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Effect of Shear Span-Depth Ratio on Shear Strength of Porcelanite Lightweight Aggregate Reinforced Concrete Deep Beams Strengthened by Externally Bonded CFRP Strips

Abstract- *This paper presents an experimental investigation of structural behaviour of reinforced concrete deep beams strengthened in shear by CFRP strips. The experimental program consisted of fabricating, casting and testing of nine identical porcelainte lightweight aggregate reinforced concrete deep beams. Three of the tested deep beams were unstrenghtened to serve as reference beams, while the remaining beams were tested after being strengthened using CFRP strips in two different orientations (vertical and horizontal). The locally available natural porcelanite aggregate is used to produce lightweight aggregate concrete. The beams were designed to satisfy the requirements of ACI 318M- 14 building code. In order to insure shear failure modes, adequate flexural steel reinforcement were provided. Effect of three different values of shear span to effective depth ratio (a/d =1.0, 0.8, 1.2) were selected. All beams have been tested as a simply supported beams subjected to two concentrated points loading. The beam specimens were tested up to failure under monotonic loads. The experimental work showed that the failure load increases as the shear span to effective depth ratio deceases. As the shear span to effective depth ratio decreased from 1.0 to 0.8, the percentage of increase in the ultimate load was about 24%. In addition, the diagonal compression strut crack of unstrenghtened control beams was changed to several diagonal cracks at mid depth within the shear span of the strengthened beams and exhibited more ductile failure mode.*

Keywords- shear span, shear strength, lightweight concrete, CFRP, Deep beams.

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1. Introduction

According to ACI 318M-14[1] a simply supported beam is classified as a deep beam when the ratio of its effective span (L) to overall depth (h) is less than (2). Continuous beam are considered as deep when the ratio (L/h) is less than (2.5). The effective span is defined as the center-to-center distance between the supports or (1.15) times the clear span whichever is less. In addition, a deep beam is defined as a member loaded on one face and supported on the opposite face, so that compression struts may develop between the loads and the supports.

Reinforced concrete deep beams are used as load distributing structural elements or as a horizontal diaphragms, pile caps, foundation walls, and offshore structures. They are also used in construction of bunkers, water tanks and bins where the walls act as vertical beams spanning between the columns supports and carrying a part of the floor load. The distribution of strain across the depth of the cross section of deep beams is nonlinear and a significant amount of load is carried to the supports by a compression strut joining the applied load and reaction [2, 3].

Generally reinforced concrete beams (including deep beams) fail in two ways; flexural and diagonal tension (shear) failure. The shear failure is more sudden, brittle and gives no warning prior to failure [4, 5]. Advanced composite materials, known as fiber reinforced polymers (FRP) have received a significant attention as one of the most promising materials for use as external reinforcement in construction for repairing and retrofitting of damaged buildings, or to enhance the load capacities.

The four main of types FRP used in the construction industry are: aramid (AFRP), carbon (CFRP), basalt, and glass (GFRP) [6]. The advantages of CFRP application includes high strength to weight ratio, flexibility and available in long lengths, rapid execution on site, high elastic modulus, high dynamic strength and no need for special equipment [6, 7].

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As stated in ACI Committee 440.2R-08[8], the three types of wrapping schemes used to increase the shear strength of reinforced concrete beams or columns are: completely wrapping around four sides of the member, U-wrap, or bonding to two opposite sides of the member [8,9] (see Figure 1) . In all wrapping schemes, the installation of the FRP can be used continuously along the span of the member or as spaced strips (see Figure 2). The second alternative could be effective in optimizing the amount of material used

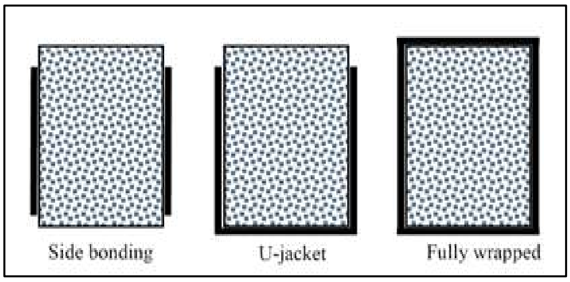


Figure 1: Shear strengthening schemes with FRP composites [8]

