



Structural Behavior of Retrofitted Reinforced SCC Continuous Deep Beam With CFRP and Hybrid Techniques

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Deep beams, Self-compacting concrete, continuous, retrofitting, Carbon fiber polymer, NSM, EBR.

ABSTRACT

In this research, the results of experimental test of seven reinforced SCC continuous deep beams after being retrofitting by CFRP with different techniques. The main objective of the current research is to investigate the structural behavior in the shear performance and failure modes. The first beam tested up to failure and assumed as reference beam, while remaining six beams firstly loaded with 65% of ultimate load capacity then retrofitting by three systems namely: externally bonded reinforcing (EBR) by CFRP strips, near surface mounted technique (NSM) CFRP rods and the third system was hybrid technique by composite between EBR CFRP strips and NSM CFRP rods. The experimental results show that applying the EBR CFRP strips in a vertical direction improved the loading capacity in comparison with the horizontal direction. On the other hand, the NSM CFRP rods applied in horizontal direction presented higher values in both ultimate loading capacity and final deflection, where the increasing in ultimate load capacity about 43.48%, and the increasing in deflection about 33.5% compared with control beam. Therefore, it can be concluded that applying the hybrid technique is more efficient when the EBR strips and NSM bars applied in the vertical, and the horizontal directions, respectively.

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1. INTRODUCTION

Continuous deep beams are extensively used as transmission girders in high-rise construction, pile caps, and other important uses. Regularly receiving many small loads and transferring it to a few numbers of reaction supports [1]. Continuous deep beams exhibit different behavior as compared to both simply supported deep beams and continuous slender beams. Continuous deep beams show a distinct 'tied arch' or 'truss' behavior, which not exist in continuous slender beams [2].

In 2013, Beshara et al. [3] reported the results of investigating the behaviors of nine of two-span reinforced concrete CBD under concentrated load. The variables studied were (a/d), Vertical (p_v) and Horizontal (p_h) web reinforcement ratio and the compressive strength of concrete (25 and 35) MPa. The conclusions were reached: The ultimate shear strength of the continuous beams increased considerably with the decrease of (a/d) ratio and the increase in the compressive strength of the concrete or the vertical web reinforcement. The shear force capacity of horizontal steel in the web was more evident in continuous beams than in simple beams. Regarding to beams with a small (a/d) ratio, horizontal shear reinforcement has always been more effective than vertical shear reinforcement.

In 2019, Nuri et al. [4] reported the results of twelve two-span deep beams of reinforced self-compacting concrete. The variables studied were shear span-to-overall depth (a/h), concrete strength (f'_c) and amount of vertical shear reinforcement ratio (p_v). Tests results indicated that the (a/h) ratio affects the beam carrying capacity as that a 50% decrease in this ratio from 1 to 0.5, makes the cracking load (P_{cr}) and the ultimate load (P_{ult}) rise by an average ratio 29% and 25%, respectively. The concrete compressive strength (f'_c) also has a noticeable effect on the behavior of continuous deep beams such as increasing (f'_c) to approximately twice from (33.81 to 67.8) MPa resulting in an increase in cracking load (P_{cr}) and ultimate load (P_{ult}) with an average ratio of 12.75% and 16.5%, respectively.

Fiber reinforced polymer (FRP) composites are generally considered as a useful technique to use in strengthening and as an alternative to some existence methods because they offer higher strength, resistance to corrosion, lightness, and ease of application. Typical FRP composite products are presented in the arrangement of prefabricated strips, precured shapes, rods or uncured sheets applied by wet lay-up procedure [5].

The shear capacity improvement of concrete members can be through using the outwardly bonded FRP with the fibers in another name External Bonded Reinforced (EBR FRP). For beams and columns, FRP sheets are attached in the vertical path to the direction of member axis, while in the instance of beam-column joints, the direction of FRP sheets is in both the direction of the column and the beam [6][7].

Javed et al. [8] performed tests on eight deep concrete beams. The parameters studied were the presence and absence of shear reinforcement and the CFRP orientation (90° and 45°) with respect to the longitudinal axis of the beam. Experimental results indicated that web reinforcement caused an increase in the ultimate load by 45%, while this increase extended from 32% to 37% when using CFRP and effected with CFRP orientation. Test results showed that when using CFRP strips, the delayed in cracks propagated and load of the first propagated shear crack was risen from 26% in control beam to 35% depending on the direction of the CFRP sheets. It was also established that the inclined CFRP proved to be more active in improving load carrying capacity and resisting the presence of shear cracks compared to the vertical CFRP strips.

