BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LXI (LXV), Fasc. 4, 2015
Secţia
CONSTRUCŢII. ARHITECTURĂ

BEHAVIOUR OF CFRP-TO-STEEL INTERFACE IN ADHESIVELY BONDED SINGLE LAP JOINTS EXPERIMENTAL SET-UP

BY

VLAD LUPĂŞTEANU*, NICOLAE ŢĂRANU, PETRU MIHAI and GABRIEL OPRIŞAN

“Gheorghe Asachi” Technical University of Iaşi
Faculty of Civil Engineering and Building Services

Received: October 14, 2015
Accepted for publication: October 30, 2015

Abstract. This paper presents the set-up of an experimental study which focuses on the behavior of carbon fiber reinforced polymer (CFRP) composite strips, adhesively bonded to steel surfaces. For that purpose, single lap shear pull-off specimens were designed and prepared. The experimental program consists of a wide range of combinations between three types of CFRP strips (with normal, medium and high modulus of elasticity) and two types of adhesives, each of them being applied in three thicknesses (1 mm, 2 mm and 3 mm). For each combination, three identical specimens were prepared. Important aspects regarding the behavior of CFRP-to-steel bonded joints, such as: identification of the failure modes, characterization of the bond-slip behavior of the interfaces, checking the validity of the effective bond length can be obtained and analyzed by performing the envisaged experimental program based on the proposed set up.

Key words: CFRP; bonded joints; steel surfaces; single lap shear pull-off.

1. Introduction

Fiber reinforced polymer (FRP) composites are widely used as strengthening materials for concrete and masonry elements, offering significant

*Corresponding author: *e-mail:* vlad.lupasteanu@gmal.com

advantages when compared to the traditional materials, in terms of durability, high strength over specific weight ratio, superior handling and ease in application. In the last two decades, strengthening solutions of steel elements based on adhesively bonded FRP composites have become increasingly popular as a direct consequence of the technological progress, developing new types of CFRP composite products, with improved mechanical properties, consistent with the ones of steel. Site applications have also been carried out, most of them being applied on construction elements belonging to the infrastructure facilities, located in U.K. and U.S.A. (Hollaway, 2014; Luke, 2001).

For most of the structural applications of FRP composite plates adhesively bonded to steel elements, the adhesive layer has a critical function, being responsible for shear stress transfer between steel and composite interfaces. For example, steel beams flexural strengthened with FRP composite strips bonded to the bottom flange belong to this category (bond critical applications), because the strengthening effect can only be achieved if the adhesive layer successfully transfers the stresses between the adherents.

Since the bond behavior is of much interest and importance in achieving an appropriate performance of the strengthening system, the need for an extensive analysis and characterization of the bonding phenomena is emphasized. Based on the vast research that has been already performed on FRP-strengthened concrete elements (Yuan *et al*., 2004; Lu *et al*., 2005) it has been recommended that the analysis of the bonded joints should be firstly performed on simplified models. For this reason, the experimental program presented in this paper consists of single lap shear pull-off tests.

Even analyzed on simplified models, the bonding process and the bond behavior are still complicated issues, being affected by many factors, some of them referring to the intrinsic physical properties and to the quality of components preparation (surface treatment of the steel interface, proper mixing and application of the adhesive, appropriate handling and installation of the FRP strips etc.). Further on, as the execution phase ends, depending on the mechanical properties of the constituents and on the geometrical configuration of the joint, other critical parameters can be highlighted, such as: the effective bond length (L_e), the effective thickness of the adhesive layer (t_a), the influence of the elastic and strength properties of the adhesive and of the FRP composite element, the ultimate load that can be carried out by the joint (P_{ult}) and the specific failure mode.

2. Literature Review

The most important experimental studies carried out by various research teams, aiming to describe and synthetize the behavior of FRP-to-steel bonded joints are presented in this chapter. Most of the studies that are presented were designed and carried out for two main reasons: firstly, to identify the aspects which are similar (or not) to the behavior of FRP composites-to-concrete bonded joints (in both physical and analytical terms) and secondly, to develop valid models which can describe the specific behavior of FRP composite-to-steel bonded joints.

