Advanced Materials Research Vols. 1025-1026 (2014) pp 938-943
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doi:10.4028/www.scientific.net/AMR.1025-1026.938

Submitted: 14.05.2014
Revised: 05.07.2014
Accepted: 05.07.2014

Reinforced Concrete Deep Beams with Openings Strengthened Using FRP – A Review

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Keywords: Deep beams, Opening, Shear, Strengthening, Carbon fiber reinforced polymer

Abstract. In the modern building construction, different size of openings are provided in the web of reinforced concrete (RC) deep beams to accommodate utility pipes and ducts of essential services such as electricity cable, telephone network and air-conditioning network. However, accommodation of such openings caused reduction in beam strength, stiffness and caused excessive cracking and deflection. Many investigations were conducted to study the behaviour of openings in beams and relevant strengthening options to reinstate the lost capacity. One of the strengthening options considered lamination of fiber reinforced polymer (FRP) sheets due to its superior properties such as high tensile strength and stiffness, high resistance to corrosion, excellent fatigue performance and good resistance to chemical attack. FRP lamination has been widely accepted by the research community and practicing engineers in the construction industry as the material for strengthening and rehabilitation of common problems. However, quite limited literatures contained the use of FRP to strengthen RC deep beams with openings. This paper discussed the review of eleven different articles contained study of RC deep beams with openings together with effects of strengthening using FRP sheets. The outcome of this review paper outlined the way forward and future research focus in this area.

Introduction

Reinforced concrete (RC) deep beams are usually used in tall building, particularly at transfer floors, warehouses and other industrial structures. The provision of opening(s) in the web of deep beams is usually required to accommodate essential services such as air-conditioning ducts and electricity cable or to provide accessibility such as doors and windows. The creation of openings due to requirements arises from other disciplines for example; architectural, mechanical and/or a change in the building's function results in a sharp decrease in strength, which may often leads to severe safety hazard. Due to this, a number of studies have been reported in the literature on the behaviour and strength of RC deep beams with openings [1-4]. When such openings are unavoidable, adequate actions should be undertaken to strengthen the beam and reinstate the beam capacity due to the strength losses. Limited studies are covered in the literature on the topic of strengthening options of RC deep beams with openings.

Past Research on Investigating the Behaviour of RC Deep Beams with Openings

Kubik [1] studied the strength of RC deep beams with web openings, it is reported that photoelastic models could be of useful to identify the locations of stress concentrations those likely to occur in the testing of the main prototype beams either in steel or concrete. Such stress concentrations indicate the eventual formation of regions of plasticity. The presence of large square cut in RC deep beam interrupted the load path and the fringe pattern is considerably distorted. The high stress concentrations clearly occur at the corners of the cut and under the loading points. Results showed that apart from the high stress concentration occurred; regions of high intensity of tensile stress are also formed, which caused severe internal cracking.

Meanwhile, Yang and Ashour [2] investigated the structural behaviour of RC continuous deep beams with web openings. This study involved the testing of ten (10) continuous deep RC beams with openings up to the failure happened. The principal variables included the shear span-to-overall depth ratio, and the size and location of openings. The study revealed that the continuous deep beams having web openings in the region of interior shear spans suffered a higher reduction in the load capacity with the increase in opening size. Similarly, simply-supported deep beams with web openings followed the same pattern. Also, two types of failure modes observed due to influence of the size and location of web openings regardless of the shear span-to-overall depth ratio. The transition of the failure modes for beams having web openings in the exterior region of shear span was dominated by the ratio of opening area to shear span area.

Another study was carried out to determine the shear strength of large RC deep beams with web openings by Hu and Tan [5]. The authors tested a total of three (3) pierced deep beams and a solid beam with compressive strengths in the range of 35-44 MPa. The beams were tested to failure under two-point symmetric top loading. The beam samples had an overall depth of 2000 mm; an overall length of 4000 mm and a web thickness of 220 mm. Web openings of the size of 550 x 500 mm were located in the shear span of three pierced beams. In the pierced beams, the shear span was kept from 500 to 900 mm. It was reported that the web opening reduced the ultimate strength of a large deep beam significantly, if the web opening intersects the force path between the load point and the support as shown in Fig. 1. Results of the crack patterns illustrate a strut-and-tie system in large pierced deep beams. Fig. 2 shows the typical cracks appeared in deep beams.

