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Engineering bond model for corroded reinforcement

Mattias Blomfors[a,b,*], Kamyab Zandi[b], Karin Lundgren[b], Dario Coronelli[c]

[a] RISE CBI Swedish Cement and Concrete Research Institute, Sweden
[b] Chalmers University of Technology, Sweden
[c] Politecnico di Milano, Italy

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ABSTRACT

Corrosion of the reinforcement in concrete structures affects their structural capacity. This problem affects many existing concrete bridges and climate change is expected to worsen the situation in future. At the same time, assessment engineers lack simple and reliable calculation methods for assessing the structural capacity of structures damaged by corrosion. This paper further develops an existing model for assessing the anchorage capacity of corroded reinforcement. The new version is based on the local bond stress-slip relationships from *fib* Model Code 2010 and has been modified to account for corrosion. The model is verified against a database containing the results from nearly 500 bond tests and by comparison with an empirical model from the literature. The results show that the inherent scatter among bond tests is large, even within groups of similar confinement and corrosion level. Nevertheless, the assessment model that has been developed can represent the degradation of anchorage capacity due to corrosion reasonably well. This new development of the model is shown to represent the experimental data better than the previous version; it yields similar results to an empirical model in the literature. In contrast to many empirical models, the model developed here represents physical behaviour and shows the full local bond stress-slip relationship. Using this assessment model will increase the ability of professional engineers to estimate the anchorage capacity of corroded concrete structures.

1. Introduction

Many concrete structures are subjected to damaging processes, corrosion of the steel reinforcement being the most common [1]. The damage panorama ranges from corrosion in its initial stages, undetectable upon ordinary inspection, to large cracks or even spalling of the concrete cover. Climate change is expected to accelerate the deterioration, so even more severe damage over a shorter timespan may be expected in future [2]. Furthermore, demands for greater load-bearing capacity of bridges often grows with time. Thus, there is major (and increasing) demand for reliable methods to assess the capacity and remaining service life of existing infrastructure.

When reinforcement in concrete is subjected to corrosion, internal pressure is created due to the volumetric increase upon the formation of iron oxides. If the confinement of the surrounding concrete is sufficient, this may initially increase the bond capacity. As corrosion of the reinforcement bars propagates, the surrounding concrete eventually fails to carry the induced tensile stresses and longitudinal splitting cracks develop. Consequently, confinement diminishes and the bond capacity decreases [3–5]. After cracking, the capacity may either decrease markedly with further corrosion, as with minor levels of transverse reinforcement, or it may increase slightly as is the case with substantial stirrup content [6–9]. Furthermore, corrosion of reinforcement reduces the cross-sectional area of reinforcing bars, and thereby their capacity and ductility [10,11]. As many reinforcing bars have stronger steel close to the surface than in the centre of the bar, corrosion may also reduce the tensile strength of the rebar [12].

On the structural level, corrosion reduces not only the shear and moment capacity but also affects tension stiffening, and consequently the deflection and crack widths. Furthermore, plastic rotation capacity is affected. This influences moment redistribution in indeterminate structures, as well as robustness and seismic resistance [13]. In general, concrete structures are designed to show ductile failure if their ultimate capacity is exceeded, thus allowing people to avoid immediate danger. However, a corroded structure may collapse abruptly. For example, sudden bond failure in bridge beams at anchorage zones and curtailment ends can occur as a direct consequence of bond deterioration from corrosion. Reliable assessment of structural capacity is therefore particularly important.

In order to utilise the knowledge gained from previous research and advanced modelling [14,15] in engineering practice, there is a need for simplified models. These must be sufficiently accurate and time-

* Corresponding author at: Department of Architecture and Civil Engineering, Division of Structural Engineering, Sven Hultins gata 8, SE-412 96 Gothenburg, Sweden.
E-mail addresses: blomfors@chalmers.se (M. Blomfors), kamyab.zandi@chalmers.se (K. Zandi), karin.lundgren@chalmers.se (K. Lundgren), dario.coronelli@polimi.it (D. Coronelli).

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effective for assessing existing structures. Previous work has established an analytical one-dimensional model for assessing anchorage in corroded reinforced concrete structures [16], denoted here as ARC1990. Its original formulation stems from the analytical local bond stress-slip model in Model Code 1990 [17], but has been modified based on results from a parametric study using 3D nonlinear finite element (NLFE) analyses to account for the effect of corrosion [18,19]. Subsequent verification includes a comparison with test results from naturally corroded specimens [20], a validation against 3D NLFE analyses and test results from high-level corrosion attacks that have led to cover spalling [21].

The relevance of the model in a practical context has been demonstrated in a pilot study of two bridges in Stockholm, Sweden [22]. It was shown that for these two bridges, use of the model reduced costs by approximately €3 million as unnecessary strengthening could be avoided. The Swedish Road Administration manages 20,000 bridges and there are around one million bridges in EU27, a large portion of which are made of reinforced concrete and located in corrosive environments. Considering this, the potential cost savings for society are enormous, if reliable assessment methods are made available for engineering practice.

