## Journal of Engineering Research

Volume 6 | Issue 1 Article 7

2022


# Behaviour of Steel Plate Girders with Double Corrugated Webs Under Uniform Bending


Mostafa Alleboudy

Vol. 6, No. 1 – 2022 Journal of Engineering Research (ERJ)

# Behaviour of Steel Plate Girders with Double Corrugated Webs Under Uniform Bending

**Mostafa Sh. Alleboudy[1*], Mahmoud H. El-Boghdadi[2], Mostafa F. Hassanein[3], Ahmed M. El-Hadidy[2]**

[1*] *MSc Student, Structural Engineering Department, Faculty of Engineering, Tanta University*
[2] *Associate Professor, Structural Engineering Department, Faculty of Engineering, Tanta University*
[3] *Professor, Structural Engineering Department, Faculty of Engineering, Tanta University*
Emails: mostafa_alleboudy@f-eng.tanta.edu.eg

**Abstract- Corrugated steel webs have been widely used in various structures, especially in the bridges due to several advantages. Firstly, they can be used to replace the stiffened steel plates of the plate girders to prevent out-of-plane displacements. Secondly, corrugated steel webs improve the aesthetics of structures and reduce the cost of beam fabrication. Recently some researchers have studied the use of steel plate girders with double corrugated webs which showed an increase in the girder strength. Thus, the focus of this study is to investigate the behaviour of steel plate girders with double corrugated webs. The basic goal of this study is to deepen the understanding of the flexural behaviour of the simply supported plate girders with double corrugated webs (PGDCWs) by investigating the behaviour of simply supported plate girders with double corrugated webs (PGDCWs) under the influence of static loading and uniform bending moment until their failure and to verify the theoretical model. This study, also, aims to study the effect of the section properties on the behaviour and flexural strength of simply supported PGDCWs and to establish the basic input parameters and modelling criterion required for non-linear finite element analysis of simply supported PGDCWs. Then, a parametric study is conducted to investigate various design parameters.**

***Keywords:*** ***Plate Girders, Double Corrugated Webs, Uniform Bending*.**

## I. INTRODUCTION

Research on steel plate girders with corrugated webs (PGCWs) was performed by NACA in 1956 [1] for airplanes wings where the sections were built up by riveted angle connections. After that the application of the corrugated web girder was spread in the civil engineering practices as well, especially in the field of bridges [2]. The concept of using webs formed from corrugated steel plate was introduced in Japan in 1965 [3] and were then recognized in 1976 as the supporting girders for a crane in a steel factory [4]. Moreover, PGCWs have been fabricated and used in Germany, Sweden, and France. Recently in Austria. PGCWs have been used widely in recent years because of the increased production of this kind of girders. This is attributed to their advantages as they have higher out-of-plane stiffness and buckling resistance without the need for using stiffeners or thicker web plates [5]-[6], also using corrugated webs reduces the welds used which in return increases the fatigue life of the structure and reduces the fabrication cost [7]. Steel plate girders with corrugated webs have up to 10% higher lateral torsional buckling (LTB) resistance compared to standard flat web plate girders [8]. PGCWs own higher web height-to-thickness $(h_w/t_w)$ ratios compared to conventional girders with flat web which can reach up to 500 in corrugated plates rather than 200 in conventional girders with flat web plates, which in return reduces the overall own weight of the structure and subsequently on foundation, resulting in reduction in the total cost [9].

## II. FINITE ELEMENT MODELLING

### A. *General*

The finite element (FE) program ABAQUS [10] was used to simulate the behaviour of plate girders with corrugated webs (PGCWs) under uniform bending. The model used the actual measured geometric and material properties. Finite element analysis for buckling requires a two-step analysis. The buckling modes of (PGCWs) are first estimated through the Eigenvalue analysis. This is a linear elastic analysis performed using the (*BUCKLE) procedure, in the step module, available in the ABAQUS library with the load applied within the step. The first buckling mode predicted from the Eigenvalue analysis is, then, used in the next step of the analysis [10]. Then a load-displacement non-linear analysis is performed using the “static Riks” procedure. Initial imperfections, residual stresses and material non-linearity are included in this step of the analysis. From this analysis, failure modes, load-deformation responses and ultimate loads are determined.

