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Load Carrying Capacity of Corrugated Web Beam

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Abstract

The shear panels of plate girder made from corrugated in the web is investigated in this research. A corrugated web beam of plate is attached in the shear zone of the web as part of an experimental and theoretical investigation into plate girders. In experiments, seven plate girder specimens were tested under two points of load. Six of them were made of different shape of corrugated plate in the web, the last specimen was tested without corrugation as a reference specimen called control. In this study investigated the effected of (corrugation plate, thickness of corrugation with number layers of corrugated and the shape of corrugated plate) on (buckling and ultimate loads also on lateral and vertical deflection) and compared with reference specimen, these specimens have the same dimensions, the main variable was the thickness of the corrugated plate in the web (0.5, 1, and 2) mm, the depth was constant (300 mm). According to results of the experiment, the corrugated plates primarily increase the plate girder's stability. A corrugation of plate increases the buckling load and ultimate load significantly through the contribution of the corrugation to delay buckling of the plate girder in the web. In addition, it was found that increasing the plate-girder thickness leads to increased buckling and ultimate loads, because the stiffness will increase and delay the buckling. Also, the trapezoidal corrugation and the diagonal corrugate that placed perpendicular on the tension field action, give higher buckling and ultimate load than control beam. Ansys (version 17.0) computer program was used in this research represent the steel and nonlinear large structural shell was used to represent the corrugated web beam of the plate in the finite element analysis model.

Keywords: ANSYS, Corrugated web, Corrugation orientation, Load carrying capacity, Finite element analysis.

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1. Introduction

Plate girders are commonly seen in bridges and industrial structures, a plate girder is made up of welded together two flange plates with a web in its most basic form. A plate to make an I-section the use of a deep plate for big spans or loads is recommended. Girders result in thin webs, increasing the risk of web buckling; stiffeners are used to allow thin webs to be used.

A stiffener is used in most situations in order to divide the web into panels that are supported along the length of the panel, Stiffener welding lines, on the other hand, has two drawbacks, the first is that it is quite expensive to manufacture, and the second point to mention is the short time of exhaustion. It is common to use corrugated plates as plate girder webs possible way of achieving adequate out-of-plane stiffness and buckling resistance without using stiffeners or thicker webs [1], [2] as shown Fig. 1 and 2. Girders made of the corrugated web were originally used in the field of aircraft design before being used in applications in civil engineering like bridges and structures. In prior studies, girders made of plates using a corrugated web can weigh as much as 30 % less than those of flat-web plate girders with the same static strength [3].

The structure's total dead loads will be decreased, as will the foundation loads, resulting in structural project cost savings. In some cases, the cost savings ranging from 10 % to 30 % [4] when using a flat plate in a web girder, additionally, higher out-of-plane stiffness and, as a result, enhanced torsional, and Lateral-torsion buckling capabilities result from web corrugation. It's also been proven that the corrugated plate does have a longer fatigue life and is stronger than girders made of steel plates with flat webs and transverse stiffeners, when it comes to the design of steel bridges, this is a critical consideration.

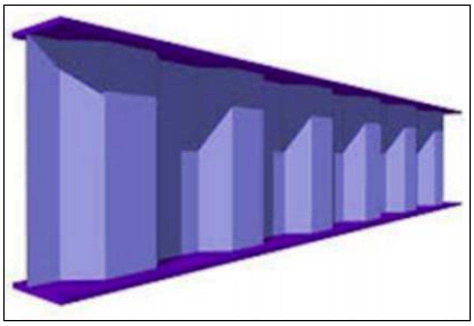


Fig. 1 Courage web on plate girders with stiffeners [3].

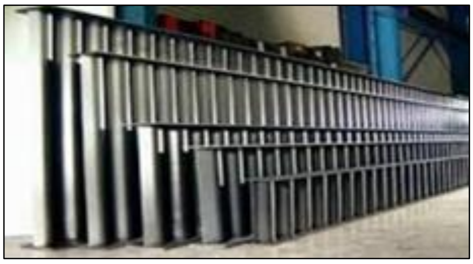


Fig. 2 Corrugate with different web heights with no stiffeners.

In general, the production of these types of plates, the welding of the wavy plate, which has both top and bottom flanges, and the surrounding components, is made by passing a web that is thin and flat through a stretch of leveler to reduce residual tensions. After that, a set of coils is utilized to corrugate the flat web plate into the appropriate web configurations [4]. Romeijna et al. (2009) [5] suggested that the finite element analysis used to investigate the basic parametric analysis of steel girders using trapezoidal corrugated webs and cutouts. Corrugated web girders with cutouts may be shown to have significant capacity to handle web stresses and out-of-plane buckling potential failure in ANSYS. The shear resistance of a corrugated girder decreases as the height of the web is increased, according to the results of the parameter study. Limaye et al. (2013) [6] studied focused on rectangular corrugated web plates for the purpose of buckling strength calculation for a plate girder. The analysis of plate girders is done using the ANSYS finite element software, and its results are compared to a plate girder with a uniformly deep planar web. Several variables, including buckling strength and ductility. Weight is taken into account while making comparisons, high buckling strength and enough thickness are found in the corrugated web plate, in comparison to plate girder with plane web, light gauge parts save weight. Al-Mazini (2015) [7] investigated steel girders that circular and square apertures in the web, testing of seven plate girder specimens under two-point loads was performed as part of the experiment. Three specimens were tested to determine the effect of the circular web opening on the strength of the circular web. The influence of the inclusion of square web apertures on the performance of the other three specimens was investigated. As a reference (control) specimen, the final one was tested without opening, the experimental results revealed the position of the plastic hinge depends on the size of the hole, and the maximum load capacity of the girders decreases as the opening size increases. Al-Azzawi et al. (2019) [8] presented an experimental study of a novel technique to strengthen web plates of steel plate girders against breathing fatigue due to shear buckling deformations. Six slender steel plate girder specimens were manufactured and the webs were strengthened with CFRP profiled sections to investigate their behaviour under cyclic loading. The results of both, experimental and nonlinear finite element modeling proved the efficiency of proposed technique in stiffening steel web against deformation of shear buckling in addition to reducing the critical stresses, consequently increasing the life expectancy of steel girders by a factor ranging between 3 and 7, this range depends on the range of applied stress and the method of fatigue resistance assessment following in 2020. Al-Azzawi et al. [9] developed their study to present the theoretical part of their experimental study to demonstrate both, critical stresses reduction and increasing life expectancy for bridges.

2. Experimental work

The experiments are being carried out in the Engineering Materials Laboratory of the University of Basra’s College of Engineering. The main purpose of the program is to generate data and provide information about the structural behavior of plate girders by using corrugated in a shear zone of the web. Plate girders made with corrugated plates are subjected to two points of load in an experimental study program. A total of seven simply supported plate girders were tested.

The following are the most important variables that were taken into account:

1. The corrugate of plate girders are different in shape, angle, and thickness.
2. The thicknesses of a corrugated plate in the webs investigate by using 0.5 mm, 1 mm, and 2 mm.
3. The orientation of corrugated plate: three different orientations are used in this study.
4. The layer of a corrugated plate by using one layer and two layers with different thicknesses.

