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Reliability analysis of FRP strengthened RC beams considering compressive membrane action

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HIGHLIGHTS

- Comprehensive reliability analysis of FRP-strengthened RC beams considering CMA was conducted.
- CMA can effectively enhance the reliability of FRP plated RC beams.
- Increasing concrete strength and yield strain increase the reliability considering CMA.
- Increasing variation decreases the reliability considering CMA.
- An alternative partial factor of FRP strength considering CMA for FRP strengthened concrete beams is provided.

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ABSTRACT

Recent research has shown that the compressive membrane action (CMA) significantly enhances the load bearing capacity of FRP strengthened concrete beams. It is of great interest to investigate the effect of CMA on the structural reliability of such beams and how to incorporate the benefits of CMA into partial factor based design. Following a CMA model and the probabilistic models of its corresponding design variables, the effect of CMA on the reliability indices of FRP strengthened concrete beams was investigated. A parameter study as well as a sensitivity analysis were also conducted with parameters including properties of FRP and steel reinforcement, concrete properties and geometrical properties. The reliability indices with respect to load ratios i.e. ratios of the variable load to the total loads is selected to quantify the effect of CMA. The results show that the CMA effect significantly improves the structural reliability of FRP strengthened concrete beams. The parameter study indicates that an increase of the concrete strength and yield strain has positive effect on the structural reliability while an increase of FRP ratio, FRP modulus, steel ratio as well as the concrete ultimate strain has an adverse effect. Furthermore, it is found that the variations of the concrete strength, the FRP Young's modulus as well as the concrete cover have a significant influence on the reliability index; the variations of the ultimate strain of FRP, the yield strain of steel reinforcement and the ultimate strain of concrete have a moderate influence on the reliability index. Finally, an adjusted partial factor for the FRP strength is derived for cases where CMA would already be considered in the design stage.

1. Introduction

The application of externally bonded fiber reinforced polymer (FRP) composites is extensively recognized as a suitable method of strengthening existing concrete structures either to restore lost bearing resistance or to meet changing load demands. Because of its advantages, e.g. small and light profiles and corrosion resistance, FRP has been frequently applied in strengthening and rehabilitation ranging from beams or slabs lacking in flexure or shearing to columns deficient in confinement. Although much of the early work of FRP applications was conducted in a deterministic way to have an understanding of FRP behavior and the interaction between FRP and concrete structures, recently several researchers have focused on the evaluation of FRP strengthened concrete structures considering a probabilistic framework.

An early attempt to examine the reliability of concrete structures with externally-bonded FRP was performed by Plevris et al. [1]. They considered flexurally strengthened beams subjected to

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changes to design variables and proposed calibrated resistance reduction factors for design. Okeil et al. [2] investigated the reliability of reinforced concrete bridge girders strengthened with CFRP laminates by focusing on the cross-sectional flexural behavior and developed the resistance models for RC cross sections rehabilitated with CFRP laminates and the corresponding appropriate design factors as well. Karbhari and Abanilla [3], Atadero and Karbhari [4], and Wieghaus and Atadero [5] have worked on the reliability analysis of FRP strengthened bridge decks. They proposed an approach for achieving a broad applicability of reliability-based design of composite materials and calibrated the resistance factors for reliability-based design after analyzing the influence of material variability on the reliability considered. Pham and Al-Mahaidi [6] presented a reliability study on RC beams retrofitted with externally-bonded FRP considering three common failure modes and provided the capacity reduction factors for corresponding failure modes. In the work of Wang et al. [7], the authors summarized some useful tools and supporting databases that can be used to develop reliability-based guidelines for design and evaluation of FRP composites in civil construction and showed their application with several practical examples. Ribeiro and Diniz [8] also presented recommendations for a reliability-based design framework by assessing the reliability indices and failure probabilities of eighty-one FRP reinforced concrete beams designed according to ACI-440. More recently, Shi et al. [9] presented a reliability analysis of intermediate crack-induced FRP debonding in FRP strengthened concrete members. They examined the probabilistic characteristics of the model uncertainties for several widely used debonding models and calibrated the reduction factors for these models using the first-order reliability method.

