Strengthening Circular Holesin Web of Steel I-Beams

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Abstract

This study aims to investigate the effect of making circular hole in web of existing steel I-beam on stiffness response and Ultimate Load Capacity (ULC) in addition how to strengthen this hole using steel ring stiffener. The experimental investigation has focused on testing four steel I-beam cases under concentrated point loads. The first one was tested steel I-beam with solid web as a reference (Control) case and the other three specimens were tested by making circular hole in web of steel I-beam without and with steel ring stiffeners. The experimental results demonstrate that the ULC and stiffness of steel I-beams significantly decrease with making a hole in web. Accordant of experimental work, it can be noted that behavior of steel I-beam with stiffening opening web using steel ring is satisfactory agreement with behavior of steel I-beam with solid web (before cutting hole). To simulate the experimental cases, the nonlinear finite element model (NFEM) using ANSYS ver.11 software was adopted in this study. The numerical resultsof load-deflection response and distribution stress along the examined beams have been compared with experimental tests. In general, good agreement between the (NFEM) and experimental results has been obtained. The purposed of NFEM has been done for implementation a parametric study to investigate the effects of three parameters: size, location of opening web and thickness of stiffener steel ring. It was found that the ULC of steel I-beam with opening web dropped almost linearly with the increase in hole diameter of web at ratio of diameter hole to beam depth (D/H) greater than (0.5). Therefore, it can be recommended to usesteel ring stiffeners to strengthen steel I-beam with opening web which have diameter greater than half depth of this beam (0.5H).

Keywords: Steel I-BeamwithOpening Web, Ultimate Load Capacity (ULC), Nonlinear Finite Element.

Notations

D	diameter of web hole.
H	depth of steel I-beam.
L_1	the distance from end support to center of circular web hole.
L	the distance from end support to mid span of steel I-beam.
t_R	thickness of stiffener steel ring.
SIBOW	Steel I-Beam with Opening Web
ULC	Ultimate Load Capacity
NFEM	Non-linear Finite Element Model

الخلاصة

في هذا البحث تم دراسة تأثير احداث فتحة دائرية في جذع عتبة حديدية على سلوك الصلابة والحمولة القصوى بالاضافة لدراسة تقوية الفتحة باستخدام انبوب حديدي. تم اختبار اربعة نماذج من العتبات الحديدية المعرضة لقوة مركزة في منتصف فضاء العتبة. العينة الاولى كانت عتبة حديدية ذات جذع صلب(قياسي) واما الحالات الثلاثة الاخرى فحصت لدراسة تأثير حفر ثقب دائري في جذع العتبة الحديدية مع وبدون استخدام حلقة حديد لغرض التقوية. اظهرت نتائج الفحص العملي ان الحمل الاقصى والصلابة للعتبة الحديدية بعد عمل فتحة دائرية في الجذع ينخفض بمقدار كبير مقارنة بالعتبة القياسية. وبالاعتماد على النتائج العملية يمكن ان نلاحظ ان سلوك العتبة الحديدية بعد تقوية الفتحة باستخدام حلقة حديدي مقاربة لسلوك العتبة القياسية (قبل احداث الفتحة). تم اعتماد نموذج اللاخطي من العناصر المحددة باستخدام برنامج (ANSYS ver.11) لمحاكات النموذج العملي. تم مقارنة النتائج النظرية المستحصلة لمنحنيات الحمل والهطول وتوزيع الاجهادات على طول العتبة الحديدية وفي محيط الفتحة مع النتائج المستحصلة من النتائج العملية. بشكل عام تم الحصول على توافق جيد بين النتائج المستحصلة من طريقة العناصر المحددة والنتائج المختبرية. حيث تم الاستفادة من نموذج العناصر المحددة في دراسة تأثيرثلاث عوامل مهمة : قطر الفتحة وموقع الفتحة و سمك حلقة التقوية الحديدي على الحمل الاقصى. من خلال الدراسة وجدنا ان الحمل الاقصى ينخفض بشكل كبير وخطي عند زيادة قطر الفتحة اكثر من نصف عمق العتبة (*D/H=0.5*). لذلك نوصي بإضافةحلقة اسناد حديدي لتقوية العتبة الحديدية بعد عمل فتحة دائرية قطرها يزيد عن نصف عمق العتبة.

الكلمات المفتاحية :عتبة حديدية ذات جذع مفتوح ، الحمل الاقصى، العناصر المحددة اللاخطية ،

Introduction

At the beginning of twenty century, the steel I-beams which had rectangular, circular and hexagonal opening web (SIBOW) were first introduced in construction technology. Aglan and Redwood published a paper in (1974)on analysis of castellated (cellular) beams using finite deference technique to study the failure in web post due to lateral buckling out of plan of castellated beam. The authors focused on how to relate the critical load of web post to ULCof castellated beams. In (2012), Wakchaure et al., tested castellated beams to indicate the effect of hexagonal opening web on the ULC and stiffness response with increasing height of web opening. They concluded that castellated beam was been agreeable for serviceability up to a maximum height of hexagonal opening in web 0.6 of beam depth.(Al-Mazini,2016) studies the behavior of steel plat girders with circular and square opening in web presented. The researcher was noted that the resistance of plate girders decreases with increasing in the size of opening web and plastic hinge location depending on size of opening web.Little investigations have been conducted on the reinforcement opening web of steel I-beam.

In 1980, Redwood and Shrivastava presented a concise recommendation to design steel I-beam withlarge hole. The cutting of a hole greater than 0.3 of beam depth will cause significant reduction in resistance of the steel I-beam under load.Using horizontal reinforcement bars to increase the resistance at large holes were also studied. (Hamoodi and Gabar;2013) studied three experimental tests to compare the structural behavior of steel plate girder with circular hole which had diameter equal 0.6 of girder depth at center of web and the effect of strengthening the circular hole by welding steel strip around edge of hole. This study was indicated that the reduction in resistance of shear load of plate girder with un-stiffener hole was 51% and the plat girder with steel strip stiffener was 35%.

Sometime, after completing the building construction, the owner asks foradditional service pipe i.e. sewer pipe, air condition duct, electric cable in place. The re-routing of service pipe under the beam leads to reduction in the floor heightwhichhas become unacceptable engineering practice. The best choice isto doa hole in web steel beam to put up service pipe. In this study, the effect of cutting hole in web of steel I-beam on structural behavior has been studied and the resistance response of steel I- beam after strengthening the opening web using steel ring as stiffeners was investigated to obtain satisfactory agreement with solid web beam (before cutting hole).

