Complex Analysis and Geometry (2022)
Clausius Scientific Press, Canada

DOI: 10.23977/compag.2022.020101
ISSN 2523-5966 Vol. 2 Num. 1

Discussion about the Models of the Stress-Slip Curve of Near Surface Mounted CFRP Reinforcement Bond

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Keywords: Strengthening Concrete Structure, CFRP, Concrete Structure Refurbishments, NSM, Bond

Abstract: Carbon-fibre-reinforced polymer (CFRP)-the currently produced materials are now widely used for bridges and the strengthening and retrofitting of concrete structures. Large amounts of research has been directed to characterize the bond behaviour since FRP rods were proved to be good composites which can be used in construction industries, especially as the near-surface mounted reinforcements. E. Cosenza, G. Manfredi and R. Realfonzo (1997) carried out a series of tests in which the influence of type of fibre, outer surface (shape and type of concrete matrix), and other significant parameters (i.e., confining pressure, bar diameter, compressive concrete strength) on bond performance was investigated. Furthermore, some analytical models of bond-slip behaviour were examined to assess their adequacy to reproduce the experimental bond behaviour. However, it is evident that more information is still required to provide confidence for the design of the CFRP structures and for the development of design standards. This paper investigates different stress-slip models of the Near Surface Mounted CFRP rods that previous researchers suggested and try to recognize the difference between different models by comparisons.

1. Introduction

The use of near surface mounted (NSM) carbon fibre reinforced polymer (CFRP) rods is proved to be a technology which can increase the flexural and shear strength of the deficient reinforced concrete (RC) members [1]. Recently, considerable research has been directed to characterize the use of the FRP bars and strips as near surface mounted reinforcement. However, it is evident that more information is still required to provide confidence for the design of the CFRP structures and for the development of design standards.

Many constitutive models have been used to model the bond stress-slip relationship, such as: the “Tri-Linear” model, the “BEP” model, the “Modified-B.E.P.” model, the “CMR” model, the “Naaman” model and the “Malvar” model. Every model has its own characteristic. In this paper, we are going to discuss the advantage and disadvantage of the above models on modelling the bond stress-slip relationship.

2. Models and Methods

The results of the short-embedded-length pull-out tests are used to calibrate constitutive models for the CFRP-concrete bond. These are in terms of the variation in shear stress(τ) with the loaded end slip(s) of the CFRP relative to the concrete [2,3]. Many constitutive models have been suggested by researchers to represent the relationship between the short-embedded-length shear stress and the slip.

Generally, there are three different zones in most of the models (The B.E.P. Model is not included):

- The primary bond mechanism (the primary zone)
- Degradation of the primary bond mechanism (the degradation zone)
- The secondary bond mechanism (the secondary zone)

The primary zone usually corresponds to the ascending branch of the τ-s curve. Degradation of the primary bond mechanism is generally brittle for CFRP reinforcement, and hence the degradation zone is generally short.

Details of all six constitutive models mentioned above are given below.

2.1 The "Tri-Linear" Model

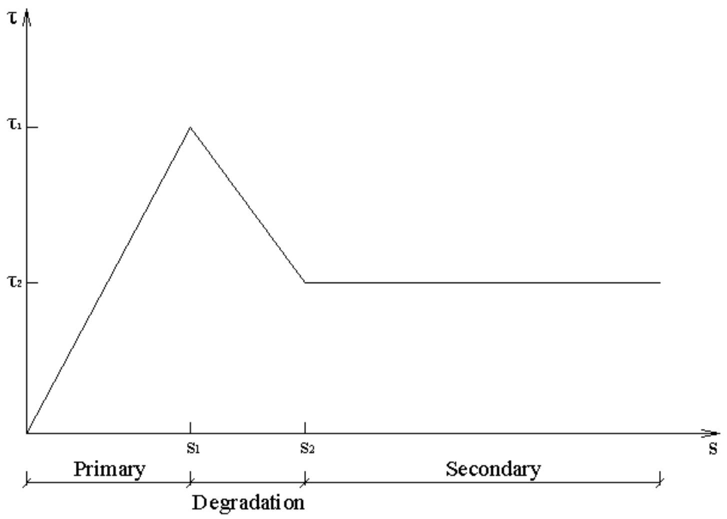

Figure 1: The Tri-Linear Model

For this model (Figure 1), it contains three liner segments. It has been used by Sheard and Rotásy & Budelmann to model short-embedded-length tests using aramid and glass fibre reinforcement respectively.

There are two significant points on the model which are defined by the peak bond-stress (τ_1) and the corresponding slip (s_1); and the bond-stress and slip at the start of the secondary bond mechanism zone (τ_2, s_2).