Xia and Teng (2005) conducted a series of single-shear pull-off tests aiming to describe the full-range behavior of FRP-to-steel bonded joints. The specimens consisted of CFRP plates adhesively bonded to a steel block. The study focused on the effect of the adhesive properties; thus four different thicknesses were applied (1 mm, 2 mm, 4 mm and 6 mm) for each of the three types of the adhesives that were selected (generically termed in the paper as A, B and C). For each specimen, the adhesive layer has been indirectly subjected to shear stresses by applying tension forces at the free end of the CFRP plate. Based on the results of the experimental program, a bond-slip model has been proposed for the FRP-to-steel interfaces.

In 2005, Fawzia *et al.* conducted an experimental program which consisted of double strap shear tests loaded in tension aiming to investigate the bond characteristics and behavior between CFRP composite sheets and steel plates. Both normal and high modulus CFRP composite sheets have been used, each of them being applied in three layers on both sides of the steel plates (the bond surface was sandblasted before the application of the adhesive). The most important parameter that was taken as a variable was the bond length, varying from 20 cm to 60 cm. The CFRP composite bonded steel plates were subjected to tension, up to failure. The results of the experimental program led to conclusions and observations regarding the different failure modes, the strain distribution along the CFRP length, the effective bond length. Also, based on the results, two models used to predict the load carrying capacity of the joints were proposed.

Further on, in 2010 Fawzia *et al*. carried out another study in which double strap joints of steel plates bonded with CFRP composite sheets were subjected to tension. Three types of adhesives were analyzed, each of them being used to bond three layers of normal or high modulus CFRP composite sheets. Also, the length of the bond varied from one specimen to another. The specimens were tested to tension up to failure, and the shear stresses and the slip were monitored throughout the entire loading stage. The results of the experimental study triggered substantial conclusions regarding the shear stress concentrations, the influence of the adhesive thickness over the maximum slip and, also, bond-slip models could be established.

As an extension to the work carried out by Xia and Teng, Yu *et al.* (2012) analyzed the behavior of FRP-to-steel bonded joints for adhesives with both linear and non-linear behavior. For this purpose, eighteen single-lap pull tests were conducted in three series. The specimens consisted of three types of CFRP strips adhesively bonded to a sufficiently stiff steel element (the stiffness of the steel element was not taken as a variable to be examined). Four types of adhesives were selected, two of them being characterized by a linear behavior (bi-linear normalized bond-slip curve) and the other two by a non-linear behavior (trapezoidal normalized bond-slip curve). Each adhesive has been applied in different thicknesses, depending on the intended purpose of the corresponding specimen series. Prior to the application of the CFRP strip, the surface of the steel was solvent-wiped, grit-blasted and vacuumed. The tension load was applied to the free end of the CFRP strip, as it has been concluded that this method is the most suitable one for studying the mode II fracture behavior of CFRP-to-steel interfaces (Fernando, 2010). The test results and the discussions that were presented in the paper enabled the formulation of conclusions regarding the influence of the interfacial fracture energy with respect to the bond behavior and bond-slip curves have been established for both linear and non-linear adhesives.

3. Description of the Experimental Program

The proposed experimental program consists of single shear pull-off tests, aiming to understand and describe the bond mechanism and behavior of CFRP composite strips adhesively bonded to steel surfaces. The parameters that are taken into account in this program are the effect of the axial rigidity of the CFRP composite strip, the modulus of elasticity of the adhesive and its thickness. For this purpose, three types of CFRP composite strips were bonded to steel elements using two types of adhesives, under three different thicknesses. Thus, 54 specimens have been prepared, consisting in 3 identical specimens for each combination of CFRP composite strip – adhesive type – adhesive thickness.

3.1. Materials Properties

The steel plates are made of common steel, S235 JR, being 10 mm thick, 500 mm long and 120 mm in width. The properties of the steel plates are presented in Table 1.

Table 1
Properties of the Steel Plates

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

Since the axial rigidity of the CFRP composite strip is of much interest in this study, three strips were selected from the catalog of the local Sika supplier, having different longitudinal modulus of elasticity (normal, medium and high). The geometrical and mechanical properties of the CFRP composite strips are presented in Table 2.

