The Effect Of Strengthening By Using Steel Ring Stiffeners On The Behavior Of The Cellular Beams With Large Web-Opening

Hayder W. Ali, Ameer H. Muhammed

Abstract: the current study included an experimental and numerical study to assign the structural behavior of the cellular steel beams with and without strengthening by placing a steel ring stiffener around web-opening. IPE 140 hot rolled I-section steel beam was used to produce three specimens; the first without opening (control beam), the second was cellular beam without strengthening and the third beams was (LBD-R) with strengthening by steel ring stiffeners around opening with geometrical properties (Br=37mm and Tr=3mm). all cellular beams were fabricated with opening diameter (130mm) that result in expansion depth ratio (1.42), span length (1700mm) and ten openings. the results showed that cellular beam without strengthening was increased the ultimate load up to (31%) than the control beam (without opening) even in case of presenting a large opening and the failure was happened due to the web post-buckling. While the cellular beam with strengthening increased the ultimate load up to (147%) than the control beam and the failure mode that noted was the Vierendeel mechanism. On the other hand, the numerical study by finite element has shown that the increasing the ring thickness can be increased the ultimate load up to (172%) when using steel ring with thickness as the same as the web thickness (0.41 time of flange thickness) and after this value is not feasible economically.

Index Terms: Cellular Steel Beams (LB), Parent section, Steel ring stiffeners, Ultimate load capacity (ULC), Web post-buckling and Vierendeel mechanism

1 Introduction

Structural engineers always try to improve the structural behavior against the geometrical and material failures to increase elastic stiffness and ultimate strength with a minimum cost of construction. The cellular steel beam is one of the most useful solutions for improving the steel members to produce a lightweight beam with high strength and low-cost Cellular beams are made by specified fabrication process start with a double cutting line with semicircular path along the web panel of parent then, re-joining these parts to product beam with a circular opening shape. This process can be increased the section depth up to (50 %) compared with the parent section [1] which is lead to an increase in elastic stiffness and flexural strength as shown in figure (1). The existence of web openings may cause different failure types [2] for example, the Vierendeel mechanism, welded joint rupture and the web post-buckling that result by shear forces additional to failure modes which happened in solid web steel beams such as the flexural mechanism and lateral-torsional buckling. These types of failure happen because of the instability of a web area. The current work aims to improve the structural behavior of cellular steel beams by adopting new strengthening technique. In this technique, ring stiffener placed around the circular web opening of the cellular beam as shown in figure (2) to avoid failure due to web post-buckling and increase the resistance of, three experimental specimens were tested in Engineering College Laboratories of Kufa University.

- *Hayder W. Ali is currently a doctor of structural engineering in Kufa University, Country-Iraq. E-mail: hayder.althabhawi@uokufa.edu.iq;*
- *Ameer H. Muhammed is currently pursuing a master's degree program in structural engineering in Kufa University, Country-Iraq. E-mail: engameer91@yahoo.com*