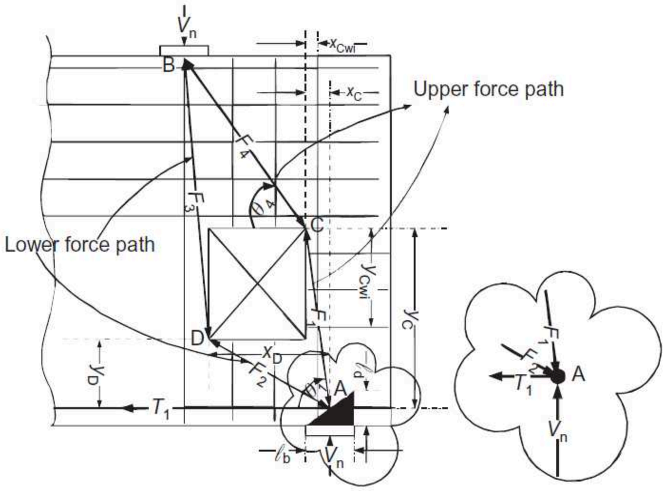

Fig. 1 Load paths of deep beams with web openings [5]

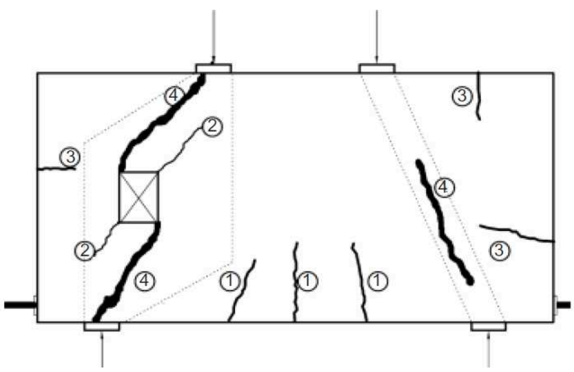

Fig. 2 Typical cracks in deep beams [5]

Strengthening of RC Deep Beams with Web Openings Using FRP Laminates

Inclusion of openings in RC deep beams reduces the beam's structural capacity and sometimes changes failure mechanism. The reduction of the concrete area in the high shear zone significantly reduces the beam shear strength and creates great serviceability problems. Hence, adequate measures should be taken in order to restore and re-gain the beam strength due to the losses caused by the openings.

An investigation was carried out by Ha [6] on the design of concrete deep beams with openings and carbon fiber laminate repair. A total of twelve (12) deep beams with and without openings were designed and constructed using the proposed design method. Among the beams, three (3) beams were repaired using carbon fiber laminates. The finding shows that the carbon fiber repair method is very effective, restoring 80% of the ultimate capacity of the beams using only one layer of repair laminate on each side of the beam. The study also found out that the increase of carbon fiber laminate layers can increase the beam stiffness.

In a research conducted by El-Maaddawy and Sherif [7] regarding the study of the potential use of externally bonded carbon fiber reinforced polymer (CFRP) composite sheets as a strengthening option to upgrade the capacity of RC deep beams with openings. The study included experimental testing and analytical prediction. A total of thirteen (13) deep beams were cast and tested under four-point bending. Beam specimens had a cross-section of 80 x 500 mm and a total length of 1200 mm. The openings were square in shape. Two openings, one in each shear span were placed symmetrically about the mid-point of the beam. Test parameters included the opening size, location and the presence of the CFRP sheets. According to the authors, the structural response of RC deep beams with openings was primarily dependent on the degree of the interruption of the natural load path. External shear strengthening using CFRP bonded around the openings was found very effective in upgrading the shear strength of RC deep beams. The presence of CFRP sheets could increase the beam strength within 35 – 73%.

In another study, El-Maaddawy and El-Ariss [8] investigated the behaviour of sixteen (16) RC beams strengthened using externally bonded CFRP sheets and subjected to short shear span with web opening. Beam dimensions were 2600 mm long with a cross-section of 85 mm x 400 mm and a shear span to beam depth ratio a/h of 2. All of the beams had the same geometry and top and bottom reinforcement and no web reinforcement provided in the test region. This test simulated the case of creating a large opening in an existing beam, which usually requires cutting of the internal web reinforcement within the opening. Test parameters of this study included the width and depth of the opening and the amount of the CFRP sheets used for shear strengthening. Results obtained show that the provision of web openings significantly reduced the beam shear capacity and stiffness. It was found that external strengthening with CFRP sheets around the opening could effectively improved the beam shear resistance and stiffness. Increasing width or depth of the opening reduced the shear capacity gained due to the presence of CFRP. By adding the amount of the vertical CFRP sheets from one to two layers increased the shear capacity; however the additional shear capacity gain was not in proportion to the added amount of the CFRP. Fig. 3 illustrates the CFRP strengthening system used in this study.

