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Effect of Transverse Stiffeners on the Lateral-Torsional Buckling Strength of Steel Beams

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Abstract

Lateral-torsional buckling occurs in beams where the section is not adequately supported against lateral movement and twisting.The lateral support can be provided by rigid floors or transverse beams. In this research the effect of transverse stiffeners on the lateral- torsional buckling strength of laterally unsupported steel beam was investigated. Simply supported beam of length 2.5 m was studied. The length of the beam was chosen between Lp and Lr of the section so that inelastic lateral-torsional buckling can occur . Finite element analysis was performed on the beam without stiffeners and with stiffeners at various locations. The analytical results indicated that the magnitude of the load causing lateral-torsional buckling increases with the increase of the number of transverse stiffeners. The analytical results were validated experimentally by testing some of the beams .

Keywords: *Lateral-torsional buckling, Steel beams, Stiffeners.*

I. Introduction

Lateral torsional buckling is a phenomenon observed in unrestrained beams, when a beam is subjected to loads result in both lateral displacement and twisting, then it is said to undergo lateral-torsional buckling.

1. Causes of Lateral Deflection in Beams

Lateral torsional buckling is observed in steel beams that are unrestrained. (Unrestrained steel beams are beams whose compression flange is free to move or displace in the lateral direction and also to rotate). The figure below shows the lateral movement of the compression and tension flange. Under the action of load, the compression flange tries to deflect away laterally. At the same time, the tension flange tries to maintain the beam straight.Certain restoring forces are created due to the lateral bending of the beam. These restoring forces oppose the lateral bending of the beam and try to keep it straight. These restoring forces alone cannot keep the beam straight. So, the lateral component of tensile forces (Tension flange) together with the restoring forces determines the resistance of the beam against buckling.

2. Causes of Torsional Effect in Beams

The forces within the flanges not only cause the beam to deflect but also to twist about the longitudinal axis of the beam, as shown in figure-3. The resistance to twisting of the beam section is dependent on the torsional resistance of the beam section. The torsional stiffness is governed by the thickness of the beam flange. Hence, the beams with large flange thickness have larger bending strength compared with the beams with the same depth but lesser flange thickness.

II. Literature Review

During execution the research there are some important studies focused on the stiffeners used to avoid torsional buckling affect on steel beam showed that lateral torsional buckling often governs design of I-beams. Vertical web stiffeners are extensively used to provide internal stiffening, their effect on lateral torsional buckling behavior is ignored in the design codes , (HASSANIEN.M, August 2008) studied the effect of stiffeners on cantilever beams under static uniform moment, uniform load, and end concentrated load , using finite element buckling solver and then linear regression analysis for output data of finite element was conducted, they show that stiffeners cause significant magnification in the critical moment than the basic critical moment of the case of beam without stiffeners. according to (RezaHaidaralin .M, 2012)predicted the true buckling behavior of cold-formed steel beams with both edge and intermediate stiffeners in their compression flanges with the aid of advanced numerical modeling, and they carried out A series of nonlinear finite element analyses to investigate the flexural behavior of cold- formed Zsections with both edge and intermediate stiffeners in their flanges, when the failure is controlled by local and/or distortional buckling. they also studied the effect of the size and position of intermediate stiffeners as well as the effect of the edge stiffener/intermediate stiffener interaction on the buckling behavior and ultimate strength of these sections. (Ulger. T, 2017) figured out that the load capacity of aged and deficient thin-walled steel structures can be accomplished by increasing member stiffness in buckling prone regions.A new strengthening concept, Strengthening-by-Stiffening(SBS), is applied to buckling prone web panels in thin walled steel beams by bonding pultruded glass fiber reinforced polymer (GFRP) sections. they focused on the construction of a finite element (FE) model for accurate simulation of experimentally obtained results.Initial imperfections, material non-linearity, interlaminar fracture law to simulate adhesive debonding, and GFRP rupture or delamination are accounted for in the construction of the FE model. Also, focused on parametric studies using the validated FE model to investigate different GFRP sizes, contact areas, panel aspect ratio and slenderness of the web panels on steel beam with SBS retrofitting. Results from the parametric study were used to establish some limits to assist in SBS design. Finally, possible use of SBS strengthening method in new construction was investigated by substituting all steel stiffeners with bonded composite GFRP stiffeners for the improvement of fatigue related behavior that is known to start at the weld toes of steel stiffeners. Also, (Ebrahimi .S, 2020) investigates the boundary condition effects of stiffened web panels in tubular and I-shaped link beams on their rotation capacity assuming similar area, moment of inertia, length and stiffener spacing. Based on the numerical results, I-shaped link beams demonstrated an approximately 78% higher rotation capacity compared to tubular link beams under the same conditions which could be due to the better behavior of the stiffened web panels of I-shaped link beams. This arrangement led to 30% increase in stiffener spacing and 15% decrease in stiffener sizing. Furthermore, another stiffener arrangement is suggested to boost the rotation capacity of long tubular link beams by utilizing additional stiffeners on flanges. Using this arrangement, the rotation capacity was enhanced up to four times the conventional tubular link beams through the Tension-Field Action taking place in the flanges due to additional flange stiffeners.