3. Steel plates

The plate girders were constructed using mild steel plates with thicknesses of 1.6 and 2 mm. Six tension coupons were cut and tested according to ASTM A370P [6], to assess the steel's material characteristics coupons were cut from a plate with a thickness of 1.6 mm and a width of 6 mm. Depicts the test setup as well as the coupons following failure, Table 1 shows the tensile characteristics of the plate steel.

Table 1. Yield and ultimate stress of steel plates.

Steel plate thickness (mm)	Yield stress (N/mm²)	Modulus of elasticity (N/mm²)	Ultimate stress (N/mm²)	Average of elongation (%)
1.6	220.1	200000	380	20
	220.0	200000	380.4	20.1
	220.1	200000	380.1	20
2	220.0	200000	381	20
	220.3	200000	380	20.7
	220.6	200000	380.1	20.3
Average	220.2	200000	380.2	20.1

4. Specimens’ identification

The sections of all girders were symmetric, with identical flange and web diameters. Steel plates with a thickness of 6 mm for (flanges, web and stiffeners), the thickness of plate girder of the web it (1 mm, 2 mm, 0.5 mm), it was used welding to create the needed plate girders. The corrugate in the web's plate had different shape according to the theoretical analysis shown, seven specimens have been produced in this investigation (one of which is a control specimen). White oil paint was used to paint it after made it.

Table 2. Detail of beam.

Beam No.	a/h ratio	Plate	Orientation (α)	Length of Beam (m)	Effective span (m)
B1	1.6	Control	90	1.6	1.3
B2	1.6	CWB One layer thick (1 mm)	90	1.6	1.3
B3	1.6	CWB two layer thick (1 mm)	90	1.6	1.3
B4	1.6	CWB one layer thick (0.5 mm)	90	1.6	1.3
B5	1.6	CWB two layer thick (0.5 mm)	90	1.6	1.3
B6	1.6	Trapezoidal	-	1.6	1.3
B7	1.6	Diagonals	90	1.6	1.3

Table 3. Geometric parameters for plane web plate girder.

Web High (h)	Web Thickness (t_w)	Flange Width (b_f)	Flange Thickness (t_f)	Overall Depth (H)	Length (mm)	F_y (N/mm)
300 mm	6 mm	200 mm	6 mm	312 mm	1600 mm	220

5. Plate with corrugate webs

A corrugated plate was used the steel test beams. In this study, the plate in the web makes corrugations in different shapes and thicknesses, the specimens formed two flanges (160 × 20 × 0.6) cm and were welded with web (160 × 30 × 0.6) cm, all of the seven specimens carried the same dimensions but different in the web plate. The last one without corrugation, called control beam B1, to compare it with the other corrugated specimen, to know the differences and the most tolerable, the corrugated plate girder was formed vertically for four specimens, two of them have thick 1 mm once in one layer and the other two layers, and the other two were thick 0.5 mm once in one layer and the other two-layer, as shown Fig. 3.

Fig. 3 Corrugate plate.

Fig. 4 Trapezoidal plate.

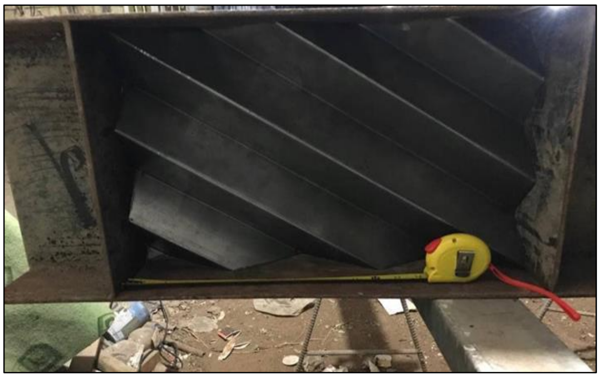


Fig. 5 Diagonal corrugate.

Fig. 6 Control model without corrugate web (B1).

Fig. 7 Beam with corrugate web one layer and thickness 1 mm (B2).

Fig. 8 Beam with corrugate web two layer and thickness 1 mm (B3).

Fig. 9 Beam with corrugate web one layer and thickness 0.5 mm (B4).

Fig. 10 beam with corrugate web two layer and thickness 0.5 mm (B5).

Fig. 11 Beam with trapezoidal corrugate and thickness 1 mm (B6).

Fig. 12 Beam with inclined corrugate web and thickness 1 mm.

6. Instrumentation

At each step of loading, the equipment was employed to detect the structural behavior of the beams. A dial gauge with a magnetic base was used to measure the vertical displacement (deflection) at the site of applied loading and lateral deflection (deformation) at the center of the web during each load step, the dial gauge has a 0.01 mm precision. Fig. 13 depicts the instrumentation of beams.

Fig. 13 Dial gauges used to measure deflection and lateral deformations.

7. Load measurement

A testing machine with a maximum capacity of 2000 kN was used to test the beams. The beams were loaded from the top at the span centers. In each loading step, approximately ten load steps were applied until failure. Total applied load, mid-span deflection, concrete strains, and crack width were measured during acceleration with monitoring and plotting cracks during acceleration. A universal testing machine is shown in Fig. 14.

Fig. 14 Universal testing machine.

8. Buckling and ultimate load (U.L and B.L)

A summary of experimental results of beams is presented in Table 4.

Table 4. experimental results of beams.

Beam No.	Type of plate in the web	Thickness of plate in the web (mm)	Orientation α	Buckling load (kN)	Ultimate load p_u (kN)	$\frac{B.L}{U.L}$
B1	flat	1 mm	Control	20	77	25 %
B2	Corrugate plate with one layer	1 mm	90	29	90	32 %
B3	Corrugate plate with two layers	2 mm (1 + 1) mm	90	79	215	36 %
B4	Corrugate plate with one layer	0.5 mm	90	16	54	29 %
B5	Corrugate plate with two layers	1 mm (0.5 + 0.5) mm	90	35	117	29.9 %
B6	Corrugate of trapezoidal	1 mm	45	36	108	33 %
B7	Corrugate (diagonal)	1 mm	diagonal 90	38	127	29 %

8.1. Effect of corrugated plate on B.L and U.L

To study the effect of corrugated plate in shear zone of the plate girder (B2, B5), which have same thickness (1 mm) and compared these results with control beam (B1). From table 4, it can be observed that the corrugated specimens (B2 and B5) have exhibited buckling about (45 % and 75 %) respectively, higher than control beam girder, while in the ultimate load the corrugated plate girder (B2 and B5) give higher than B1 about (16 % and 51 %) respectively. This is attributed to that the corrugation of plate leads to increased stiffness and delay the buckling of plate shear zone. After buckling one of diagonal the shear zone in the case behaves as truss and the tension filed action developed in other diagonal until to failure. From table 4, it is evident that corrugated plate girders have an effect on ultimate and buckling load, the corrugated plate specimens was little effected than that of control specimens that mean the corrugation of plate do not effect on tension field action as shown in Figs. 15 and 16.

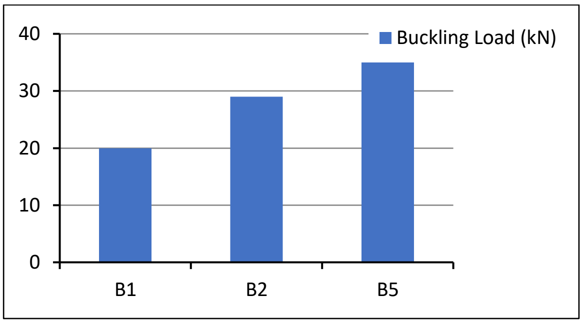


Fig. 15 Comparison of buckling load of specimens (B1, B2 and B5).