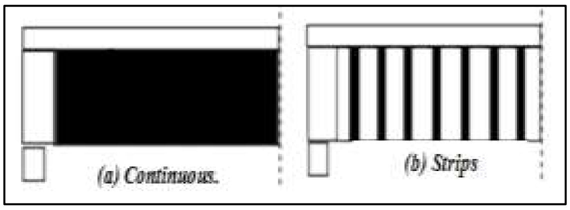


Figure 2: FRP distributions [9]

2. Experimental Program

I. Beam Specimen Description

Nine simply supported lightweight aggregate reinforced concrete deep beams were cast and tested to investigate the performance, which could be achieved by using externally bonded FRP for shear strengthening purpose. All beams were strengthened using externally bonded CFRP strips except three beams, which serve as a control beams for each different a/d ratio. All the beams have been tested as a simply supported deep beams subjected to two concentrated points loading with three different values of shear span to effective depth ratio.

II. Beam specimen details

The deep beams were with the same dimensions of (1400 mm span length, 150mm width, 400 mm depth), The cross sectional dimensions of these beam were kept constant in order to focus on the effect of a/d ratio with different strengthening schemes. The internal reinforcement were (3Φ16mm for main bars and Φ5 at 100 mm for shear reinforcement in the horizontal and vertical directions). The yield strength of the shear reinforcement was 476MPa while for flexural reinforcement was 450MPa. Dimensions and details of the internal steel reinforcement for the tested deep beams are shown in Figure 3 and Figure 4 respectively

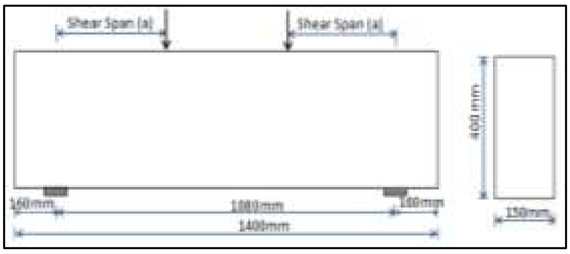


Figure 3: beam specimen geometry

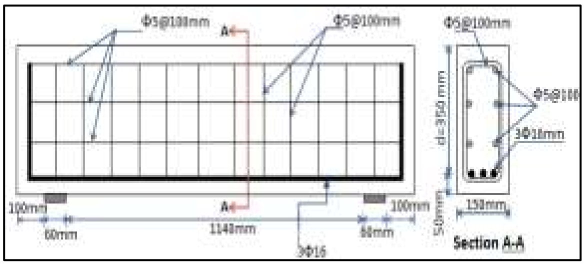


Figure 4: Beam reinforcement details

III. Concrete mix design

As recommended by ACI 213.2R-03 [10] Committee, a concrete shall be deemed to be a structural lightweight concrete if its compressive strength (f'c) is greater than (17 MPa) at (28 days) and the oven dry density less than (2000kg/m3).Hence, several trial mixes were made in order to satisfy these two conditions and reach to an acceptable concrete compressive strength of (26.34 MPa) at (28 days) with an oven dry density of about (1950 kg/m3). GLENIUM51 was used as a high performance super plasticizing admixture in the present work.

IV. Arrangement of Externally Bonded FRP

Table 1 summarizes beam specimen strengthening details. The name of the deep beams include the short (DB) which is refer to deep beam (D for Deep and B for Beam) followed by the symbols: (UN) which is used for unstrengthen beams, (V) for vertical strips orientation and (H) for the horizontal strips orientation. The last number in beam specimen designation refers to a/d ratio. The strengthened deep beams were bonded with one layer U-warp CFRP strips spaced at 100mm center to center. The width of strips was kept constant of 50 mm. Sika Wrap-300 C/60 unidirectional woven Carbon fiber fabric and Sikadure-330 two parts epoxy impregnation resin were used in the present study to strengthening the tested beams. Table 2 summarizes properties of each constituent material. Figure 5 illustrates design drawings and all details of the strengthening pattern of the tested beams.