III. Materials , Methods and procedures

This research depends on three stages,first stage will be analytical method using FEM program, ANSYS, to collect and analyze data by testing steel beam samples stiffened by stiffeners with different spacing and locations, and the second stage will be experimentally conducted on the same samples of steel beams , then the final stage is comparing the results obtained and collected by the two mentioned stages.

1. Steel

Steel is used for both of the search components,the beam and the stiffeners, the stiffeners role is to increase the strength of the beam by putting it on different lengths with constant dimensions Length (L) is 138mm,Width is 37.5mm, Thickness (t) is 5 mm,welded on the both sides. First one (Stiffener 1) welded on the middle of the beam (L=1000 mm) and the second one (Stiffener 2) welded on the three-quarter of the beam length with the presence of the first and the second. so, the beam with 6 stiffeners at the last, as shown in the below figures 1,2,3. Both of beam and stiffeners are having the same mechanical properties of the A36 steel used in

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fabricating the beam specimens and conducting the search tests. The beam is tested as it acts in the inelastic lateral torsional buckling.

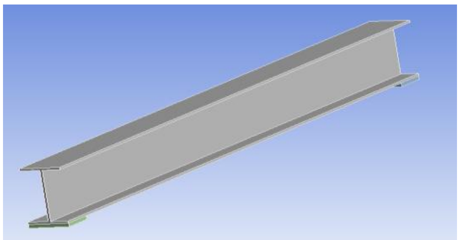

Fig.1: Beam with no stiffeners

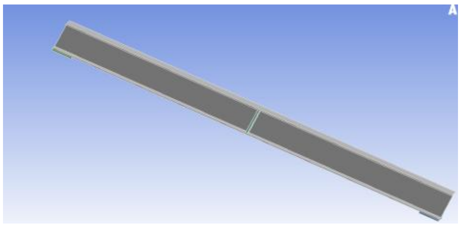

Fig.2: Stiffeners at middle of the beam

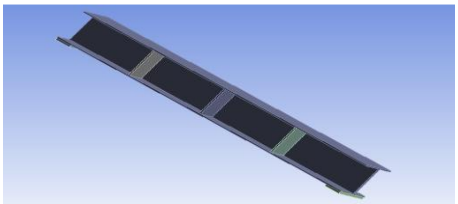

Fig.3: Stiffeners on different locations on the beam

Finite Element Analysis

A finite element model of beams tested by Finite element software was built in ANSYS . The steel and steel stiffeners parts of the beam were modeled using three-dimensional (3D) SOLID elements from ANSYS element library. The element is defined with several nodes; each having three translational degrees of freedom in x, y and z directions. Simplified enhanced strain formulation was used for all components; i.e. steel (beams or stiffeners) , with the exception of the layered formulation that was accounted for in modeling the stiffeners in the aforementioned exploratory study.The weld thickness was neglected in the FE model of welded connections between the steel parts (e.g. flanges and web), which were assumed to be perfectly connected. We were able to perform finite element analysis on the models on three stages , to simulate the tests on the computer for the purpose of comparison. The computer software ANSYS Mechanical 2020 R 2 was used for that purpose.After the analysis was done and the results were obtained, force-displacement diagrams were drawn and compared with each other, and later with those of the experimental results and FEA of the steel I-beams.

