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Reinforcing the Octagonal Web Openings of Castellated Beam by Steel Rings

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A R T I C L E I N F O

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A B S T R A C T

Castellated steel beams are section steel members with hexagonal or octagonal web openings which they are made from standard hot rolled steel section I or H. The main advantage of these members is their economic material. An additional important advantage is a possibility to guide service ducts through the openings. The presence of the web openings influences the members' failure behavior around the openings, new local failure modes will come into existence, such as the buckling of the web post between the openings, or yielding around the openings. Castellated beams with octagonal openings usually fail due to web post-buckling because of the increase in depth. The current study focused on improving the behavior of the castellated beam with octagonal openings using steel ring stiffener and adjusting the best dimension and distribution for the stiffeners. All the models of specimens have been fabricated from a parent I section (IPE 140). The models have been modeled and analyzed using finite element software ANSYS (version 15). The analysis results showed that reinforcing octagonal castellated beams by adding steel ring stiffeners around octagonal web opening was very active way to increase the ultimate load for long span, where the ultimate load of reinforced octagonal castellated beam increased up to (286%) compared with parent I-section beam. Economically, the percentage of additional steel material which used to expansion and reinforce the castellated beams (spacer plate and steel ring stiffeners) was (36%) when compared with the weight of parent I-section beam. While the allowable load at deflection (L/180) was (260 %) compared to the allowable load of parent section at the same deflection. The gained benefit was increasing the ultimate and allowable load of reinforced octagonal castellated beams by (186%) and (160%) respectively by using additional steel material only (36%) from the weight of parent I- section, which the additional steel material consisted from the spacer plates and steel rings. Also, the results indicate that the best dimensions for the ring were when thickness equal to the web thickness of the parent section and the width equal to the half of the parent section flange width.

1. Introduction

Castellated beams are steel I or H section members with evenly spaced hexagonal or octagonal web openings. Sometimes, it can be added spacer plate to obtain octagonal opening with increasing the depth of members as shown in **Fig. 1**. The castellated steel beam is one of the important improvement in the field of steel structures. Most of the castellated members used nowadays are made by thermally cutting the web of a hot-rolled parent section according to a certain pattern as shown in **Fig. 2**, after that, the obtained halves are welded together to form a member with

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a higher web and with hexagonal web openings. The process of producing castellated beams from rolled sections has been used in steel construction since the late 1930s Boyer [1]. Today the castellated beams are produced widely and the production cost has been reduced due to the development of equipment of the two main steps, the cutting, and welding, which made them as an alternate choice to open-web steel joists in floor systems.

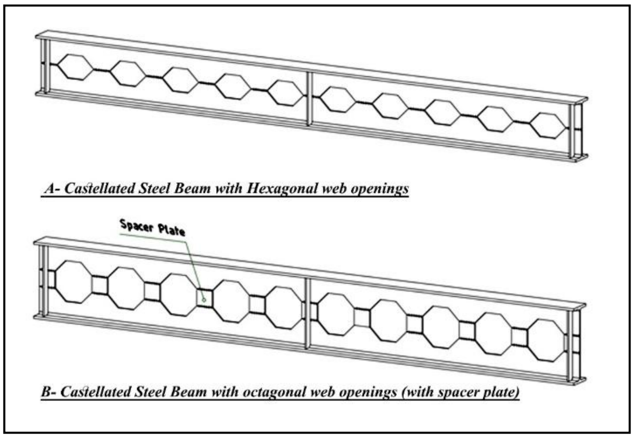


Figure 1: Castellated Steel Beam with Hexagonal and Octagonal Opening

Figure 2: Thermally Cutting the Web of a Hot-rolled Parent Section for Tested Specimen

The castellation process increases the overall depth of the parent section, this increasing contribute effectively in modifying the strength of castellated beams in comparison with the strength of parent section. The other type of castellated beams is with octagonal openings which could be produced by adding addition steel plate between the two parts of the tee sections, this steel plates called "Spacer Plates" " (Zaarour and Redwood, [2]),and this raises the depth up to two times of parent section depth, as shown in **Fig. (1-B)**. The existence of openings in the web in this type of steel members leads to redistribute the stresses around the openings which as a results effects on its collapse behavior Soltani et al. [3]. Also, the presence of these openings decreases the stiffness of beams which leads to larger deflection. Castellated beams with octagonal openings had larger web depth than castellated beams with hexagonal openings and this lead to an increase in the slenderness of web post which as result lead to failing the web by buckling.

The present research aims to establish a numerical study to develop strength the castellated beams with octagonal openings by reinforcing the openings with steel ring as shown in **Fig. 3** and adjusting the best dimensions and distribution for the steel rings. The numerical study deals with both materials and geometric nonlinearity in analyzing the tested beams to perform the finite element using (ANSYS Ver.15) program.

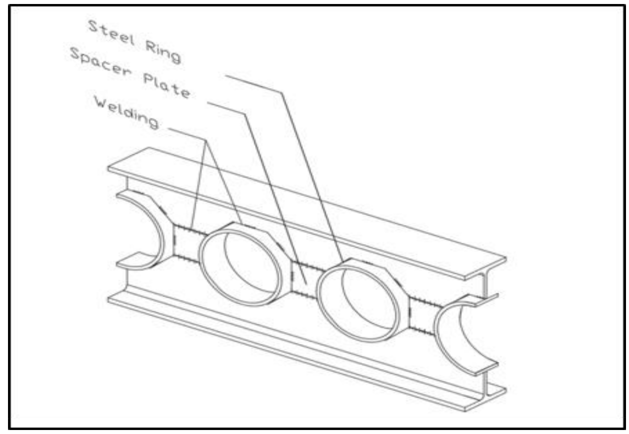


Figure 3: Octagonal Castellated Steel Beam Reinforced by Steel Rings

Numerical models using finite element software ANSYS (Ver. 15) are developed in order to validate the modelling process. The verification process included simulation the experimental specimens numerically using ANSYS program and comparing the results with those conducted from experimental results.