The model is inaccurate in the primary zone and a liner relationship cannot be solved for long-embedded-length specimens [4].

2.2 The “B.E.P.” Model (or C.E.B. Code Model)

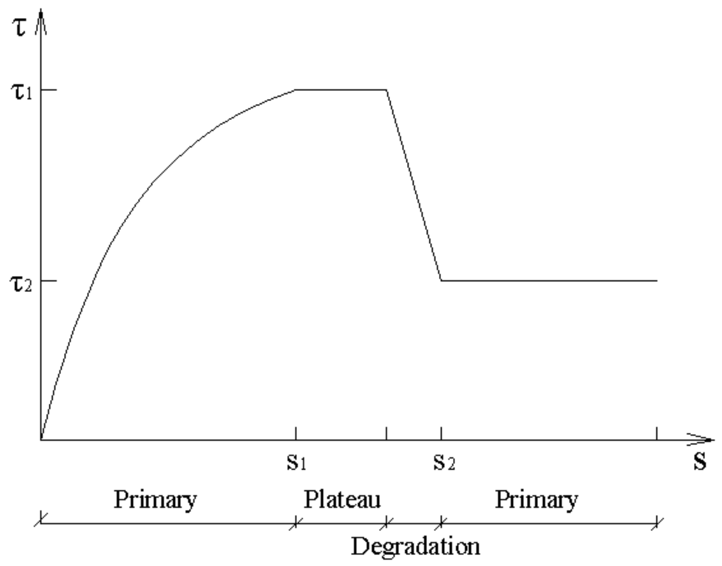

Figure 2: The “B.E.P.” Model

For this model shown in Figure 2 above, the primary zone is non-liner:

$$\tau = \rho_1 s^{\Omega} \quad (1)$$

Where,

$$\rho_1 = \tau_1 / s_1^{\Omega} \quad (2)$$

Ω is an empirical constant (|Ω|<1) which describes the shape of the *τ-s* curve. The plateau followed by a degradation zone is at the peak stress (τ_1) and the bond-stress due to the secondary bond mechanism is constant (τ_2).

This model is used in the CEB-FIP Model Code for steel-reinforced concrete, so it is not applicable to CFRP reinforced concrete [5].

2.3 The “Modified-B.E.P.” Model

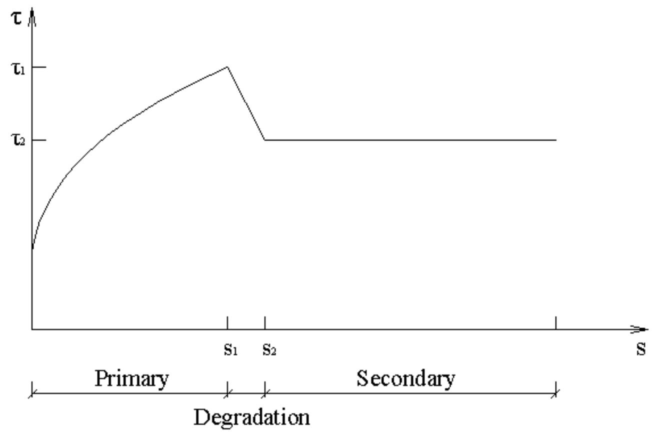

Figure 3: The “Modified-B.E.P.” Model

After applying the BEP Model to the CFRP reinforcement, many researchers found from their results that the peak bond-stress plateau is not present, that gives the Modified BEP Model which is shown in Figure 3 above.

Behaviour in the remaining three zones is as for the B.E.P. model. In the degradation zone [6]:

$$\tau = \rho_2 - \rho_3 s \quad (3)$$

$$\rho_2 = \tau_1 + \rho_3 s_1$$

And,

$$\rho_3 = \frac{\tau_1 - \tau_2}{s_2 - s_1} \quad (4)$$

2.4 The "CMR" Model

Cosenza et al. proposed an alternative formulation for primary zone, which fits experimental results more closely [7]:

$$\frac{\tau}{\tau_1} = (1-\exp[-s/s_r])^{\beta} \quad (5)$$

Where β and s_r are empirical constants.

