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Determination of the Load-Bearing Capacity of the Bonded Joint of Hot-Dip Galvanised Steel Elements with CFRP Fabric – Pilot Laboratory and Numerical Investigations

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ABSTRACT

In this paper, an attempt was made to determine the load-bearing capacity of a bonded joint of galvanized steel elements with carbon fiber reinforced polymer (CFRP) fabric. This issue is extremely relevant to the use of bonded carbon fiber fabric as a mean of reinforcing hot-dip galvanized steel structures. This technique is used in engineering practice for both hot-rolled and cold-formed steel elements. In order to obtain the necessary parameters for modelling bonded joints of galvanised steel thin-walled elements, laboratory tests were carried out. In the first stage, four specimens made of 50 mm diameter steel cylinders bonded to 16 mm thick hot-dip galvanised steel sheet of S350 GD were subjected to the pull-off test. In this connection the SikaWrap 230C composite fabric embedded in SikaDur 330 adhesive layer was investigated. In the second stage, the axial tensile test of the bonded butt joint using the same materials was performed. In this stage, 10 hot-dip galvanised steel sheet samples of S350 GD and 16 mm thickness were tested. The discussion on the failure mechanism in the context of the bonding capacity of the composite joint was carried out. Moreover the advanced numerical model using the commercial FE program ABAQUS/Standard and the coupled Cohesive Zone Model was developed. The significant influence of the preparation method of steel element surface and the thickness of the adhesive layer on the failure mechanism of the joint and the value of the maximum failure force was shown.

Keywords: adhesive joints, composite fabric, cold-formed steel elements.

INTRODUCTION

In the era of high use of steel as a construction material, more and more important issue became the problem of their retrofitting. One of the easy, fast and cheap method to strengthen them is the use of carbon fiber reinforced polymer (CFRP) composites and bonding techniques. Research on the effectiveness of reinforcements using bonded composite materials is increasingly described both in the case of steel structures made of hot-rolled elements and in the case of cold-formed steel structures [1, 2, 3]. The article [4] presents aspects of strengthening hot-rolled steel elements of railway bridges using overlays made of CFRP tapes. Particular attention was paid to the distribution of internal forces in the reinforced element due to the flexibility of the adhesive connection. The authors determined the susceptibility of the adhesive joint based on laboratory tests and proposed their own factor for assessing the relevant effectiveness of the reinforcement. In [3] the experimental and analytical results of eccentrically loaded short cold-formed thin-wall steel channels strengthened with CFRP tapes were presented. In the proposed methods, transversely oriented carbon fiber reinforced polymer (CFRP) tapes were imposed around the channel's web and flange. It was shown that the reinforcement using the CFRP tapes results in increases in ultimate load capacity and, occurring local buckling phenomenon, prior to global buckling. In addition, the comparison between experimental tests and numerical results was discussed.

