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Effect of Shear Span to Effective Depth Ratio on the Behavior of Self-Compacting Reinforced Concrete Deep Beams Containing Openings Strengthened with CFRP

Nabeel A. Al-Bayati [1], ***Bassman R. Muhammed*** [2], and ***Muroj F. Oda*** [3,*]

[1] *Building and Construction Engineering Departmen University of Technology t , Baghdad, Iraq, nabalbayati@yahoo.com*

[2] *Building and Construction Engineering Departmen University of Technology t , Baghdad, Iraq, bassman.riyadh@gmail.com*

[3] *Building and Construction Engineering Departmen University of Technology t , Baghdad, Iraq, blue_lily2002@yahoo.com*

**Corresponding author: Muroj F. Oda, blue_lily2002@yahoo.com*

Abstract— Results of test on seven simply supported self-compacting reinforced concrete deep beams, including six of these beams containing circular openings in center of load path are reported in this paper. The objective of the tests was determined the in-fluence of, changing shear span to effective depth ratio a/d, the existence of circular openings in shear span and using inclined strips of carbon fiber polymer (CFRP) on behavior of deep beams. The general trend in crack pattern, the load-deflection re-sponse, and the mode of failure of reinforced SCC deep beams were also investigat-ed. All specimens had the same geometry, details of the flexure and shear reinforce-ment in both vertical and horizontal directions and they were tested under symmet-rical two-point loads up to failure. The experimental results revealed that the web openings within shear spans caused an important reduction in the deep beam capaci-ty by 50% when compared with the corresponding solid beam. The increase a/d ratio from 0.8 to 1.2 decreases the ultimate load by 21.7% and 22.5 % for the reference un-strengthened beam and strengthened beam, respectively, also it was found that the externally inclined CFRP strips in deep beams increased the ultimate strength up to 39.5%, and enhanced the stiffness of deep beams with openings.

Keywords— CFRP, Deep beams, Openings-strengthening, Self-compacting concrete, Shear span to depth ratio

1. Introduction

Generally, reinforced concrete beams are categorized as deep and slender beams according to their shear span to effective depth ratio (a/d) or clear span to overall depth (Ln/h). The term (Deep beam) applied to any beam which has a/d small enough to cause non-linearity in elastic flexural strain distribution over its height and the distribution of shear stress to be non-parabolic [13]. According to the ACI 318M-14 [1] the term "deep beam" is applies to any member which has clear spans (Ln) less than four times, the height (h) or region of beam with concentrated load located at a dis-tance not exceeding 2h from the face of the support that is loaded on one face and supported on the opposite face. They are commonly used in en-gineering buildings such as panel beams, deep girders, walls of the bun-ker, pile caps, etc. In some cases, the openings in the web region of deep beams are considerably provided for main services and accessibility such as, ventilating ducts, door openings, windows, water supply, and air con-ditioning. The openings cause many problems in behavior of the deep beams such as increase cracking and deflection and may cause reduction in ultimate strength of deep beams as a result of reduction in their stiffness. Because of the geometry of deep beams, especially when they contain dense web reinforcement, the utilize of self-compacting concrete (SCC) when casting of these members is more suitable to a void the usual problems of using conventional concrete like, segregation, voids and bleeding. Self-compacting concrete is an innovative concrete that does not need any vibra-tion for casting and compaction. It has the ability to flow and filling molds under its self-weight even in the presence of heavy reinforcement, also; the hardened concrete is dense, homo-geneous and has the same engineering properties as conventional concrete [5]. The reinforced concrete deep beams may need strengthening, re-pairing and rehabilitation programs, like other structural element because of increased loads, design and con-struction faults, corrosion problems in reinforcing steel, and change of structural system. Carbon Fiber Rein-forced Polymer (CFRP) can give a good solution to those problems due to their properties such as high strength to weight ratio as compared to other construction materials and the resistance to corrosion. Moreover, they are available in irregular shapes and long strips, with possessing high electric strength and ease of handling and application [9, 10].

