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Numerical investigation on the moment redistribution of continuous concrete beams reinforced with FRP bars

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ABSTRACT

Fiber reinforced polymer (FRP) has excellent characteristics, including lightweight, high strength and non-corrosion. Currently FRP bars are increasingly used in civil engineering, especially in harsh environments. Most of the researches focused on simply supported beams in the past, and there are relatively fewer works on continuous beams, which are more widely used in actual engineering. In this paper, a numerical model is developed using ABAQUS software and the accuracy of the finite element model is verified. Then, parametric study of continuous reinforced concrete (RC) beams is carried out using the finite element model, where the main variables are the type of reinforcement, reinforcement ratio and reinforcement arrangement. A comprehensive analysis of various parameters that affect the mechanical behavior and moment redistribution of FRP-RC continuous beams is conducted.

1. INTRODUCTION

In our society, reinforced concrete (RC) structures have become prevalent across various types of projects. However, corrosion of reinforcing steel is a major problem in the application of RC structures. The corrosion of steel reinforcement significantly undermines structural durability and diminishes mechanical properties (Nasrollahzadeh and Aghamohammadi 2018). Fiber reinforced polymer（FRP）bars offer notable advantages, for instance, high strength, lightweight, corrosion resistance and fatigue resistance (Amran et al. 2018). Currently, FRP bars have gained widespread adoption in civil engineering as alternatives to conventional steel bars in RC structures.

Most of the previous studies have primarily examined the application of FRP bars in simply supported beams (Benmokrane et al. 1995; Al-Sayed et al. 2000). However, research on moment redistribution in FRP-RC continuous beams is limited. Continuous

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beams are more prevalent in practical engineering. In continuous members, the moment redistribution capacity tends to give more flexibility in design. Many codes address the moment redistribution capacity of RC continuous beams. However, FRP has the low modulus of elasticity and does not yield during loading, which results in lower ductility of the member. From the safety point of view, existing design codes often do not consider moment redistribution in FRP-RC continuous beams.

Several experimental studies have investigated the moment redistribution phenomenon in FRP-RC continuous beams. Grace et al. (1998) conducted experiments on T-shaped continuous beams using steel, CFRP, and GFRP for longitudinal and hoop reinforcement. Habeeb et al. (2008) conducted experiments on three continuous beams reinforced solely with GFRP bars. El-Mogy et al. (2010) studied two GFRP-RC continuous beams and one CFRP-RC continuous beam through the test. The above studies showed that moment redistribution is achievable in FRP-RC concrete beams with appropriately configured reinforcement. Kara and Ashour (2013) found that FRP-RC continuous beams with different ductility have different ability to redistribute the bending moments. Rahman et al. (2017) tested five GFRP-RC continuous beams and one CFRP-RC continuous beam, concluding that asymmetric loading conditions can detrimentally affect moment redistribution capability. Therefore, different factors can distinctly impact moment redistribution in FRP-RC continuous beams.

This study develops a numerical model using ABAQUS and validated its accuracy by comparing with experimental results. Based on this model, the influential parameters of FRP-RC continuous beams are analyzed to explore the influence of reinforcement type, reinforcement ratio, reinforcement arrangement on the mechanical properties and moment redistribution of FRP-RC continuous beams.

2. FE MODEL

2.1 Test beams

In this paper, two two-span continuous beams are selected, including one CFRP-RC continuous beam (CS1) and one GFRP-RC continuous beam (GS1), each with a total length of 6000 mm and a cross-section of 200 mm × 300 mm, as depicted in Fig. 1, based on the experiments conducted by El-Mogy et al. (2010). Each beam is reinforced with FRP bars, three at the bottom and two at the top. For the CFRP bars, the tensile strength is 1388 MPa, the ultimate strain is 0.012 and the modulus of elasticity (E_r) is 116 GPa. For GFRP bars, the tensile strength is 731 MPa, the ultimate strain is 0.016 and the modulus of elasticity is 46 GPa. The hoops consist of 8 mm diameter reinforcing steel bars spaced at 120 mm intervals, possessing a modulus of elasticity of 190 GPa, yield strength (f_y) of 300 MPa, and corresponding strain (ε_y) of 0.0016. In addition, for the concrete, the compressive strength (f_{ck}) is 26 MPa, ultimate strain (ε_u) is 0.0035, tensile strength (f_t) is 2.6 MPa and modulus of elasticity (E_c) is 31 GPa.

