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Experimental and Finite Element Analysis of Lateral Torsional Buckling of Concrete Filled Tubular Flange Steel Girders

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Abstract

The structural behavior of concrete filled Tubular Flange Girders (CFTFGs) has been studied in this research. This study aims to investigate the ability of tubular flange to increase resistance of steel girders against Lateral-Torsional Buckling (LTB). For this purpose, experimental, and numerical analysis were carried out.The experimental work consisted of fabricating and testing of five specimens. The first specimen with flat plate flange considered as a control specimen and the other specimens with tubular flanges. In tubular flanges specimens the effect of filled and non-filled tubular flanges with concrete also, the geometry effect of tubular flange sections, i.e. depth (40 and 20 mm) were studied. These specimens have the same length (1920 mm) and the same overall depth (170 mm). The specimens were tested under two point loads applied at the third-span points. The second part was a numerical one using the finite element method by software package (ANSYS 14), then employed to investigate the nonlinear behavior of tubular flanges girders and a similar numerical study of conventional I-girders was conducted, then the results compared with those of tubular flange girders.The measured experimental results were; the ultimate load capacity, load- vertical deflection, load- lateral deflection and load- twisting angle. Finally, the tubular flange specimens increased the lateral torsional buckling capacity comparing with the standard I-shaped steel members by about (66-97%), while bending strength increased by about (33-55%) for tubular flange section filled with concrete of 42.5 MPa. The concrete filled tubular flange increased the LTB capacity by about (14- 22 %) comparing with the unfilled specimens, also increased the flexural strength by about (13-22%). Thus, tubular flanges girders allowed using for large unbraced girders due to increasing the torsional stiffness of the girder. The numerical models were carried out by software package (ANSYS 14). The results were found to be in a convergent state with those obtained from the experimental tests.

Keywords: Lateral–torsional buckling, finite element analysis, and tubular flange girder.

1. Introduction

Lateral- Torsional Buckling (LTB) is phenomenon of failure occurs in beams, columns and bridges girders due to the bending moment. To avoid this phenomenon of failure without increasing section dimensions or decreasing length of beam, cross-frame (diaphragm) must be used in bridges girders and building. The bracing system is provided to prevent the lateral- torsional buckling. During the construction stage, the casted concrete of the deck slab which is fresh, must be considered as a dead load and had no ability to prevent lateral torsional buckling of the steel girders. Therefore a lateral bracing system must be used to prevent such phenomenon. Usually these bracing system are costly, need time and jobs. The tubular flange girders, is a solution to increase capacity of these girder to resist LTB and to minimize these costs by eliminating the required lateral bracing system or to reduce their costs.

1.1Tubular Flange Girder

The tubular flange girder system is one of several innovative steel bridge girder systems. This research has established fundamental information on the behavior of these girders under simulated bridge loading conditions. In particular, increasing torsional stability of the girders may reduce the number of diaphragms (or cross-frames) needed to brace the girders, and thus may reduce the time, cost of fabricating and erecting the bridge girder system. The specimens are Tubular Flange Girders (TFGs) comprised of a conventional web plate and bottom flange plate, and a top flange fabricated from a rectangular tube.

Girders with rectangular tubular flanges were studied because rectangular tubes are easier to use in fabricating and constructing bridge girders. For example, it is easier to attach a flat web to a rectangular tube than a round tube. Welds to make the girders composite with the tubular flanges are easier to attach to a rectangular tube. Figure 1 shows some uses of tubular flange girder.

Figure 1: Some Uses of Tubular Flanges Girders [1].

2. Experimental work

All the plate elements that are used to fabricate the plate girder (stiffeners, flanges, tubular flanges and webs) were cut by using cutting machine system to achieve better dimension accuracy and rapid cutting speeds. Then tubular flange were cold form to U- Shape to achieve all dangerous by using cutting and welding such as shear strength at the bottom tubular flange, but cold form section when steel is formed by press-braking or cold rolled-forming, there is a change in the mechanical properties of the material by virtue of the cold working of the metal. When a steel section is cold-formed from flat sheet or strip, the yield strength, and to a lesser extent the ultimate strength, is increased as a result of this cold working, particularly in the bends of the section. Since cold work produced during forming increases the strength of the steel, it permits the designer to treat the formed steel as a stronger material than the original unformed steel [2], then welded all the part to gather by MAG welding. Figure 2 shows the fabrication stage.

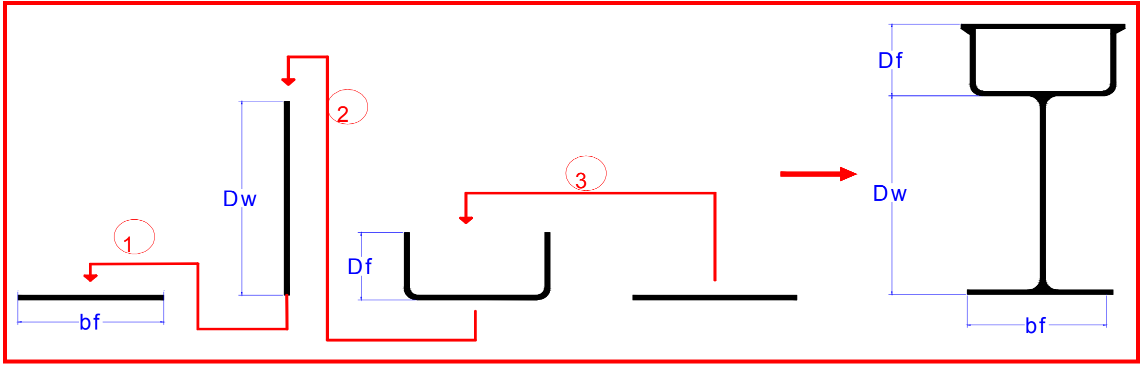

Figure 2. Fabrication Stage.

