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Compressive membrane action in FRP strengthened RC members

Yihua Zeng *, Robby Caspeele, Stijn Matthys, Luc Taerwe

Magnel Laboratory for Concrete Research, Ghent University, Department of Structural Engineering, Technologiepark-Zwijnaarde 904, 9052 Ghent, Belgium

HIGHLIGHTS

- We propose a prediction model for FRP-strengthened RC beams when considering CMA.
- We examine effects of properties of FRP laminate, steel bar and concrete on CMA.
- CMA can effectively enhance the load bearing capacity of FRP-plated RC beams.
- Increasing area of FRP and steel bar will increase CMA effect.
- Increasing strength and ultimate strain of concrete will increase CMA effect.

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ABSTRACT

This study focuses primarily on examining the compressive membrane action (CMA) in FRP (fibre reinforced polymer) strengthened reinforced concrete (RC) beams or one-way slabs. Considering a rigid-plastic mechanism, in combination with strain compatibility and force equilibrium, a model is proposed to predict the load bearing capacity of FRP strengthened RC members when considering CMA. Comparison with experimental tests proves the proposed model to be realistic and effective. A parametric study has been undertaken and an enhancement factor was used to qualify the CMA effect in FRP strengthened RC members. The parameters include the properties of FRP, steel reinforcement and concrete, and the span to depth ratio. The results indicate that CMA can effectively enhance the load bearing capacity of FRP strengthened RC members. Results also indicate that the effect of CMA increases with the increase of FRP area, steel reinforcement ratio, strength and ultimate strain of concrete but decreases with increasing span to depth ratio.

1. Introduction

Design of structures with acceptable robustness has been recognized to be significantly important. Robustness has been incorporated in both European codes [1,2] and American guidelines [3–5]. In general, indirect design and direct design are the two main design concepts for increasing structural robustness. In the direct design, alternative load path design is efficient for structures in resisting disproportional collapse. One solution to increase the robustness could be the use of Fibre Reinforced Polymer (FRP) [6–8]. For simply supported reinforced concrete (RC) one-way members strengthened with externally bonded FRP, previous research proved that instead of strength criteria the deflection criterion and debonding criteria tend to control the design of the strengthened members and dominates the composition of the cross-section along the length of the members. However, in FRP strengthened RC one-way members with longitudinal lateral restraints, the design is governed by concrete compressive strength due to compressive membrane action (CMA) [9].

Since CMA (also referred to as arching effect) was first recognized by Turner in 1909 [10], much work has been done in this topic particularly in the field of concrete slabs, as can be seen in a detailed overview by Taylor et al. [11]. Many researchers found that the experimental observations on two-way RC slab behaviour showed a considerable increase in the ultimate loading capacity compared to that predicted using the yield-line theory (e.g. [12–13]). These capacity enhancements observed in tests were believed to be attributed to the CMA effect. To throw a light on this enhancement, Park proposed a model to predict the ultimate loading capacities of two-way RC slabs using a strip approximation and deformation theory [13]. This theory was later modified to consider the effects of long-term loading as well as the lateral displacement due to partial restraint which were both found to

* Corresponding author.
E-mail addresses: Yihua.Zeng@UGent.be (Y. Zeng), Robby.Caspeele@UGent.be (R. Caspeele), Stijn.Matthys@UGent.be (S. Matthys), Luc.Taerwe@UGent.be (L. Taerwe).

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have an adverse effect on the enhancement [14]. This strip method was then developed/extended to take into account other boundary conditions and further applied to one-way RC strips by considering only one strip in the method e.g. [15–17]. Following the proposal and the application of this strip method, the CMA effect in one-way RC members has gained much attention.

Since the 1980s several tests on the development of CMA in one-way RC slab strips representing floor slabs or bridge decks were conducted by serval researchers [18–25]. It was found that the slope in the early stage of the load deflection curve is noticeable at relatively small deflections of the fully rigid slab strips and the activation of CMA enhances the load bearing capacity of one-way RC slabs. The major influencing factors were found to be concrete strength, reinforcement ratio, edge restraint and span-to-depth ratio.

For beam systems, Ruddle et al. [26] tested thirty rectangular and T-shaped RC beams with parameters the span-to-depth ratio, boundary conditions, web width and reinforcement ratio to investigate the influence of CMA on flexural and shear behaviour. Test observations from all specimens showed that the boundary conditions affect the peak capacity and deformation, and that the increase of span-to-depth ratio results in a reduction of the peak capacity. Later, several FRP strengthened RC beams with discontinuous and continuous reinforcement were tested under three-point loading to investigate the phenomenon of membrane action by Orton et al. [27]. It was found that beams with continuous longitudinal bars were able to develop an adequate degree of membrane action and it was found from the test observations that a RC beam can be modelled as a sequence of rigid blocks. Recently, many beam-column sub-assemblies representing RC frame structures were tested to investigate the effects of disproportionate collapse caused by an unexpected scenario of an interior column removal (e.g. [28–30]). Normally a beam-column sub-assembly comprises two beam spans, a center column stub and two side column stubs. These specimens were designed with different configurations of reinforcement ratio, reinforcement detailing, span-to-depth ratio and were subjected to a quasi-static monotonically increasing loading pointed at the center column stub. It was found, consistent with in previous literature, that the initiation of CMA resulted in clear enhancements of the load bearing capacities compared to the predicted ones using conventional plastic hinge theory. Also it was observed that an increase of reinforcement ratio (either top or bottom or both) or span-to-depth decreases the strength enhancement, which is consistent with the findings in one-way RC slab strips. Furthermore, these tests also demonstrated the dependency of CMA on the shift of the neutral axis due to the occurrence of cracks in the tensile zone of the cross-section.