2.5 The "Naaman" Model

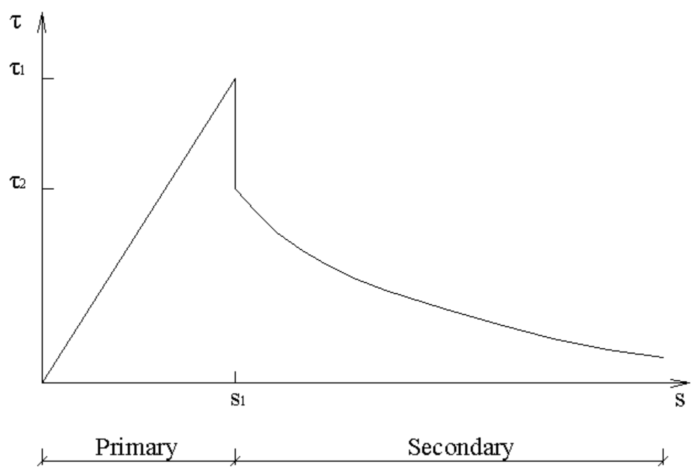

Figure 4: The "Naaman" Model

Figure 4 above shows the Naaman model which uses a liner-elastic primary zone, with a sudden drop in bond-stress at s_1. For higher slips friction dominates, but unlike other models, the bond-stress in the friction zone varies. Poisson effects and deterioration of the interface are considered to determine the bond-stress in the secondary zone [8].

2.6 The "Malvar" Model

A single relationship for all zones of the τ-s curve was proposed by Malvar [9]:

$$\frac{\tau}{\tau_1}=\frac{F_1(s/s_1)+(G-1)(s/s_1)^2}{1+(F_1-2)(s/s_1)+G(s/s_1)^2} \qquad (6)$$

Where, F_1 and G are empirical constants.

The lack of the discontinuities aims to simplify subsequent analysis. However, the primary bond mechanism is not modelled accurately.

For the relationships of how the peak stress and corresponding slip vary with the radial confining pressure (σ_d), and how the concrete strength affects bond, Malvar gave other two formulations which involve five constants (*A, B, C, D* & *E*) which are readily related to specimen properties:

$$\frac{\tau_1}{f_t}=A+B(1-\exp[-C\sigma_d/f_t]) \ ; \qquad s_1=D+E\sigma_d \qquad (7)$$

Where: f_t is the tensile strength of the concrete.

The relationship were derived from specimens that failed by splitting along the reinforcement.

3. Discussions

Comparing the CEB, Modified-B.E.P. and the CMR models, it seems that the CMR model is the one that fits the primary zone best, and the Malvar model is inaccurate for the primary zone; all of them are well fit for the remaining zones.

4. Conclusions

Although, the CMR model is slightly more accurate in the primary zone than the other two, solution of the resulting governing equation is more complicated. The Modified-B.E.P. model is used widely at present.

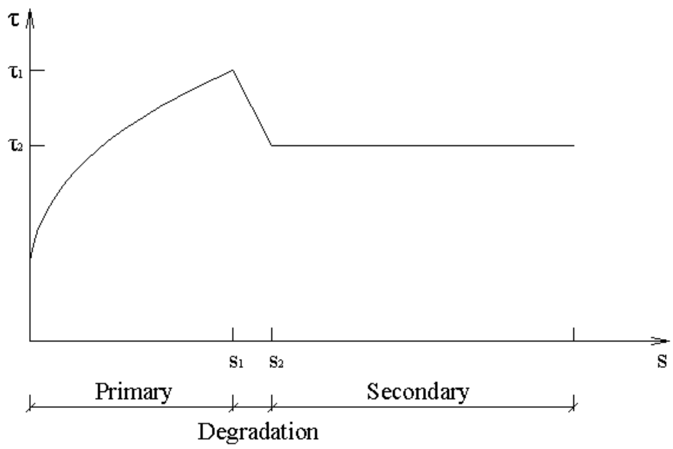

Figure 5: The Modified-B.E.P. model

There are three parts in the Modified-B.E.P. model (Figure 5) [10]:

- A non-linear ascending branch, of the form ($s<s_1$) [Primary zone]:

$$\frac{\tau}{\tau_1} = (\frac{s}{s_1})^{\Omega} \quad \text{or} \quad \tau = \rho_1 s^{\Omega} \tag{8}$$

Ω describes the shape of the ascending branch, τ_1 is the peak shear stress and s_1 is the corresponding slip and $\rho_1 = \tau_1 / s^{\Omega}$.

• A linear descending branch, describing degradation of the concrete- reinforcement bond ($s_1<s<s_2$) [Degradation zone]:

$$\tau = \tau_1 + \frac{\tau_2 - \tau_1}{s_2 - s_1}(s - s_1) \quad \text{or} \quad \tau = \rho_2 - \rho_3 s \tag{9}$$

Where,

$$\rho_2 = \frac{s_2 \tau_1 - s_1 \tau_2}{s_1 - s_2} \quad \text{and} \quad \rho_3 = \frac{\tau_1 - \tau_2}{s_2 - s_1}$$

• A constant shear stress, representing residual friction ($s_2<s$) [Secondary zone]:

$$\tau = \tau_2 \tag{10}$$

The values of σ_1, σ_2, σ_3 and Ω are parameters to be found.

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