Rasheed [9] studied the effect of CFRP Sheets for retrofitting of reinforced concrete of nine deep beams. Variables studied include: shear span to total depth ratio (a/h), the amount of vertical and the horizontal web shear reinforcement. The results exhibited that the ultimate strength of all deep retrofit beams has increased in different proportions from 8% to 161% of the ultimate load of the control beams. Also indicated that the retrofit deep beam without shear reinforcement gives an increase in the improvement of the strength and the deflection more than the deep beam with shear reinforcement. The NSM rods have an advantage over the FRP strip which is no surface preparation needed in the former case, as opposite to externally bonded strips case where the suitable bond to the concrete surface must be ensured to attain efficient strengthening system [10].

In 2001, De Lorenzis and Nanni [11] studied eight shear strengthened RC beams with NSM CFRP bars. The specimens consisted of two beams with shear steel reinforcement while the rest were without shear steel reinforcement. The following parameters were examined during the experiment: NSM FRP bar spacing, NSM FRP shear resisting bar inclination (vertical and 45°), and the presence of internal steel stirrups. In the absence of a steel shear reinforcement, it was found a 106% increase in beam capacity compared to the control beams without shear reinforcement. In beams with internal shear reinforcement, NSM technique increased capacity by 35% relative to the companion beam with stirrups but without NSM FRP bars. Barros and Dias [12] performed preliminary experiments by developing an NSM shear strengthening technique using CFRP strips. The NSM retrofit technique greatly improves the load carrying capacity of both reinforced and unreinforced concrete beams. It was also the most effective method of strengthening shear in CFRP

systems and provided the highest deformation capacity at the failure point of the beam. Anis et al.[13] reported the results of testing five rectangular RC deep beam. All samples were tested under two-point monotonic load at mid-span., without shear reinforcement and tested to failure except for one beam tested with no strength to serve as a base line control beam. The strengthening parameters were the spacing and orientation of CFRP bars they used with NSM technique. The study concluded that beams backed externally by CFRP bars provided improvement in ultimate loads by (12-28.57%). The orientation of CFRP rods by 45-degree angle inclined increased the resistance of shear by (6.4-11.3%) compared to 90 degrees.

Sarsam et. Al. (14) presented an experimental research to investigate the structural behavior of reinforced concrete deep beams strengthened in shear by CFRP strips. The program consisted of nine identical lightweight aggregate reinforced concrete deep beams. Three of the tested deep beams were unstrengthened to serve as reference beams, while the remaining beams were tested after being strengthened using CFRP strips in two different orientations (vertical and horizontal). Effect of shear span to effective depth ratio (a/d) were studied. All beams have been tested as a simply supported beams subjected to two concentrated points loading. The experimental work showed that the failure load increases as (a/d) decreases. The results shown that CFRP strips reduces deflections by about 50% and increases the load carrying capacity by about 45%, cracks were smaller and more distributed in the strengthened beams compared with their controls ones and 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 different of (a/d) ratio. Sarah et al. (15) studied the effect of confining the Strut region of the deep beam by using Struts Reinforcement. Six specimens were tested for investigating the structural behavior of deep beams. The specimens were tested under two symmetrical points load and compressive strength of 38 MPa. The test results showed that the Strut confinement generally decreased deflection at the earlier age of loading by about 28.75%, while the ultimate deflection increased by about 42.64 %, The confinement of the strut by reinforcement changed the failure mode of deep beams from shear with some flexure cracks to the pure flexure mode of failure and Strut Reinforcement confined shear cracks propagation, stresses, and strain at the strut region.

2. EXPERIMENTAL PROGRAM

1. Continuous deep beam specimens Description

The experimental program consists of testing seven specimens of (two-span) reinforced concrete deep beams designed as continuous deep beam constructed using SCC. All beams have the same dimensions and flexural and shear reinforcement. They have an overall length of 2400 mm, a width of 150 mm and a height of 350 mm as shown in Figure 1. The tested was applied by two symmetrical point loads.