2. Previous Studies and Research Gap

Sung C. Lee, et. al. [4] three numerical models have been analyzed of plate girder using ADINA ("Automatic Dynamic Incremental Nonlinear Analysis", 1999) program, and evaluate the same model with three stiffeners plate. Shear analogy model has been used to explain the buckling behavior of the shear web. The results showed that the transverse stiffeners contribute effectively in strengthening the web of a beam in spite of the stiffeners are not subjected to a compression force. Ehab Ellobody [5] : the interaction buckling failure modes have been studied experimentally and nautically for castellated beams with normal and high strength. The experimental program consists of six full-scale beams with different lengths and depths. Then, the numerical results verified against experimental tests. After that a numerical parametric study to investigate the effect of beam length, the geometry of cross section, and steel strength. They concluded that the incidence of buckling of web leads to a significant decreasing in the failure load of beam, also the results shown that using high strength steel increasing considerably the failure load. Also, it observed that the lateral torsional buckling more likely to happen in normal strength castellated beam, while high strength castellated beam tends to fail in web distortional buckling. Wakchaure M.R [6]: An experimental parametric study to investigate the effect of increasing the depth of castellated beams with hexagonal opening shape, for various failure modes. The tested beams were simply supported with two applied point loads. The parent beam depth increased by 40,50 and 60% with angle 60o of hexagonal opening in process of castellation. The results showed that the increase of depth increases the moment carrying capacity, and the castellated beam behaves satisfactorily with increasing the depth 40, 50 % up to maximum depth 60 % of parent beam which shows average results. They also recommended providing a transverse stiffener to under applied load in order to avoid local failure and reinforcing the beam's weak sections.

Jamadar and Kumbhar [7] : A parametric study concerned about optimizing castellated beam with circular and diamond opening shape through two factors, the first was the ratio between the castellated beam overall depth to opening depth, the second was the ratio between the spacing between openings to opening depth. The numerical models were modeled through finite element software ABAQUS, the models were following the Eurocode 3 provisions. The results showed the optimized dimension for diamond shape opening castellated beams was when the opening depth of 0.67 times original beam depth, and for circular opening shape castellated beams when opening depth 0.73 times overall beam depth. The castellated beams with diamond shape gave a better strength than the other openings shape. Al- Thabhawee [8], analyzed experimental results of six hexagonal castellated steel beams and parent section (control beam). He investigated the effect of hexagonal opening geometry and number on the behavior of castellated steel beams that have the same span and ratio of expansion. The test results showed that best dimension of castellated steel beam was a ratio of length to opening space (L/S =8.0) and a ratio of opening high to beam depth (h/H=0.56) and the failure load of castellated steel beam was increased about (50%) stronger than the control beam. In 2018, Al-Thabhawee and Al-Kannoon [9] used finite element models by ANSYS14 software to improve the behavior of hexagonal and octagonal castellated beam with spacer plate by reinforced opening by steel ring. The increment of castellated beam depth by spacer plate leaded to post buckling in its web and to many other modes of failure when these beams are subjected on loading." It was revealed that using ring steel stiffeners can reduce the stress concentration around the edge of openings and improve the behavior of these beams by increasing the failure load and minimizing the deflection.

From the previous studies, it can be concluded that due to ease of manufacturing castellated beams with hexagonal or circular opening shape, so most of the researches focused on these types of castellated beams and they are widely used in different constructions, these lead to lack in researches that concern about the castellated beams with octagonal openings (by additional spacer plate) and examining the structural behavior of this type of castellated beams, in addition, most of the research indicated the failure of this type happened due to local buckling in web portion. Also, most of the studies focused on optimizing the dimension of castellated and as noticed there is no studies has been carried out to improve castellated beam with octagonal openings to avoid local failure. It noted that increase in the strength of castellated beams leads to significant changing in the behavior. Also, the previous studies deal with a response, failure modes and the interaction between the failure modes.

3. Finite Element Analysis

The calibration process has been prepared by comparing the experimental results with the result of nonlinear finite element models. Two types of non-linearity have been implemented in the analysis of numerical models in order to determine results as close as to real cases, which they were geometrical and material non-linearity. The element (SHELL 181) was chosen to simulate the castellated beams models, as shown in **Fig. 4**. The element used to the model of steel I-section and stiffeners. It consists of a four-node element with six freedom degrees per node. This element is well suited for analyzing application with nonlinear behaviors [10].

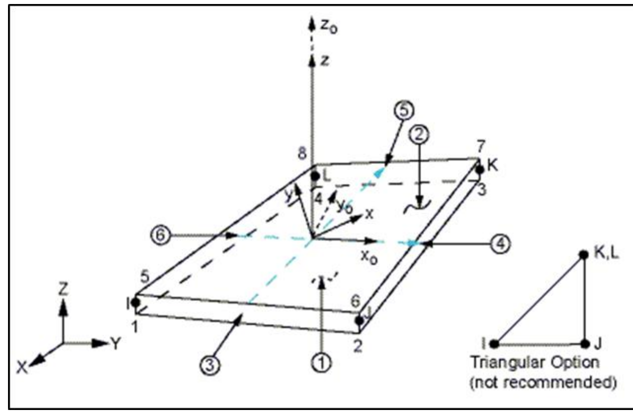


Figure 4. SELL181 Element (ANSYS)

4. Verification of Finite Element Models

Three experimental specimens (Control, CBC-02, and CBC-03) tested by Al-Thabhawee and Mohammed at Laboratories of Engineering Faculty of Kufa University and selected to verify the analysis using ANSYS software (ver. 15) as shown in **Fig. 5**. These beams were loaded by one concentrated load at mid-span. The dimensions and properties of a castellated steel beam in experimental and numerical work were clarified in **Fig. 6**.

Figure 5: Test Setup for Specimens

The analysis of castellated beams models performed to be calibrated with results executed from the experimental tested castellated beam. The verification process focused on verify control beam (IPE140) and octagonal castellated beams with and without reinforcement with properties and dimensions as same as the experimental program. The material properties were obtained by tension tests on flat tensile specimens according to ASTM [11] as clarified in **Fig. 6**. The results of models obtained by the finite element analysis which included the load versus deflection curves have been compared with experimental load

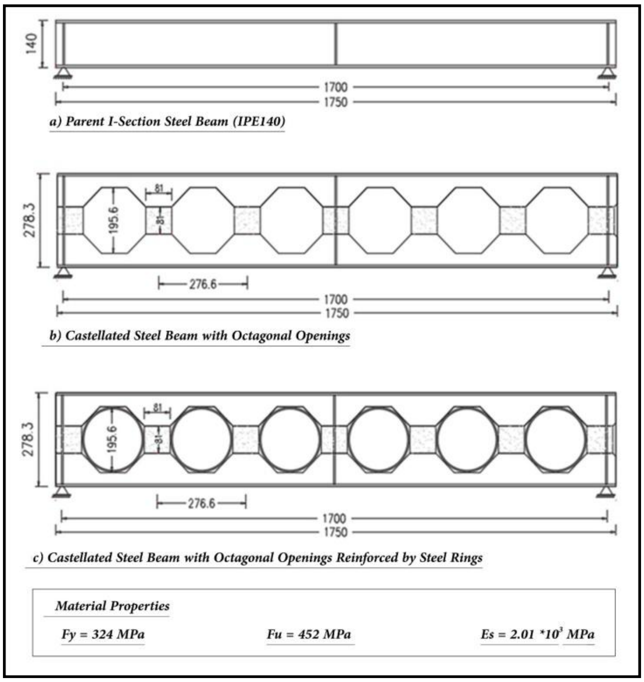


Figure 6: Dimension and Properties for Tested Specimen

In addition to the distribution of stresses which represent the stress concentration along the beam areas, for tested beams were presented in the following paragraphs. The finite element models for the parent section and octagonal castellated beam with six openings and meshing are displayed in **Fig. 6**.