2. Experimental Program

The experimental program in this re-search consists of fabricating, casting, and testing seven self -compacting re-inforced concrete (SCC) deep beams. All the beams had same length of 1400 mm, depth of 400 mm and width of 150mm and have an effec-tive span between the simply sup-ports of 1070 mm as shown in Fig-ures 1 and 2 giving Ln/h ratio (clear span-to-effective depth ratio) of 2.67 less than 4 as recommended by ACI 318M-14 [1] for deep beam require-ments. One of them was solid and others containing circular openings with a diameter equal to 110 mm placed in center of load path (the line joining the load bearing edge and support bearing edge) [11,12]. These beams were divided into three groups according to a/d ratio, which varied between (0.8, 1, and 1.2). There are two specimens in each group, one of them was strengthened by two in-clined (orthogonal to the load path) unidirectional CFRP strips of 40 mm wide (U) shape mirrored on each side of the deep beam and another was a control beam (without strengthening). Table (1) and Figure (3,4, and 5) illus-trates details of the beams. The beam notation contained three parts; in the first part the letter (D) refers to deep beam, (O) refers to presence the circu-lar openings, the second part refers to the shear span to effective depth ratio; and the third part refers to strengthen-ing. As an example, DO-0.8-I refers to deep beam with openings, a/d equals to 0.8 and this beam was strengthened with inclined CFRP strips.

3. Material properties

3.1 *Cement*

Ordinary Portland ce-ment (Type I), was utilized throughout this work. Its physical and chemical properties are com-plying with the requirements of the Iraqi standard specifications IQS NO.5, 1984 [8] as shown in Tables 2 and 3.

3.2 *Fine Aggregate*

Natural sand from Al-ukhaider region was utilized for concrete mixes in this study. The physical properties of this aggre-gate and the sieve analysis results are shown in Table (4) and (5) re-spectively. These results indicate that this fine aggregate was within zone 2 according to the require-ments of the IQS No. 45,1984 [7].

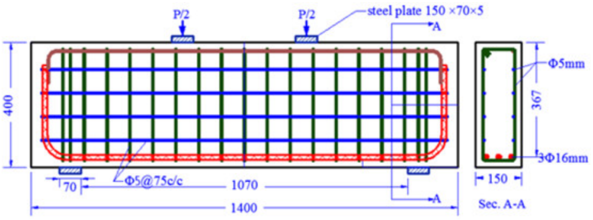

Figure 1: Reinforced concrete solid deep beam

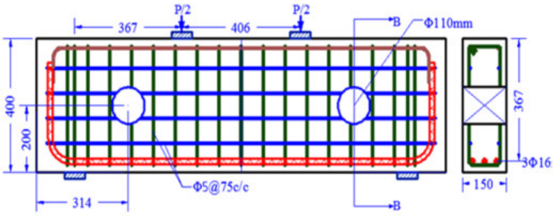

Figure 2: Reinforced concrete deep beam with openings

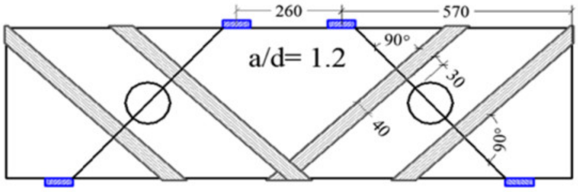

Figure 3: Details of strengthened deep beam with openings (DO-1.2-I)

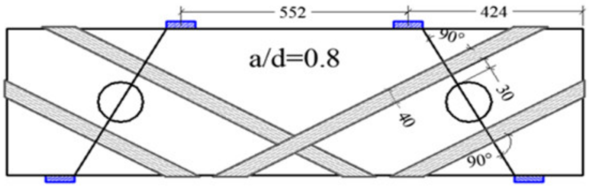

Figure 4: Details of strengthened deep beam with openings (DO-0.8-I)

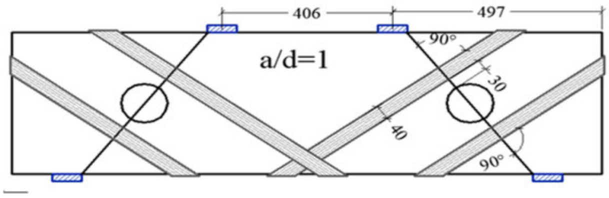

Figure 5: Details of strengthened deep beam with openings (DO-1-I)

Table 1: Summary of the specimens details

Group NO.	Specimen symbols	Opening diameter (mm)	a/d	Strengthening details
Solid beam	D-1	-	1	No strengthening
1	DO-1	110	1	No strengthening
	DO-1-I	110	1	Two inclined U-shape strips
2	DO-0.8	110	0.8	No strengthening
	DO-0.8-I	110	0.8	Two inclined U-shape strips
3	DO-1.2	110	1.2	No strengthening
	DO-1.2-I	110	1.2	Two inclined U-shape strips

3.3 *Coarse Aggregate*

Crushed riv-er gravel brought from Al-Niba'ee region has a maximum size of 14mm was used in this work as a coarse aggregate. Tables (6 and 7) illustrate physical and chemical properties and grading of it, re-spectively. These properties com-ply with the Iraqi specification IQS No.45, 1984 [7].

