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Experimental Study to Investigate the effect of Longitudinal and Transverse Openings on the Structural Behavior of High Strength Self Compacting Reinforced Concrete Beams

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Abstract: Service runs considered as a major nerve of any building. Thus, beam with longitudinal and transverse opening (BLTO) was creative solution for the purpose of serve those runs with other benefits, especially when utilized high strength self-compacting concrete (HS-SCC). This study examined the behavior of eight reinforced concrete (RC) beams. These beams were involved into two groups. All beams had identical in dimensions, reinforcement, concrete type, and hole dimensions. The evaluation used to elect the optimum hollow core section, and position effect of web openings with fixed hollow core section. Due to recorded load capacity, a reduction was produced by hollow core position at mid and bottom section by about (2%-14%), respectively, with comparing by solid section. Therefore, the optimum hollow core section was when it locate in mid beam section which used to unify BLTO sections. BLTO types indicated different loading data according to web opening position. The decrement of opening provision was about (20.4%) by compared with hollow beam (without transverse opening) and about (22%) by compared with the solid beam. The optimum BLTO was when the web opening located in mid-shear zone, while the critical one recorded in web opening position in mid-span and near supports in same BLTO. The registered failure mode of all beams was contained two main types, suddenly flexural failure in compressive zone by concrete cover crushing and flexural-shear failure.

Keywords: *Beam, High-strength, Hollow, Longitudinal, Opening, Self-Compacting, Transverse, web*.

الدراسة العملية لتحري تأثير الفتحات الطولية والجانبية على السلوك الإنشائي للعتبات الخرسانية المسلحة عالية المقاومة ذاتية الرص

الخلاصة: تعتبر التمريرات الخدمية عصب أساسي لأي بناية. لذلك تكون العتبات ذات الفتحات الطولية والجانبية (BLTO) حل ابداعي لغرض خدمة تلك التمريرات مع المنافع الأخرى، وخاصةً عند تطبيق الخرسانة عالية المقاومة ذاتية الرص (HS-SCC). تستقصي هذه الدراسة سلوك ثمانية عتبات خرسانية مسلحة. تنطوي هذه العتبات تحت مجموعتين. كافة العتبات متماثلة في الابعاد، التسليح، نوع الخرسانة وأبعاد الفجوات. إستُخدم التقييم لانتخاب المقطع المجوف النواة وتأثير مواقع فتحات الوترة مع ثبوت المقطع المجوف النواة. على خلفية قابلية التحمل المسجلة، أنتج تجويف النواة الواقع في منتصف وأسفل المقطع انخفاضاً بحوالي (٢ الى ١٤) %، على التوالي، مقارنةً مع المقطع المصمت. بناءً عليه، كان المقطع الأمثل لتجويف النواة عندما تقع في منتصف مقطع العتبة والتي استخدمت لتوحيد مقاطع الـ(BLTO). أشارت أنواع الـ(BLTO) الى بيانات تحميل مختلفة تبعاً لمواقع فتحات الوترة. بلغ الانخفاض في وجود الفتحات حوالي (٢٠.٤%) من خلال المقارنة مع العتبة المجوفة (التي لاتتضمن تجاويف عرضية) وحوالي (٢٢%) من خلال المقارنة مع المقطع المصمت. كان (BLTO) الأمثل عندما تقع فتحة الوترة في منتصف منطقة القص، بينما سُجل الأحرج لموقع فتحة الوترة في منتصف الفضاء وقرب المساند لنفس الـ(BLTO). شمل نمط الفشل المسجل لجميع العتبات نوعين رئيسيين، فشل الانثناء الفجائي في منطقة الضغط بواسطة تهشم الغطاء الخرساني وفشل الانثناء-القص.

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1. Introduction

In modern building construction, service runs such as (pipes, ducts, wires, etc.) had produced several shortcomings when congested in one place or intense for linkage to far places. The shortcomings can be summarized as deformation the aesthetic aspects, loss of properties of these installations over time due to the exposing to environment and created dead space. Most of the designs were not regard this problem. In order to serve these runs longitudinal and transverse opening beam (BLTO) may apply with provide many benefits like aesthetic aspects, reductions in materials quantities and self-weight, saving cost and effort of using services covers, and protect and insulate the runs from environmental damages [1,2]. The requirement of structural improvement has been imposed on increasing reinforcement quantities, and using complex framework, all of that lead to increase the difficulty of compaction. Modern application of self compacting concrete (SCC) meets the above requirements when utilize to produce high strength concrete with more benefits as reduce member dimensions, ultimate durability, much economic, and less pouring time as comparing with traditional vibrated concrete [3,4]. High strength self compacting concrete (HS-SCC) should be satisfied the codes of EFNARC to evaluate fresh condition [5], American standards to ensure the compressive strength exceed 42MPa for cylindrical samples [6-8], besides British and European standards used to actualize strength exceeded 50MPa for cubic samples [9,10] at age of 28 days.

In 2014, Alshimmeri and Al-Maliki tested six simply supported RC hollow beams under partial uniformly distributed load. The results show when hollow ratio increased by about (7.4%-14.8%), the deflection increase about (71.6%-75.5), respectively, and the load capacity decrease by about (37.14%-58.33%), respectively. Ductility is increased in all cases when hollow ratio decreased by about 50% or shear steel reinforcement [11]. Hafiz et al. (2014) studied the effects of web openings on the behavior of RC beams without special reinforcement around opening zone. With circular web openings of diameter less than (44%) of beam depth (D) had exerted no effect on the ultimate load capacity; nevertheless, circular openings with a diameter greater than (44%) of (D) reduced the ultimate load capacity by at least (34.29%). Their team also realized that the circular opening exhibits more strength than the equivalent square opening, with a variation of (9.58%) in ultimate load [12].

