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FAILURE PARTICULARITIES OF ADHESIVELY BONDED JOINTS BETWEEN STEEL AND CARBON FIBRE REINFORCED POLYMERS COMPOSITE ELEMENTS

BY

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Abstract. One of the most recent development directions of composite materials that are used in the civil engineering industry consists in applying these materials in the strengthening applications of metallic elements. This paper presents some particularities of the failure process for adhesively bonded joints between carbon fibre reinforced polymers (CFRP) composite products and steel elements. The specific outcomes presented in this paper are part of the results obtained by carrying out a complex experimental program at the Faculty of Civil Engineering and Building Services of Iaşi, which focused on the bond behaviour between CFRP composite products and steel.

Keywords: CFRP-to-steel adhesive bonds; single lap shear joints; bond behaviour; failure mechanism.

1. Introduction

Using the fibre reinforced polymer (FRP) composite materials in strengthening applications of metallic elements is one of the most recent areas of development for the composite materials industry oriented to the field of civil engineering. Being a relatively recent area of research and application, the

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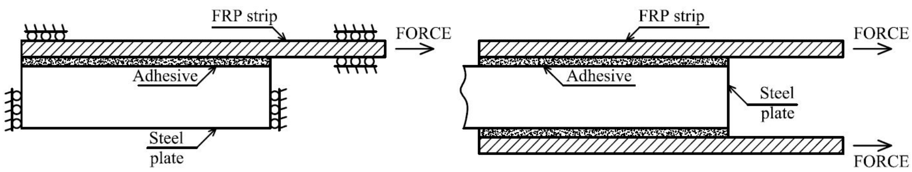
number of metallic constructions that have been strengthened with FRP composite materials is not very large (Zhao, 2014). Nevertheless, multiple research programs have been conducted so far in this field, aiming to investigate various aspects related to the efficiency of strengthening steel elements with FRP composite materials, such as: improving the flexural capacity of beams with I-shaped cross-sections (Shulley *et al*., 1994; Gillespie *et al*., 1996; Patnaik & Bauer, 2004; Haedir *et al*., 2009; Elchalakani and Fernando, 2012) or with composite cross-sections (Sen *et al*., 2001; Schnerch, 2005; Teng & Hu, 2007), improving the local or general stability of members subjected to compression (Shaat & Fam, 2006; Wu *et al*., 2012) or enhancing the fatigue response (Mosallam *et al*., 1998; Tavakkolizadeh & Saadatmanesh, 2003).

Usually, strengthening applications consist in attaching the CFRP composite elements on the faces of the steel member. Most of these connections are obtained by bonding the adherents with appropriate structural adhesives that have two main functions: keeping the bonded elements in contact and transferring the stresses. Thus, the adhesive layer has a critical function and the bond behaviour between the steel member and the composite element represents a key parameter that has a major impact upon the general performances of the strengthening process.

In case of applications where the adhesive layer is responsible for transferring the stresses between the elements of the joint, keeping the bonded elements in firm contact is a basic condition. The research programs that have been carried out to investigate the bond behaviour of FRP-to-steel connections (Xia & Teng, 2005; Fernando, 2010; Bocciarelli *et al*., 2007) revealed that the most efficient method consists in analyzing simplified bond configurations. Thus, the suitable configurations that can be used are the single lap (Fig. 1 *a*) or double lap (Fig. 1 *b*) shear joints between steel plates and composite strips. Usually, the tensile load is applied at the free end of the composite strip, producing a shear effect in the adhesive layer.



a *b*

Fig. 1 – Lap shear joints: *a* – single (Xia and Teng, 2005; Fernando, 2010, Chiew *et al.*, 2011; Ceroni *et al.*, 2016); *b* – double (Hart-Smith, 1973; Castro & Keller, 2008).

The key parameters that describe the bond behaviour in these configurations are: the ultimate force (P_u) that corresponds to the final failure of the system, the effective bond length (L_e) that defines the overlapping length that even if it is exceeded it does not produce any increase in the bond strength, the shear stresses (τ, τ_{max}) that are the most important stress components in the adhesive layer, the slip (δ) between the steel and composite surfaces and the interfacial fracture energy (G_f) equal to the area described by the bond-slip curve.