The suggested method

Referring to the previous section, the structural works in any building has been designed according to safety and serviceability considerations but the designer has to study the function requirements depending on the purposeof which the building is put up.The girders and beams,which are used in the construction of building floors, are hinder the installation of service pipes, air conditioning ducts and electric cables required for satisfactory functioning for which the buildingis built.

Significant spaces are normally needed to enable the passage of pipes and ducts under steel beams leading to additional cost and are generally unacceptable. Various methods can be adopted to solve these problems, i.e.: castellated,hunched andtapered beams or composite trusses and stub girders, but all these methods are implemented during the construction of building.Sometime a service engineer needs to extend service pipes or ducts post-construction of steel I-beam structure. To do so, there are two solutions can be adopted the first solution is to pass the service pipe under the existing beams and the second one is to drill a circular hole in web of existing steel I-beam as shown in Fig.(1). The first solution causes reducing the level of roof but the second solution is almost adopted because this form of erection keeps a smaller construction height with placement of services pipe within the height of girder, at the suitable locations. The ULC and stiffness response of steel I-beam will be dropped due to cut of its web therefore reinforcement along the periphery of the openings could be provided to restore the strength lost.

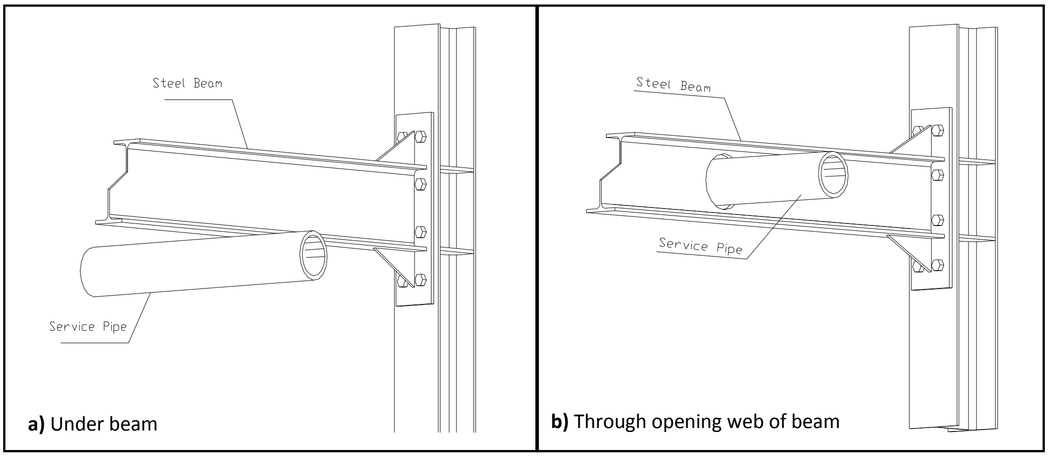


Fig.(1):Passing service pipe; a) Under beam b) Through opening web of beam

In this paper, the ULC of SIBOW will be studied and used steel ring stiffeners to obtain same strength of control beams (Steel I-beam solid web before making the hole) as shown in Fig.(2). Four IPE 200 steel beams will be tested until failure load as shown in Fig.(3) and the software ANSYS ver. 11.0 will be predicted to construct Non-linear Finite Element Model (NFEM) for simulation the SIBOW specimens. The validity of predictedNFEM resultsarecompared with the experimental test results.