In order to conduct an accurate finite element analysis, a 3D model of I-beams was created on three stages, first stage the steel I-beam was analyzed with no stiffeners, so it used as basic beam for comparison purposes, second stage and third stage were conducted by adding stiffeners at the middle, at the middle and at the quarter length from both ends of the beam. Since pinned support is not available in ANSYS Mechanical 2020 R2, we attended to express it as a plates at both ends of the bottom flange of the I-beams, and the displacements on these rectangle elements are districted on the both axes, x and y directions. To make sure the I-beams are expressing the same experiments conditions both ends on the top flange were districted from moving by applying zero displacements on all directions (x ,y ,z) axes, and a concentrated load at the mid-span of the upper flange.

This solution gave a correct results showing logic and very -well distributed stresses, as these added rectangle elements meaning that they performed good as pinned supports, the rectangle elements were added with stronger mechanical properties (to eliminate the affect of their deformation), and the concentrated force due to applying the load at limited number of nodes.

A rectangular mesh was used for the finite element analysis because the beam is mainly made of planer elements with no curved sections, a nonlinear analysis was conducted with a medium mesh of 2.5 mm, element size.

The final model and the mesh for the analysis are shown in figure 4,5, and the force-displacement diagrams of both the structural and the finite element analysis are shown in figure 6.

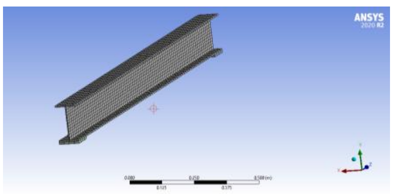

Fig.4 : Model and mesh for the finite element analysis

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The results of the finite element analysis suggest an early failure due to lateral torsional buckling.This behavior is captured by the structural analysis conducted with ANSYS Mechanical 2020 R2 ,its simulates the real behavior of the section under these conditions of loading .The 3D models shown in figures 1, 2, 3 were drawn into ANSYS Mechanical 2020 R2, the same supports and loading conditions mentioned previously.The meshing method selected here was rectangular meshing, in order to capture the performance of the beams.Bilinear analysis method was used with a force applied at the middle of the beam upper flange over the interval of one second.The solution was divided onto 143 sub-steps that took a different number of iterations for each model to complete. The results of the analysis as the maximum lateral displacement plotted against the load for an easy comparison are shown in figure 6, figure 20 shows the deflected shapes and the results of the beam with no stiffeners .

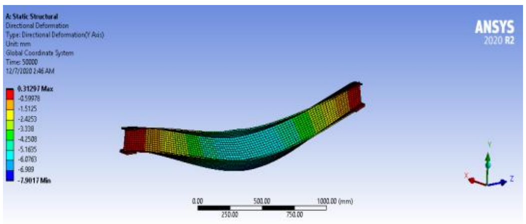

Fig.5: Mesh and lateral displacement for beam with no stiffeners

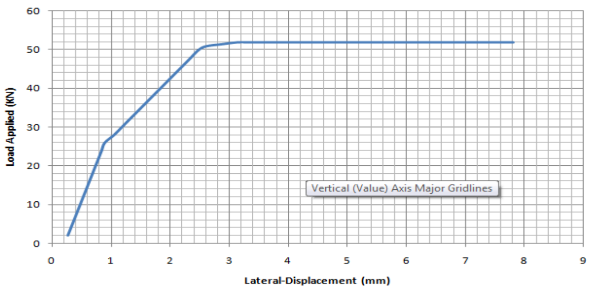

Fig.6 : Force -Displacement diagram for beam with no stiffeners

Figure 6 indicates an early failure of the beam with no stiffeners due to the instability as a result of lateral- torsional buckling, and as a result preventing it from reaching its full capacity, the results for this beam took as a base values to compare the effect of adding stiffeners on the beam.The next step was to conduct similar analysis on the beam with middle stiffeners , the same conditions and element types were used, and the results of the analysis as force-displacement diagram is shown in figure 7 and figure 8.