### B. *Finite element type and meshing*

The compact flange, corrugated web, and stiffeners, in case of PGCWs are meshed using 4-node shell element (S4R) according to previous investigations [8, 11, 12]. According to Elkawas et al [12], using 4 elements across each fold provides results with adequate accuracy as shown in Fig. (1).

### C. *Boundary condition and load application*

In this study, the specimens were subjected to uniform bending by loading the girders with two concentrated loads at equal distances from both girders’ ends. The loads were applied in increments using the modified Riks method available in the ABAQUS library [10]. In the RIKS method, the load is applied proportionally in several load steps. In each load step, the equilibrium iteration is performed, and the equilibrium path is tracked in the load-displacement space. This method is often used in static analysis and shows to be a strong method for nonlinear analysis. The loads were applied as a static load at the loaded point using displacement control. The nonlinear geometry parameter (*NLGEOM) was included to deal with the large displacement analysis. The girders, under study, were simply supported at the nodes at the intersections between the end stiffeners and the lower flange as shown in Fig. (1). These intersections, at both ends, were defined as roller and hinged supports to simulate the actual test setup. To assign roller support, the displacements in the directions X and Y were restrained as well as the rotation about Z-axis. Similarly, to assign hinged support, the displacements in the directions X, Y and Z were restrained as well as the rotation about Z-axis. The load line was prevented from out of plane displacement (i.e., X direction), similar to the experimental program described in [12].

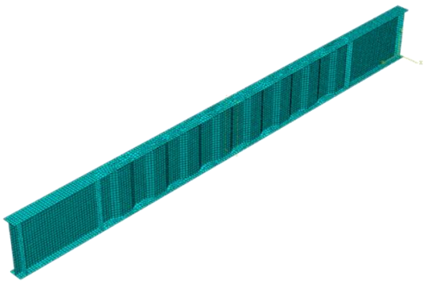

**Fig. 1. Finite element mesh of a typical girder.**

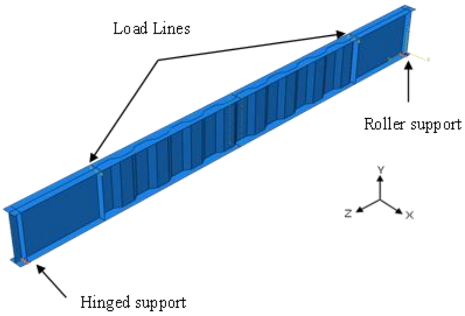


**Fig. 2. Load and boundary conditions of a typical girder.**

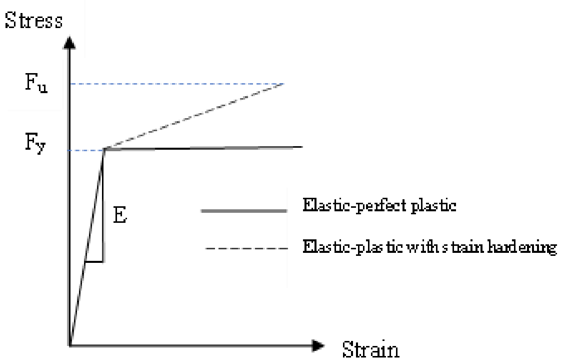


**Fig. 3. Different stress-strain curves for steel material.**

## D. *Material modelling*

In FE modelling, two types of stress-strain curves are often used to simulate the steel material. The two types used are the bi-linear elastic-plastic stress-strain curve with linear strain hardening curve and the elastic-perfect plastic stress-strain curve are shown in Fig. 3. According to Elkawas et al [12], it was noticed that the first curve gives slightly higher flexural strengths compared to the experimental results compared to the second one. Hence, the elastic-perfect plastic stress-strain curve was used in the modelling to provide better design results. The elastic-perfect plastic curve requires inserting the true yield stress and its corresponding plastic strain.

## E. *Initial imperfections*

In non-linear analysis, the geometric imperfections were found to play a significant role in the behaviour and strength of steel girder as explained by Elgaaly et al. [11] in previous results. An initial imperfection with a value of L/1000, where L is the span of the distance between the two supports of the girder, was introduced in the non-linear analysis in the finite element models, in accordance with previous studies and investigations [8, 12]. According to Elkawas [12], the initial imperfections are not related to the boundary conditions used in the non-linear analysis but related only to the production of the specimen. Thus, the elastic eigenmode buckling shape is over the whole length of the girder as shown in Fig. (4).