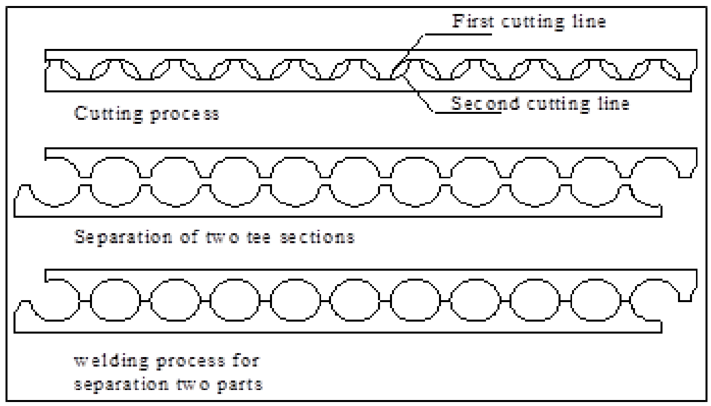

Fig.(1). *Fabrication procedure Of Cellular Beams*

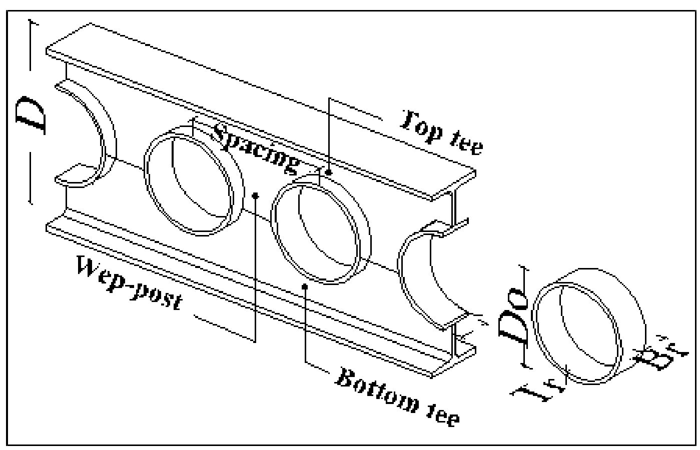

Fig.(2). *Steel Ring Stiffeners Around Web-Opening*

2 PREVIOUS STUDIES

Many experimental and numerical studies were executed to study the behavior of the cellular steel beams and the increasing in load carrying capacity achieved by increasing the depth than the parent section. Some of these studies will be mentioned in the next paragraphs.

2.1 Nimmi K.P and Krishnachndran 2016[3]: finite analysis has been executed to investigate the buckling load for the cellular beam with a different type of stiffeners (normal stiffener between openings and ring stiffener around openings).Three cases of L/D (length to depth ratio) 5,10and 15 for each case using three beams, the first without any stiffener, the second with normal stiffener and the third with a ring around openings. This test showed effective of using stiffener to resist the buckling load, where normal stiffener acts as a short column and ring stiffener reduce the stress around openings.

2.2 Erdal, FerhatSaka, Mehmet Polat 2013 [4]: An experimental and finite element study was introduced to inspect the load carrying capacity of the cellular steel beams. The test was carried out with twelve simply supported cellular beams that which designed by using harmony search method according to BS5950. Three types of the cellular beam were used with four beams for each type. The first type NPI 240 with opening diameter= 251mm and eight openings, the second type NPI 260 with opening diameter=286mm and seven openings and the last type NPI 270 with opening diameter=277mm and six openings. All beams were tested under single point load at mid-span. Lateral supports were used for all beams except two beams of NPI 240. This test showed that the failure mode was lateral torsional buckling for unrestrained two beams of NPI 240 and the failure mode was web buckling for the other two beams. On the other hand, the failure mode for NPI 260 and NPI 280 was due to Vierendeel mechanism and web-post buckling respectively. The finite element results showed a stiffer response than the experimental about (7.01%-11.45%). Also, this test recommended using transverse stiffener or steel ring stiffener under an applied load to increase web-buckling strength and increase the shear resistance.

2.3 Konstantinos.D.T and Grigorios.G 2015 (2015) [5]: finite element study has been presented to investigate the effect of using transverse stiffeners on the structural behavior of cellular beams with a small clear distance between openings. The results showed that the dominant failure type which noted was Vierendeel failure for closely openings spaced sections. On the other hand, the result showed that the transverse stiffeners become less effective in case of increased spacing and the failure mode transfer to the web-post buckling. Moreover, it was suggested a maximum spacing between the web openings. In this literature, it can be observed that the geometric failure that due to Vierendeel mechanism and web post-buckling is more frequent due to the geometric properties of cellular beams section and the effect of shear force (vertical and horizontal) especially in the large opening size and in the same time, there is a gap in experimental studies to assign the behavior of cellular beams when the opening is reinforced by placing steel ring stiffener around web-opening. The target of the current study was to investigate the effectiveness of strengthening cellular steel beams with a different value of expansion depth ratio by using ring stiffeners around web openings.

3 SPECIMENS PREPARATION

In this work, hot-rolled I-section steel beam (IPE 140) was used as a parent section to product three specimens: the control beam and two cellular steel beams with an opening diameter (Do=130mm) that result in expansion depth ratio (D/d=1.43) and spacing ratio (S/Do=1.3). All specimens having the same flange thickness, web thickness, flange width, and span length were (t_f=7mm), (t_w=5mm), (b_f=74mm) and (L=1700mm) respectively. One of the cellular beams was without strengthening and the second with strengthening by placing a steel ring stiffeners with (br=37mm) and thickness (tr=3mm). The material properties were obtained from tension tests on coupon specimens according to ASTM A370 [6]. A plasma CNC mechanism was used to obtain a semicircular bath by cutting the web of standard I-section along its longitudinal axis to produce two parts with T-section, after that rejoining these two parts by using electrode welding to form a cellular beam with circular web-opening as shown in figure (3)

Fig. (3). *Cutting By CNC Technique*

Since this research focused on studying effaced of using steel ring stiffeners around the web opening of the cellular beam. Consequently, four cellular beams with different expansion depth ratio were reinforced by insulation steel ring stiffener as shown in figure (4).