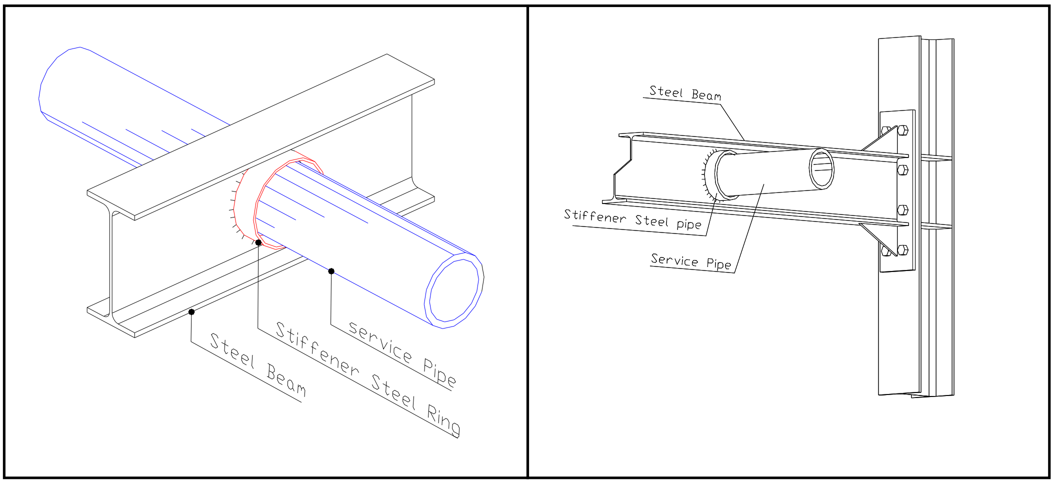


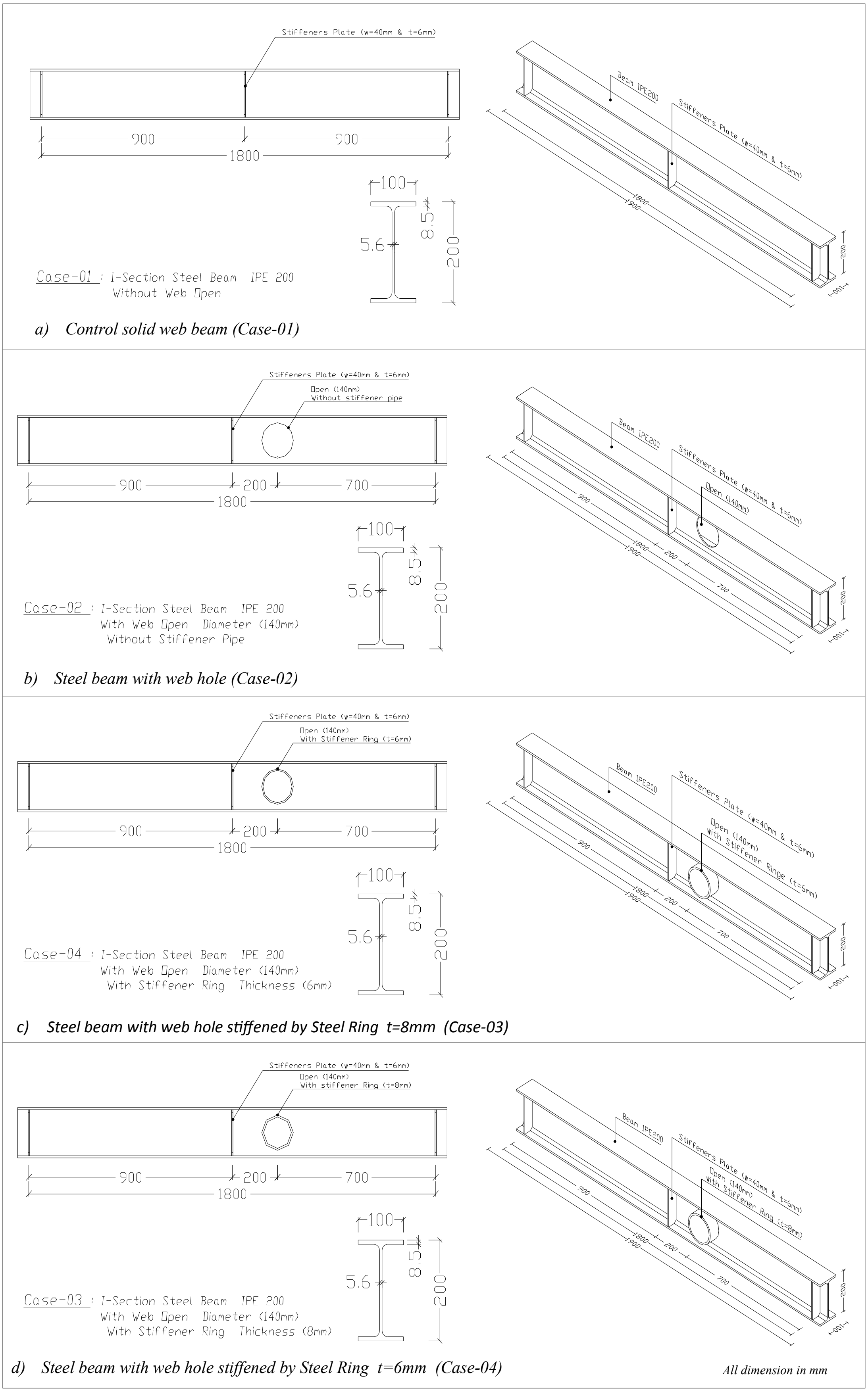
Fig.(2): Strengthening the circular web hole by steel ring stiffener

Experimental work

Experimental procedure

In order study the effect of drilling and opening web of existing steel I- beam and reinforced this opening by using steel ring toget same strength as that a solid web beams (Before making hole), four IPE200 beams with and without hole in web were tested to failure and all the cases had effective length equal (1800mm). Fig. (3-a) is shown first specimen (Case-1) which was solid section steel I-beam and second specimen (Case-2) was tested after made a circle hole in web that diameter of hole was (140mm) and its center was eccentricity (200mm) of mid-span as shown in Fig.(3-b). Third specimen (Case-3)and fourth specimen (Case-4) were stiffeners the circle hole by using steel ring with different thickness (t=8mm and t= 6mm) respectively as shown in Fig.(3-c) and Fig.(3-d). For all beams, overall depth was kept at (200 mm) with the corresponding top and bottom flange width of (100 mm) and flange thickness of (8.5 mm) and that thickness of web (5.6 mm). Flat plates (40mm) wide and (6mm) thickness were used to make transverse stiffeners. In order toavoid any failure modes not required in this testing, a transverse stiffeners were installedat mid-span under concentrated forces and at locations of end supports.

All simple supported steel I-beam specimens were put up in test machine with adequate care taken to ensure that beams were installed correctly placed in the test machine and the mid-span of beam was in line with the hydraulic jack center line as shown in Fig.(4). The steel I-beams were loaded using load test machine of (1000 kN) capacity inlaboratory of Kufa Engineering Collage.



a) Control solid web beam (Case-01)

b) Steel beam with web hole (Case-02)

c) Steel beam with web hole stiffened by Steel Ring t=8mm (Case-03)

d) Steel beam with web hole stiffened by Steel Ring t=6mm (Case-04)

Fig.(3): Dimensions and details of steel I-beam specimens

(a): Case(1): Steel I-beam with solid web.

(b): Case(2): Steel I-beam with opening web.

(c): Case(3): Steel I-beam with opening web stiffened by steel ring (t=8mm).

(d): Case(4): Steel I-beam with opening web stiffened by steel ring (t=6mm).

Fig.(4): Experimental work inLaboratory of Kufa Engineering.

Materials properties

In order to determine material properties which will be required for simulation Non-linear Finite Element model (NFEM) of steel I-beam, three tensile test specimenstaking from the IPE200 section were tested. These specimens were cut according to "*The American Standard for Testing and Materials (ASTM)*". The standard shapes and dimensions of steel specimenwere specified by ASTM E-8M. Steel specimens were tested by Universal Testing Machine which have load capacity 590KN as shown in Fig.(5). The ultimate stress, yield stress and elasticity modulusthat recorded from universal testing machine were listed in Table (1).

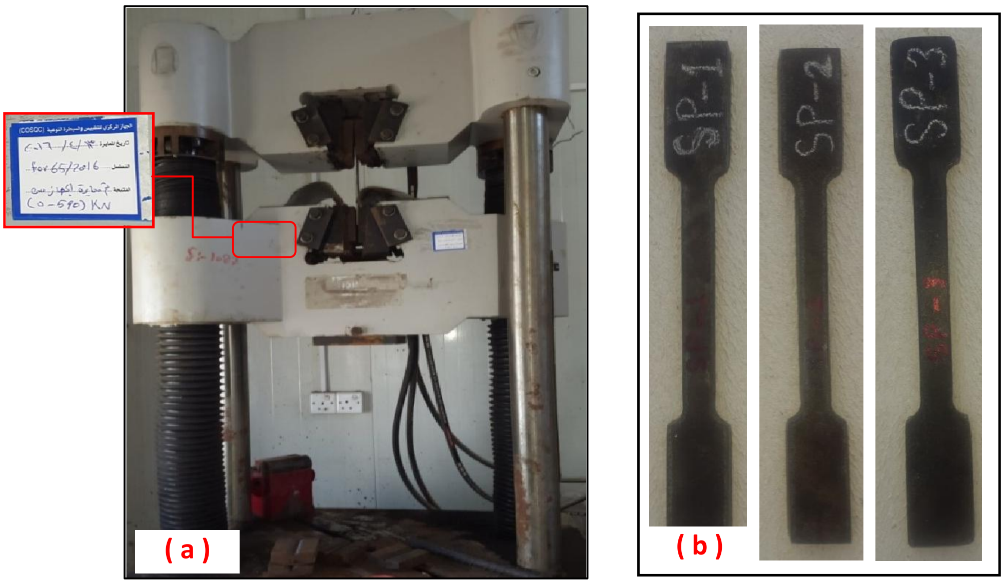
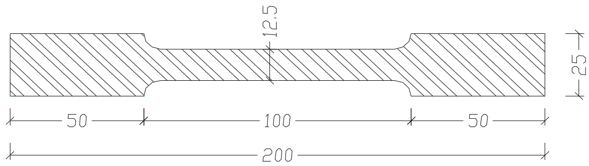