3.4 *Limestone Powder*

To increase the amount of fine materials and enhancing the segregation re-sistance and the cohesiveness in the SCC mixture, fine limestone was used for concrete mixes in this research as a filler. Its properties are summarized in Table (8).

3.5 *Superplasticize*

Aqueous solu-tion of modified poly-carboxylate commercially known as Sika vis-cocrete was utilized to obtain fresh properties of SCC. The main properties of this material are men-tioned in Table (9).

3.6 *Steel Reinforcement*

The flex-ural reinforcement consisted of three bars of 16mm in diameter while the web reinforcement was made of 5mm diameter deformed steel wire spaced at 75mm in both vertical and horizontal directions as shown in Figures (1 and 2). Test results, as shown in Table (10), in-dicated that the steel reinforcement of Ø16mm conforms to the re-quirements of the ASTM A615/615M-14 [4]. Furthermore, the steel wire reinforcement of Ø5mm complies with the require-ments of the ASTM A1064/A1064M–14 [3].

3.7 *Carbon Fiber Strengthening Polymer (CFRP)*

Unidirectional woven carbon fiber fabric named as Sika Wrap-300 C/60 was uti-lized for strengthening deep beams in this study. The main properties of CFRP are mentioned in Table (11).

3.8 *Bonding Materials*

Sikadur®-330 is the suitable adhesive mate-rial for CFRP strips it consisting of two parts, white resin named part A and grey hardener (part B). Ta-ble (12).

4. Mix–casting and curing of con-crete deep beams

Mixing and casting processes were carried out using laboratory mixer with a capacity of 0.1 m3 at the Structural Laboratory of Building and Construction Department/University of Technology. The self-compacting mix was designed according to re-quirements in EFNARC [6] to accom-plish both fresh and hardened proper-ties of SCC. Three tests (slump flow, T50, L-box and V-Funnel) were carried out to ensure the SCC requirements. Table (13) mentioned details of the adopted mixture while Table (14) in-dicates the results of those tests. Moreover, splitting tensile strength (fct) and concrete compressive strength (f'c) were determined by testing three cylinders with a dimension of 150×300 mm of its diameter and height respectively, from each batch at 28 days, while the modulus of rup-ture (fr) was determined utilizing three 100 × 100 × 400 mm prisms. The re-sults of these tests are illustrated in Table (15). Each beam was cast utiliz-ing two batches of self-compacting concrete mix in steel mold and the curing continued for 28 days using wet burlaps after removing the mold. Three beams with openings were strengthened according the failure mode of the control beams by one layer of inclined CFRP strips that have a constant width of (40mm).

Table 2: Physical properties of the cement

Physical Properties	**Unit**	**Test results**	**IQS 5/1984 [8]**
Fineness using a Blaine air permeability apparatus	m^2/Kg	380	230 min
Soundness using autoclave method	%	0.24	0.8 max
Time of setting(Vicat) Initial time Final time	 minutes minutes	 158 273	 45 min 600max
Compressive strength of cement paste cube mold (50 mm) at: 3days 7days	 MPa MPa	 29.52 34	 15 min 23min

Table 3: Chemical composition of cement

No.	Compound name	Chemical composition	% by Weight	IQS 5/1984[8]
1	Lime	CaO	61	-
2	Silica	SiO_2	21.1	-
3	Alumina	Al_2O_3	4.64	-
4	Iron oxide	Fe_2O_3	4.2	-
5	Magnesium oxide	MgO	1.51	5 max
6	Sulfur trioxide	SO_3	2.35	2.8max
7	Loss on ignition	L.O.I	2.79	4max
8	Insoluble residue	I.R	0.81	1.5max
9	Lime saturation factor	L.S.F	0.88	0.66-1.02
10	Tricalcium aluminates	C_3A	5.2	-
11	Tricalcium silicate	C_3S	44	-
12	Dicalcium silicate	C_2S	27.39	-
13	Tetracalcium	C_4AF	12.8	-