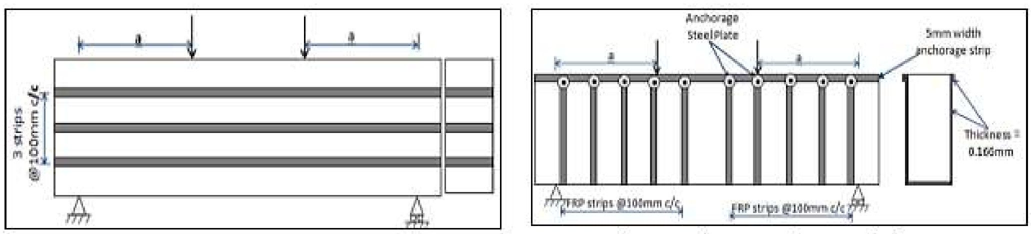
Table 1: Beams specimen strengthening details

Beam No.	Geometry properties		Orientation of CFRP strips
	a (mm)	a/d ratio	
DBUN0.8			none
DBV0.8	280	0.8	Vertical
DBH0.8			horizontal
DBUN1			none
DBV1	350	1.0	Vertical
DBH1			horizontal
DBUN1.2			none
DBV1.2	420	1.2	Vertical
DBH1.2			horizontal

Table 2: Sika Wrap-300 C/60 and Sikadure-330 epoxy properties [11, 12]

material	properties	Description*
Sika Wrap-300 C/60	Thickness	0.166 mm
	Fiber Density	1.79 g/cm^3
	Tensile strength	3900 MPa (nominal)
	Tensile E-modulus	230000 MPa (Nominal).
	Ultimate strain	0.015
Sikadure-330 two parts epoxy	Tensile Strength	30 MPa (@ 7 days with +23
	Tensile E-Modulus	3800MPa (@ 7 days with +23 ^{o}C)
	Thermal Resistance	Continuous exposure (+45 ^{o}C)
	Mixing ratio	Part A to part B=4:1 by weight
	Service Temperature	(-40) to (+45) ^{o}C
	Potlife	90 minutes @+10^{o}C, 30 minutes @+35^{o}C

**** provided by the CFRP manufacturers***



Horizontal strengthening scheme of the deep beams DBH 0.8, DBH1.0, DBH1.2

Vertical strengthening scheme of deep beam DBV 0.8, DBV1.0, DBV1.2

Figure 5: CFRP strengthening configurations

V. Surface Preparation and CFRP Installation

The CFRP strips were applied by a manual lay-up process on the external surface of concrete as describe in the following steps:

- Initially, the concrete surface was uniformly abraded at the locations of gluing carbon fiber strips on concrete.
- The side or/and lower corners of the strengthened specimens were chamfered to provide a radius of approximately (13 mm) (Figure (6)) according to ACI Committee 440.2R-08[8] recommendations and the Carbon fiber manufacturers [11] (minimum radius required for applications around corners is greater than 10 mm) to avoid any stress concentration in the carbon fiber strips at the corners of the beams.
- Prior to application of adhesive on concrete beam, the bonding surfaces were solvent wiped with acetone cleaner to remove the remaining contaminants.
- Just before composites application on concrete beam, the epoxy resin is mixed in accordance with manufacturer's instructions [12]. Then a thin layer of epoxy resin was applied along the concrete substrate in specified locations where the fiber will installed. The strips are placed on top of the epoxy resin coating and bonded to the tensile soffit. Then, the resin is squeezed through the roving of the fabric with a special roller.

VI. Test Setup and Loading Procedure

All tested beams were subjected to two-point monotonic load as shown in Figure 7. The constant length of an overhang beyond the supports was maintained to be (130mm). For all tested beams, one-dial gauges of (0.01 mm) accuracy capacity was positioned at midspan of each beam to measure the midspan deflection. The test was done by a hydraulic testing machine (AVERY Denison testing machine) of (2500 kN) maximum capacity which was available in the structural laboratory of the Building and Construction Engineering Department/ University of Technology (Figure 7). The machine was calibrated by Iraqi Central Organization for Standardization and Quality Control (COSQC) in the same year of testing.