Fig.(4). *Installation Of Ring Stiffeners*

The geometrical details of experimental specimens are shown in figure (5) and Table (1).

Table 1. *specimen Details*

Symbol of Beam	Overall Depth	Opening diameter (Do)	Spacing (S)	Ring width (Br)	Ring thickness (Tr)
control	140 mm	NA	NA	NA	NA
LBD-O	201mm	130 mm	170 mm	NA	NA
LBD-R	201mm	130 mm	170 mm	37 mm	3 mm

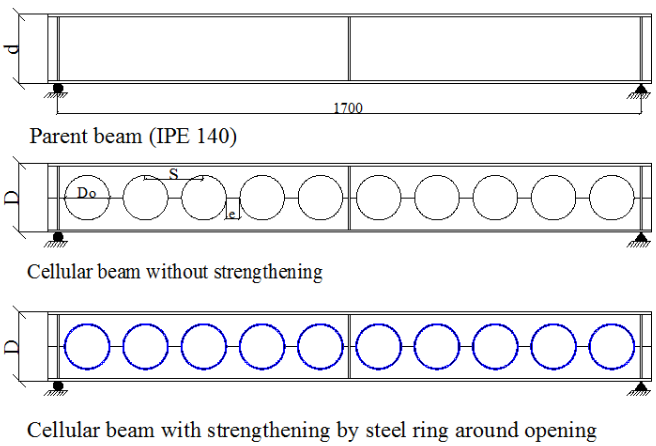

Fig.(5). *Specimens Details*

Where :
D: overall depth of cellular beams.
d: parent, I section depth.
D_O: opening diameter.
e: the clear distance between two successive openings.
S: spacing between two openings center to center.
Br: Steel ring width.
Tr: Steel ring thickness

4 MATERIALS PROPERTIES

In this test, a tensile test was carried out on standard coupon specimen according to ASTM A370 [6] as to select the yield and ultimate stress that were (Fy=300MPa) and (Fu=400MPa). On the other hand, the elastic modulus and Poisson ratio were considered (E=200GPa) and (0.3) respectively.

5 TEST PROCEDURE

In this study, all specimens were strengthening by placing transverse stiffeners under applied load and supports position to prevent local buckling in the web due to the effect of the point load. Also, a bracing system was provided to avoid the lateral torsional buckling [7] that which was not considered in this study. The specimens were placed in the test machine with adequate care taken to make sure that specimens were placed in correct situation and the mid-span of the beam was in line with the hydraulic jack centerline as explain in figure (6). All specimens were tested with simply supported conditions and single applied load at mid-span. The load was applied using load machine of (1000 kN) capacity that connected with a data logger to record the load and deflection value. The test was executed at Engineering College Laboratories of Kufa University.

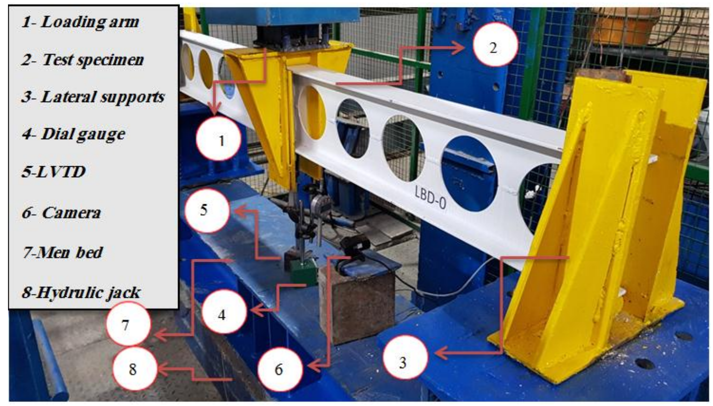

Fig.(6). *Test Procedure*

6 EXPERIMENTAL RESULTS

The experimental results that will be explained in the next paragraphs including the failure mode yield load, ultimate load and load against mid-span deflection curves to assign the structural behavior of cellular steel beams in case of with and without strengthening by steel ring stiffeners around openings and compare the results with the parent section to indicate if there is a benefit in the fabrication procedure.

