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Retrofit of Reinforced Concrete Deep Beams with Different Shear Reinforcement by Using CFRP

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Abstract
The purpose of this paper is to study the experimental behavior and efficiency for retrofitted of reinforced concrete deep beams by carbon fiber reinforced polymer sheets, CFRP. An experimental program was conducted to retrofit nine failed deep beams by external CFRP sheets. Horizontal and vertical transverse reinforcement and shear span to depth ratios, were the main studied parameters in this paper. It was concluded that using this retrofitted method is very efficient and a gain in the ultimate load capacity of the deep beams was obtained. This gain was due to the efficiency of the external carbon fiber sheets to resist an extra applied load after failure. The failure in most of the retrofitted specimens was due to separate carbon fiber sheets from concrete or due to concrete crushing.
Keywords: Deep beams, Retrofit, CFRP sheets, Web reinforcements, Shear span/depth ratio.

1. Introduction

There are many ways to rehabilitation of reinforced concrete deep beams. Adding new concrete jacket with additional reinforcement, using external steel sections, and wrapping the section with Fiber-reinforced polymers, FRP are the most popular methods of strengthening and retrofitting concrete beams.

A Fiber Reinforced Polymer (FRP) composite is defined as a polymer matrix that is reinforced with a fiber with a sufficient aspect ratio to provide a discernable reinforcing function. In the last decade, the investigation on the behavior of reinforced concrete structures retrofitted by FRP has become a very important research field.

Several studies were implemented to study the behavior of retrofitted beams and analyzed the various parameters influencing their behavior (Alferjani *et al.* 2013).

The complex nature of behavior of a reinforced concrete beam in shear gives difficulty to predict accurate. For this reason, the shear capacity of beams is assumed empirical in most codes.

The shear behavior depends on the detailing and type of shear reinforcement, size of the element, the position and type of applied loading and the concrete shear resistance capacity. External shear strengthening using FRP composites gained very popular because of several reasons including ease of application, lightweight feature and aesthetic appearance (Mosallam 2002).

Several researchers investigated the effective of externally bonded FRP system as an external reinforcement to strengthening RC deep beams.

Zhang and Moren (2004) studied the effect of the vertical CFRP on the shear strength of deep beams, they noticed that strengthening system gives least contribution in shear strength with reducing the shear span/depth ratio. Strengthening specimens which have shear span/effective depth ratio of 1.875 given an increasing in the shear strength of 79%, whereas only a 46% increasing of shear strength was recorded for 1.25 shear span/effective depth ratio.

Islam *et al.* (2005) investigated on the contribution of CFRP in strengthening of deep beams, they reported that use of FRP sheet systems lead to enhance of shear strengthening up to 40% for specimens which have 1.3 shear span/depth ratio.

Maaddawy and Sherif (2009) studied the structural response of RC deep beams with opening. The shear strength of specimens was majorly dependent on the degree of the interval of the ordinary load path.

Asghari *et al.* (2013), presented an experimental investigation on shear strength enhancement of reinforced concrete lightweight deep beams externally reinforced with vertical CFRP sheets. The shear span/depth ratio was taken equal to 1, and the percentage of shear strength improving by strengthening was 30%.

Khudair and Atea (2015), studied the shear behavior of self-compacting concrete deep beams strengthened with CFRP sheets. The experimental work includes testing of reinforced concrete self-compacting concrete (SCC) deep beams with shear span/depth ratio of 2. The tested results show that the specimens strengthened by vertical CFRP sheets provided enhancement in ultimate loads reached 30%.

1.1 Summary of Literature

From the above literature review we have observed the following results. The efficiency of enhancing the shear strength of reinforced concrete deep beams by strengthening with vertical CFRP sheets was not depend only on span/depth ratio and the concrete shear resistance capacity but also depend on; the shear reinforcement

(Bousselham and Chaallal 2006) and the type of anchorage of the CFRP sheets (Kim and Smith 2009).
The following research includes the effect of the vertical and horizontal web reinforcements and span to depth ratios on the behavior of the retrofitted deep beams by CFRP sheets. Also to understand the contribution of CFRP sheets in the shear strengthening for specimens loaded to fail before retrofit.