2. Failure Modes of the FRP-to-Steel Adhesively Bonded Joints

The characteristic failure modes of the FRP-to-steel adhesively bonded joints represent a critical set of factors in the evaluation of these systems. Moreover, if the failure process cannot be controlled, the efficiency and the utility of these joints are strongly reduced (Lupăşteanu, 2016). The failure mechanism was studied by multiple research teams that carried out complex experimental programs and performed extended numerical or analytical simulations (Xia & Teng, 2005; Fernando, 2010; Ceroni *et al.*, 2016). In order to thoroughly understand and describe the failure process, the bond configurations consisted of simple or double lap shear joints. The specific failure modes of the FRP-to-steel adhesively bonded joints are graphically presented in Fig. 2 (adapted from Zhao, 2014).

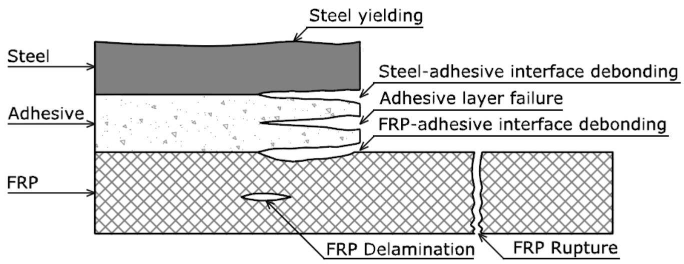


Fig. 2 – Failure modes for FRP-to-steel adhesively bonded joints.

3. Experimental Set-Up

In order to study the bond behaviour of adhesively bonded joints between steel elements and composite products a complex experimental program was carried out (Lupăşteanu *et al.*, 2015). One of the main objectives of the experimental program consisted in investigating the specific failure modes of these types of joints and, in particular, correlating the failure mechanism with the mechanical and geometrical properties of the constituents. 34 samples composed of carbon fibre reinforced polymer (CFRP) strips adhesively bonded to the surface of steel plates were prepared, obtaining a single lap configuration. In order to achieve experimental results with an increased degree of accuracy, two types of CFRP strips and two categories of adhesives were selected. Each type of adhesive was applied in three different thicknesses, of 1, 2 and 3 mm. The steel class and the bond length were not considered as variables; therefore they were kept constant for all samples. The most important properties of the materials used for assembling the samples are presented in Table 1 and the geometrical configuration of the single-lap joints is illustrated in Fig. 3.

Table 1

Properties of the materials

Steel plates (according to SR EN 1993-1-1:2006)				
Steel class	Dimensions, l × b × t [mm]	Yielding strength, f_y [MPa]	Ultimate tensile strength, f_u [MPa]	Young's modulus, E [GPa]
S235JR	500 × 120 × 10	235	360	210
CFRP strips (according to Technical Sheet Sika CarboDur, 2008)				
Type	Cross-sectional area [mm^2]	Tensile strength, $f_{t,\mathrm{CFRP}}$ [MPa]	Young's modulus, E_{CFRP} [GPa]	Ultimate strain [%]
Sika Carbodur S512	1.2 × 50 = 60	3,100	165	> 1.30
Sika Carbodur M514	1.4 × 50 = 70	3,200	210	> 1.35
Adhesives (according to Technical Sheet Sikadur 30 – 2008, Sikadur 330 – 2006)				
Type	Density [kg/l]	Tensile strength, $f_{t,a}$ [MPa]	Young's modulus, E_a [GPa]	Ultimate strain [%]
Sikadur 30	1.65	25,...,28	12.8	1
Sikadur 330	1.31	30	4.5	0.9

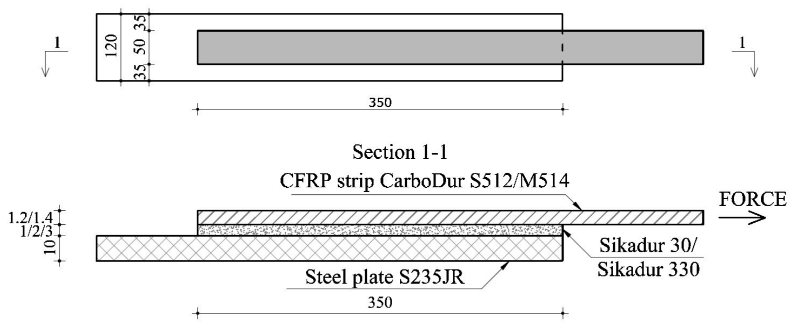


Fig. 3 – Configuration of the samples.

For each combination between the CFRP strip type, adhesive type and thickness, two or three identical samples were prepared. Thus, a total number of

30 samples were obtained. For each steel plate, the contact surface had been prepared before bonding by blasting with metallic grit, air blasting to remove contaminants and solvent cleaning. Moreover, four distinct samples were prepared without blasting the steel surface with metallic grit to identify the differences that come from this surface treatment method.