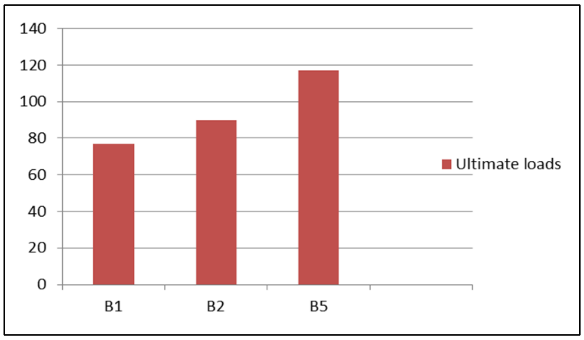


Fig. 16 Comparison of ultimate load of specimens (B1, B2, and B5).

8.2. Effect of thickness and number of layers of corrugated plate on B.L and U.L

For specimens (B2 and B5) that have the same thickness but a different layer, B2 has one layer of corrugated plate with a thickness of 1 mm, and B5 has two layers of corrugated plate, each of which has a thickness of 1 mm. When compared between B2 and B5, it can be found that the girder B5 give higher buckling and ultimate loads about (17 % and 23 %) respectively than B2, as Fig. 17. Accordingly, it is lead to increase the stiffness and delay buckles. While (B2 and B4) are made of one layer of corrugate but have different thicknesses (B2 has a thickness of 1 mm and B4 has a thickness of 0.5 mm), as shown in Fig. 18. The girder B2 provides higher buckling and ultimate loads than B4 (44 % and 40 %, respectively). This means that an increase in thickness results in an increase in stiffness and delays the buckling of the plate in the shear zone.

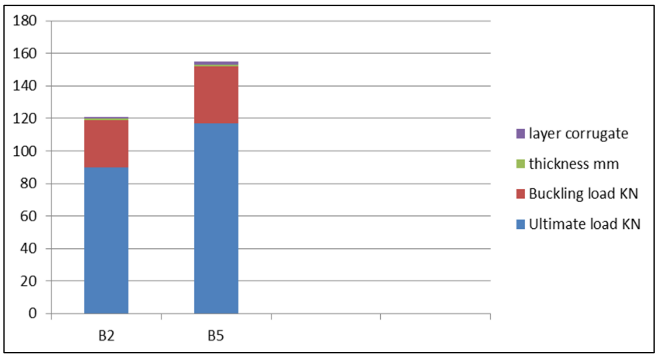


Fig. 17 Compared U.L and B.L between B2 and B5.

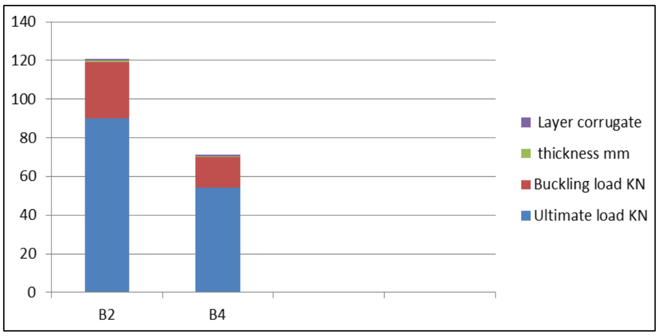


Fig. 18 U.L and B.L load between B2 and B4.

For specimens (B3, B5) which have two layer of corrugated but they have different thickness, the girder B3 which have thickness 2 mm, but the girder B5 with thickness 1 mm. When compared between the girders B3 and B5 it found that, the girder B3 give higher buckling and ultimate load about (55 % and 45 %) than B5 as Fig. 19, this is attributed to the increase of thickness leads to increase of stiffness and delay buckling.

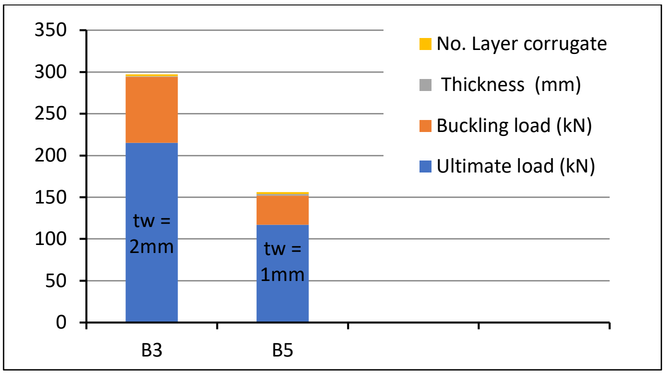


Fig. 19 Compared B.L and U.L between B3 and B5.

8.3. Effect the shape corrugated plate on B.L and U.L

In this study, the specimens (B2, B6, B7) which have same thickness (1 mm) with one layer of corrugate and different orientation or shape, the girder B7 made from diagonal corrugated placed perpendicular on tension filed action, while B6 trapezoidal corrugate and B2 (vertical corrugated). From table 5, it can be observed that the girder B7 give higher buckling and ultimate load than (B2 and B6) about (23 % and 5 %) than B2 and (29 % and 14 %) than B6 respectively. It means that the corrugated panels oriented perpendicular to tension field action and parallel to compression diagonal, contribute directly to reducing the effect of compression stress to the web and thereby delaying buckling. While the girder B6 give higher buckling and ultimate load than (B2) about (19 % and 16 %) respectively, and it is giving less than B7 about (17%, 5%). According to the experiment results, web thickness is a significant factor that determines the behavior of girders following patch loading on corrugated webs. The ultimate strength increased when the web thickness was changed from 0.5 mm to 2 mm.

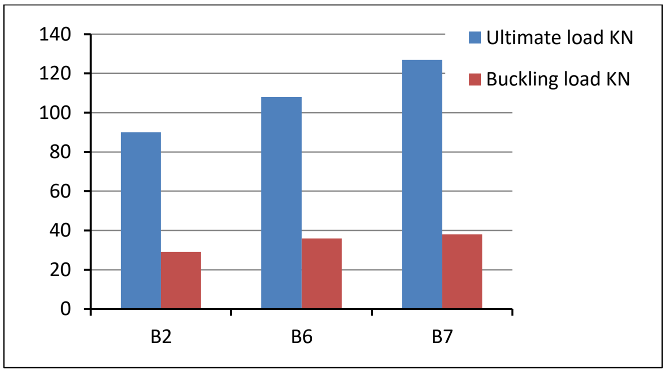


Fig. 20 Comparison of B.L and U.L of corrugated specimens with different shape.

9. Girder behavior under loading vertical and lateral deformations V.D and L.D

The experimental results of beams are summarized in table 5, it was observed that for specimens, the vertical and lateral displacements were different because of the effect of corrugate, orientation, and thickness of plate girders. A vertical load applied to a beam results in compression in upper flange and tension in lower flange of the section, tension flange supporting member to stay straight while compression flange tries to deflect laterally from original position. When applied load cause both lateral and vertical displacement of member lateral torsional buckling has occurred, the lateral torsional buckling was affected by the distance between the shear center of the beam and location at an application of load. To study the effect of corrugation on were considered, the vertical and lateral displacement, from table 5, it can be observed that the girders (B2 and B5) with corrugation reduces the lateral deflection as compared with control B1, while the vertical deflection a little increased than B1, that mean the corrugated increased stiffness therefore, reduce the lateral deflection in shear zone, but the corrugated little effected of vertical deflection.