Although the aforementioned investigations paid attention to the reliability analysis regarding concrete beam elements with externally-bonded FRP and recommended reduction factors for design, there are still many research questions. On the one hand, few works can be found focusing on the reliability aspects for concrete beam beams with externally-bonded FRP. Although the global reduction factor for resistance, as proposed in Plevris et al. [1], Atadero and Karbhari [3,4], Pham and Al-Mahaidi [7] and Shi et al. [9], is adopted by several design codes, its use constitutes a divergence from the Eurocode, in which partial factors for actions or material properties are more widely used. On the other hand, membrane actions (especially compressive membrane action) has been recognized as a significant benefit to the resistance enhancement for longitudinally restrained concrete members (e.g. Valipour et al. [10]). Moreover, the compressive membrane action proved to have a beneficial influence on load-bearing capacities and service behaviour in FRP reinforced concrete members (e.g. by Taylor et al. [11] and Zheng et al. [12]) as well as in FRP strengthened concrete beams (e.g. by Zeng et al. [13,14]). Unfortunately, no reliability based studies on FRP strengthened concrete members considering the effect of compressive membrane action are available.

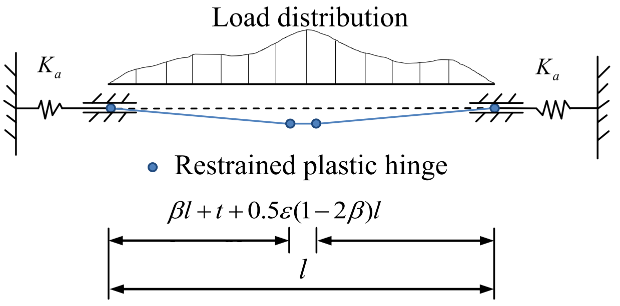

Fig. 1. Schematic view of longitudinally restrained beam.

The objective behind this work has been mainly the reliability analysis of FRP strengthened reinforced concrete (RC) beams considering compressive membrane action (CMA). Following this introduction, the compressive membrane action in FRP strengthened beams is briefly explained and described, followed by a description of the structural reliability calculations. Further, a parameter study as well as a sensitivity analysis are performed. Finally, a partial factor for the FRP strength considering CMA is calibrated.

2. Compressive membrane action in FRP strengthened RC beams

Membrane action consisting of compressive membrane action and tensile membrane action is exhaustively explored in conventional RC one-way concrete beams since the first attempt by Turner in 1909. A detailed summary related to CMA in FRP strengthened RC members is referred to Zeng et al. [14]. For concrete beams strengthened with externally-bonded FRP, CMA is believed to be efficient in improving the load bearing capacities, which is exclusively elaborated in the authors' previous publications (e.g. in Zeng et al. [14]). An outline of the CMA model in FRP strengthened RC beams is briefly given below.

2.1. Assumptions

A model with four idealized plastic hinges formed symmetrically along the considered beam is chosen to represent a standard RC beam or a FRP strengthened RC beam. The perfectly rigid plastic mechanism is the basic preassumption, which means that the segments between the idealized plastic hinges (or pseudo-hinges in case of a FRP strengthened element) remain rigid. For simplicity, a complete symmetry along the span is assumed with respect to geometry, reinforcement, loading, boundary conditions and deformations. The longitudinal restraints from surrounding structures are idealized by equivalent axial springs with stiffness K_a. Fig. 1 shows the schematic view of the longitudinally restrained beam structures, where β_r is the ratio of the span length l_n from the assumed plastic hinge at the beam end to the nearest hinge in the span, to the beam span l.

When calculating the sectional moments and forces, widely-adopted assumptions are used, including the assumptions of plane-section, a full composite action of FRP, an idealized equivalent rectangular stress block for concrete in compression, an ignorance of concrete tensile strength and the compressive strength of FRP, a bilinear stress-strain relationship for steel bars and a linear stress-strain relationship for FRP, all of which can be referred to *fib* bulletin 14 [15]. The constitutive properties of component materials are shown in Fig. 2. Further, the compressive strain of the beam is assumed to be distributed uniformly along the beam span, i.e. $\varepsilon \approx N/(E_c A_c)$, where N is the axial force, E_c is elastic modulus of concrete and A_c is the cross-sectional area.

2.2. Failure modes

It is well known that the mode of failure of a FRP strengthened concrete section depends on the amount of the materials used (i.e. concrete, steel and FRP) and their corresponding mechanical properties, as well as the geometric configurations of the considered member. The critical failure mode of such a section could be either tensile steel yielding/concrete crushing (before FRP rupture or debonding) or tensile steel yielding/FRP rupture (or FRP debonding). The consideration of failure mode in the context of this work also accounts for the stress state (yielding or not) of the compressive steel reinforcement. If the stress state of the compressive steel