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Local bond–slip behavior between cold-formed metal and concrete

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ABSTRACT

Composite action in systems consisting of steel and concrete depends on an effective shear-transfer mechanism between the two materials. Such mechanism for smooth steel surfaces inside concrete will be limited to the bond–slip behavior at the steel/concrete interfaces. This research investigates the bond–slip behavior of galvanized cold-formed (light gauge) steel profiles embedded in normal weight normal strength concrete. A new innovative pull-out test is presented which is convenient to set up and perform and reduces the undesirable parameters to the minimum. Global bond–slip curves for different values of concrete strength are obtained from such tests. Through an innovative procedure, mathematical equations and selected points from the experimental global bond–slip curves are used to develop a bi-linear local bond–slip model which represents the discussed bond–slip behavior. By curve fitting, empirical equations are proposed to determine the suggested model's parameters based on the concrete compressive strength. Finally, validity of the proposed model is explored by two methods: (1) by comparing the results from analytical equations with test results, (2) by comparing the results from finite element modeling with test results. An excellent agreement has been observed in both verification methods.

1. Introduction

While there can be found ample scientific documents in the literature regarding the bond–slip behavior between ribbed (deformed) rebars or fiber reinforced polymer (FRP) sheets and concrete, very few focus on bond–slip of plain surface steel plates. This has been due to the little importance of the latter in structural designs to this date. However, with the recent growth of light gauge steel use in composite constructions [16,17,32], a necessity for studying the behavior of light gauge steel profiles embedded in concrete has become significant.

The aim of this research is to develop and verify a local bond–slip model which can represent the behavior of cold-formed (light gauge) galvanized profiles and plates embedded in normal weight normal strength concrete. The paper begins with setting up and solving the bond–slip governing differential equation based on a bi-linear behavior and specific boundary conditions to obtain the necessary mathematical equations, then a new and unique test set-up is introduced for the experimental studies and the results are presented. Afterwards, a new innovative procedure is described and followed to calibrate the mathematical equations based on pieces of information from the test data and from there; a local bond–slip model is developed. Finally, the suggested model is verified to explore its validity.

1.1. Bond tests

Experimental studies on bond–slip behavior are often conducted through the pull-out test. Generally in this test, a steel member is partially embedded into a concrete block. While the concrete block is kept fixed in place, the steel member is pulled out by a gradually increasing force. In a push/pull-out test, the concrete block is fixed at the plate embedment side such that the tension increase on steel plate causes compressive stress in concrete (see the set up in Fig. 1). In a pull/pull-out test, however, the concrete block is fixed on the opposite side of plate embedment and is consequently subjected to tensile stresses (see the set up in Fig. 6).

Although it is possible to directly find an experimental local bond–slip curve through this test, the procedure requires a sophisticated and precise set-up and in the end the results can be inaccurate [15]. Results from the pull-out test with an easy set-up will be a load–displacement curve in which the load represents total bond force and the displacement represents slip of the plate at the beginning of embedment in concrete. This

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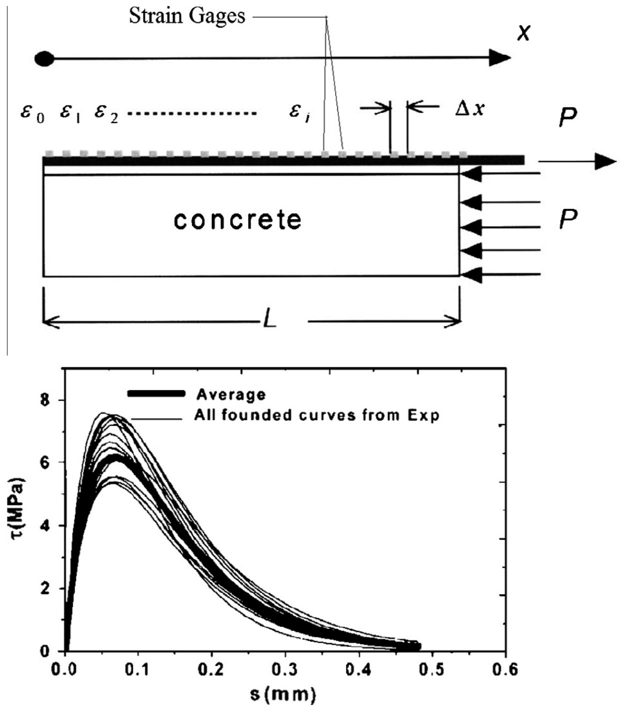

Fig. 1. Test set-up and resulting local bond–slip curve [11].

load–displacement curve can be referred to as "Global Bond–slip Behavior" and will be used to predict the local bond–slip behavior through an analytical procedure.

