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Crack opening prediction at casting joints with a new modified stress-strain law for embedded reinforcement

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HIGHLIGHTS

- An accurate Finite Element method to calculate crack width at joints is proposed.
- The procedure that is proposed is not computational demanding.
- The method relies on a modification of the stress-strain law od steel bars based on rational bond-slip model.

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ABSTRACT

Durability of concrete infrastructures is highly influenced by crack openings. Sensitive components of concrete structures are construction joints that appear both at "in situ" and pre-cast structures. Current codes do not accurately predict, nor in the side of safety, crack openings at joints. This paper provides a new calculation tool in order to accurately calculate these cracks to enhance the durability prediction of construction joints. In order to validate the new calculation method, results obtained with the new methodhave been compared with test results. This tool is based on an equivalent stress-strain constitutive law for reinforcements that considers the bond-slip model provided by Model Code 2010. Models calculated with this new equivalent embedded reinforcement stress-strain law showed accurate predictions for crack openings at construction joints for different types of concrete.

1. Introduction

Reinforced concrete structures constitute a large part of the existing critical infrastructure stock. Improving the durability of such structures is a critical factor in moving towards having more sustainable infrastructures [1–4]. A key structural component that is detrimental to a reinforced structure's durability is construction joints. These joints, however, have been found to be prone to early cracking and, thus, susceptible to corrosion damage.

The ASCE Report Card for America's Infrastructure pointed out in 1998 that 31.4% of American bridges were structurally deficient or functionally obsolete and would require an investment of 80 billion dollars [5]. In the United Kingdom, repair and maintenance accounts for almost 45% of the UK's fiscal activity in the building and construction industry. Furthermore, according to the Department of Environment, Food & Rural Affairs (DEFRA), the building and construction industry is estimated to be responsible for up to 50% of the CO2 production in the UK [6]. Maintaining expansion joints at bridges accounts for 7–8% of the global maintenance cost of bridges in France [7]. With regard to Chloride-induced corrosion, according to the UK Department for Transport, the annual cost to repair concrete structures damaged by reinforcement corrosion is estimated at £755 million [8].

Current codes such as Model Code 2010 [9], Eurocode 2 [10] and EHE [11] predict crack openings as a function of bond-slip ($\varepsilon_{sm} - \varepsilon_{cm}$) which depend on the tensile strength of concrete (f_{ctm}) as can be seen in Eqs. (1–3).

$$w_k = S_{r,max}(\varepsilon_{sm} - \varepsilon_{sm}) \quad \text{Model Code 2010} \tag{1}$$

$$w_k = S_{r,max}(\varepsilon_{sm} - \varepsilon_{sm}) \quad \text{Eurocode 2} \tag{2}$$

$$w_k = S_{r,m}\left(\frac{\sigma_s}{E_s}\right)\left[1 - k_2\left(\frac{f_{ctm,fl}}{\sigma_s}\right)^2\right] \quad \text{EHE (Spanish Code)} \tag{3}$$

Previous research under the direction of Ph.D. Turmo, carried out at the Materials and Structures Laboratory of the School of Civil Engineering of Ciudad Real at the University of Castilla-La Mancha, Spain, to study crack opening behaviour at casting joints [12,13]

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revealed that equations provided by current codes are not accurate to predict crack openings at joints. The amount of cracks at casting joints predicted by these current codes are much lower than those that actually appeared during tests carried out in laboratories. This implies that current code formulae to predict crack openings at joints is at the side of unsafety. The same study [12] suggested that the inaccuracy of the prediction could be explained by the lower resistance of the joint faces. In the study, smooth casting faces were replaced with the use of phenolic wood panels to perform the laboratory tests, which could have reduced the tensile strength of the concrete at the joint. In order to avoid this problem and to keep at the side of safety, the use of a corrective parameter was proposed when calculations of crack openings at casting joints were required. This parameter would reduce the tensile strength of the concrete at the joint so that the presence of the smooth joint could be considered in the calculations. In Diaz de Teran et al. study [12] different types of concrete were considered: normal strength concrete, high strength concrete and self-compacting concrete. Test results suggested that a reduced parameter of 0.14 could be applied to the tensile strength of concrete (f_{ctm}) allowing researchers to obtain very accurate predictions of crack openings.

The aforementioned research proved to be very accurate [12] but the reduction of the tensile strength of the concrete is not enough to provide an accurate prediction of crack openings using Finite Element Models (F.E.M). The reasoning for this is that F.E.M. assume perfect bonding in embedded bars, while current formulae to calculate cracks assume cracks are due to the bond-slip effect. The introduction of the bond-slip phenomena should be implemented in F.E. Models so that they can better predict crack openings.