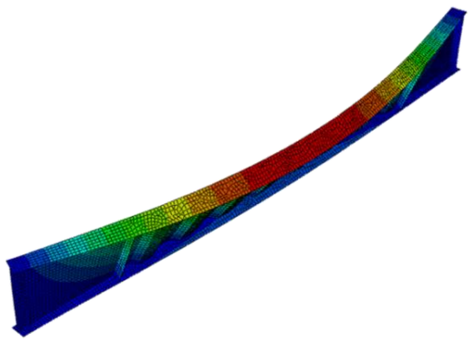

**Fig. 4. First positive eigen mode.**

# III. VALIDATION PROCESS

Before generating parametric studies on the plate girders with double corrugated webs (PGDCWs), it was necessary to prove that the established FE models are capable of simulating properly their structural behaviour. Within the available resources, no experimental results on such girders existed in literature. Conversely, the available experimental database contains results for plate girders with corrugated webs (PGCWs). Accordingly, the accuracy of the FE model was verified by using the results of the PGCWs. In this section, three PGCWs were tested by Elakawas et al [12]. Then, the three PGCWs were modelled using the ABAQUS computer program [10].

## A. *Verification of (pgcws)*

The FE models are verified herein through the simulation of the test specimens G-400-80, G-400-100 and G-300-80 which were tested by Elkawas et al. [12]. Table 1 and table 2 show the test specimens' nominal dimensions and the average measured dimensions of the fabricated girder, respectively. The test girders were loaded with two concentrated loads at equal distances from both supports, to subject the girders to uniform bending, and modelled as simply supported. The load was about 600 mm from both supports the same as experimental tests as shown, previously, in Fig. 2. The load lines were prevented from out of plane displacements due to the friction between the loading surfaces. Tensile coupon test specimens were prepared in advance and tested to provide the required data about the materials used. Table 3 gives the average values of yield and ultimate strengths of the test specimens. The Poisson ratio, υ, was taken as 0.3.

For the non-linear inelastic analysis, an elastic-perfect plastic stress-strain curve was used. The comparisons between the FE models and the experimental studies were mainly between the ultimate flexural capacity reached and moment-deformation responses. The failure modes of the girders are characterized as lateral-torsional buckling (LTB) failures in the upper compression flanges without any local buckling in either the flanges or the webs. From the comparison with the results obtained from the experimental study [12], the FE models provided the same failure modes.

**Table 1. Nominal test specimens' dimensions for (PGCWs) [12].**

| Girder | a [mm] | $b$ [mm] | $c$ [mm] | $h_r$ [mm] | $s$ [mm] | $q$ [mm] | $\alpha$ [°] | $b_f$ [mm] | $t_f$ [mm] | $h_w$ [mm] | $t_w$ [mm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G-400-80 | 100 | 50 | 57.7 | 28.9 | 315.5 | 300 | 30 | 80 | 16 | 400 | 3 |
| G-400-100 | 100 | 50 | 57.7 | 28.9 | 315.5 | 300 | 30 | 100 | 16 | 400 | 3 |
| G-300-80 | 100 | 50 | 57.7 | 28.9 | 315.5 | 300 | 30 | 80 | 16 | 300 | 3 |

**Table 2. Average measured test specimens' dimensions for (PGCWs) [12].**

| Girder | a [mm] | $b$ [mm] | $c$ [mm] | $h_r$ [mm] | $s$ [mm] | $q$ [mm] | $\alpha$ [°] | $b_f$ [mm] | $t_f$ [mm] | $h_w$ [mm] | $t_w$ [mm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G-400-80 | 100 | 50 | 57 | 27.4 | 314 | 300 | 28.7 | 80 | 16 | 400 | 3 |
| G-400-100 | 100 | 49 | 56 | 27.11 | 311 | 296 | 28.9 | 100 | 16 | 400 | 3 |
| G-300-80 | 99 | 50 | 58 | 29.39 | 318 | 298 | 30.45 | 80 | 16 | 300 | 3 |

## *B. Results discussion*

Table 3 provides the experimental ultimate moment capacity $(M_{ul,Ex})$, the ultimate moment from finite element modelling $(M_{ul,FE})$ and the plastic moment $(M_{pl.R})$. The value of the plastic moment is dependent only on the flange dimensions and the steel grade due to the accordion effect [8].