Fig.(5): a) Tensile test of steel b) Steel specimens

Table (1): Test Specimen and Steel Properties



Specimen	f_y *(MPa)*	f_u *(MPa)*	*E (MPa)*
SP-1	325.1	556.1	2.01 x10^5
Sp-2	323.3	551.7	2.03 x10^5
SP-3	321.7	543.2	2.07 x10^5
Average	323.3	550.4	2.0367 x 10^5

Discussion the results

To investigate the effect of drilling large hole in web of existing steel I-beam on its behavior and ULC, steel I-beam with and without opening web have been tested. Fig.(6) shows the experimental test results obtained for control Case-1(without opening web) and SIBOW Case-2 (after drilling webto make circular hole with diameter 140mm near the mid-span).It can be noticed that stiffness of load-deflection response and ULC are significantly decreased with opening web. The percentage of reduction inultimate load capacity of SIBOW (after drilling) compared with corresponding steel I-beam solid web (before drilling) were (37.0%).

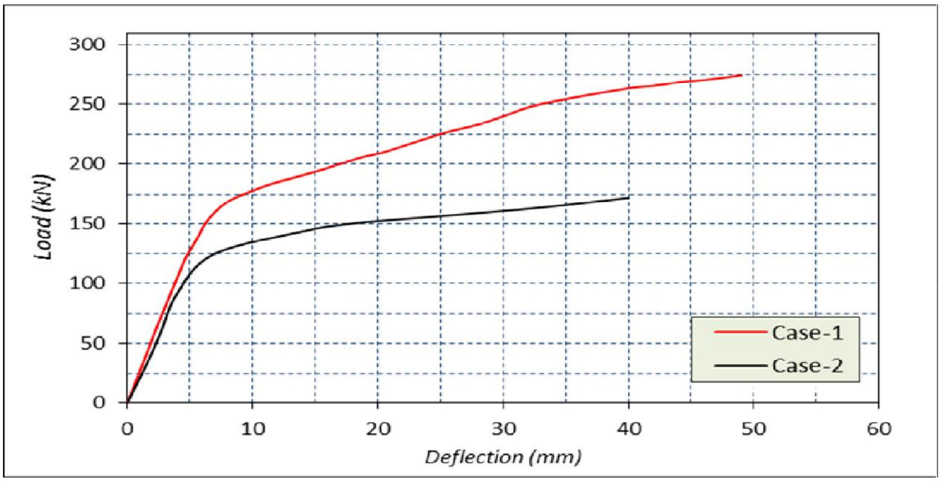


Fig.(6): Load - Deflection response of experimental results of (Case-1) and (Case-2)

In order to restore the ULC and stiffness response lost due to make circular hole in web, steel ring with diameter (□= 140mm) has been welded along the edge of the web openings with two different values of thickness (t=8mm) and (t=6mm) to increasestiffens response and ULC and compared results with the corresponding beam with normal solid web.The results obtained from the experimental tests of the Case-3 (circular hole in web with reinforcement steel ring with t=8mm) and Case-4 (circular hole in web with reinforcement steel ring with t=6mm) additional to previous Case-1 and Case-2 are illustrated in Fig.(7). Load-deflection curves presented in Fig.(7). The figures reveals that a significantly increase in ULC have been achieved by using steel ring to reinforce the boundary of opening web.

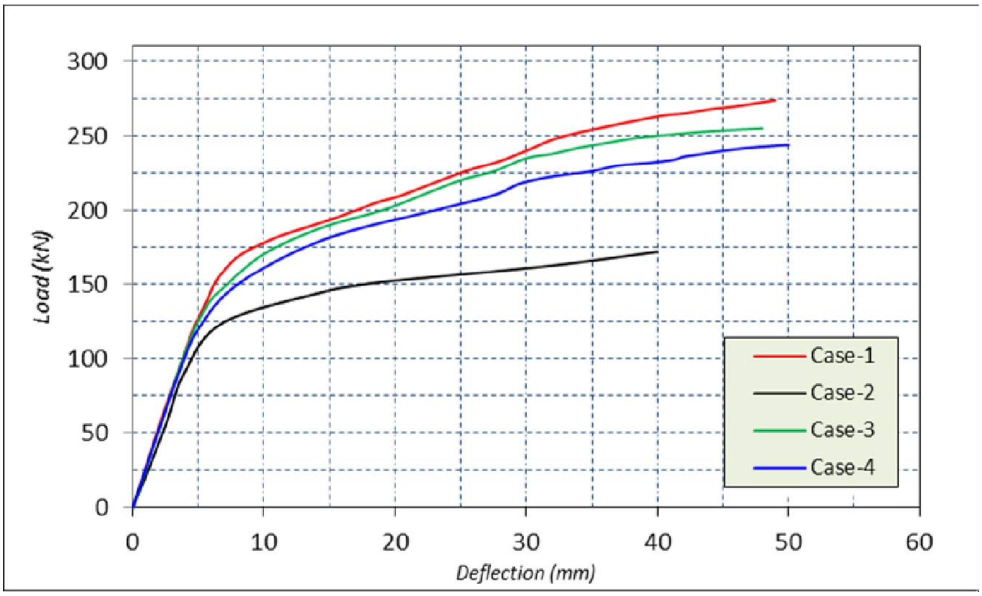


Fig.(7): Load - Deflection response of experimental results of (Case-1), (Case-2),(Case-3) and (Case-4)

It can be observed that ULC obtained for the SIBOW with reinforcement hole using steel ring (t=8mm) and (t=6mm) increases by a ratio of (47.8%) and (41.4%) compared with SIBOW without reinforcement hole, respectively. Comparisons between load-deflection curves of Case-1 and Case-3 have shown in Fig.(7)displays a satisfactory agreement between the normal solid web and stiffened opening web by using steel ring with thickness (t=8mm).