Different procedures have been developed to simulate the bond-slip behavior between steel and concrete in embedded bars. Kwak and Filippou [14] proposed a model based on bond-link elements that suits well for pull-out and push-pull tests. Monti et al. [15–17] proposed a new finite element type which used forces instead of displacements. Kwak and Kim [18] suggested a more similar procedure that considers a layered section method and a bilinear stress-strain law and a reduced stiffness for steel to simulate indirectly the bond-slip. Finally, Dehestany and Mousavi [19] proposed a similar procedure that considered a value of slip at the peak of the bond-slip curve so a lineal stress-strain law and a reduced yield strength (f_y^*) based on Belarbi and Hsu proposal [20] could be obtained (Eqs. (4) and (5)).

Otherwise, the model that is proposed in this paper, although considers indirectly bond-slip, deduces the stiffness of the steel by an interpolation of the bonding law provided by Model Code [9] and do not require a reduced yield stress for the steel. This paper suggests a new embedded bar model that considers bond-slip behavior derived from the interpolation of the Model Code bond-slip model, and can be employed using Finite Element Models (F.E.M) with embedded reinforcing bars in order to accurately determine crack openings at construction joints. The embedded model consists of a modified rational stress-strain law for steel reinforcing bars, based on the Model Code bond-slip model [9], to ensure that both non-linearity has been kept and that the yield strength of steel has been kept at 500 MPa.

$$E_s^{eq} = \frac{f_y^{eq}}{\varepsilon_s + \frac{\delta}{l}} \quad (4)$$

$$f_y^{eq} = f_y\left(0.93 - \frac{2}{\rho}\left(\frac{f_{cr}}{f_y}\right)^{1.5}\right) \quad (5)$$

Although the purpose of this paper is to provide a Finite Element tool in order to simply and accurately calculate crack widths at joints produced by monotonic loads, other previous researches [21] can be revised to study cyclic and fatigue response, mainly regarding stiffness degradation and hysteretic phenomena [22–25]. Models can be derived considering these effects and they can be validated with the results obtained by Villalva et al. [21].

2. Bond-slip model

Different bond-slip models have been developed to date [previous paper]. This study considers a Model Code bond-slip model [9] that is based on the study conducted by Eligehausen, Popov and Bertero [26]. The Model Code presents a segmental bond-slip law, as shown in Fig. 1 and Table 1, and takes into account different confinement and failure modes that define the different segments of the law. Eq. (6) defines the Model Code law for well confined concrete (concrete cover ≥ 5 d_b, clear spacing between bars ≥ 10 d_b). Araujo [27] and Gambarova [28] described failure modes as:

1) Splitting failure: if confinement is insufficient or does not exist, then splitting failure can occur. This failure is brittle and is due to the propagation of tensile hoop stresses around steel bars.
2) Pull-out failure: if sufficient confinement is provided by stirrups and concrete cover, splitting failure can be avoided and failure occurs by pull-out.
3) Steel failure: if bonding length is high, shear stress can be below the bonding strength and steel bar stress can reach their strength limit.

$$\begin{cases} \tau = \tau_{max}\left(\frac{\delta}{\delta_1}\right)^{\alpha} & \text{if} \quad 0 \leqslant \delta \leqslant \delta_1 \\ \tau = \tau_{max} & \text{if} \quad \delta_1 \leqslant \delta \leqslant \delta_2 \\ \tau = \tau_{max} - (\tau_{max} - \tau_f)\left(\frac{\delta-\delta_2}{\delta_3-\delta_2}\right) & \text{if} \quad \delta_2 \leqslant \delta \leqslant \delta_3 \\ \tau = \tau_f & \text{if} \quad \delta_3 \leqslant \delta \end{cases} \quad (6)$$

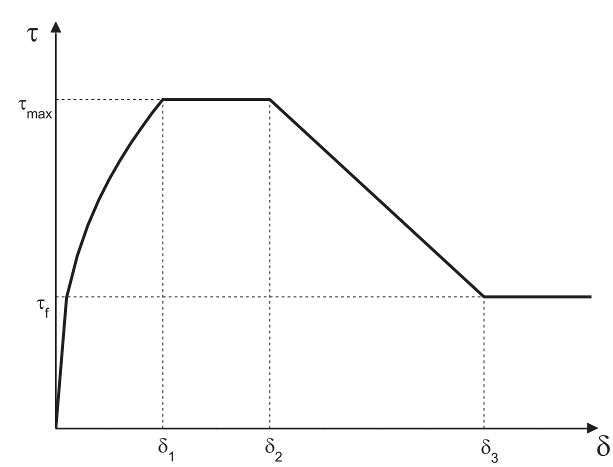

Fig. 1. Bond stress-slip relationship.

Table 1
Parameters of Model Code bond-slip model.

Parameters	Good bond conditions	Other bond conditions
δ_1	1.00 mm	1.80 mm
δ_2	2.00 mm	3.60 mm
δ_3	c_{clear}	c_{clear}
α	0.40	0.40
τ_{max}	$2.50\sqrt{f_{ck}}$	$1.25\sqrt{f_{ck}}$
τ_f	0.40 τ_{max}	0.40 τ_{max}

c_{clear} is the clear distance between ribs.