Table 4: Physical properties of fine aggregate

Properties	%Passing by weight	IQS45/1984[7] for zone 2
Specific gravity	2.63	-
SO_3 %	0.07	0.1 max
Absorption %	0.8	-

Table 5: Grading of fine aggregate

Sieve size (mm)	% Passing by Weight	IQS45/1984[7] for zone 2
10	100	100
4.75	100	90-100
2.36	88	75-100
1.18	76.9	55-90
0.6	57.9	35-59
0.3	20	8-30
0.15	2	0-10

Table 6: Properties and sulfate content of coarse aggregate

Physical Properties	Test Results	Limits of Iraqi Standard IQS.No.45, 1984[8]
Specific Gravity	2.59	-
Sulfate Content%	0.12	≤ 0.5
Absorption%	0.75	-

Table 7: Grading of coarse aggregate

Sieve size (mm)	% Passing by weight	IQS No. 45/1984[8]
14	100	90-100
10	80	50-85
5	5	0-10

Table 8: Chemical composition of limestone powder

Oxide Composition	Content by weight %
CaO	54.1
MgO	0.12
SiO2	1.4
Fe2O3	0.13
Al2O3	0.7
SO3	0.21
Loss on ignition	42.57

Table 9: Properties of superplasticizer

From	Liquid
Color	Turbid liquid
Specific Gravity	1.08Kg/l
pH	7.0-9.0
Normal dosage	0.8-2%
Chorides	Free from choride
Transport	Non-hazardous
Labeling	No hazard label required

Table 10: Properties of steel bars

Bar Diameter (mm)	Yield Stress (MPa)	Ultimate stress (MPa)	Elongation%
16	590	692	15.16≥ 9 (ASTM A615M-14)
5	554	617	5≥ 4.5 (ASTM A1064M–14)

Table 11: Properties of CFRP

Properties	Sika Warp 300C/60
Tensile strength (MPa)	3900
Density (g/cm2)	1.79
Elongation at break%	1.5
Tensile modulus (MPa)	230000
Weight (g/m2)	300
Thickness (mm)	0.166

Table 12: Properties of epoxy resin

Properties	Sikadur-330
Density (kg/l)	Mixed Resin:1.31
Mixing ratio by weight A:B	4:1
Tensile strength (MPa)	30
Flexural modulus (MPa)	3800
Elongation at break (%)	0.9
Setting time (minute)	30
Full cure (day)	7

Table 13: SCC mix proportions by weight

Super plasticizer, (L/m3)	4.9
Fine aggregate, (Kg/m3)	797
Coarse aggregate, (Kg/m3)	767
W/P, (by Weight)	0.34
Water, (Kg/m3)	180
Limestone powder, (Kg/m3)	175
Cement, (Kg/m3)	350

Table 14: Fresh SCC test results

Test method	Results	EFNARC (2002) Limits[5]
Slump flow (mm)	710	650-800
T_{50} (Sec)	3	2-5
L-box (H_2/H_1)	0.9	0.8-1
V-Funnel (Sec)	10	6-12

Table 15: Test results of hardened SCC

Beams	D-1 DO-1	DO-1-I	DO-1.2 DO-0.8	DO-1.2-I DO-0.8-I
f'_c (MPa)	34.14	34.3	33.25	32.65
fct (MPa)	3	3.35	3.22	3.1
fr (MPa)	4.5	6.2	5	4.35

5. Testing procedure and instru-ments

The universal testing machine (AVERY) of 2500kN capacity was used for testing the deep beams at the Structural Laboratory of Build-ing and Construction Department of the University of Technology. Dial gage of 0.01 mm/div. accuracy was used to evaluate midspan vertical de-flection during the test at each load level. The crack patterns were marked. To avoid the local failure at applied load regions and to make sure that bearing stress was uniformly distributed at these locations, two steel plates with dimensions of (70,150, and 20 mm) welded to two cylindrical steel shaft of (40 mm in diameter and 150 mm in length) were used at the two load points. To simulate the boundary conditions of the simply supported beam, the pin and the roller end supports designed as per Al-Bayati [2] were utilized.

