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BEHAVIOUR OF REINFORCED HIGH-STRENGTH CONCRETE BEAMS WITH OPENINGS SUBJECTED TO STATIC AND REPEATED LOADINGS

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This paper presents the results of an experimental research on reinforced high strength concrete beams with web rectangular openings to determine their behaviour and ultimate strengths, and to compare these strengths with those predicted using the available equations. Test variables were length of openings, details of steel reinforcement around the openings, longitudinal main steel ratio, and type of loading (static-repeated). Test results showed that the ultimate load of beams with openings reduces by about 10 to 45% compared to similar solid beams. Provided that the same amount and scheme of reinforcement used, an increase in opening length, decreases both stiffness and strength of the beam. Diagonal bars at corners of openings results in spreading of cracking away from openings and reducing beam deflection, but it does not have significant influence on strength of the beam. The effects of transverse openings on overall response of reinforced concrete beams in shear becomes remarkable as main steel ratio (ρ) increases. Increasing shear reinforcement (stirrups) in the top and bottom chords of the openings increases slightly the cracking load; while increases significantly the ultimate load. Repeated load has no effect on either strength or mode of failure of the tested beams. The available equations do not produce satisfactory results for predicating the ultimate shear strength of high-strength concrete beams with openings.

KEYWORDS: *High-strength concrete; beams; opening; shear strength, deflection.*

NOTATION

A_d	Cross sectional area of diagonal reinforcement, mm^2.	H_o	Opening depth, mm
A_v	Cross sectional area of vertical stirrups, mm^2.	L_o	Opening length, mm
b_w	Beam width, mm	S_o	Spacing of stirrups, mm
D	Effective beam depth, mm	V_c	Shear strength provided by concrete, kN
d_v	Distance between top and bottom longitudinal reinforcing bars, mm	V_s	Shear strength provided by shear reinforcement, kN
f_{cu}	Cube compressive strength of concrete, MPa	V_u	Shear strength of beam, kN

f_c'	Cylinder compressive strength of concrete, MPa	***Greek Symbols:***	
f_{yd}	Yield strength of diagonal bars, MPa	ρ	Tensile reinforcement ratio,
f_{yv}	Yield strength of stirrups, MPa,	α	Inclination of diagonal reinforcement.

1. INTRODUCTION

Transverse openings through beams are often required for the passage of utility ducts and pipes. However, rectangular openings are required to accommodate air conditioning ducts.

In recent years, there has been rapid growth in the use of high-strength concrete. The benefits of such concrete are now fully apparent and more than compensate the increased costs of raw materials and quality control. Also, recently a considerable interest has developed in the fatigue behaviour and strength of reinforced concrete members, and there is a new recognition of the effects of repeated loading on such members, even if repeated loading does not causes a fatigue failure [1].

Most of the researches carried out so far for beams with openings, are for beams made of normal strength concrete [2-9], but a few is known about those made of high-strength concrete [10]. Therefore, the objective of this research is to estimate experimentally and analytically the influence of web openings on the structural behaviour of reinforced high-strength concrete beams subjected to static and repeated loadings. Test variables included in this study are: length of openings (L_o), stirrups spacing in both top and bottom chords (S_o), diagonal steel reinforcement provided at each corner of openings, longitudinal steel ratio (ρ), and type of loading (static-repeated).

2. EXPERIMENTAL PROGRAM

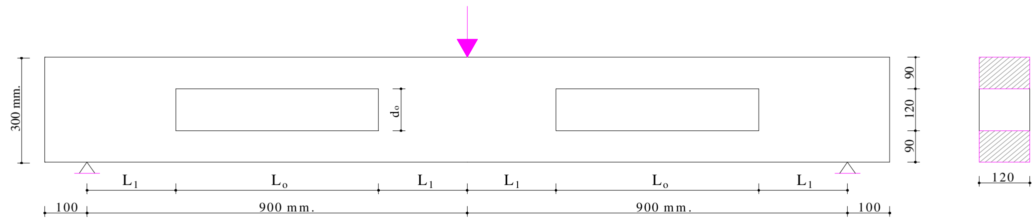
2.1 Details of Beams:

A total of sixteen reinforced high-strength concrete beams were tested. Ten were tested statically and six under repeated loading. All beams were of 120-mm thick and 300-mm total depth, and tested under three-points loading over a simple span of 1800 mm. **Table (1)** and **Figure (1)** give summary of specimen details. All openings were 120 mm deep, which represents 40% of the overall beam depth. For beams tested under static loading, two beams were solid and served as reference beams (stirrups of these beams were ϕ 6 @ 15cm), while the other beams contained one opening in each side of the point of central load. Openings were always located halfway between the end supports and the point of load application.