6.1 Control Beam Results

The parent I-section (IPE 140) was the first beam which tested in this study and it was used as a control beam for others specimens to compare the results with cellular beams with and without ring stiffeners. This specimen was failed due to the overall flexural mechanism where, the region above the neutral axis becomes under compression while tension stress was generated in the bottom region as shown in figure (7). The yield load was recorded (50.2 kN) with deflection (7.9mm) while, the ultimate load was (55.6KN) with deflection (35.3mm)

Fig.(7). *Failure Mode In Control Beam*

6.2 Results Of Specimen LBD-O

The first specimen of the cellular beam that which tested in this study was (LBD-O). It was failed due to the formation of web post-buckling where, the first signification for this failure appeared with load (56.7KN) with mid-span deflection (5.5mm) and the web-post was keep moving outside of the web plane until the failure load (72.9KN) with mid-span deflection (39). This beam was achieved an increasing ratio of about (31%)

than the parent beam. figure (8) illustrated the web-Post Buckling mechanism where, a horizontal shear force that was effect along the welded joint of web-post formed a tensile stress region along opening edges (AB and DG) while, compression zone was formed at edges (CD and BE). The compressed side tends to move away from the longitudinal axis of the web plane while the tensile stress zone tends to keep in the same position. This contrast in stress distribution makes the web-post failed with distortion shape is like a propeller.

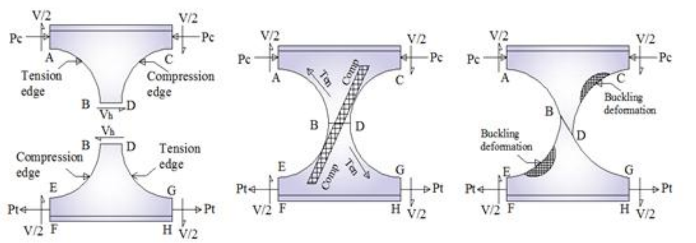

Fig.(8). *Web-Post Buckling Mechanism*

The deformation of this specimen before and after the test is shown in figure (9)

Fig.(9). Failure Mode In LBD-O

6.3 Results of specimen LBD-R

The second specimen of cellular beams (LBD-R) was fabricated with the same geometric properties of (LBD-O) but, the opening was strengthened with steel ring stiffeners with geometric properties (Br=37mm and Tr=3mm). This specimen was failed due to the formation of plastic hinges at four corners of mid openings that which located under the applied load where the maximum shear and moment was presented that result Virendeel mechanism failure. The first yielding appeared with load (63.8KN) with mid-span deflection 5.1 and the ultimate load was (137KN) with mid-span deflection (46mm). this beam was achieved an increasing ratio in ultimate load about (147%) than the parent beam. This tested showed the effects of using a steel ring to prevent the web-post buckling. The failure mode of this beam is shown in figure (10)

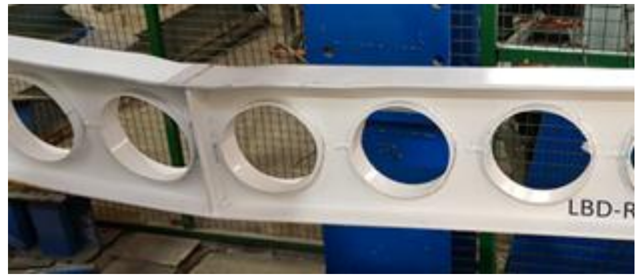

Fig.(10). Failure Mode In LBD-R

7 LOAD-DEFLECTION RESPONSE

After testing of all specimens, there are different behavior was noted due to the difference in geometric properties of specimens. In this test, the load-deflection curves considered as an indication to assign the structural behavior. The load-deflection curve was recorded by using LVDT (linear vertical displacement transducer) that which connected with a data logger. Figure (11) illustrates the load-deflection curves for all tested beams.

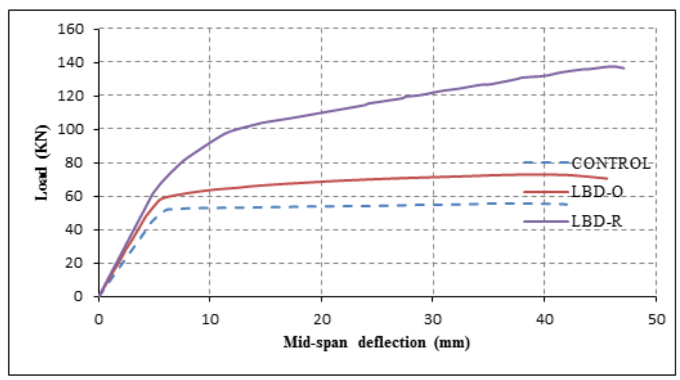

Fig. (11) *Load –Deflection Curves For Tested Beams*

In general, it can be divided the curve for three stages: the first is the linear stage that refers to the linear relationship between load and deflection, the second stage is elasto-plastic stage that refers to starting yielding in specimen where increasing in deflection happened with a small increase in load increment and the final stage is the plastic stage where in this stage a large increase in deflection with small load increasing ratio and the failure has happened in this stage In general, this test was showed that the cellular beam has a stronger response than the solid beam that because increasing depth led to increasing the moment of inertia that has a reverse relationship with the deflection. Also, the cellular beam with strengthening showed more response than the other beams because of the additional moment of inertia the provided by a steel ring.