Table 2

Properties of the CFRP Composite Strips (Sika strips - Technical sheet)

Type	Thick ness, t_{CFRP} [mm]	Width, b_{CFRP} [mm]	Cross sectional area, A_{CFRP} [mm^2]	Longit. modulus of elasticity, E_{CFRP}, [GPa]	Tensile strength, $f_{t,\mathrm{CFRP}}$ [MPa]	Elongation at break, $\varepsilon_{u,\mathrm{CFRP}}$, [%]
Sika Carbodur S512	1.2	50	60	165	3,100	> 1.30%
Sika Carbodur M514	1.4	50	70	210	3,200	> 1.35%
Sika Carbodur UH514	1.4	50	70	400	1,900	> 0.45%

The CFRP composite strips are bonded to the steel elements using two different bi-component adhesives, Sikadur 30 and Sikadur 330. The main parameter which differentiates the adhesives is the modulus of elasticity which is almost three times higher for the first one when compared to that of the second one. The physical and mechanical properties of the adhesives are presented in Table 3.

Table 3

Properties of the Adhesives

Type	Density [kg/dm^3] (mixed)	Compressive strength, $f_{c,\mathrm{adh}}$ [MPa]	Tensile strength, $f_{t,\mathrm{adh}}$ [MPa]	Modulus of elasticity, E_{adh}, [GPa]	Elongation at break, $\varepsilon_{u,\mathrm{adh}}$, [%]
Sikadur 30	1.65	70,…,80	25,…,28	12.8	> 1.30%
Sikadur 330	1.30	75,…,80	34	4.5	> 1.35%

The mechanical properties of steel were taken according to EN 1993-1-1 and those of the CFRP composite strips and of the adhesives were taken according to their Technical data sheet, provided by the supplier. The effective mechanical properties, obtained by experimental tests, will be presented in a future paper.

3.2. Preparation of the Specimens

Since the full range behavior of the single lap joints will be investigated, the bond length was taken 350 mm, much higher than the effective one. Thus, the CFRP composite strips, 550 mm in length, were cut using a special diamond blade. Prior to the bonding stage, the surface of the steel plates was cleaned with acetone, to remove any grease and dust, and sandblasted with a 0.18 mm steel grit. After the sandblasting process, the surface of the steel was vacuumed so that, any dust or remaining grit particles were eliminated.

Within 24 hours after the surface preparation of the steel plates, the CFRP composite strips were bonded. The bi-component adhesives were mixed according to the indications presented in their technical data sheets, with a volumetric ratio of 1:3 for Sikadur 30 and 1:4 for Sikadur 330. The components were mixed in clean recipients, with a special drill at slow speeds (400,…,600 rotations/min). For each group of specimens, the quantity of mixed adhesive was carefully chosen, taking into account that the proper workability period is 45,…,50 min. For every combination of CFRP composite strip–type of adhesive, three thickness were applied, of 1 mm, 2 mm and 3 mm. The designed adhesive thickness were obtained by fixing steel bearing balls of 1 mm, 2 mm and 3 mm to the steel surface. The steel plate, before the application of the CFRP composite strip, is presented in Fig. 1.

Fig. 1 – Steel plate with bearing balls.

Before the application of the adhesive, the surface of the CFRP composite strip that comes in contact with the joint was cleaned with Sika ColmaCleaner solvent. A special attention has been paid to the application of the adhesive on the surface of the strip. Even if the thickness of the adhesive layer is controlled by the bearing balls, an insufficient quantity of adhesive applied on the strip may lead to an inconsistent bond. On the other hand, if there is too much adhesive on the strip, the excess will come out during the roll-pressing stage and it could become difficult to eliminate. For this reason, a special rig was designed, composed of a rigid base on which steel strips are fixed at 50 mm clear distance. The thickness of the first set of steel strips is 1.3 mm or 1.5 mm being 0.1 mm thicker than the corresponding CFRP composite strips while the second set of steel strips are 1 mm, 2 mm or 3 mm thick, corresponding to the designed thickness of the adhesive layer. In this way, the steel strips are installed according to the designed thickness of each nominal specimen, being only 0.1 mm thicker than the latter. Hence, during the roll-pressing stage, the adhesive will fill the entire bond length and the excess that will be forced out will be minimum. The rig is presented in Fig. 2.