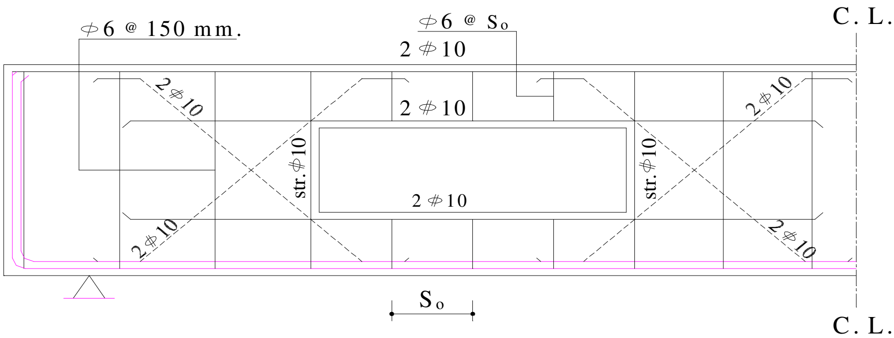
Beams tested under repeated loading were similar to those tested under static loading in series 1 **(see Table 1).** It has to be mentioned that, to contain the cracks, one full depth closed stirrups of 10 mm diameter deformed bar was fixed close to the vertical edges of each opening.

Table (1): Details of specimens

Series No.	Beam No.	Dimensions of opening		L_1 (mm)	Concrete strength		Main Reinforcement		Long. Bars in chord members	Stirrups of chord members		Corner shear reinforcement		Type of loading
		L_o (mm)	H_o (mm)		f_{cu} (MPa)	f_c' (MPa)	No.& dia.	ρ		Diam. (mm)	S_o (mm)	Closed stirrup	Diagonal bars	
1	BS-1	-	-	-	66.00	57.12	4φ12	0.014	2φ10	-	-	-	-	Static
	BS-2	240	120	330	65.00	56.17	4φ12	0.014	2φ10	6.0	50	1φ10	-	Static
	BS-3	360	120	270	65.20	56.36	4φ12	0.014	2φ10	6.0	50	1φ10	-	Static
	BS-4	480	120	210	70.80	61.71	4φ12	0.014	2φ10	6.0	50	1φ10	-	Static
	BS-5	360	120	270	67.60	58.65	4φ12	0.014	2φ10	6.0	100	1φ10	-	Static
	BS-6	360	120	270	65.00	56.17	4φ12	0.014	2φ10	6.0	50	1φ10	2φ10	Static
2	BS-7	-	-	-	71.00	61.90	4φ16	0.025	2φ10	-	-	-	-	Static
	BS-8	360	120	270	70.00	60.94	4φ16	0.025	2φ10	6.0	50	1φ10	-	Static
	BS-9	360	120	270	70.00	60.94	4φ16	0.025	2φ10	6.0	100	1φ10	-	Static
	BS-10	360	120	270	71.00	61.90	4φ16	0.025	2φ10	6.0	50	1φ10	2φ10	Static
3	BR-1	-	-	-	66.00	57.12	4φ12	0.014	2φ10	-	-	-	-	Repeated
	BR-2	240	120	330	65.00	56.17	4φ12	0.014	2φ10	6.0	50	1φ10	-	Repeated
	BR-3	360	120	270	65.20	56.36	4φ12	0.014	2φ10	6.0	50	1φ10	-	Repeated
	BR-4	480	120	210	70.80	61.71	4φ12	0.014	2φ10	6.0	50	1φ10	-	Repeated
	BR-5	360	120	270	67.60	58.65	4φ12	0.014	2φ10	6.0	100	1φ10	-	Repeated
	BR-6	360	120	270	65.00	56.17	4φ12	0.014	2φ10	6.0	50	1φ10	2φ10	Repeated



(a) Specimen dimensions



(b) Details of reinforcement

Fig.1: Specimen details.

2.2 Materials:

- Concrete mix design was made to produce high-strength concrete having a 28 day cube compressive strength of about 70 MPa. Concrete mix proportions are given in **Table (2)**.

- Ordinary Portland cement and local natural sand were used. Crushed basalt with maximum size of about 20 mm was used as course aggregate. To enhance the workability and strength of concrete, water reducing admixture and Silica Fume were used.
- High strength deformed bars 10, 12 and 16 mm diameter of 490, 520 and 550 MPa proof strength, and 6 mm diameter plain bars of 330 MPa yield strength were used for reinforcement.

Table (2): Concrete mix proportions.

Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Silica Fume (kg/m^3)	Sekament N.N (Lit/m^3)	Water (lit/m^3)
500	600	1200	100	20	150

2.3 Test Procedure and Instrumentations:

All beams were tested simply supported and the load was applied at mid span of the beam as shown in **Fig. (1)**. In static tests, the load was applied in increments of 2.5 kN. In repeated tests, the fatigue loading was applied as stationary pulsating concentrated load at the mid-span of the beam. The applied minimum load was constant at 14 kN (weight of steel tar of testing machine). The maximum load was taken as the static ultimate load of the companion beam tested statically divided by 1.6. The frequency was chosen to be 500 load cycles per minute and the chosen stroke was 0.2 mm. The loading regime is shown in **Fig. (2)**. For all specimens, mid-span deflection, first crack load, and failure load were measured. Crack patterns and failure modes were observed carefully.