Is should be pointed out that the authors of this work are involved in conducting research on the use of CFRP composite tapes and mats to strengthen thin-walled cold-formed steel beams, which they describe, among others, in the papers [5, 6]. This is an extremely important issue, because due to the wall thickness of these types of steel elements, it is not recommended to reinforce them using welding or mechanical connectors. When strengthening steel structures using bonding, special attention should be paid to selecting the correct thickness of the adhesive layer. This issue was discussed in more detail in [7, 8]. The selection of the correct anchorage length is also extremely important [9, 10]. Another issue which should be taken into account is appropriate method of surface preparation, which may lead to a change in roughness parameters and an increase in mechanical adhesion [11, 12]. In [12], the authors focused on modifying the standard boric-sulphuric acid anodising process in order to increase the quality of structural bonding. They proposed three methods, i.e. the use of an electrolytic phosphoric acid deoxidiser, high-temperature anodizing and the use of a phosphoric acid bath. Other papers have pointed out that a very important factor that increases the load-bearing capacity of the adhesive joint is the shape of its ending. In [13], the influence of shaping the FRP composite bonding on the load-bearing capacity of the joint was investigated. Based on experimental and numerical studies, the influence of the shape properties of the final CFRP bonding on the adhesive between the CFRP laminate and steel elements was presented. It was also indicated which shape should be used for strengthening or renovation depending on the size of the damage, the thickness of the crack or the missing cross-section necessary to transfer the loads. However, in the paper [14] the method was proposed to reduce the value of interfacial stresses by narrowing the ends of the laminate. In addition, a comprehensive FE study has been conducted to investigate the effect of using normal and reverse tapering with and without adhesive fillets on the interfacial stress distribution in the adhesive joints. The results indicate that using the correct combination of tapering and adhesive fillet can reduce the magnitude of the interfacial stresses significantly. The selection of the composite material and, of course, the strength parameters of the adhesive are also important. In [15] the results of own research on selected modification methods epoxy resin used as the adhesive in structural joints were presented. The main aim of study was to ensure effective mixing of the adhesive in the case of fillers by using the ultrasonic energy. After the resin hardened, tests were carried out to determine the hardness and tensile strength of the obtained composites. In [16] it was proved that the adhesion of the modified epoxy resin can be increased by the addition of carbon nanotubes. Moreover, it was pointed out that the used modifications has also reduced impact on weakening of the adhesive joints caused by oxidation of the resin over time. Adhesive manufacturers provide basic information on the mechanical properties of the adhesive in their material cards, i.e. shear strength, temporary tensile strength, longitudinal and lateral modulus of elasticity. Unfortunately, they are often insufficient to prepare a reliable numerical model, which is why researchers often conduct their own laboratory tests to determine the necessary strength parameters of the adhesive layer [17]. In laboratory tests during the failure of a reinforced steel component, usually attention is paid to failure mechanisms e.g. how the bonded joint was delaminated, whether the failure occurred at the steel-adhesive interface, at the adhesive-composite material or in the adhesive layer. As it was mentioned before, obtaining accurate data on the strength parameters of the bonded joint is also important in order to be able to develop reliable numerical models. Investigations of adhesive joints of hot-rolled steel components have been described, for example, in papers [17, 18], which provide a very broad review of the literature on the use of bonded joints in metal structures. In case of thin-walled, cold-formed steel structures, the top surface of the steel element is hot-dip galvanised. Therefore, in this case the data regarding strength parameters of the bonded joint with the steel surface it is not sufficient. There are needs of more specific information referring to the strength parameters of the adhesive bonded to the hot-dip galvanized surface. Due to the lack of studies on determining this strength parameters, in this paper, it was decided to carry out the laboratory tests in order to collect the quarried data of bonded joint between the hot-dip galvanised steel elements and CFRP fabric. Special attention was paid on investigation of failure mechanism of SikaWrap 230C fabric embedded in the adhesive layer, which was used as reinforcement of thin-walled cold formed sigma (Σ) beams.

THE LABORATORY TESTS – STAGE I

In order to obtain the necessary strength parameters of the adhesive for modelling bonded joints of galvanized steel thin-walled, col-formed elements, laboratory tests were carried out. In the first stage, the pull-off strength of the adhesive with the embedded composite mat (CFRP fabric) was tested in accordance with the PN-EN ISO 4624 [19] standard. It should be noted that the test carried out in step I was performed in a similar way to the tests carried out by Sika. The innovation lies in the fact that the manufacturer specifies the pull-off strength for a concrete surface, while the authors undertook the test for galvanised steel plate.

Scope of research and equipment used

The adhesive pull-off strength was determined based on the [19] standard. Samples (OK 1.1 – OK 1.4) were made of steel cylinders with a diameter of 50 mm connected with hot-dip galvanized steel sheet using SikaDur 330 adhesive. In the adhesive layer there was embedded composite fabric SikaWrap 230 C. Samples were made in accordance with the Figure 1. The arrow indicates the direction of the peeling force. Before starting the test, the adhesive layer was cut off along the outline of the cylinder so that the adhesive surface area was consistent with the cross-sectional area of the cylinder. The automatic Pull-off tester Proceq DY-216 was used to measure the adhesive strength. Pull-off tests were performed under stress-controlled conditions. The rate of stress increase was 0.05 MPa/s and the test was carried out until the sample failed. The test stand is shown in Figure 2.

Results

The obtained results are summarized in Table 1 and an average normal stress-time graph was presented in Figure 3. In the graph, "time" means the duration of the pull-off test until the connection is destroyed. On this graph, a linear dependence of the increase in normal stresses can be observed in the range from 0 to 118 s. Table 1 specifies the arithmetic mean value of the adhesive pull-off strength (OK1 series), which is amounted to 5.84 MPa, and the standard deviation is equal to 0.21 MPa. The failure of the samples occurred suddenly on the entire bonded surface of the adhesive joint at a maximum normal stress of 6.07 MPa (OK 1.3) and a minimum normal stress of 5.5 MPa (OK 1.1). The performed tests provide only information on the nominal value of normal stresses in the adhesive and do not allowed to describe the equilibrium paths and thus do not provide any information about the deformation. Therefore, based on the results obtained from pull-off test, it is not possible to determine the all necessary parameters to develop a relevant computational model of the composite connection.