8 RESULTS SUMMARY OF TESTED BEAMS

Table 2 is summarized the result of tested beams at yield and ultimate stage

***Table 2:** Results Summary*

Beam	Py (kN) Yield load	Mid- span deflection (mm)	Pu Ultimate load (KN)	Mid-Span Deflection (mm)	Failure mode
control	35.2	7.9	55.6	35.4	Overall bending
LBD-O	72.9	5.5	72.9	39	Web-post buckling
LBD-R	63.8	5.1	137.4	46	Vierendeel mechanism

9 ECONOMIC FEASIBILITY OF USING CELLULAR BEAMS WITH AND WITHOUT STRENGTHENING

Since the test results showed that the fabrication process to transfer the solid webbed beam to cellular beam with large web-opening that provide a service path for different serviceability purpose can be increased the ultimate load up to (31%) without any additional materials therefore it can be considered that the cellular beams as a good solution to increase the load carrying capacity than the solid beam without any additional material. On the other hand, this test showed a considerable increase in ultimate load when using steel ring stiffeners around openings where, the ultimate load increased with ratio about (147%) than the control beam with only added (10.6%) of steel material for strengthening. So, it can be considered strengthening as a very economical solution to improve the structural behavior of cellular steel beams as shown in Figure (12).

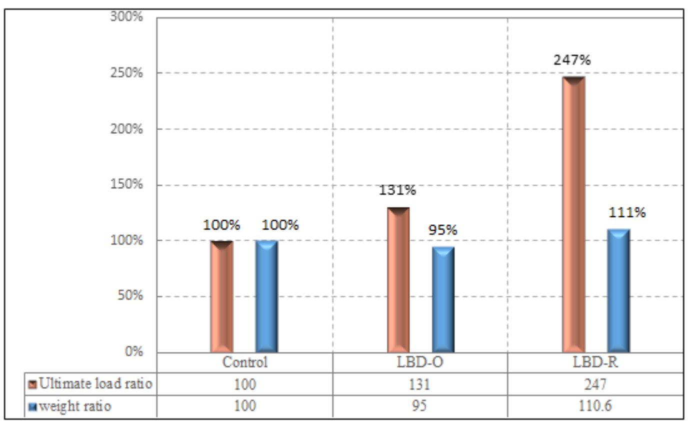

Fig. (12). Economic Feasibility Of Cellular Beams

10 EFFECT OF USING STEEL RING STIFFENERS

The experimental test showed that the dominant failure mode which happened for cellular beams with large web-opening was web-post bucking. This type of failure happened due to the effect of horizontal shear force along the welding joint in the web-post especially with a small clear distance between openings. Therefore, in this study, a new technique was suggested to resist the horizontal shear force which was placing a steel ring stiffener inside the web-opening. The main aim of using this type of stiffeners was to transfer the section at the opening from (T-section) to (I-section) as shown in Figure (13) that mean increase the are of web-post that which locate perpendicular to the horizontal shear force.

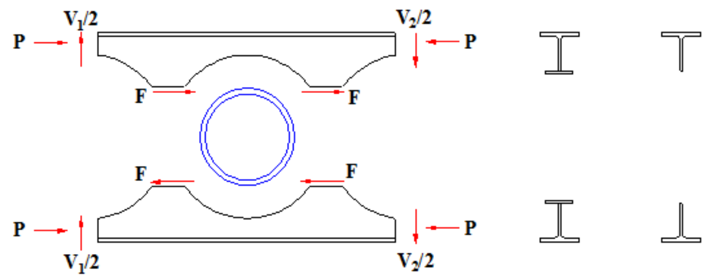

Fig. (13) Effect Of Steel Ring On Cellular Beams Behaviour

11 FINITE ELEMENT ANALYSIS

Finite element analysis was executed by using ANSYS program version.15. The purpose of current study was to model the tested beams and compare the results with experimental results. Also, study more parametric study which related to steel ring stiffeners such as steel thickness and distribution.

