Journal of Engineering and Sustainable Development
Vol. 22, No.05, September 2018
ISSN 2520-0917
https://doi.org/10.31272/jeasd.2018.5.5

Structural Behavior of HS-SC Reinforced Concrete Beams with Longitudinal and Transverse Openings Strengthened with CFRP Laminates

Dr. Yaarub Gatia Abtan[1], * Hussain Dhafer AbdulJabbar[2]

1) Assist Prof., Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.
2) M.Sc., Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.

Abstract: Service runs had produced several shortcomings when congested in one place. So, using longitudinal and transverse opening in beams (BLTO) was creative solution for the purpose of serve those runs with other benefits, especially when utilized high strength self-compacting concrete (HS-SCC). To control cracks in web opening regions which lead to possible leakage, carbon fiber reinforced polymer (CFRP) laminates was significant strengthening system to realize that purpose. This study examined the behavior of thirteen reinforced concrete (RC) beams. These beams were involved into three groups. All beams were identical in dimensions, reinforcement, concrete type, and hole dimensions. The evaluation is used to elect the optimum hollow core section, position effect of web openings with fixed hollow core section, and effect of strengthened web openings. 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 web-opening) and about (22%) by compared with solid beam. The optimum BLTO is 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. Presence of CFRP system in same BLTO copy had enhanced beam resistance by about (29%) and prevents cracks to reach in web opening or with minimum hairline cracks without delaminating problem. The registered failure mode of all beams was contained two main type, suddenly flexural failure in compressive zone by concrete cover crushing and flexural-shear failure. Additionally, local failure occurred at central CFRP strips by ripping-off concrete cover through the edges of it.

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

السلوك الإنشائي للعتبات الخرسانية المسلحة عالية المقاومة ذاتية الرص ذات الفتحات الطولية والجانبية المقواة بصفائح ألياف الكربون بالبوليمرية

الخلاصة: تؤدي التمريرات الخدمية الى عدة مشاكل عندما تلتقي في مكان واحد.لذا استخدام الفتحات الطولية والجانبية في العتبات (BLTO) يعتبر حل ابداعي لغرض خدمة تلك التمريرات مع المنافع الأخرى، وخاصةً عند تطبيق الخرسانة عالية المقاومة(HS-SCC). لأجل كبح التشققات في مناطق فتحات الوترة التي تؤدي الى إحتمال حدوث تسريب، صفائح صفائح ألياف الكربون بالبوليمرية (CFRP) من أنظمة التقوية المهمة لتحقيق ذلك الهدف. تستقصي هذه الدراسة سلوك ثلاثة عشر عتبة خرسانية مسلحة (RC). تنطوي هذه العتبات تحت ثلاثة مجاميع. كافة العتبات متماثلة في الابعاد، التسليح، نوع الخرسانة وأبعاد الفجوات. إستُخدم التقييم لانتخاب المقطع المجوف النواة، تأثير مواقع فتحات الوترة مع ثبوت المقطع المجوف النواة، وتأثير فتحات الوترة المقواة. على خلفية قابلية التحمل المسجلة، أنتج

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*Corresponding Author en_hdaa@yahoo.com

تجويف النواة الواقع في منتصف وأسفل المقطع انخفاضاً بحوالي (2 الى 14) %، 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). ان وجود نظام الـ(CFRP) في نفس نموذج الـ(BLTO) قد حسن من مقاومة العتبة بنحو (29 %) مع الحُؤول دون وصول الشقوق الى فتحة الوترة أو بالحد الأدنى من الشقوق الشعرية وبدون مشكلة انفصال الصفائح. أشارت أنواع الـ(BLTO) الى بيانات تحميل مختلفة تبعاً لمواقع فتحات الوترة. بلغ الانخفاض في وجود الفتحات حوالي (7 الى 20.4) % من خلال المقارنة مع العتبة المجوفة (التي لاتتضمن تجاويف عرضية) وحوالي (22%) 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. بالإضافة لذلك، حدث فشل موضعي في قطع الـ(CFRP) الوسطية من خلال تمزيق الغطاء الخرساني بواسطة أطرافها.

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. 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 dead space, self-weight and materials quantities; saving cost and effort of using services covers; and protect with 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]. The provision of openings in both direction of member leads to reduce its capacity. Accordingly, strengthening or updating system may demand for enhancing member resistance against shear, flexural, torsion stresses [5,6]. Carbon fiber reinforced polymer (CFRP) is one of those efficient systems in same context which it utilized in numerous researches in order to strengthening RC beams, columns, and slabs [7].

In 2003, Abdalla et.al.[8] investigated CFRP strengthening for web openings of RC beam to control cracking in opening regions due to applied load. The test results concluded that the opening existing led to reduced ultimate load with more ultimate deflection. While in case of strengthened openings by CFRP strips, the significant of its effect was in ultimate deflection.

In 2013, AL-Maliki[9] studied the influence of carbon fiber reinforced polymer laminates which retrofitting on five RC hollow core deep beams (with single or double or sides strips). The investigation was also included the effect of hollow (shapes and materials) as (Ø50mm circular PVC and 50x50mm square steel). It was indicated from test results that due hollow provision the strength capacity was decreased and an increased in deflection and strain by compared with solid section. The enhancement of CFRP laminate was significant in loading capacity and less deflection for same applied load. Also, the strength had more increased in retrofit with CFRP strip against horizontal shear. When retrofit hollow section by utilizing double CFRP strips the result gives equivalent strength capacity or more than solid section.

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 with/without strengthened by externally bonded with carbon fiber reinforced polymer (CFRP) laminates in RC beams with longitudinal and transverse opening (BLTO).

Finally, examine the efficiency of anchorage of the CFRP strips that strengthen the opening in shear zone without any opening cracks or CFRP delaminating problem.

3. Methodology

Firstly, the experimental investigation involves achieving 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 RC beams and concrete samples had been tested according related procedure.

4. Experimental Program

The experimental program consisted of casting and testing thirteen RC beams divided in three groups after achieve the desired mix of HS-SCC by using local material with superplasticizer in numerous trial mixes. The first group had two hollow core RC beams where the hollow 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 other two groups had five RC beams for each group but with/without CFRP strengthening system. These beams were identical in geometrics and reinforcement details but had different 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 holes dimensions. The dimensions of beams were (length 1910 x height 250x width 150) mm and properties are shown in Figs (1 to 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 at Faculty of Engineering of Al-Mustansiriyah University.

A schematic representation and photographs of the molds, testing setup and instrumentation are shown in Figs. (1 to 8).