2. Importance of Study

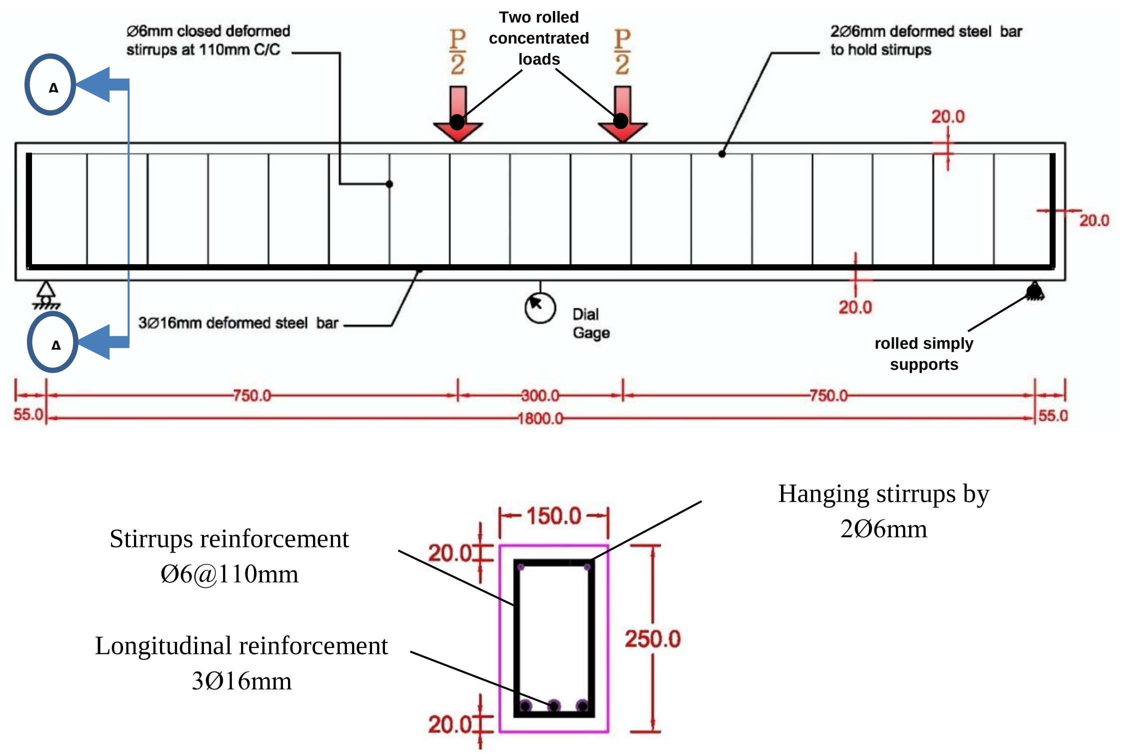
The objective of this study was to investigate and evaluate the optimum hollow zone in beam section, also to show effect of different web-opening locations in RC beams with longitudinal and transverse opening (BLTO) on load carrying capacity, deflection, crack pattern and failure mode.

3. Methodology

Firstly, the experimental investigation involves achieve high strength self-compacting concrete with satisfied properties and use the same proportion to cast the beams as well as the control specimens. After 38 days from casting, curing and preparing, all beams and concrete samples had been tested according to related procedure.

4. Experimental Program

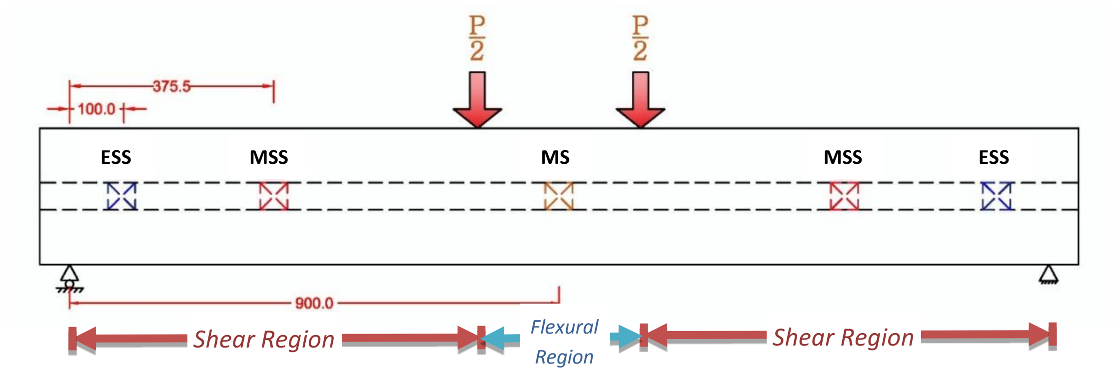
The experimental program consisted of cast and examines eight HS-SCC beams in two groups. The first group had two hollow core RC beams in position at mid and bottom sections as well as the solid one. This group used to elect the optimum hollow core section intention to unify the sections of next group. The second group had five beams which identical in everything but positions of web opening which were arranged symmetrically, without any special reinforcement around the openings. All RC beams had similarity in dimensions, reinforcement, concrete type, and hole dimensions. The dimensions of beams were (length 1910 x height 250x width 150) mm and properties are shown in Fig.1 to Fig 3). The beams were tested by simply supported over clear span of (1800mm). The experimental program was performed in the Structural Laboratory of the Civil Engineering Department Mustansiriyah University. A schematic representation and photographs of the mold, testing setup and instrumentation are shown in Fig. 1 to Fig. 8.



