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Assessment of the flexural behavior of reinforced concrete beams strengthened with concrete jackets

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ABSTRACT

Analysis of continuous jacketed Reinforced Concrete (RC) beams requires accounting for the nonlinear behavior of the interface and the materials as well as redistribution of moments. This kind of analysis is complex and require an advanced level of knowledge and experience to perform. Engineers need simplified yet robust tools to practically predict the actual behavior of jacketed RC beams. In the current practice, slip is neglected in the analysis and monolithic behavior is assumed for the jacketed section, which result in higher estimates of stiffness and/or capacity. This paper provides a simplified method to analyze continuous jacketed RC beams taking into account the interfacial slip distribution and the actual nonlinear behavior of both concrete and steel. An iterative calculation algorithm is developed to determine the moment–curvature curves of a jacketed beam at different sections. The developed method allows the evaluation of interfacial slip and shear stress distributions in ductile reinforced concrete beams. The developed method is utilized to conduct an extensive parametric study, which resulted into modification factors that can be used to calculate the capacity and deformations of a strengthened beam considering the interfacial slip.

1. Introduction

The need to strengthen Reinforced Concrete (RC) structures emerges from various reasons, such as new safety requirements, a change of structure occupancy, an incorrect design calculations and/or degradation of materials with time. Jacketing is one of the widely spread procedures to strengthen and repair RC beams. It comprises the addition of concrete layers that are usually reinforced with longitudinal steel bars, stirrups, welded wire mesh or various kinds of fibrous materials.

In the current practice, monolithic action is assumed between the original beam and the attached jacket. This implies that the internal stresses developed in both substrates due to the applied loads are distributed among them assuming infinite interfacial slip stiffness. This assumption may result in higher estimates of stiffness and/or capacity depending on the geometrical properties and interfacial surface treatment. The actual behavior of typical jacketed beams is partially composite and depends on the frictional resistance between the surfaces and the presence of steel anchors connecting the two substrates [1]. This implies that the analysis of jacketed beams requires a knowledge of the nonlinear behavior of the interface as well as the nonlinear properties of both concrete and the embedded steel bars at each loading step along the beam.

Literature is ample with experimental programs and numerical investigations that have been performed to address the influence of jacketing schemes, geometrical characteristics, mechanical properties and interfacial treatment on the flexural behavior of determinate jacketed RC structural members. For instance, Altun [2] and Bousias et al. [3] examined the effect of RC jacketing on the mechanical performance of statically-determinate RC beams considering the load-displacement behavior, ultimate load, ductility and toughness. Other researchers [1,4] investigated the significance of surface preparation of concrete members before applying the new concrete jacket. The use of fiber reinforced cementitious composites as an alternative to adding steel reinforcement within the jacket has been addressed by other studies [5–10]. In addition, the impact of using shear studs to further attach the existing beam with the additional concrete layers has been investigated by Shehata et al. [11]. Furthermore, the influence of varying the method of applying the jacket on site, such as shotcrete or cast-in-place concrete, have been considered by many researchers [12–14].

Experimental and numerical studies related to strengthening indeterminate RC beams using concrete jackets is scarce in literature. At the time of writing, the only available relevant experimental work was performed by Cheong and MacAlevey [15]. The rather extensive use of indeterminate RC beams in building structures and bridges requires further research regarding the influence of partial composite action on

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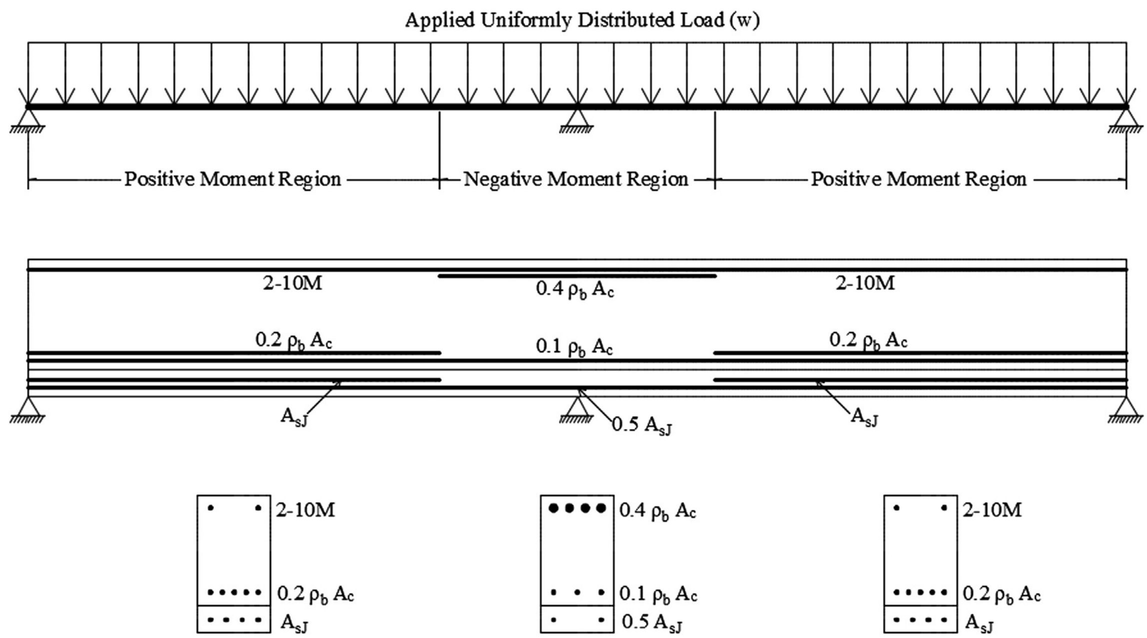

