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Nonlinear finite element modeling of concrete deep beams with openings strengthened with externally-bonded composites

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ABSTRACT

This paper aims to develop 3D nonlinear finite element (FE) models for reinforced concrete (RC) deep beams containing web openings and strengthened in shear with carbon fiber reinforced polymer (CFRP) composite sheets. The web openings interrupted the natural load path either fully or partially. The FE models adopted realistic materials constitutive laws that account for the nonlinear behavior of materials. In the FE models, solid elements for concrete, multi-layer shell elements for CFRP and link elements for steel reinforcement were used to simulate the physical models. Special interface elements were implemented in the FE models to simulate the interfacial bond behavior between the concrete and CFRP composites. A comparison between the FE results and experimental data published in the literature demonstrated the validity of the computational models in capturing the structural response for both unstrengthened and CFRP-strengthened deep beams with openings. The developed FE models can serve as a numerical platform for performance prediction of RC deep beams with openings strengthened in shear with CFRP composites.

1. Introduction

The creation of a web opening in reinforced concrete (RC) deep beams is frequently required to accommodate utility services such as electricity and air conditioning conduits. The inclusion of an opening in the web of an existing beam leads to early diagonal cracking and significantly reduces the beam shear capacity and stiffness [1–4]. The reduction in the shear capacity depends on the degree of interruption of the natural load path that is the line connecting the load and support points. The reduction in shear capacity is more significant when the opening fully interrupts the natural load path [5–7].

Structural strengthening of deficient RC elements with externally bonded carbon fiber reinforced polymer (CFRP) composite sheets has gained a wide acceptance worldwide [8,9]. Numerous studies have demonstrated the effectiveness of using externally bonded CFRP composites to upgrade the shear capacity of shallow RC beams without openings. The studies conducted by Triantafillou [10] and by Triantafillou and Antonopoulos [11] demonstrated that the contribution of CFRP to shear capacity was controlled by a maximum effective CFRP strain. The effective CFRP strain decreased with increased CFRP axial rigidity. Based on the findings of these studies an analytical model for prediction of CFRP shear resistance was developed and adopted by the European design guidelines *fib* TG 9.3 [12]. Chen and Teng [13] introduced a simple, accurate and rational design approach for the shear capacity of CFRP-strengthened beams which fail by CFRP debonding. The proposed design approach was validated against experimental data collected from the literature, and finally adopted by the Austrian design standards HB 305 [14].

Chaallal et al. [15] and Micelli et al. [16] reported that increasing the amount of CFRP may not result in a proportional increase in the shear strength especially if debonding of CFRP controls the failure. Bousselham and Chaallal [17] studied the parameters that most influence the shear behavior of RC beams strengthened with CFRP. The contribution of CFRP composites was found more significant in slender beams than in deep beams The study showed that increasing the amount of transverse steel decreased the shear strength gain caused by CFRP. Results of the studies by Carolin and Taljsten [18] and by El-Maaddawy and Chekfeh [19] showed that CFRP shear strengthening restored the shear strength of damaged RC beams. In some cases, the shear capacity after strengthening exceeded the beam original shear capacity. The use of proper end anchors delayed or prevented CFRP debonding which increased the shear strength gain caused by CFRP.

The viability of using externally bonded CFRP composite system to improve the shear behavior of shallow RC beams containing openings has also been reported in the literature by few researchers [20–22]. Pimanmas [21] indicated that the use of inclined

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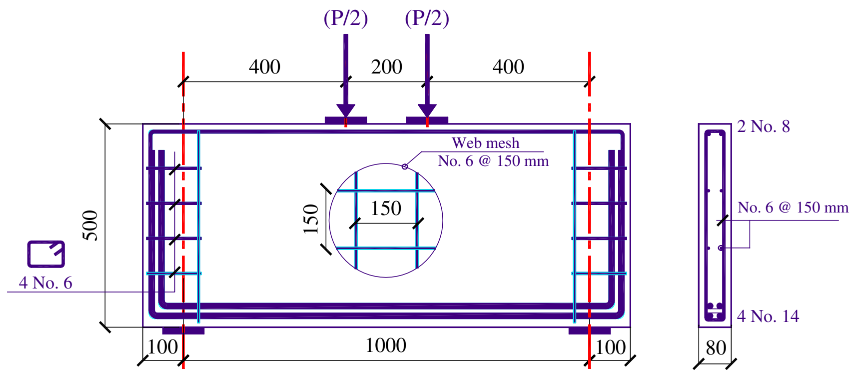

Fig. 1. Details of test specimen [7].

near-surface-mounted composite rods externally installed diagonally to the beam axis alongside the opening throughout the entire beam depth can fully restore the shear capacity of RC beams with web openings. El-Maaddawy and El-Ariss [22] reported that CFRP external strengthening around the opening improved the beam shear resistance and stiffness. Increasing the opening width or depth reduced the gain in shear capacity caused by the CFRP. Doubling the amount of the vertical CFRP sheets from one to two layers increased the shear capacity but the additional shear capacity gain was not in proportion to the added amount of the CFRP. An analytical approach for prediction of the shear capacity of RC beams with openings strengthened in shear with CFRP was introduced based on the ACI 440.2R-08 [23].