In Figure 4 the failure mechanism of the tested connections was shown. It can be observed that the destruction occurred at the galvanized steel - adhesive interface, accompanied by cohesive damage of the adhesive and delamination of the CFRP fabric. It is worth to emphasize that the highest value of pull-off strength (6.07 MPa) was obtained for sample OK 1.3, in which the least damage to

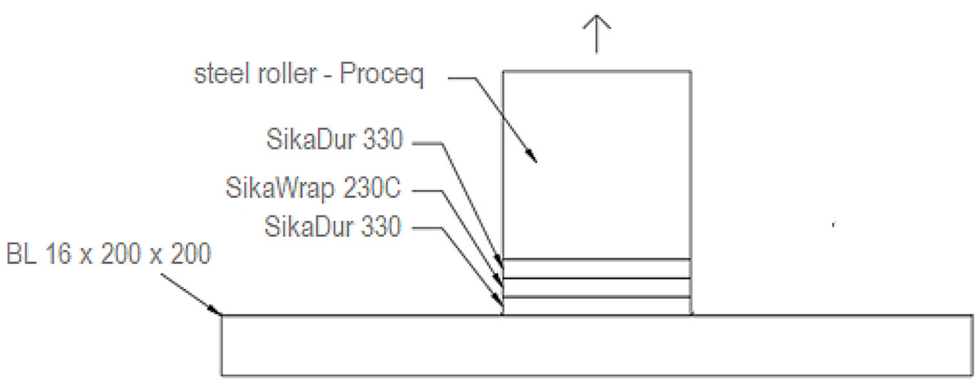

Figure 1. The sample for pull-off testing

Figure 2. The test stand – OK1 series sample attached to Proceq DY-216

Table 1. Test results for adhesive peel strength

Number	Sample symbol	Normal stress [MPa]
1	OK1.1	5.50
2	OK1.2	5.89
3	OK1.3	6.07
4	OK1.4	5.90
Average value		5.84
Standard deviation		0.21

the connection in the CFRP fabric layer is visible (no delamination of the fabric). In the case of sample OK 1.1, significant delamination of the CFRP fabric, which resulted in obtaining the lowest pull-off strength value (5.5 MPa) is observed.

Normal stresses in adhesive layer, in literature, have received significantly less attention than shear stresses. Analytical formulas for normal stresses are limited to nominal values. Simultaneously there are no formulas for the distribution of normal stresses in the adhesive. In comparison for shear stresses, e.g. Volkersen's, Goland&Reissner's or Hart-Smith's formulas are commonly known and used. The distribution of normal stresses in the adhesive is influenced by local phenomena, e.g. "barrelling". In the case of bonded butt joints, local phenomena cause both, normal and shear stresses, occured in the adhesive layer.

THE LABORATORY TESTS – STAGE II

Scope of research and equipment used

Due to the limitations of the first stage of research, consisting in the inability to determine all necessary strength parameters of the connection, and thus the impossibility of developing a numerical model, the second stage of laboratory tests was carried out. In the second stage, an tensile test was performed on the bonded butt joint with a composite fabric embedded in the adhesive layer. In this stage, 10 samples made of galvanized steel sheet, S350 GD, 16 mm thick and 100 mm side dimension (sample symbols P1 - P10) were subjected to the axial tensile test in the MTS 809 AXIAL/TORSIONAL TEST SYSTEM (2010) testing machine. In the middle of the width of the end plate, a 6 mm thick steel plate was welded (necessary to place the

Table 2. Results of measuring the thickness of the adhesive layer

Sample symbol	Section height at point 1 [mm]	Section height at point 2 [mm]	Section height at point 3 [mm]	Section height at point 4 [mm]	Average section height [mm]	Glue layer thickness [mm]	Thickness SikaWrap 230 C [mm]
P1	33.37	33.24	33.19	33.06	33.22	1.09	0.129
P2	33.60	33.48	33.66	33.31	33.51	1.38	0.129
P3	32.90	33.07	32.97	33.14	33.02	0.89	0.129
P4	33.24	33.53	33.08	32.99	33.21	1.08	0.129
P5	33.32	32.95	33.39	33.10	33.19	1.06	0.129
P6	33.15	33.31	33.01	33.13	33.15	1.02	0.129
P7	33.14	33.37	33.07	33.30	33.22	1.09	0.129
P8	33.19	33.18	33.25	33.17	33.20	1.07	0.129
P9	33.24	33.08	33.15	33.05	33.13	1.00	0.129
P10	33.10	33.05	33.29	33.36	33.20	1.07	0.129