The first attempt in numerical simulation of CMA was based on an elastic-plastic analysis of rectangular RC slabs by Massonet [31]. Regarding Finite Element (FE) methods, a nonlinear FE model for RC frames was proposed by Vecchio and Tang [32] using layered sectional analysis. The verification by experimental results showed a reasonable agreement with a slight overestimation. Recently, a generic beam element model on CMA was proposed for lightly reinforced members subjected to fire conditions with axial restraints [33]. Another generic nonlinear compound FE model for investigation of CMA in RC members was developed and applied by Valipour et al. [25]. This model accounts for geometrical and material nonlinearities, combining a non-local model to resolve the numerical sensitivity due to concrete softening and shows reasonable accuracy when compared to test results.

The research programmes mentioned above have been conducted to demonstrate and promote the advantages of CMA. This research has shown that CMA is beneficial in both strength enhancement and serviceability behaviour for laterally restrained concrete flexural members. Thus, the concept of CMA makes it possible to construct functional, economic and durable concrete members and has been incorporated specifically into the design guidelines of e.g. Northern Ireland, the United Kingdom, Canada and New Zealand [34–37].

With the increased application of FRP for the strengthening of concrete structures and the consistent requirement to enhance structural robustness, a model to predict the CMA capacity of one-way FRP strengthened concrete flexural members (beams and slabs) is desirable. With simple inputs of geometrical properties, material properties and boundary conditions, an analytical model that accounts for the stress state of both steel and FRP reinforcement is presented. The proposed model is validated with available test results in literature and then compared with traditional calculations (which do not consider CMA) according to the *fib* guideline [38]. In addition, a parametric study is conducted and design recommendations are presented.

2. Proposed method

In general, the prediction of CMA in concrete members can be based on two main methods. Although both methods are based on a rigid plastic approach, as shown in Fig. 1, the consideration of CMA is quite different between them. As proposed by Park and Gamble [17], one method is using plasticity theory and deformation theory to obtain member's resistance under CMA by considering strain compatibility and force equilibrium at the sectional level. This method considers CMA to be initially associated with the bending capacity and is has been proved valid for estimating CMA capacity of laterally restrained RC members [17]. Another main method accounts for the ultimate load of laterally restrained members by taking the sum of the bending capacity and the additional three-hinge arch load due to CMA. Hence, bending load and additional compressive arch load are considered separately. This method was first proposed by McDowell et al. [39] for masonry walls, and was then further developed by Rankin and Long [40], and by Taylor et al. [20] for RC slabs. Both methods share the idealized geometry of deformation. However, there exists an important difference in these approaches: the plasticity theory for concrete behaviour and the deformation theory approach (total strain rule) are adopted in the Park and Gamble method; while in the second method the elastic-plastic theory for concrete behaviour and strain increment approach (flow rule theory) are adopted. Both the plasticity theory and deformation theory approaches are adopted in European codes and guidelines (e.g., Eurocode 2 [41] and *fib* bulletin 14 [38]) to obtain the ultimate loading capacity of RC members (method by Park and Gamble). This assumption is also consistent to the fact that the CMA capacity is associated with the pure bending capacity.

Fig. 1 displays the general description of laterally restrained beam structures. It could be a regular beam, or a beam-column sub-assemblage that represents the behaviour of a continuous beam under a column removal scenario. As shown in Fig. 1, it is assumed

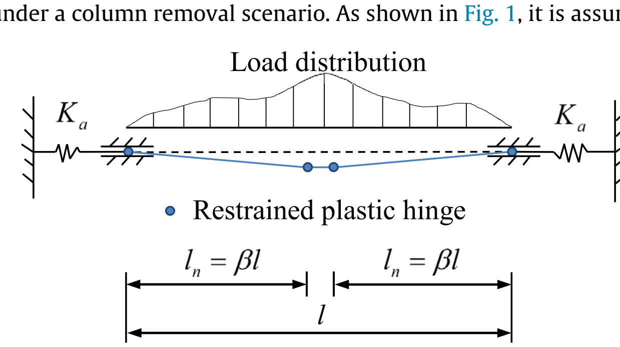

Fig. 1. Rigid plastic assumption and equivalent boundary condition.