Table 5. Experimental results of vertical and lateral deflection.

NO. Beams	Ultimate Vertical Deflection (mm)	Ultimate Lateral Deflection (mm)
B1	9	36
B2	15	0.9
B3	12	0.44
B4	17	2.6
B5	14	1.9
B6	13.5	2.3
B7	30	1

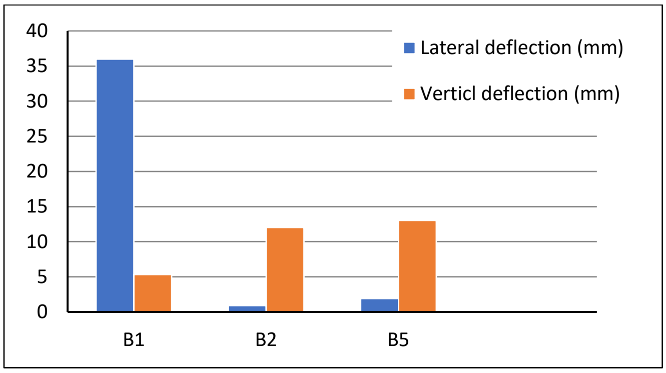


Fig. 21 Compared the specimens B1, B2, B5 for V.D and L.D.

From Figs. 22 and 23, it is noted in the initial loading stage, the girder (B1) beaver as elastic, the buckling occurred at center of the shear zone and directed along the compression diagonal to the support and point load. At the load (20 kN), the curve changes the slope, the vertical and lateral displacement at this load were (0.043 and 0.22) mm respectively. The buckling continued until the plastic hinge created at the end of diagonals tension in top and bottom of flange near stiffeners diagonal as Fig. 32, and in final failure, the ultimate load is (77 kN) and maximum vertical and lateral deflection are (9 and 36.1) mm respectively.

Also, in the first stages the girder B2 behave as elastic, the buckling occurred at center of the shear zone in the corrugation, the buckling continued until the plastic hinge created at the middle of corrugation, this mean the corrugate worked as a stiffener as shown Fig. 33, the buckling load was 29 kN. The lateral and vertical displacement deflection in this buckling (0.017, 0.076) mm respectively. The final failure of the girder B2 at the ultimate load of 90 kN, the lateral and vertical deflection is (0.9 and 15) mm respectively. The girder B5, in the first stage behavior as elastic, and the buckling began at load 35 kN, in the bottom at three of corrugate near stiffeners, the lateral and vertical displacement is (0.025 and 0.08) mm respectively. The buckling continued until the plastic hinge created at the end of tension at three of corrugate near stiffeners, to make the structure more stable, this corrugator serves as a stiffener as shown 36. The final failure the ultimate load is 117 kN, the lateral and vertical is (1.9 and 14) mm respectively, that's mean the corrugation contributed on lateral and vertical deflections.

From Figs. 22 and 23 at the same load, the vertical and lateral displacement of the specimens (B2 and B5) with corrugated plate are less than that of the control girder (B1). This is attributed to effect of corrugation lead to increase stiffness. The vertical displacement of corrugated plate girder with same thickness (1 mm), the girder with one layer (B1) give displacement higher than that of specimen two layer (B5), while the difference lateral displacement was stilly.

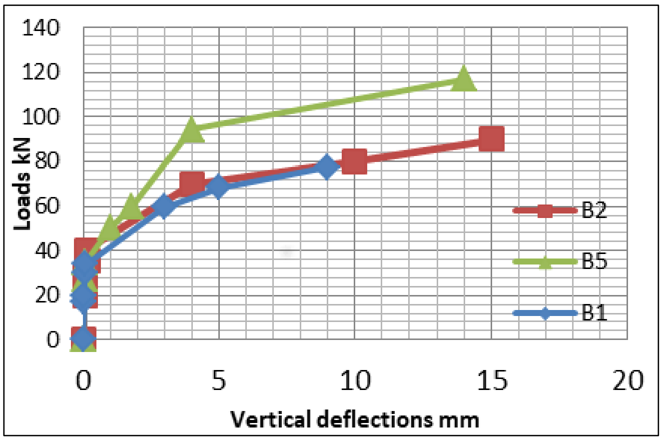


Fig. 22 Compared the vertical deflection for specimens B1, B2, B5.

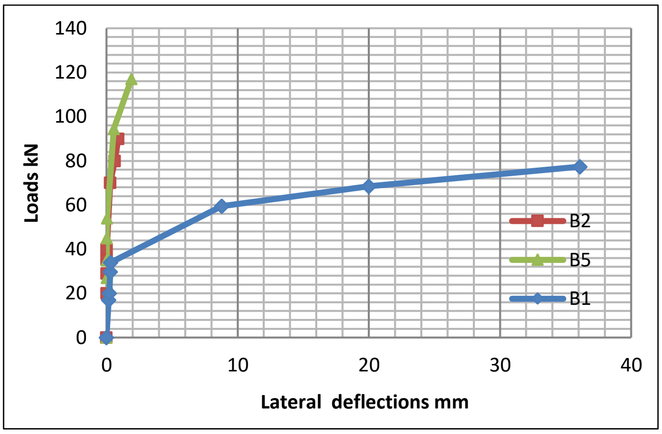


Fig. 23 Compered lateral deflection for specimens B1, B2, B5.

In the first stage behavior, the girder B3 behavior as elastic as shown Figs. 24 and 25, the buckling occurs in the bottom at two corrugate near the stiffeners at load 79 kN, the lateral and vertical deflection is (0.1, 0.018) mm respectively, then the buckling continued until the plastic hinge created at the bottom of two corrugate near stiffeners. In this case, the corrugator became as stiffeners to increase stability as shown 34, this formula is reason of final failure the ultimate load is 215 kN, the lateral and vertical deflection is (0.44 and 12) mm respectively.

From Figs. 24 and 25 it can be observed, at the same load, the vertical and lateral displacement of specimens (B3, B5) with corrugated plate are less than that of the control girder (B1). This is attributed to effect of corrugation lead to increased stiffness. The vertical displacement of corrugated plate girder (B3) with large thickness (2 mm) give displacement less than of specimen with thickness (1 mm), while the difference lateral displacement was stilly. Fig. 24 compared the specimens B1, B3, B5 for (V.D)

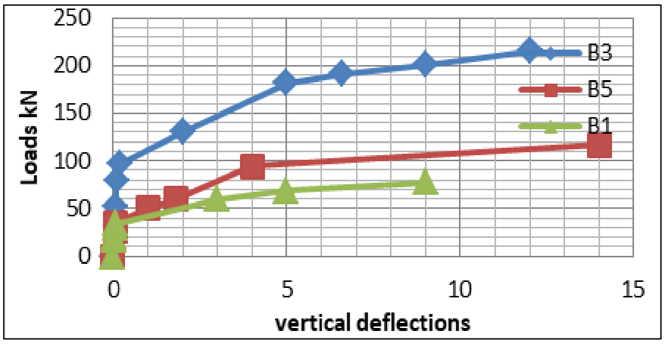


Fig. 24 Compared the specimens B1, B3, B5 for (V.D).