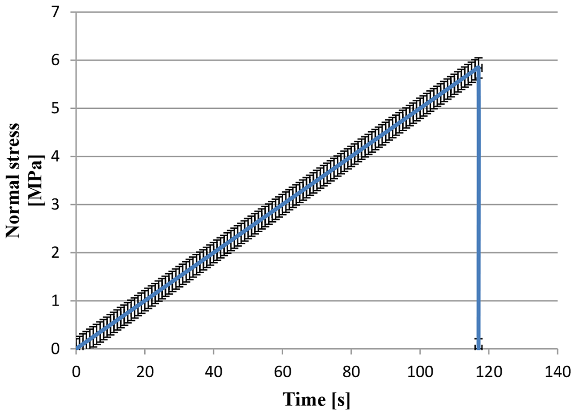

Figure 3. Relationship of the average normal stress – time for the OK 1 series

samples in the testing machine). In this way, the T-sections visible in Figure 5 were created. The bonded butt-joint consist of SikaWrap 230 C carbon fiber fabric embedded in the adhesive layer of SikaDur 330 adhesive. The connection was prepared in accordance with the manufacturer's instructions. So, the connection surface was properly prepared, i.e. cleaned of all kinds of dirt and grease, and the thickness of the adhesive layer was checked. The samples were tested after 7 days to achieve full adhesive strength. During the test, the force-displacement relationship was measured. The displacement increment speed was 0.01 mm/s and the test was carried out until the sample was destroyed.

Figure 4. Failure mechanism of the tested connections – OK 1 series samples

Table 2. Results of measuring the thickness of the adhesive layer

Sample symbol	Section height at point 1 [mm]	Section height at point 2 [mm]	Section height at point 3 [mm]	Section height at point 4 [mm]	Average section height [mm]	Glue layer thickness [mm]	Thickness SikaWrap 230 C [mm]
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P2	33.60	33.48	33.66	33.31	33.51	1.38	0.129
P3	32.90	33.07	32.97	33.14	33.02	0.89	0.129
P4	33.24	33.53	33.08	32.99	33.21	1.08	0.129
P5	33.32	32.95	33.39	33.10	33.19	1.06	0.129
P6	33.15	33.31	33.01	33.13	33.15	1.02	0.129
P7	33.14	33.37	33.07	33.30	33.22	1.09	0.129
P8	33.19	33.18	33.25	33.17	33.20	1.07	0.129
P9	33.24	33.08	33.15	33.05	33.13	1.00	0.129
P10	33.10	33.05	33.29	33.36	33.20	1.07	0.129

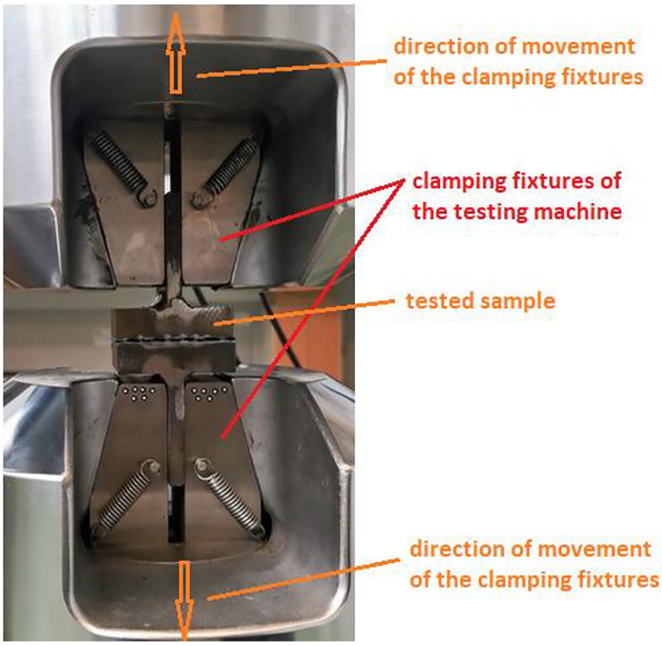

Figure 5. Tensile test stand - sample in a testing machine

As it was mentioned earlier, before starting the tests, the thickness of the adhesive layer was measured, assuming that the thickness of the CFRP mat was 0.129 mm. Each sample was measured at 4 points, 35 mm from the edge of the sample. The location of the measurement points is shown in Figure 6 and the measurement results in Table 2.

RESULTS

The obtained results of the force-displacement relationship for the tested samples are summarized in Table 3 and a force-displacement diagram was developed (Figure 7). In addition, Table 3 specifies the average, maximum and minimum values as well as the standard deviation for the maximum force and displacement.

Figure 8 and 9 show the failure mechanisms of the tested samples. In each case, failure mode occurred suddenly over the entire bonded surface of the adhesive joint. It can be seen that in the case of samples P1, P3, P4, P6, P7, P8 and P9 (Figure 8), the dominant failure mechanism was delamination of carbon fibres from the adhesive matrix. In the case of the three remaining samples (P2, P5 and P10 - Figure 9), the destruction occurred at the galvanized steel - adhesive interface, accompanied by cohesive damage of the adhesive layer and delamination of the CFRP fabric, i.e. similarly to the results obtained in the tests of stage I.