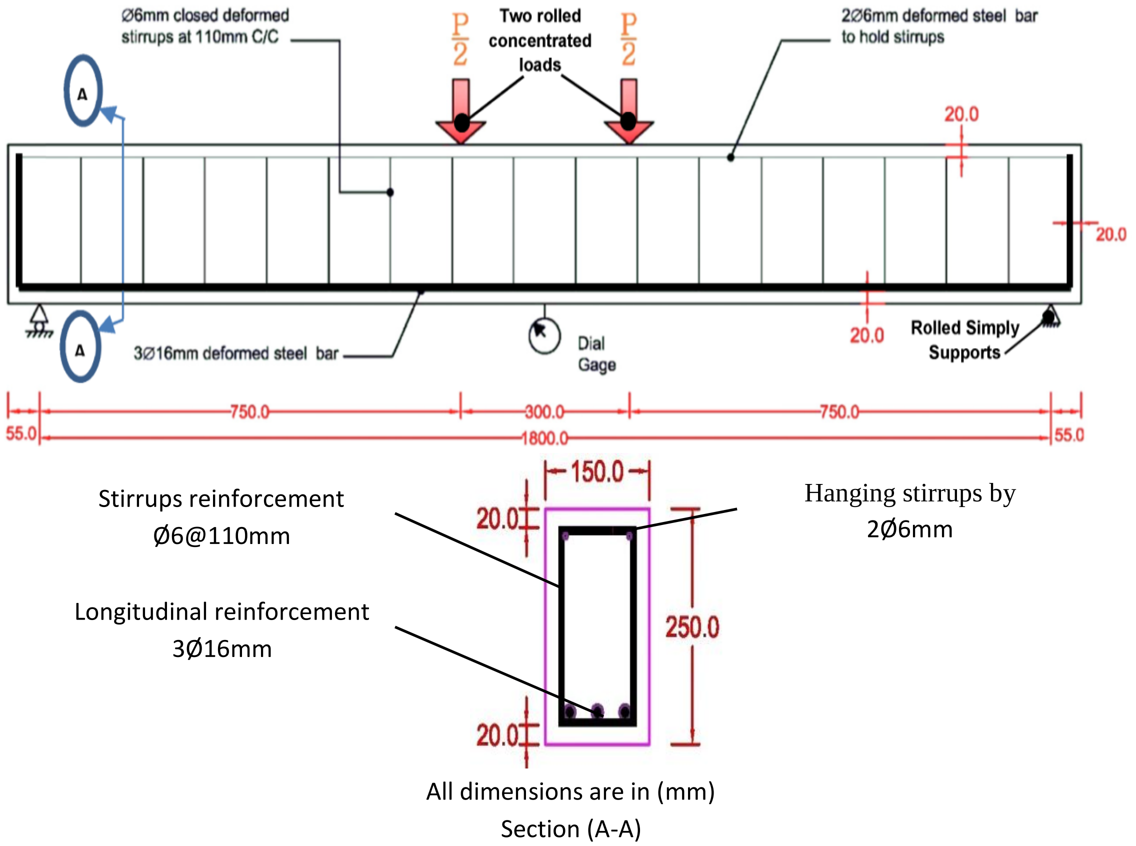
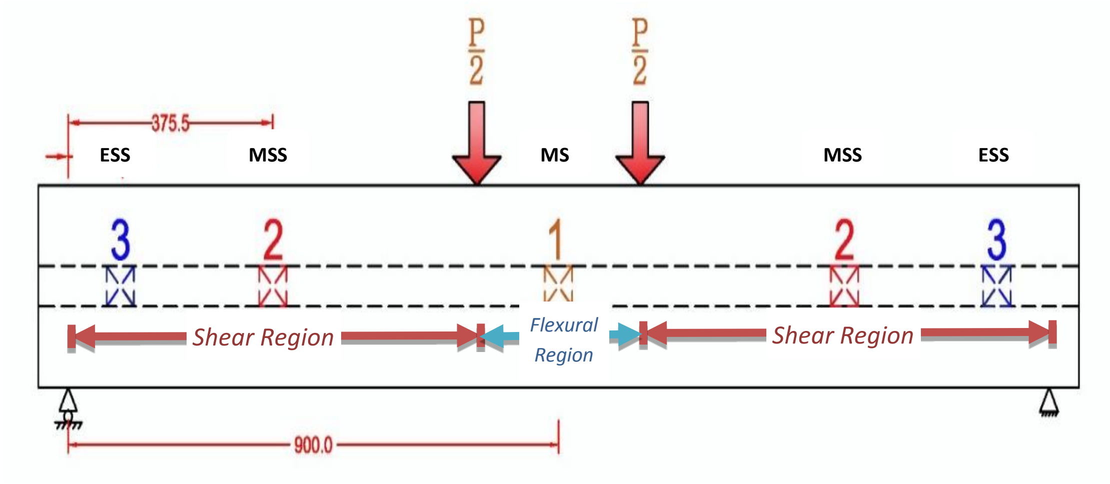
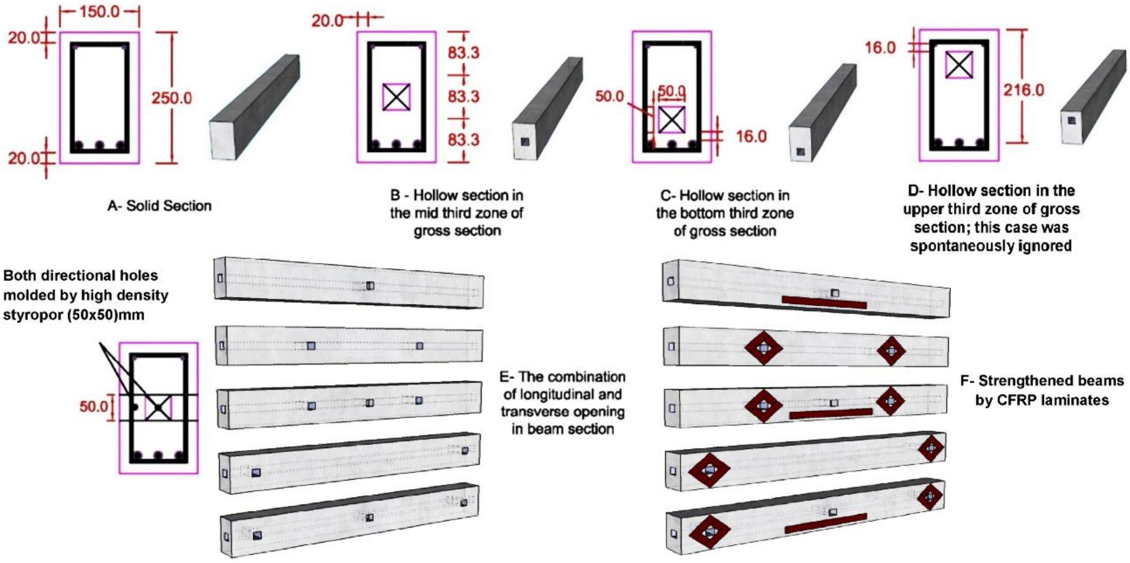


Fig (1): Setup of Beams with Reinforcement Arrangement.



