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Bond behavior of FRP carbon plates externally bonded over steel and concrete elements: Experimental outcomes and numerical investigations

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The paper is firstly aimed to furnish a review of the current knowledge about the bond behavior of Fiber Reinforced Plastic (FRP)-steel joints with reference to: a) experimental results of bond tests available in the technical literature, and b) existing strength model for estimating the debonding load. In order to assess the influence of geometrical and mechanical properties of the adhesive on the debonding load, parametric analyses have been carried out by means of some selected bond strength models. The effectiveness of these models has been also checked by means of comparisons with experimental debonding loads collected from technical literature.

The second objective of the paper is the comparison of the bond behavior of FRP-steel and FRP-concrete joints in order to identify the role of the adhesive on the bond behavior separately from the concrete. The comparison is aimed to assess bond laws for FRP-concrete joints taking into account the only nonlinearities of the adhesive and to model the concrete as a nonlinear material. To this purpose few experimental bond tests were carried out by the Authors on carbon FRP plates bonded over both steel and concrete support according to the same lay-out and set-up. Finally, basing on the experimental bond law assessed for the FRP-steel joints, a Finite Element (FE) plane model with interface elements is developed for validating the experimental results of bond tests.

1. Introduction

Strengthening and repair of steel structures (old industrial buildings, bridges, off-shore platforms, etc…) are becoming increasingly necessary to extending their lifetime. Rehabilitation of steel structures is needed due to several reasons: 1) aging of steel elements and connections, 2) increasing of bearing load, especially traffic loads for bridges, 3) review of design codes, 4) need of higher grade of protection against corrosion due to environmental factors.

Traditional retrofitting techniques of steel structures consist in bonding external steel plates to the existing elements, nevertheless, innovative strengthening methods based on the use of Fiber Reinforced Polymers (FRP) materials are gaining more and more interest in the scientific community and diffusion in practical applications. Both experimental tests and real applications have, indeed, showed that high modulus CFRP externally bonded plates can be successfully used for repairing fatigue-damaged steel members; such technique allows, indeed, giving high structural efficiency and extending the life of the structural components at an economical cost [1]. FRP materials present several advantages compared to steel, such as: high strength-to-weight ratio, easier and fast transportation and installation [2], excellent corrosion and environmental resistance [2,3], reversibility and sustainability of retrofitting intervention [4], ability to follow irregular surfaces and high fatigue resistance [5]. Carbon and glass fiber-reinforced polymers (CFRP and GFRP, respectively) are the most widely used composite materials for strengthening steel structures, mainly because CFRP materials [6–8] have an elastic modulus comparable or higher than steel, while GFRP materials have large values of ultimate strain [2]. The main drawbacks of using FRP materials are the high costs, the sensitivity of strengthening effectiveness to application procedure, i.e. the control of adhesive thickness, the absence of an in-depth knowledge about durability of such

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reinforcing system, the possibility of galvanic corrosion between carbon and steel materials in presence of an electrolyte [7]. In Ref. [9] it was, indeed, evidenced that surface preparation and environmental exposure conditions can significantly affect bond durability of FRP-steel joints and potential galvanic corrosion problems for CFRP-steel systems should be considered.

In this paper a review of the current knowledge about the bond behavior of steel-FRP joint is carried out with the following purposes: 1) collect a database of experimental bond tests on FRP-steel joints; 2) review the existing formulations predicting the debonding load of FRP-steel joints subjected to pure shear stresses and assess their effectiveness by means of comparisons with experimental results of bond shear tests; 3) develop parametric analysis aimed to check the sensitivity of the selected bond strength models to adhesive properties. This later point is based on the experimental observation that the failure of FRP-steel joints generally occurs in the adhesive; thus, there is no influence of steel or FRP strength on the failure load [10] and design strength models based on only material strength (adhesive, steel) could be not reliable.

The second objective of the paper is the comparison of the bond behavior of FRP-steel and FRP-concrete joints in order to identify the effects of the adhesive in the bond law separately from the effects of the concrete. For FRP materials bonded over a concrete support, indeed, a major role in the bond behavior is played by the nonlinear behavior and the cracking phenomena of the concrete, while a secondary role is played by the adhesive. On the contrary, in case of FRP-steel joints, the nonlinearities of the bond behavior are related to the nonlinear behavior of the adhesive because the steel support usually remains in the elastic field and the yielding threshold is never attained. A numerical and experimental study aimed to investigate the strain distribution in CFRP-steel bonded joints carried out by Ref. [11] founded, indeed, that the non-linear deformation of the adhesive, even at low levels, can contribute to the redistribution of strain and joint capacity. This means that failure criteria based on maximum stress/strain coming from linear-elastic analysis are not able to give reliable predictions of bond strength for joints where nonlinear adhesives are used.