2. Literature review

Several researches in the literature on bond of reinforcing rebar in concrete [13,7] provide excellent insight into such bond–slip behavior. such bond–slip behavior is out of the scope of this research. The bond between smooth plates and concrete mainly depends on chemical adhesion and friction, and there is only a very small mechanical interlocking due to the roughness of the plate surface.

Although the material properties of FRP sheets are quite different from those of steel plates, their general bond–slip behavior with concrete is very close to that of steel plates since their bond also mostly depends on chemical adhesion and friction. That is why some researchers have considered the same principles of local bond–slip behavior for both FRP and steel sheets [8]. Dai et al. [11] directly studied the local bond–slip behavior between externally bonded FRP sheets and concrete through an experiment (bonding agent was used between two materials). In their study, a set of single lap pull-out tests were carried out on FRP sheets characterized by different values of FRP stiffness. Many pairs of strain gauges were used with small spacing to capture local slips. Local bond stress can be obtained when local strain of FRP, the amount of applied load and the FRP constitutive law are known. In Fig. 1, the test set-up is shown together with the output graph. Based on the average output graph, the researchers were able to establish a relationship for the bond–slip behavior.

Lu and Dong [24] conducted a special experiment to study the local bond–slip behavior between a concrete wall and the steel profile encased in it. They also proposed a bond–slip relationship and compared it with the test results. The researchers eventually used their obtained bond–slip relationship in a finite element simulation and compared the results with the experiment.

In order to find the local bond–slip behavior through an analytical procedure, a local bond–slip relationship has to be initially assumed. In Fig. 2, some local bond–slip relationships proposed by Yuan et al. [30] for steel/composite laminates are shown. Other local bond–slip relationships have also been proposed in literature such as the one in CEB-FIP Model Code [9] for ribbed bars. Obviously, the local bond–slip relationships for plain surfaces should be different from the ones for ribbed surfaces.

In Fig. 2, τ_f is called local bond strength and G_f, which is the total area under the curve, is called interfacial fracture energy and can be defined as the energy required to bring a local bond element to shear fracture (debonding) [30]. The unknown parameters, τ_f, δ_1 and δ_f can be estimated on the basis of a global bond–slip behavior from tests and using an analytical procedure.

There are many researches regarding the study of bond–slip behavior between concrete and FRP sheets through analytical modeling and experiments. Cosenza, Manfredi, and Realfonzo conducted an investigation on the bond of "FRP rebars" to concrete [10]. Focacci et al. [14] calibrated the unknown parameters of a local bond–slip relationship and then used it to simulate their pull-out test. By comparing the numerical results with the experimental data, they concluded that the longer the embedment length, the more consistent results can be obtained.

Lu et al. [22] assessed a group of proposed bond–slip relationships for FRP sheets in simulation using a new method of finite element modeling and calibrated the models using a large test database. They eventually proposed three new bond–slip relationships with different levels of sophistication which were claimed to be more accurate. These researchers in another similar work [23] concluded that typical bond–slip curves should consist of an ascending branch with continuous stiffness degradation to the maximum bond stress and a curved descending branch reaching a zero bond stress at a finite value of slip. While a precise bond–slip relationship should consist of a curved ascending branch and a curved descending branch, other shapes such as bilinear relationship can be used as a good approximation.

Pellegrino et al. [28] during an extensive experimental program, tested 39 specimens with various types of FRP reinforcement in both shear and bending. They evaluated some common bond–slip relationships and came up with some expressions for effective bond length, maximum bond stress, slip at peak value of bond stress and slip at the ultimate state of debonding.

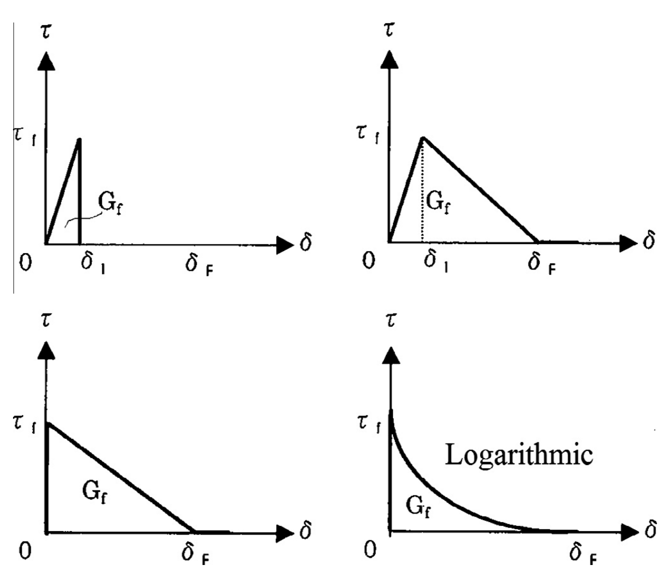

Fig. 2. Some proposed local bond–slip relationships [30].