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): Details of Model Sections and Locations of Web Opening with Strengthening Systems

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

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

Fig (6): Hollow Core Location (Different Zone) in Reinforcing Steel Cages.

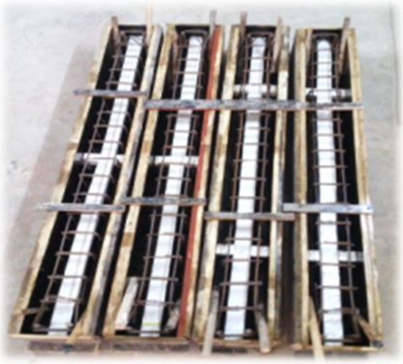


Fig (7): Molds Layout before Casting for BLTO Models

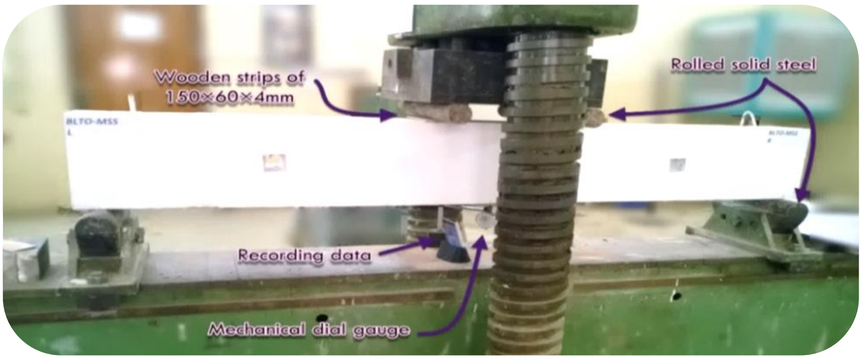


Fig (8): Beams Setup under Testing Machine.

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 stress Fu about (660, 625)MPa, respectively. All those test were carried out at the Faculty of Engineering, Al-Mustansiriayah University.

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

The mixing procedure and mix ratio are important factors to obtain the required workability and homogeneity. Tables (1) illustrate reliable ratio of HS-SCC that achieved based on several trial mixes.

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

Material		Density* (Kg/m^3)	Per 1 m^3 Concrete		Volumetric Ratio per 1m^3 Cement
			Weight (Kg)	Volume (m^3)	
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.

4.3 CFRP Strengthening Procedure

After 28 days of casting and curing, all beams had been preparing before testing process by white pigment and testing marks except the third group. In regard to BLTO with CFRP strengthening, each BLTO had additive job than other that externally prepared by CFRP system according to web-opening regions. Tables (2 and 3) show materials properties of CFRP system.

The strengthening procedure was performed accordance to ACI 440.2R-08[12] which can be clarified by Fig(9). The first step CFRP plates should be clean and divide into proper measurements, Fig(9-A). Also, for making the concrete surfaces more bonding with the adhesive, it must be free of dust and notches by using grinding machine, Fig(9-B). Because of effect of hot temperatures, the two components of Sikadur-30LP were cooled by refrigerator but without freezing.

The mixing of two components was processed by a spindle attached to a slow speed electric drill for about (max. 300 rpm at least 3 minutes) until the material becomes smooth in consistency with a uniform grey color, Fig(9-C and D). The strengthening scheme was to overspread two types of openings in each side. By spreading the epoxy mixer to specific area of the beam for each side RC beams, Fig(9-E). Central opening was strengthened by 60cm long of CFRP strips attached to tensional faces by each side of beam. While, the other openings were stripped by 45° with priority of settled the strips, Fig(9-F). The prefabricated CFRP strips may arrange with pressuring accordance with CFRP configuration proposal. Then, scraping off excess paste from the edge of CFRP strips, Fig(9-G). Eventually, Fig(9-H) showed the final form for strengthened BLTOs after white colored. Notable, the resin must be left in adequate time (one week in this case) to obtain more strength to provide bonding strength between concrete and laminate.

Table (2): Characteristics of CFRP Laminates [10]

Trade Mark		Sika CarboDur S512
Fiber Type		High strength carbon fibers
Geometrical Data of Cross Section	Width (mm)	50
	Thickness (mm)	1.2
	Length (m)	up to 50 m
Tensile E-Modulus (GPa)		165
Tensile Strength (MPa)		3100
Strain at Break (%)		>1.7%

Table (3): Characteristics of Adhesive [11]

Trade Mark		Sikadur® -30 LP
Adhesive Type		Impregnating Pasty epoxy resin
Geometrical Data of Cross Section	Width (mm)	50
	Maximum Layer Thickness (mm)	30
	layer Thickness in This Work (mm)	1-2.2
	Length (m)	Up to strips length
Mixing Ratio		Part A (resin): part B (hardener) = 3: 1 by weight or volume.
Tensile Elastic Modulus (N/mm2)		10000 (at +25°C)
Tensile Strength after 7 Days		(> 25 -42) Mpa at curing temperature equal to (+25°-+55°C)

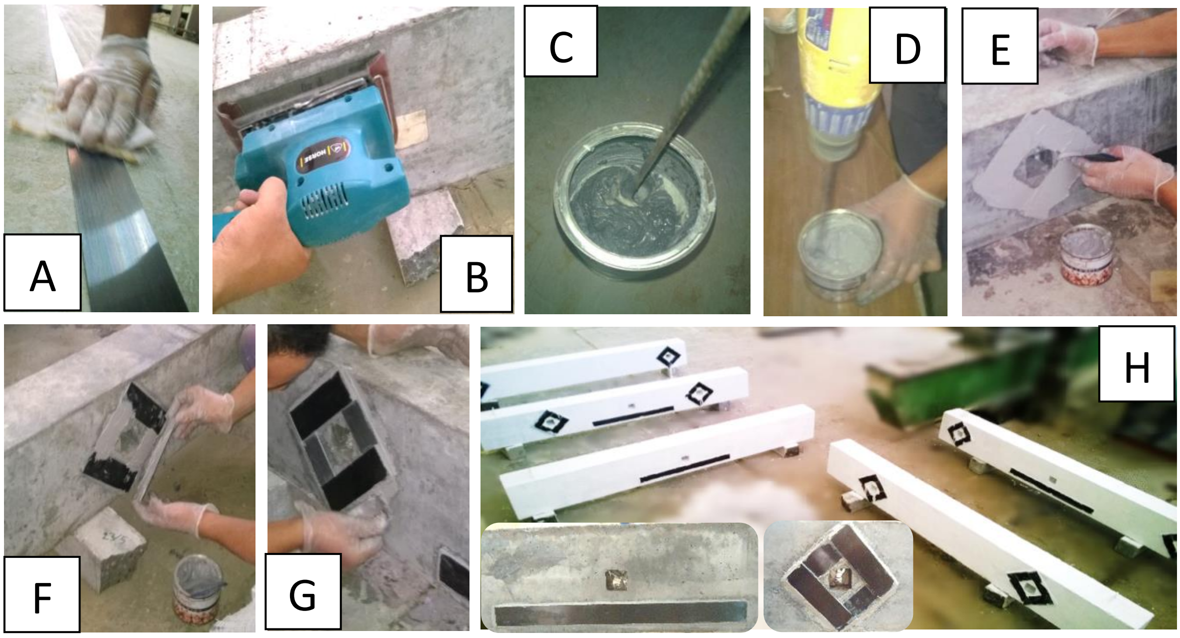


Fig (9): BLTOs Strengthened by CFRP Strips at Web Opening

After 38 days from casting, curing and mobilization, each model had been 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 Figs (1 and 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 on till final failure. The recorded data included failure mode and crack patterns.