The results and comparison between the ULC obtained from stiffen and un-stiffen opening web with normal section (Solid web) are presented in Table (2). This table shows that theULC obtained for the steel beam with circular hole with reinforcement by steel ring stiffener thickness (t=8mm) and (t=6mm) decreases by ratios of (6.9%) and (10.9%) comparing with the corresponding normal beam with solid web respectively. Whilethe reduction of ultimate load of un-stiffen opening web was significantly dropped (37.0%). However, it can be noted that reduction in the ultimate load of stiffened opening web (Case-3) and (Case-4) were very small in comparing with reduction of ultimate load for corresponding section un-stiffened opening web (Case-2).

Table(2):Results of experimental test

Specimen	Hole of Web	Stiffeners	ULC (kN)	$\left(\frac{ULC_{Solid} - ULC_{SIBOW}}{ULC_{SOLID}}\right)$ x100
Case-1(solid)	Solid (Control)	——	274.0	——
Case-2(SIBOW)	Open (140mm)	——	172.5	37.0%
Case-3(SIBOW)	Open (140mm)	Steel ring t=8mm	255.0	6.9%
Case-4(SIBOW)	Open (140mm)	Steel ring t=6mm	244.0	10.9%

Finite element model (FEM)

The aim of this section is to verify the present nonlinear finite element model (FEM) developed to investigate the behavior and failure load of SIBOW. The NFEMs were implemented in the ANSYS Ver.11.0 program for each experimental case studyin parallel with the experimental testing. As recorded in Table (1), the properties of steel are adopted in the numerical model.

Amultilinear stress- strain response (Elastic – Plastic – strain hardening model) and the Von Mises yield criterion were adopted to simulate the nonlinear material modeling of steel as shown in Fig.(8).The geometrical nonlinearity was presented by a large strain theory.The elements of steel beams were presented by a SHELL181 element which have a 4-nodal element with 6-DOF per node(translations in the x, y, and z directions, and rotations about the x, y, and z axes) as shown in Fig.(9). This type of element is suitable for modeling thin elements. The numerical models of the case studies (steel I-beams with and without opening web specimens) were constructed to studydistribution and value of stress, strain, failure load and displacement due to concentrations load.

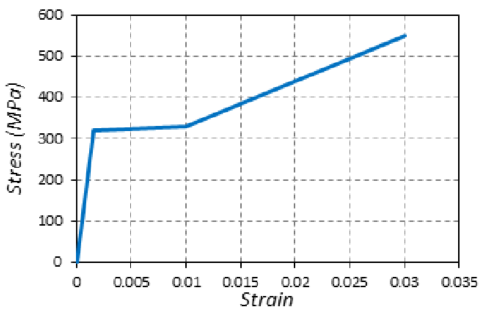


Fig.(8): Strain – Stress of steel plate.

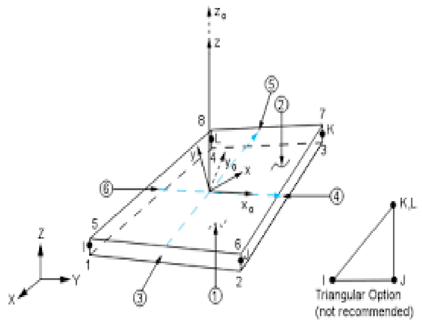


Fig.(9): SHELL181 element (ANSYS library).

In this section, the results obtained from the finite element analysis carried out for the four cases are presented and compared with the experimental results. The experimental and numerical load-deflection curves are shown in Fig.(10), Fig.(11), Fig.(12) and Fig.(13). Good agreement is obtained between the predicated finite element and experimental load-deflection curves throughout the entire range of behavior of the tested specimen. The computed failure load was slightly higher than the experimental failure load. The experimental and numerical models ultimate load values of each case are listed in Table 3. These results verify the capability of the presented ANSYS model to deal with SIBOW steel I-beam with opening web under concentrated load at mid-span. At failure load stage of case-1, case-2 and case-3, the Von- Mises stress distribution of FEM results and photograph of failure mode of experimental results are shown in Fig.(14). It can be observed that FEMs for each case is very similar to the experimental failure mode.

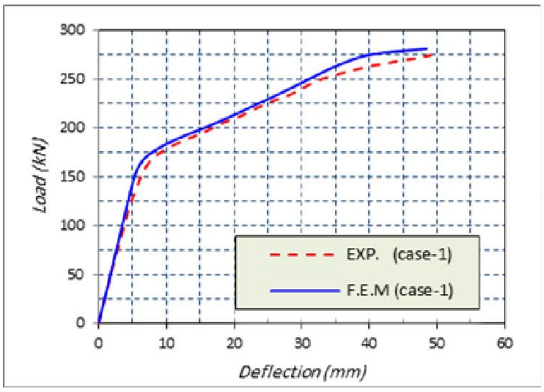


Fig.(10): Experimental and FEM models Load - Deflection curve of case-1.

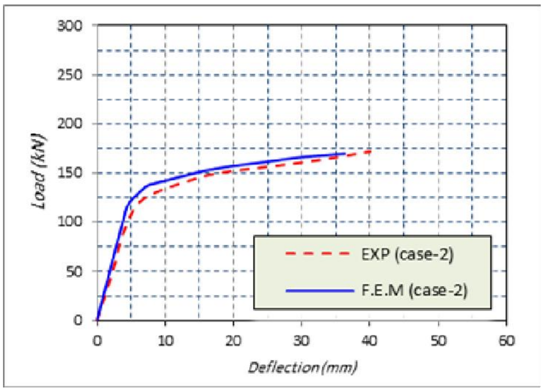


Fig.(11): Experimental and FEM models Load - Deflection curve of case-2.

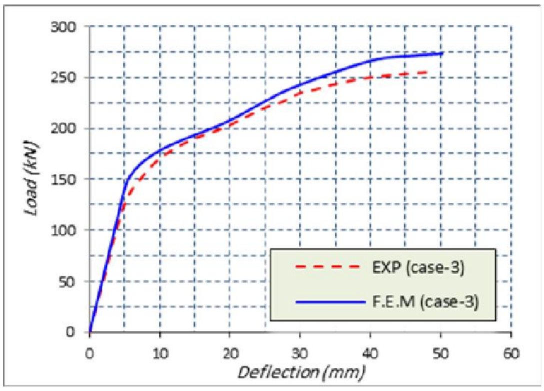


Fig.(12): Experimental and FEM models Load - Deflection curve of case-3.