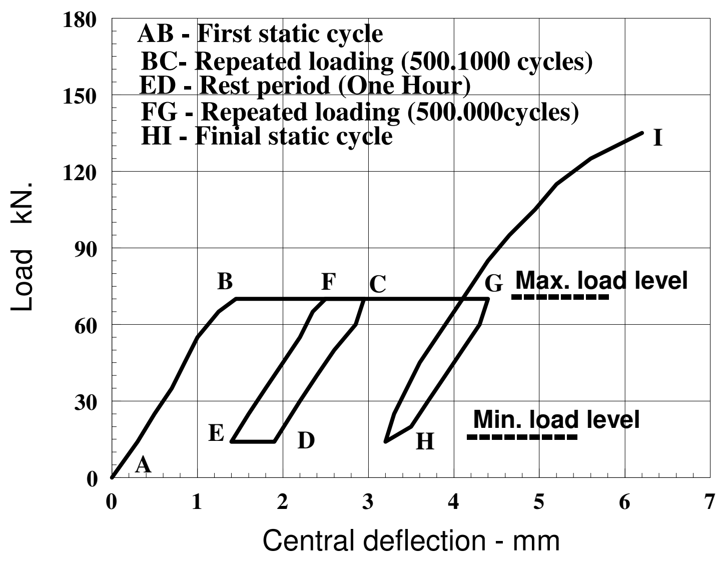


Fig.2: Sketch of sequence of loading versus deflection (Repeated tests)

3. TEST RESULTS AND DISCUSSION

3.1 Failure Mode:

In case of static tests, the solid beam (BS-I) failed in a classical flexural mode, but at ultimate load the deflection increased rapidly and a diagonal tension crack was observed, while beam (BS-7) failed by diagonal tension, in a ductile manner **(Fig. 3).** For all beams with openings, the first crack appeared nearly in the center of the middle solid segment or in the bottom chord at the high moment end of the openings. The mode of failure of these beams was due to shear at opening region. At failure the compression chord of the openings of these beams has been splitted diagonally with crushing of concrete at the height moment end **(see Fig. 3)**. This was more sever in beam (BS-5), while beams with additional diagonal bars showed less number of cracks and crack widths in comparison with similar beams without diagonal bars.

In case of repeated tests, all beams with openings were capable to sustain 62.5% of their static failure load for one million load cycles including an intermediate rest period of about one hour without failure, and failed statically after that in the same manner as that of the beam tested directly under static loads, i.e. the repeated loading did not influence the mode of failure of fatigue specimens, but the cracking pattern due to repeated loading was more segmental and extensive than that due to the static loading.

BS-7

BS-3

BS-8

BS-6

BR-3

Fig.3: Failure patterns of some test beams

3.2 Load Deflection Curves:

Figures (4) to (7) show the load deflection curves for all test specimens. The following observations can be made from these figures:

- An increase in the length of the opening resulted in a substantial decrease in both post cracking stiffness and failure load of the beam. At any particular load, the deflection is larger for beams with longer opening.
- Increasing the distance between stirrups in top and bottom chords of the opening decreased the stiffness of the beam and consequently higher deflection at any load level was recorded.
- The use of additional diagonal bars has a slight influence on the ultimate load level, but has a moderate influence on the stiffness of the beams, especially those with higher longitudinal steel ratio (ρ).
- The effect of openings on overall behaviour of beams in shear becomes more remarkable as longitudinal steel ratio (ρ) increases
- Deflection at service load (in this study, service load is taken as the experimental ultimate load divided by 1.6), increases as length of opening increases, or as spacing of stirrups (S_o) increases [**see Table (3)**].
- Deflection value at failure load of beams subjected to repeated loading is considerably higher than the corresponding value obtained from companion beam tested statically.
- For all specimens tested under repeated loading, more than 90% of the value of the deflection occurred at the end of one million load cycles, occurred in the first 100,000 load cycles.

