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A numerical procedure for determining FRP bar-concrete bond parameters

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Abstract
In bond tests of FRP bar-concrete bond behaviour, if the FRP bar has a low elastic modulus or its bonded length is large, there may be a large difference between the slips at the loaded and free end. In such cases, the conventional approach for deriving the bond-slip relationship based on the assumption of a constant distribution of both bond stress and slip may be inadequate. In this study, an FE-based numerical optimization procedure for the identification of the bond-slip model parameters of FRP bar-concrete is proposed. This is accomplished by coupling the Open System for Earthquake Engineering Simulation (*OpenSees*) with Sparse Nonlinear Optimization (SNOPT). Here *OpenSees* serves as the finite-element analysis tool for modelling the bond behavior of FRP bars embedded in concrete. The SNOPT is the optimization tool, used to identify the optimal parameters of the bond-slip model. This approach is applied to a number of pull-out tests to determine the bond parameters. A good agreement is observed between the numerical and experimental pull-out load-slip curves at both the loaded and free end. This approach can take into account the non-uniform distribution of slip and bond stress along the embedment length, suitable for any bar type (steel or FRP) with any embedment length.

Keywords: FRP bar; bond-slip model; numerical approach; optimization

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Introduction

The bond behaviour of reinforcing bars strongly influences the performance of reinforced concrete structures at both the serviceability and the ultimate limit state. This applies to both steel and fibre reinforced polymer (FRP) reinforcement bars. Compared to steel, FRP bars are usually anisotropic and linear elastic with lower elastic modulus, leading to different bond characteristics between them. The bond behaviour between an FRP bar and concrete is commonly tested using either the pull-out test or a beam type test. Several methods have been used to identify the bond-slip model parameters from the test data. However, there is still a lack of objective assessment of the reliability and suitability of these methods, especially for FRP bars. In this study, the available methods are first reviewed and both their advantages and disadvantages are discussed. An FE-based optimization procedure is proposed to identify the local bond-slip model parameters. This approach is then applied to some bond tests of FRP bars with different embedment lengths to assess its validity.

Existing methods for determining bond-slip models

The first method is based on the assumption that both the bond stress and slip are uniformly distributed along the embedment length [1]. The average bond stress versus the slip at either the loaded or the free end curves are considered as the local bond-slip relationship. However, experimental studies have shown that slips at the loaded and free end are significantly different, and the average bond strength is dependent on the bond length due to the nonlinear distribution of the bond stress along the bond length.

Focacci et al. [2] and Pecce et al. [3] later developed a numerical procedure for identifying the bond parameters from the test data. Firstly, a preliminary set of parameters is chosen for a certain bond-slip model. Next, the pull-out test is numerically simulated by solving the governing equation. Thirdly, the numerical results are compared with the test data to determine their differences. Fourthly, these steps are repeated with a new set of bond parameters, until the optimal set is identified. In this method, a proper objective function shall be carefully selected, and the optimal bond parameters are obtained by minimizing this function. This numerical method is suitable for any bar type with any embedment length. In contrast, the first method may only be applicable for cases with short embedment lengths.

An FE-based numerical optimization approach

In this study, an FE-based numerical optimization procedure is proposed for the identification of local bond-slip model parameters of reinforcing bars embedded in concrete. This is accomplished by coupling the Open System for Earthquake Engineering Simulation (*OpenSees*) with Sparse Nonlinear Optimization (SNOPT) [4]. As an open-source object-oriented FE analysis software framework, *OpenSees* serves as the finite-element analysis tool and is used to model the pull-out behaviour of FRP bars embedded in concrete. The concrete is assumed to be a rigid body. The FRP bar is discretised into many elastic elements. The FRP bar-to-concrete interface is modelled using spring elements, whose properties are defined using the bond-slip model. The numerical optimization procedure can be implemented in the following steps:

1) For a given pull-out test, organise the pull-out force versus the loaded or free end slip (depending on the availability) in pairs, such as (P_{li}, s_{li}) or (P_{fi}, s_{fi});
2) For a selected bond-slip model $\tau = \tau(s)$, select a preliminary set of values for the model parameters;

3) Conduct an FE analysis using the above set of parameters to determine the relationship between the applied pullout force and slip, i.e. $(\overline{P_{li}}, \overline{s_{li}})$ or $(\overline{P_{fi}}, \overline{s_{fi}})$;
4) Calculate the error function value using the above two sets of data, e.g. Eq. 1a or 1b:

$$E_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\overline{P_{li}} - P_{li}}{P_m}\right)^2} \quad (1a)$$

$$E_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\overline{P_{fi}} - P_{fi}}{P_m}\right)^2} \quad (1b)$$

where N = the number of loading steps; P_m= the maximum pullout force of the test;

5) Repeat steps 3) and 4) until the optimal values of the parameters for the local bond-slip model are achieved through minimizing E_r. The SNOPT-based optimization based on a sequential quadratic programming (SQP) algorithm [4] is used in this study to minimise E_r.