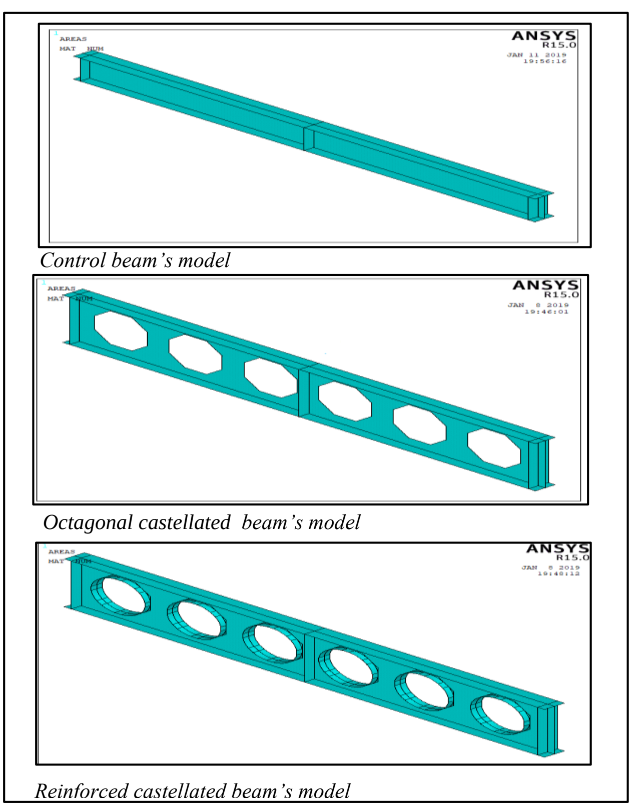


Figure 7: Models of Parent and Castellated Steel Beams

The numerical models for tested beams and them mesh shown in **Fig. 7**. The results showed that the numerical ultimate load capacities were a little greater than the experimental ultimate load capacities for the tested cases. The results showed a convergent response between the experimental results and finite element solution through the range of loading. These results confirm that it could be used the numerical model to deal with castellated steel beam specimens for this load and support conditions as shown in Load-deflection response curves for the numerical and the experimental work for specimens in **Fig. 8**. The Von-Mises stress distribution of the model results at failure load is shown in **Fig. 9** at failure load. It could be noticed that the numerical models' behavior is similar to experimental behavior.

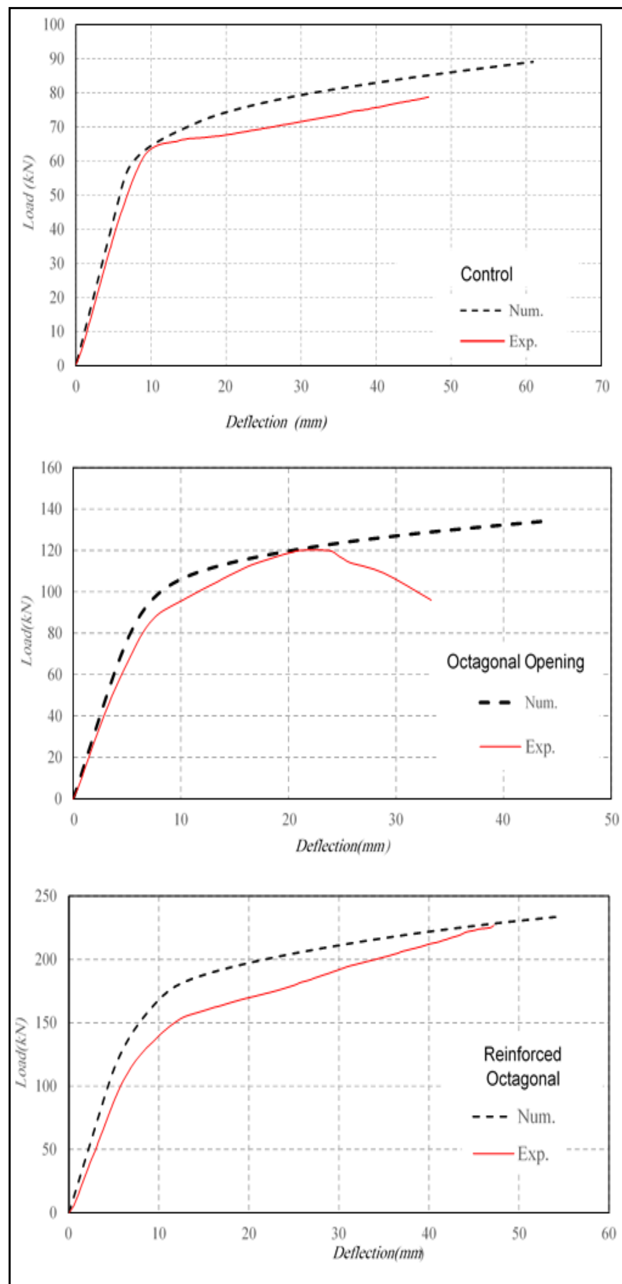
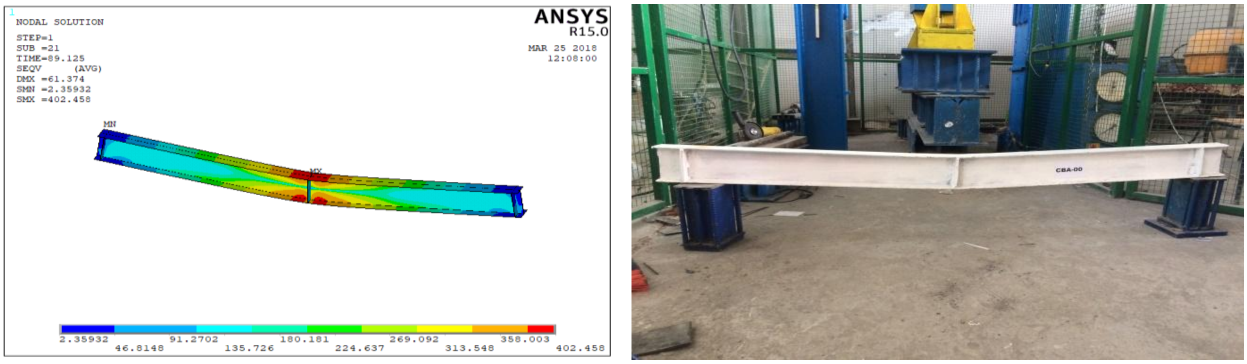
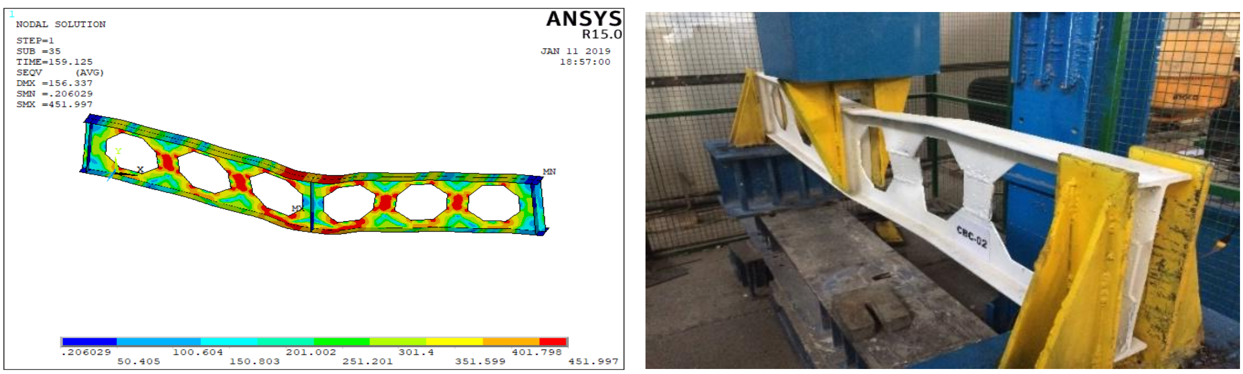