Kumar [9] also studied the behaviour of glass fiber reinforced polymer (GFRP) strengthened beams with openings using experimental investigation and numerical simulations using finite element analysis with the help of ANSYS. A total of five (5) deep beams with openings were cast without shear reinforcement and tested under three-point loading. GFRP lamination configuration was one of the test parameters considered in this study. Beam cross-section was 150 x 460 mm and the total length was kept as 1200 mm. A circular opening was created in each of the shear spans and placed symmetrically with respect to the mid-point of the beam. Strengthening scheme using externally bonded GFRP around the openings increased the beam capacity to about 68 – 125%. It was found that closely spaced GFRP in four layers of U-wrap and largely spaced GFRP in four layers of full wrap showed better results as compared to double layered U-wrap (closely spaced) and double layered full wrap (largely spaced). Finite element analysis results using ANSYS found well agreed with the experimental results.

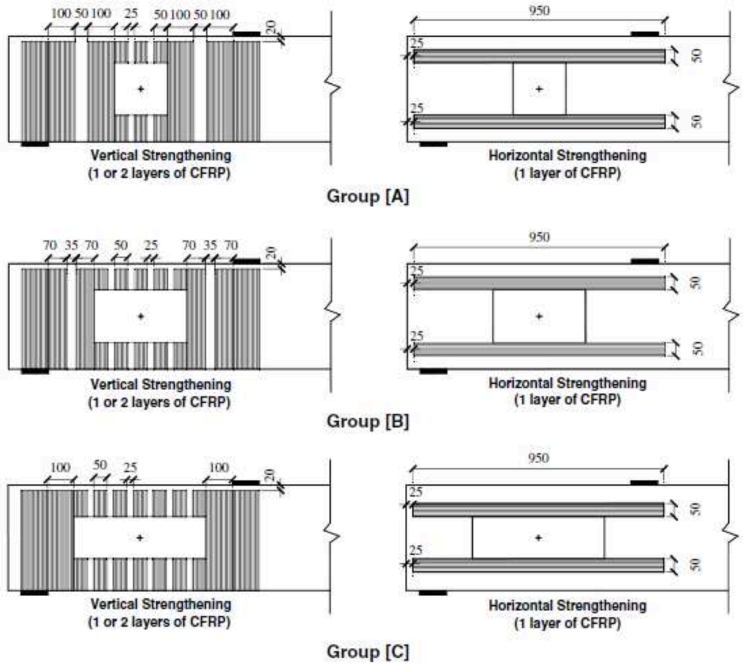

Fig. 3 CFRP shear strengthening system [8]

On the other hand, further research was conducted by Abduljalil [10] to study the shear resistance of RC deep beams with opening strengthened by CFRP strips. The experimental study tested a total of eight (8) RC deep beams. The research parameters in this study included the effect of fiber orientation (90° or 45° CFRP strips with respect to beam longitudinal axis), the effect of using longitudinal CFRP strips with vertical CFRP strips and the effect of anchoring the vertical CFRP strips. Discussion of test results was in terms of shear resistance – midspan deflection, strain in CFRP and maximum crack width of beams. Experimental results demonstrated that externally bonded CFRP strips can significantly increase the ultimate shear capacity, limit the shear crack width and increase the stiffness of the deep beams with opening. RC deep beams with opening strengthened with 45° CFRP strips exhibited higher cracking load and ultimate load as compared with 90° CFRP strips. In addition, strengthening scheme of 45° CFRP strips with additional longitudinal CFRP strips is more efficient in upgrading the shear resistance of deep beam with opening than 90° CFRP strips with longitudinal CFRP strips.

It has been a trend that most of the experimental study must be verified or validated with either theoretical approach or numerical analysis. Hence, recent investigation reported by Hawileh et al. [11] on nonlinear finite element (FE) modelling of concrete deep beams with openings strengthened with externally bonded composites. The 3D nonlinear FE models adopted realistic materials constitutive laws that account for the nonlinear behaviour of materials as shown in Fig. 4. In the FE modelling, solid elements for concrete, multi-layer shell elements for CFRP and link elements for steel reinforcement were used to simulate the physical models. In terms of the bonding behaviour between CFRP composites and concrete, special interface elements were implemented in the FE models to simulate the interfacial bond behaviour. The results of the FE analysis were compared with the experimental data in literature showed the validity of the computational models in capturing the structural response for both un-strengthened and CFRP –strengthened deep beams with openings. The crack patterns predicted by the FE models were in good agreement as compared with the experimental results. The predicted failure loads were within 3.2% error band while the predicted deflection capacities were within 14% error band. Results of the FE analysis confirmed the experimental findings that CFRP shear strengthening can significantly increase the load capacity. The developed FE models verified in this research could be used as an alternative to experimental testing. The FE modeling also can serve as a numerical platform for performance prediction of RC deep beams with openings strengthened in shear using CFRP composites.