3. Specimens Dimensions

A W-shape steel section with dimensions ($h = 170\ mm,\ b_f = 80\ mm,\ t_f = 2.85\ mm,\ and\ t_w = 2.85\ mm$) was used as a control specimen, and another specimens were tubular flanges specimens. Each specimen has got two depths of tubular flange (40 mm and 20 mm) and width of tubular flange (80 mm), also specimens were used have overall depth equal to 170 mm. All beams were tested under two point loads applied at the third-span points. Also, specimens have been stiffeners with full depth of web, width (30 mm), and thickness (2.85 mm) were provided under concentrated loads and reaction points. Furthermore, Bearing plates with dimensions (90x80x10) mm under each load have been designed to carry the maximum load to prevent any local buckling in steel section. Figures 3 and 4 show specimens' dimensions.

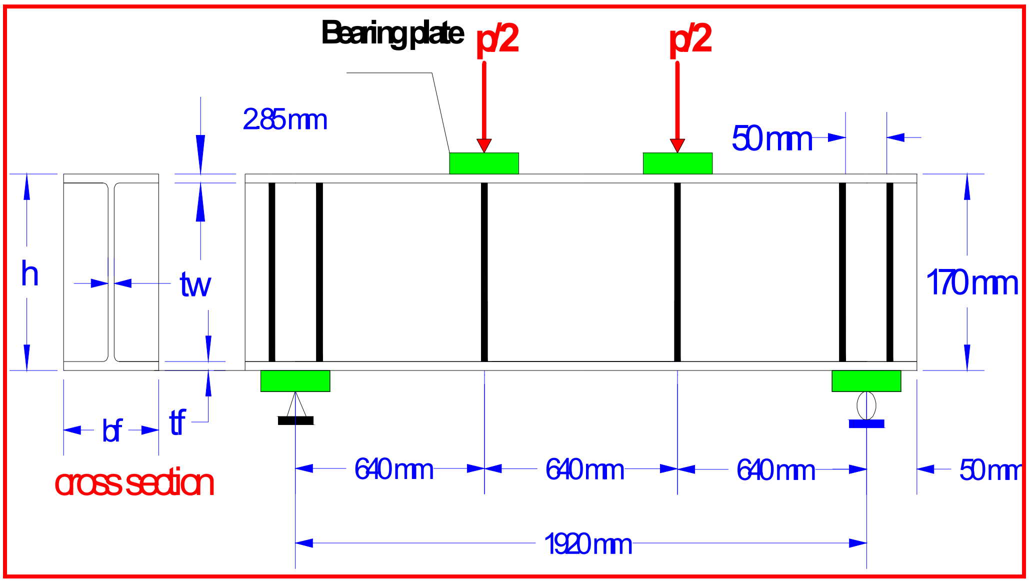

Figure 3: Dimensions and Details of Tested CB Specimen.

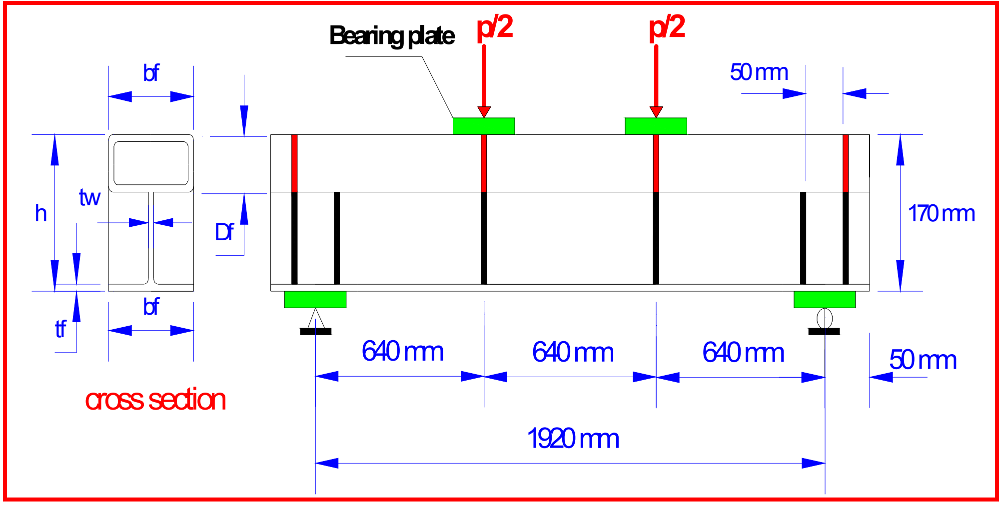

Figure 4: Dimensions and Details of Tested tubular flanges Specimens.

4. Material properties of tested specimens

4.1 Properties of Steel Section

Tensile tests are carried out on specimens obtained from the steel sheets used to fabricate the plate girders (thickness 2.85 mm) according to the ASTM Standard Test (A370-05) [3]. The yield stress and ultimate stress for flanges, webs and stiffeners that obtained by using three tension coupons from steel plate that have been used to manufactured plate girders and the test results are summarized as (fy= 236.8 MPa and fu= 377.2 MPa) . To obtained Poisson's ratio and modulus of elasticity need some measuring devices, which are not obtainable in the laboratory. Subsequently the Poisson's ratio and modulus of elasticity will be assumed as 0.3 and 200 Gpa respectively.

4.2 Concrete

Concrete was used in this research self-compacting concrete (SCC) and the material used in producing SCC as:

1- Ordinary Portland cement was used throughout this investigation for filled all tubular flange specimens.
2- Natural sand of maximum size of 4.75 mm
3- Crushed gravel with a maximum size 9 mm

4- A powder of lime stone with maximum size of 200 μm was used as inert mineral filler.
5- High range water reducing admixture was used in order to reduce the amount of water used in mix design.
6- Tap water has been used for mixing concrete.

5. Mechanical properties of hardening concrete

The average value of tested three cylindrical specimens (150 x 300 mm) for compressive strength (fc' = 42.5

MPa) and the average value of tested three cylindrical specimens (100 x 200 mm) for splitting tensile strength (f_t = 4.5 MPa).