2. Experimental Program

2.1 Specimen Details

The experimental program was planned and executed to investigate the effect of the retrofitted by vertical CFRP sheets on the shear strength of simply supported reinforced concrete deep beams which were tested to failure in previous study (Faraj 2014). The program consisted of testing nine retrofitted simply supported deep beams to failure load. The deep beam models have an overall length of 1200 mm, width of 115 mm and overall depth which varied 333 mm, 400 mm and 500 mm, as shown in Figure 1. All beams have the same flexural reinforcement. The parameters considered in this study are the shear span to depth ratio (a/h) and the amounts of vertical and horizontal shear reinforcements (ρ_v, ρ_h). Details of the nine tested reinforced concrete deep beams are listed in Table 1. The tested deep beams were designed according to (ACI 318M-14) by using the strut and tie model.

Table 1. Details of tested specimens

Model No.*	d (mm)	Web R. ratio ρ_v	Web R. ratio ρ_h	Web R. spacing (mm) Vertical	Web R. spacing (mm) Horizontal
DB1	365	0	0	-	-
DB2	365	0.0025		Ø 4 @ 200	Ø 4 @85
DB3	365	0.0052		Ø 6 @ 160	Ø 6 @ 110
DB4	365	0.003	0	Ø 4 @ 60	
DB5	365	0.005	0	Ø 6 @ 80	-
DB6	365	0	0.003	-	Ø 4 @ 45
DB7	365	0	0.005	-	Ø 6 @ 65
DB8	465	0.0025		Ø 4 @ 130	Ø 4 @ 110
DB9	298	0.0025		Ø 4 @ 265	Ø 4 @ 65

*DBn is refers to deep beam model before retrofitted

The tested deep beams (before retrofitted) are defined by symbol "DBn", where n represents the beams number (from 1 to 9). While retrofitted tested deep beams are defined by symbol "RDBn". Where n represents the same beams number for each of reference and retrofit beam.

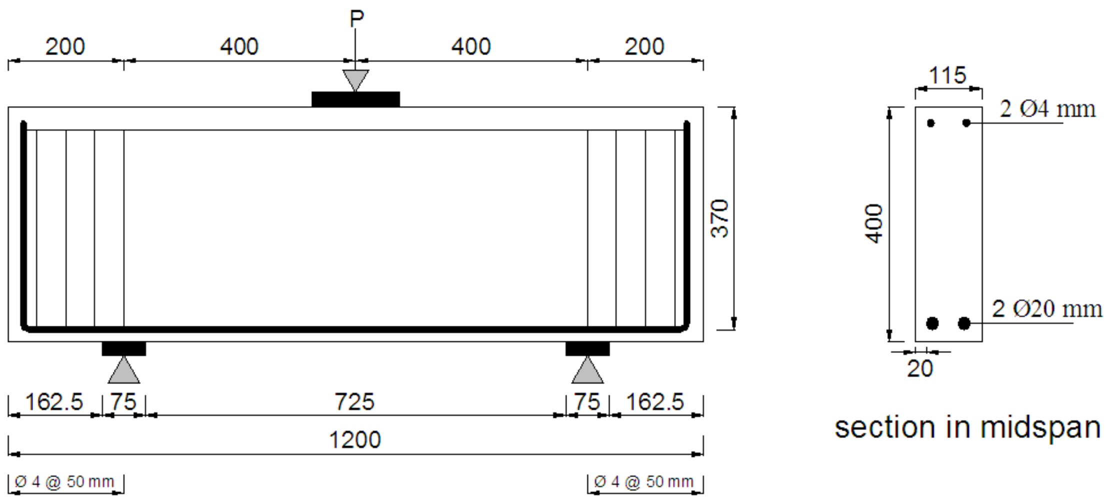

Figure 1. Details of the control tested beam (All dimensions are in mm).