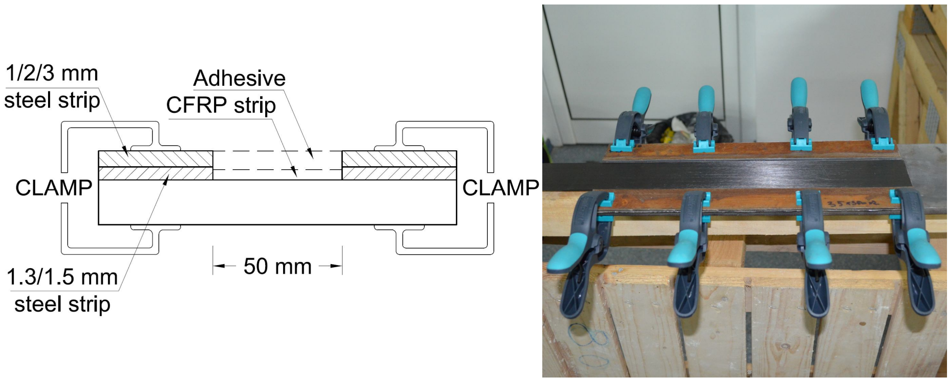

Fig. 2 – Rig for control of the adhesive thickness.

The position of the strip was carefully marked on the surface of the steel plate, assuring the 350 mm bond length. The CFRP composite strips were softly pressed with a special roll aiming to obtain the design adhesive thickness. After that, the strips were fixed with clamps at the end, and stored for 14 days, until the adhesive cured (Fig. 3).

Fig. 3 – Roll-pressing the strip and fixing the specimen.

For the ease of manipulation and identification, each specimen was marked with a nominal code (*i.e.* S514-30-1-I) referring to the type of CFRP composite strip, to the type of adhesive and its thickness, respectively. The last digit (I, II or III), stands for identifying identical specimens. In this way, each of the 54 specimens could be easily identified and appealed to, when the results will be analyzed and compared. The general configuration of the specimens is illustrated present in Fig. 4.

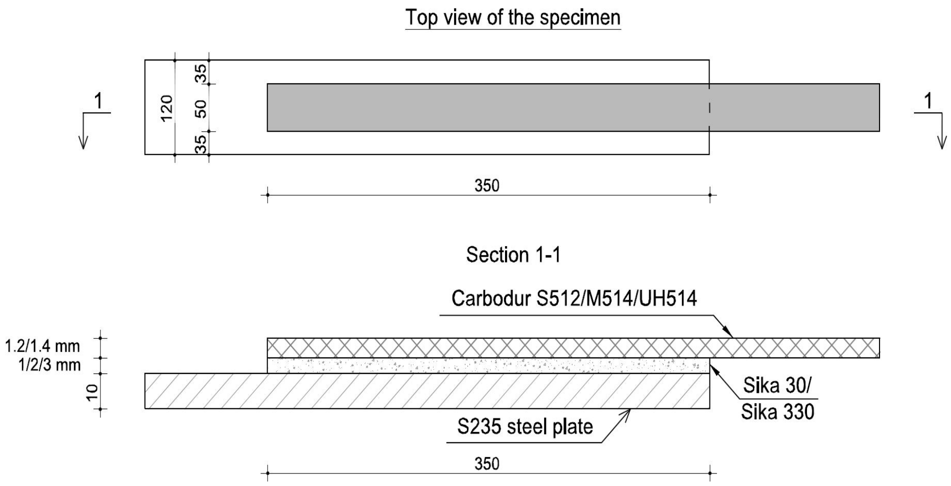

Fig 4. – General configuration of the specimens

3.3. Instrumentation of the Specimens and Experimental Set-Up

During the curing time of the adhesive, the specimens were prepared for the loading stage. Since the stresses in the mid-plane of the adhesive cannot be recorded, 5 mm strain gauges have been installed on the upper side of the CFRP composite strips. Also, additional strain gauges were installed on the free, unbonded end of the CFRP composite strip and on the free end of the steel plate. These two strain gauges will collect information regarding the state of stress outside de bond length. The strain gauges were installed with great care, respecting the indications given in their technical sheet. The complete flow chart that was applied during the installation stage is presented in Fig. 5.

When the installation of all ten strain gauges was finished, the wires were welded and attached at the free end to electrical bridges fixed on the steel plate. In this way, the cables of the data acquisition system could be easier connected to the strain gauges, when the specimen is fixed in the testing machine. The locations of the strain gauges are presented in Fig. 6.