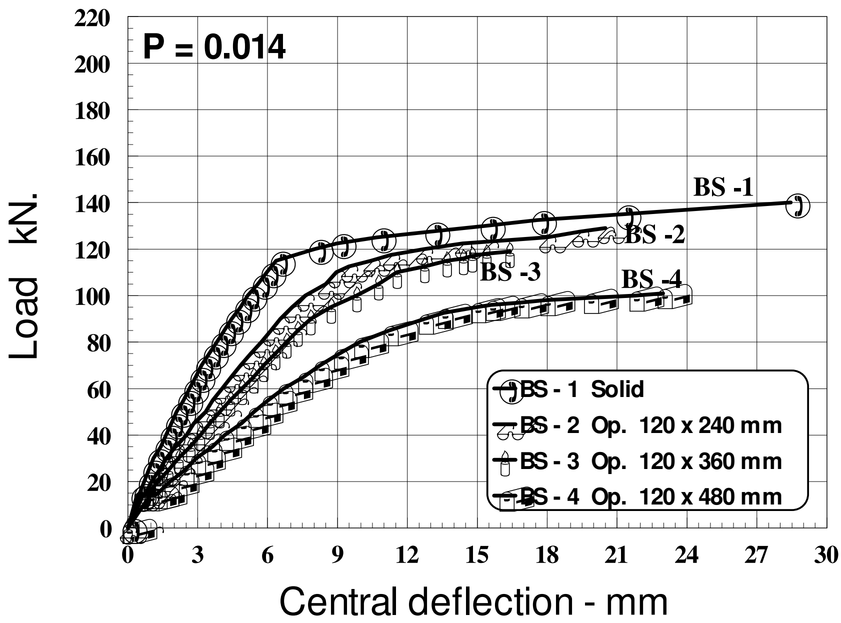
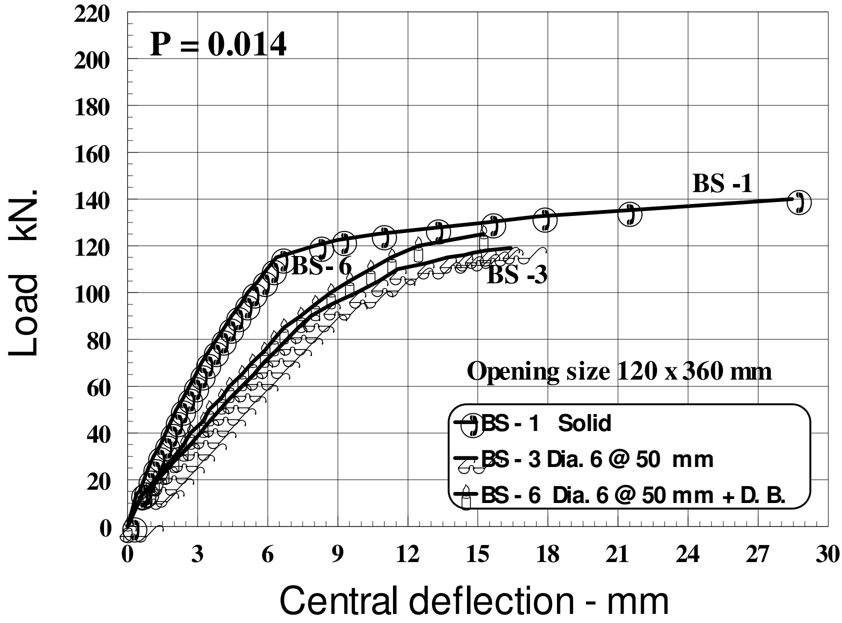
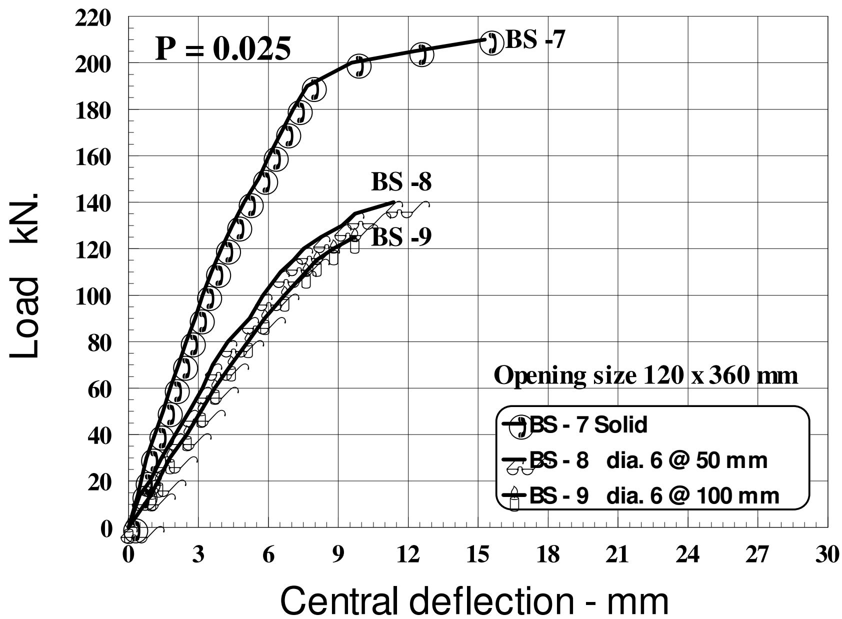


Fig. 4: Effect of opening length (L_o).

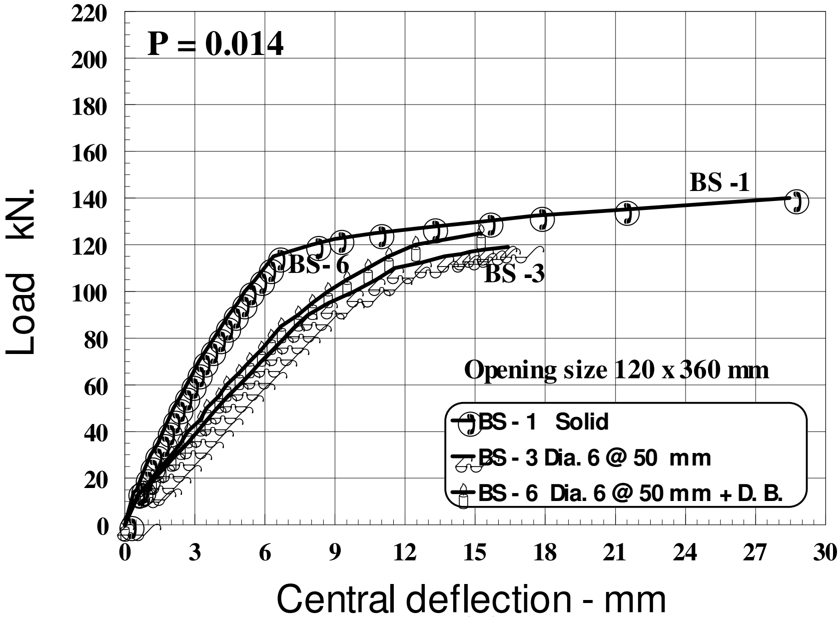


(a)



(b)

Fig. 5: Effect of stirrups spacing (S_o).