2.2 Material Properties

The mix proportions used to cast the specimens are designed according to (ACI 211.1-91). Single batch was used to cast all the specimens, which having an average cylindrical compressive strength (f'c) of 34 MPa at 28 days. It was made from ordinary Portland cement, river sand and crushed gravel of 10mm maximum size. The cement-sand-aggregate ratio was 1:2:2.5 by weight and the water-cement ratio was 0.45 by weight.

The longitudinal steel reinforcement was deformed bar with characteristic yield stress of 500 MPa. To insure a sufficient anchorage capacity, the bars were bent up and enclosed by additional vertical stirrups at each end with the spacing of 50 mm. The beam webs were reinforced with smooth bars of 400 MPa yield strength. Carbon fiber reinforced polymer (CFRP) sheets with 0.13 mm thickness wraps all models with unidirectional. Each deep beam retrofits by six sheet wraps aligned vertically as shown in Figure 2. The fixing process is implemented according to (ACI 440.2R-08).

The mechanical properties of the selected CFRP material are introduced as 230 GPa elastic modulus, 3500 MPa tensile strength and 1.5% elongation at break. The epoxy resin has 3.8 GPa elastic modulus and 30 MPa tensile strength with optimum 1.0 mm thickness required for each CFRP sheet wrap as recommended by manufacturer.

2.3 Test Set-Up and Instrumentation

The test set-up for the deep beams is illustrated in Figure 3. All tested beams were loaded under three-point bending and supported as simply by two steel rollers located 200 mm from each end of the beams, which having various shear span to depth ratios of 0.8, 1 and 1.2. Steel bearing plates of 20 mm thick and 75 mm width were used and inserted between deep beam model and roller of testing machine to prevent the bearing failure at the supports. Another steel plate of 20 mm thick and 150 mm width was placed under the piston of the hydraulic jack at the loading location. The load was applied using a universal hydraulic machine with a maximum capacity of 3000kN. Mid-span deflection of the beams was measured by dial gauge.

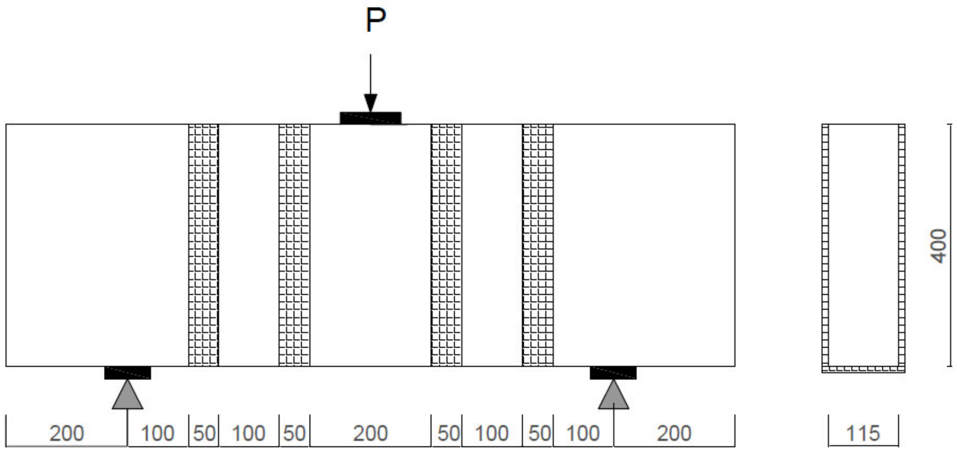

Figure 2. Details of retrofitted tested beams (All dimensions are in mm).