11.1 Element type and boundary conditions

A full-scale steel beam was modeled by using a single element type that was SHELL 181. This type of element was needed to define the element thickness only. On the other hand, the supporting conditions and loading type were modeled as the same as of the experimental test as much as possible where, one of the specimen ends was restrained against the horizontal movement while the second end restrained against horizontal and vertical movement (as simply supported beam) as shown in fig Figure (14). Also, the applied load was modeled with a line load along the flange width at the mid-span as shown in Figure (15).

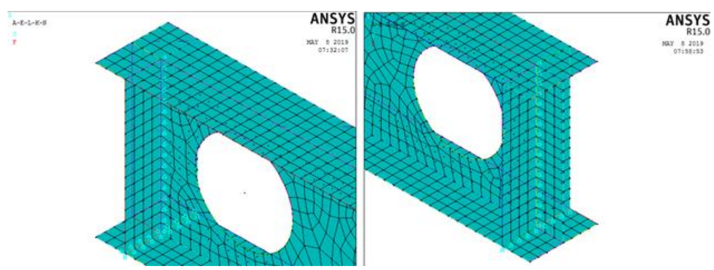

Fig. (14). Supporting Condition

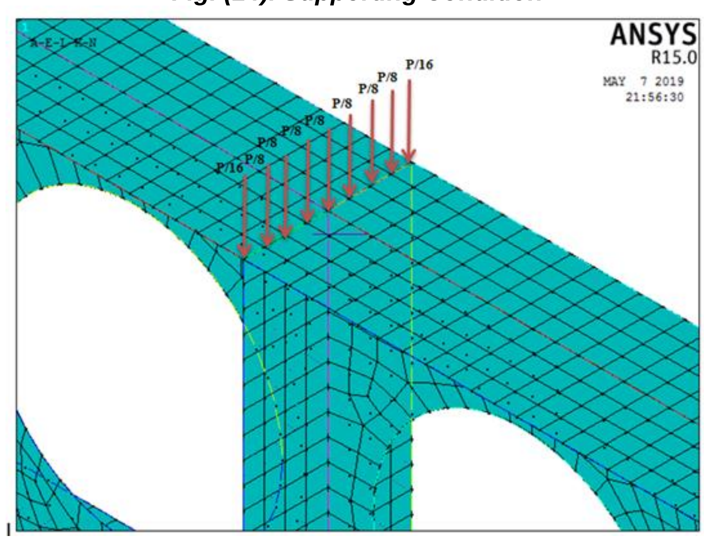

Fig. (15). Applied Load By ANSYS

11.2 Meshing Size

Before the analysis of any specimen in ANSYS program, it's very important to choosing a suitable element size to get accurate results. Therefore in this study, many element lengths were tested they were (50, 40, 30, 20, 15, 10, 5, and 205) mm with fixed load value (KN)and record the deflection value. It was noted that when element length equal to or more than (10mm) the results approximately have the same value as shown in Figure (16). Therefore, in this study fixed the element length with (10mm).

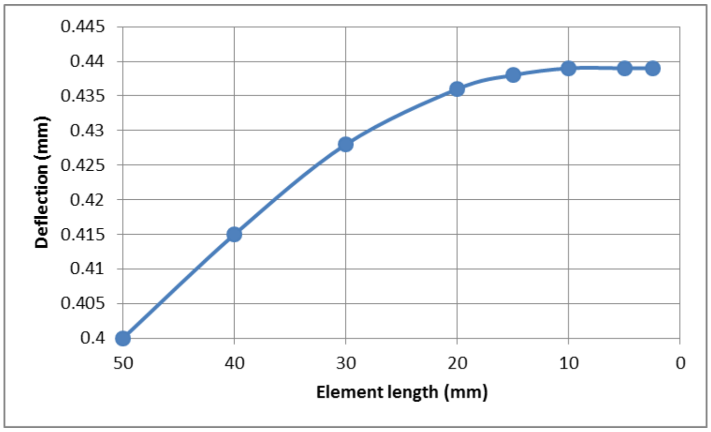

Fig.(16). Testing Element Length

11.3 Finite Element Results

Since the load-deflection curves considered as an indication for structural behavior of cellular steel beams, the next paragraphs explain the load-deflection curve for all tested beams. Based on the finite element results, it was founded a good agreement with experimental results where, the control beam record an ultimate load (57.1KN) with increasing ratio about (2.8%) than the experimental results. While (LBD-O) achieved ultimate load value (83.4KN) with increasing ratio (14%). And finally, the (LBD-R) recorded ultimate load (145KN) with increasing ratio (5%). Figure (17), Figure (18), Figure (19) shown the load-deflection curves of the finite element with comparing with experimental curves.