5. Results and Discussions

Fresh and harden condition of high strength self compacting concrete had showed in Tables (4) and (5). Examination results for each model are reported. Table (6) shows the measured cracking loads, ultimate loads, and vertical central deflection of all models. The comparison between results is shown in Figs (10 to 12) which were demonstrate the crack patterns of all models.

Table (4): Results of Properties of Fresh HS-SCC.

SCC characteristic	Test method	HS-SCC mixture	Accepted limits of EFNARC2002[13]
Flowability (filling ability)	Slump flow by Abrams cone, D (mm)	697	650 -800
Viscosity and Filling ability	T_{50cm} slump flow (sec)	6	3-7*
	V-funnel time, T_V (sec)	11.4	6-12
Passing ability (confined flowability)	L-box, BR%	0.81	0.8-1.0

* is acceptable range for civil engineering applications by EFNARC2002 [13].

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].

5.2 General Behavior of Tested models

After overstepping the elastic stage manner in loading progress; all beams had been observed first crack which was developed at tension zone near the loading area at maximum moment region (flexural zone) or at near edge of center CFRP laminate. Non-linear behavior stage began as the load was further increased, the cracks propagates with climbing the neutral axis. Foregoing, the flexural cracks were 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 ($\rho=0.5\rho_b$) for all RC beams; therefore, the bars yielding before ultimate failure.

Table (5): 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^{*} $_{(GPa)}$	
	Tested according to (BS. 1881: Part 116:1983[14]	Tested by ASTM C39/C39M-01[15]	Tested according to ASTM C 496/C 496M – 04[16]	Predicated By ACI 318M-11[17]	By test according to ASTM C293-02[18]	Predicated By ACI-363R-92[19]	By experimental job with ASTM-C469[20]	Predicated By ACI-363R-92[19]
R-S-SEC. R-HM-SEC. R-HB-SEC.	57.20	48.00	3.10	4.24	11.25	6.51	31.24	32.01
Duplicated BLTO of MSS and MS	65.00	55.34	3.45	4.51	14.60	7.00	34.22	33.67
Duplicated BLTO of ESS-MS and ESS	66.40	56.60	3.66	4.56	15.75	7.07	36.37	33.95
Duplicated 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 specimens.

Accordingly, ductility behavior was predicted in these beams. That confirmed by the failure mode types and cracks pattern between all models.

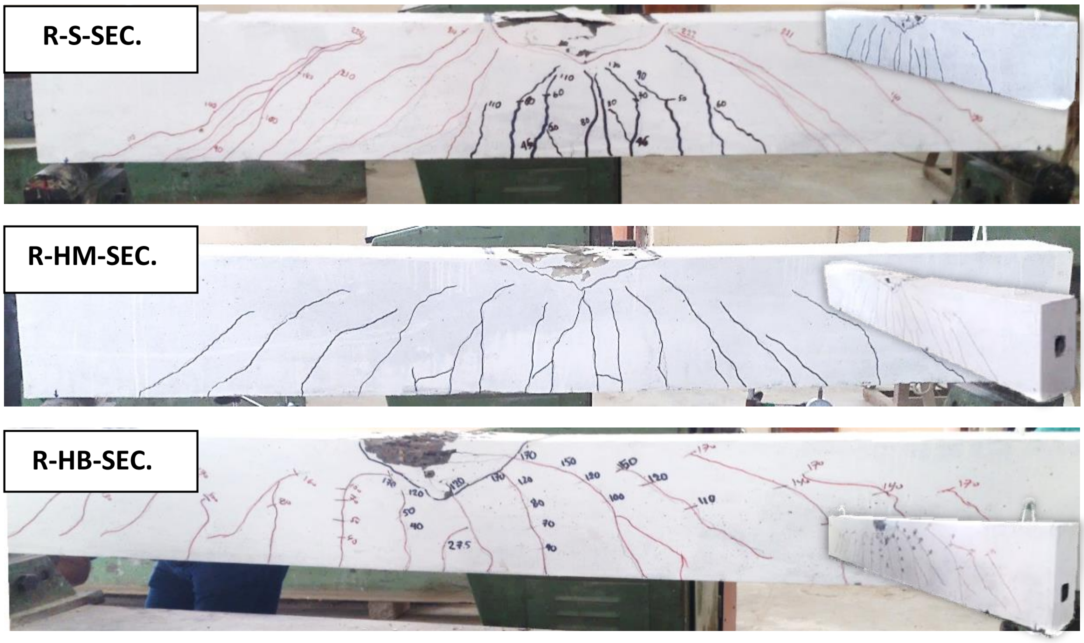
Table (6) and Figs (10 to 12) show that all groups had semi-identical in cracks pattern and failure mode which was flexural failure by crushing top concrete cover at flexural region, and flexural-shear failure comes by combined action of bending and shear, as shown in Fig(13). However, there was another failure mode which was a particular case and belongs to third group that was illustrated later in strengthened BLTO article.

Also, the similarity may had confirmed by the behavior of load-central deflection curves of all beams which had approached action because of small opening behavior.

Table (6): Tests Results of Tested HS-SCC Beams.