Identification of a bond-slip model parameters

The proposed FE-based optimization approach was applied to 5 pullout tests of FRP bars from [5, 6]. These specimens are summarised in Tale 1. The modified BPE model was used to describe the local bond behaviour, the details of which can be found in [1].

The identified optimal parameters of the modified BPE model for each specimen, as well as the corresponding error E_r are listed in Table 1. Using these bond-slip model parameters, the numerical relationship between the applied load and the free end (or loaded end) slip were determined for each specimen by using the FE model in *OpenSees*. These load-slip curves were then used to calculate the average bond stress along the embedment length, resulting in the numerical average bond stress-slip curves. Fig. 1 shows a close agreement between the numerical and experimental average bond stress-slip curves for these specimens. This close agreement is also confirmed by the low values of E_r (less than 5.0%) for all the specimens.

Table 1. Details of tested specimens and main results.

							Peak state			BPE modified model					
Specimen	Reference	N	f_c' (MPa)	E_f (GPa)	Fiber type	D (mm)	δ_L (mm)	δ_F (mm)	τ_{ave} (MPa)	α	s_m (mm)	τ_m (MPa)	P (MPa/mm)	k	E_r (%)
13-6d-2	Tekle et al. (2016)	6	43.4	68	G	12.7	0.71	0.45	16.0	0.231	0.450	16.2	1.69	0.60	3.4
16-6d-2		6	42	62.6	G	15.9	0.56	0.27	13.7	0.160	0.308	14.1	4.89	0.20	2.0
16-9d-1		9	42	62.6	G	15.9	0.81	0.18	12.3	0.248	0.275	12.6	1.81	0.48	4.6
B10-70-1	Refai et al. (2014)	7	50	48	B	10	0.48	0.2	10.5	0.15	0.240	10.5	1.61	0.39	4.7
B10-150-1		15	50	48	B	10	1.33	0.23	10.80	0.076	0.332	11.2	1.01	0.48	3.3

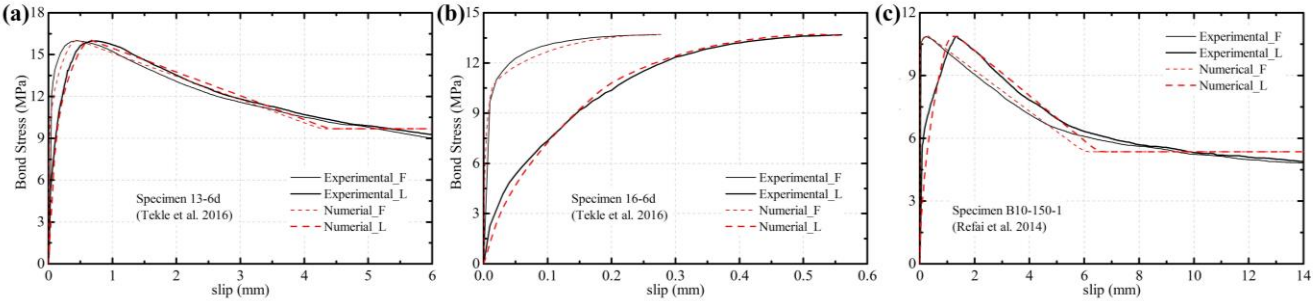

Fig. 1. Experimental results and numerical predictions using the optimal model parameters

Conclusions

To identify the local bond-slip model parameters of FRP bars embedded in concrete, a new FE-based optimization approach has been proposed. The new approach combines the Open System for Earthquake Engineering Simulation (*OpenSees*) with Sparse Nonlinear Optimization (SNOPT) to obtain the optimal parameters for the bond-slip model. *OpenSees* serves as the finite-element analysis component and is used to model the bond behaviour of FRP bars embedded in concrete. The SNOPT is used as the optimization tool for minimising the error function E_r. This approach has been applied to some pull-out tests with different bar types, concrete compressive strength and embedment lengths. A good agreement is achieved between the numerical and experimental average bond stress-slip curves at both the loaded and free end.

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