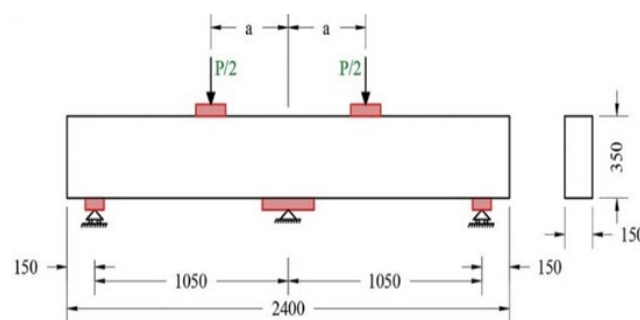


Figure 1: Dimensions of the tested deep beams in (all dimension in mm)

The steel reinforcements were kept constants for all beams. The main longitudinal reinforcements at the top and bottom were intentionally designed so that the specimens fail in shear. Steel bars of 3Ø 16mm diameter were used as the top and bottom reinforcements with flexural reinforcement ratio equal to ($\rho = 0.01268$). While the vertical and horizontal web reinforcements consisted of (5mm@ 100 mm) with shear reinforcement ratios equal to ($\rho_v = 0.0026$) and ($\rho_h = 0.0026$), respectively. The selected vertical and horizontal shear reinforcement ratios were nearly equal to the minimum requirement ($\rho_{min} = 0.0025$), which is recommended by the ACI 318M-2014 Code [16]. The shear span to overall depth ratio of the tested specimens was ($a/h = 1.2$). Figure 2 shows steel reinforcement details.

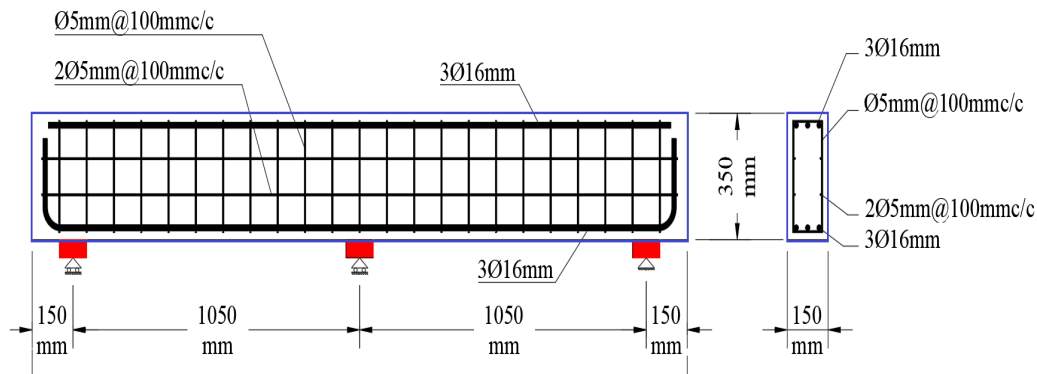


Figure 2: Steel reinforcement details

II. Materials Mechanical and Mix Proportions of SCC

The mix was designed according to the European Guidelines for Self-Compacting Concrete 2005 [17] and specification of EFNARC 2002[18]. Table I illustrated the final amounts by weight of materials per cubic meter used in preparation of normal self-compacting concrete. The mechanical properties of hardened SCC obtained by control specimens were concrete compressive strength (f'_c) 43.22 MPa, Modulus of rupture (f_r) 4.64 MPa, splitting tensile strength (f_t) 3.87 and modulus of elasticity (E_c) 29487 (MPa). Steel bars properties were for bar 16mm: yield stress 613 MPa and tensile strength 689 MPa, while bar 5mm were yield stress 564 MPa and tensile strength 619 MPa.

TABLE I: SCC mix proportions

Cement kg/m ³	Limestone Powder (kg/m ³)	Water (kg/m ³)	W/p* By weight	Coarse** aggregate (kg/m ³)	Fine aggregate (kg/m ³)	Superplasticizer *** (l/m ³)
400	150	150	0.272	830	770	10

* W/P = Water/Powder, Powder = Cement + Limestone

** Coarse aggregate with 12mm maximum size

*** Superplasticizer product (SikaViscocrete-5930)

III. Retrofitting Systems

Table II summarizes specimens retrofitting details. The first specimen CDB1 selected to be control beam which tested without any external reinforcement. The remaining six specimens, load with 65% of ultimate loading carry capacity of control beam then, retrofitted with different retrofitting systems. Two specimens were selected to be retrofitting by externally bonded (CFRP) sheets. The fully wrapped EBR strips applied at two directions (horizontal and vertical). Other two specimens selected to be retrofitted with CFRP rods 12mm diameters. Specimens retrofitting details CFRP rods are imbedded into groves as near surface mounted technique, this grove filled with epoxy resin-based adhesives. The remaining two specimens retrofitted with hybrid technique (composite action between EBR CFRP strips and NSM CFRP rods).