Figure 6: Smoothing the concrete corners prior to fix CFRP strips

Figure 7: Testing rig and positioning of the beam on the test rig

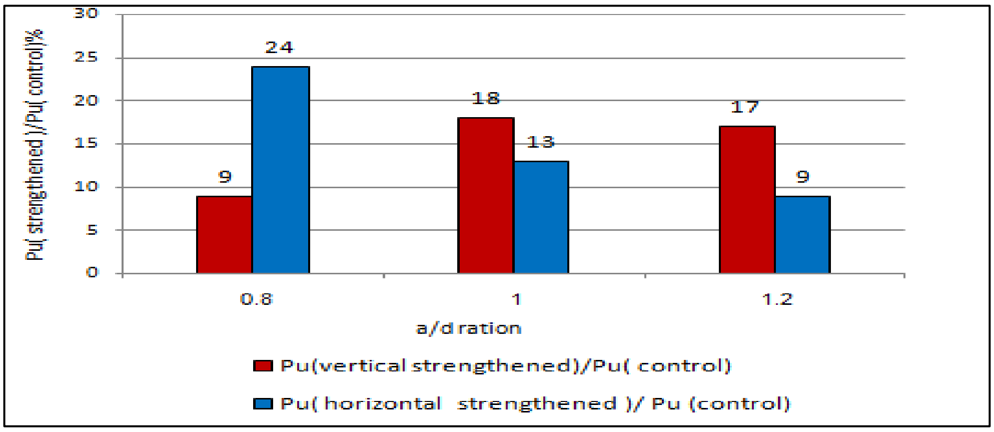
3. Results and Discussion

I. First Cracking Load and Ultimate Load Capacity

Table 3 presents the summary of test results including first cracking load and ultimate load gain by carbon fiber strengthening technique. It is observed that the initial cracks in the strengthened beams are developed at a higher load than their control specimens because the CFRP strips provide a good restraint to the cracks growth. The increase in the first cracking load of the strengthened deep beams can be attributed to the increase of stiffness due to the CFRP strips restraining effect. The ratios of ultimate load carrying capacity of the strengthened beams to the control beams are computed and presented in Table 3. The highest value was recorded for beam specimen DBH0.8 among all the tested beams, which was equal to 124%.

The effect of a/d ratio on shear capacity gain in case of vertical or horizontal strips strengthening is illustrated in Figure 8. This figure and the results in Table 3 indicate that the increase in a/d ratio has led to a reduction in shear capacity, for an example, increasing a/d ratio from 0.8 to 1.2 leads to decrees in shear carrying capacity by about40%, for strengthened control beam and by about 26% and 54% for tested beams strengthened by vertical and horizontal CFRP strips orientation respectively.

Results show that beam specimen DBH0.8 (which has the smallest a/d ratio (0.8)) exhibited an increase in ultimate load capacity of about 24% over its control beam specimens (DBUN0.8). While the increasing in ultimate load capacity of beam specimens DBH1 and DBH1.2 was about 14% and 9% over their control beams. As a concluding remark, the contribution of horizontal strengthening orientation to shear capacity appears to decrease with the increasing a/d ratio and its effect decreases with increased a/d ratio.



$Pu_{(Str.)}$: ultimate strength for strengthened beams; $Pu_{(cont)}$: ultimate strength of control beam

Figure 8: Effect of shear span to depth ratio on ultimate load gain by CFRP application

Beam No.	*a/d*	*CFRP orent.*	$P_{cr(shear)}$ *kN*	*Increasing in shear loads %*	P_u *kN*	*Increasing in ultimate load %*	$P_u)_{str.} / P_u)_{cont.}$ *%*
DBUN0.8		-	100	-	620	-	-
DBV0.8	0.8	V	170	70	680	10	110
DBH0.8		H	120	20	770	24	124
DBUN1		-	100	-	440	-	-
DBV1	1.0	V	160	60	520	18	118
DBH1		H	120	20	500	14	114
DBUN1.2		-	120		460	-	-
DBV1.2	1.2	V	140	17	540	17	117
DBH1.2		H	100	-20(decrease)	500	9	109

Table 3: Experimental results of the tested beams

In general, it is clearly indicated vertical placement of CFRP strips is more efficient than horizontal placement. A comparison of strength enhancement of 9 % for DBV0.8 against 18%, and 17 % for DBV1 over their control beams respectively, indicates that the effect of externally vertical bonded carbon fiber strips increases with increasing a/d ratio.