All samples were loaded in tension until failure, which was applied at the free end of the CFRP strip. The single lap joints were instrumented in such a way that, during the loading stage, the following parameters could be recorded: the tensile loads, the slips between steel plates and CFRP strips and the strain variations along the bond length.

4. Experimental Results – Failure Particularities

The investigation of the failure mechanism consisted in recording the patterns of the failure initiation and propagation during the loading stage and analysing the interfaces after the final failure had occurred. The following failure modes were identified:

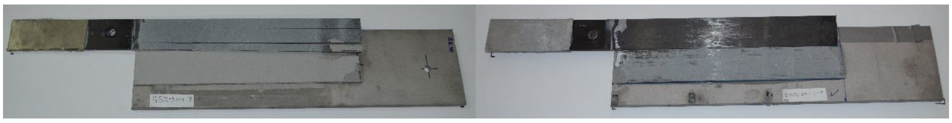
– cohesive failure, due to the shear effect in the adhesive layer (C);
– debonding, at the steel-adhesive interface (SAI);
– debonding, at the CFRP-adhesive interface (CAI);
– delaminations of the CFRP strip (D).

Table 2
Failure modes

Sample	Failure mode	Sample	Failure mode
1. S-S512-30-1-I	C+D	2. S-S512-30-1-II	C+D
3. S-S512-30-1-III	C+D+SAI	4. S-S512-30-2-I	C+D+SAI
5. S-S512-30-2-II	C+D	6. S-S512-30-2-III	C+D+SAI
7. S-S512-330-1-I	CAI	8. S-S512-330-1-II	CAI
9. S-S512-330-1-III	CAI+D	10. S-S512-330-2-I	CAI
11. S-S512-330-2-II	CAI+SAI	12. S-M514-30-1-I	C+SAI
13. S-M514-30-1-II	C+CAI+D	14. S-M514-30-1-III	C+CAI+D
15. S-M514-30-2-I	C+D	16. S-M514-30-2-II	C+D
17. S-M514-330-1-I	SAI+CAI+D	18. S-M514-330-1-II	CAI
19. S-M514-330-1-III	CAI+SAI	20. S-M514-330-2-I	CAI+D
21. S-M514-330-2-II	CAI+SAI	22. S-S512-30-3-I	C+D+SAI
23. S-S512-30-3-II	C	24. S-S512-30-3-III	C+D
25. S-S512-330-3-I	CAI+D	26. S-S512-330-3-II	CAI
27. S-M514-30-3-I	C+D+SAI	28. S-M514-30-3-II	C+D
29. S-M514-330-3-I	CAI+D+SAI	30. S-M514-330-3-II	CAI+SAI
31. NS-S512-30-1-I	C+IAO	32. NS-S512-30-1-II	C+SAI
33. NS-M514-330-1-I	SAI+CAI	34. NS-M514-330-1-II	SAI+CAI

Table 2 presents the failure modes for each of the 34 specimens that were tested. In case of multiple failure modes, the dominant mode is listed first, being followed by the secondary ones which, in most cases, had a local effect. The codes of the samples correspond to the degree of surface treatment of the steel plate (grit-blasted or not grit-blasted), the type of CFRP strip, the type of adhesive and its thickness, respectively.

Fig. 4 displays some of the samples after the final failure took place, whereas Fig. 5 presents a statistical interpretation of the failure modes with respect to the two types of adhesives, Sikadur 30 and Sikadur 330.



Sample 2 S-S512-30-1-II - C+D   Sample 11 S-S512-330-2-II - IAC+IAO

Sample 14 S-M514-30-1-III – C+CAI+D   Sample 33 NS-M514-330-1-I – SAI+CAI

Fig. 4 – Failure surfaces of the specimens.

