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A multi-scale approach for crack width prediction in reinforced-concrete beams repaired with composites

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Abstract

The effects of externally bonded composite plates on the mechanical behaviour of a cracked RC beam loaded in flexure are modelled by a multi-scale approach. The problem of crack width prediction is addressed. Firstly, the state-of-the-art methods for crack width prediction in concrete beams are recalled. Then, they are confronted to experimental data obtained with a full-field optical method. It is shown that classical models are not suited for the prediction of crack widths in repaired beams. In order to improve the modelling, a new approach is considered: the structural behaviour of the beam is assessed from numerical computations conducted over a relevant representative volume element. The contribution of this multi-scale approach is that input parameters have a physical meaning and that the results are consistent with full-field measurements conducted on repaired beams. Finally, the paper focuses mainly on the validation of the model for computing displacement fields, crack widths and curvatures in repaired beams. The benefit for the identification of bonding properties between the composite sheet and concrete is also pointed out.

Keywords: Reinforced-concrete; C. Crack

1. Introduction

The context of this work is within the rehabilitation of civil engineering infrastructures. The issue of upgrading the civil engineering infrastructures has become of great importance for over a decade. The main reasons are increasing traffic volume, lack of maintenance, environmentally induced degradation, earthquakes, etc.

Many experimental studies have shown that carbon fibre reinforced-plastic (CFRP) sheets are mechanically effective for upgrading damaged RC structures. Especially concerning flexure, bonding CFRP sheets can significantly increase the moment of failure of damaged beams [1–4]. For the design, both the ultimate limit state (ULS) and the serviceability limit state (SLS) of the structure must be verified. Despite of the moment of failure increase, the experimental studies cited previously have also shown that externally bonded composites do not really enhance the serviceability. This has been confirmed by on-site investigations. Hag-Elsafi et al. [5] have applied CFRP composite laminates to strengthen an aging reinforced-concrete T-beam bridge in the USA. They have shown that rebar stresses were only moderately reduced after installation of the laminates. Actually, the mechanical effect of the CFRP sheet is only clear after yielding of internal steel re-bars, i.e., beyond the SLS of the structure. Indeed, on one hand, CFRP materials have high strength and no large amount of CFRP are needed for ULS. On the other hand, the

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modulus of elasticity of CFRP manufactured directly onto the damaged structure can be relatively low (60 GPa). Higher amounts of CFRP may be needed to introduce sufficient stiffness for meeting the serviceability design criteria.

As both ULS and SLS must be taken into account for the design, serviceability appears more restrictive than failure for the beams which have been tested. Among serviceability aspects, the most critical one is often cracking. Crack widths should be limited for insuring infrastructures durability. In the absence of specific requirement and for exposure classes 2–4, Eurocode2 [6] recommends that a limit of 0.3 mm under quasi-permanent (long-term) loads should be satisfied.

Wide cracks are also harmful for the durability of RC beams repaired with CFRP sheets because wide cracks may be at the origin of CFRP debonding. Therefore, the value of 0.3 mm utilized in Eurocode2 should be kept as the SLS of repaired beams. However, the use of this limit value as a design criterion implies that sound methods are available for the assessment of crack widths in repaired beams.

This problem is addressed in this paper. Firstly, the state-of-the-art methods for crack width prediction in concrete beams are collected. Then, they are confronted to experimental data obtained with a full-field optical method [7,8]. It is shown that classical models are not suited for the prediction of crack widths in repaired beams.

In order to improve the modelling, a multi-scale approach is suggested. The assets are that input parameters have a physical meaning and that the results are consistent with full-field measurements conducted on repaired beams.

Finally, the paper focuses mainly on the validation of the model for computing displacement fields, crack widths and curvatures in repaired beams. The interest for the identification of bonding properties between the composite sheet and concrete is pointed out as well.

2. Theoretical background

2.1. Concrete reinforced with steel rebars

The post-cracking behaviour of RC structures depends on a great number of influencing factors: the tensile strength of concrete, anchorage length of embedded rebars, concrete cover, steel spacing, which are strongly related to the bond characteristics between concrete and steel. The approach which has been the most widely used for assessing crack widths in concrete reinforced with steel rebars is based on bond-slip models [9,10]

$$l_{tr} = \frac{A_c f_t}{\tau_m \Sigma_0}, \tag{1}$$

where τ_m is the average bond stress over a given transfer length l_{tr} (the subscript m is linked to the word "average"), f_t is the tensile strength of concrete (the subscript t is linked to the word "tensile") and Σ_0 is the bar perimeter.

From the strain distribution, the crack width w_k can be defined as the total difference of elongations between the reinforcement and the concrete matrix measured between two adjacent cracks, which is equivalent to the crack spacing. Structural concrete codes generally use this type of approach for computing allowable crack width. For example, the relation supplied by Eurocode 2 [6] for the design of reinforced-concrete beams writes

$$w_k = \beta s_{crm} \varepsilon_m, \tag{2}$$

where w_k is the assessed crack width (the subscript k is linked to the word "crack"), ε_m is the average tensile strain difference between the steel and the concrete, taking into account bond stress, tension stiffening, shrinkage effects, etc., s_{crm} is the average crack spacing for the final load, β is a design coefficient.

The use of this theory for crack widths prediction in flexure is based on a large number of simplifying assumptions. Crack width cannot be assumed to be constant over the depth of the element, naturally equalling zero in zones of compressive stress for example. Moreover, tests have shown that the concrete cover can have a significant effect on surface crack widths. Attempts to apply Eq. (2) have led to the development of simple empirical equations to compute ε_m. For example, the approach adopted by CEB-FIP [11] is based on the average strain in the member. It has been kept by Eurocode2

$$\varepsilon_m = \frac{f_s}{E_s}\left[1 - \beta_1 \beta_2 \left(\frac{f_{sr}}{f_s}\right)^2\right], \tag{3}$$

where f_s is the stress in the tension steel under the service conditions being considered, calculated on the basis of a cracked section (the subscript s is linked to the word "steel"), f_{sr} is the stress in the steel rebars under the relevant conditions that just causes the tensile strength of concrete to be reached, calculated on the basis of a cracked section, β_1 is a coefficient that accounts for the bond properties of reinforcements, which are responsible for the tension stiffening effect, β_2 is a coefficient that accounts for repeating stressing of the bars. Eq. (3) obviously has an empirical basis but it leads to quite good results for RC beams [11].

2.2. Concrete reinforced with steel rebars and external FRP sheets

The post-cracking behaviour of RC beams strengthened with composites is quite similar to unstrengthened ones [12,13]. It is still relevant to assess crack widths by using bond-slip models. However, bonding properties