Table III summarized All technical data and mechanical properties of CFRP products. Figure 3 presented all details of the retrofitting patterns of the tested beams. Table III illustrated all properties of CFRP products were used in this study.

TABLE II: Specimens retrofitting details

Beam No.	Retrofitting system	External CFRP Strip 50mm width		NSM CFRP Rods 12mm		Note
		Spacing	Orientation	Spacing	Orientation	
CDB1	Non	-	-	-	-	Control beam
CDB2	External CFRP Strip	100	Horizontal	-	-	Strips (100mm c/c)
CDB3	External CFRP Strip	100	Vertical	-	-	Strips (100mm c/c)
CDB4	NSM CFRP bars	-	-	120	Horizontal	2 bars at each Side of beam 120 mm c/c
CDB5	NSM CFRP bars	-	-	175	Vertical	12mm @ 175 mm c/c of CFRP rods at each Side of beam
CDB6	Hybrid (External CFRP Strip & NSM CFRP bar)	100	Horizontal	175	Vertical	Horizontal CFRP Strip (100mm c/c) and 12mm @ 175 mm c/c of CFRP rods at each Side of beam
CDB7	Hybrid (External CFRP Strip & NSM CFRP bar)	100	Vertical	120	Horizontal	Vertical CFRP Strip (100mm c/c) and 12mm @ 120 mm c/c of CFRP rods at each Side of beam

TABLE III: Properties of CFRP products

Materials	Property	Description*
Sika Wrap-300C	Tensile Strength	3 200 kN/mm ²
	Modulus of Elasticity in Tension	210 kN/mm ²
	Elongation at Break in Tension	1.59 %
	Fiber Density	1.82 g/cm ³
	Fiber thickness	0.167 mm
Sika CarboDur BC 12	Tensile Strength	3 100 N/mm ²
	Modulus of Elasticity in Tension	148 000 N/mm ²
	Elongation at Break in Tension	> 1.70 %
	Density	1.6 g/cm ³
	Diameter	12 mm
	Cross section Area	113 mm ²

In this research, strain gauge uniaxial electrical resistance (foil) with a resistance of (120 Ohms) were used to measure the strain of surface concrete. Deflection under applied load measured by linear variable displacement transducers (LVDTs) as show Figure 4. The LVDTs were connected to same data logger which used for strain gauges to register the deflection measurements during all load test time.