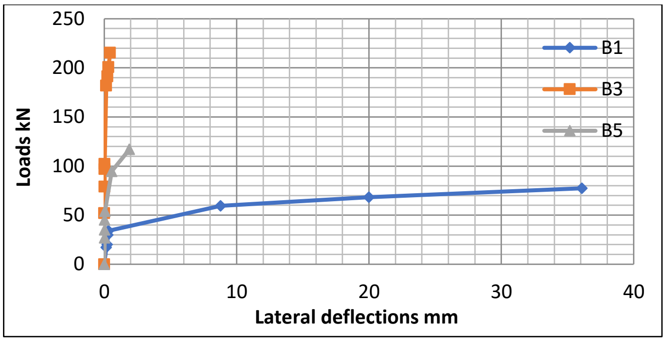


Fig. 25 Compared the specimens B1, B3, B5 for (L.D).

From Figs. 26 and 27 in the first stage of behavior the girder B4 displayed elastic behavior, and the buckling started at the bottom corrugation along the shear zone at 16 kN is (0.073 and 0.033) mm, the buckling continued until the plastic hinge created at the end of diagonal tension to the supported and point load as shown 35. This formula is reason of final failure the ultimate load is 54 kN, the vertical and lateral deflection is (17 and 2.6) mm.

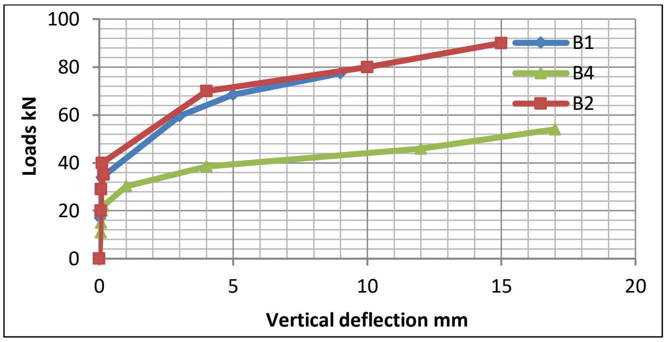


Fig. 26 Compared the specimens B1, B4, B2 for (V.D).

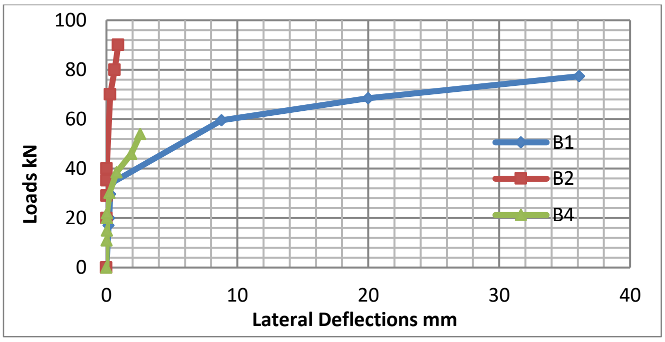


Fig. 27 Compared the specimens B1, B4, B2 for (L.D).

From Figs. 26 and 27, it can be observed that the vertical and lateral displacement of the girder (B4) with corrugated plate is higher than that of the specimens (B1, B2), this is attributed to effect of thickness of corrugation lead to reduced stiffness. From Figs. 28 and 29, it can be observed at the same load the vertical and lateral displacement of the girder (B5) which have two layers of corrugate plate is less than that of the girder B2 that has one layer of corrugate. This is explained by effect of increased layers of corrugation lead to increase stiffness. While the difference lateral displacement was stilly.

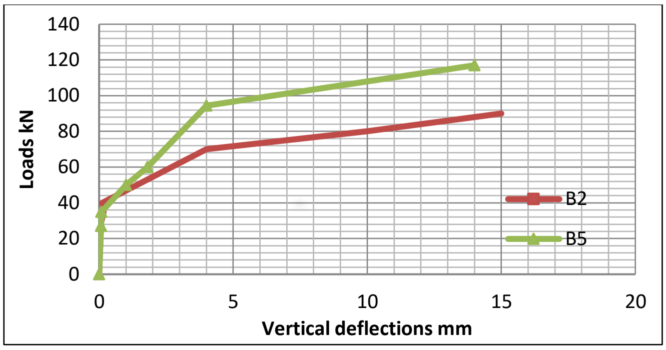


Fig. 28 Compared the specimens B5, B2 for (V.D).

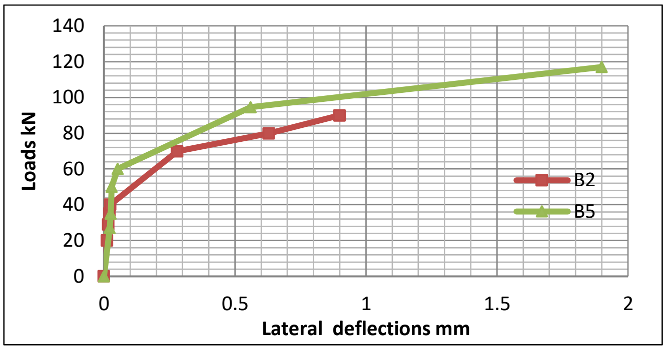


Fig. 29 Compared the specimens B5, B2 for (L.D).

From Figs. 30 and 32, in the initial loading stage, it is evident that the girder B6 behavior as elastic then the buckling started to happen at the part of trapezoidal plate of the shear zone near the load point at 36 kN, the vertical and lateral displacement is (0.022 and 0.076) mm respectively. The buckling continued until the plastic hinge created at the end of diagonal tension near the stiffeners and point load as shown 36, this formula is reason of final failure the ultimate load at 108 kN. The vertical and lateral displacement is (2.3 and 13.5) mm. The girder B7 in the first stage behave as elastic as Figs. 30 and 31, then at two corrugations in the shear zone, buckling appeared at a 38 kN force, with lateral and vertical displacements of (0.014 and 0.095) mm, respectively. The buckling continued until the plastic hinge created at the two corrugation in the center of the shear zone, as shown 37. The final failure the ultimate load is 127 kN. The lateral and vertical displacement (1 and 30) mm respectively.

From the Figs. 30 and 31 it can be observed at the same load, the vertical and lateral displacement of the specimens (B6 and B7) with of corrugated plate are less than that of the control girder (B1), this is attributed to effect of different shape of corrugate lead to increase stiffness. The vertical displacement of diagonal corrugate plate girder (B7) gives higher displacement than that of trapezoidal corrugate. While the different lateral displacement was stilly.

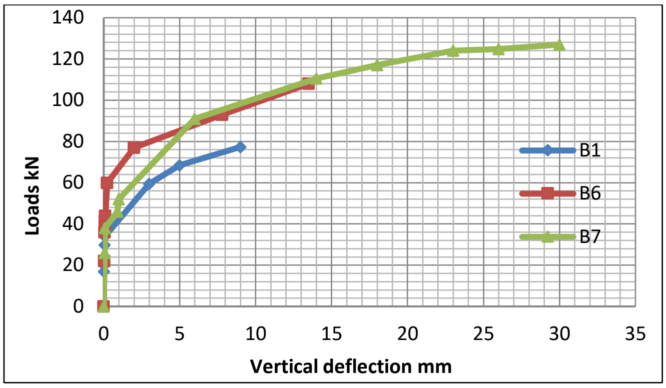


Fig. 30 Compared V.D for the specimens B1, B6, and B7.