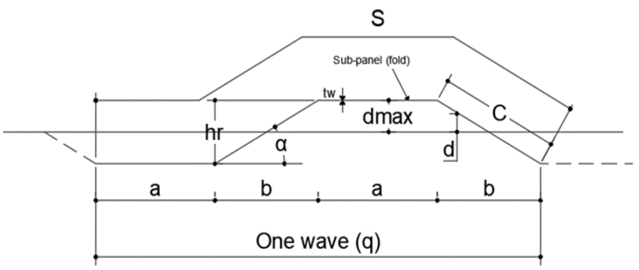


**Fig. 5. Corrugation configuration and geometric notation.**

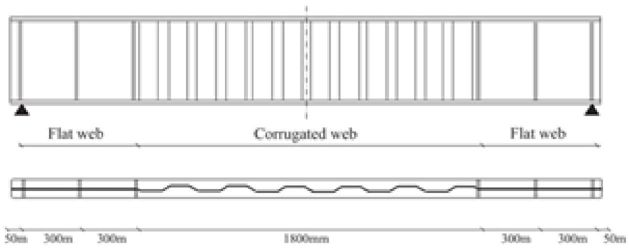


**Fig. 6. Details of the test specimens.**

**Table 3. Average value of yield and ultimate strengths of tested tensile coupon specimens [12].**

| Specimens | $f_y$ [MPa] | $f_u$ [MPa] | $\varepsilon_y$ [με] | $\varepsilon_u$ [με] |
|---|---|---|---|---|
| Flange | 295 | 462 | 1815 | 30545 |
| Corrugated web | 304 | 371 | 903 | 19486 |
| Flat web and stiffeners | 287 | 387 | 1823 | 59106 |

**Table 4. Comparison between experimental and FE flexural strength.**

| Girder | $M_{pl.R}$ [kN.m] | $M_{ul,Ex}$ [kN.m] | $M_{ul,FE}$ [kN.m] | $M_{ul,FE}/M_{ul,Ex}$ |
|---|---|---|---|---|
| G-400-80 | 157.1 | 135.0 | 146.0 | 1.08 |
| G-400-100 | 196.4 | 183.6 | 185.27 | 1.01 |
| G-300-80 | 119.3 | 124.4 | 117.29 | 0.94 |
| Average | | | | 1.01 |
| Standard Deviation | | | | 0.07 |

From comparing the finite element and the experimental results, it can be noticed that the finite element modelling reflects the real behaviour of the (PGCWs). The ratios between FE ultimate moment strength and experimental ultimate moment strength $(M_{ul,FE}/M_{ul,Ex})$, are given in Table 4. The lateral displacements of the three girders obtained from the experimental tests and the finite element modelling are presented in Figs. 7, 8 and 9.