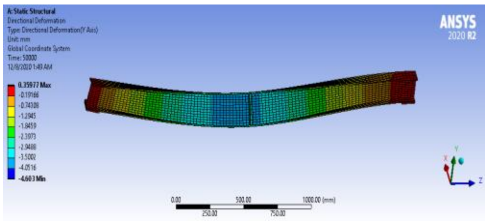

Fig.7: Mesh and lateral displacement for beam with middle stiffeners

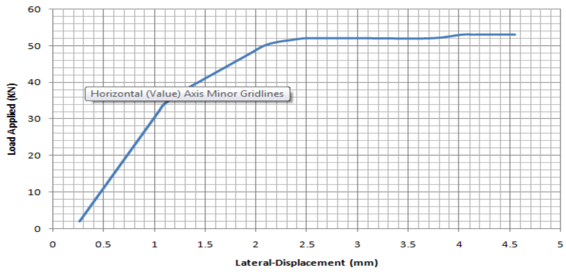

Fig.8 : Force-Displacement diagram for the beam with middle stiffeners

It can be seen that the general expected behavior of the beam with middle stiffeners are shown, where this beam reaches to lower lateral-torsional buckling compared with the first beam, with a failure occurring at roughly 1.01 times the ultimate strength and 0.58 times the total displacement of the beam with no stiffeners .These variations in ratios are due to the changes in behaviors because of adding stiffeners at the middle of the beam. The final step in the analytical part, is analyzing the last beam which has three stiffeners , this analytical procedure was conducted in a similar analysis on the first two beams, the same conditions and element type were used.Figures 9 and 10 shows the beam with adding more stiffeners and the results showing how the beam acts by adding three stiffeners on different locations.

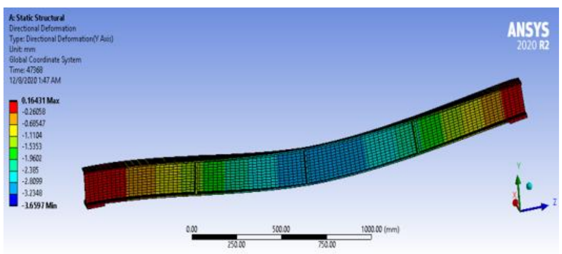

Fig.9: Mesh and Lateral-displacement for beam with six stiffeners

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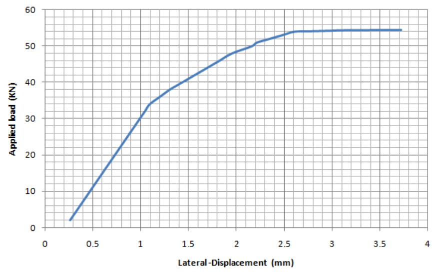

Fig.10: Force -displacement diagram for the beam with three stiffeners

The results shows that this beam behaves as expected with a failure occurring at roughly 1.1 times the ultimate strength and 0.42 times the total displacement off the beam with no stiffeners. Also, the variations in these ratios are due to the changes in behaviors occurring at different stiffeners numbers and locations.

Table1: Results of the analysis of all beams

Model	Yielding load (KN)	Ultimate load (KN)	Total deflection (mm)
Beam with no stiffeners	28.5	51	7.8
Beam with middle stiffeners	45	52	4.55
Beam with three stiffeners	50	55	3.3

A summary of the analysis for all the models shown in table 1, these values will be useful later for the comparison of the experimental results between the beam with no stiffeners and beams with stiffeners with different numbers and locations.

IV. Experimental testing program

After the analytical part has been conducted , an experimental study was conducted to validate the analytical results. In this part all the test prototypes of the analytical beams were created. All the necessary precautions were taken to succeed with the tests providing the necessary gadgets for supporting the prototypes and applying the load on a proper manner.

1. Manufactured prototypes

For the steel I-beams that were tested theoretically, with different locations for the stiffeners, steel I-beam without stiffeners was used as a base beam in comparing the effect of using stiffeners, steel I-beam with middle stiffeners and steel I-beam with middle and on the both sides of it.

- These steel I-beams were created using steel plates, as a built-up sections. -Six steel plates of 80 mm width ,6mm thickness and 2500 mm for the length of the flanges. -Three steel plates of 138mm width,5mm thickness and 2500 mm for the length of the webs. - 14 stiffeners were created using steel plates with 37.5 mm width, 5mm thickness and 138 mm length.

- For the beam was conducted with no stiffeners as shown in figure 11.

Fig. 11 : Beam with no stiffeners

- For the beam was created with middle stiffeners, these stiffeners were located at 1250 mm from the both sides of the beam as shown in figure 12.

Fig.12: Beam with middle stiffeners

- For the beam was created with sides stiffeners, and middle stiffeners, these stiffeners wee located at 625 mm , and 1250 mm respectively as shown in figure 13 .

Fig.13 : Beam with three stiffeners

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- Two stiffeners were created and located at the both ends for each beam as shown in figure 14.