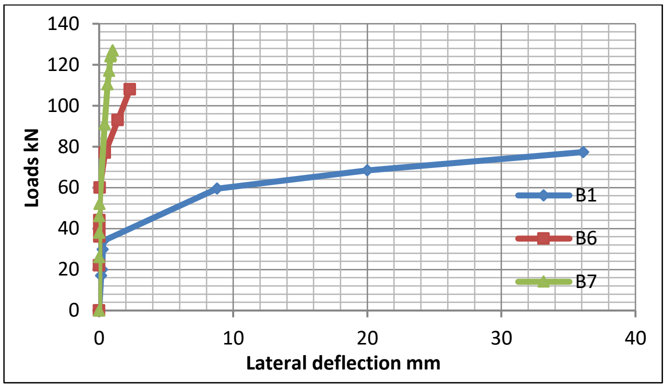


Fig. 31 Compared vertical deflection for specimens B1, B6, B7.

From Figs. 32 to 38 it can be noted that the buckling and failure of corrugated plate in the web for specimens.

Fig. 32 Control beam.

Fig. 33 Corrugated beam with one layer thickness 1 mm (B2).

Fig. 34 Corrugated beam with two layer and thickness 2 mm B3.

Fig. 35 Corrugated beam with one layer and thickness 0.5 mm B4.

Fig. 36 Corrugated beam with two layer and thickness 0.5 mm B5.

Fig. 37 Trapezoidal corrugated beam with thickness 1 mm B6.

Fig. 38 Diagonal corrugated beam with thickness 1 mm (B7).

10. Result and discussions

Finite element analysis is a powerful tool for solving a variety of engineering problems. Stress analysis can be applied to a wide range of engineering projects. A finite element method has been used to analyze linear and nonlinear plate girder [8], [9]. Finite element methods based on nonlinearity have gained popularity over the past four or five decades, the finite element method was designed for models that were two-dimensional and axi-symmetrical, then it was expanded to describe plate, shell, and beam systems in general loading conditions, although two-dimensional analysis is an adequate and computationally efficient solution to many problems, it is not without deficiencies. Based on the results of the three-dimensional analysis [10]. The present chapter discusses powerful nonlinear three-dimensional finite element analysis software ANSYS release 17.0, which is used for the present analysis. Additionally, it describes the current techniques used for finite element modeling of plate girder flat plates.

10.1. Meshing of plate girders

After the model has been geometrically established, the structure should be meshed. A mesh is a graphic division of an entire structure into smaller components, or finite elements as they are majorly known, these items must be properly linked by nodes within their boundaries. Choosing the mesh density is an important step in finite element modeling, when a suitable elements number is utilized in the model, the results will converge, this is really when increasing mesh density has no effect on the results.

The mesh density selection is a crucial stage in finite element modeling. Eight alternative numbers of components were employed to test the convergence of the findings for the control beam No. B1: 200, 277, 280, 400, 660, 1390, 1414. The deflection at the beam's mid-span was chosen for the same applied load to investigate the data convergence relationship between the number of elements in a beam and its mid-span deflection, as shown in Fig. 39. When the number of subdivisions of mesh exceeds 1414. The deflection at mid-span becomes essentially constant, according to the graph. As a result, the 1414 elements model was chosen, which was comparable to a mesh size of 15 × 15 mm. This mesh size served as the foundation for the rest of the beams.

10.2. Load boundary conditions

For the model to be constrained and produce a unique solution, displacement boundary conditions are required. Applying boundary conditions at the plane of beam, as well as the locations of the supports and loadings, will guarantee that the model behaves in the same way as the test beam. The first, boundary conditions for beam were established, the model being used has one plane on which it is symmetrical.

A roller was made by modeling the support in such a way. The rotation of the beam at the support will be permitted by constraining one line of nodes in the y-direction, applied load and boundary conditions are shown in Fig. 39.

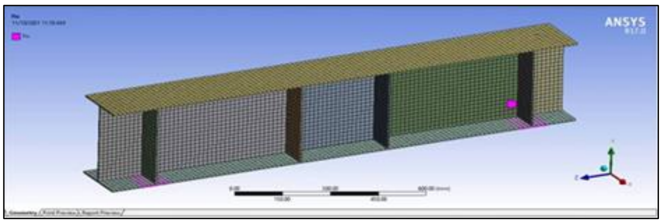


Fig. 39 Applied load and boundary conditions.

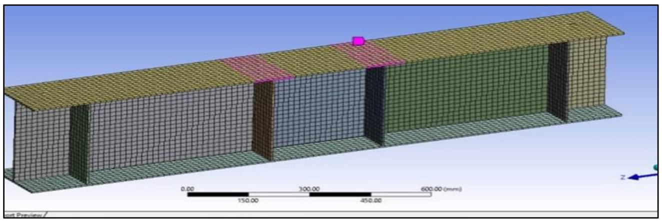


Fig. 40 Distribution of applied load at nodes.

The equivalent nodal force on the top nodes of the beam represents the external applied load, because only half of the full beam was modeled. The applied load on it will be equal to half of the total applied load, as shown in Fig. 40. The loads were applied incrementally up to failure as required by the Newton-Raphson procedure. As a result, a series of load increments were created from the total applied load (load steps).

10.3. Buckling and ultimate loads of plate girders

Table 6 summarizes the buckling and ultimate loads of plate girders determined from finite element analysis as well as the related experimental, the finite element and the test buckling and ultimate load are in good agreement. The predictions of the finite element approach for both control and reinforced beams are quite the ultimate loads were quite near to their matching experimental values. The comparison indicates that buckling and ultimate load may be reliably predicted using finite element modeling.

Table 6. Buckling and ultimate load of beams.

Beam No	**Buckling Load Exp. (p_{cr})**	**Ultimate Load Exp. (p_u)**	**Buckling Load Ans. (p_{cr})**	**Ultimate Load Ans. (p_u)**	$\frac{Ans_{pu}}{Exp_{pu}}$	$\frac{Ans_{\ pcr}}{Exp_{PCR}}$
B1	20	77	29	85	1.09	1.48
B2	29	90	35	100	1.11	1.21
B3	79	215	97	260	1.2	1.22
B4	15	54	20	55	1.01	1.33
B5	35	117	45	130	1.11	1.28
B6	36	108	41	110	1.01	1.15
B7	38	127	46	135	1.06	1.21

The resulting ultimate load from the experimental test for control beam (B1) is 77 kN. Simulating a similar load case with the FE-model resulted in an ultimate load of 85 kN. This corresponds rather well with the results of test B1 from which it deviates by 1.1 %. The load-deformation curves obtained from the experimental tests and the FE-model correspond very well throughout the entire loading range. The rather drastic drop in capacity after reaching the ultimate load is present in all curves, this behavior reveals a structure with high stiffness, similarly as for the load cases B2, B3, B4, B5, B6 and B7, the FE-model is stiffer in the elastic part of the loading range than the tested girder. However, in this case, the difference is comparatively small.

10.4. Load-deflection plots

The deflections of test beams were measured at the two directions (vertical and lateral) of the beam after loading. Deflections are computed in ANSYS at the same position as test beams. The load-deflection plot from the finite element model is shown in Figs. 41 to 47, all beams were subjected to element analysis and experimental findings. The numbers demonstrate that the load-deflection curves are in excellent accord connections derived from FE models and those seen experimentally.

