NS – M514-330-1-I	Sika 330	1	210	34	4.5	54.05	CAI+SAI
S25NS – M514-330-1-II	Sika 330	1	210	34	4.5	50.60	CAI+SAI
Failure modes: Steel yielding (Y); Steel-adhesive interface debonding (SAI); Cohesive adhesive layer failure (C); CFRP-adhesive interface debonding (CAI); FRP Delamination (D); FRP Rupture (R).							

bonded steel ones develop substantial different failure modes. In case of concrete, the most common one is the debonding of the FRP plate with a thin layer of the exterior concrete layer [28], because of the brittle nature and low tensile strength of concrete. This failure mode is not specific for the case of steel substrates due to its high tensile and shear strengths.

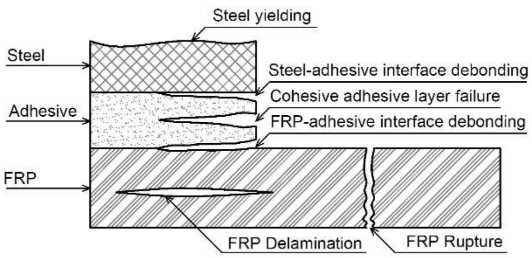


Fig. 5 - Typical failure modes (adapted from [10]) / *Moduri tipice de cedare.*

By investigating the specimens after the pull-off tests, it has been concluded that only 6 of them failed in a single mode, by debonding either at the CFRP-adhesive interface or at the steel-adhesive interface while the others failed under combined modes. For the latter, the dominant failure modes are enumerated first in the corresponding cells in Table 4. Figure 6 presents some of the specimens after failure. For specimens bonded with Sika 30 adhesive, the dominant failure mode was the cohesive one while for those bonded with Sika 330 adhesive, the interface debonding, mostly between the CFRP strip and the adhesive, was the principal failure mode. Since the bond length was larger than the optimum one, for most of the specimens, but especially for those with a cohesive dominant failure mode, the failure mechanism initiated at the loaded end and propagated gradually towards the opposite one. Usually, the final failure of the bond triggered the other, non-dominant, failure modes which proved to be either delamination of the CFRP strip or interface debonding. These secondary failure modes occurred due to the high concentrations of peeling stresses at the free end of the bonded joint and because of the minor eccentricities that occur in alignment of the specimen.

The last four specimens, for which the steel surface was not mechanically treated (i.e. grit blasted), failed only by interface debonding, especially between the steel and the adhesive, at lower ultimate loads when compared to the specimens having identical configurations but mechanically treated steel surfaces. This fact indicates that by increasing the roughness of the steel surface the mechanical bonding between the steel and the adhesive will be improved, leading to a higher bond strength.

Figure 7 shows the load-displacement curves for some representative specimens. The specimens for which the dominant failure mode was the cohesive one (S1-5, S16), had a ductile behaviour, with long deformation plateaus.

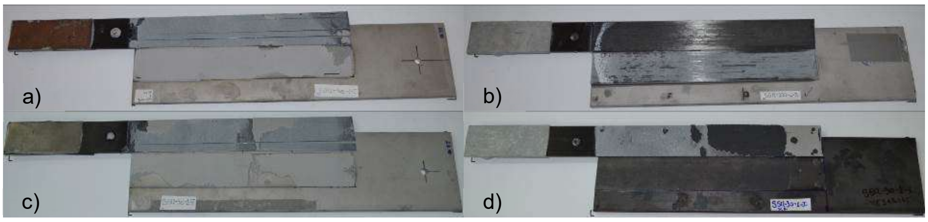


Fig. 6 - Examples of failure modes / *Exemple ale modurilor de cedare:*
a) Cohesive failure + CFRP Delamination (Specimen 1) / *Cedare coezivă + delaminare CPAF (Proba 1)*
b) CFRP-adhesive interface debonding (Specimen 7) / *Cedare la interfaţă CPAF-adeziv (Proba 7)*
c) Cohesive failure + CFRP delamination + steel-adhesive interface debonding (Specimen 3) / *Cedare coezivă + delaminare CPAF + cedare la interfaţa oţel-adeziv (Proba 3)*
d) steel-adhesive interface debonding (Specimen 22) / *Cedare la interfaţa oţel-adeziv (Proba 22)*