Fig. 1. Continuous beam loading scheme and reinforcement configuration.

their flexural performance.

This paper is a continuation of an ongoing research [16], which aims at proposing a simplified method to capture the influence of interfacial slip on the moment-curvature (M-φ) and load-deflection (P-Δ) relationships of jacketed continuous RC beams. This is achieved by performing nonlinear analysis in view of the material properties and interfacial behavior. A calculation algorithm is proposed to determine the slip distribution along the beam length and to obtain the corresponding M-φ diagram at both the sagging and hogging moment regions. This analysis procedure is sensitive to the bending moment distribution along the beam; therefore, the concept of moment redistribution in indeterminate beams is illustrated and considered in the analysis. The validated model is used to perform a parametric study aiming at examining the flexural behavior of the strengthened beams. Finally, a regression analysis is performed to propose slip modification factors that can be used to obtain the actual M-φ diagram of continuous RC beams considering interfacial slip. The scope of the proposed work is limited to ductile RC beams by considering sufficient reinforcement to prevent brittle modes of failure.

2. Material models

The stress-strain relationship of concrete in compression is considered in view of Scott et al.'s model [17] due to its simplicity and robustness. The tensile capacity of concrete is assumed to drop after reaching the cracking point.

The constitutive relationship of the embedded steel bars is expressed according to the model reported by Karthik and Mander [18] that was derived in view of the general formula proposed by Ramberg and Osgood [19]. It conveniently combines the initial elastic response, yield plateau and strain hardening stages in a single rigorous form to model the actual behavior of steel reinforcement. The value of the strain hardening strain (ε_{sh}) is set equal to the yield strain (ε_y) and the strain hardening modulus (E_{sh}) is taken as 1% of the Young's modulus of elasticity (E_s).

3. Interfacial shear stress (τ) and slip (S) relationship

The shear transfer mechanism is activated by the frictional resistance between the contact surfaces and the axial forces developed in the anchors crossing the interface. The former mechanism represents the concrete contribution; whereas the second case represents the influence of dowel action. The concrete contribution (v_c) is determined in view of Tassios and Vintzeleou [1] empirical model as a function of the lateral slip (S), ultimate slip value at the onset of frictional mechanism failure (S_{cu}) and ultimate frictional capacity of the interface (v_{cu}). The overall interfacial shear stress (τ) corresponding to any slip (S) value can be obtained as the summation of concrete contribution and dowel action contribution for given material properties and interfacial surface condition. A detailed description of this calculation procedure considering simply supported beams is provided by Alhadid and Youssef [16].

4. Assumptions

Assumptions considered in the current study encompasses the following:

(1) Plane sections remain plane after deformation, implying that shear deformations are small relative to bending deformations.
(2) Perfect bond exists between steel reinforcement and the surrounding concrete material. Thus, strain in both concrete and steel bars at the same location is identical.
(3) The failure criterion of the composite beam is defined by crushing of the extreme compression fiber at a concrete ultimate strain (ε_{cu}) of 0.0035 [21].
(4) The original RC beam and the added concrete layer are considered to deform by the same curvature through the beam length [20,23].
(5) The interfacial shear stress distribution within each region is assumed to vary as a cubic function with the distance from the zero moment section [22].

5. Typical jacketed section

The developed model is applicable to analyze symmetric continuous RC beams subjected to either uniform or concentrate loads. Fig. 1 shows the geometry and reinforcement details of a typical continuous beam that will be used for discussion throughout the chapter. The main steel reinforcement in the positive and negative moment regions are assumed to be 20% and 40% of the balanced steel reinforcement ratio,