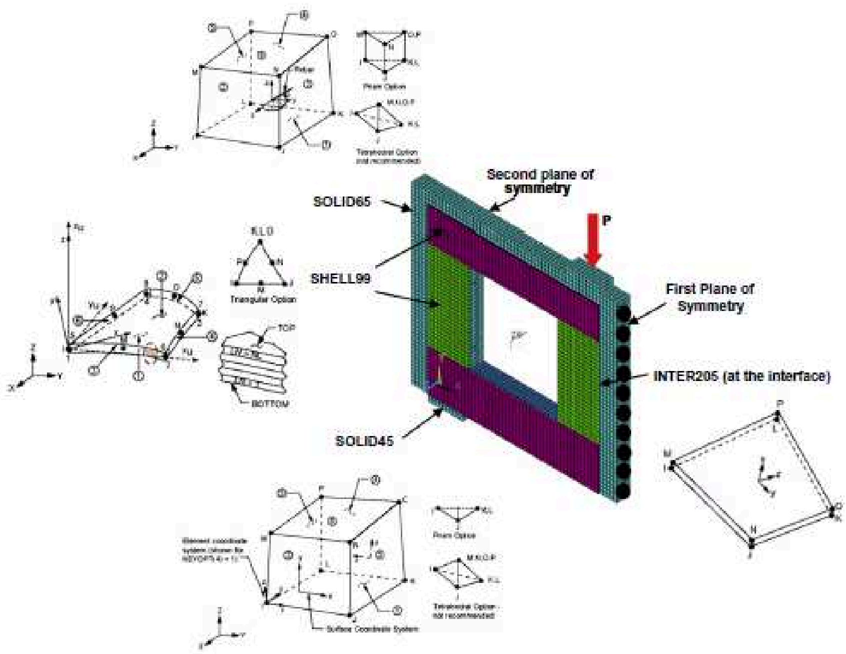

Fig. 4 Typical FE models [11]

Summary

Table 1 summarizes the investigations conducted by various researchers on the behaviour of RC deep beams with openings strengthened using FRP.

Table 1 Summary of FRP Strengthened RC Deep Beams with Openings

Author	Strengthening Material	Opening			Strengthening System	Method of Study	Strength Re-gain
		Shape	Location	Size (mm)			
Abduljalil (2014)	CFRP strips	Square (two openings-one in each shear span)	Symmetrical about the beam axes	65 x 65 mm	45° & 90° CFRP strips, & additional longitudinal CFRP strips	Experimental	Combination of 45° and longitudinal CFRP increase in cracking & ultimate load 8%, & 40.2%
Kumar (2012)	GFRP	Circular (Two openings-One in each shear span)	Mid-point of beam	-	Double layer U-wrap , four layer U-wrap, four layer full wrap GFRP, double-layer full wrap (closely and largely spaced)	Experimental and Numerical Method	68 -125%
El-Maaddawy and El-Ariss (2012)	CFRP composite sheets	Rectangular and Square	Middle of short shear span	200 x 200 350 x 200 500 x 120 500 x 160 500 x 200	Vertically and Horizontally -1 layer & 2 layers	Experimental and Analytical approach	Restore up to 70% of shear capacity of solid beam (θ=9°)
Hawileh et al. (2012)	CFRP	Square (Two openings-One in each shear span)	Mid., top and bottom of shear span	200 x 200 250 x 250	Vertically and Horizontally around the opening, U-wrap and full wrap	Finite Element Analysis	Good agreement of results
El-Maaddawy and Sherif (2009)						Experimental and Analytical method	Increase beam strength 35-73%.
Ha (2002)	Carbon fiber laminates	Square (A single opening in the mid-span)	Mid, top, bottom of span & near to support	12 in. x 12in.	One layer of repair laminate on each side of the beam	Experimental and Finite Element Analysis	Restoring 80% of the ultimate capacity

Way Forward and Future Research Needs

Further work to investigate the behaviour of RC deep beams containing large openings and strengthened using externally bonded CFRP is still on-going. The gaps as identified for future research include (i) strengthening options of deep beams containing openings using different type of lamination sheets for external bonding. (ii) studying the shear behaviour of deep beams with openings by varying the opening sizes and locations and (a/d) ratio, (iii) effective strengthening configuration around the openings in RC deep beams (iv) debonding behaviour of strengthening material and mitigation options.

Acknowledgements

This work is financially supported by the University of Malaysia Pahang, Malaysia Internal Grant (RDU130383). The authors wish to express their gratitude for financial support.

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