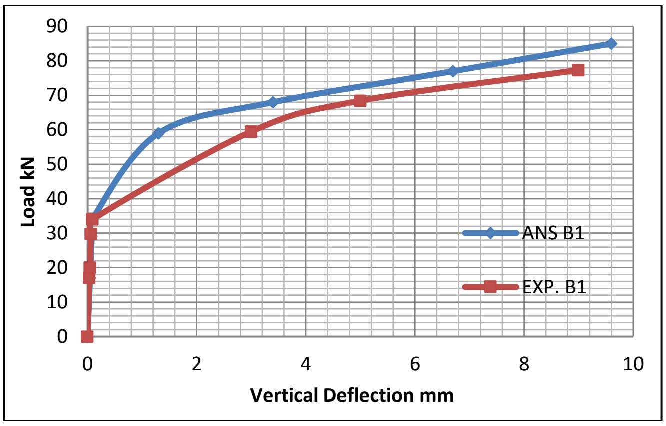


Fig. 41 Variation of deflection with load for beam B1.

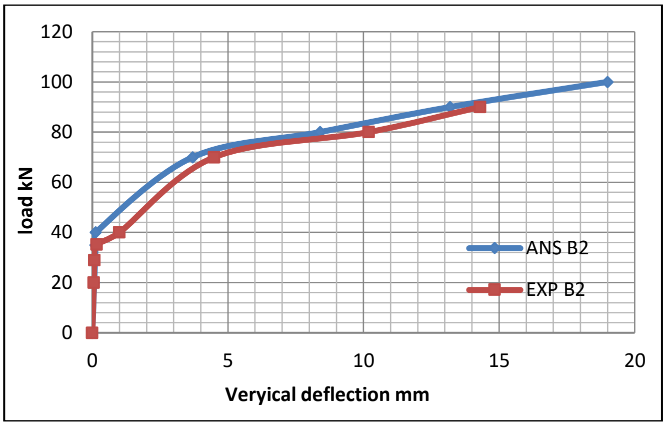


Fig. 42 Variation of deflection with load for beam B2.

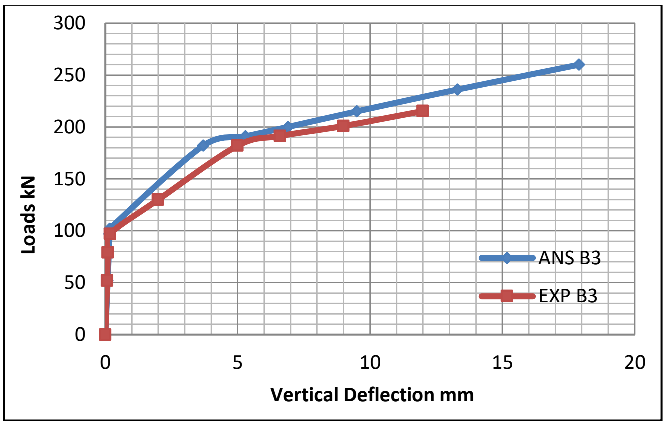


Fig. 43 Variation of deflection with load for beam B3.

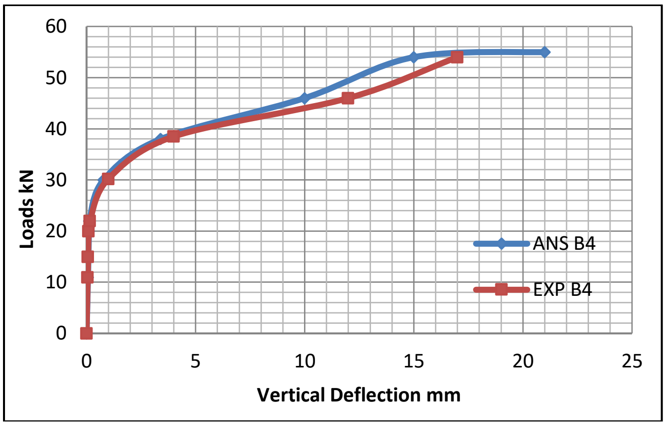


Fig. 44 Variation of deflection with load for beam B4.

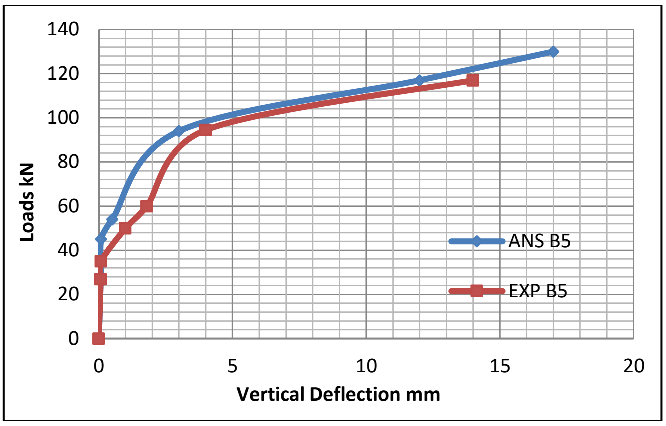


Fig. 45 Variation of deflection with load for beam B5.

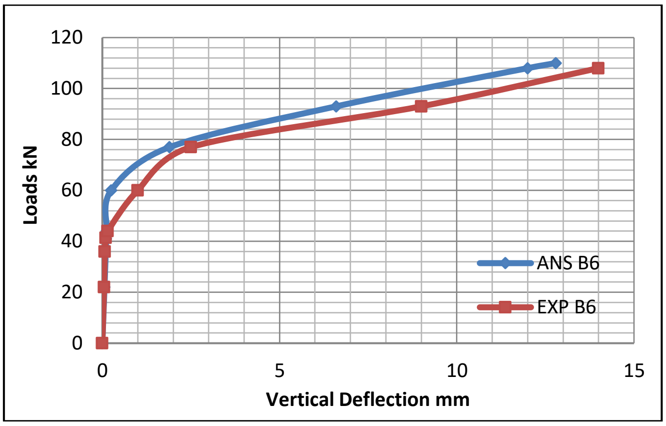


Fig. 46 Variation of deflection with load for beam B5.

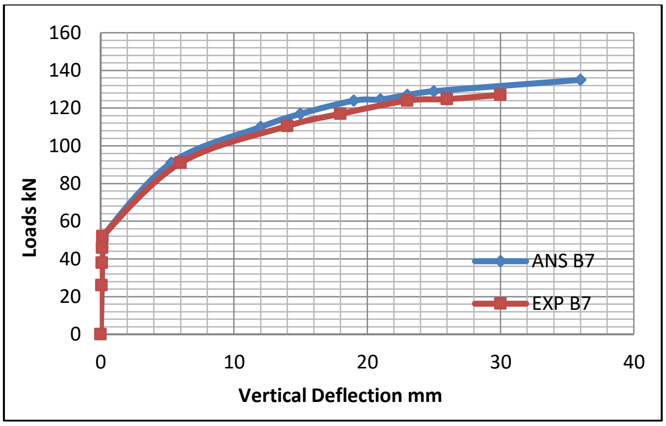


Fig. 47 Variation of deflection with load for beam B7.