The specimens are subjected to tension in a ZWICK/ROELL 100 kN hydraulic test machine (Fig. 7), located in the structural laboratory of the Faculty of Civil Engineering and Building Services, Iaşi. After the specimens are fixed in the grips of the machine, the acquisition system is connected.

During the application of the force, the following parameters can be monitored: the applied force, the relative displacement between the steel plate and the CFRP composite strip (using a linear variable differential transformer – LVDT) and the strain variations. In order to perfectly align the specimen in the grips of the testing machine, steel plates of different thicknesses were utilized to compensate the offsets which appeared as a result of the single lap configuration. The tension test are force controlled, with a 5 kN/m loading speed.

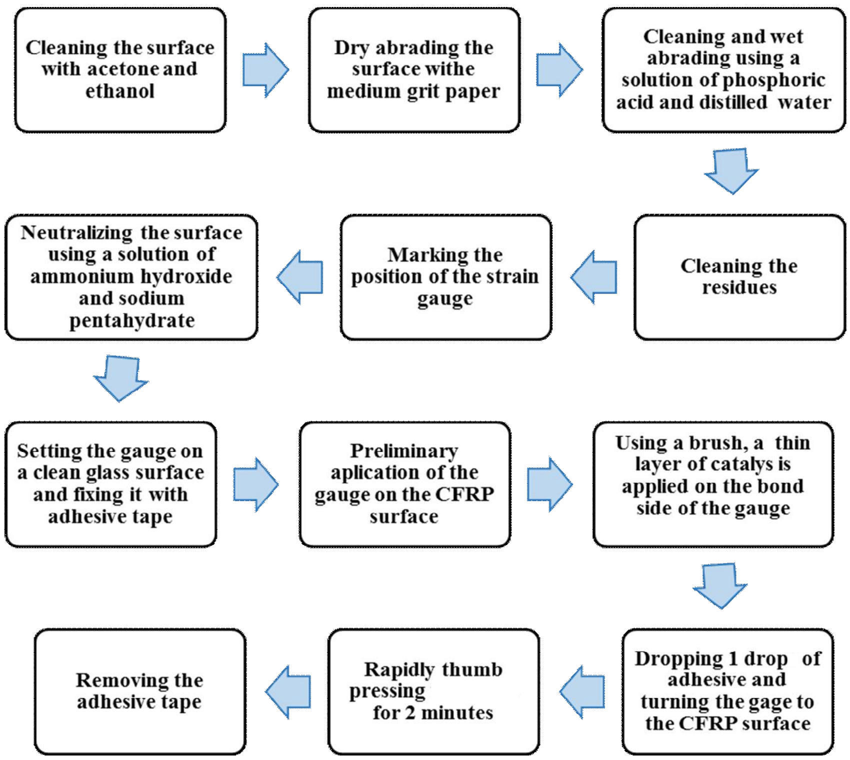

Fig. 5 – Flow chart of strain gauge installation.

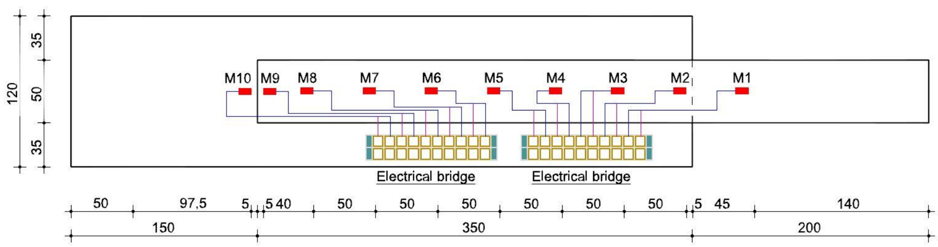

Fig 6. – Location of the strain gauges

Fig. 7 – Zwick/Roell 100 kN hydraulic test machine.