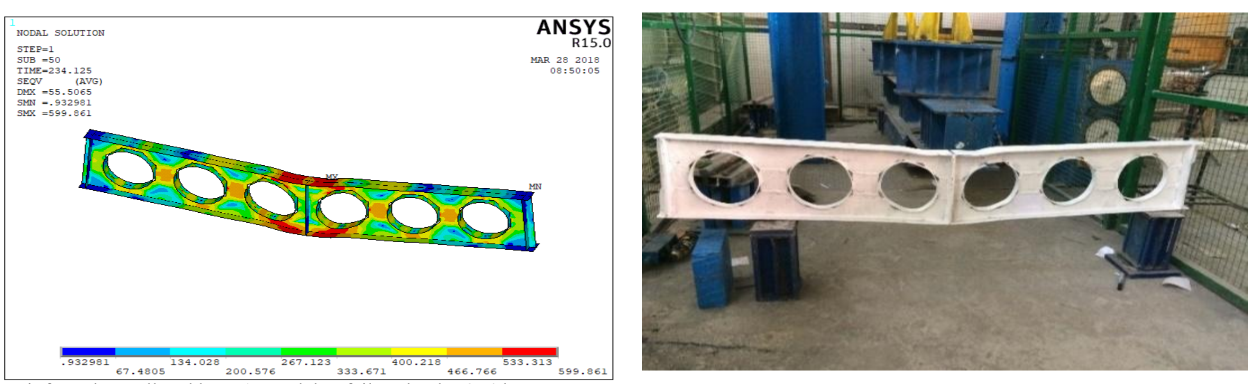
Figure 8: Experimental and Numerical Load -Deflection Curves for Specimens



Control beam's model at failure load = 89 kN



Octagonal castellated beam's model at failure load = 159 kN



Reinforced castellated beam's model at failure load = 254 kN

Figure (9): Distribution of Von-Mises Stress for Specimens

5. Reinforcing the Octagonal Web Openings

The second portion of the numerical study after modelling the tested castellated beams and calibrate the process of modelling by comparing the numerical results by experimental results, a study has been established. Based on the experimental program the steel ring stiffener for the octagonal castellated beam with expansion depth ratio (1.99) gave the maximum results, so the study focused on this type of stiffener and this expansion ratio of the castellated beam.. The verified finite element modelling process was used to study the effects of using different span length with different properties for ring stiffener which included using the steel ring stiffeners in regions where the maximum moment will be located in manner similar to reinforcing, also study the effect of thickness and width of rings for castellated with octagonal openings. The specimen's length was (5.50m) length. **Fig. 10** displays the key details and dimensions of the steel ring which used as reinforcement to strengthen the octagonal openings of castellated beam. The steel rings were with thickness (t=5 mm) and width (B=36.5 mm). All the models were modelled by using the finite element software ANSYS (Ver. 15). **Fig. 11** summarizes the dimensions' properties of the studied castellated beams and the parent section. These parameters used to study the effect of steel ring parameters on the load versus deflection response and allowable load also the increment in weight due to these parameters.