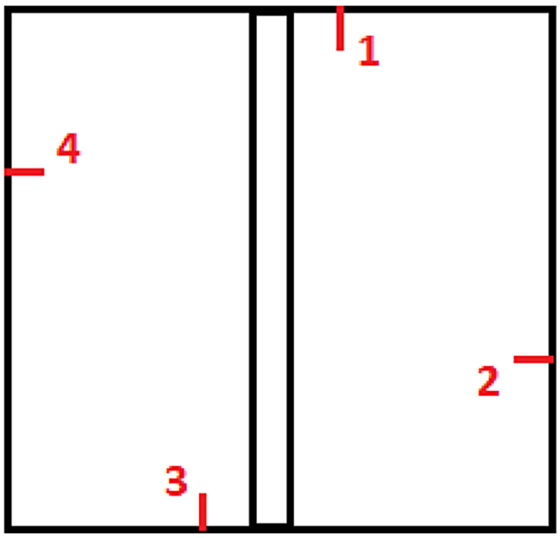

Figure 6. Location of points for measuring the thickness of the adhesive layer

Analysing the obtained results, it can be concluded that the type of sample failure mechanisms has a significant impact on the value of the failure force in the bonded connection. When destruction occurs at the galvanized steel-adhesive interface, the failure force is more than half lower (P2, P5) than in the case of samples where damage occurs in the adhesive layer with the CFRP fabric (P6). This may be caused by incorrect preparation of the hot-dip galvanized steel surface (inadequate degreasing or matting) or an inappropriate

Table 3. Results of laboratory tests of stage II

Number	Sample symbol	Failure load [kN]	Displacement at failure [mm]
1	P1	39.55	0.1768
2	P2	22.60	0.1079
3	P3	44.00	0.2071
4	P4	39.77	0.1962
5	P5	20.21	0.0877
6	P6	46.08	0.2248
7	P7	34.29	0.1540
8	P8	44.77	0.2459
9	P9	44.13	0.2093
10	P10	31.84	0.1432
Average value		36.72	0.1753
Maximum value		46.08	0.2459
Minimum value		20.21	0.0877
Standard deviation		9.30	0.0513

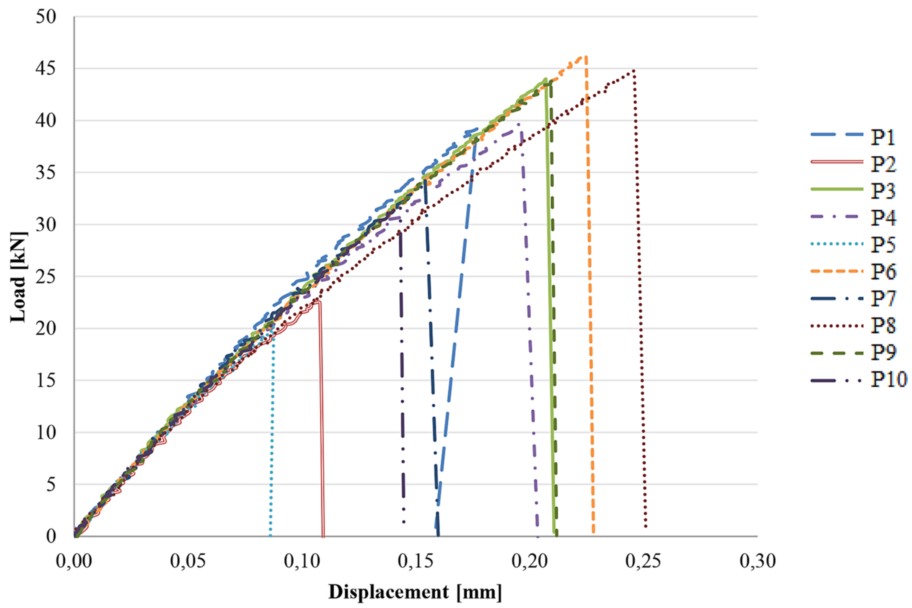

Figure 7. Load-displacement relationships for the tested samples – stage II

adhesive layer, resulting in incomplete embedded CFRP fabric in adhesive or excessive accumulation of CFRP fibres, which makes it difficult for the adhesive to be penetrate.

In the case of SikaDur 330 adhesive, due to its liquid nature, it is very difficult to obtain a specific connection layer. In sample P2, in which the damage occurred at the interface between adhesive and galvanized steel, the thickness of the adhesive layer was much greater than in the other samples, while in the case of sample P5 (for which the lowest value of the failure force was obtained), the thickness of the adhesive layer was uneven - between measuring point 2 and 3 The thickness difference is of 0.44 mm.