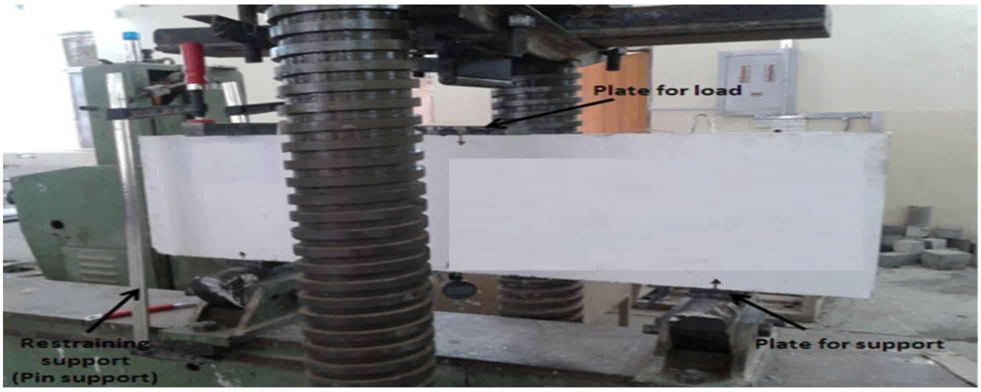

Figure 3. Test setup

3. Experimental Results

Firstly, all deep beams were tested under static loading until failure. Then, retrofitted by external CFRP sheets and re-loading to failure again. Experimental applied load and mid span deflection were automatically recorded. The crack pattern of reference and retrofitted tested beams are shown in Figure 4. Test results of all tested specimens are listed in Table 2.

3.1 Crack Pattern

Shear cracks initiated in the web which connect from the loading point to the support. These diagonal cracks propagated upward to the loading point and downward to a location of support and the width of diagonal shear cracks became wider with incremental loads. According to the previous study [10], Figure 4a shows the crack pattern for specimens without CFRP. And Figure 4b shows the crack pattern for the same spaceman's after retrofit. The crack pattern of the retrofitted deep beams have a different shape in comparison with the reference beams. There are appearance new cracks and disappearance of old crack in retrofitted beams.

Table 2. Summary of test results for the tested beams.

Model No.	Reference Models		Retrofitted Models		
	P_u (kN)	Mode of failure	P_{ur} (kN)	Mode of failure	Increasing of P_u
DB1	189	Shear-compression failure	418	Separate fibers	1.21
DB2	398	Shear-compression failure	535	Separate fibers	0.34
DB3	435	Strut crushing failure	469	Separate fibers	0.08
DB4	415	Diagonal-splitting failure	555	Concrete crushing	0.34
DB5	418	Strut crushing failure	604	Concrete crushing	0.45
DB6	198	Shear-compression failure	518	Separate fibers	1.61
DB7	269	Shear-compression failure	472	Separate fibers	0.76
DB8	417	Strut crushing failure	534	Separate fibers	0.29
DB9	357	Strut crushing failure	503	Separate fibers	0.41

P_u: ultimate load for reference model, P_{ur}: ultimate load for retrofitted model

3.2 Ultimate Strength and Mode of Failure

All the beams failed in shear. The references deep beams are failed by one of the following mode; shear compression failure, strut compression failure and diagonal splitting failure between the load point and support point in shear-span, as can be seen in Figure 4a and listed in Table 2. While the retrofitted deep beams are failed either by separate of CFRP from concrete or concrete crushing, as can be seen in Figure 4b and listed in Table 2.
According to test results listed in Table 2, deep beams DB6, which has a minimum horizontal web reinforcement of ratio 0.3% and retrofitted by CFRP sheets, failed at a load 161% of ultimate loading. This beam appears a highest percentage of repair enhancement in comparison with others beams. While the ultimate strength of this beam before retrofit was closely to the strength of beam without shear reinforcement, DB1. The second highest percentage of enhancement 121% is appeared in the beam without shear reinforcement, DB1. So, one can conclude the importance of minimum horizontal reinforcement is more obviously in retrofitted beams. And generally, the horizontally reinforced deep beams (DB6 and DB7) appearance good retrofit enhancement in comparison with vertically reinforced deep beams (DB4 and DB5) for the same steel ratio (0.3% and 0.5%) as mentioned in Table 2.