Section (A-A)

All dimensions are in (mm)

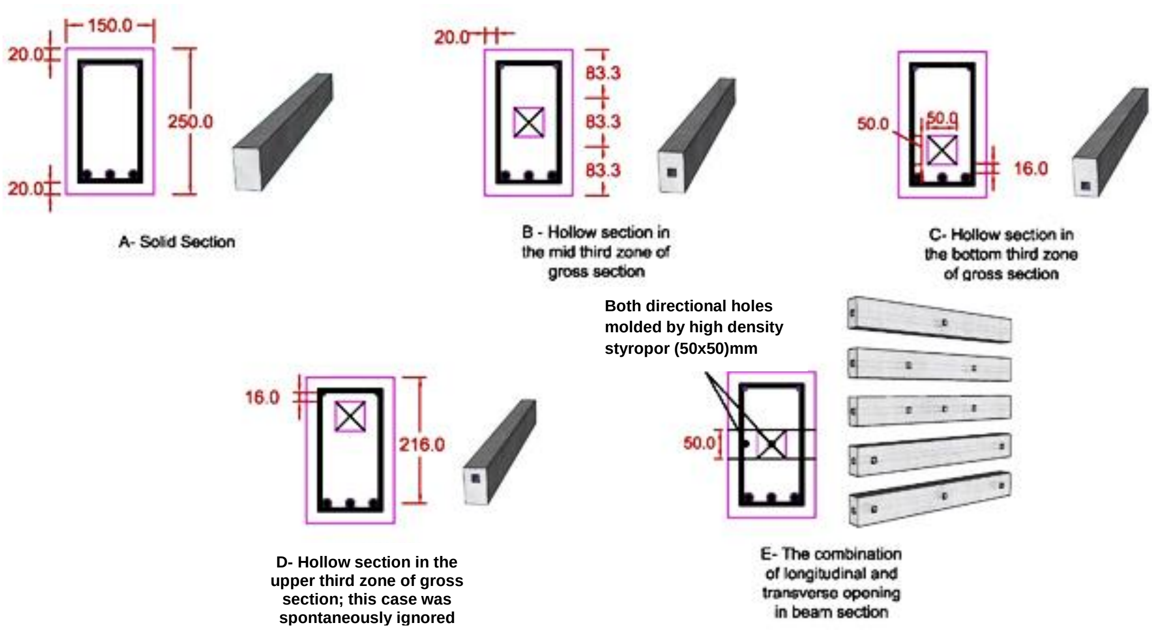
Fig (1): Setup of Beams with Reinforcement Arrangement.



MS: *the web opening located at mid-span of RC Beam.*
MSS: *the web openings located at mid-shear span of RC Beam.*
ESS: *the web openings placed at edge shear span of RC Beam.*

All dimensions are in (mm)

Fig (2): Location of Openings



All dimensions are in (mm)

Fig (3): Model Sections with Locations of Hollow Core and Web Opening

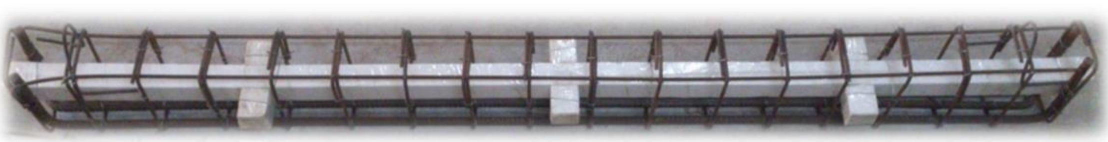


Fig (4): Reinforcing Steel Cage Connected with Opening Molds.

Fig (5): Preparing the Opening Mold (Top View)

Fig (6): Reinforcing Steel Cages of 2-Referential Prototypes to Choose the Optimum Zone of Hollow Core Section.

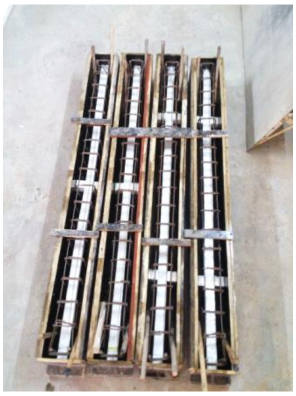


Fig (7): Mobilizing of BLTO Prototypes before Casting by Fastening Reinforcement Cages and Styropor with Temporary Covers Inside the Plywood Molds.