2.2 FE modeling

The finite element model was developed using ABAQUS to simulate the continuous beams CS1 and GS1. Concrete behavior was characterized using the plastic damage model in ABAQUS, incorporating two damage factors—tensile loss and plastic loss—to enhance the representation of concrete cracking. According to Eurocode 2 (CEN 2004), the stress-strain models for concrete in compression is illustrated in Fig. 2a, while that of concrete tension in Fig. 2b. The concrete was simulated using C3D8R 3D solid element. The two-node linear three-dimensional truss element (T3D2) was employed for both hoop and longitudinal bars, with constitutive models depicted in Fig. 2c and d. To avoid stress concentration phenomenon, linear elastic steel pads were positioned at support and loading points along the span, utilizing C3D8R 3D solid elements.

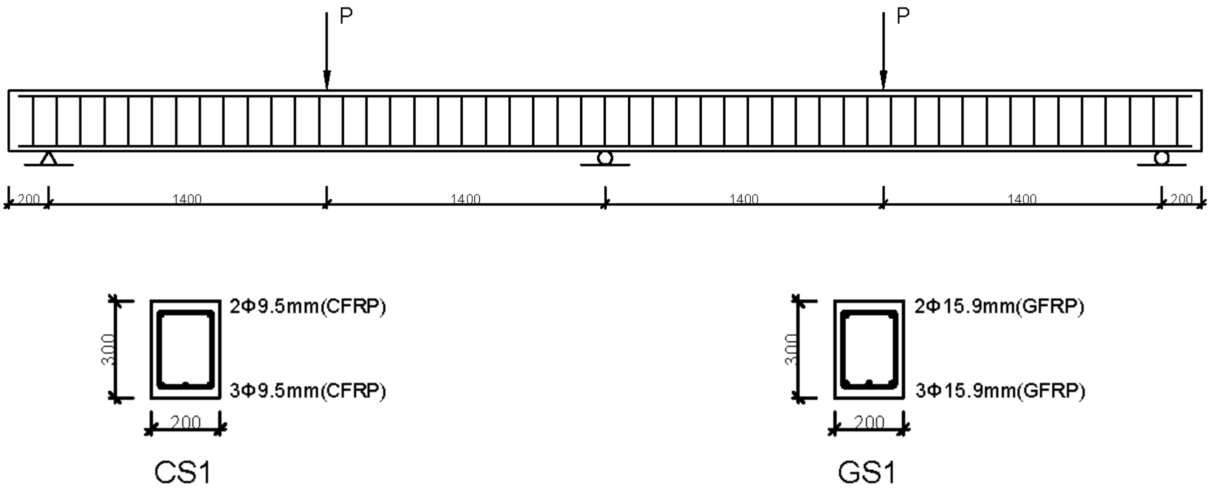
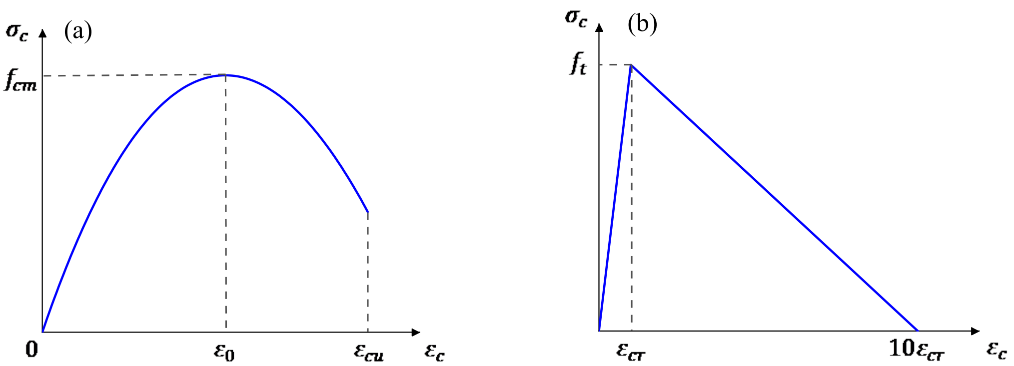
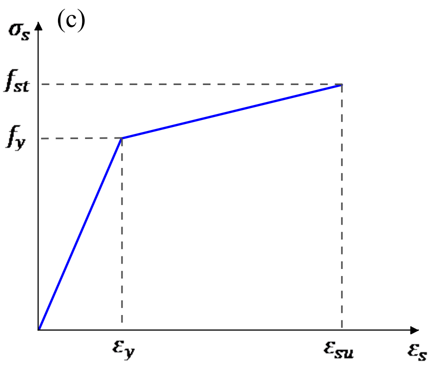


Fig. 1 Details of FRP-RC test beams (units: mm)





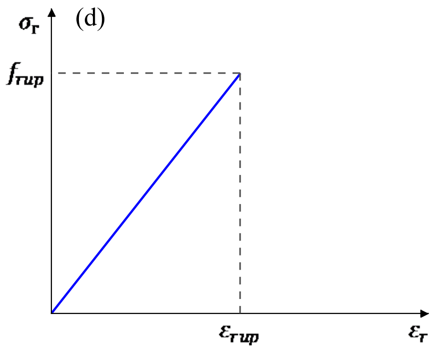


Fig. 2 Material stress-strain curves. (a) concrete in compression; (b) concrete in tension; (c) steel; (d) FRP.