The retrofit enhancement is decreased with increasing of shear reinforcement, as fixed for total shear reinforcement, when reinforcement ratio increased from 0.25% to 0.5% the enhancement strength of retrofit beams decrease from 34% to 8% of ultimate load for DB2 and DB3, respectively.

Also, for horizontally shear reinforcement with ratio 0.3% and 0.5% the enhancement strength of retrofit beams decrease from 161% to 76% of ultimate load for DB6 and DB7, respectively. While the behavior of vertically reinforced deep beams appear a different behavior in comparison with others. By increasing the vertical reinforcement ratio from 0.3% to 0.5% the enhancement strength of retrofit beams increase from 34% to 45% of ultimate load for DB4 and DB5, respectively.

For the same reinforcement ratio 0.25%, when the shear span to depth ratios increase from 0.8 to 1 to 1.2, the enhancement strength of retrofit beams increase from 29% to 34% to 41% of ultimate load for DB8, DB2 and DB9, respectively.

a- Reference model ***b- Retrofitted models***

Figure 4. Crack pattern for tested deep beams

3.3 Load Deflection Behavior

The applied load versus mid span deflection of the reference and retrofitted beams are shown in Figure 5 to Figure 13. The behavior of most of the deep beams demonstrated a nearly linear response up to failure because the flexural reinforcement didn't yield. It was noted that retrofitted beam by externally CFRP sheets given a good enhancement in the shear strength for the deep beams. Using CFRP sheet increase the deflection capacity of deep beams without shear reinforcement, DB1, for beams with horizontal reinforcement only, DB6 and DB7 and for deep beams with vertical reinforcement greater than the minimum ratio, DB5.

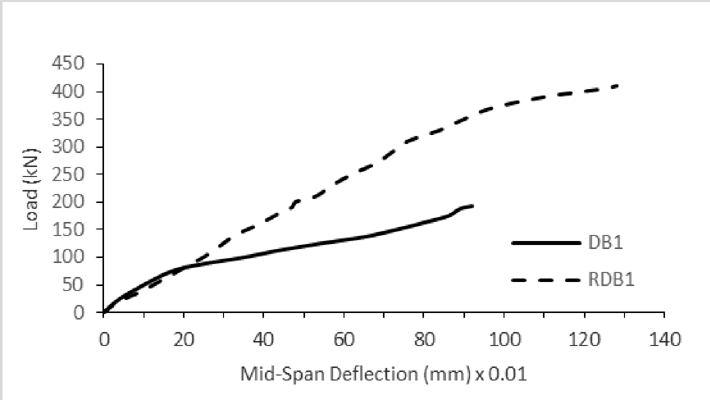

Figure 5. Load deflection for tested beam (DB1 and RDB1).

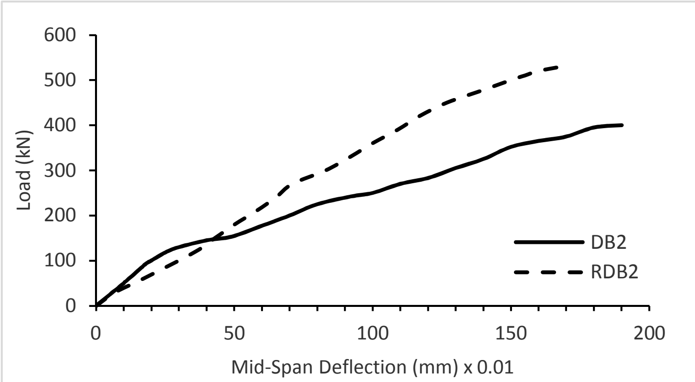

Figure 6. Load deflection for tested beam (DB2 and RDB2).