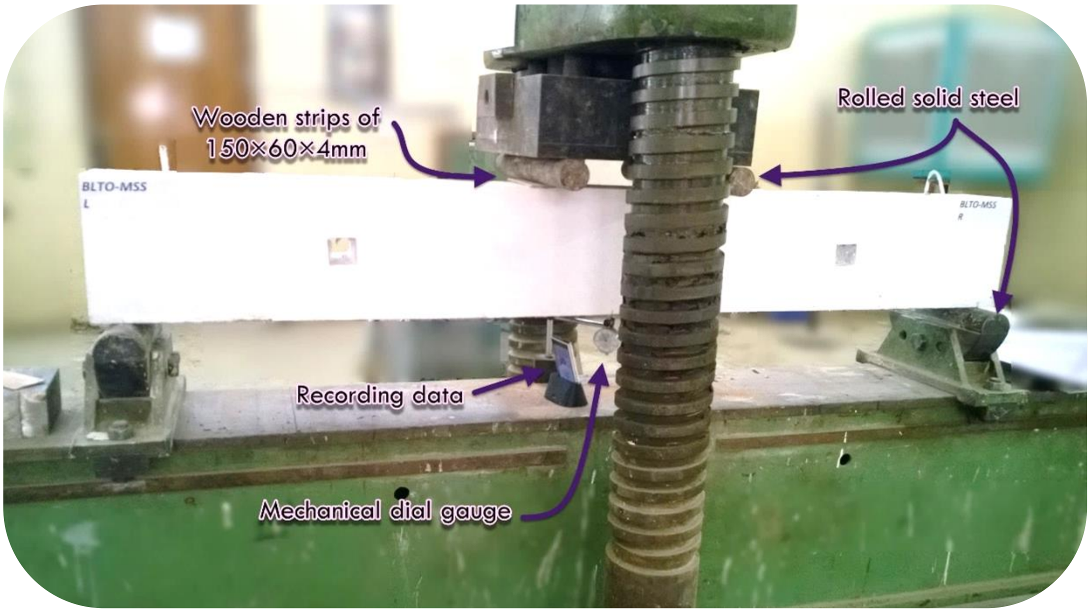


Fig (8): Beams Setup on Universal Testing Machine.

After 38 days of casting, curing and preparing, each model had placed in position over rolled supports of universal testing machine with capacity of 3000kN.The load of testing machine applied into two concentrated points were applied at the top face of beam as shown in Fig .8. The load was increased gradually at increments of (10kN). The deflections were measured at center of models per each loading stage using mechanical dial gauge accuracy of (0.01). Test process was carried out till final failure. The recorded data included failure mode and crack patterns.

4.1 Material Properties

Ordinary Portland Cement (ASTM Type I) was used for HS-SCC mixtures. Natural sand of 2.36 mm maximum size was used as fine aggregate. Crushed gravel with maximum size of 12.5mm. In addition to limestone Powder (L.S.P) which had been used as filler for concrete production to enhance fresh condition of mixture.

polycarboxylates based high range water reducing admixture (superplasticizer) (density =1.09 kg/l at 20 °C). Deformed steel bars of nominal diameter of 6mm for closed ties and 16 mm for main reinforcement were used in the tested models with yield stress Fy about (416, 523)MPa ,respectively, and ultimate strength Fu about (660, 625)MPa, respectively.

4.2 Mixing Procedure for High Strength Self-Compacting Concrete (HS-SCC)

The mixing procedure and mix ratio are the important factors to obtain the required workability and homogeneity. Table (1) illustrates reliable ratio of HS-SCC that achieved based on several trial mixes. This study followed specific procedure which outlined by Emborg[13] and modified by Al-Jabri[14].

Table (1): Details of the Successful Trial Mix.

Material		Density* (Kg/m^3)	Per 1 m^3 Concrete: Weight (Kg)	Per 1 m^3 Concrete: Volume (m^3)	Volumetric Ratio per 1m^3 Cement
Cement		3150	550	0.175	1
Water		1000	154	0.154	0.882
Fine aggregate		2610	830	0.32	1.83
Coarse aggregate		2580	766	0.291	1.664
Limestone powder		2400	50	0.021	0.12
S.P (Superplasticizer)		1100	×20Lr 1.1=22kg	0.02	0.115
Total powder		-	600	0.196	1.12
W/Binder ratio by weight	Without S.P WC †	28%			
	With S.P WC ††	30.6%			
W/Powder ratio by weight	Without S.P WC †	25.7%			
	With S.P WC †	28%			

* This values had been obtained by laboratory practice. † If water content of superplasticizer is not considering. Otherwise, †† WC represent ratio of 65% water content by weight of S.P. Binder=Cement. Powder= Cement+ Limestone powder.

5. Results and Discussions

Fresh and harden condition of high strength self-compacting concrete had showen in Tables (2) and (3). Examination results for each beam are reported. Table (4) shows the measured cracking loads, ultimate loads, and vertical central deflection of beams of all the beams. The comparisons between results are shown in Fig. 9 and Fig.10 which were demonstrating the crack patterns of all models.

5.1 Control Specimens Results

The fresh properties of (HS-SCC) had been practically tested according to EFNARC2002 which had complied with this code limitation as shown in Table (2). The harden condition data had examined experimentally and theoretically according to standards as shown in Table (3). The average compressive strength of concrete are (62.4 and 53) MPa according to (BS. 1881: Part 116:1983)[9] and (ASTM C39/C39M-01)[6], respectively, and the average tensile strength is (3.4) MPa based on (ASTM C496/C 496M–04)[15].

Table (2): Results of Properties of Fresh HS-SCC.