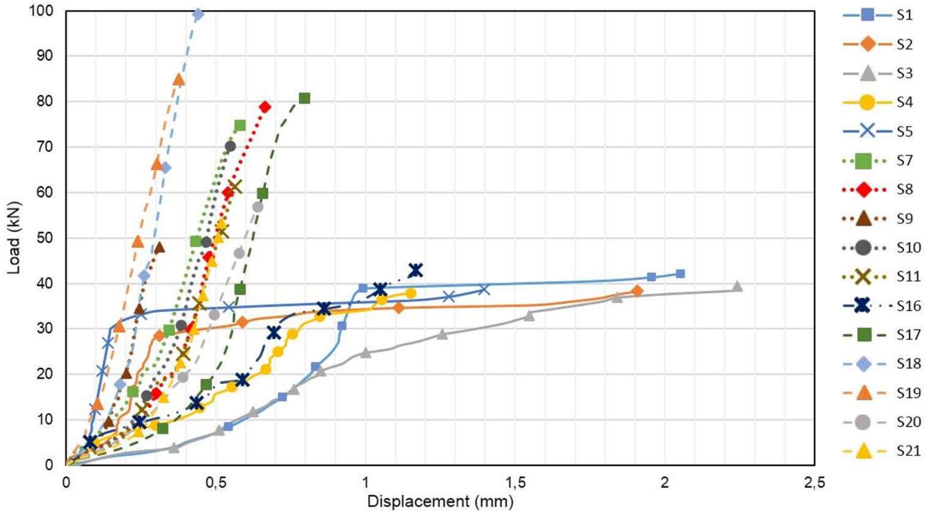


Fig. 7 - Load – Displacement curves / *Grafice forţă – deplasare.*

The progressive failure mechanism, under the form of crack initiation and propagation, is shown by the numerous small discontinuities in the values of the displacements. In the same time, this pattern is also caused by the intermediate delamination of the CFRP strip. Because all specimens that failed cohesively were bonded with Sika 30, the ultimate loads had closed values.

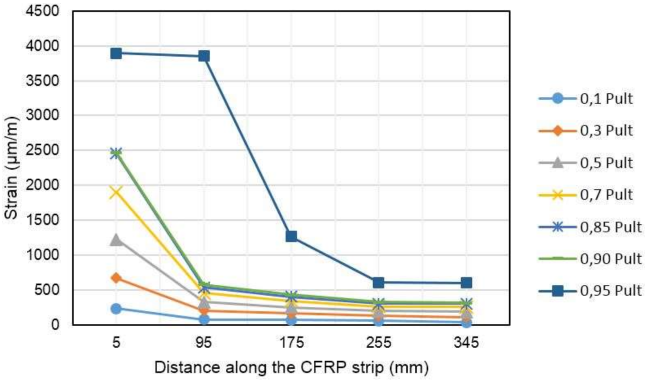
For the other specimens presented in Figure 7, which mostly failed by debonding at the CFRP-adhesive interface, the behaviour was noticeably brittle. None of them exhibited any deformation plateaus and the rare discontinuities in the values of the displacements are caused by the delamination of the CFRP strips.

It can be seen that by increasing the axial stiffness of the CFRP strip, the initial stiffness of the specimen is also increased, especially in the case of joints bonded with Sika 330 adhesive. In contrasts, specimens with adhesive thicknesses of 2 mm experience slight losses of the initial stiffness, when compared to the ones with 1 mm adhesive thickness.

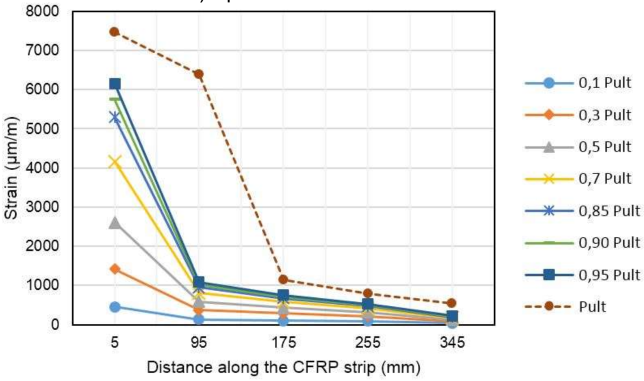
When comparing the ultimate tensile forces, it is clear that the highest values have been obtained for the specimens bonded with Sika 330 adhesive, which failed by interface debonding. However, these values cannot be used in the evaluation of the bond strength since the failure was not governed by the adhesive (like in cohesive failure). For specimens with the same type of adhesive it resulted that an increase of the axial stiffness of the CFRP strip usually leads to an increase of the ultimate tensile load. Further, when the thickness of the adhesive is increased form 1 mm to 2 mm, decreases of the ultimate tensile loads have been observed.

For the last four specimens (S21-S23) whose bonding surface was not mechanically treated, the ultimate tensile forces were smaller than the corresponding ones of the sandblasted specimens. Hence, the validity of this surface treatment method is confirmed again.