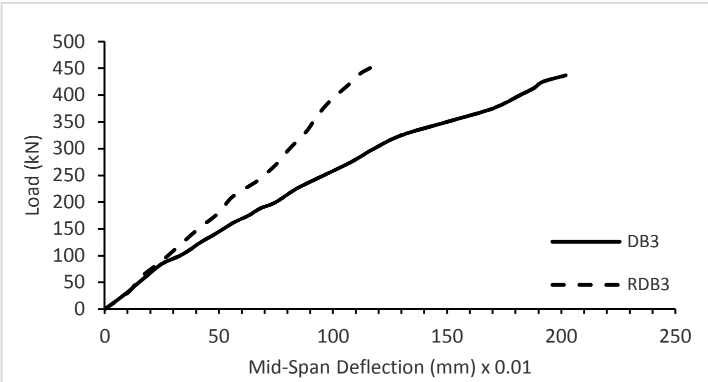

Figure 7. Load deflection for tested beam (DB3 and RDB3).

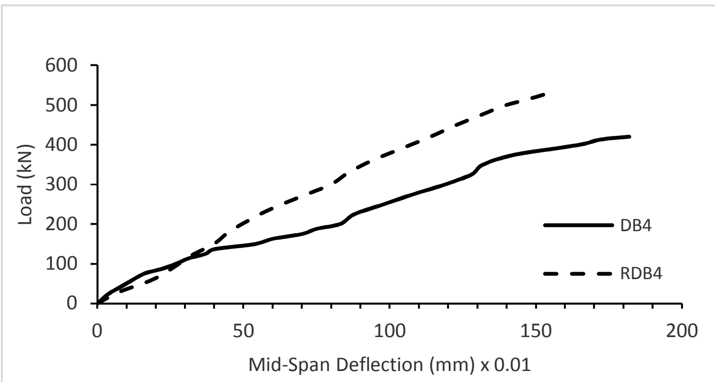

Figure 8. Load deflection for tested beam (DB4 and RDB4)

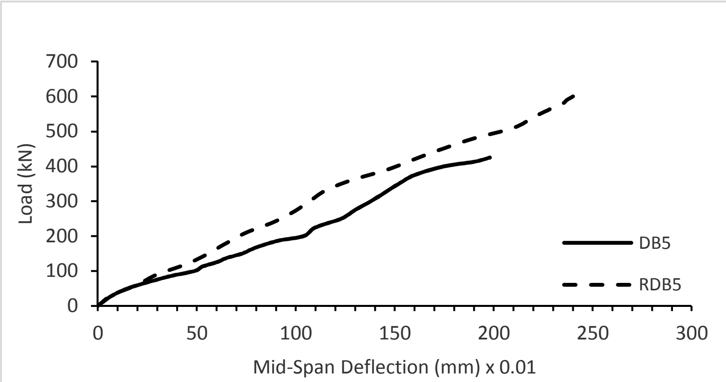

Figure 9. Load deflection for tested beam (DB5 and RDB5).

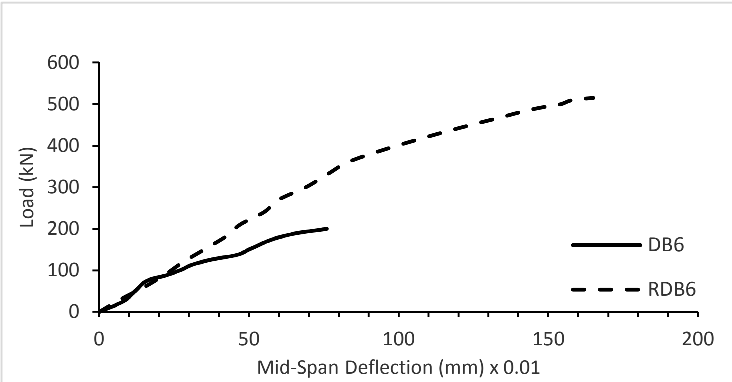

Figure 10. Load deflection for tested beam (DB6 and RDB6).