6. Experimental results and discus-sion

6.1 *Behavior of solid deep Beam*

Beam (D-1) tested to be as a control deep beam to compare its behavior with other hollow deep beams. Gradually, two types of cracks ap-peared in this beam, the flexural cracks formed at the central zone of the beam at about 21% of the failure load which propegate vertically with additional increment in the load and then stopped at about 0.65h. Mean-while the visible first shear crack was observed at 26.3% of the failure load approximately in the mid-height of the beam within the shear zone in the direction of load path then extended towards the load and the support points. The width of the diagonal cracks became more wider at later stages of loading. Finally, at a load of 760kN, solid beam failed in a shear mode with crushing of concrete near the loading zone as shown in Plate (1). The load-deflection curve for (D-1) is shown in Figure. (6). Re-lationship between the mid-span ver-tical deflection and the applied load is approximately linear in the main part of the loading, then it began to bend slightly in the last part of load-ing, because of the increased number of flexure cracks and propagation of the initial one.

6.2 *Behavior of control deep beam with openings*

6.2.1 Crack patterns and failure modes

The crack patterns and failure modes of these beams are shown in Plates (1). It can be seen, that existence of the openings significantly affected by the formation and expansion of the cracks in the shear span as compared with solid beam (D-1). The cracking process started by the formation of shear cracks from the diametric ends of the openings in both sides of spec-imen. With further increments in the load, those cracks extended toward the support and load points, then flexural cracks appeared at the beams soffit. It is observed that the length and number of the flexural cracks in the specimens of group three (a/d=1.2) were more than those of group two (a/d=0.8). This is be-cause of the higher bending moment which accelerates crack development and increases the tension stresses causing more cracks. The summary of test results for these beams men-tioned is given in the Table (16) which illustrates that the cracking and failure loads were significantly decreased when compared with solid beam (D-1) due to the presence of the openings even when shear span distance was reduced. It can also be seen that the cracking and ultimate loads in beam (DO-0.8) were (140, 460 kN) respectively, while, these loads reduced in beams (DO-1) to (100, 380kN) and in beam (DO-1.2) to (100, 360kN) respectively. The percentage of reduction in cracking and ultimate load due to increase in the a/d ratio from 0.8 to 1.2 were (28.5%, 21.7%), respectively. However, the mode of shear failure of all beams (DO-0.8, DO-1, and DO-1.2) was similar.

6.2.2 Load-midspan deflection re-sponses:

Figure (6) illustrates a comparison between the behavior of the un-strengthened reference deep beams (DO-1, DO-1, DO-0.8, and DO-1.2). It is clear that the reduction in a/d ra-tio causes all decrease in the deflec-tion when compared at the same load levels; this is attributed to, the de-crease in shear span caused reduc-tion in the applied moment and the curvature which leaded to decreasing in the deflection of the beam.

6.3 *Behavior of the strengthened Beams*

6.3.1 Crack patterns and failure modes

The crack patterns of strengthened deep beams (DO-0.8-I, DO-1-I and DO-1.2-I) were characterized by the formation of inclined cracks in a similar way to that occurred in beam (DO-1) as shown in Plate (1). It can be seen from Table (16) that the first shear cracks in the strengthened beams (DO-0.8-I, DO-1-I, DO-1.2-I) are appeared at higher load values those of than control beams (DO-0.8, DO-1, and DO-1.2) because the CFRP strips provide good restraints to the cracks appearance. The failure loads for strengthening beams (DO-0.8-I, DO-1-I, DO-1.2-I) were (620,530,480kN) with percentages of increase (34.8%, 39.5%, and 33.3%), respectively as compared with control beams (DO-0.8, DO-1, and DO-1.2) as shown in the Table (16) This increase in ultimate strength was because of involvement of CFRP in resisting the tension stresses which govern the shear failure. Finally, The mode of failure for all the strengthened beams was debonding CFRP strips after expansion diagonal cracks and crushing concrete along path load as shown in Plate (1). Moreover, it has been found that the increase in a/d ratio from 0.8 to 1.2 caused reductions in cracking and ultimate loads for these beams about by (25%, and 22.5%) respectively.

6.3.2 Load-midspan deflection responses

Figures (7), (8) and (9) are show the load-deflection relationships for the two beams of groups No. one, two and three respectively. It can be seen that this relation is somewhat linear throughout the loading. This behavior is observed in all specimens because of controlling of shear rather than flexure in failure incidence. Generally, the strengthened beams show smaller de-flection values at the same load levels as compared to the reference non-strengthened beams in all groups because of the presence of CFRP as external strengthening elements which lead to increase their resistance and stiffness. Furthermore, Figure (10) shows a comparison between the behavior of the strengthened deep beams (DO-0.8-I, DO-1-I, and DO-1.2-I). It is clear that reduction in a/d ratio causes a decrease in deflection compared to the same load stage of the control beams.