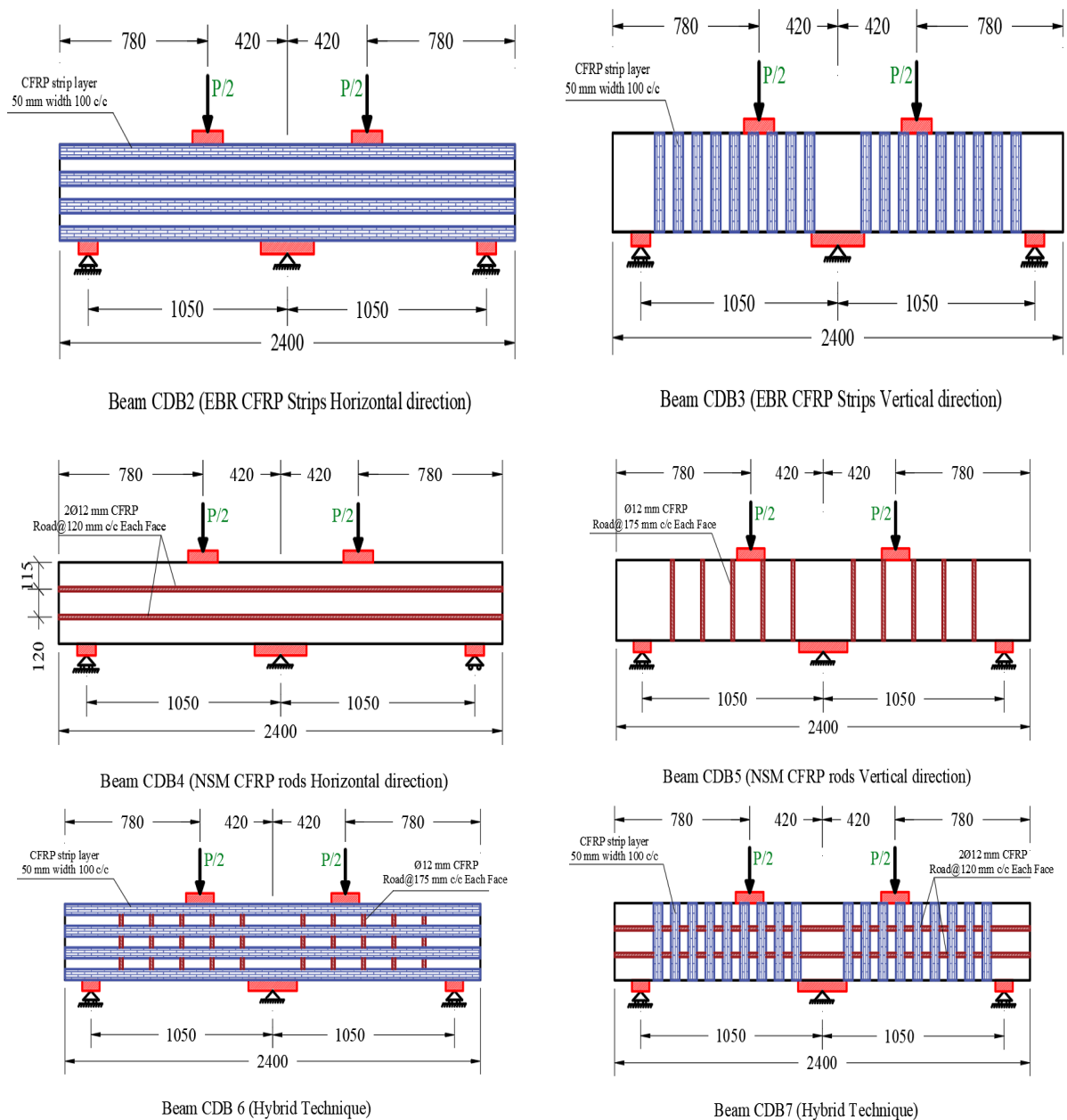


Figure 3: Retrofitting beams, strain gauge installation and testing machine and beam setup.



Figure 4: CFRP retrofitting configuration details of the tested beams.

3. EXPERIMENTAL RESULTS

I. Crack patterns and failure modes

Table IV summarizes the increasing in ultimate load capacities, deflections, and failure modes as compared with the control beam CDB1, which was loaded till failure without retrofitting. The results show that there was a significant improvement in the ultimate load capacities when using different types of retrofitting. For example, retrofitting with hybrid technique leads to increase the ultimate load about 27.17% and 43.48% in beams CDB6 and CDB7 as compared with the control beam CDB1, respectively.

In beam CDB2, it can be noted that the horizontal EBR CFRP strips restricted cracks from expanding. While, in beam CDB3, applying CFRP strips in vertical direction confining concrete, and restricting of the cracks from expanding. Hence, inspection of these specimens which retrofitted with EBR CFRP strips shows that the method of applying the strips played a major role in increasing stiffness of the beams because of the strips in restraining the tensile stresses. The increasing in ultimate carrying loading capacities when it compared to the control beam results is 13% and 19.56%, respectively.

Regarding to specimens retrofitted with NSM technique, it can be noted that the beam CDB4 shows increasing in ultimate load capacity more than beam CDB5. An explanation for this is in beam CDB4, the NSM CFRP rods that applied in the horizontal direction played a major role in resisting and preventing the propagated shear cracks from expansion because they intersect these cracks. While, in beam CDB5, it was found that the cracks split the concrete cover and override the CFRP rods, which results in concrete splitting around the CFRP rods.

TABLE IV: Experimental results for the tested deep beams.