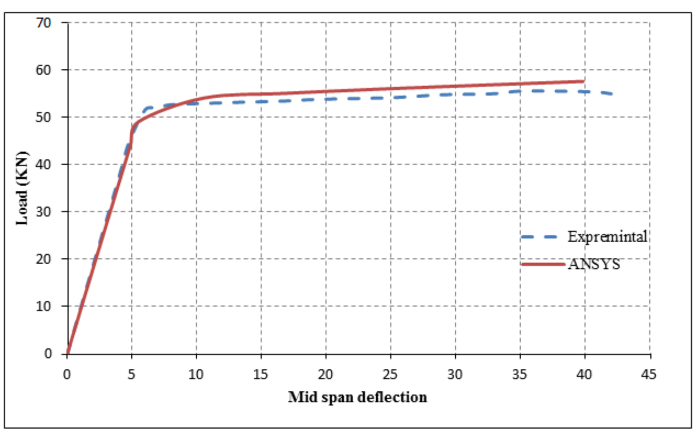

Fig. (17). Load-Deflection Curves Of Control Beam

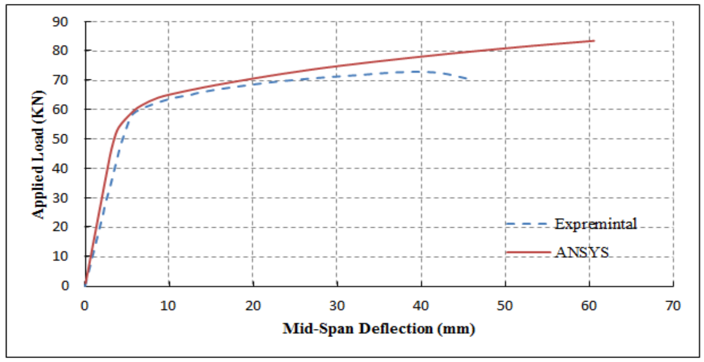

Fig. (17). Load-Deflection Curves Of LBD-O

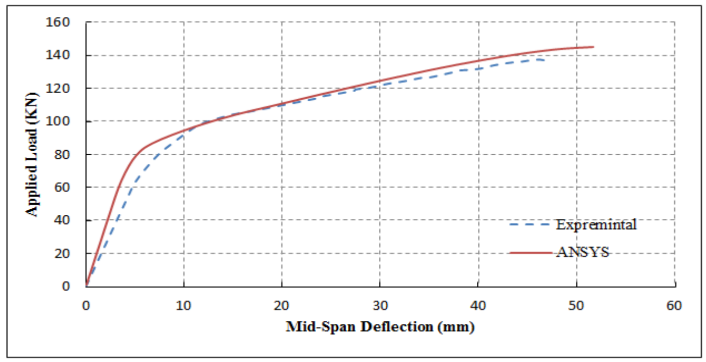

Fig. (19). Load-Deflection Curves Of LBD-R

11.4 Deformation Behavior Of Modeled Beams

Finite element analysis showed a deformation shape similar that was appeared in the experimental program. Where, the control beam was failed due to the overall flexural mechanism shown in Figure (20)., for beam (LBD-O) it can be noted the stress concentration in the web-post area that causing the web-post buckling shown in Figure (21). and for beam (LBD-R), it was clear that the effect of strengthening to reduce the stress concentration in the web-post area and transfer to concentrate around the middle openings (under applied load that which result in a Vierendeel mechanism as shown in Figure (22).