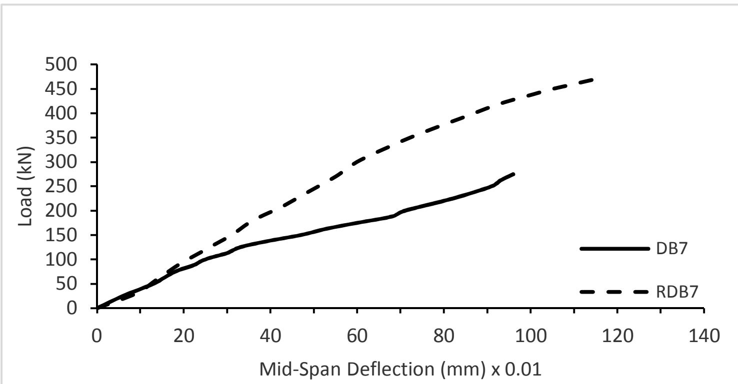

Figure 11. Load deflection for tested beam (DB7 and RDB7).

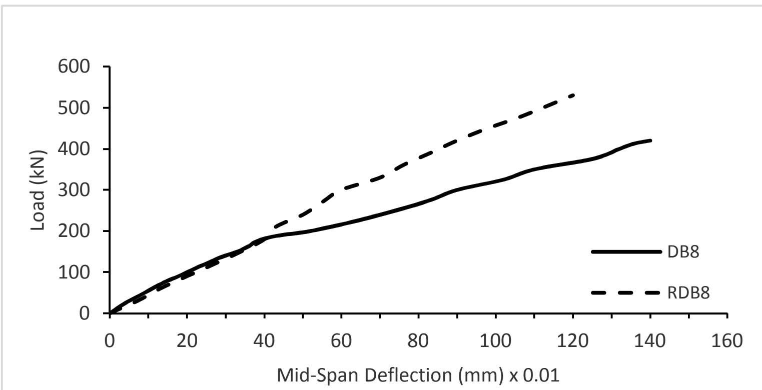

Figure 12. Load deflection for tested beam (DB8 and RDB8).

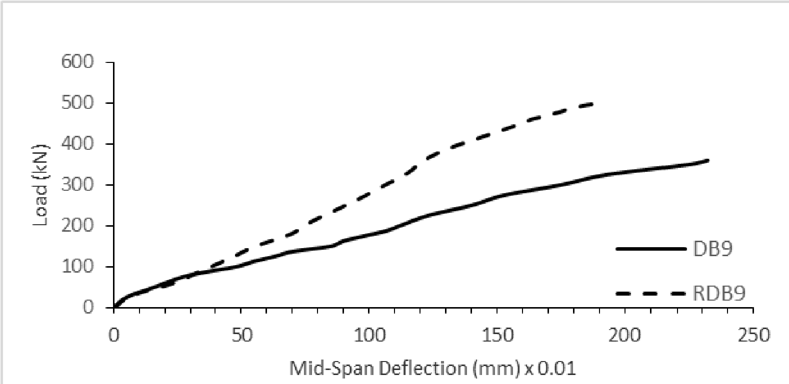

Figure 13. Load deflection for tested beam (DB9 and RDB9).

4. Conclusion

According to the experimental results of retrofit deep beams by using CFRP, the following conclusion can be recorded:

1. All retrofit deep beams given an increase in ultimate strength with represents to reference model. The enhancement magnitude of retrofit deep beam start from 8% to 161% of ultimate load of reference.
2. Deep beam reinforced by horizontal shear reinforcement gives high enhancement strength of retrofit beam in comparison with beam vertically reinforced for the same steel ratio.
3. The increasing of horizontally shear reinforcement from minimum to maximum ratios given decreasing of enhancement strength of retrofit beams. While the behavior of vertically reinforced deep beam appears a different behavior. By increasing the vertical reinforcement from minimum to maximum ratio conduct to increase of enhancement strength of retrofit beams.
4. Retrofit deep beam without shear reinforcement given an increasing in enhancement strength and deflection greater than deep beam with shear reinforcement.
5. For the same reinforcement ratio, when the shear span to depth ratios increase, the enhancement strength of retrofit beams also increase.
6. The enhancement in ductility of retrofit deep beam is appear when the model without or with horizontally shear reinforcement.

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