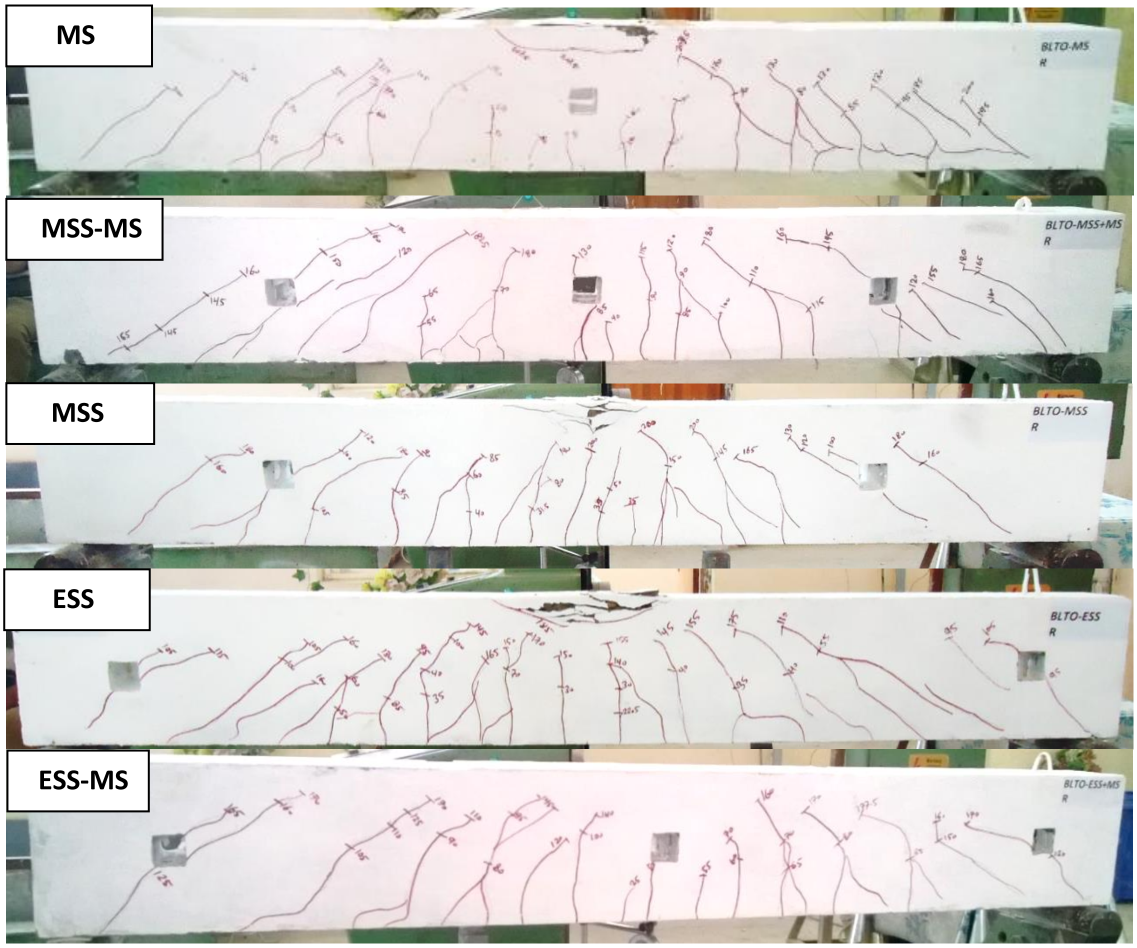
Group Description	Beam Symbol	Load Characteristics (kN)		Maximum Deflection (mm) at central	$\frac{Pcr}{Pu}$%	Mode of Failure
		First crack	Ultimate			
1st Group: Referential Beams	R-S-SEC.	47.5	227.5	8.4	20.88%	Flexural
	R-HM-SEC.	32.5	223	10.05	14.57%	Flexural
	R-HB-SEC.	27.5	195.5	11.6	14.07%	Flexural
2nd Group: 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
3rd Group: Strengthened RC BLTO	MS+CFRP	45	245	16.3	18.37%	Combination +concrete ripping-off by flexural-CFRP edges
	MSS+CFRP	40	200	13	20.00%	Combination +concrete ripping-off by flexural-CFRP edges
	MSS+CFRP	45	227.5	18.55	19.78%	Flexural
	ESS+CFRP	43	260	19.08	16.54%	Flexural
	ESS-MS+CFRP	52.5	215	13.81	24.42%	Combination +concrete ripping-off by flexural-CFRP edges

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.

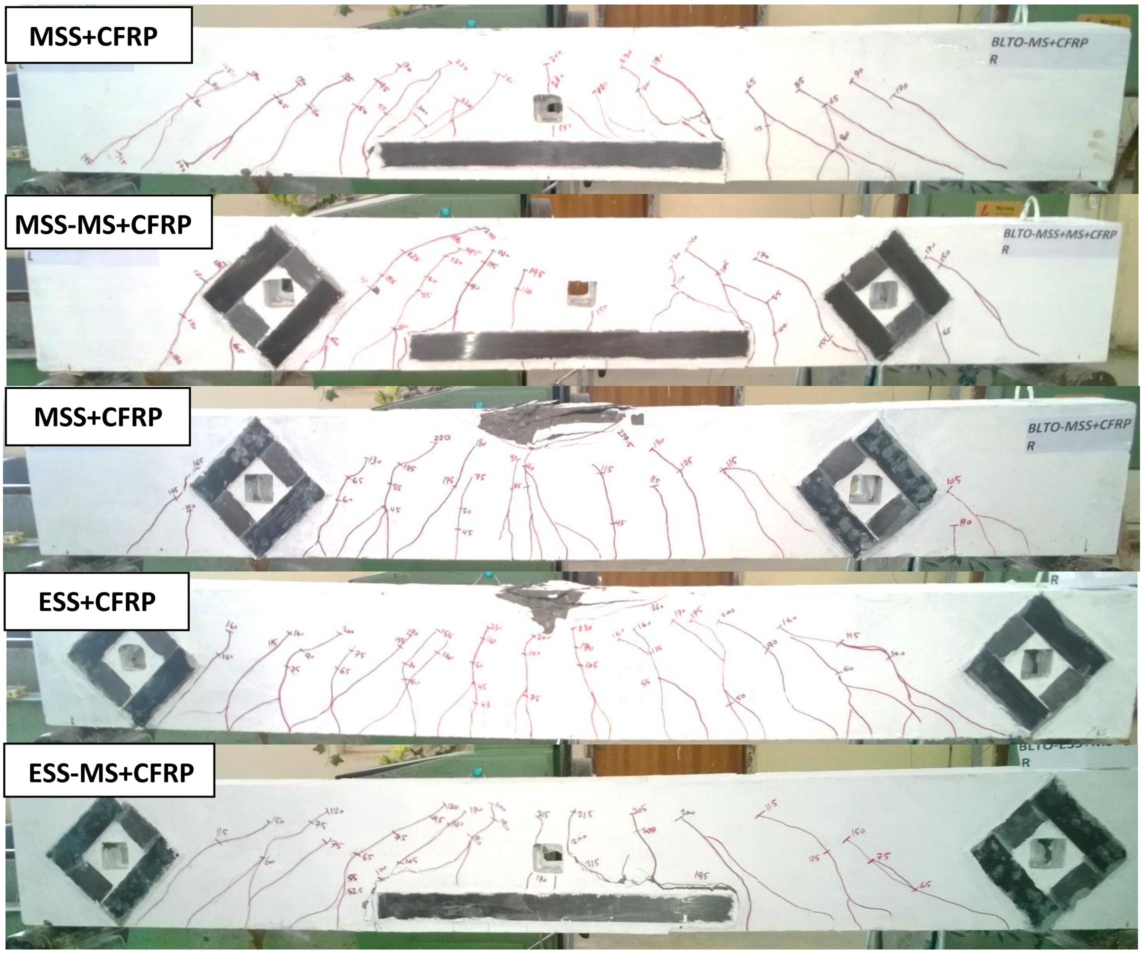


*The numbers shown beside the cracks indicated the load when the crack had reached that position.