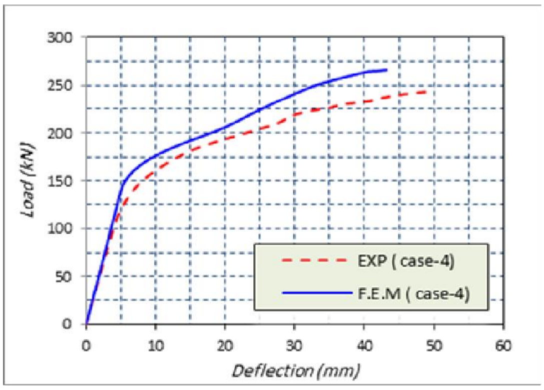


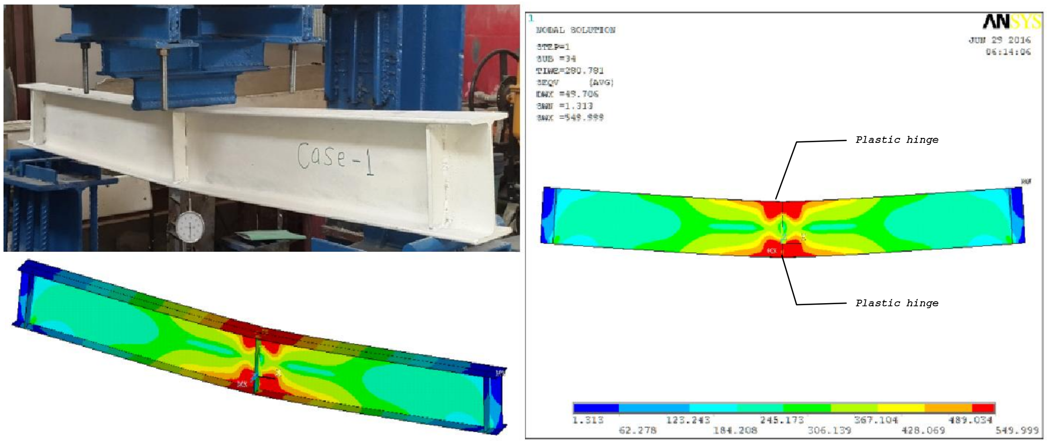
Fig.(13): Experimental and FEM models Load - Deflection curve of case-4.

Table(3): Experimental and NFEM ultimate load capacity comparison

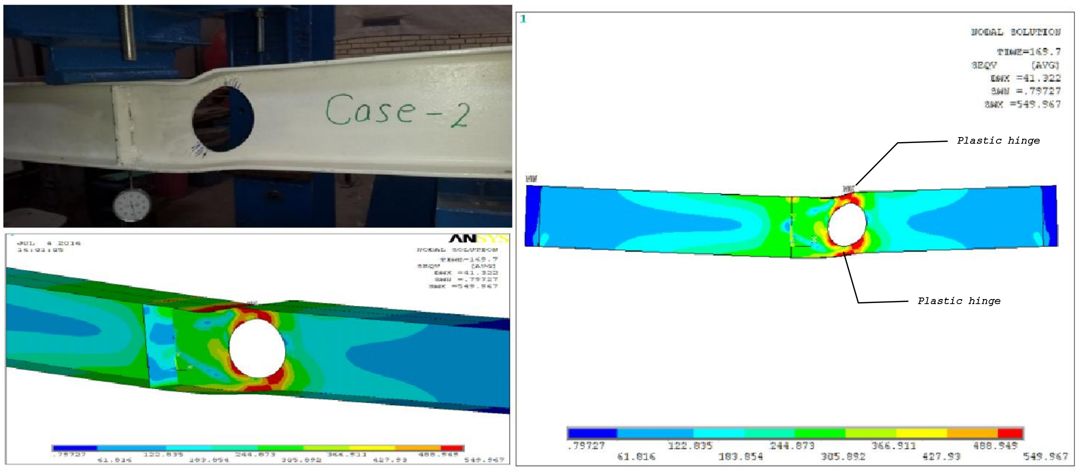
Specimens	Ultimate Load Capacity (kN)		$\frac{ULC_{EXP}}{ULC_{FEM}}$
	Exp.	FEM	
Case-1: Steel I-beam solid web	274.0	280.8	0.98
Case-2: SIBOW without stiffener	172.5	169.7	1.02
Case-3: SIBOW with stiffener	255.0	273.3	0.93
Case-4: SIBOW with stiffener	244.0	266.0	0.917

From the failure mode of the solid web beam, Fig.(14-A), it can be noticed that the maximum stress and plastic hinge occurred at mid span but Fig.(14-B)shows that the maximum stress distributed around the hole of SIBOW and the plastic hinge formed at located of hole. The stress distribution of SIBOW with using steel ring to strengthening the circular hole in Fig.(14-C)reveals that plastic hinge and maximum stress formed are close to mid-span. It can be observed that behavior of SIBOW with steel ring stiffener is similar to the solid steel beam.

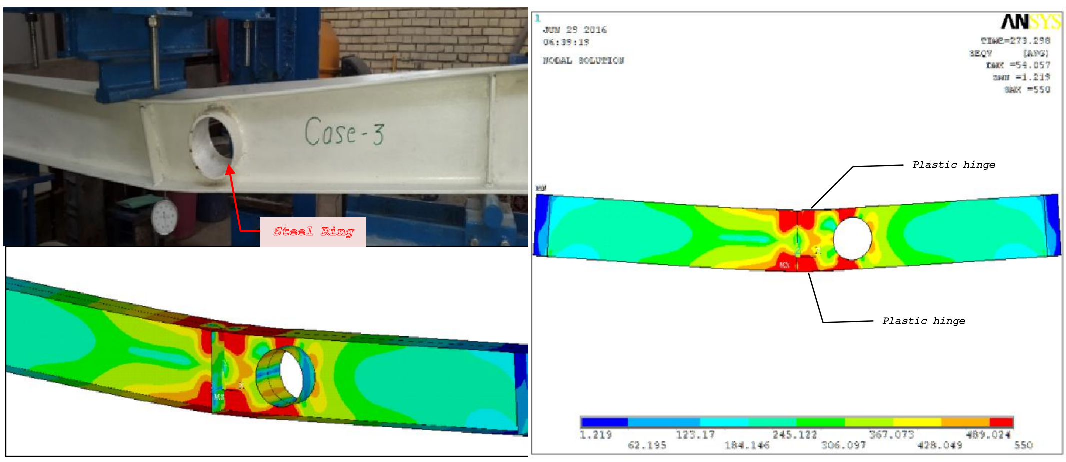
The contour line of distribution stress is close to the hole of SIBOWwithout stiffensmodels (Case-2) and SIBOW with stiffens model (Case-3) at failure load of Case-2 (169.7kN) are shown in Fig.(15). It is obvious from this figure that the stress of SIBOW model reaches to ultimate stress and plastic hinge formed at opening web while the stress distribution patterns of SIBOW with stiffens at same load remainsat elastic stage. Using steel ring to strengthen the hole of web is assisted to restore the stress lost due to cut steel I-beam web.