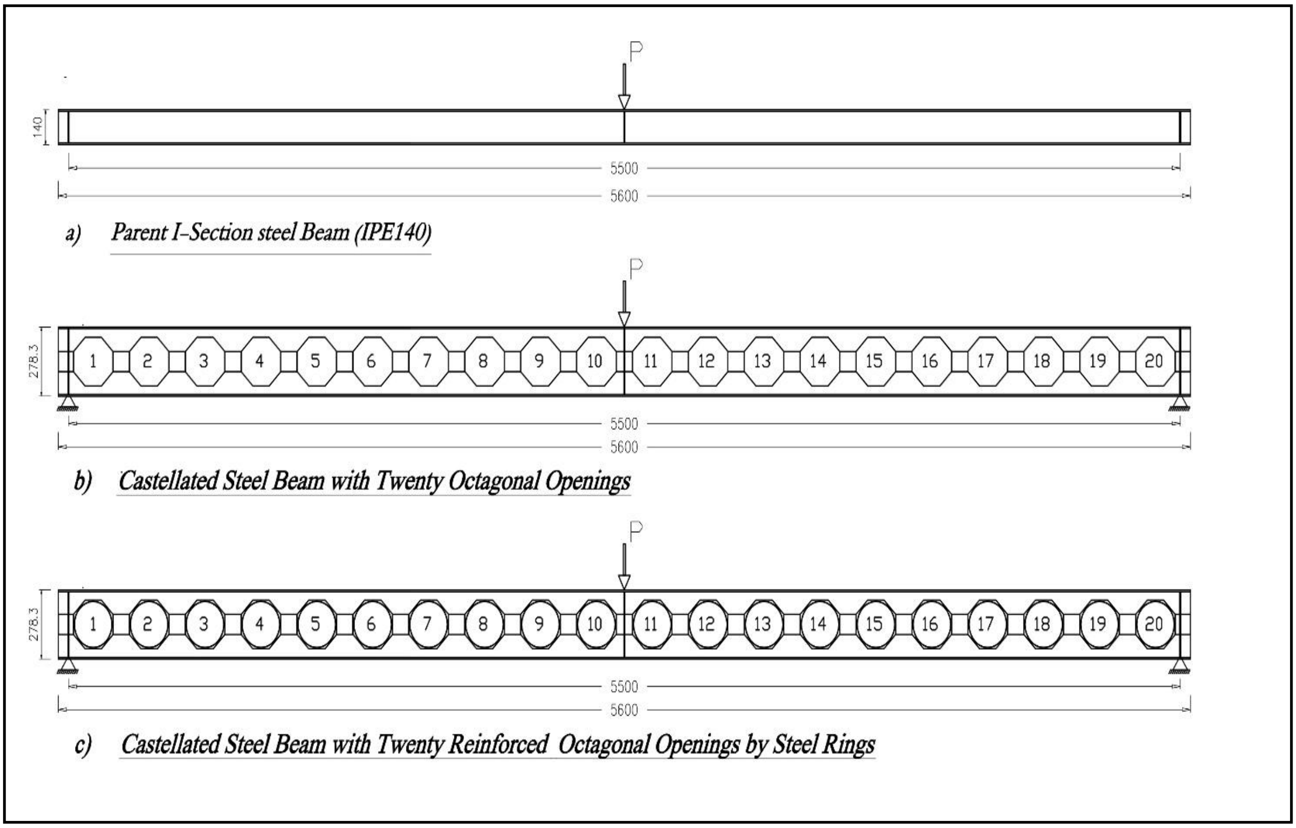


Figure 10: Dimensions of Models

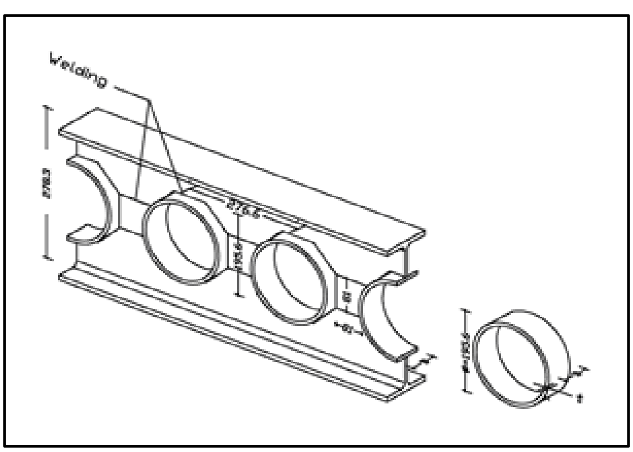


Figure 11: Characteristics of Ring Steel Stiffener

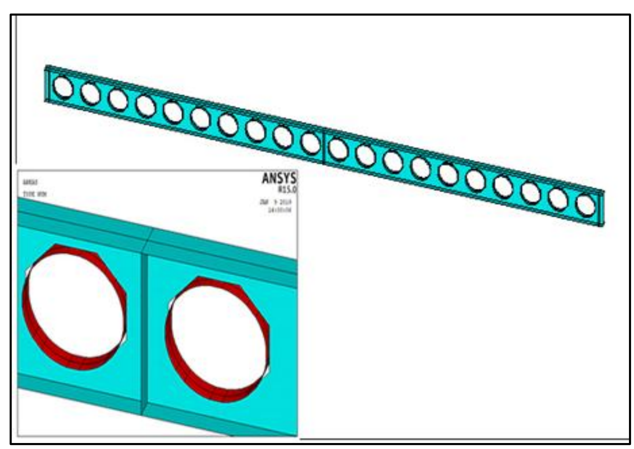


Figure 12: Model of Reinforced Castellated Beam

Fig. 12 illustrates the model of the reinforced octagonal castellated beam by welding steel ring stiffener around octagonal opening, which is modeled using ANSYS software. The analysis results showed that the ultimate load of castellated beam with octagonal opening (with adding spacer plate) is (110 %) more than the ultimate load of the parent beam.

In addition, the ultimate load of the reinforced castellated beam by steel ring stiffeners was improved up to (186 %) more than the ultimate load of parent section, while the ultimate load of reinforced castellated beams is improved to (76 %) compared to the ultimate load of castellated beam without reinforcement, as illustrated in **Fig. 1**3.

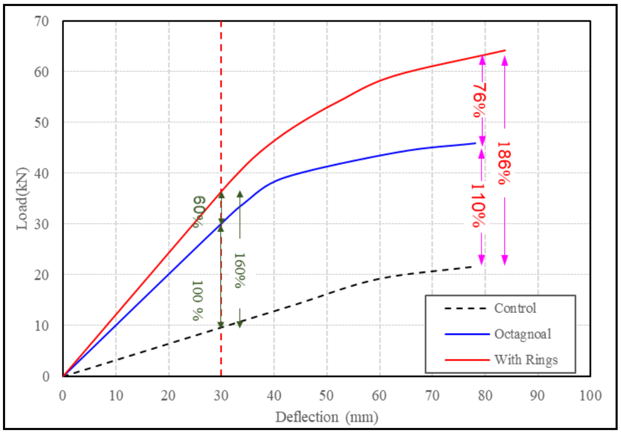


Figure 13: Load - Deflection Curves of Castellated Beam With and Without Ring Stiffeners

Most of the times, flexural members are required by IBC (International Building Code) [12] to be designed to have adequate stiffness to limit deflections. In this study, the allowable load of castellated beams estimates based on the limited deflection that IBC is recommended (L/180). For model specimen the maximum deflection which its length was (5.5 m), the deflection was (30 mm), and based on that results the comparison between cases of study have been prepared. The results based on this criterion showed that the allowable load of octagonal castellated beam without steel ring is (100 %) more than the allowable load of the parent beam and the allowable load of the reinforced octagonal castellated beam by steel ring stiffeners was reached up to (160 %) more than the allowable load of parent section, while the allowable load of reinforced castellated beams by steel ring stiffeners is improved to (60%) compared to the allowable load of castellated beam without steel ring stiffeners, as clarified in **Fig. 13**.