Fig(10): Cracks Formation for Group No.1 (Referential Beams).



Fig(11): Cracks Formation for Group No.2 (Untrengthened Reinforced HS-SCC BLTOs).



Fig(12): Cracks Formation for Group No.3 (Strengthened Reinforced HS-SCC BLTOs by CFRP Laminates).

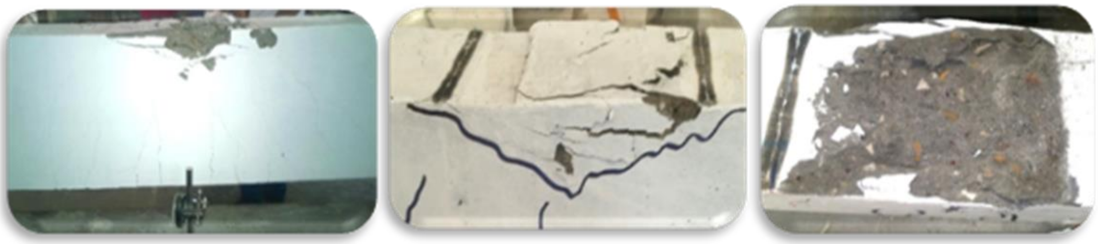


Fig. (13): Concrete Crushing Failure in Upper Layer of Some Beams

5.3 Effect of Hollow Core Position in RC Beam Section

Table (6) and Figs (10,14 and 15) 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 (14) indicated 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 (15) defined 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 (7). This may be due to the concrete at this area is neglected and can be omitted in structural calculation.

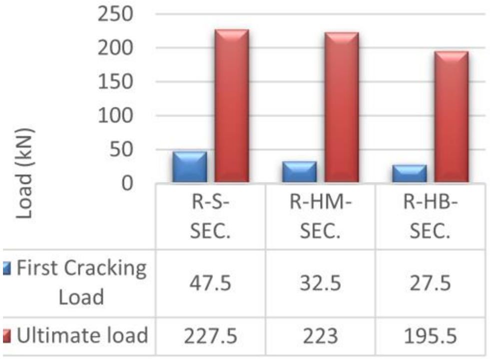


Fig.(14): First Cracking and Ultimate Loads of first Group (Referential Beams).

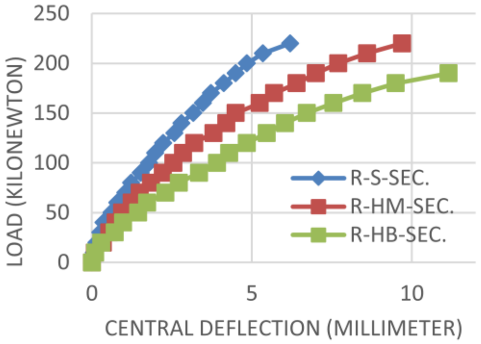


Fig.(15): Load-Central Deflection Relationship for first Group.

Table (7): 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
3	MS+CFRP	245	16.3	200	12.92
	MSS-MS+CFRP	200	13	200	13
	MSS+CFRP	227.5	18.55	200	13.45
	ESS+CFRP	260	19.08	200	12.11
	ESS-MS+CFRP	215	13.81	200	12.9

5.4 Location Effect of Web Opening

Table (6) and Fig.s (11, 16 and 17) show results of second group. The first crack was noticed at loading level ranging between about (12.2%-14.7%) of ultimate load which lower of mid hollow core beam between about (3.6%-20.4%) and about (5.5%-22%) from that of 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) of 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) considered as optimum BLTO between all beams of second group. Fig. (17) illustrates 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, as shown in Table (7). That may be because of the compatibility of flexural effect with under reinforced section with constrained major area of shear effect.

The openings in this research can be classified as small openings according to Alnuaami [21] and Mansure [22]. After final failure of beam, these openings allowed to convergence failure mode between BLTO models.

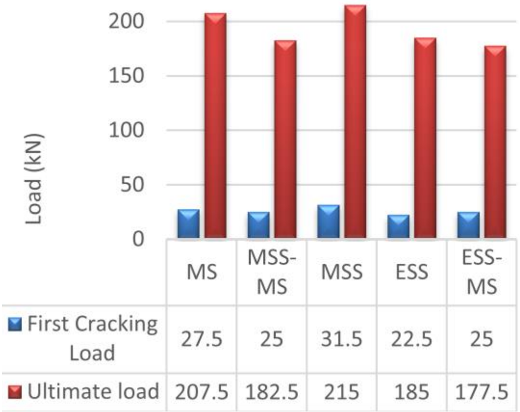


Fig.(16): First Cracking and Ultimate Loads for RC BLTO of second Group.