The behavior of solid RC deep beams strengthened with CFRP composites has received little attention in the literature [24–26]. Islam et al. [25] reported up to 40% enhancement in the shear strength of deep beams due to the use of externally bonded CFRP system. The study by Zhang et al. [26] indicated that CFRP shear strengthening of deep beams resulted in about 46% increase in shear capacity.

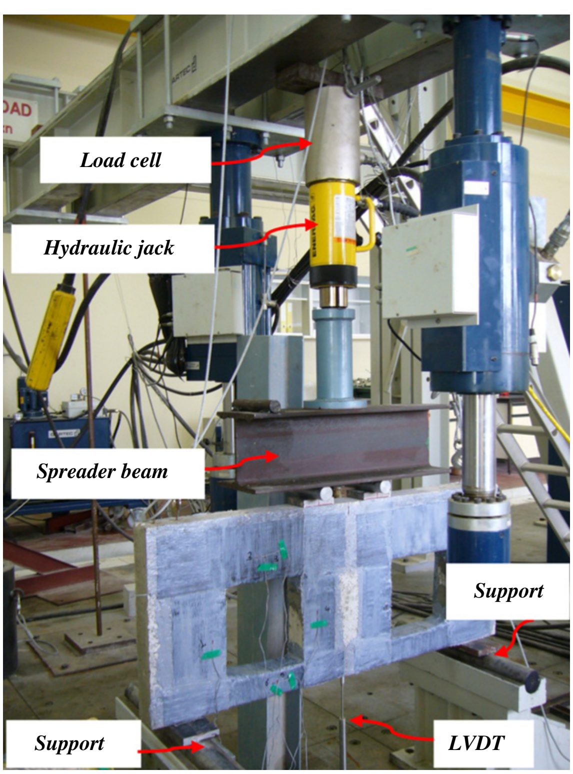

Fig. 2. Test set-up.

There is not enough information on the behavior of RC deep beams with openings strengthened in shear with CFRP composites. The experimental results published in the literature by El-Maaddawy and Sherif [7] demonstrated the effectiveness of using CFRP shear strengthening around web openings in RC deep beams to upgrade the beam shear capacity. The shear strength gain caused by CFRP was in the range of 35–73%. In a recent study conducted by Ahmed et al. [27], it was recommended to conduct further research to better understand the behavior of RC beams containing openings strengthened with externally bonded CFRP composite sheets.

The analysis of RC deep beams with openings is a complex problem. The application of CFRP composites around the openings as a structural engineering solution to upgrade the shear capacity makes the problem more complex. Current codes of practice provide little guidance in this regard, and hence an appropriate and consistent approach for performance prediction of such unusual structural concrete members is required. In this context, twelve 3D nonlinear finite element (FE) models for CFRP-strengthened RC deep beams with openings have been developed in this study using the finite element package ANSYS ver. 11.0 [28]. The

Table 1
Summary of experimental program and FE models.

Specimen	FE model	Opening location	Opening size (mm)	External CFRP strengthening
NS-200-C	FE NS-200-C	Middle of shear span	200 × 200	No
NS-250-C	FE NS-250-C	Middle of shear span	250 × 250	No
FS-200-C	FE FS-200-C	Middle of shear span	200 × 200	Yes
FS-250-C	FE FS-250-C	Middle of shear span	250 × 250	Yes
NS-150-T	FE NS-150-T	Top of shear span near support	150 × 150	No
NS-200-T	FE NS-200-T	Top of shear span near support	200 × 200	No
NS-250-T	FE NS-250-T	Top of shear span near support	250 × 250	No
FS-250-T	FE FS-250-T	Top of shear span near support	250 × 250	Yes
NS-150-B	FE NS-150-B	Bottom of shear span near loading point	150 × 150	No
NS-200-B	FE NS-200-B	Bottom of shear span near loading point	200 × 200	No
NS-250-B	FE NS-250-B	Bottom of shear span near loading point	250 × 250	No
FS-250-B	FE FS-250-B	Bottom of shear span near loading point	250 × 250	Yes