SCC characteristic	Test method	HS-SCC Mixture	Accepted Limits of EFNARC2002[5]
Flowability (filling ability)	Slump flow by Abrams cone, D (mm)	697	650 -800
Viscosity and Filling ability	T_{50cm} slump flow (sec) V-funnel time, T_V (sec)	6 11.4	3-7† 6-12
Passing ability (confined flowability)	L-box, BR%	0.81	0.8-1.0

† is acceptable range for civil engineering applications by EFNARC2002 [5].

Table (3): Tests Results of Mechanical Properties for Hardened HS-SCC.

Symbol of Beam Sampling	$f_{cu(MPa)}$	$f'_c{}^{*}$ (MPa)	f_{sp}^{*} (MPa)		f_r^{*} (MPa)		E_c^{*} (GPa)	
				Predicated		Predicated		Predicated
	Tested according to (BS. 1881: Part 116:1983[9]	Tested by ASTM C39/C39M-01[6]	Tested according to ASTM C 496/C 496M – 04[15]	By ACI 318M-11[16]	By test according to ASTM C293-02[17]	By ACI-363R-92[7]	By experimental job with ASTM-C469 [18]	By ACI-363R-92[7]
R-S-SEC., R-HM-SEC., and R-HB-SEC.	57.20	48.00	3.10	4.24	11.25	6.51	31.24	32.01
BLTO of MSS and MS	65.00	55.34	3.45	4.51	14.60	7.00	34.22	33.67
BLTO of ESS-MS and ESS	66.40	56.60	3.66	4.56	15.75	7.07	36.37	33.95
BLTO of MSS-MS	61.00	51.85	3.40	4.37	13.50	6.77	32.90	32.83

* Each value was an average of three or more test results of control specimens.

5.2 General Behavior of Tested Beams

After overstepping the elastic stage manner in loading progress. All beams had been observed that the first crack was developed at tension zone which had maximum moment (flexural zone). Non-linear behavior stage began as the load was further increased, the cracks propagated with climbing the neutral axis. Foregoing, the flexural cracks developed through a vertical direction; while, inclined cracks began to appear with developed in more area of both side of beams. The tensile stresses which provided by main steel bars had function of redistribute the concentrated stresses from cracks to another concrete part. The cracks had stopped when no distributed stresses possible. At position near loading area with load level close to final failure, one of cracks began to enlarge and extend faster with maximum width. The section design in this study considers as under reinforcement ($\rho=0.5\rho$) for all RC beams. Therefore, the bars yielding before beams collapse. Accordingly, ductility behavior was predicted in these beams. That confirmed by the failure mode types and cracks pattern between all models. Table (4) and Fig.9 to Fig.11 show that both groups had semi-identical in cracks pattern and failure mode which is flexural failure by crushing top concrete cover at flexural region, and flexural-shear failure comes by combined action of bending and shear. Also, the similarity may have confirmed by the behavior of load-central deflection curves of all beams which had approached action because of small opening behavior.

Table (4): Tests Results of Tested HS-SCC Beams.

Group Description	Beam Designation	Load Characteristics (KN)		Maximum Deflection (mm) at central	$\frac{Pcr}{Pu}$ %	Mode of Failure
		First crack	Ultimate			
Group No.1: Referential Beams	R-S-SEC.	47.5	227.5	8.4	20.88%	Flexural
	R-HM-SEC.	32.5	223	10.05	14.57%	Flexural
	R-HB-SEC.	27.5	195.5	11.6	14.07%	Flexural
Group No.2: RC BLTO	MS	27.5	207.5	12.44	13.25%	Flexural
	MSS-MS	25	182.5	11.54	13.70%	(flexural-shear) Combination
	MSS	31.5	215	15.11	14.65%	Flexural
	ESS	22.5	185	13.54	12.16%	Flexural
	ESS-MS	25	177.5	15.63	14.08%	Combination

R-S-SEC.: referential solid section beam
R-HM-SEC.: referential beam with hollow core in mid-section
R-HB-SEC.: referential beam with hollow core in bottom-section
BLTO: beam with longitudinal and transverse opening.
MS: the web opening located at mid-span of RC Beam.
MSS: the web openings located at mid-shear span of RC Beam.
ESS: the web openings placed at edge shear span of RC Beam.

**The numbers shown beside the cracks indicated the load when the crack had reached that position.*

Fig (9): Cracks Formation for Group No.1 (Referential Beams).