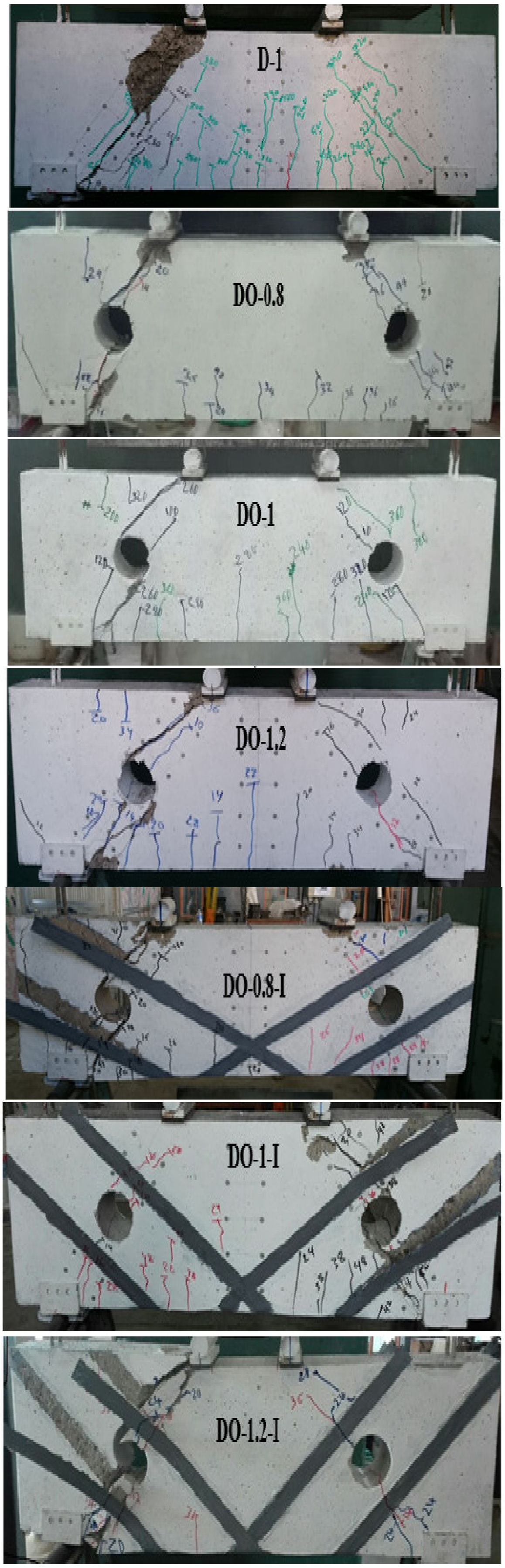

Plate 1: Deep beams after failure

Table 16: Test result of all beams

Group	Beam Symbols	Shear Force		Flexural Force		Ultimate Force		Increase in Ultimate load%	Pcrs/Pu	Mode of Failure
		Pcrs kN	Δcrs mm	Pcrf kN	Δcrf mm	Pu kN	Δu mm			
Solid beam	D-1*	200	1.55	160	1.26	760	7.5	-	26.3	DS+ CC
Group one	DO-1*	100	1.15	140	1.75	380	4.55	-	26.3	DS
	DO-1-I	120	0.98	240	2.06	530	4.7	39.5	22.6	FRPD
Group two	DO-0.8*	140	1.4	240	2.39	460	4.55	-	30.4	DS
	DO-0.8-I	160	1.3	260	2.1	620	5.5	34.8	25.8	FRPD+FRPT+CC
Group three	DO-1.2*	100	1.35	140	1.9	360	4.9	-	27.7	DS
	D0-1.2-I	120	1.33	260	2.82	480	6	33.3	25	FRPD+ CC

Where: Pcrs=the load at initiated first shear crack, Pcrf=the load at initiated first flexural crack, Pu=failure load, Δcrs=vertical deflection at initiated first shear crack, Δcrf=vertical deflection at initiated first flexural crack, Δu=vertical deflection at failure stage, * =control specimen, DS=Diagonal splitting failure, FRPD= FRP debonding, FRPT=FPR tearing, CC=concrete crushing.