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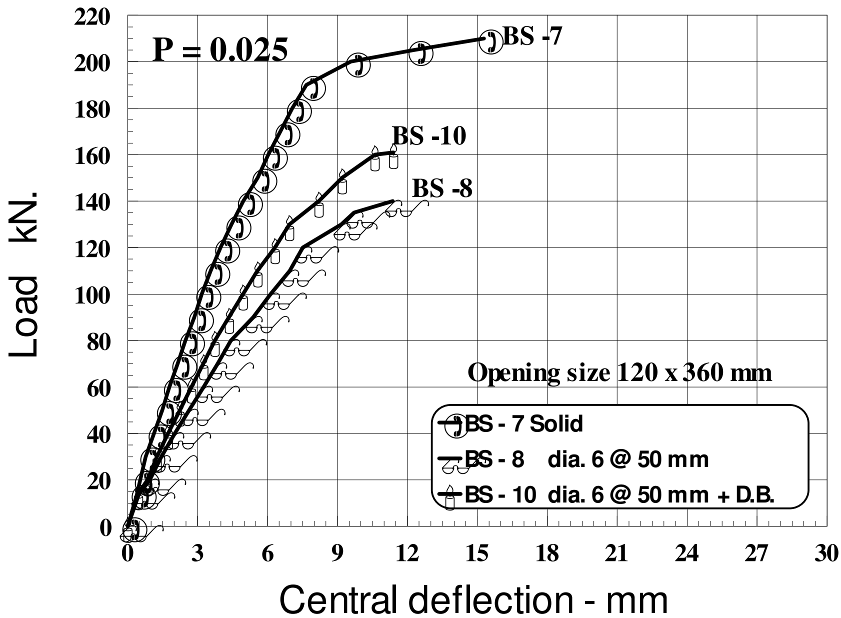
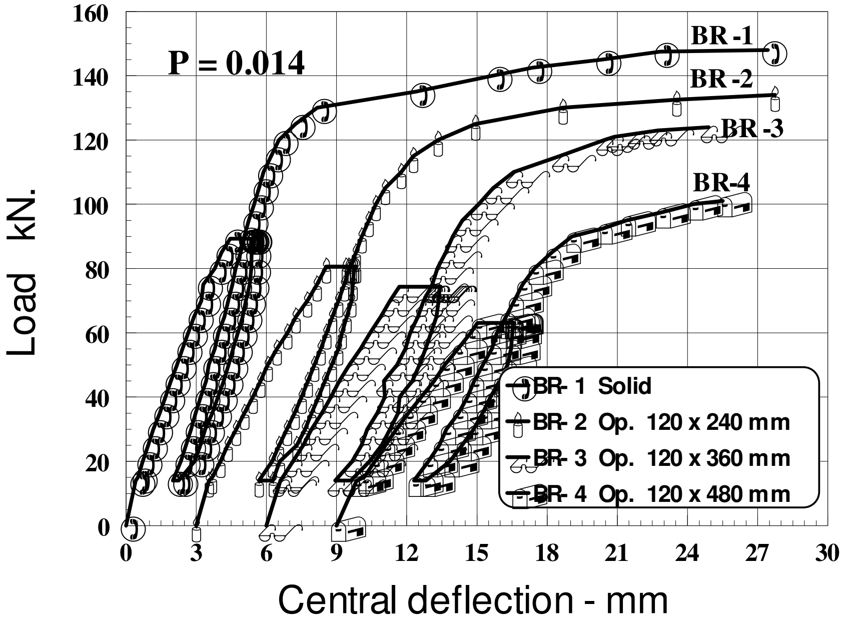


(b)

Fig. 6: Effect of using diagonal bars.



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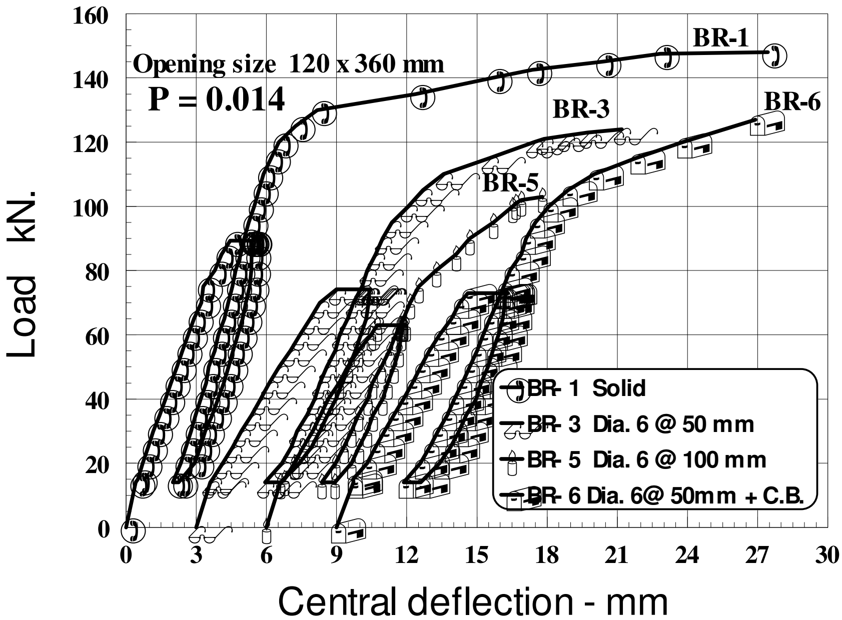