Figures 9 and 10 depict the effect of a/d ratio on cracking load and ultimate load for tested beams respectively. The largest difference in cracking load was observed in the beam specimen strengthened by vertical CFRP strips compared with the others, even though the spacing and the area of CFRP was kept constant. The ultimate load of unstrenghtened beam with a/d of 0.8 (beam specimen DBUN0.8) was 41% and 35% higher than those with a/d of 1.0 (beam specimen BDUN1) and 1.2 (beam specimen DBUN1.2), respectively.

II. Crack Pattern and Failure Modes

Figures 11 *to* 13 show the failure mode of the tested beams. Examination of these figures indicates that all tested beams experienced shear failure, in spite of the different strengthening schemes. In all of the strengthened beams, the presence of CFRP strips was found to alter the crack pattern from that observed in control beams. The splitting line for beam specimen DBUN1.2 is more pronounced than those of beam specimen BUN0.8 that may be because of the higher tension stress due to higher value of a/d ratio of beam specimen DBUN1.2, as well as, the failure loads of tested beams of a/d=0.8 are higher than those of the corresponding beams of a/d=1.2 because of the shorter shear span length. Some diagonal cracks were prevented from progressing upward towards the loading zone in beam specimen DBV1.2 by the help of CFRP strips. The beam was failed by a total load of 17% greater than corresponding control beam. This beam exhibited a gradual increase in load up to the peak and failed in a ductile manner without CFRP debonding. CFRP tearing was noticed in beam specimen DBH1.0 companied with a relatively wide shear crack in contrast of beam specimens DBH0.8 and DBH1.2. The latest two strengthened beams did not show any evidence of CFRP debonding. The failure of beam specimen DBV0.8 was similar to that of beam specimen DBV1.2 in which rupture occurred in the CFRP strips at midspan.