6. Loading and support condition

All specimens were provided simply supported fixed the lateral deflection and rotation of compression and tension flanges in both ends of beams. Figure 5 shows support and system load was used through the test.

7. Test procedure

Five simply supported specimens were investigated in this research, a first specimen was a control specimen and the other specimens were tubular flange specimen's filled and non-filled with concrete, also with different depth of tubular flange (40 and 20 mm). All these specimens were tested under to two concentrated load at third point of span of specimens by using testing of hydraulic machine with the capacity 600 kN in the structural laboratory of civil engineering department at university of Babylon. Start applying the load and recording the reading of stain, vertical deflection, lateral deflection and twisting angle curve, readings were recorded each 5 kN. Figure 5 shows the details of the testing machine.

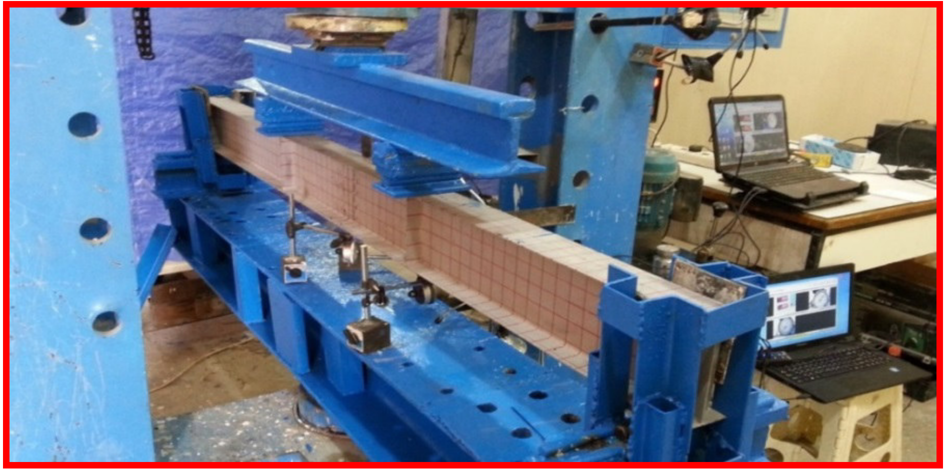

Figure 5: Machine was used for Testing, System Load and Support.

8. Instrumentation

Instrumentation consisted of linear variable displacement transducers (dailgage) and load cells for measurement of beams vertical deflections, lateral deflection and rotation of specimens. During test webcam cameras was used to record the load and dialgages reading wherein connected these cameras to computer by program works on collecting these cameras by computer. These techniques were used to ensure not losing any reading of lateral and vertical deflection as shown in Figures 6 and 7.

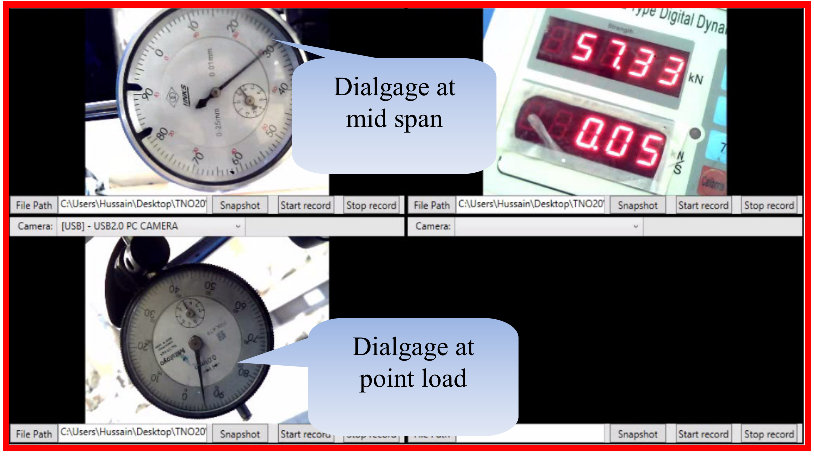

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Figure 6: Instrument Used for Measuring Vertical Deflection.

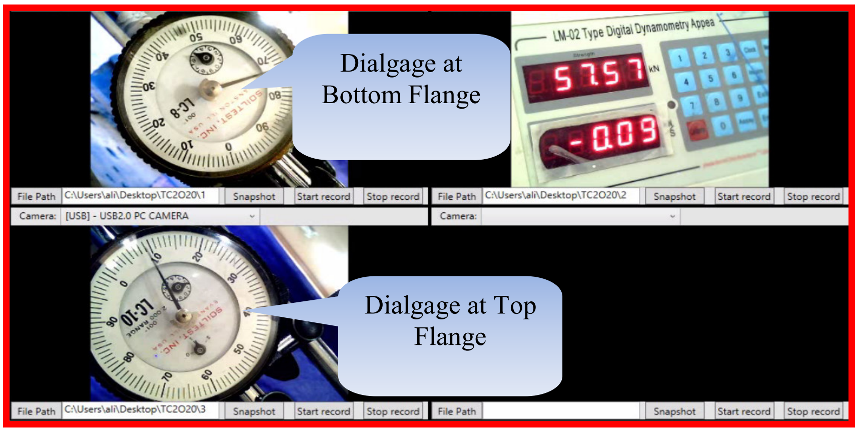

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Figure 7: Instrument Used for Measuring Lateral Deflection.

9. Experimental Results

For the loading stages the vertical-deflection, lateral-deflection, and twisting angle curves were drawn for the load stages verses the deformations of the mid span section. All beams were tested under the same type of loading. Table 1 shows the influence of tubular flange girder filled and non-filled with concrete, also depth of tubular flange on lateral torsional buckling. Five beams were taken in this research, first beam with flat plat flange as a control beam and other beams were tubular flange beams with different depth of tubular flanges (40 and 20 mm) filled and non-filled with concrete. From experimental test shows that the tubular flanges increase stability of girder against lateral torsional buckling, and increase bending strength of girder as listed in Table 1 and shown in Figures (8, 9 and 10). Figures (11, 12, 13, 14 and 15) show the beams failure after testing. The lateral deformation of these beams was very small compared with the lateral deformation of control beam (CB). Because of these beams gave high vertical deflection, the failure was occurred in these beams as serviceability failure. Here, it is suggested that the worst acceptable limit of allowable deflection is (L/120), and multiplied by factor of safety (Ω=1.67) [4]. For the present case, this limit equals to (26 mm) for all beams, and this limit was used to evaluate the worst acceptable service load. The ultimate load capacity was considered as one of the following criterion;

1- The serviceability limit (SRL)
2- The maximum load that cause lateral torsional buckling (LTB) and,
3- The load at ultimate strength, (USL), whichever is less.