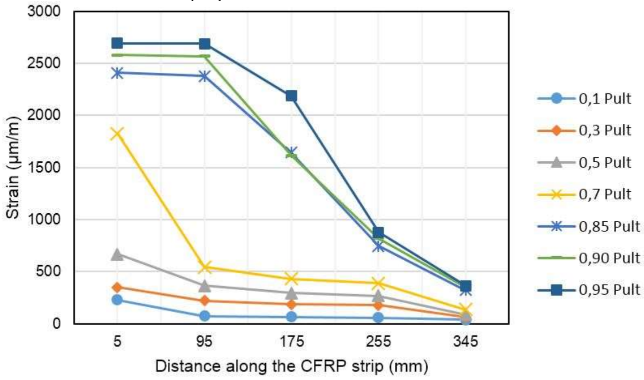
Figure 8 presents the variation of the strains along the bond length, starting from the loaded end (before strain gauge M2 as presented in Figure 3), at different values of the axial force for four different types of specimens. It can be seen that for the ones bonded with Sika 30 and thus failing cohesively (S1 and S16), the progressive failure mechanism is confirmed. The strains are developed on a sufficient large area and close to the failure load, amplifications of the strain were recorded near end of the bond length. In contrast, for the specimens bonded with Sika 330 and thus failing at the interface, for specimen 8, the strains were concentrated only in the first part of the bond length almost until the brittle failure occurred while for specimen 20, the distribution was developed on a larger area since the overall stiffness was smaller.



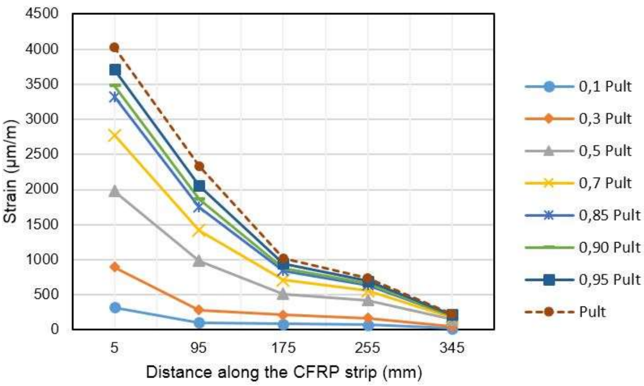
a) Specimen 1 – S512-30-1-I



b) Specimen 8 – S512-330-1-II



c) Specimen 16 – M514-30-2-II



d) Specimen 20 – M514-330-2-II

Fig. 8 - The strain distribution along the bond length at different values of the axial force / *Distribuția deformațiilor specifice în lungul zonei de îmbinare la diferite valori ale forței axiale.*

4. Conclusions

This paper presents and comments the results of an experimental program organized to investigate the bond mechanism and behaviour of single shear CFRP composite strips adhesively bonded to steel elements. The main variables in the configuration of the specimens were the adhesive type and its thickness as well as the axial stiffness of the CFRP composite strips. Based on the results and discussion presented in the paper, the following conclusion can be summarized:

- The ultimate tensile forces recorded for the specimens bonded with Sika 330 adhesive were higher than those of the corresponding specimens bonded with Sika 30. Nevertheless, the ultimate tensile forces of the specimens that did not failed cohesively cannot be used in the evaluation of the bond strengths since it is not an adhesive dependant failure mode.

- Generally, the initial stiffness of the specimen increases with the axial stiffness of the CFRP composite strip and decreases when the thickness of the adhesive layer increases;

- The distribution of the strains along the bond length confirmed the ductile behaviour of the specimens failing cohesively and the brittle one of those failing by interface debonding.

- The mechanical treatment methods (i.e. grit blasting) increase the roughness of the steel bond surface thus leading to stronger mechanical bonding between the steel and the adhesive. Weak mechanical bonds between the latter produce premature interface debonding.

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MANIFESTĂRI ȘTIINȚIFICE / SCIENTIFIC EVENTS

CDCC 2017
The Fifth International Conference on Durability of Fiber Reinforced Polymer (FRP) Composites for Construction and Rehabilitation of Structures, 19-21 July 2017, Sherbrooke, Quebec, CANADA

The conference will focus on durability of Fiber Reinforced Polymer (FRP) composites for construction and rehabilitation of structures with these materials. Undoubtedly, durability is the key element for successful application of FRP composites in construction where life cycle cost has, by large, proven to be the most important issue for new construction materials.

Topics:

- Effect of resins and fibers on the durability of FRP
- Effect of environment on the durability of FRP bars,
- repair patches, and shapes
- Degradation mechanisms of FRP in concrete
- Durability of FRP-concrete bond
- FRP reinforcement under cyclic and sustained loading
- Material resistance factors and design criteria for durability
- Durability of Glass FRP and Basalt FRP bars
- GFRP bent bars durability
- Fire and thermal cycling
- Durability of FRP-reinforced concrete structures and bridges
- Durability of concrete/steel/wood structures externally reinforced with FRP
- Durability of FRP composite bridge decks
- Durability of FRP in submerged environment
- Durability test methods
- Durability data from field studies
- Monitoring durability performance in field applications
- Prediction of long-term durability and modelling
- Design approaches for durable FRP structures
- Service life prediction and life cycle cost

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