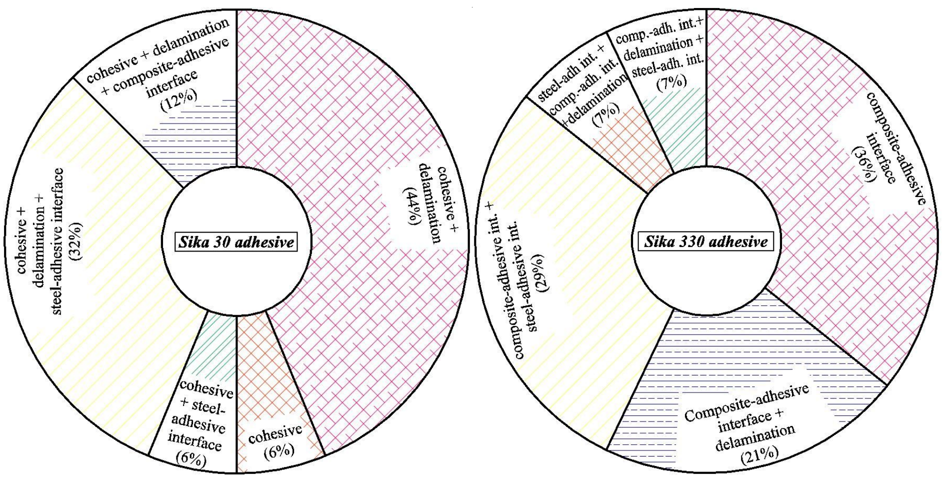


Fig. 5 – Failure modes with respect to the adhesive type.

5. Conclusions

All 34 specimens developed failure modes that correspond to the ones that had been previously identified in other similar experimental programs (Xia & Teng, 2005; Fernando, 2010; Zhao, 2014; Ceroni *et al*., 2016). Only 6 specimens failed under a single mode, while the other 28 developed combined failure patterns. However, the specimens that failed under combined modes were characterized by a dominant pattern and the secondary ones occurred locally.

For the samples that were bonded with Sikadur 30 adhesive, the predominant failure mode was the cohesive one, being characterized by the shear failure of the adhesive. The cohesive failures occurred in a progressive manner, being initiated at the loaded end of the bond and propagating towards the free end until the ultimate load was reached. For combined failure patterns the cohesive mode corresponds to the initial loading stage and, once the first part of the bonded area failed by shearing the adhesive, the final failures of the specimens occurred by either delamination of the CFRP strip or debonding at the interfaces level. Due to the change of the failure mode, from cohesive to delamination or debonding, the ultimate loads decreased by up to 55% (Lupăşteanu, 2016).

For the samples that were bonded with Sikadur 330 adhesive no cohesive failure was recorded. The most frequent failure modes consisted in debonding at the interface between the CFRP strips and adhesive that occurred in a brittle manner. For the combined failure patterns, the debonding at the interface level between the steel plate and the adhesive took place prematurely, at relatively low values of the ultimate forces.

By comparing the specific failure modes of the samples having the same type and thickness of adhesive with respect to the axial rigidity of the CFRP strips, no clear variation was identified for the failure patterns. Also, by increasing the thickness of the adhesive layer for samples with identical CFRP strips and adhesives, the failure modes did not changed considerably.

However, all samples for which the surface of the steel plates was not grit-blasted failed at lower ultimate forces when compared to the samples having identical configurations but surface-treated steel plates. Moreover, for the samples that were not grit-blasted the predominant failure mode consisted in premature debonding at the interface between the steel and the adhesive. Therefore, it can be concluded that the blasting process increased the surface roughness of the steel element, which produced mechanical and physical bonding forces of high intensity.

The relatively high number of failures by delamination of the CFRP strips is related to the minor eccentricities between the longitudinal axis of the bond and the loading direction, which occurred due to the initial cohesive failures of the adhesive layer (normal stresses developed in the adhesive layer).

Also, the combined failure mechanism of the samples is a result of the large bond length. Being higher than the effective one, it allowed the propagation of the initial failures and, in some cases, it produced changes of the failure mode due to the changes in the stress state.

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PARTICULARITĂȚI PRIVIND CEDAREA ÎMBINĂRILOR COMPOZITE ADEZIVE DINTRE OȚEL ŞI ELEMENTE DIN COMPOZITE POLIMERICE ARMATE CU FIBRE DE CARBON

(Rezumat)

Una dintre cele mai recente direcții de dezvoltare a materialelor compozite utilizate în domeniul ingineriei civile este reprezentată de aplicarea acestora în cadrul soluțiilor de consolidare a elementelor metalice. Această lucrare prezintă o serie de particularități privind tipologiile de cedare a îmbinărilor adezive realizate între materiale compozite polimerice armate cu fibre de carbon şi elemente din oțel. Rezultatele provin dintr-un program experimental complex efectuat la Facultatea de Construcții şi Instalații din Iaşi, în cadrul căruia s-a studiat fenomenul de conlucrare dintre materialele compozite şi cele din oțel.