Table 1: Influence of Tubular Flange with different depth of tubular flange also, filled and non-filled with concrete on Lateral Torsional Buckling.

beams	Load at serviceability limit, P_s kN	LTB, Load (P_{LTB}), kN	Ultimate tested load P_u, kN	Failure criteria	Improvement of P_{LTB}, %	Improvement Ultimate load, %
CB	47.25	**35**	47.25	LTB	-	-
TN40	**54**	55	58	SRL	51	23
TN20	**55**	57	61	SRL	63	29
TF40	**63**	65	71	SRL	86	50
TF20	**65**	69	73.5	SRL	97	55

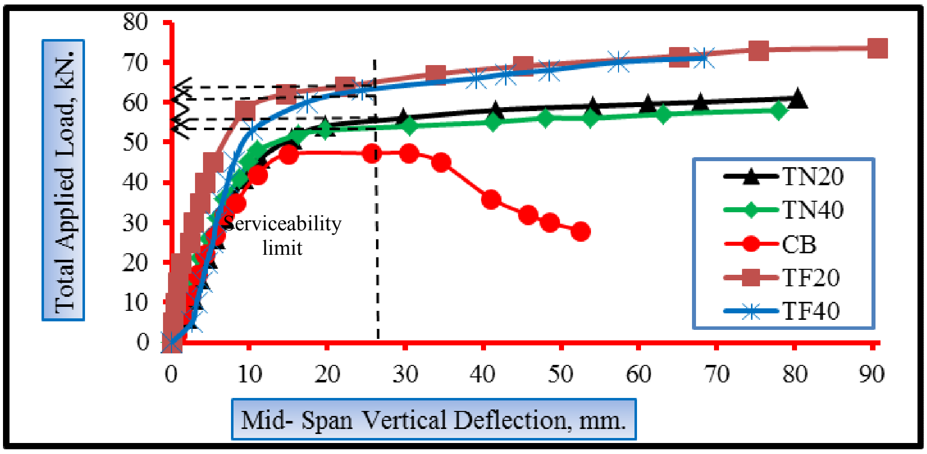

Figure 8: Load- Vertical Deflection Curves of Beams.

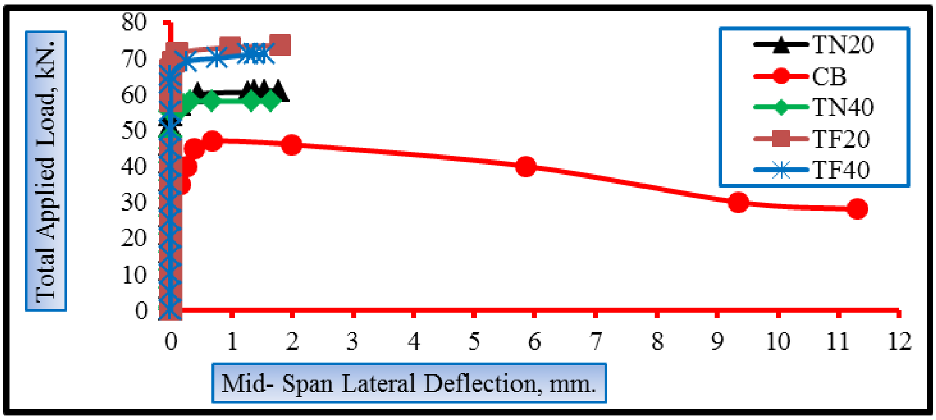

Figure 9: Load- Lateral Deflection Curves of Beams.

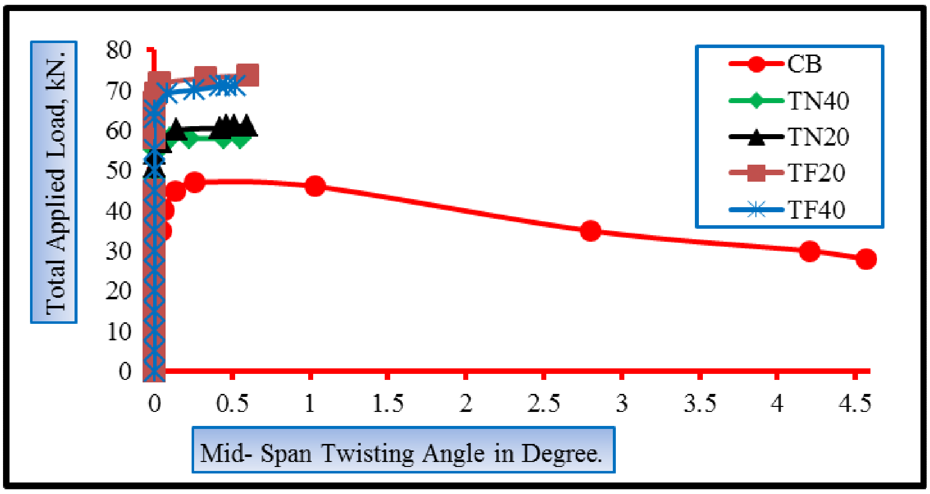

Figure 10: Load- Twisting Angle Curves of Beams.

Note:
T: Tubular flange girder.
N: non-filled tubular flange.
F: Filled tubular flange with concrete.
20: Depth of tubular flange 20 mm.
40: Depth of tubular flange 40 mm.