Beam No.	Retrofitting system	Pu kN	Δv Ultimate mm	%Increase in Ultimate Load	Increase in Deflection %	Failure* Mode
CDB1	Non	920	4.532	Control	Control	D.S
CDB2	H EBR Strip	1040	4.744	13	4.7%	D.S+ FRPT
CDB3	V EBR Strip	1100	5.405	19.56	19.3%	D.S+ FRPT
CDB4	H NSM bar	1150	5.293	25.00	17.1%	D.S+CC
CDB5	V NSM bar	1060	5.187	15.22	14.2%	D.S+CCS
CDB6	Hybrid (EBR & NSM)	1170	5.702	27.17	25.8%	D.S+CCS+ CC
CDB7	Hybrid (EBR & NSM)	1320	6.048	43.48	33.5%	D.S+CC+ FRPT

For the rest beams CDB6 and CDB7, which retrofitted with hybrid technique, the experimental observation showed that the number of cracks that appeared at the surface of the beam were less before failure. For beam CDB6, the damage marked by formation of major diagonal cracks, splitting of concrete cover, and concrete crushing around NSM bars in the compression strut zone. While, in beam CDB7, the hybrid retrofitting system had two contributions: the first one was resisting the propagated cracks and prevented the diagonal cracks from expansion. While the second strengthening effect was confining concrete at strut zone by EBR CFRP strips, and it participated in resisting the cracks that attempted to split concrete, like that occurred in beam CDB6. Hence, beam CDB7 shows the highest value of loading carrying capacity among all tested beam, about 43.48% relative to the control beam. Figure 5 shows pattern cracks and failure modes of tested beams.

*Failure modes: DS=Diagonal splitting failure, FRPT= FRP Tearing, CC=Concrete crushing, CCS= Cover Concrete Splitting