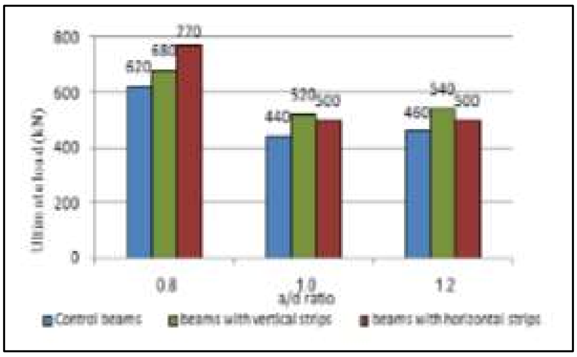


Figure 9: Effect of a/d ratio on cracking load

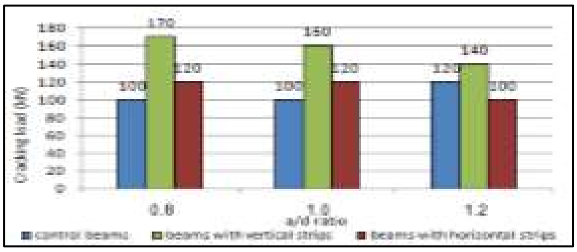


Figure10: Effect of a/d ratio on ultimate load

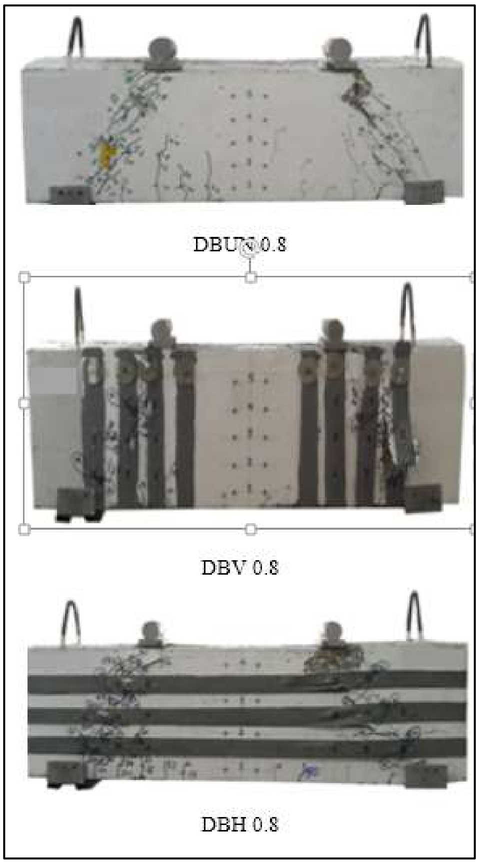


Figure 11: Failure mode of beam specimens with a/d =0.8

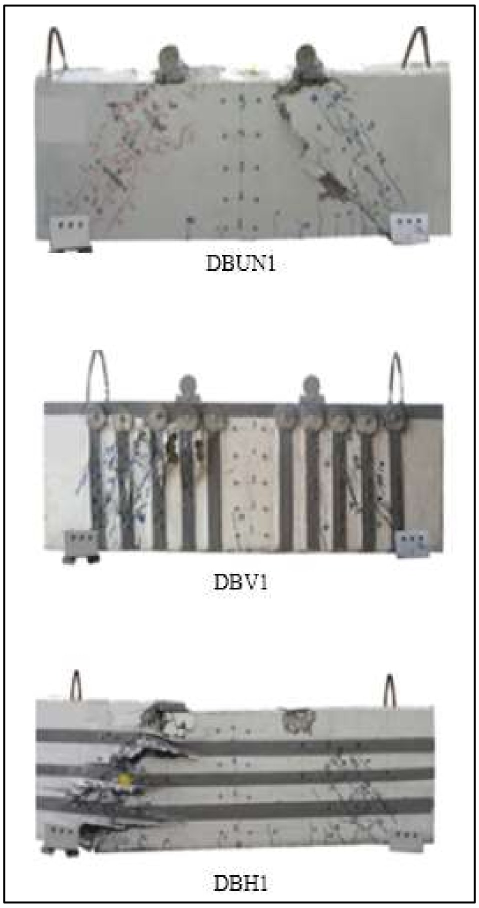


Figure 12: Failure mode of beam specimens with a/d =1.0

III. Load-Midspan Deflection Response

Table 4 elucidates the ultimate load and midspan deflection for the tested beams to show the effect of CFRP strips on the deflection values. The largest deflection at failure load was recorded to beam specimens DBV 1.2 with a/d = 1.2 which was (10.3mm). As shown in Table 4, the decrease in deflections for vertical and horizontal strengthening schemes is almost equal for each a/d ratio at the first crack load stages except for beam specimen DBV1.0.

The midspan deflection response versus applied load for the three sets of tested beams (a/d=1.0, 0.8, 1.2) is shown in Figures (14(a) to (c)), respectively. It is clear that the relation is linear throughout the entire path, but before failure, the line slightly bends. This behavior is observed in all beams due to controlling of shear rather than flexure in failure incidence especially for small values of shear span to depth ratio.

The vertical strengthening scheme (using vertical strips of CFRP) is more efficient in upgrading the shear resistance of reinforced concrete deep beams than the horizontal one for the higher a/d ratio as could be seen in Figure (14 b and c) and Table 4. As an example; the percentage increase in shear carrying load capacity was 31% for vertical strips versus 24% for horizontal strips for a/d =1.0 as compared with the control beam.

It is noticeable from Figure (14b) that the three curves are identical in shape up to about 40% of the ultimate load. Then the strengthened beam specimens (DBV0.8, DBH0.8) exhibited slightly greater overall stiffness and deflected more than the control beam at ultimate load. Same trend was observed for the ratio a/d =1.0 and 1.2 where is the strengthened beams seem to be stiffer than their control ones.

A comparison between the behavior of the unstrenghtened control beam specimens (DBUN0.8, DBUN 1, and DBUN1.2) for different a/d ratios (0.8, 1.0, and 1.2) respectively, is presented in Figure (15a). The three beams behaved in a similar manner for a while. After that, the reduction in stiffness of beam specimen DBUN1.2 was greater than that of the other because it has greatest a/d ratio. That may be due to the increase in shear span length, which leads to an increase in the applied moment and hence increasing in deflection of the beam due to increasing in curvature. The increase in a/d ratio has shown a reduction in shear capacity of the beam. A similar comparison is presented in Figure (15b) for

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behavior of strengthened beam specimens (DBH0.8, DBH 1, and DBH 1.2) which have an a/d values of (0.8, 1.0, and 1.2) respectively. All beams were strengthened with one horizontal layer of CFRP strips spaced at (100mm) as mentioned previously.