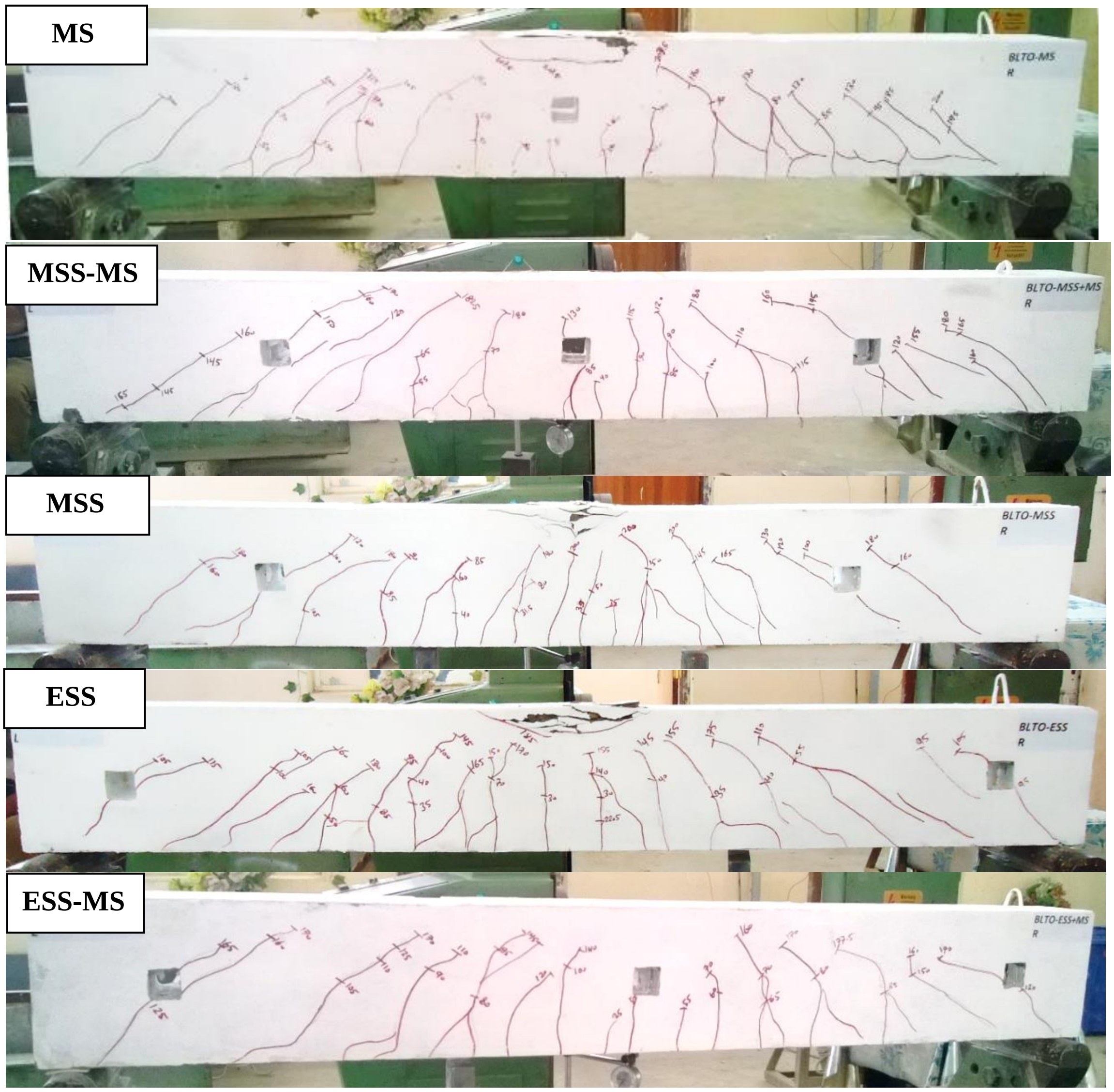


Fig (10): Cracks Formation for Group No.2 (Reinforced HS-SCC BLTOs).

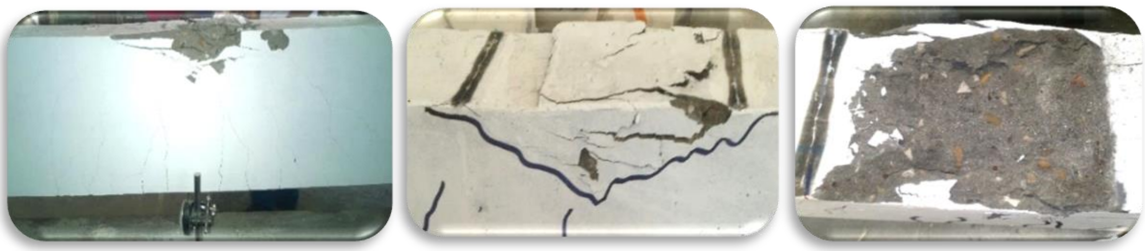
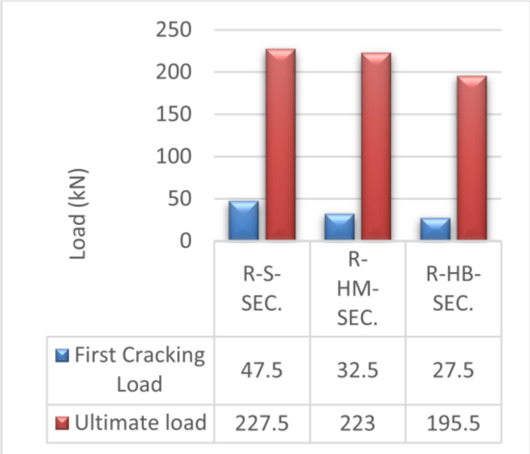


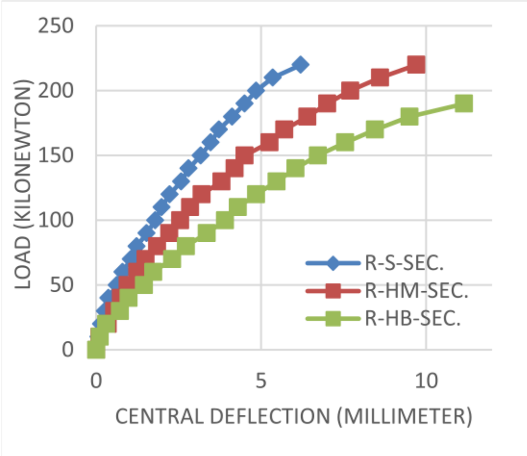
Fig (11): Concrete Crushing in Upper Layer of Some Beams