In the other hand (economically), the total weight of reinforced octagonal castellated beam increase with using spacer plate and steel ring stiffeners. In the presented work, the percentage of original section and additional steel material which used to expansion and reinforce the castellated beams was (136%) compared to the weight of parent beam. The benefit gained was increasing ultimate and allowable load of reinforced octagonal castellated beams by (186%) and (160%) respectively with using additional steel material only (36%) as shown in **Fig. 14**.

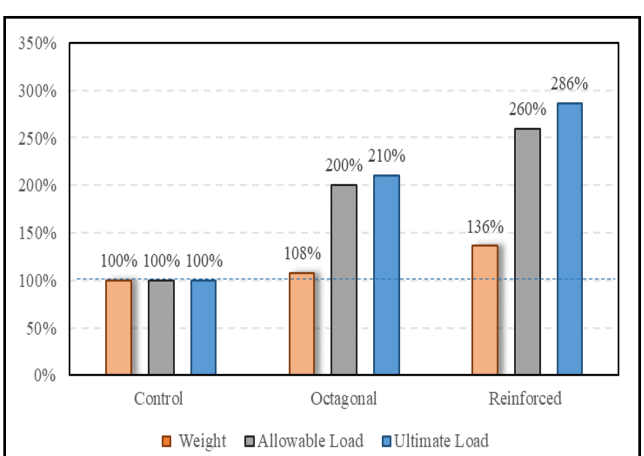
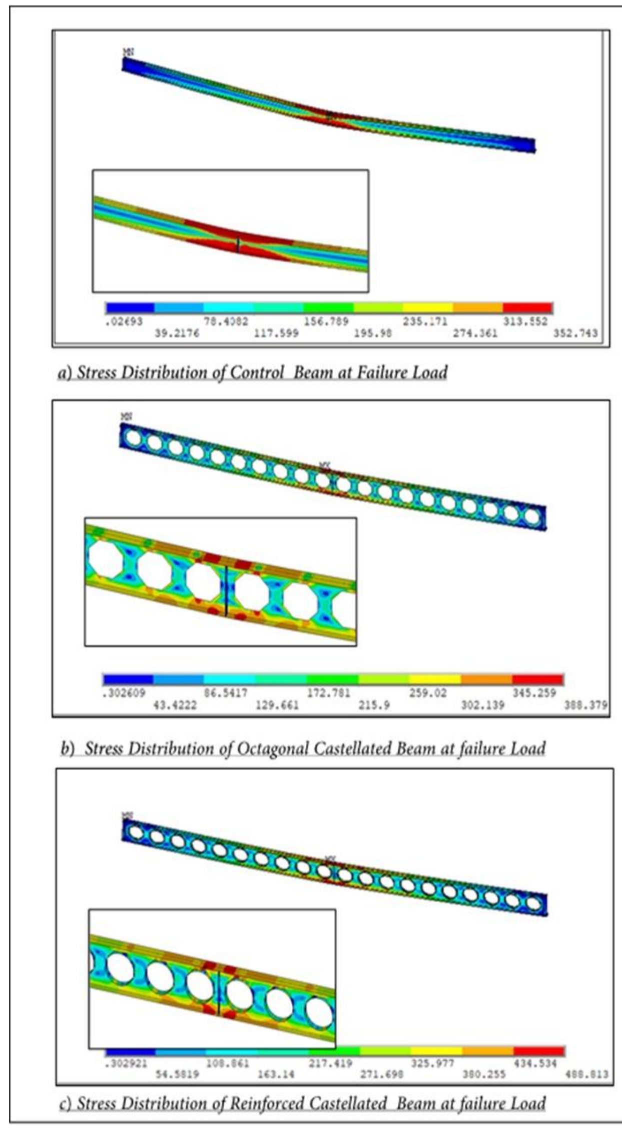


Figure 14: Ratios of Weight, Ultimate Load and Allowable Load of Models

Due to high strength of reinforced octagonal castellated beam as shown in results, it could use compositely with concrete since the concrete slab contributes in increasing the ultimate load of composite section Al-khekany and Muteb [13]. The finite element results showed that reinforcing castellated beams by steel ring improved the stress distribution compared with non-reinforcing castellated beam and parent section, as displayed in **Fig. 15**. Also, it can be observed that the use of ring steel stiffeners contributes effectively in minimizing the deflection and increasing the ultimate and allowable load, this may do to that the steel rings reduced the stress concentration around the openings.



a) Stress Distribution of Control Beam at Failure Load

b) Stress Distribution of Octagonal Castellated Beam at failure Load

c) Stress Distribution of Reinforced Castellated Beam at failure Load

Figure 15: Stress Distribution for Castellated beam and Control Beam of Reinforcing Study

5.1. Effect of Thickness of Ring Steel Stiffeners on Allowable Load

The first parameter was ring thickness. Different thicknesses have been studied based on the thickness of the web (as a ratio of web thickness). The thicknesses were (1.5,1.25, 1.5,1.25,1,0.75 and 0.5) from web thickness for the same width which was equal (0.5) flange width.