A) Case-1: Steel I-beam without opening web.
Distribution stress and deformation at failure load = 280.78 kN



B) Case-2: Steel I-beam with opening web.
Distribution stress and deformation at failure load = 169.70 kN



C) Case-3: Steel I-beam with opening web and stiffness by steel ring.
Distribution stress and deformation at failure load = 273.29 kN

Fig.(14): Comparison distributed stress of experimental and NFEM models for case-1 , case-2 and case -3.

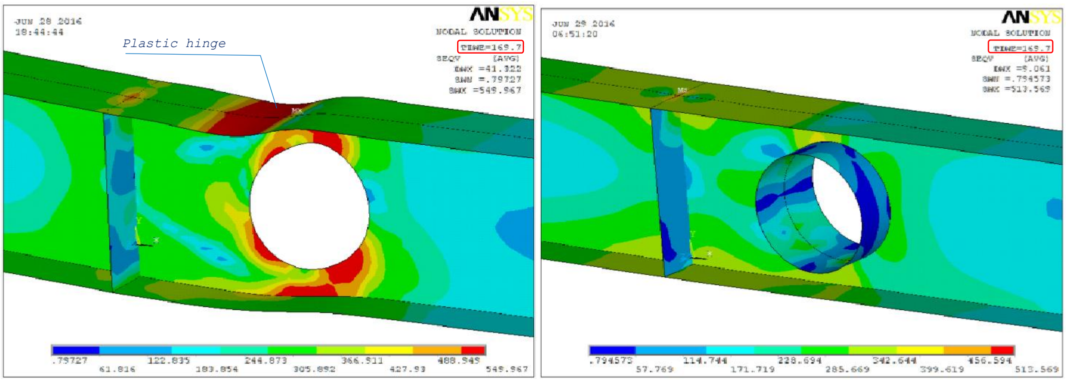


Fig.(15): Comparison distributed stress of FEM models between SIBOW without and with stiffener at stage load = 169.7 kN.

Parametric study

The main objective of the present section is to investigate the effect of three important parameters on the behavior of SIBOW using the NFEM which was calibrated in previous section. These parameters include ratio of hole diameter to steel I-beam depth (D/H), thickness of stiffener steel ring (t_R) and the web hole position in relation to half-span beam (L1/L). Deferent ratios for diameter of hole to beam depth of SIBOW were taken in NFEM to study the effect of the size of hole on the load-deflection response of SIBOW and their ULC are illustrated in Fig.(16). In this figure, the stiffness of steel I-beam is decreased by increasing the hole diameter. The overall behavior obtained from these tests ranges from very soft response when ratio (D/H) greater than (0.5) to relatively stiff response for solid steel beam. Also, the ULC decrease by about (63.0 %) is increased ratio (D/H) from (0.5) to (0.9) while slightly lower ULC about (4.1%) is increased ratio (D/H) from (0.0) to (0.5) as shown in Fig.(17) and Table 3.

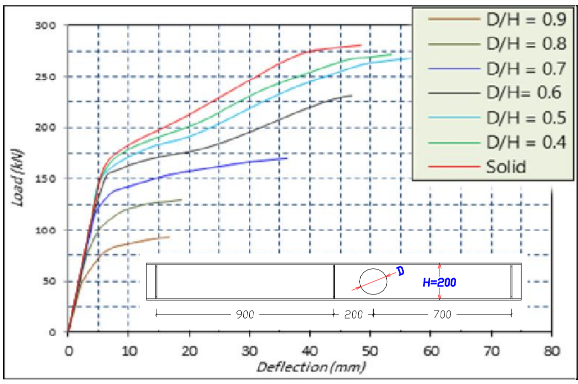


Fig.(16): Effected of hole size (D/H) on Load-deflection response of Steel I-Beam Opening Web (SIBOW).

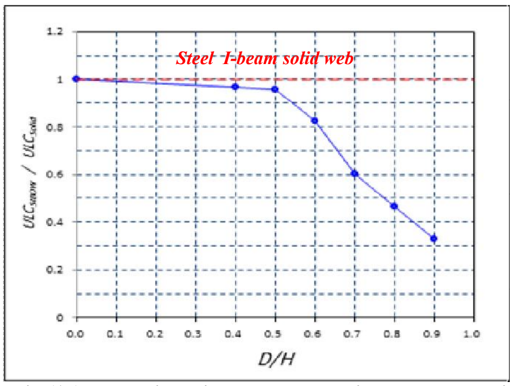


Fig.(17): Relationship between Ultimate Load with diameter hole web of (SIBOW).

Table(3): Effected of diameter web hole on ULC.

Specimen	Hole Diameter	Section Depth	ULC	$\frac{ULC_{SIBOW}}{ULC_{SOLID}}$x100
D/H = 0.0	Solid	200 mm	280.78 kN	100.0%
D/H = 0.4	80 mm	200 mm	271.56 kN	96.8 %
D/H = 0.5	100 mm	200 mm	269.35 kN	96.0 %
D/H = 0.6	120 mm	200 mm	230.92 kN	82.3 %
D/H = 0.7	140 mm	200 mm	169.72 kN	60.5 %
D/H = 0.8	160 mm	200 mm	129.42 kN	46.1 %
D/H = 0.9	180 mm	200 mm	92.86 kN	33.1 %

In order to investigate the effect of hole position on the load –deflection behavior and ultimate load capacity, four different relations of web hole location to the beam half-span (L_1/L) for FEM were shown in Fig.(18). It has been noticed that high value of ratio (L_1/L) when the location of hole near to mid span leads to decrease stiffness response and ultimate moment because of, in mid-span concentrated load, the shear force is a constant along the half-length of span while the bending moment decreases with moving away from center of the beam.