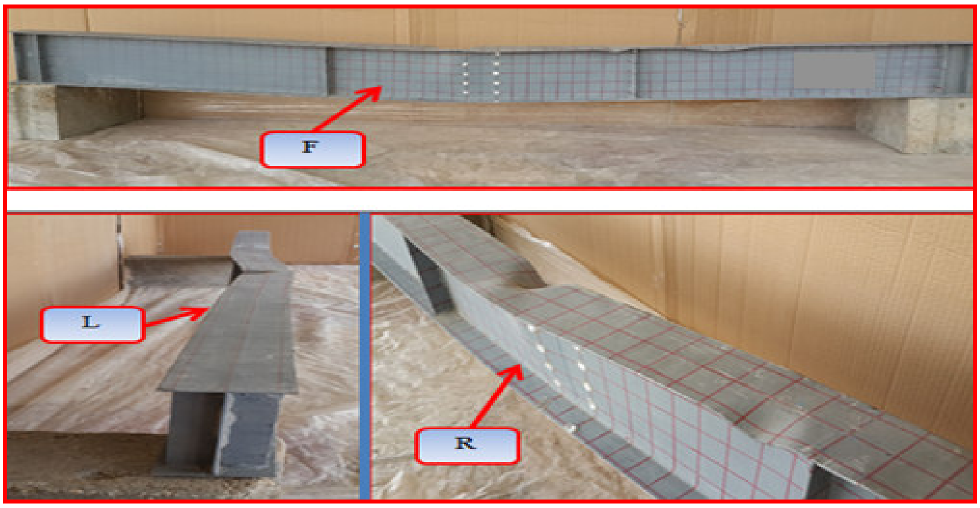

Figure11: Failure of CB after Testing.

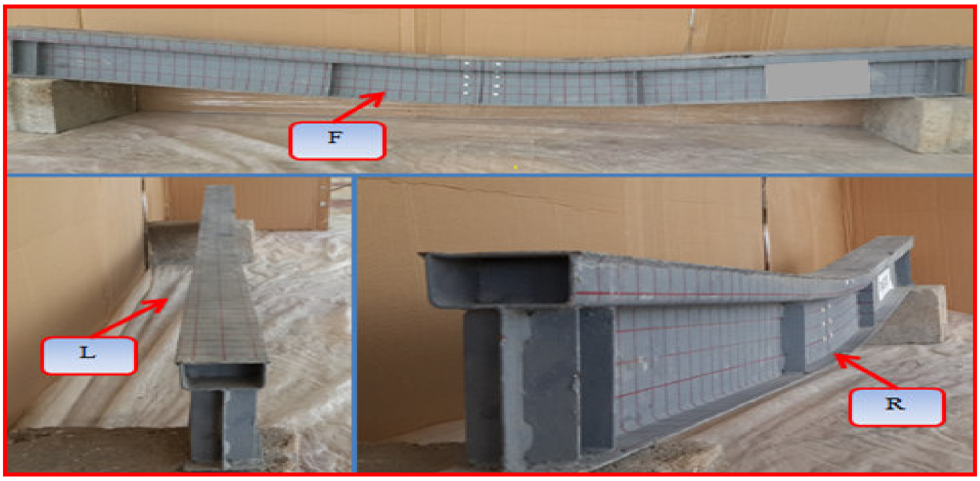

Figure12: Failure of Beam TN40 after Testing.

F: Front view
R: Right view
L: Left view

Figure13: Failure of Beam TF40 after Testing.

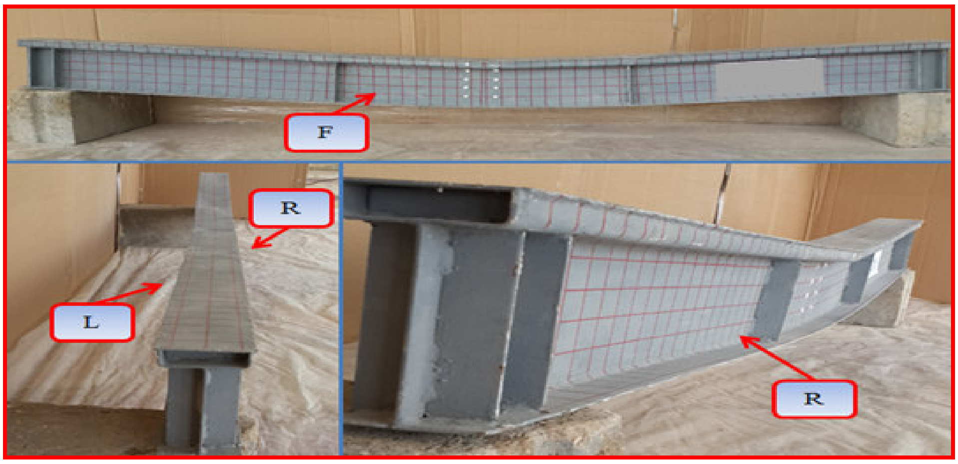

Figure14: Failure of Beam TN20 after Testing.

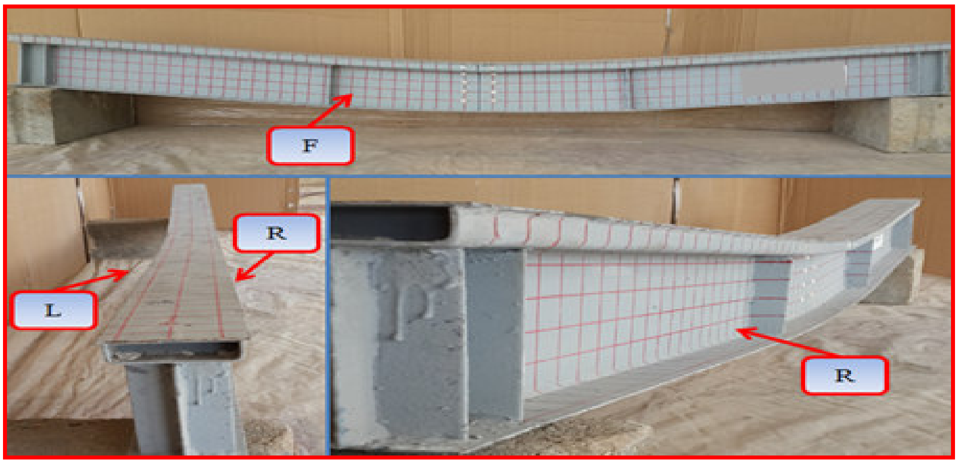

Figure15: Failure of Beam TF20 after Testing.