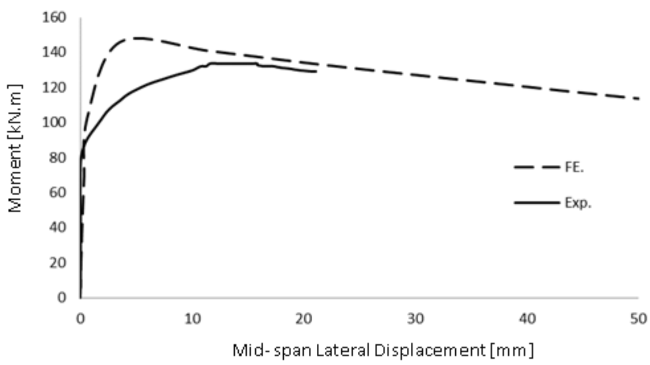


**Fig. 7. Moment versus lateral displacement of G-400-80.**

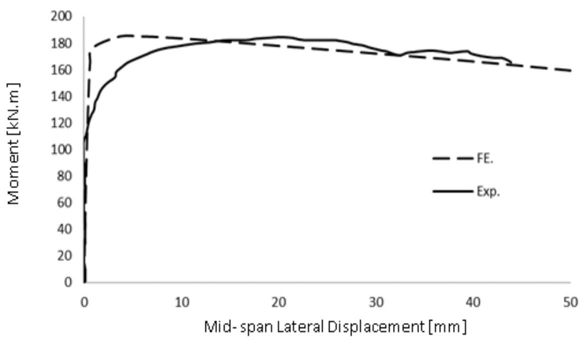


**Fig. 8. Moment versus lateral displacement of G-400-100.**

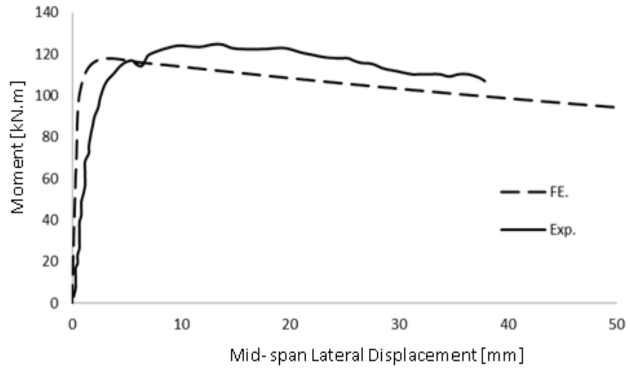


**Fig. 9. Moment versus lateral displacement of G-300-80.**

Also, the comparisons between the vertical deflection versus ultimate moment between the results obtained from the experimental and the finite element modelling are presented in Figs. 10, 11 and 12.

## IV. PLATE GIRDERS WITH DOUBLE CORRUGATED WEBS

### *A. Finite element modelling*

After verifying the accuracy of the FE models of the plate girders with corrugated webs (PGCWs) with the experimental test results, a parametric study was carried out to study the behaviour of plate girders with double corrugated webs (PGDCWs) under uniform bending, and to compare the results with that of plate girders with corrugated webs (PGCWs). Table (5) presents the data of the analysed FE models. The modulus of elasticity, E, was taken equal to 210,000 MPa and Poisson's ratio, υ, was taken as 0.3. For the non-linear inelastic analysis, an elastic-perfect plastic stress-strain curve was used. The yield stress of the flange and web material was 280 MPa.

### *B. Results and discussions*

From the previous results it can be noted that using two webs instead of only one web greatly improved the girder resistance to lateral torsional buckling and increased the efficiency of the whole section at resisting pure bending moment. Figs. (14, 15 and 16) and table (6) show that increasing the girder span doesn't significantly reduce the girder capacity compared to that of the normal PGCWs. As can be seen from the figures, increasing the span from 3m to 10.20m reduced the efficiency of the PGDCWs section from 100% to 83% for girder (G-400-80) and from 100% to 87% for girder (G-400-100) and 100% to 90% for girder (G-3000-80).