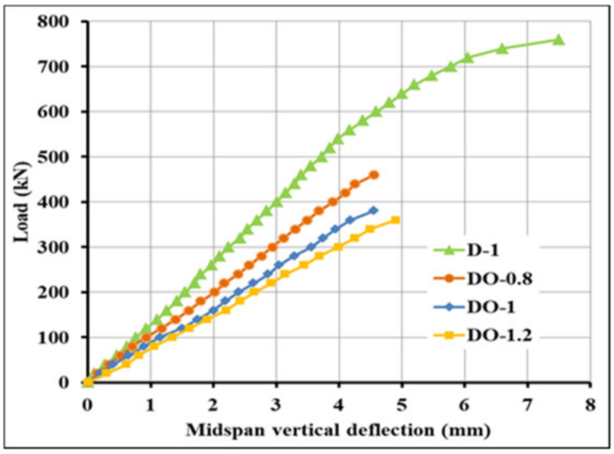

Figure 6: Effect of openings and a/d on load-deflection relations of unstrengthened deep beam

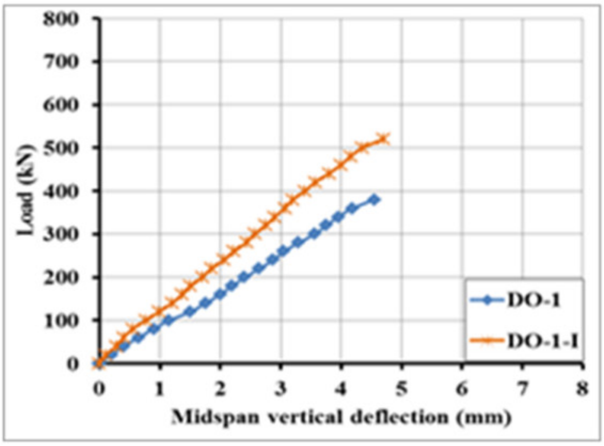

Figure 7: Load-deflection relations of beams in group one

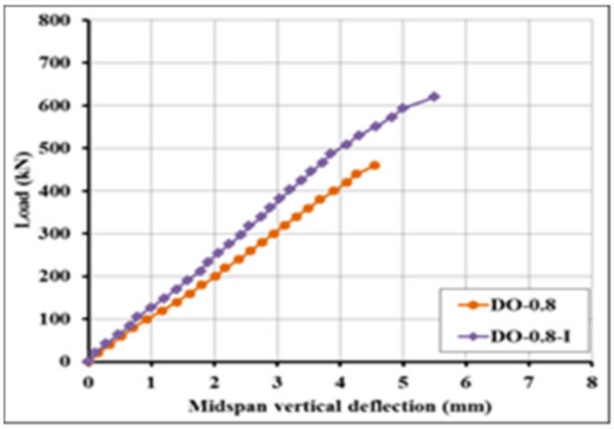

Figure 8: Load-deflection relations of beams in group two

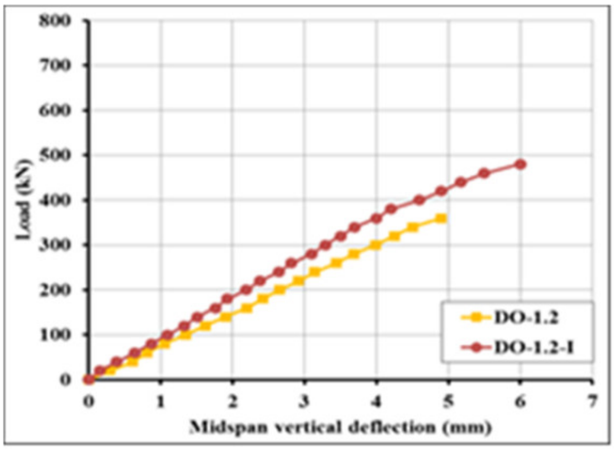

Figure 9: Load-deflection relations of beams in group three

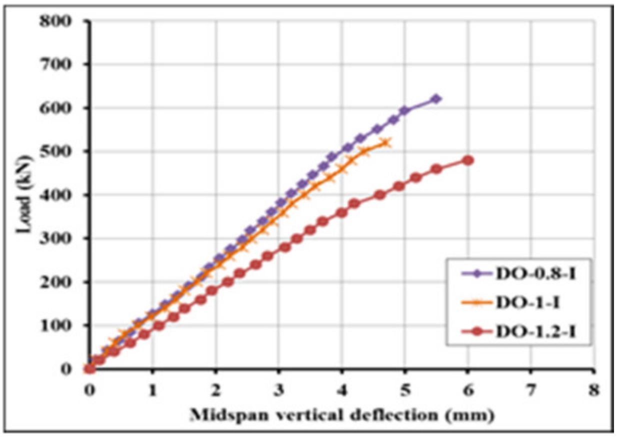

Figure 10: Effect of a/d on load-deflection relations of the strength-ened deep beams with openings