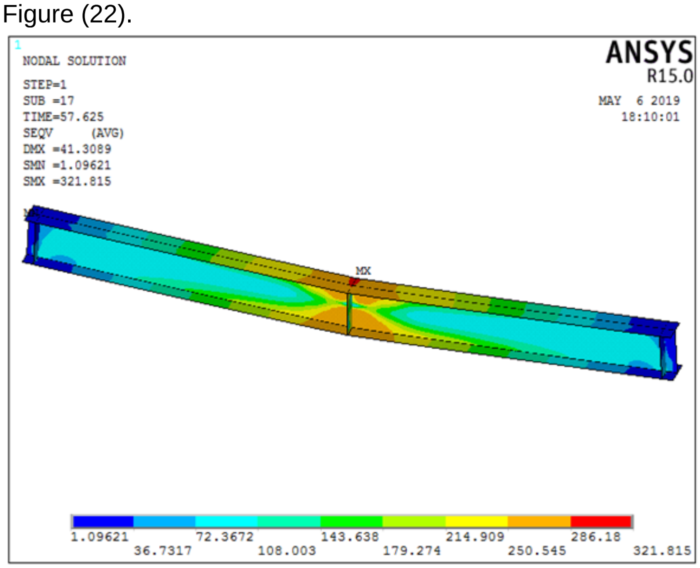

Fig.(20). Deformation Shape Of Control Beam

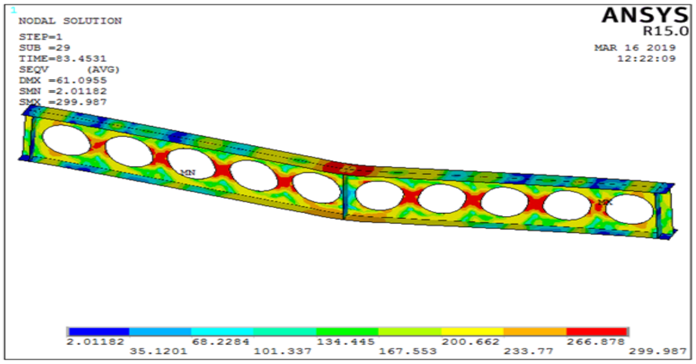

Fig.(21). Deformation Shape Of LBD-O

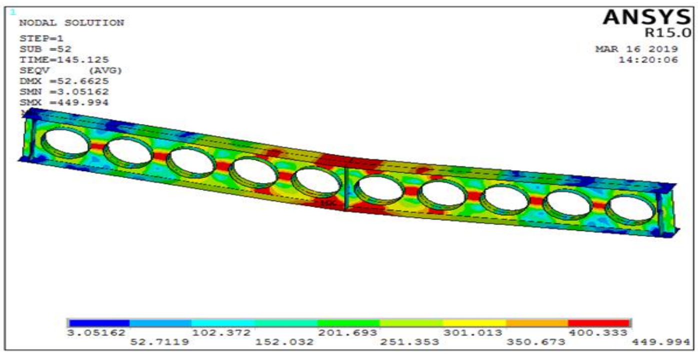

Fig.(22). Deformation Shape Of LBD-R

11.5 Parametric Study

Since this study has approved the effect of steel ring to improve the structural behavior of cellular steel beams and increase the load carrying capacity, therefore, it was very important to study more parametric study that related with the steel ring properties to select the perfect case of strengthening. In this study, the effect of steel ring thickness was investigated with four cases (0.25, 0.41, 0.69, and 1) times of flange thickness. The results showed it's no feasible to use ring thickness more than 0.69 times of flange thickness (Br=5mm as the same as the web thickness) as shown in Figure (23).

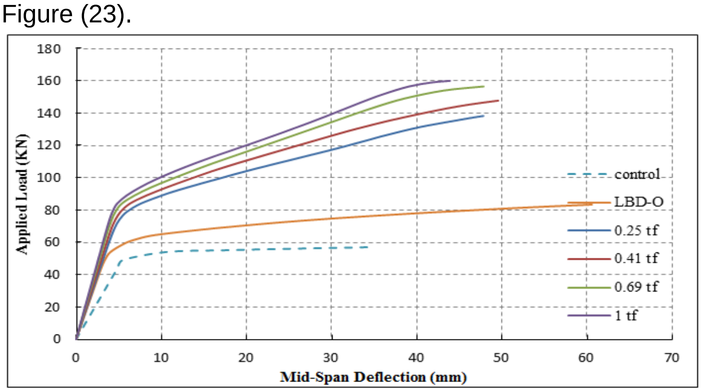

Fig.(22). Load-Deflection Response for Different Strengthening Thickness

12 CONCLUSIONS

1) The fabrication process of the solid beam to cellular beam with expansion depth ratio equal to (1.42) can be increased the ultimate load up to (31%) without any additional material
2) The dominant failure mode for the cellular beam with large web-opening is web-post buckling due to the effect of horizontal shear force that acting in welded joint and using strengthening was prevent this type of failure and transfer it to Virendeel mechanism
3) The results showed that using of steel ring stiffeners is a very effective solution to increase the load carrying capacity up to (147%) than the parent section by using steel ring with geometrical properties (Br=37mm and Tr=3mm) that caused an increase in weight ratio only about (10.6%)
4) Finite element analysis showed a good agreement with experimental results
5) Finite element results showed that increasing steel ring thickness rises the ultimate load up to (172%) than the parent section

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