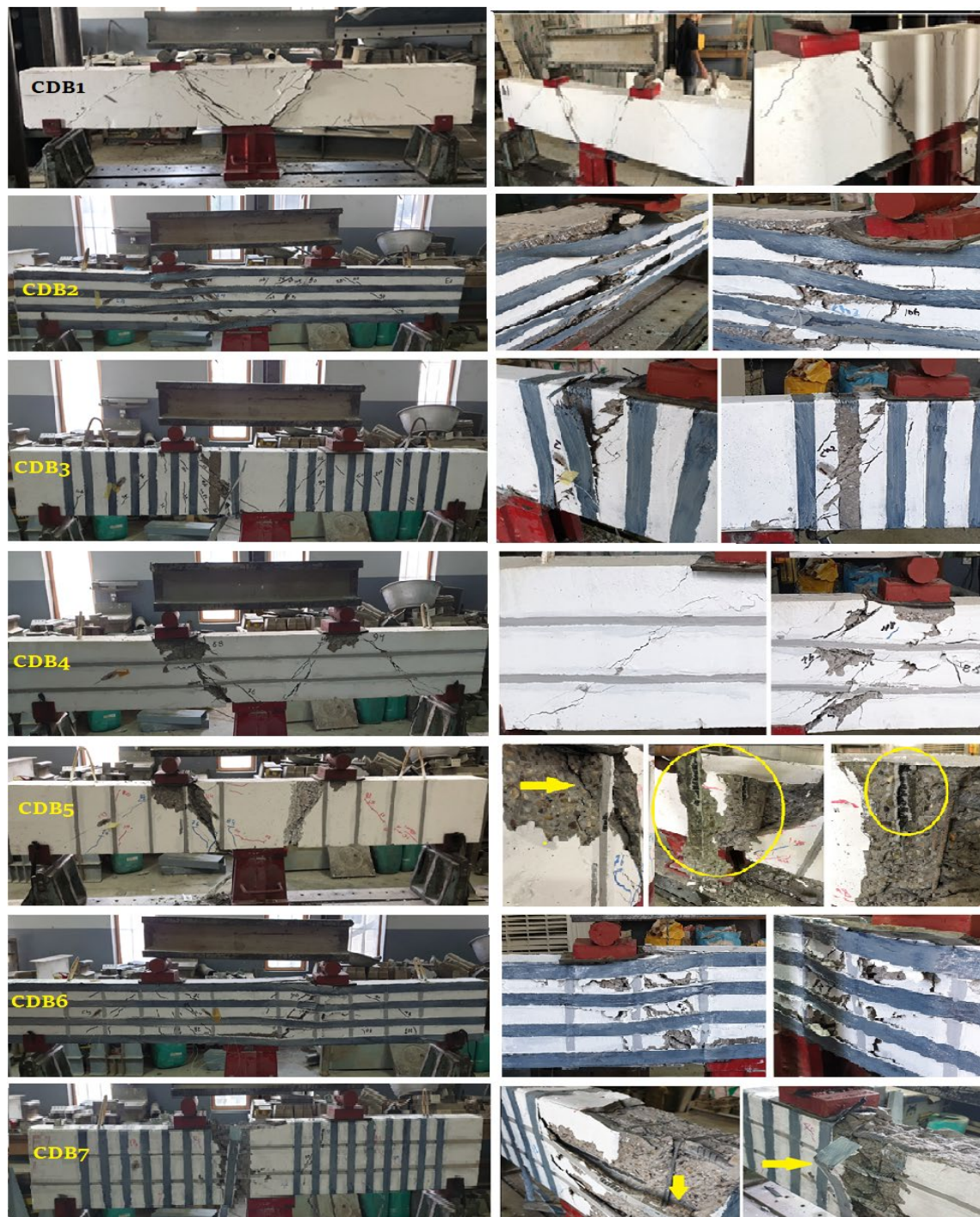


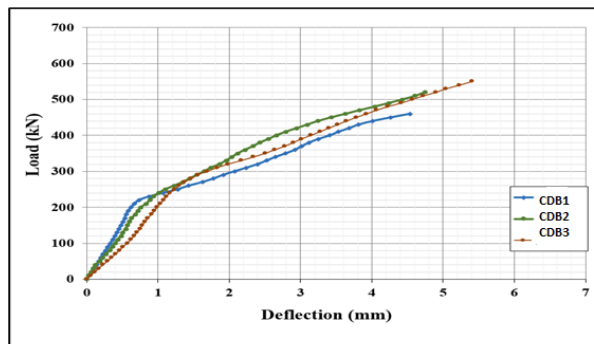
Figure 5: Crack patterns and failure modes of tested beams

II. Point load deflection response

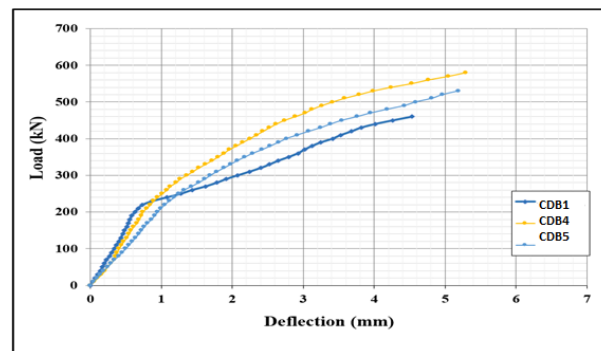
Curves of load-deflections response for all tested beams were show in Figure 6. These three curves classified according to strengthening system type, EBR, NSM and hybrid. The load-deflection curves are strongly affected with the type of strengthening system. At low load levels, the load-deflection relations tend to be linear with almost constant sloping. Then the relationship between the load and deflection response became nonlinear in shape with variable slope, where an increase in deflection rate occurred as the applied load increase. This figure shows sensible effect of CFRP Strips in vertical direction in beam CDB3 on increasing the deflection value compared with horizontal direction in CDB2. As previously explained the effect of CFRP strips in vertical direction which act to confine the strut zone causing an increase in the load carrying capacity.

TABLE V: Deflection at ultimate loads and the increase percentage.

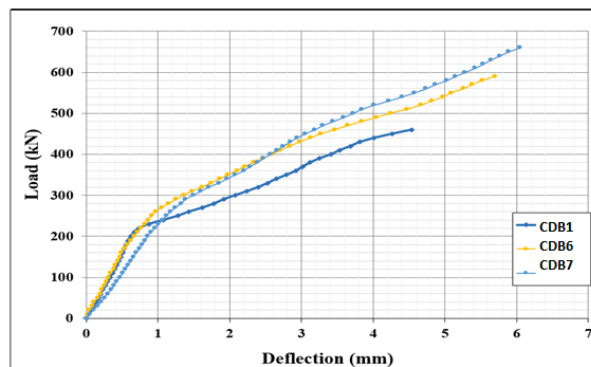
Beam No.	Ultimate Force		Increase in Deflection %
	P_u kN	D_v Ulti mm	
CDB1	920	4.532	control
CDB2	1040	4.744	4.7%
CDB3	1100	5.405	19.3%
CDB4	1150	5.293	17.1%
CDB5	1060	5.187	14.2%
CDB6	1170	5.702	25.8%
CDB7	1320	6.048	33.5%



Load- deflection response effect of EBR CFRP Strips of beams CDB2 and CDB3



load- deflection response effect of NSM rods of beams CDB4 and CDB5.



load- deflection response (effect of hybrid strength) of Beam CDB6 and CDB7.