5.3 Effect of Hollow Core Position in RC Beam Section

Table (4) and Fig. 9,12 and Fig. 13 show results of first group. The first crack was observed at loading level by about (21%, 14.5%, and 14.1%), respectively of ultimate load for (R-S-Sec., R-HM-Sec. and R-HB-Sec.). Fig .12 indicates that the presence of hollow core led to decrease load resistance which also had lower value when hollow core approaches to tension or compression zone. Thus, the beam (R-HM-Sec.) was preferred to produce BLTO models under unified hollow core sections. Fig .13 defines the central load-central deflection curves which began in approaching from each other, then divergence according to hollow core presence and position in beam section. The extra evident of election (R-HM-Sec.) as optimum hollow section was behavior of approaching its curve to solid beam, as well as, higher ultimate load value with less deflection than hollow core in bottom of beam section for same load level, as shown in Table (5).



Fig(12): First Cracking and Ultimate Loads of Group No.1 (Referential Beams)



Fig(13): Load-Central Deflection Relationship for Group No.1.

Table (5): Deflections per Specific Loads.

Group No.	Beam Designation	Ultimate Load (kN)	Maximum Central Deflection (mm)	Specific Load (kN)	Central Deflection (mm)
1	R-S-SEC.	227.5	8.65	190	5.66
	R-HM-SEC.	223	10.4	190	7
	R-HB-SEC.	195.5	11.65	190	11.15
2	MS	207.5	12.44	175	10.05
	MSS-MS	182.5	11.54	175	10.74
	MSS	215	15.11	175	9.75
	ESS	185	13.54	175	11.51
	ESS-MS	177.5	15.63	175	15.63

5.4 Location Effect of Web Opening

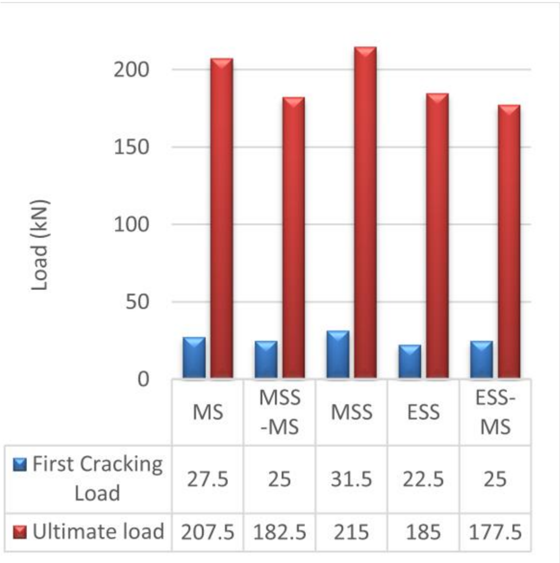
Table (4) and Figs (10, 14 and 15) show results of second group. The first crack was noticed at loading level ranging between about (12.2%-14.7%) of ultimate load which reduced than mid hollow core beam between about (3.6%-20.4%) and about (5.5%-22%) from that of the solid beam.

That may due to the presence of web opening and/or hollow core in beams, also, the verification in decreasing refers to the opening occupied a considerable portion of concrete to strength and the influence for bending and shear.

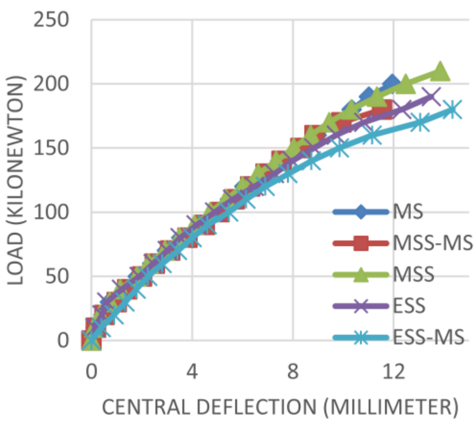
The smallest strength value of BLTO models founded in (ES-MS) which is hollow core beam with web opening which located near supports and central beam span. While, the highest strength value registered in hollow core beam with web opening which located in mid shear span (MSS). Therefore, (MSS) considers as optimum BLTO between all beams of second group.

Fig.15 illustrated the difference between load -central deflection curves of BLTO models especially after linear parts. The central deflection of BLTO (ESS-MS) had more magnitudes than other beams at certain load level that may due to the response of opening locations which were near the effect of flexural and shear, as shown in Table (5).

The openings in this research can be classified as small openings according to Alnuaami [13] and Mansure [14]. After final failure of beam, these openings allowed to convergence failure mode between BLTO models.



Fig(14): First Cracking and Ultimate Loads for RC BLTO of Group No.2.



Fig(15): Load-Central Deflection Relationship for Group No.2.

5.5 Comparison Between Web Opening and Its Combination

By comparing with less voiding beams, the inclusion of openings into the beams causes an increase in the deflection values at specified stages of loading and a reduction in their capability to resist deformation, as shown in Table (5).

This may be due to that the presence of opening was caused to decrease the capacity of moment resistance of such sections.

It can be noticed from Fig (10), the existence of multi-opening includes central opening was led to absence of concrete crushing such as beams of (MSS-MS) and (ESS-MS).