Besides demonstrating the great capabilities of the analytical local bond model, the pilot study helped identify areas for its improvement. Areas identified as important for practical use were: incorporating the cross-sectional position of the bar being studied, and the influence of transverse reinforcement. This was enabled by implementing the *fib* Model Code 2010 [23] in the model, denoted as ARC2010. The primary aims of this paper are implementation and verification of the new model against a large bond test database of corroded specimens, plus an empirical expression.

Section 2 presents a background for assessing anchorage in corroded reinforced concrete and a comparison between local bond stress-slip relationships in *fib* Model Code 1990 and 2010. There is also a description of ARC2010, the proposed engineering bond model for corroded reinforcement. Section 3 presents a collection of bond tests of corroded specimens, plus calibration and verification of the proposed bond model. The results are discussed in Section 4, and conclusions and an outlook are given in Section 5.

2. A proposed engineering bond model

2.1. Assessment of anchorage in corroded RC structures

Analytical procedures for assessing anchorage capacity and other aspects of structural behaviour can differ in complexity, depending on the extent to which actual physical behaviour is to be captured. Ideally, a more complex analysis should mean improved representation of actual behaviour in comparison with a simpler analysis. However, the cost in terms of an analyst's time and expertise will be higher.

2.1.1. Different levels of assessment

The level of detail in a structural assessment can be divided into several categories. This approach is based on the principle of successively improved evaluation in structural assessment and comprises four different assessment levels [24], level I being the simplest and level IV the most advanced. A description of the assessment levels is presented in Fig. 1.

Assessment levels I and II are strength based and one dimensional (1D) approaches, respectively. These do not require a non-linear finite element (NLFE) analysis and are considered suitable for application in engineering practice. In level I assessments, only the residual capacity given by the local bond stress-slip relationship is considered over an assumed anchorage length. In the more refined level II approach, the entire local bond stress-slip relationship is used to solve the 1D differential equation over the available anchorage length and obtain the anchorage capacity. Levels III and IV require the use of NLFE analyses. The main difference is that in level III the interaction between reinforcement bars and concrete is treated using local bond stress-slip relation, whilst in level IV the interaction is explicitly represented by models describing the bond action, cf. Lundgren 2005a [25] and models accounting for the influence of corrosion, cf. Lundgren 2005b [26], applied to the interface between reinforcement bars and concrete. The latest developments include advanced models for the interaction between mechanical and non-mechanical effects of corrosion, cf. Ožbolt et al. [27]. In this paper, the assessment of anchorage has been carried out according to assessment level II. A more detailed description of this level is presented in the following section.

2.1.2. Description of anchorage assessment level II

In assessments at level II, the force that can be anchored is calculated by solving the equilibrium conditions along the reinforcement bar. The differential equation [16] is:

$$\frac{\pi\cdot\phi_m^2}{4}\cdot\frac{d\sigma_s}{dx}-\pi\cdot\phi_m\cdot\tau_b=0 \tag{1}$$

where ϕ_m is the reinforcement diameter, σ_s is the stress in the reinforcement and τ_b is the local bond stress. The reinforcement bar within the anchorage length is assumed to be in the elastic range, thus:

$$\sigma_s=E_s\varepsilon_s,\quad \varepsilon_s=\frac{du}{dx} \tag{2,3}$$

where E_s is the elastic modulus, ε_s is the strain and u denotes the displacement of the reinforcement bar. The bond stress τ_b is defined by the local bond stress-slip relation. For an uncorroded case, the local-bond slip relationship from, say, Model Code 2010 [23] can be used to assess the anchorage. For a corroded bar, modified local bond stress-slip curves as suggested in this paper can be used; see Section 2.3. If the deformation of the surrounding concrete is neglected, the slip, s, equals the displacement of the rebar:

$$u=s \tag{4}$$

When considering pull-out of a reinforcement bar with embedment length l_b and prescribed displacement u_{l_b}, the boundary conditions are:

$$\sigma_s(0)=0,\quad u(l_b)=u_{l_b} \tag{5,6}$$

The differential equation can be solved numerically to obtain the steel stress and deformation along the rebar, and accordingly also the pull-out force and average bond stress over the embedment length.

2.2. Comparison of local bond stress-slip relationships in model Code 1990 and 2010

The difference between the local bond stress-slip relationships from the two versions of Model Code and the resulting influence when used in a level II assessment are presented in Sections 2.2.1 and 2.2.2 respectively.

2.2.1. Original local bond stress-slip relationships in model Codes 2010 and 1990

The analytical one-dimensional model for the assessment of anchorage in corroded reinforced concrete structures in [16] was based on the local bond stress-slip relationship in Model Code 1990 [17]. There, the confinement conditions are defined as either "confined" or "unconfined", corresponding to pull-out and splitting failure respectively. Interpolation between these cases can be carried out based on concrete cover to bar diameter ratio and stirrup content.

In Model Code 2010, the local bond strength corresponding to splitting of the specimen is calculated explicitly; this governs the local bond stress-slip relation, if it is smaller than the pull-out strength [23]. The local bond strength expressions in Model Codes 1990 and 2010 have a common feature in the differentiation between "Good bond conditions" and "All other bond conditions". "Good bond conditions"