Figure 6: load-deflection response for tested beams

Regarding to beams retrofitted with NSM bars together with the control beam. Beam CDB4 shows higher final deflection value before failure. The applied NSM CFRP rods in horizontal orientation reduce and limited the cracks expansion and this lead to limit the reduction in beam stiffness. While beam CDB5 shows similar behavior to control beam.

The load-deflection of beams CDB6 and CDB7 which were retrofitted with hybrid technique, shows that the vertical EBR CFRP strips plus the horizontal NSM bars in beam CDB7 have significant effect to increase the maximum deflection about of 33.5% as compared with control beam CDB1. While beam CDB6 has an increase in the deflection up to 25.8%. The comparison in magnitude of deflection at the ultimate loads is demonstrated in Table IV.

III. Surface concrete load-strain behavior

Strain's surface of concrete that developed during testing with effect of different retrofitting systems were registered. The locations of strain gauges are selected at the middle of strut line connected between the applied load and interior support. Figure 7 shows the concrete surface strain

behavior with loading stages for the tested beams. The presence of EBR, NSM and hybrid CFRP reduced the strains. In all tested retrofitted beams, it is noted that the strain values of concrete surface became less than control beam CDB1. From this Figure, it can be noted that the retrofitted system type of beam CDB7 was efficient to decrease the compressive strain values more than the other types of retrofitting systems, while the responses of beams CDB2 and CDB5 exhibited a similar behavior.

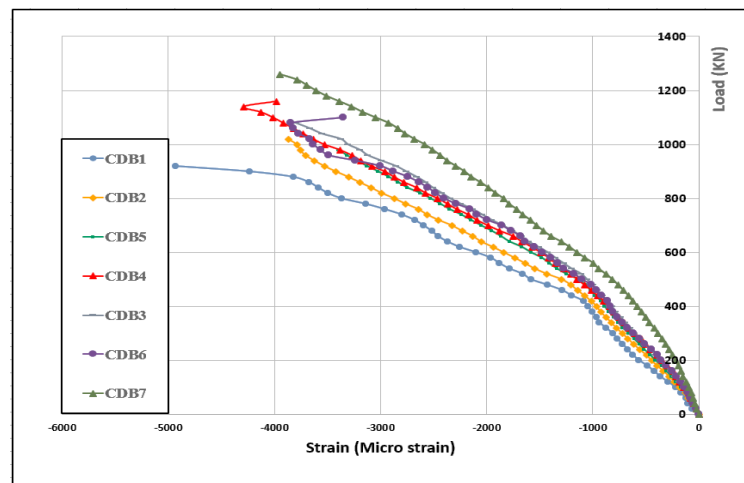


Figure 7: Compressive strain of concrete surface for tested beams.

4. CONCLUSIONS

According to the experimental results the following conclusions were obtained:

1. The applied EBR CFRP strips in vertical direction more efficiency than horizontal direction and increase in ultimate loading capacity about 19.56% while retrofitting beam with CFRP strips in horizontal direction caused increase in ultimate capacity about 13%. The CFRP strips in vertical direction play it is ruled to confining concrete plus restricting of the cracks from expanding.
2. Beam retrofitted with NSM CFRP bars in horizontal direction shown better enhance in beam loading capacity compared with beam strength in vertical direction. The results show increase in ultimate load about 25% compared with NSM in vertical direction which give increase about 15.22%.
3. The enhancement obtained from applied NSM CFRP rods in horizontal direction can be attributed to the effect CFRP rods, which resisted and transmitted the generated tensile stress and distributed it in for a long way from strut zone throw CFRP rods.
4. The shear cracks intersect the CFRP rods vertically when the rods applied in the horizontal direction, and that limits their propagations.
5. Retrofitted beams with hybrid technique show the highest values to increase ultimate loading capacity. The results shown increase about 43.48% compared with control beam.
6. Composite action between EBR CFRP strips in vertical direction and NSM CFRB bars in horizontal direction represent the best retrofitting system among all other studied systems.
7. Retrofitted beam with hybrid technique decreases the maximum deflection about 33.5%, therefore the beam was more ductile before failure.

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