Fig.14: Sides stiffeners

First the steel plates that would later form the flanges of all the prototypes and the webs were obtained and cut into the desired lengths and dimensions for each prototypes, then the stiffeners with desired dimensions were created .After all the needed parts were obtained, the welding process began joining the plates and the stiffeners to create all the prototypes mentioned. The overall process of preparing and welding took a considerable amount of time, effort and needed accuracy even with the presence a professional welder.The figure 15 shows the prototypes created.

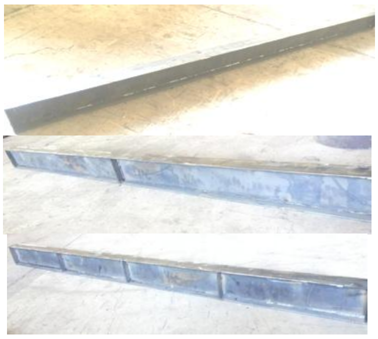

Fig.15: All prototypes created

2. Preparing for the test

In the preparing stage , bolts were used to make the beams stable and prevent them from moving upside down due to the increasing of the loads. Also, bolts were used to make sure that beams are simply supported as it in the analytical part. Flexure test machine was used to conduct the tests,this machine applying load by using solid cylindrical part and the load is increased by the time automatically.

3. Testing Procedure

The testing phase was divided into three phases,testing the beam with no stiffeners to determine how stiffeners can affect the lateral-torsional buckling values, second phase is testing the beam with middle stiffeners and last phase is testing the beam with adding three stiffeners .

3.1 Testing the steel I- beams

The first prototype to be tested was the beam with no stiffeners , the same test setup from the trial test was used during the testing , the prototype was subjected to the effect of lateral - torsional buckling , causing a lateral deformation of the web and creating more stresses on the upper flange . The prototype then failed due to local buckling of the compression flange , figure 16 shows the test setup and figure 17 the failed prototype after that , prototypes that has middle stiffeners and sides stiffeners were tested with the same test setup , figure 18 shows the test setup for this beam and figure 19 shows the failure mode . Also, the same test was conducted to the beam with middle stiffeners and figure 20 shows the test setup and figure 21 shows the failure mode . During the test all the models continued to bend in a stable manner , the bending was reducing with increasing the stiffeners numbers . Also, the beams failed due to the yielding of the compression flanges that buckle horizontally with the web as a result .

Fig.16 : The test setup for beam with no stiffeners

Fig.17: The failure mode for beam with no stiffeners

Fig.18: The test setup for beam with middle stiffeners

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Fig.19: The failure mode for beam with middle stiffeners

Fig.20: The test setup for beam with three stiffeners

Fig.21: The failure mode for beam with three stiffeners

V. Results and Discussion

Figures 22 ,23 and 24 show the results of the tests for all the prototypes, table 2 summarizes the results of all the analytical and experimental tested prototypes. The results of the finite element analysis of the prototypes with stiffeners and without, showed that increasing the number of stiffeners affect the lateral displacement and the values for the load causes it, the highest number of stiffeners are used, the lowest lateral displacement and the higher load capacity are produced. It was noted that not only the lateral torsional buckling is less than expected by the analysis, but also that the reduction value is high due to the thickness of stiffeners used. Also, the beams were having greatest increasing in the load capacity. This is mainly because the effect of using stiffeners directly connected to the models using just welding. The experimental results showed almost close values to the finite element analysis as shown before, this shows that adding stiffeners experimentally and analytically gave nearly the same effect and the simulation gave almost exact results for the experiments. The experimental results showed that adding stiffeners to the beams can affect the values for the lateral displacements occurred, and the values of the ultimate loads, this can be described by the values produced through the tests, so, if the results for beams with stiffeners compared with the results for the beam with no stiffeners , this comparison shows the values of lateral torsional buckling for beams with middle and three stiffeners which are 2.9 mm and 2.2 mm respectively are less than the lateral displacement for the beam with no stiffeners which is 3.9 mm . Also, the values of ultimate load for beam with middle and three stiffeners , 54 KN , 72 KN ,respectively are greater than the ultimate load for beam with no stiffeners ,52 KN .Since the beams are tested analytically and experimentally and due to define if the finite element analysis simulates the experimental tests , the experimental results showed that the beam with middle stiffeners had strength of 1.04 of that of the finite element analysis , beam with three stiffeners had the strength of 1.3 of that of the finite element analysis ,but beam with no stiffeners had a strength of less than the beam mentioned above with a value of 1.01 , this shows that the experimental tests had close performance to the finite element analysis .