NUMERICAL ANALYSIS

The numerical model which reflect the laboratory test performed in in stage II was developed using the commercial FE program ABAQUS/Standard. The adhesive layer was defined using 8-node three-dimensional cohesive elements (COH3D8) and the CFRP fabric was defined using 4-node quadrilateral membrane with reduced

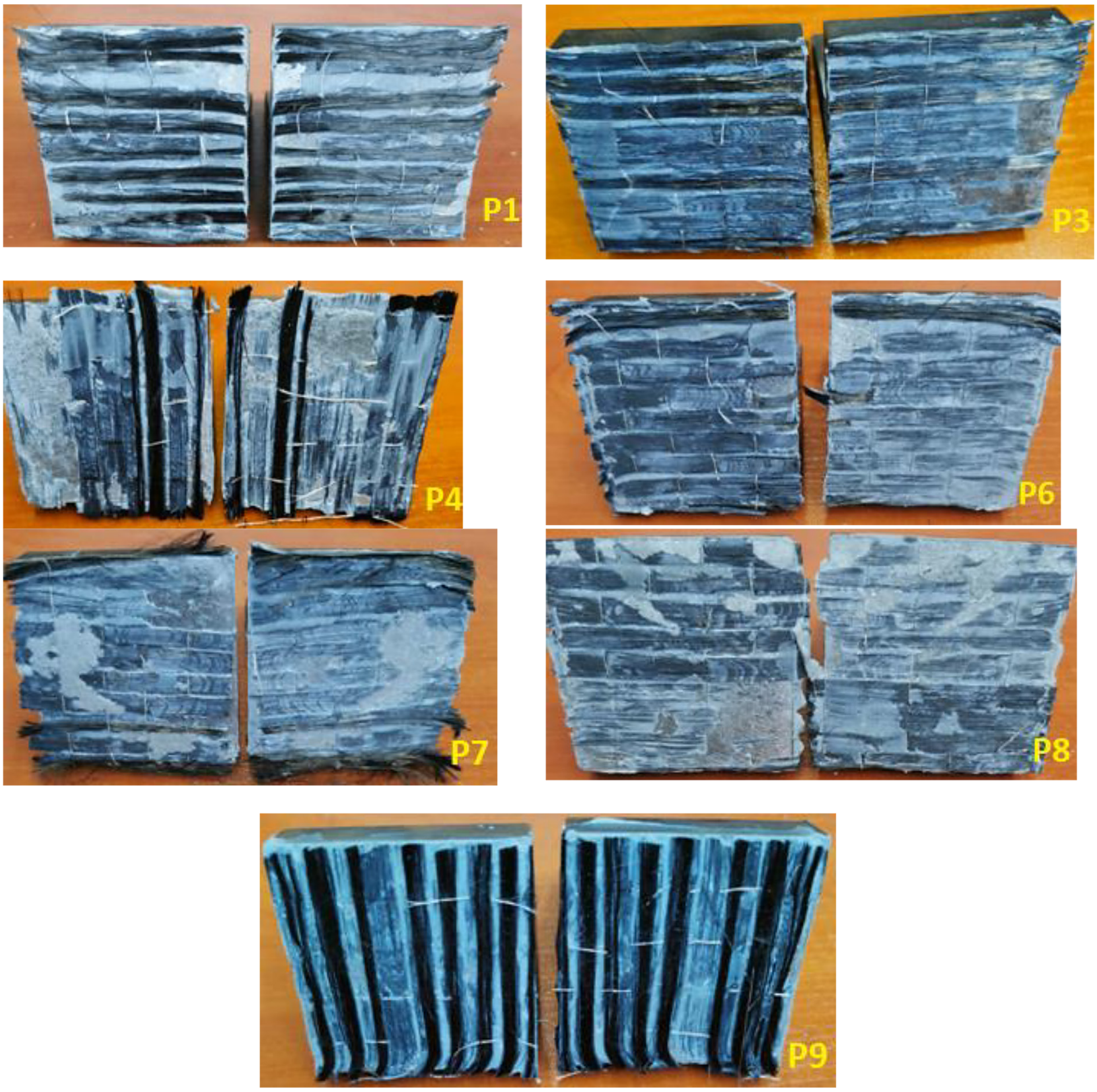

Figure 8. Failure mechanisms of samples P1, P3, P4, P6, P7, P8 and P9

integration (M3D4R). The steel plates were defined using 4-node 3-D bilinear rigid quadrilateral elements (designated as R3D4). The type of analysis was defined as dynamic implicit including non-linear analysis. The solver was defined to use full Newton solution technique with the time period set to 200 s. The steel-adhesive and fabric-adhesive interaction was defined as "tie". In the numerical analysis, displacement control was used, so connection response was enforced by defining the vertical displacement of 0.25 mm upwards. The boundary conditions were defined in appropriate reference points (RP). The structure of the composite connection and boundary conditions are presented in Figure 10. Size of mesh element for all parts was set as 0.5 mm. For damage initiation criterion, the quadratic nominal stress criterion was adopted. Furthermore, CFRP fabric material properties were taken from on laboratory test presented in [20]. Table 4 presents implemented CFRP properties in FEM.