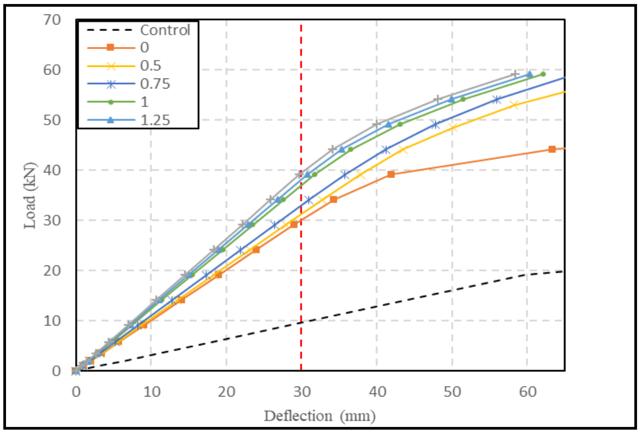


Figure 16: Effect of Ring Thickness on the Behavior of Castellated Beams

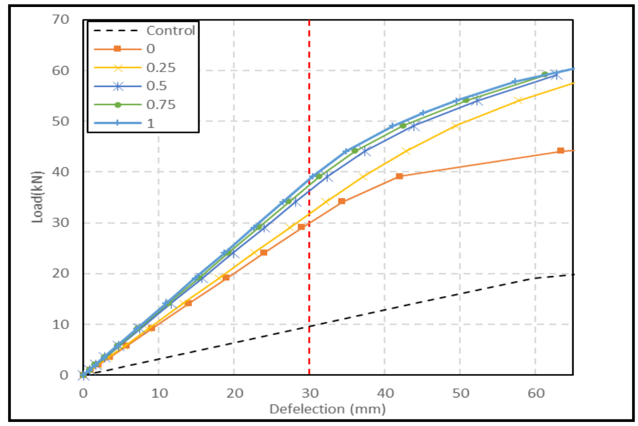


Figure 18: Effect of Ring Width on the Behavior of Castellated Beams

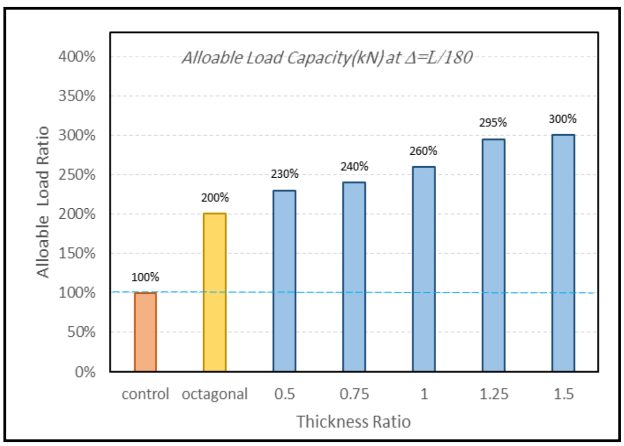


Figure 17: Allowable Load Capacities of Different Ring Thicknesses

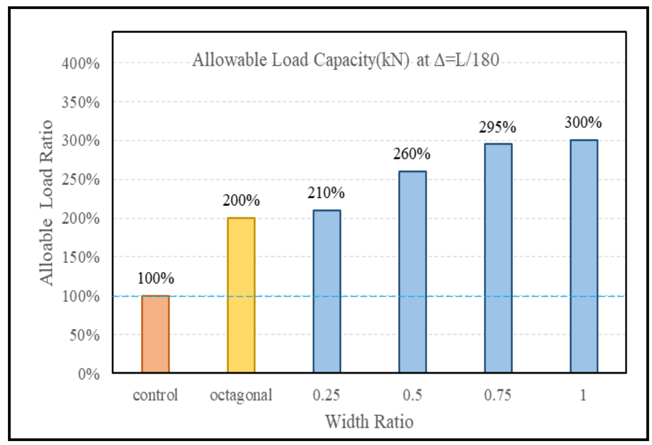


Figure 19: Allowable Load Capacities of Different Ring

The models were analyzed by nonlinear finite element method using the ANSYS program. **Fig.** 16 summarized the effect of thickness on the behavior of the castellated beam. It could notice that thickness contributes effectively in increasing the stiffness of ring and thus increase allowable load capacity, also it noticed that effect of increasing the thickness become less effective when the ring thickness exceeds the web thickness. As shown in **Fig.** 17.

5.2. Effect of Width of Ring Steel Stiffeners on Allowable Load

The other parameter was the width of the steel ring stiffener; different sizes of width have been studied based on the flange width. The steel ring width were (1,0.75,0.5,0.25) times of flange width and for the same thickness which was equal to the web thickness. All the models were analyzed numerically using the nonlinear finite element method. **Fig. 18** summarized graphically the load versus deflection response for the different width of the stiffener steel ring. It could be noticed that the effect of the steel ring width become negligible if it exceeds half of the flange width. **Fig. 19** summarized the allowable load capacities for the different steel ring stiffeners widths, in addition to the control beam and non-Reinforced castellated beam. The results confirmed that the width of steel ring stiffeners effect become less effective in increasing allowable load when it exceeds (0.5) times of flange width.

5.3. Distribution of Openings Reinforcing

The third parameter was using steel ring stiffener on the places where the maximum moment concentrated, which in case of simply supported beam concentrated in the mid-span. Five cases of reinforcing octagonal castellated beam by steel ring stiffeners have been studied in this study. The steel ring stiffener added dependent on the distribution of bending moment along the span. The cases categorized according to the ratio between the reinforced length (L_r) of octagonal castellated beam and the effective length of beam (L), the five cases ratios were (0.2, 0.4, 0.6,0.8 and 1) as described in **Fig. 20**. The results showed that steel ring stiffeners contribute effectively in improving the strength of castellated beam with octagonal openings, the effect of adding rings mainly enhancing the large web depth of castellated beam with octagonal openings which as aforementioned produced by adding the spacer plate between the two halves of hexagonal castellated beam, and this process increases the depth about two times of the depth of parent I section, which as a result increases the slenderness of web post and made it tend to failure by buckling. In case of applying a concentrated load at mid-span the maximum moment will be concentrated under point load, so to decrease the number of used steel rings will be added in areas where high moment concentration. The analysis results showed that rings effectively in increasing the strength of castellated beams as shown in **Fig. 21**. The analysis results showed that steel ring stiffeners increase effectively the allowable load as presented in **Fig. 22**.