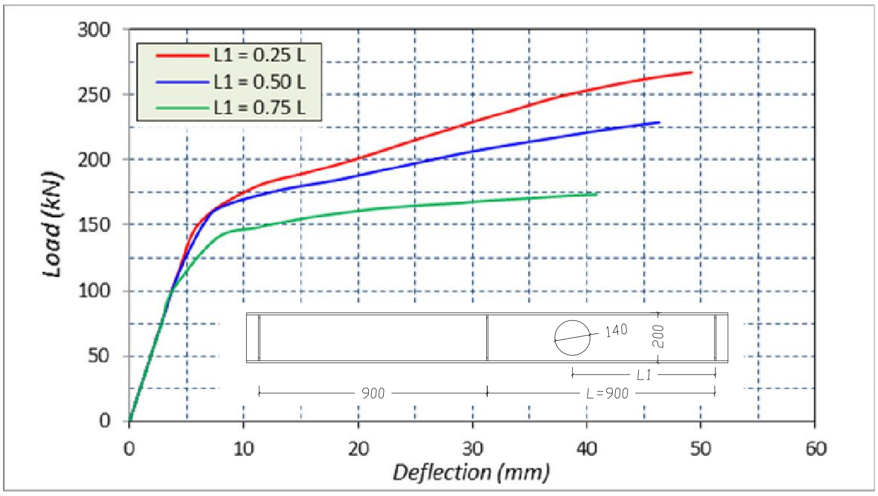


Fig.(18): Effected of hole located (L1/L) on Load-deflection response of SIBOW.

To study the effect of thickness of stiffener steel ring on stiffens response and ULC for steel I-beam with large hole in web, six different thickness of stiffeners steel ring (t_R) (2mm, 4mm, 6mm, 8mm, 10mm and 12mm) for reinforcement larger hole (D/H=0.9) which can be made in web of steel I-beam were analyzed by using Non-linear Finite Element Model (NFEM). Fig.(19) was displayed effected the different thickness of stiffener steel ring on the load –deflection behavior of SIBOW.In Fig.(20) and Table (4), it has been noticed that the ULC is increased with increasing thickness of stiffenersteel ring (t_R).The Ultimate load capacity (ULC) of steel I-beam with opening web increase from (33%) at un-stiffener up to (92%) at stiffener by using steel ring which had thickness (t_R=12mm) relative to ULC of reference beam (Steel I-beam without opening web) which was equal (280.8kN).

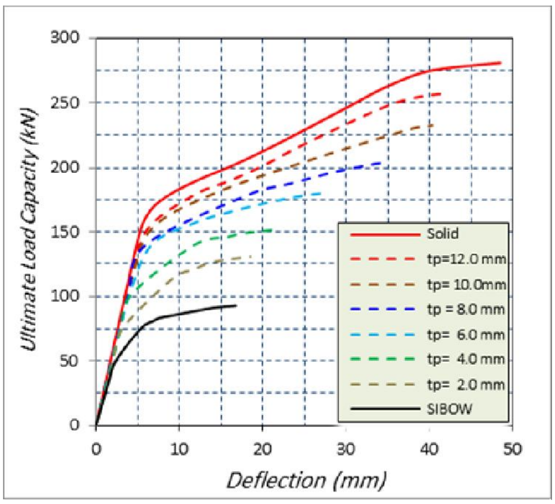


Fig.(19): Effected of thickness of stiffener steel ring on Load-deflection response of (SIBOW).

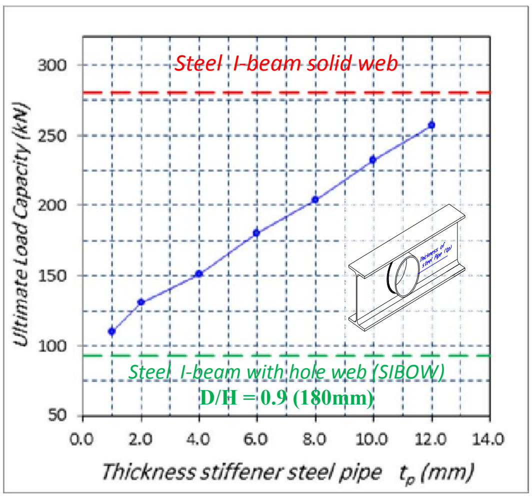


Fig.(20): Relationship between Ultimate Load with thickness of stiffener steel ring of (SIBOW) .

Table(4): Effected of thickness of stiffener steel ring on ULC.

Specimen	Hole Diameter	Thickness of stiffener Steel Ring (t_R)	Ultimate load capacity (ULC)	$\frac{ULC_{SIBOW}}{ULC_{SOLID}}$
SIBOW without stiffener	**180 mm**	**——**	**92.8 kN**	**33%**
SIBOWwith stiffener	180 mm	1.0 mm	110.3 kN	39%
SIBOWwith stiffener	180 mm	2.0 mm	130.5 kN	46%
SIBOW with stiffener	180 mm	4.0 mm	151.4 kN	54%
SIBOW with stiffener	180 mm	6.0 mm	180.6 kN	64%
SIBOW with stiffener	180 mm	8.0 mm	203.7 kN	73%
SIBOW with stiffener	180 mm	10.0 mm	232.0 kN	83%
SIBOWwith stiffener	180 mm	12.0 mm	257.4 kN	92%
Steel I-beam with solid web	**Solid**	**——**	**280.8 kN**	**100%**

Conclusion

This study has come with the following conclusions:

1- It was found that the reduction in resistance of steel I-beam which has aweb hole with a diameter of0.70from the beam depth is equalto 37% of resistance steel I-beam without web hole.

2- According to the results obtained from the experimental works, strengthening steel I-beam with opening web bysteel ring recovers the ULC which loosed due to cutting of web. Using steel ring which has thickness 8mm as stiffener in Steel I-Beam with Opening Web (SIBOW)increases the ultimate load capacity41% comparison with similar beam without steel ring stiffener.

3- Non-linear Finite Element Model(NFEM) resultsare capable of simulatingthe behavior of steel I-beam with solid web and with opening web.The analytical tests carried out for the four cases studies showedthat load-deflection response and ULCs are in a good agreement with the predicted experimental test results. These results reveal the accuracy and efficiency of the NFEM in predicting the behavior and ULC of SIBOW.

4- Best diameter of circular hole in steel I-beam webwithout stiffenersshould be notmore than half of the steel I-beams height (0.5 H).

5- When the ratio of hole diameter to depth of steel I-beam greater than 0.5H, the ULCof SIBOW dropped almost linearly with increase in hole diameter of web.

6- The adopted steel ring stiffeners, which are welded around edge of web holes,are strongly advised for using in steel I-beams with diameter hole larger than half of beams depth (D/H > 0.5). It can be shown that the welded steel ring stiffeners enable of improved stress redistribution around of hole region and contributed for an increase of stiffens and ULC of SIBOWs.

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