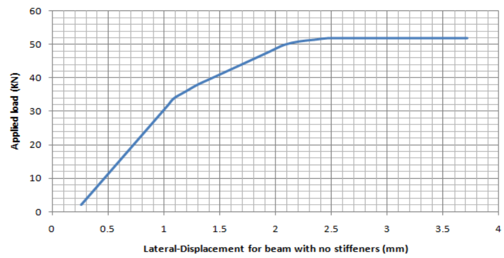

Fig.22: Results of test for beam with no stiffeners

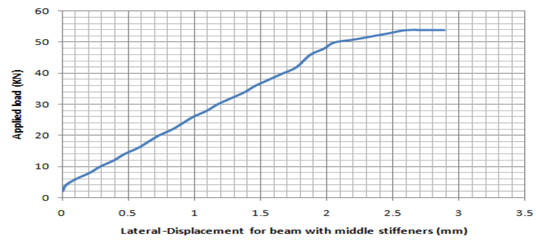

Fig.23: Results of the test of beam with middle stiffeners

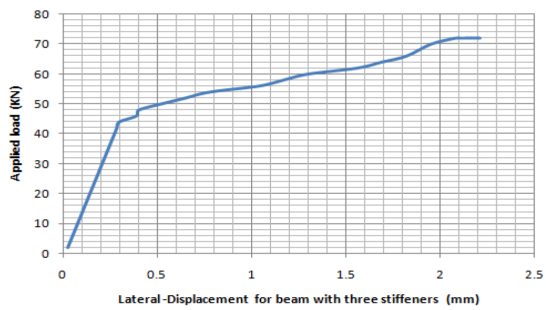

Fig.24: Results of the test of beam with three stiffeners

Table 2:Results of the analysis and experimental tests.

Beam model	Type of results	Yielding (KN)	Ultimate Load (KN)	Total deformation (mm)	Ultimate load compared	Deflection compared
With no stiffeners	FEA results	28.5	51	7.8	0.98	2
	Exp. results	35	52	3.9	1.01	0.5
With middle stiffeners	FEA results	45	52	4.5	0.96	1.56
	Exp. results	43	54	2.9	1.04	0.64
With three stiffeners	FEA results	50	55	3.37	0.76	1.4
	Exp. results	49	72	2.21	1.3	0.66

This is not only beneficial in terms of the load carrying capacity , but also in terms of predictability as with higher certainty and smaller margins of error , the engineer can use smaller factors of safety which would also result in lighter structural systems .

7. Conclusion and Recommendations

It can be concluded that the study yielded satisfactory results that were very close to what was expected , showing how steel stiffeners can affect the lateral torsional buckling values for steel beams .The main points can be concluded are :

- Adding stiffeners on the steel I-beams is a highly effective method of reducing lateral torsional buckling .

- Both finite element analysis and the experimental tests showed that adding stiffeners on different locations on the beams length gave the beam a higher level of stability and could withstand higher loads than the beams with no stiffeners.

- The more of stiffeners added to the beams, the more reduction in lateral torsional buckling is noticeable , as it noticed for the third beam using three stiffeners.

- However,steel I-beam with no stiffeners is designed to be able to carry loads and behave.

according to the loads applied until failure as shown for the first beam , but adding stiffeners could increase the load capacity as shown for the second and the third ones .

-The beams with stiffeners failed on a higher load values .

- However, some critical points that can affect how much stiffeners are capable to reach it goals like welding process , which needed to e very accurate along the the beam parts .

- Due to the higher level of load redistribution of the beam with three stiffeners , this beam could withstand higher loads , even after the failure .

Final notes, the research shows how advantageous adding stiffeners on different locations on the beam is .The tests showed ideal and close results to the computer simulation , which showed adding more stiffeners reduced the values of lateral torsional buckling and increasing the load capacity, welding is still exists in these process and it would still affect the properties of the beam as the beam used is a built-up section. Future studies, can be conducted to further explore the full potential of adding stiffeners with different dimensions, shapes and materials and study how much can affect in the field of structural engineering.Also, exploring the possibility of creating connections more suitable for the process, using the technology.

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