10. Finite Element Analysis

The FE program ANSYS (Version 14) was used for the FE analyses. The FE models were developed for girders with simply supported boundary conditions and two point loads was applied over the unbraced length. Details of the models are discussed below.

10.1 Loading and Boundary Conditions

In the experimental work, two concentrated loads were applied at the third point over a bearing plate with dimensions 80 mm length, 90 mm width and 10 mm thickness. The finite element model was loaded at the same locations for all beams in the experimental work. The applied load was represented by dividing the total distributed load on the top nodes according to the area surrounded by each node to represent the distributed load in ***ANSYS*** program. The supports was approximately as similar as in the experimental work, in which a single line of nodes was constrained in the Uy, Uz directions and ROT_X for both ends, but a single node chosen at support was constrained in the Ux direction to avoid the instability state. The beams will not be permitted to rotate at the supports.

10.2 Material models and properties

In this FE models were used three-dimensional four node shell element181 to model the specimens (flanges, webs and transverse web stiffeners). A linear elastic isotropic material model is used for steel in the elastic range, with an elastic modulus of 200 GPa and a Poisson’s ratio of 0.3. For this study, a bilinear stress–strain curve with strain hardening is used for the uniaxial stress–strain relationship of the steel. The yield strength of steel is 240 MPa, and the modulus in strain hardening is taken as 2 GPa based on tension coupon test. Also SOLID185 was used to modeling the bearing plate [5].

10.3 Optimum mesh

Once the model is defined, the structure must be meshed. In other words, the model is divided into a number of small elements. These elements must be properly connected in their boundaries by nodes. In finite element modeling, a finer mesh typically results in a more accurate solution. However, as a mesh was made finer, the computation time increased. Therefore, selecting mesh density is an important step in the finite element modeling. The convergence study was made for, I- Girder (CB) using four different numbers of elements as listed in Table 2.

Table 2: Optimum Dimension of Mesh.

No.	Dimension of element		No. of element	Deflection, at load 40 kN mm.
	Flange (X,Z)	Web (X,Y)		
1	(40x40)	(40,42.5)	452	6.370
2	(30x20)	(30x28)	850	8.223
3	(20x20)	(20x28)	1580	8.631
4	(15x20)	(20x18)	2290	8.635

The deflection at mid- span of beam was chosen for the same applied load (40 kN) to investigate the convergence of results. From the Figure 7 it was found that the deflection at mid- span was approximately constant when the number of elements is more than 850, and any increase in number of elements do not affect the behavior of these beam. From these results, the optimum dimension of mesh was taken in this research (No. 3) with dimension as listed in Table 2. The relationship between the number of element and the deflection at mid- span of beam was drawn in Figure 16.

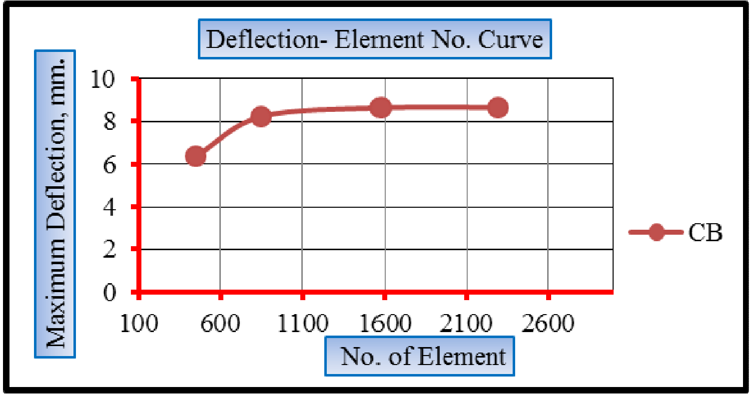

Figure 16: Results of Convergence Study for CB.

10.4 Results of the finite element analysis

Five beams were tested experimentally and using ANSYS. The results of finite element analysis were compared with experimental results to check the validity of using the computer program in modeling the tested beams. ANSYS results including ultimate load, load- vertical deflection, load- lateral deflection and load- twisting angle at mid span response were a close to the experimental results. The finite element results for these modeled beams show a convergent response compared with the experimental results as shown in Figures (17, 18 and 19). Figures (20, 21, 22, 23 and 24) show the von-Mises stresses of these beams.

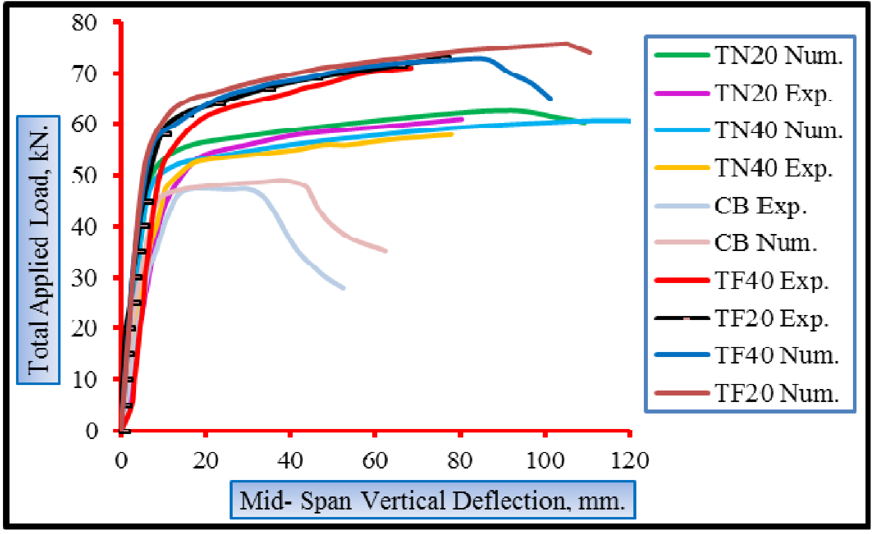

Figure 17: Experimental and Numerical Load- Vertical Deflection Curve of Beams.