The coupled Cohesive Zone Model (CZM) was implemented in the commercial FE program ABAQUS. The cohesive elements were adopted and their constitutive behaviour was defined by the independent mode cohesive law. The cohesive behaviour was defined by creating traction-separation behaviour with coupled and specified stiffness coefficients. The damage initiation behaviour was defined using quadratic traction criterion.

Figure 9. Failure mechanisms of samples P2, P5, P10

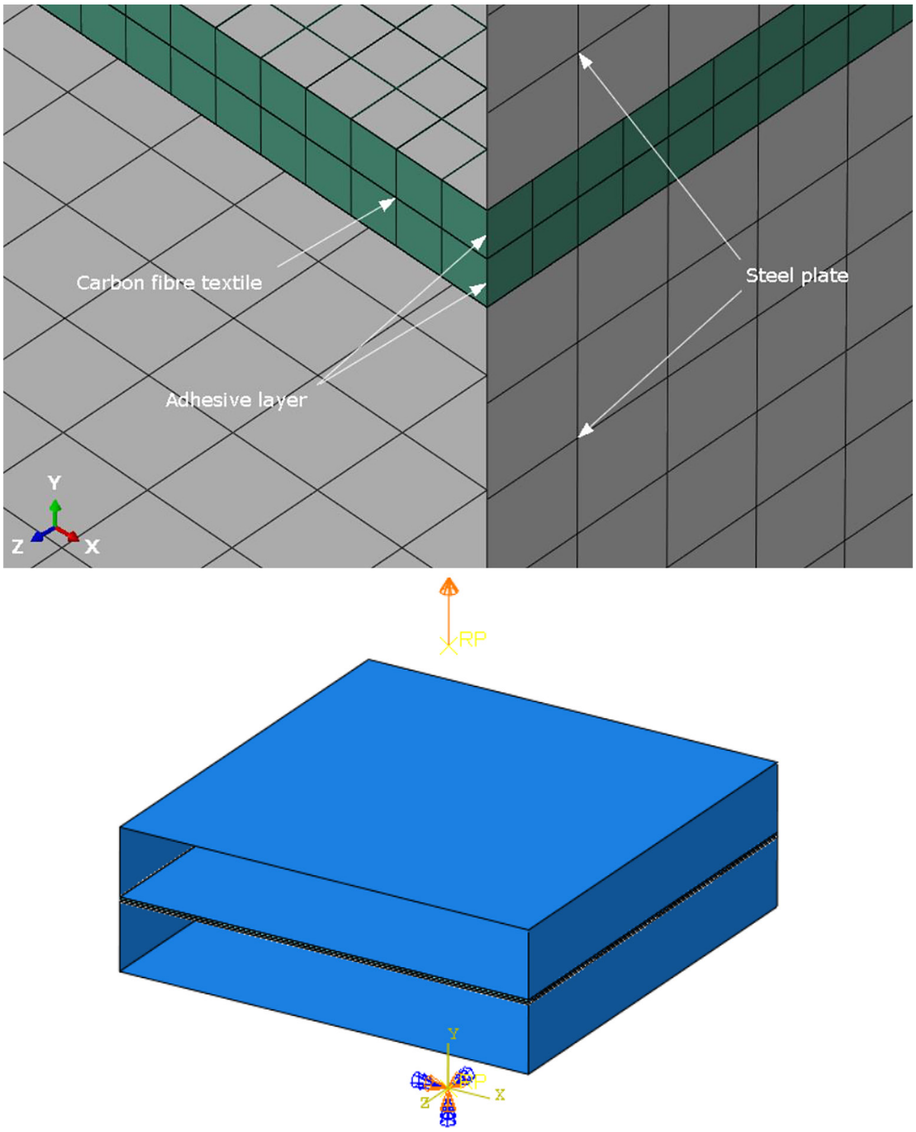

Figure 10. The structure of the composite connection and boundary conditions

Table 4. CFRP properties implemented in FEM

Parameter	Quantity	Unit
Density	1.83e-9	t/mm3
Elastic modulus of fabric E1	220000	MPa
Elastic modulus of fabric E2	15750	MPa
Longitudinal and transverse Poisson's ratio	0.3	[-]
Shear modulus G12	8730	MPa
Shear modulus G13	11650	MPa
Shear modulus G23	5615	MPa

The damage evolution behaviour was defined as energy type with linear softening behaviour. The young's modulus matrix can be described as:

$$E = \begin{bmatrix} E_{nn} & 0 & 0 \\ 0 & E_{ss} & 0 \\ 0 & 0 & E_{tt} \end{bmatrix} = \begin{bmatrix} 4500 & 0 & 0 \\ 0 & 1730 & 0 \\ 0 & 0 & 1730 \end{bmatrix} \quad (1)$$