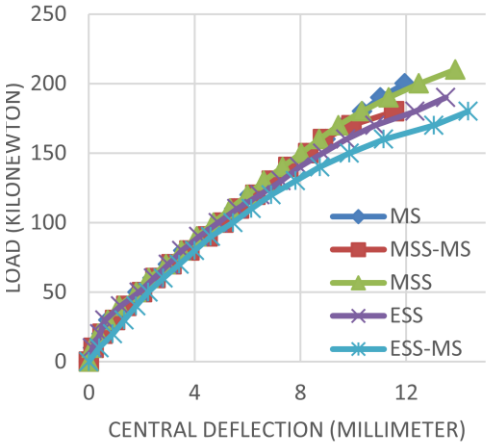


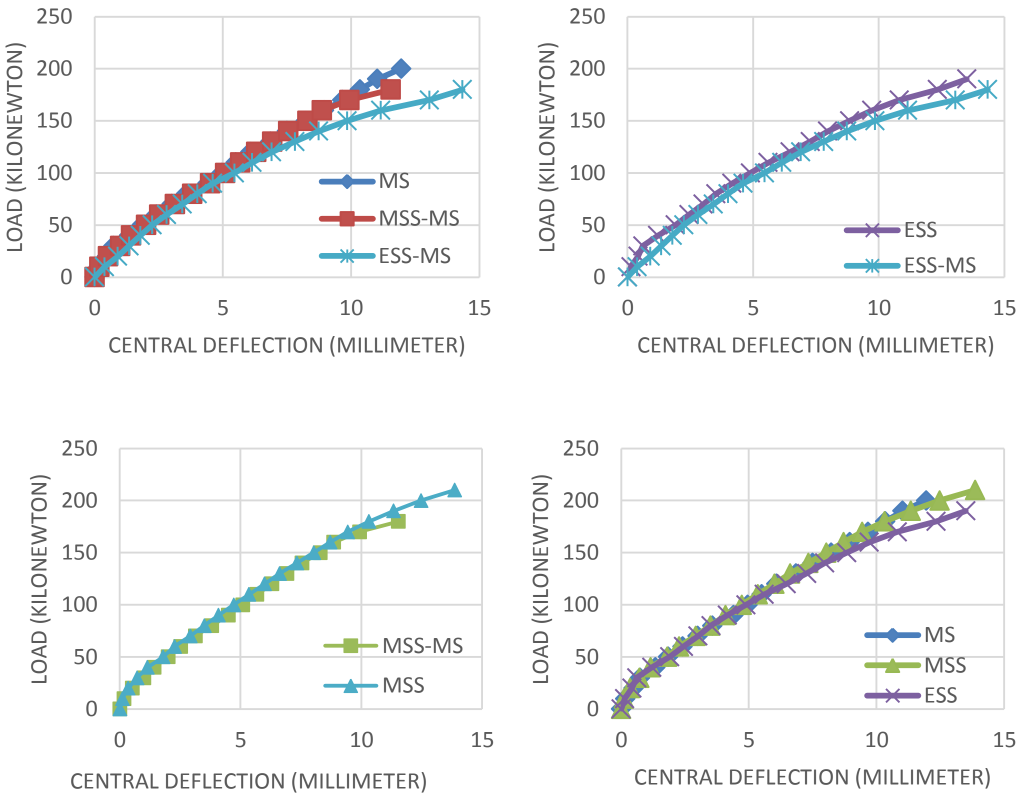
Fig.(17): Load-Central Deflection Relationship for second Group.

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 (7). 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(11), 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 considering 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 (8) and Fig(18), proclaimed the difference amid beams of the second group and describe the load-central deflection relationship for harmonical opening locations.



Fig(18): Load- Central Deflection Relationship for BLTOs Combinations of Web Opening.

5.6 Location Effect of Strengthened Web Opening

Table (6) and Figs (12, 19 to 21) show results of third group. The first crack was also observed at loading level by about (24.4%) of ultimate load. In case of unstrengthened flexural area, the first crack was appeared near flexural zone, while it was appeared near edge of flexural CFRP. The concrete deformation was generating in one of two separated portions which define failure mode at beams failure. The provision of any one was eliminating the other. The first portion was related to crush the top concrete cover in flexural region, as shown in Fig(13). However, the second portion referred to rip-off concrete cover at flexural CFRP edges before reaching ultimate beam strength, as shown in Fig(19). The efficacy of CFRP system demonstrated by preventing cracks access CFRP laminate to opening regions or with one to two hairline cracks which specific in flexural CFRP laminate, as shown in Fig(12).

Figs (20 and 21) indicated that higher load values of third group when the strengthening targeted weakness position in beam, and vice versa. Thus, smallest strength value of this group had observed in (MSS-MS+CFRP). While, highest value was recorded on (ESS+CFRP). Also, those caused by the effect of flexural and shear on configuration of that strengthened BLTO.

From Fig(22), it can be noticed that the strengthened BLTO curves had comparable behavior in load-central deflection harmony.

Table (8): Comparison between Web Opening and its Combination.

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

Fig.(19): Photographs of Concrete Ripping-Off by Flexural-CFRP Edges

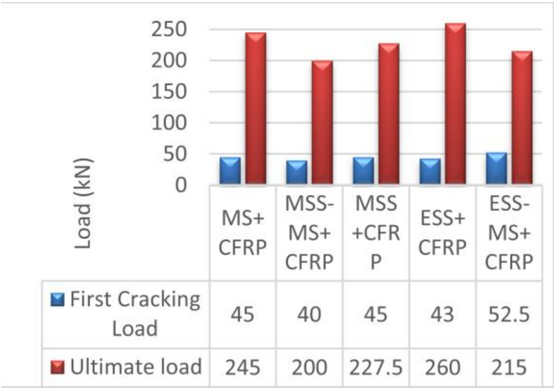


Fig.(20): First Cracking and Ultimate Loads of 3rd Group with Strengthened RC BLTO by CFRP.

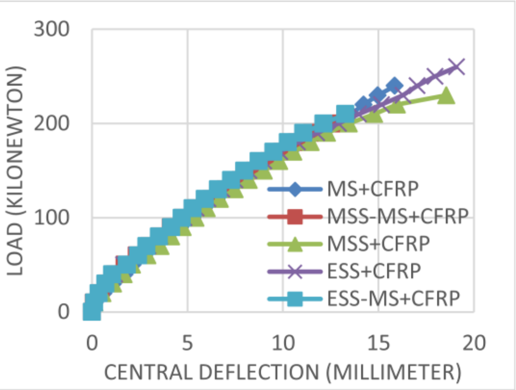
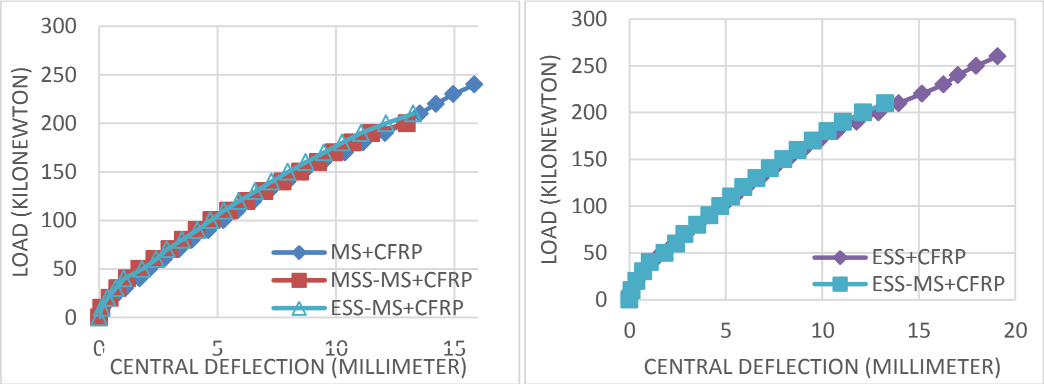
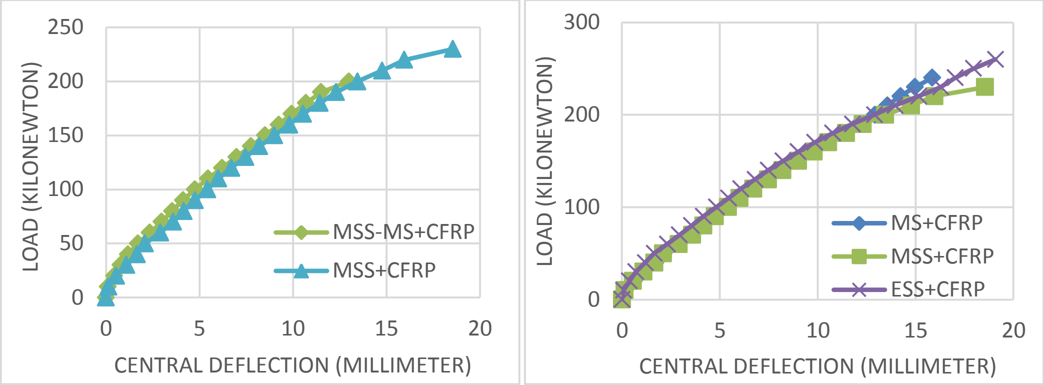


Fig.(21): Load-Central Deflection Relationship for third Group.