(b)

Fig. 7: Load central deflection curves for repeated tests.

3.3 Cracking and Ultimate Loads:

Table (3) lists the experimental cracking and ultimate loads for all beams tested in this study. The following observations can be made from the results given in this table:

- The presence of an opening in the shear zone of reinforced high-strength concrete beam significantly decreases its cracking and ultimate load. The ultimate loads of beams with openings were reduced by 10 to 45% compared to similar beams without openings.
- Increasing opening length causes a corresponding decrease in both cracking and ultimate loads. For example increasing the opening length from 0.267 to 0.533 times shear span length decreases the cracking and ultimate loads by 40% and 22.3% respectively. Abdalla *et al.*[11] concluded that the presence of an un-strengthened opening in the shear zone of reinforced normal concrete beam significantly decreases its ultimate capacity. An opening with height of 0.4 the beam depth may reduce the beam capacity by 50%, but increasing the opening width for the same opening height has a minor effect. They [11] mentioned that this is true for beams with opening length less than 1.2 the beam depth. Meanwhile, Abd El-Shafy [10] mentioned that increasing the opening length from 0.32 to 0.64 times shear span decreases, the cracking and ultimate loads by about 64.7% and 30% respectively for reinforced high-strength concrete T-beams. In addition to that Tan *et al.*[7] concluded that the presence of large web opening leads to a decrease in both cracking and ultimate strength of beams made with normal strength concrete.
- The use of diagonal bars at the corners of the opening has a slight influence on both cracking and ultimate loads of beams with openings. Mansur et al. [5] concluded that, diagonal bars for corner reinforcement are more effective in controlling crack width, reducing beam deflection, and also help to increase the ultimate strength of beam.
- Increasing the shear reinforcement (stirrups) in the top and bottom chords of the openings, increases slightly the cracking load, while increases significantly the ultimate load.
- The influence of the presence of end openings on the behaviour and strength of reinforced concrete beams becomes more remarkable as the percentage of main longitudinal steel (ρ) increases.
- Repeated load seems to have no significant influence on the ultimate load of the tested beams either with or without openings.

3.4 Comparison between Experimental and Predicated Values of Ultimate Shear Strength:

For estimating the ultimate shear strength of beams with circular opening, Tan et al. [9] suggested that the ACI code equations [12] can be used with some modification, depending on the type of failure occurred. The first type of failure (beam-type failure) is the typical failure commonly observed in prismatic beams, except that the failure plane passes through the center of the opening.

Table (3): Results of Static and Repeated Tests.

(A) Static tests

Series No.	Beam No.	Experimental		Service Load (kN)	Deflection at		Mode of failure
		Cracking Load (kN)	Ultimate Load (kN)		Service Load (mm)	Ultimate Load (mm)	
1	BS-1	30.0	145.0	90-63	4.45	28.45	Flexural
	BS-2	25.0	130.0	81.25	5.79	20.50	Shear at opening
	BS-3	20.0	120.0	75.0	6.35	16.40	Shear at opening
	BS-4	15.0	101.0	63.13	7.22	22.96	Shear at opening
	BS-5	22.5	102.0	63.75	6.00	13.34	Shear at opening
	BS-6	25.0	130.0	81.25	6.04	15.20	Shear at opening
2	BS-7	37.5	220.5	137.81	5.05	15.28	Diagonal tension
	BS-8	27.5	145.0	90.63	5.20	11.37	Shear at opening
	BS-9	25.0	120.0	75.00	4.75	9.70	Shear at opening
	BS-10	27.5	161.0	100.63	5.33	11.40	Shear at opening

(B) Repeated tests

Series No.	Beam No.	Experimental		Deflection at (mm)					Mode of failure
		Cracking Load (kN)	Ultimate Load (kN)	Service Load (kN)	10^5 cycles	5×10^5 cycles	10^6 cycles	Failure	
3	BR-1	25.0	148	4.46	5.15	5.25	5.41	29.43	Flexural
	BR-2	20.0	129	5.56	6.27	6.63	6.84	24.73	Shear at opening
	BR-3	20.0	124	5.70	6.82	7.19	7.45	19.15	Shear at opening
	BR-4	17.5	101	6.02	7.19	7.47	7.60	16.51	Shear at opening
	BR-5	20.0	102	4.73	5.62	5.79	5.97	11.80	Shear at opening
	BR-6	25.0	127	6.10	6.52	7.00	7.22	18.00	Shear at opening

In the second type (frame-type failure), the formation of two-independent diagonal cracks, one in each chord member that bridges the two prismatic beam segments, leads to failure.