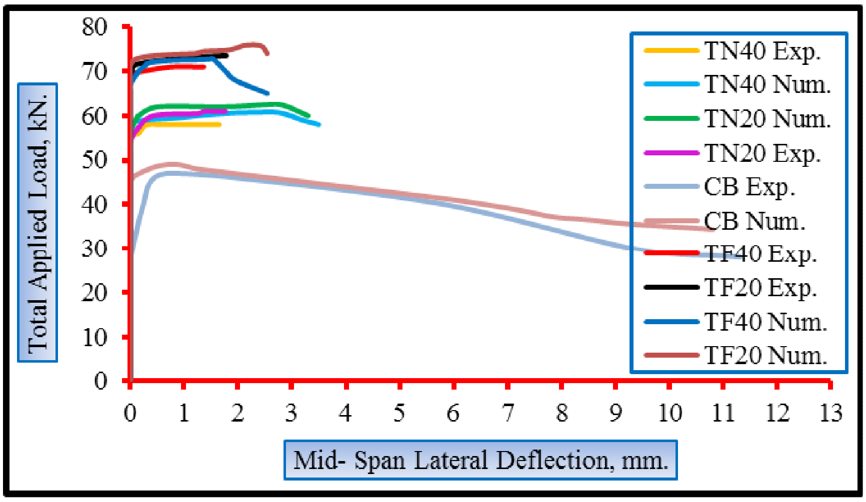

Figure 18: Experimental and Numerical Load- Lateral Deflection Curve of Beams

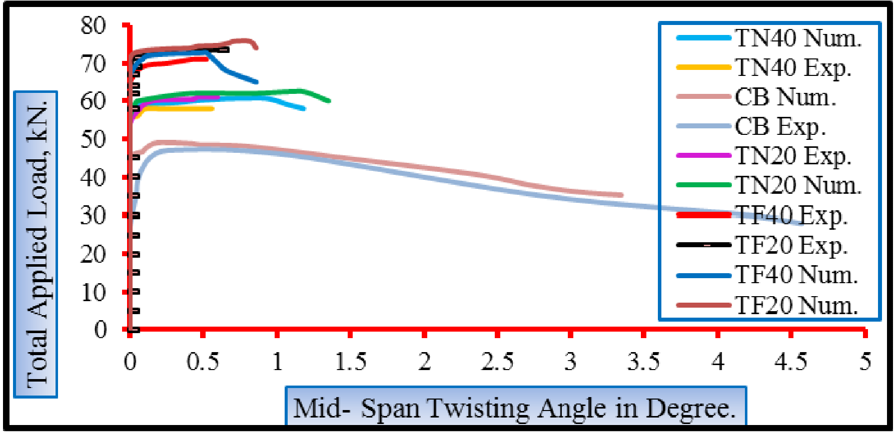

Figure 19: Experimental and Numerical Load- Vertical Deflection Curve of Specimens

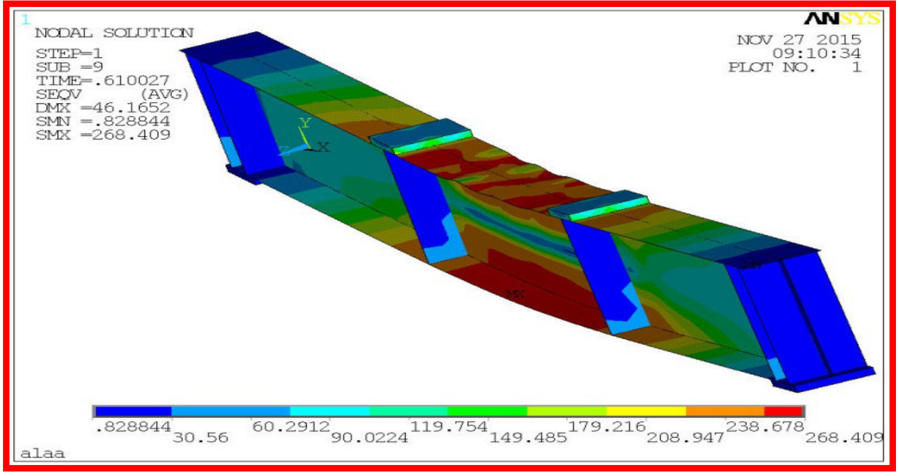

Figure 20: Distribution of von Mises Stresses for CB.

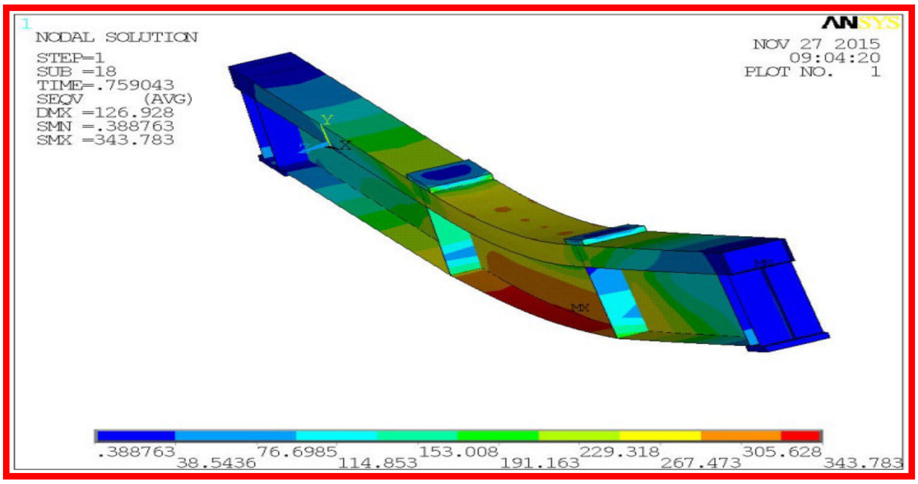

Figure 21: Distribution of von Mises Stresses for Beam TN40.