7. Conclusions

1. The failure mode in all beams was shear failure. But the presence of the circular openings in centre of assumed load path has a signifi-cant effect on ultimate strength. It dropped in beam (DO-1) by 50% when compared with solid beam (D-1) whereas the deflection in beam (DO-1) increased at same load stage when compared with beam (D-1)

2. The behavior of tested SCC deep beams is influenced by a/d ratio. It is concluded that the increase a/d ratio from 0.8 to 1.2 decreases the ultimate load by 21.7% and 22.5 % for the reference unstrengthened beam and strengthened beam, re-spectively. Furthermore, the ratio a/d has an effect on midspan de-flection values, that a reduction in a/d led to decrease in deflection values if compared at same load stage whilst, the shear cracking loads increased slightly when the a/d ratio was reduced to 0.8.

3. Bonded CFRP system in the shear span delayed the formation of di-agonal shear cracks slightly and provided good restraint to the sub-sequent growth of cracks. The shear crack load of the strength-ened beams varies from (22.6 to 25.8%) of their ultimate loads.

4. Using inclined strips of CFRP is ef-ficient in upgrading the shear re-sistance of the reinforced SCC deep beams.

5. Generally, the use of CFRP strips in strengthening reinforced SCC deep beams reduces the deflection if compared at same loads levels and increases the load carrying ca-pacity.

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تأثير نسبة فضاء القص الى العمق الفعال على سلوك العتبات الخرسانية المسلحة العميقة ذاتية الرص الحاوية على فتحات والمقواة بألياف الكاربون البوليميرية

نبيل عبد المجيد البياتي [1]***، بسمان رياض احمد*** [2]***، مروج فائق عودة*** [3]*

[1] *الجامعة التكنولوجية قسم هندسة البناء والانشاءات ، بغداد، العراق ، nabalbayati@yahoo.com*

[2] *1 الجامعة التكنولوجية قسم هندسة البناء والانشاءات ، بغداد، العراق ، bassman.riyadh@gmail.com*

[3] *1 الجامعة التكنولوجية قسم هندسة البناء والانشاءات ، بغداد، العراق ، blue_lily2002@yahoo.com*

* *الباحث الممثل: مروج فائق عودة ، blue_lily2002@yahoo.com*

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الخلاصة – يتضمن هذا البحث نتائج فحص سبعة عتبات عميقه مسلحة ذاتية الرص من ضمنها ستة نماذج تحتوي على فتحات دائرية في مركز مسار الأحمال. المتغيرات التي تمت دراسة تأثيرها على سلوك العتبات العميقة هي تغير نسبة فضاء القص الى العمق الفعال, وجود الفتحات الدائرية واستخدام شرائح الكاربون البوليميرية المائلة. تم التحقق ايضا من الاتجاه العام لنمط التشقق, استجابة الانحراف للاحمال المسلطة ونمط الفشل لهذه العتبات. جميع النماذج تمتلك ابعاد متساوية ونفس تفاصيل حديد الانحناء والقص بالاتجاه العمودي والافقي وتم فحصها تحت تأثير نقطتي تحميل متناظرتين حتى حدوث الفشل. أظهرت النتائج العملية بان وجود الفتحات الدائرية في منطقة القص سبب نقصان مهم في قابلية تحمل الجسور العميقة وبنسة تصل الى حوالي 50% عند المقارنة مع الجسر الصلد المقابل له وأن زيادة نسبة فضاء القص الى العمق الفعال من 0.8الى 1.2 خفضت الاحمال القصوى بنسبة 21.7% و 22.5% للجسور المرجعية غير المقواة والجسور المقواة على التوالي وجد بأن استخدام شرائح الكاربون المائلة تحسن من المقاومه القصوى للعتبات وجساءتها بنسة تصل الى 39.5%كذلك تحسن من جساءة الجسور الحاوية على فتحات دائرية

الكلمات الرئيسية – .