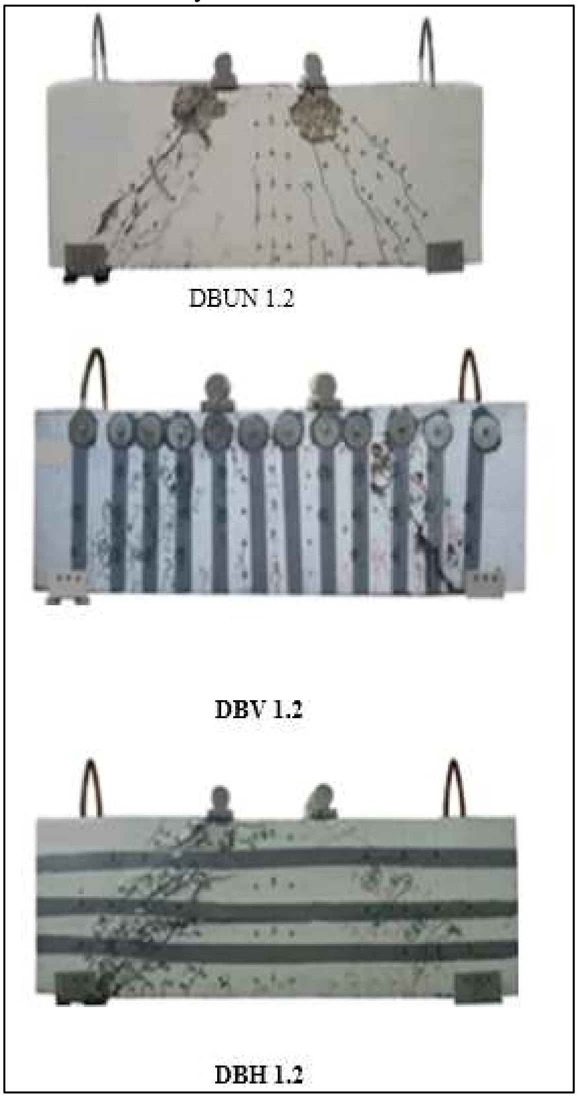
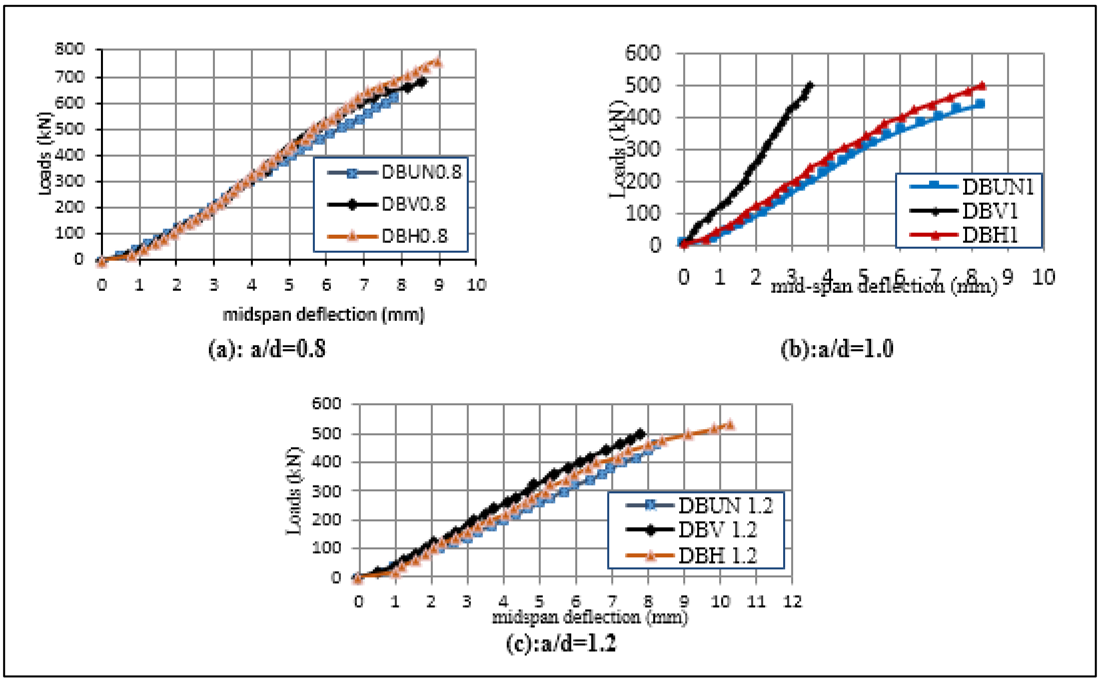