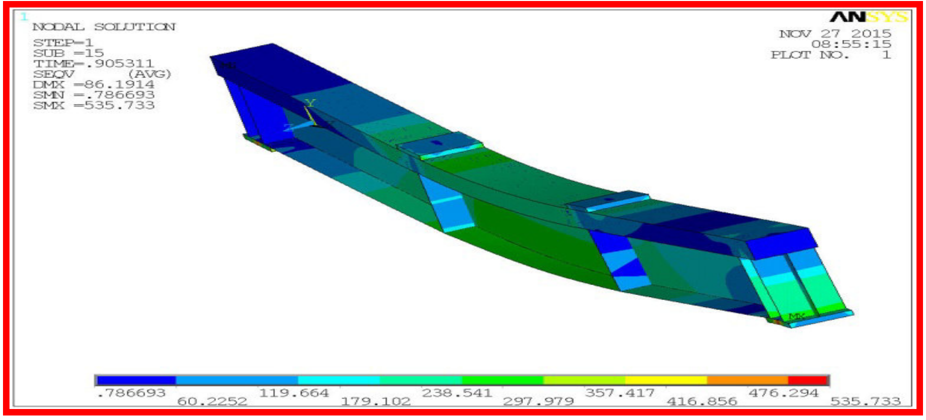

Figure 22: Distribution of von Mises Stresses for Beam TF40.

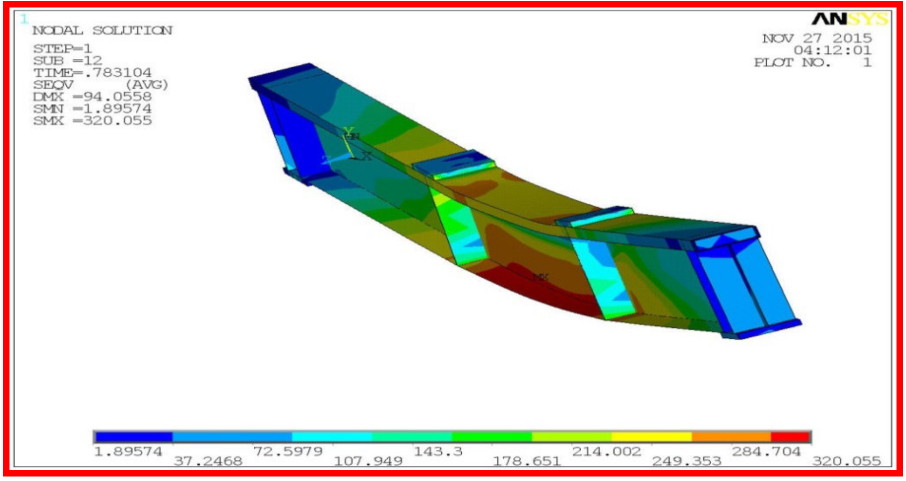

Figure 23: Distribution of von Mises Stresses for Beam TN20.

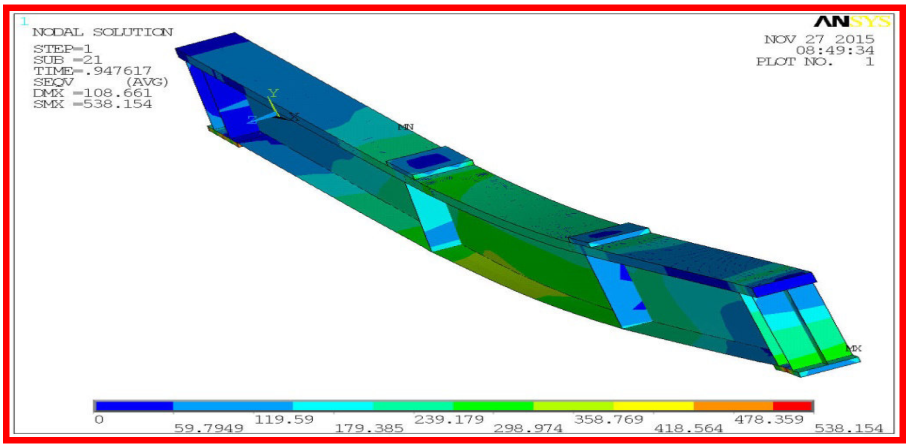

Figure 24: Distribution of von Mises Stresses for Beam TF20.

11. Conclusions

This study presented an experimental test for the topics of improving the lateral- torsional buckling strength capacity of steel members stiffened by Tubular Compression Flange. In addition, the modeling and analyzing of the problem, using ANSYS program to be the theoretical analysis, several conclusions were detected. Most important conclusions are:

1. The tubular flange specimens considered in this study, have higher LTB capacity from the standard I-shaped steel members (CB); by about (86- 97%) for tubular flange filled with concrete of 42.5 MPa strength,
2. The tubular flange girders considered in this study, increase the bending strength capacity about major axis comparable with the (CB) by about (50-55%) for tubular flange girders filled with concrete of 42.5 MPa strength.
3. The concrete filled tubular flange increased the LTB capacity by about (14- 22 %) comparing with the unfilled specimens, also increased the flexural strength by about (13-22%).
4. In the specimens that have the same overall depth, increase the tubular flange depth from (20-40 mm) was caused decrease the LTB capacity by about (4-10%); also decrease the flexure strength by about (3-5%).
5. Tubular flanges girders allowed for the use of large girders unbraced lengths by increasing the torsional stiffness of the girder.
6. The finite element modeling overestimated generally the ultimate load in comparison with the experimental results. The percentage of overestimation for the numerical results in case of ultimate loads ranged between (1.63 to 4.85%).

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