In Fig. 2, σ represents stress, ε denotes strain, and subscripts c, s, and r denote concrete, steel, and FRP bars, respectively. In Fig. 2a, the symbol f_{cm} denotes the average compressive strength of concrete, ε_0 and ε_{cu} denote the compressive strains at the maximum and ultimate stresses, respectively. In Fig. 2b, the symbol f_t represents the tensile strength of the concrete, and its counterpart, ε_{cr}, represents the cracking strain of the concrete. In Fig. 2c, the symbol f_y represents the yield strength of the steel reinforcement, f_{st} represents the ultimate strength of the steel reinforcement, ε_y and ε_{su} are yield strain and ultimate strain of the steel reinforcement, respectively. In Fig. 2d, the symbol f_{rup} represents the fracture strength of the FRP bars, and its counterpart, ε_{rup}, represents the fracture strain of the FRP bars.

To simplify the model, under the premise of ensuring the accuracy of the overall performance of the model, it is assumed that no relative slip occurs between the bars and the concrete. To achieve this, "Embedded" constraints are applied between the bars and the concrete during modelling. Additionally, “Tie” constraints are used in the contact between the pad and the beam, and “Coupling” constraints are used between the pad and the loading point. The model of the continuous beam CS1 is depicted in Fig. 3.

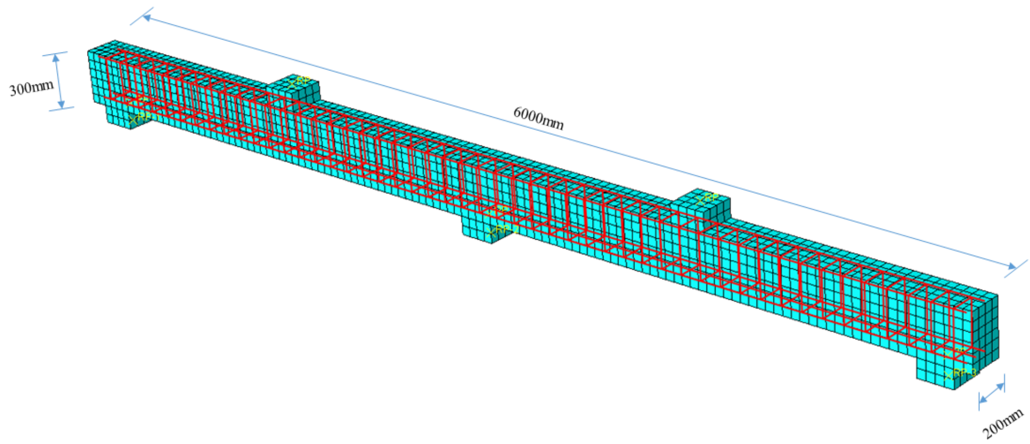


Fig. 3 Meshed finite element model

2.3 FE model analysis and validation

Comparison of the model predictions with experimental results reveals that the model's predictions of the load-deflection behavior for Beams CS1 and GS1 align well with corresponding experimental observations, as depicted in Fig. 4. This alignment demonstrates the feasibility and reliability of the modeling approach described. For Beam CS1, a higher value of the ultimate load by FEA is obtained when compared to the experimental value. The discrepancy can be attributed to excessive slip of the CFRP bars before reaching the crushing damage threshold during testing.