The damage properties of cohesive elements are presented in Table 5. The applied boundary conditions are presented in Figure 10b. On bottom surface the displacements and rotations were blocked. Similarly, on top surface displacements and rotations were blocked except the vertical displacement which was set to 0.25 mm upwards in order to enforce tension. The FE equilibrium path obtained for the numerical model developed in Abaqus program is presented in Figure 11. In the Table 6 the average value of the maximum failure force and the average value of displacements at failure mode are shown. The presented results refer to those obtained from numerical analysis and laboratory tests performed in stage II. Some discrepancies can be noticed between the obtained results. For example in the case of the maximum failure force the discrepancy between the results obtained from numerical and laboratory tests is small and amounts to 4.5%. While in the case of values referring to displacements at failure mode, unfortunately, the discrepancy between the results obtained from FE model and laboratory tests is significant (99.3%). This means that the numerical model requires further improvement, with particular emphasis on parameters regarding connection stiffness, which can be obtained from further laboratory tests.

Table 5. Cohesive surface properties implemented in FEM model

Parameter	Quantity	Unit
Maximum nominal stress in all directions	4	MPa
Fracture energy	0.01	N/mm

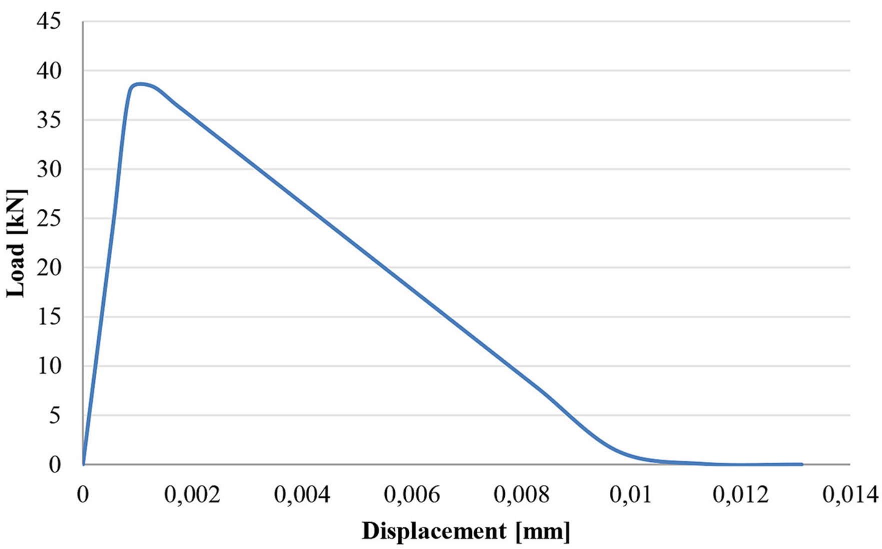

Figure 11. Equilibrium path for the FE numerical model

Table 6. The average value of the maximum failure force and the average value of displacements at failure mode

Parameter	Maximum force [kN]	Corresponding displacement [mm]
Lab	36.72	0.1753
FEM	38.45	0.0012

CONCLUSIONS

In this paper the results of laboratory test and numerical simulation performed in order to determine the load-bearing capacity of a bonded joint of galvanized steel elements with CFRP fabric are presented. Special action was paid on failure load and the displacement at failure of the composite connection between hot-dip galvanized steel sheet of S350 GD and the SikaWrap 230C composite fabric embedded in SikaDur 330 adhesive layer. In frame of laboratory test two stages were carried out including the pull-off and axial tensile test. The observations refer to the failure mechanism in the context of the bonding capacity. It was also shown the significant influence of the preparation method of steel element surface and of the thickness of the adhesive layer on the failure mechanism of the joint and the value of the maximum failure force. Based on the obtained results, the following detailed conclusions can be formulated:

- when the damage occurs at the interface between galvanized steel and adhesive layer, the failure load is almost 57% lower (P5) than in the case of a sample where failure occurs between the adhesive layer and CFRP fabric (P6);
- in sample P2, in which the damage occurred at the interface between adhesive and galvanized steel, the thickness of the adhesive layer was approximately 0.3 mm greater than in the other samples, while in the case of sample P5 (for which the lowest value of failure load was obtained), the thickness of the adhesive layer was uneven – between the measurement points the difference was of 0.44 mm.

The results of the laboratory tests presented in the paper can be used to calibrate numerical models and allow obtaining convergent results of the maximum failure load (difference less than 5%). Nevertheless it should be pointed out the presented results should be considered as the pilot analysis and further and extended test should be continued. Based on the obtained results it could be concluded that the particular attention should be focused on determining the constant and optimal thickness of the adhesive layer.

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