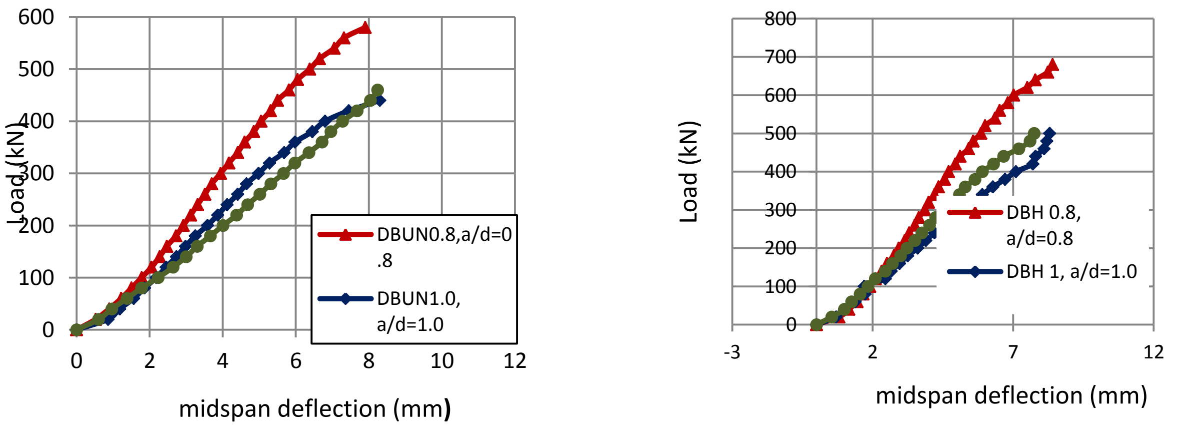
Figure 13: Failure mode of beam specimens with a/d =1.2

Table 4: Comparison between failure load and deflection of tested beams

Beam Designation	*a/d*	P_u *kN*	*Deflection at first crack load*		*deflection at ultimate load*		
			δ_v *mm*	*Ratio to the controls*	δ_v *mm*	*Ratio to the control*	*% increase of max. deflection*
DBUN0.8		620	1.78	-	7.90	-	-
DBV0.8	0.8	680	1.79	1.07	8.54	1.08	8.0
DBH0.8		770	1.76	0.99	8.95	1.13	13.3
DBUN1		440	2.18	-	8.3	-	
DBV1	1.0	520	0.8	0.35	3.6	0.43	-52.6*
DBH1		500	2.12	0.97	8.3	1	-
DBUN1.2		460	2.64	-	6.7	-	-
DBV1.2	1.2	540	2.32	0.88	10.3	1.54	53.7
DBH1.2		500	2.08	0.78	7.75	1.15	15.6



Figures 14: Load-midspan deflection curves for tested beams



(a): *unstrengthened control deep beams* (b): *strengthened by horizontal CFRP strips*

Figure 15: Load-midspan deflection curves for unstrengthened and horizontally strips strengthened beams with different a/d ratio

4. Conclusions

Based on the experimental results, the following conclusions can be drawn:

1. The use of CFRP strips in the strengthening lightweight aggregate deep beams reduces deflections by about 50% and increases the load carrying capacity by about 45% for the present work. Cracks were smaller and more distributed in the strengthened beams compared with their controls ones.
2. The load-displacement response of the tested deep beams strengthened with CFRP strips was influenced by changing the a/d ratio in such a manner that more deformability was achieved with the increasing of a/d ratio, which was due to the reduction of arch action effect.
3. By slowing the growth of diagonal cracks and reducing their progression into the compression zone in case of using CFRP composite materials , more uncracked concrete section available at the head of the crack in the compression zone to enhance the shear resistance provided by concrete contribution.
4. The debonding failure of CFRP strips does not appear to be related to the a/d ratio because this kind of failure was seen in all the three groups of a/d ratio.

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