Beam-type failure:

In this case Tan et al. [9] suggested that the simplified ACI expression can be used by replacing the effective depth by the net depth ($d–d_o$), irrespective of vertical and horizontal location of the opening, where d_o is the diameter/depth of the opening, as follows:

$$V_u = V_c + V_s \quad \text{kN} \qquad (1)$$

$$V_c = \qquad b_w (d - d_o) \quad \text{kN} \qquad (2)$$

$$V_s = \frac{A_v . f_{yv} (d_v - d_o)}{S_o} + A_d f_{yd} \sin \alpha \quad \text{kN} \qquad (3)$$

It has to mentioned that in this research, d_o was taken equals to H_o , and the effect of the diagonal bars was ignored in computation of ultimate shear strength of the tested beams, because the results of this research showed that the diagonal bars has a slight effect on ultimate shear strength of the tested beams. In addition to that the failure took place in an area away from the position of the diagonal bars.

Frame-type failure:

In this type of failure, each chord member behaves as an independent entity similar to that in framed structure. The compressive and tensile force N_u in the member above and below the opening can be obtained as follows:

$$(N_u)_t = \frac{M_u}{(d - \frac{a}{2})} = -(N_u)_b \quad \text{kN} \qquad \textbf{(4)}$$

Where a is the depth of the ultimate compressive block, and the subscripts t and b denote the top and bottom member through the opening.

The applied shear V_u is, however distributed between the two members in proportion to their cross-sectional areas.

$$(V_u)_t = V_u \left(\frac{A_t}{A_t + A_b} \right) \qquad \textbf{(5)}$$

$$(V_u)_b = V_u - (V_u)_t \qquad \textbf{(6)}$$

Knowing the shear and axial force in each member the ultimate shear strength of the beam can be calculated as follows:

$$(V_c)_t = \left(0.167 + 0.012 \frac{(N_u)_t}{A_t} \right) \sqrt{f_c^{'}} \quad (b_w\, d_t) \quad \text{kN} \qquad \textbf{(7)}$$

$$(V_c)_b = \left(0.167 - 0.05 \frac{(N_u)_b}{A_b} \right) \sqrt{f_c^{'}} \quad (b_w\, d_b) \quad \text{kN} \qquad \textbf{(8)}$$

$$V_c = (V_c)_t + (V_c)_b \quad \text{kN} \qquad \textbf{(9)}$$

$$V_s = \frac{A_v\, f_{yv}\, (d_v - d_o)}{S_o} \quad \text{kN} \qquad \textbf{(10)}$$

$$V_u = V_c + V_s \quad \text{kN} \qquad \textbf{(11)}$$

It has to be mentioned that, in this study M_u was taken equals to the moment at the centerline of the opening and (d–a/2) was taken as the distance between the centerline of the top and bottom chords.

Data given in **Table (4)** showed that the ratio of the experimental to the predicated values of the ultimate shear strength of beams with openings, using the above equations ranges from 0.66 to 1.24 for case of beam-type failure, and from 0.70 to 1.39 for frame type failure, i.e. the difference between the two methods is very small (nearly 7%).

Table (4): Comparison between experimental and predicated ultimate loads

Series No.	Beam No.	Experim. Ult. Load (kN) (1)	Predicated ultimate load (kN)		V_u exp. / V_u pred.	
			Beam-type failure (2)	Frame-type failure (3)	[(1)/(2)]	[(1)/(3)]
1	BS-1	145.0	147.30	-	0.98	0
	BS-2	130.0	152.43	142.24	0.85	0.91
	BS-3	120.0	152.51	142.29	0.79	0.84
	BS-4	101.0	154.31	143.57	0.66	0.70
	BS-5	102.0	99.69	89.11	1.02	1.14
	BS-6	130.0	152.44	142.24	0.85	0.91
2	BS-7	220.5	150.65	-	1.46	-
	BS-8	145.0	154.31	143.39	0.94	1.01
	BS-9	125.0	100.58	89.66	1.24	1.39
	BS-10	161.0	154.67	143.62	1.04	1.12

The scattering in the predication of the ultimate shear strength of the test specimens using the above equations may be due to the following facts:

- These empirical equations are based on experimental results of members made of normal strength concrete rather than high strength concrete.
- These equations ignored the effect of opening length, although the results of this study and others [7 and 10] showed that the opening length has a significant influence on the ultimate shear strength of beams with openings, especially those with large openings. In addition to that, El-Awadi et al. [13] concluded that the amount of shear force sustained by each chord depends not only on the chord sectional properties, but also on the size and location of the opening.
- These equations ignored the influence of main longitudinal steel content (ρ) although previous experimental results [14 and 15] have shown that the ultimate shear strength of beams increases as longitudinal steel ratio increases.

Therefore, further experimental work in this subject still needed. This will lead either to develop new equations, or at least modify the available ones for more accurate predication of the ultimate shear strength of these beams.