4. Conclusions

This paper presents the experimental set-up of a study that focuses on the behavior of CFRP composite strips adhesively bonded to steel surfaces. The preparation and instrumentation of single lap shear pull-off specimens was extensively detailed. The aim of this experimental program is to obtain information about the main parameters that characterize the bond behavior of such elements, such as: specific failure modes, the effective bond strengths, the evaluation and validation of the effective bond length, the distribution of the shear stresses along the bond length, the influence of the axial rigidity of the CFRP composite strip and the effect of adhesive thickness over the bond strength. Also, based on the results of experimental program, the validity of the existing bond-slip models can be checked and, if necessary, corrections of the existing ones or new models can be proposed.

REFERENCES

Holloway L.C., *Using Fibre-Reinforced Polymer (FRP) Composites to Rehabilitate Different Types of Metallic Infrastructure*. In Rehabilitation of metallic civil infrastructure using fibre reinforced polymer (FRP) composites. Edited by V.M. Karbhari, Elsevier Woodhead Publishing, UK, 2014.

Luke S., *The Use of Carbon Fibre Plates for the Strengthening of Two Metallic Bridges of an Historic Nature in the UK.* Proc. of the FRP Composite in Civil Engng. (CICE2001), Hong Kong, Edited by J.G. Teng, Elsevier, Oxford, 2001, 975-983.

Yuan H., Teng J.G., Seracino R., Wu Z.S., Yao J., *Full-Range-Behavior of FRP-to-Concrete Bonded Joints*. Engineering Structures, **26**, *5*, 553-565 (2004).

Lu X.Z., Teng J.G., Ye L.P., Jiang J.J., *Bond-Slip Models for FRP Sheets/Plates Bonded to Concrete*. Engineering Structures, **27**, *6*, 920-937 (2005).

Xia S.H., Teng J.G., *Behaviour of FRP-to-Steel Bonded Joints.* Proc. of the Internat. Symp. on Bond Behaviour of FRP in Struct. (BBFS 2005), Hong Kong, China, Edited by J.G. Teng and Chen J.F., 2005, 419-426.

Fawzia S., Zhao X.L., Al-Mahaidi R., Rizkalla S., *Bond Characteristics Between CFRP and Steel Plates in Double Strap Joints.* Adv. Steel Constructions, **1**, *2*, 17-28 (2005).

Fawzia S., Zhao X.L. Al-Mahaidi R., *Bond-Slip Models for Double Strap Joints Strengthened by CFRP*. Composite Structures, **92**, *9*, 2137-2145 (2010).

Yu T., Fernando J.G., Teng J.G., Zhao X.L., *Experimental Study on CFRP-to-Steel Bonded Interfaces.* Composites: Part B, **43**, *5*, 2279-2289 (2012).

Fernando N.D., *Bond Behavior and Debonding Failures in CFRP-Strengthened Steel Memebers.* Ph.D. Diss., The Hong Kong Polytechnic University, Hong Kong, China, 2010.

* * * *Design of Steel Structures*, Part 1-1: *General Rules and Rules for Buildings*. EN 1993-1-1.

* * * *Sika CarboDur strips Technical sheet*.

* * * *Sikadur 30 adhesive Technical sheet*.

* * * *Sikadur 330 adhesive Technical sheet*.

COMPORTAREA INTERFEȚEI CPAF-OȚEL LA ÎMBINĂRILE ADEZIVE PRIN SUPRAPUNERE SIMPLĂ

Organizarea programului experimental

(Rezumat)

Se prezintă programul experimental proiectat pentru studiul conlucrării materialelor compozite polimerice armate cu fibre (CPAF) din carbon ataşate de suprafețe din oțel, folosind adezivi specifici. In acest sens, programul experimental cuprinde asamblarea unor probe formate prin suprapunere simplă, compuse din lamele compozite (având moduli de elasticitate normali, medii şi mari) şi din două tipuri de adezivi, fiecare dintre aceştia fiind aplicați în grosimi de 1 mm, 2 mm şi 3 mm. Pentru fiecare combinație de tip de lamelă – tip de adeziv – grosime de adeziv, s-au executat câte trei probe, urmărindu-se obținerea unor valori concludente. Prin efectuarea acestui program experimental se analizează aspectele specifice conlucrării dintre oțel şi materialele compozite, dintre care, cele mai importante sunt : identificarea modurilor de cedare, descrierea procesului de aderență-lunecare dintre interfețe şi verificarea lungimii optime de conlucrare. Se pot verifica, de asemenea modelele de aderență şi eventualele corecții necesare.