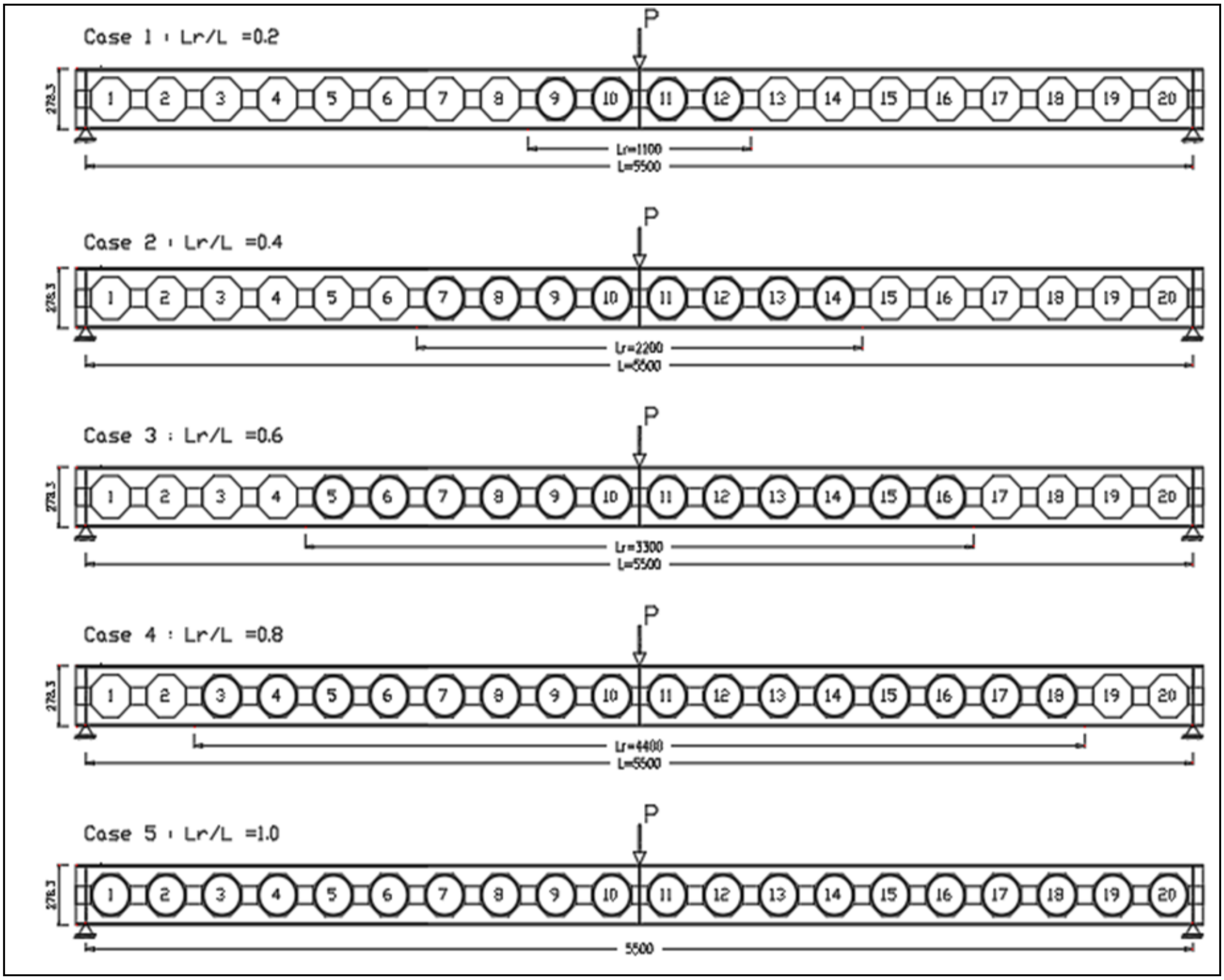


Figure 20: Reinforcing Cases of Different (Lr/L) Ratios.

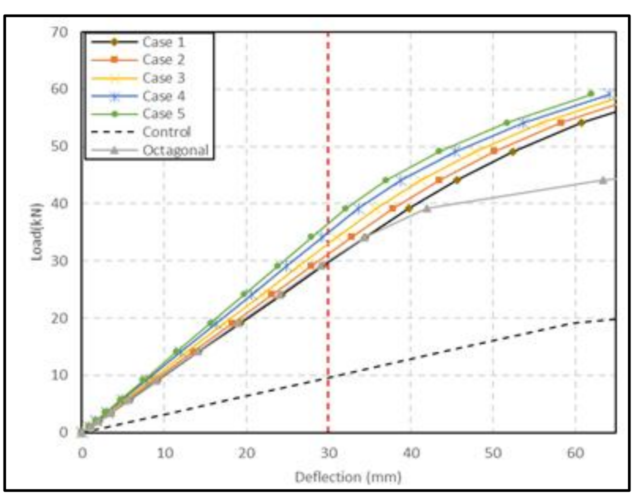


Figure 21: Load- Deflection Curve of Distribution Steel Ring Stiffeners.

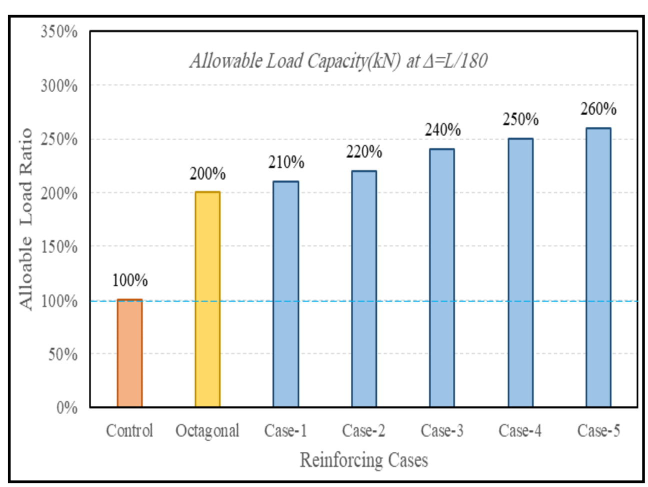


Figure 22: Allowable Load for Deferent Cases of Reinforcing by Steel Ring Stiffeners.

6. Conclusions

1. The finite element model used in the present study is able to simulate the castellated beams with and without stiffeners with a good agreement between response. The predicted ultimate load capacities are in good agreement with the experimental results.

2- Reinforced octagonal castellated beams by steel rings a very active way to increase the ultimate and allowable load for long span castellated beams. The ultimate and allowable load of reinforced octagonal castellated beam increased (186%) and (160%) respectively, while the additional steel material which used to expansion and reinforces the castellated beams (spacer plate and steel ring stiffeners) increased only (36%).

3- Furthermore, the results showed that ultimate load of reinforced was (76 %) larger than ultimate load of non-reinforced castellated beam, while the allowable of reinforced castellated beam was (60 %) larger than the allowable of non-reinforced castellated beam.

4- The results showed that using a steel ring stiffeners with a thickness larger than web thickness become less effective in increasing allowable load.

5- Numerical results indicated that by using steel ring stiffeners with a width larger than half of the flange width did not contribute effectively in increasing the allowable load proportioned to reinforced castellated beam with ring width equal to half flange width.

6- The distribution of steel ring stiffeners according to the applied load contribute effectively in decreasing amount of addition steel material and consume effectively in preventing web post-buckling and such enhancing the allowable load capacity.

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