Figures 48 to 54 show the photographed failure modes of tested beams as well as the failure modes predicted by the FE. The FE results are consistent with the actual failure mechanism seen during testing. These findings provide assurance that the output of the following FE models will be accurate.

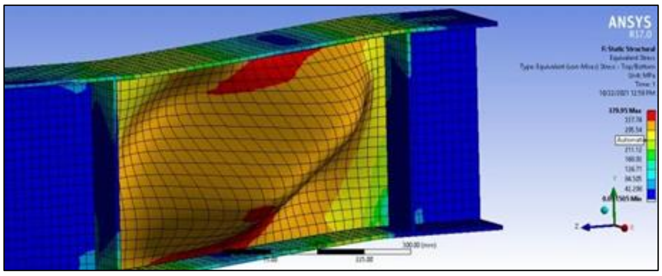
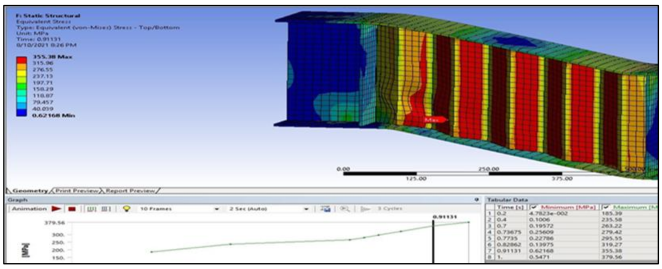


Fig. 48 Von-Mises stress contour for B1.



	Time [s]	✓ Minimum [MPa]	✓ Maximum [M
1	0.2	4.7823e-002	185.39
2	0.4	0.1006	235.58
3	0.7	0.19572	263.22
4	0.73675	0.25609	279.42
5	0.7735	0.22786	295.55
6	0.82862	0.13975	319.27
7	0.91131	0.62168	355.38
8	1.	0.5471	379.56

Fig. 49 Von-Mises stress contour for B2.

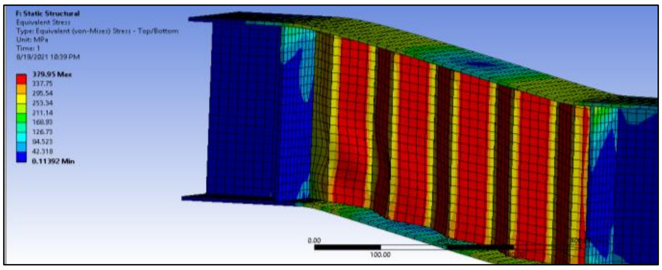


Fig. 50 Von-Misses stress distribution for B3.

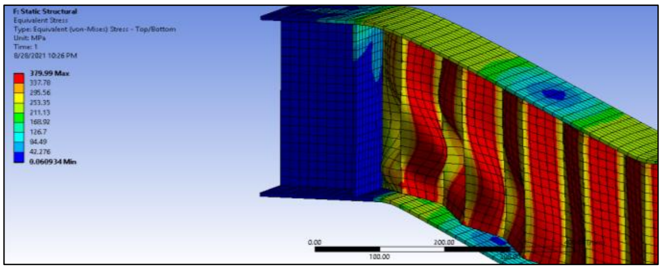


Fig. 51 Von-Misses stress distribution for B4.

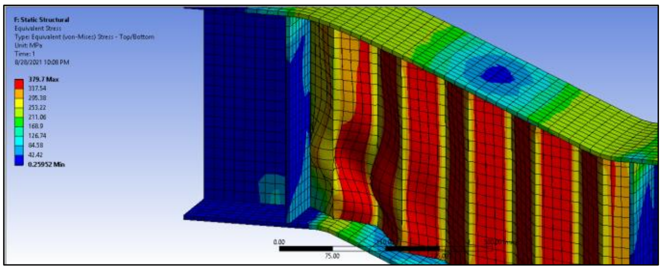


Fig. 52 Von-Misses stress distribution for B5.

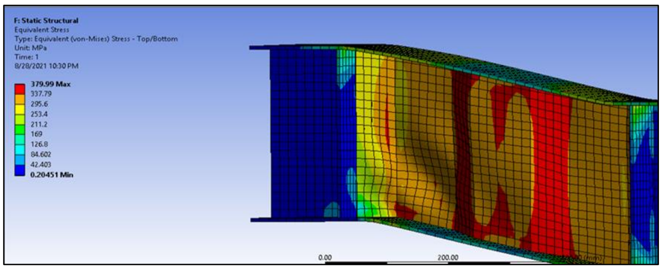


Fig. 53 Von-Misses stress distribution for B6.

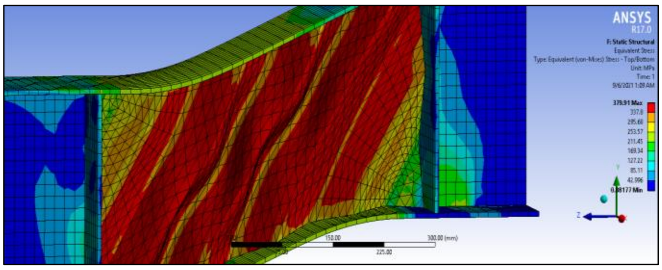


Fig. 54 Von-Misses stress distribution for B7.

11. Conclusions

In this work of study of plate girder with corrugate web, plate girders were designed and build to investigate the effects of corrugation, thickness of corrugated plate, and shape corrugate on the buckling load, ultimate load, vertical deflection and lateral deflection. A total of seven simply supported plate girders were tested were designed, tested and solved with ANSYS software. Four specimens with corrugate, which have different thickness and layers. The other specimens were the trapezoidal corrugated with thickness 1 mm, and diagonal corrugated placed perpendicular on tension field action with thickness 1 mm, the last specimen without corrugate called control beam with thickness 1 mm.

1. According to experimental results, the failure of the section is mostly caused by web plate buckling.
2. The behavior of specimens, in the first stages of loading was elastic, then (after reaching the critical buckling stress) the buckling began and the post-buckling stiffening effect started due to the tension field action and continued until the plastic hinge formulated.
3. As the thickness of the corrugated web increases, the load-carrying capacity improves as well. The girder which had corrugated web with a large thickness give higher buckling and ultimate load than control beam (without corrugate), while the corrugate girder which had less thickness giving less buckling and ultimate loads than control beam, about 20 % and 29 % respectively.
4. Comparing the corrugated web with flat web, it is found that the corrugation increased both the buckling and ultimate loads, the major effect of the corrugated web is to enhance the stability of the web of the plate girder, as a can be seen from the flowing:
   a) In same thickness and layer, the girder with corrugated web giver higher buckling and ultimate load than control beam about 45 % and 16 % respectively.
   b) The girder in same thickness but increased layers of corrugate, give higher buckling and ultimate load than control beam, about 75 % and 51 % respectively.
5. The inclination of corrugated web toward compression diagonal will significantly increase the buckling and ultimate load of the plate girder, give higher buckling and ultimate load than control beam about 47 % and 64 % respectively.
6. The size of mesh of 15 × 15 mm in finite element analysis model for plate girders made with corrugated plates, give best good agreement theoretical results comparison with experimental results.
7. The corrugation in the web reduced the compression failure.

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[9] Al-Azzawi et al. “developed their study to present the theoretical part of their experimental study to demonstrate both”, critical stresses reduction and increasing life expectancy for bridges.