The experimental assessment of the role of the adhesive is also motived by the consideration that, in numerical analyses of FRP-concrete joints, nonlinear bond laws at the FRP-concrete interface are often considered, while a linear behavior is assumed both for adhesive and concrete. Thus, such nonlinear bond laws implicitly take into account all the nonlinearities related to both adhesive and concrete behavior. On the contrary, if the concrete is assumed nonlinear, with the aim of monitoring in detail the evolution of the cracking pattern in the concrete under the reinforcement, the nonlinearities of the bond law should be related to the only adhesive behavior. In this case the bond law, which has to be introduced in the model, should be different from the experimentally-based ones that take into account all the nonlinearities. Whatever approach is pursued, the use of zero-thickness interface elements is a very computationally efficient option for simulating the interface behavior of FRP-concrete joints in Finite Element (FE) models [12–14].

It is worth no tote that few studies are available in the technical literature about the comparison of the bond behavior of FRP materials applied over concrete and steel elements [1], nevertheless the strength models used for prediction the bond strength have often similar origin, i.e. the design methods based on fracture mechanics [10].

About this topic, the Authors present in this paper the results of some experimental bond tests carried out on CFRP plates bonded over both steel and concrete elements and tested according to the same lay-out and set-up. Because steel has a linear behavior and concrete a nonlinear behavior, the tests are aimed to identify the role of the adhesive in the bond law by comparing the experimental results of the two types of FRP joint; thus, the nonlinear bond laws experimentally assessed in the tests on the FRP-steel joints could be used in analytical or FE models where the concrete behavior is assumed nonlinear.

Finally, a FE plane model with interface elements simulating the FRP-steel bond behavior has been developed and compared with the experimental results of the FRP-steel joints evidencing a very satisfactory agreement both in terms of local and global measures.

2. Literature review of existing bond models for steel-FRP interface

As in concrete elements, both in simple steel-FRP joints and in steel elements, i.e. beams, externally bonded with FRP plates, debonding was the governing failure mechanism [5,15,16]. Bond behavior at FRP reinforcement–steel interface plays, thus, a key role in the evaluation of the maximum load, usually indicated as bond strength, that a FRP-steel joint can sustain.

The application of FRP materials on steel elements is a recent technique compared to application on concrete elements, even if such a strengthening technique for existing elements originates as the '*beton-plaquè*' technique based on the application of glued steel plates. However, development of solution methods for stresses in bonded joints with elastic adherends has been a popular area of research since the 1930s. Detailed experimental and theoretical studies about the bond behavior between steel elements bonded by adhesive were carried out by Ref. [17] in 1970s and general numerical procedures for solving stress analysis were developed by Ref. [18] at beginning of 1980s before the more recent use of FRP materials as strengthening technique for steel elements.

In the following, a brief review of the bond strength models available in literature for calculating the maximum load of steel-FRP bonded joints subjected to pure shear stresses (debonding load) is reported. In particular, attention has been focused on the strength models that are based on a fracture mechanics approach and furnish predictions for the maximum tensile loads in the FRP reinforcement.

2.1. *Strength model of Hart-Smith [17]*

One of the first study on the bond behavior between glued metallic materials was conducted by Ref. [17] that investigated the influence of the mechanical properties of the adhesive on the bond strength of double shear laps joints. The experimental tests evidenced that the peeling stresses were as more relevant as the steel plates are thicker and led to a premature bond shear failure before plate yielding. By contrast, for very thin plates, the bond strength increased and the failure occurred consistently outside the bonded joint. Moreover, the shape of the stress-strain curve of the adhesive was founded not influencing the bond strength, but affecting the bond stress distribution along the interfaces. The results and the model proposed in Ref. [17] can be extended to the case of steel-FRP joints. In particular, the ultimate load, P_{max}, of the joint is given by the following expression:

$$P_{\max} = b_f \cdot \min\{P_i, P_0\} \tag{1}$$

$$P_i = \sqrt{2 \cdot \tau_{\max} \cdot t_a \cdot \left(\frac{1}{2}\gamma_e + \gamma_p\right) \cdot 2 \cdot E_s \cdot t_s \cdot \left(1 + \frac{E_s \cdot t_s}{2 \cdot E_f \cdot t_f}\right)}$$
$$if\ E_s \cdot t_s < 2E_f \cdot t_f$$