CONCLUSIONS

This paper summarized the results of an experimental study of the strength and behaviour of reinforced high-strength concrete beams with web openings subjected to static and repeated loadings. Within the scope of this study the following conclusions can be drawn:

1. An increase in the size of the openings by increasing its length resulted in a substantial decrease in cracking load, ultimate carrying capacity, and post cracking stiffness of the beam.
2. The use of diagonal bars at each corner of the opening resulted in the spreading of cracking away from the openings, reducing crack width and beam deflection, but it does not have remarkable effect on strength of the beam.
3. Increasing the ratio of conventional stirrups in the top and bottom chords of the opening by reducing stirrup spacing increases the strength and the stiffness of the beam significantly.
4. The influence of the presence of end openings on the behaviour and strength of reinforced concrete beams becomes more remarkable as the percentage of main longitudinal steel ratio (ρ) increases.
5. All beams with openings were capable to sustain 62.5% of their static failure load for one million load cycles without failure.
6. Repeated loading has no significant influence on the ultimate load carrying capacity of the tested beams, but deflections and propagation of cracks increase successively. In addition to that, more than 90% of the value of defection at one million load cycles occurred in the first 10,000 load cycles.
7. Type of loading (static-repeated) has no effect on the mode of failure of beams. But the cracking pattern due to repeated loadings was more segment and extensive than that due to static loading.
8. The available equations do not produce satisfactory results for predicating the ultimate shear strength of beams with opening. Therefore, further experimental works is needed. This will lead either to develop new equations, or at least modify the available ones for a more accurate predication of ultimate shear strength of there beams.
9. Using diagonal bars and vertical stirrups in both sides of the opening, as well as adequate short stirrups in both top and bottom chords of the opening are recommended for improving the behaviour and strength of beams with openings.

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سلوك الكمرات الخرسانية المسلحة المصنوعة من خرسانة عالية المقاومة ذات الفتحات تحت تأثير الأحمال الاستاتيكية والمتكررة

في المنشآت الحديثة خصوصاً الصناعية والإدارية منها يتطلب الأمر تزويدها بفتحات في عصب الكمرات لمرور خطوط وأنابيب الأجهزة الميكانيكية والكهربائية والتكييف، كما أن بعض هذه المباني يتعرضن لأحمال متكررة بالإضافة إلى الأحمال الاستاتيكية، بالإضافة إلى ذلك فإنه مع تقدم تكنولوجيا صناعة الخرسانة أصبح إنتاج خرسانة عالية المقاومة أمراً يسيراً.

بالرغم من أن كثيراً من الباحثين استفاضوا في دراسة سلوك الكمرات الخرسانية المسلحة المصنوعة من خرسانة ذات مقاومة عادية ذات الفتحات، فإن القليل منهم درس سلوك تلك الكمرات المصنوعة من خرسانة عالية المقاومة.

لذا فإن الهدف من هذا البحث هو دراسة سلوك الكمرات الخرسانية المسلحة المصنوعة من خرسانة عالية المقاومة ذات الفتحات المستطيلة تحت تأثير الأحمال الاستاتيكية والمتكررة. هذا وقد أجريت التجارب المعملية على ستة عشرة كمرة، اختبرت عشرة منها استاتيكياً والباقي تعرضن لحمل متكرر، وكانت المتغيرات التي تم دراستها كالتالي: طول الفتحة . تفاصيل التسليح حول الفتحة . نسبة حديد الشد الرئيسي . نوع الحمل (إستاتيكي – متكرر). وقد تم دراسة تأثير تلك المتغيرات على شكل الشروخ . طراز الانهيار . قيم الترخيم . مقاومة القص القصوى لتلك الكمرات، كما تم أيضاً مقارنة مقاومة القص القصوى التي تم الحصول عليها تجريباً لهذه الكمرات بتلك المحسوبة من المعادلات المتاحة في هذا الشأن.

من أهم النتائج التي تم الحصول عليها ما يلي:

- إن وجود فتحات مستطيلة في عصب الكمرات في منطقة القص له تأثير فعال على قيم سهم الانحناء . حمل التشريخ . مقاومة القص القصوى . طراز الانهيار، وقد توقف هذا التأثير على طول الفتحة . تفاصيل التسليح حول الفتحة . نسبة حديد الشد الرئيسي فقط.
- إن استخدام تسليح قطري حول جانبي الفتحة الرأسيين ليس له تأثير واضح على حمل التشريخ أو مقاومة القص القصوى، ولكن له تأثير على تقليل قيم الترخيم وإزاحة أماكن الشروخ بعيداً عن مكان الفتحة كما يقلل من عرض الشروخ الحادثة.
- التحميل المتكرر ليس له تأثير ضار على قيم مقاومة القص القصوى ولا على طراز الانهيار، ولكن يزيد من التشكلات الحادثة وعدد الشروخ المتكونة مقارنة بالحمل الاستاتيكي.
- فشلت المعادلات المتاحة في التنبؤ بقيم مقاومة القص القصوى للكمرات المصنوعة من خرسانة عالية المقاومة ذات الفتحات المستطيلة، وإن هناك حاجة لمزيد من الدراسة لتعديل تلك المعادلات أو استنباط معادلات جديدة.