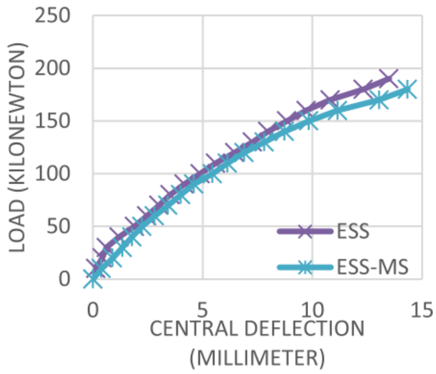
The remainder of the BLTO combination had conducing to crush the top concrete cover in flexural region at last stage of loading history.

While, the second case was considered as (flexural failure) by crushing the top concrete cover at the last stage of loading. That because of the beams designed to be under-reinforced as mentioned before.

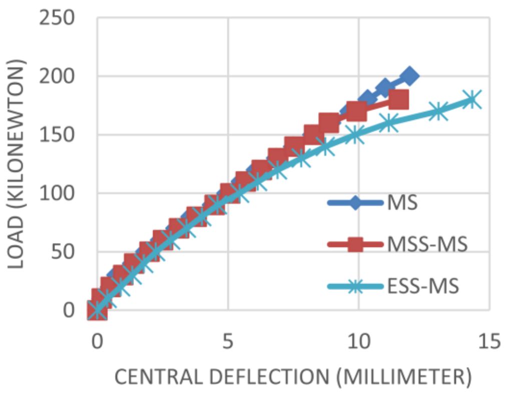
Table (6) and Fig (14 to 19), proclaimed the difference amid beams of the second group and describe the load-central deflection relationship for harmonical opening locations.

Table (6): Comparison between Web Opening and its Combination.

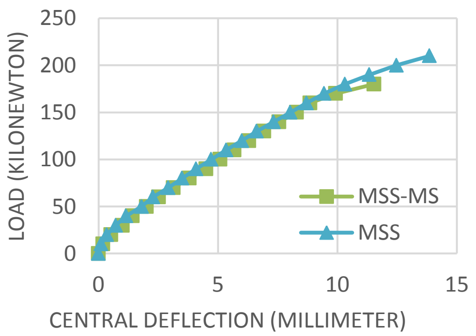
Web Opening	Combination	Reduction Ratio	Combination	Reduction Ratio
ESS	ESS-MS	4.05%		
MS	MSS-MS	12.05%	ESS-MS	14.46%
MSS	MSS-MS	15.12%		
MSS	MS	3.49%	ESS	13.95%



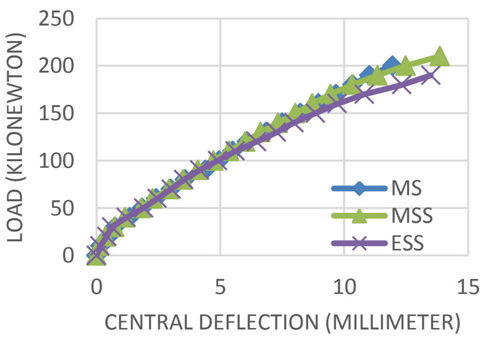
Fig(16): Load-Central Deflection Relationship for BLTO which had Openings in Edges and Their Combinations with Central of Beam.



Fig(17): Load-Central Deflection Relationship BLTO which had Opening in Central and Its Combinations with Mid and Edges Shear Span of Beam.



Fig(18): Load- Central Deflection Relationship for BLTO which had Openings in Mid-Shear Span and Its Combinations with Central of Beam.



Fig(19): Load- Central Deflection Relationship for BLTO which had Openings in different Regions in Beam.

6. Conclusions

1. By using local material with super plasticizer through trial mixes, high strength self-compacting concrete can be produced with acceptance properties.
2. The results of first crack and ultimate load evident that the resistance of beam was decreased at presence of hollow core. Also, more depreciation if hollow core founded in tension zone or compression zone.
3. The hollow core in mid-beam section was more approaching to solid beam section. Therefore, hollow core in mid-beam section consider optimum hollow core section and preferred to unify the hollow section and produce BLTO models.
4. The results indicated a reduction in hollow beam strength with greater deflections in case of web opening presence without any special reinforcement around it.
5. Due to recorded load capacity, a reduction was produced by hollow core position at mid and bottom section by about (2%-14%), respectively, with comparing by solid section. While, BLTO types indicated decrement up to (20.4%) by compared with hollow beam without opening and to (22%) by compared with solid beam.
6. Any extra void in beam let the deflection had more increase; thus, as respect to solid beam, the deflection per unified load was increase about (23.67 to 346.5 %) according to existence and position of hollow core and web openings.
7. The smallest values for BLTOs capacity registered in case of web openings were in mid-span, as well as, near supports in the same beam due to the critical position. As opposed to BLTO situation that included openings in mid-shear span which indicated highest load capacity and can be regarded as optimum case between all the BLTO models.
8. The recorded mode of failure was contained two main types, flexural failure by compressive concrete cover crushing and flexural-shear (combination) failure.
9. The first visible crack was appearing in position near flexural zone for all beams.
10. Although, small openings may consider weakness sources in RC beam, but the failure plane not always passes through the opening.
11. It can be noticed that the strengthened BLTO curves have clarified the nearly similar behavior in load- deflection harmony. That comes up with the semi-identical failure mode and crack formations for these beams due to priority of cracks that passed into BLTO body.

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