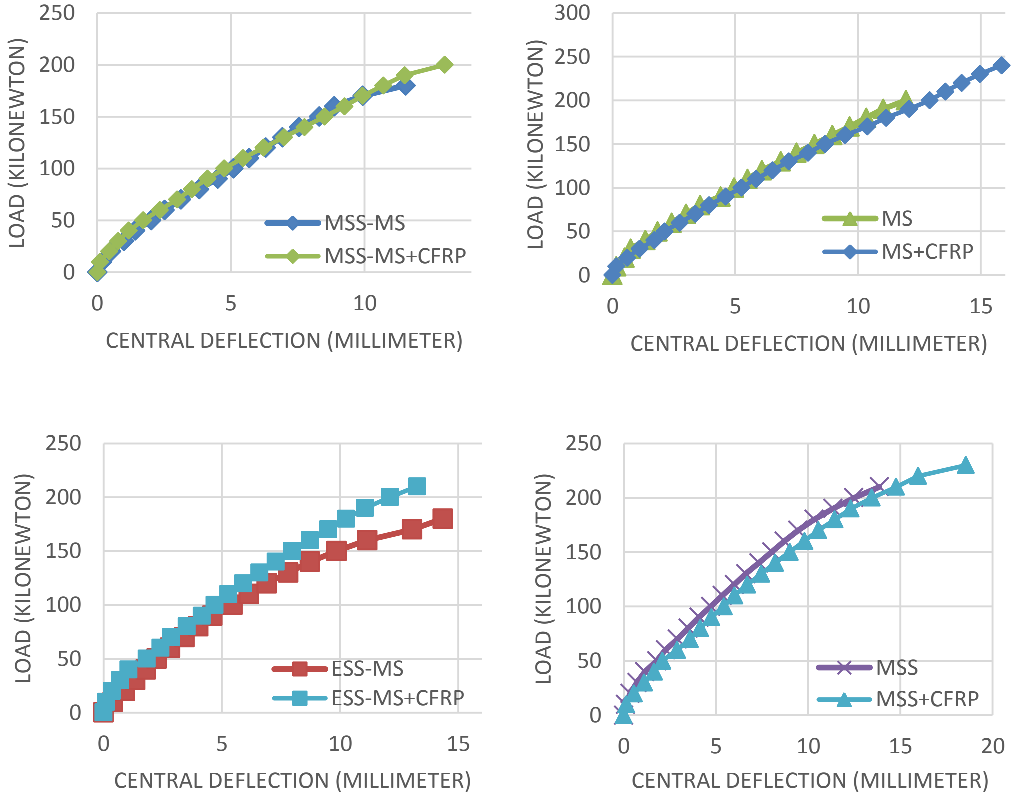
Fig(22): Load- Central Deflection Relationship for Strengthened BLTOs Combinations of Web Opening.



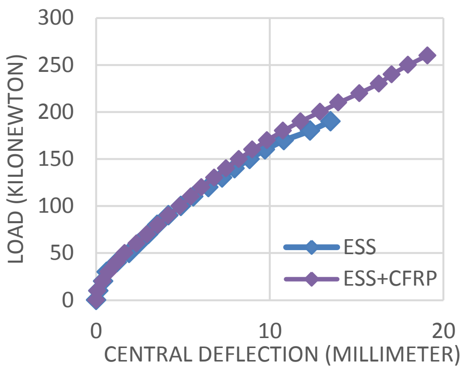
Fig(22): (Continued).

5.7 CFRP Strengthening Effect on Web Opening

The applied strengthening system in this study consider as partially constraint in accordance with web-opening position. The initiation of cracks in strengthened BLTOs were delayed and appeared at more loading stage than same copies of unstrengthened BLTOs. That may be because of redistributing stresses during loading process by CFRP laminate which led beams of third group to resist more applied stresses. Table (9) and Fig(23) reveal the enhancement of BLTO strength.



Fig(23): Load-Central Deflection Relationship for BLTOs with/without Strengthening by CFRP.



Fig(23): (Continued).

Table (9): Enhancement of BLTO after Strengthened by CFRP Laminates

BLTO Designation	Load Capacity (kN)		Enhancement ratio
	Unstrengthened RC BLTO (1)	Strengthened RC BLTO (2)	$(\frac{2-1}{1})$
MS	207.5	245	18.1%
MSS-MS	182.5	200	9.66%
MSS	215	227.5	5.81%
ESS	185	260	40.54%
ESS-MS	177.5	215	21.3%

6. Conclusions

1. The results of loading data evident that the provision of transverse and/or longitudinal opening in RC beams section lead to reduce its resistance. With comparing by mid-hollow core, beam resistance value had more reduction values if hollow core positioned in upper or lower zone of beam section. Also, the reduction had been more in case of web opening presence in hollow RC beam. 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 web opening and up to (22%) by compared with solid beam.
2. Any extra void in beam let the beam 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 presence and location of hollow core and web openings. After strengthening web openings by CFRP laminate, the enhancement of deflection was reach to (38.9%) less than the same copy of ustrengthened BLTO.
3. Further web opening position from loading influence (shear and flexural) in tested RC hollow beam lead to get BLTO closer to the optimum situation, and vice versa.
4. The first visible crack was appearing in position near flexural zone for all beams. While, it was appeared approximately near the edges of flexural CFRP laminates of BLTOs which appears in more load level on the unstrengthened parts of strengthened RC BLTOs and have more crack width than same unstrengthened copies of BLTO.
5. The recorded mode of failure was contained two main types, flexural failure by compressive concrete cover crushing and flexural-shear (combination) failure. Failure mode of strengthened beams was defined by concrete deformation which

generate in one of two separated portions which occurs in flexural region. That contains concrete cover suddenly crushing in compressive zone or concrete cover gradually ripping-off by the edges of central CFRP strips.

6. Although, small openings may consider weakness sources in RC beam, but the failure plane not always passes through the opening.
7. 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 unstrengthened body of RC BLTO.
8. Strengthening configurations of web opening was succeeded in prevent cracks to reach in web openings or decreasing hairline cracks to minimum number without any delaminating problem.
9. The smallest value of load capacity has been observed in case of strengthened openings that located in mid-shear and central beam. While the highest value was recorded when strengthened openings were located near supports which are considers as optimum strengthened BLTO.
10. Presence of CFRP system in same BLTO copy had enhanced beam resistance by about (29%) due to function of cracking delay.

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