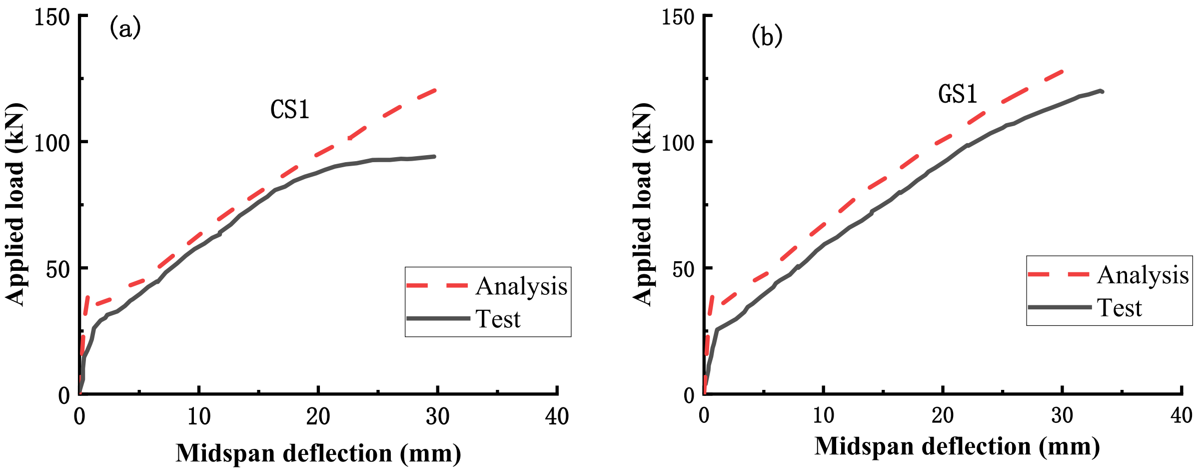


Fig. 4 Comparison between finite element and experimental data for the load-deflection characteristics of specimens (a) CS1 and (b) GS1

3. ANALYSIS OF IMPACT PARAMETERS

3.1 Effect of reinforcement type

This part of the study is based on the finite element model of CS1. Other parameters are kept unchanged during the modeling process, and only the reinforcement type is changed, as shown in Table 1.

Table 1 Details of the beams with different reinforcement types

Beam	Type of reinforcement	Modulus of elasticity (GPa)	Reinforcing bars (mm)	
			Top	Bottom
CS1	CFRP	116	2Φ12	3Φ12

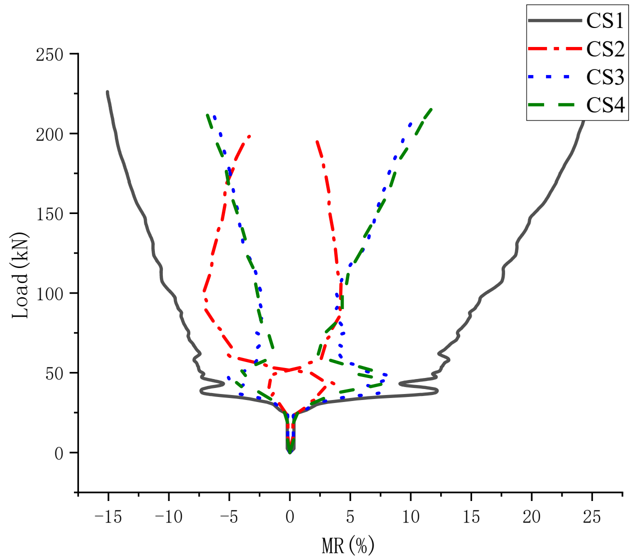


Fig. 11 Moment redistribution-load curves of CS1, CS2, CS3 and CS4

3.3.2 Moment redistribution

Fig.11 illustrates the variation in moment redistribution with external load application for four concrete continuous beams featuring different reinforcement arrangements. In particular, the moment redistribution-load curves of CS3 and CS4 exhibit similarities, attributed to their identical ratio of bottom to top reinforcement area. Compared to CS3 and CS4, Beam CS1 demonstrates significantly higher moment redistribution, attributable to an increased ratio of bottom to top reinforcement area. This increase enhances the axial stiffness of the sagging section reinforced with FRP bars, thereby boosting its moment capacity and enabling greater transfer of moments from intermediate supports to mid-span. In addition, for CS2, its moment redistribution at the two critical sections is opposite, which is due to the low ratio of sagging reinforcement area to hogging reinforcement area. This disparity results in reduced stiffness in the sagging section, leading to greater redistribution of moments from the sagging zone to the hogging zone.

4. CONCLUSIONS

This study develops a finite element model of FRP-RC continuous beams using ABAQUS, and the model is validated with experimental results. The FRP-RC beams are analyzed with investigated parameters including the reinforcement type, reinforcement ratio and reinforcement arrangement. The main findings are summarized as follows:

(1) Prior to concrete cracking, the load-deflection behaviors of steel-RC continuous beams and FRP-RC continuous beams exhibit similarity. After cracking, FRP-RC beams demonstrate lower stiffness and moment redistribution coefficients compared to steel-RC beams.

(2) CFRP-RC continuous beams exhibit greater stiffness and higher moment redistribution coefficients than GFRP-RC continuous beams under similar conditions.

(3) FRP-RC continuous beams with varying reinforcement ratios exhibit similar pre-cracking load-deflection behavior. After cracking, higher reinforcement ratios correspond to increased stiffness and moment redistribution capacity.

(4) For FRP-RC beams, increasing bottom reinforcement enhances stiffness and moment redistribution. Conversely, higher top reinforcement ratios decrease stiffness, reduce moment redistribution, and may lead to reverse moment redistribution.

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