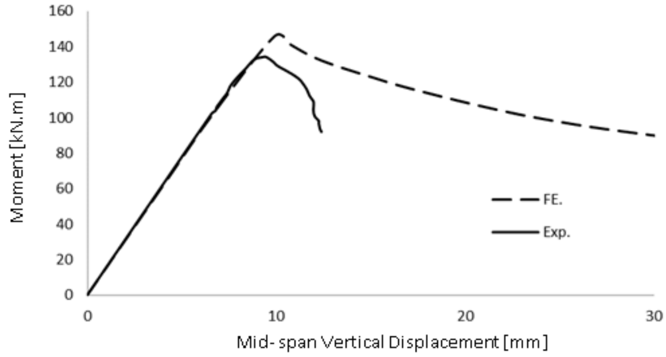


**Fig. 10. Moment versus Vertical displacement of G-400-80.**

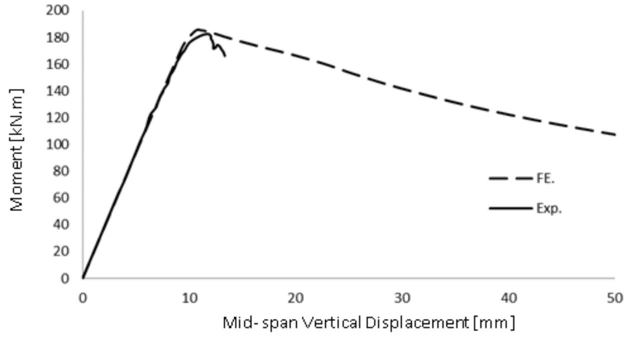


**Fig. 11. Moment versus Vertical displacement of G-400-100.**

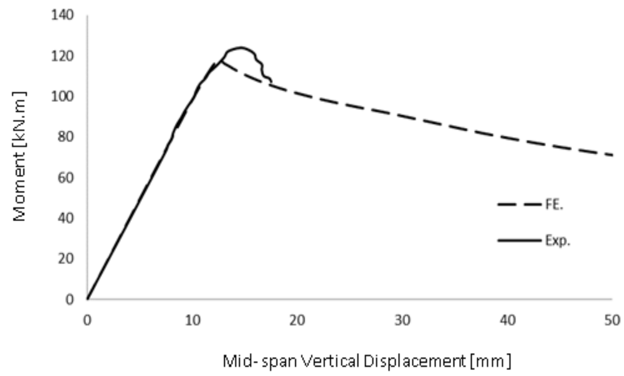


**Fig. 12. Moment versus Vertical displacement of G-300-80.**

**Table 5. The dimensions of the analysed FE models.**

| Girder | $a$ [mm] | $b$ [mm] | $c$ [mm] | $h_r$ [mm] | $s$ [mm] | $q$ [mm] | $\alpha$ [°] | $b_f$ [mm] | $t_f$ [mm] | $h_w$ [mm] | $t_w$ [mm] | $X_{max}$ [mm] | $X_{min}$ [mm] | $X_{avg}$ [mm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G-400-80 | 100 | 50 | 57.7 | 28.9 | 315.5 | 300 | 30 | 80 | 16 | 400 | 1.5 | 67.74 | 10.0 | 38.87 |
| G-400-100 | 100 | 50 | 57.7 | 28.9 | 315.5 | 300 | 30 | 100 | 16 | 400 | 1.5 | 67.74 | 10.0 | 38.87 |
| G-300-80 | 100 | 50 | 57.7 | 28.9 | 315.5 | 300 | 30 | 80 | 16 | 300 | 1.5 | 67.74 | 10.0 | 38.87 |

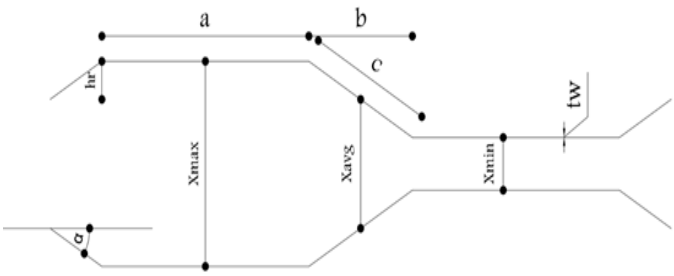


**Fig. 13. Corrugation profile of double corrugated web girders.**

**Table 6. The ultimate moment capacity of the finite element models.**

| Girder | Type | Span [m] | Number of Waves (n) | $M_{ul,FE}$ [kN.m] | $M_{pl.R}$ [kN.m] | $M_{ul,FE}/M_{pl.R}$ |
|---|---|---|---|---|---|---|
| G-400-80 | PGDCWs | 3.00 | 6 | 150.5 | 149.1 | 1.01 |
| | | 3.60 | 8 | 149.8 | 149.1 | 1.00 |
| | | 4.20 | 10 | 148.4 | 149.1 | 1.00 |
| | | 4.80 | 12 | 147.7 | 149.1 | 0.99 |
| | | 5.70 | 15 | 146.1 | 149.1 | 0.98 |
| | | 7.20 | 20 | 140.8 | 149.1 | 0.94 |
| | | 8.70 | 25 | 134.1 | 149.1 | 0.90 |
| | | 10.20 | 30 | 123.0 | 149.1 | 0.83 |
| | PGCWs | 3.00 | 6 | 142.0 | 149.1 | 0.95 |
| | | 3.60 | 8 | 134.9 | 149.1 | 0.91 |
| | | 4.20 | 10 | 130.2 | 149.1 | 0.87 |
| | | 4.80 | 12 | 117.1 | 149.1 | 0.79 |
| | | 5.70 | 15 | 98.8 | 149.1 | 0.66 |
| | | 7.20 | 20 | 75.6 | 149.1 | 0.51 |
| | | 8.70 | 25 | 59.4 | 149.1 | 0.40 |
| | | 10.20 | 30 | 48.8 | 149.1 | 0.33 |
| G-400-100 | PGDCWs | 3.00 | 6 | 187.7 | 186.4 | 1.01 |
| | | 3.60 | 8 | 186.5 | 186.4 | 1.00 |
| | | 4.20 | 10 | 185.4 | 186.4 | 0.99 |
| | | 4.80 | 12 | 184.8 | 186.4 | 0.99 |
| | | 5.70 | 15 | 182.4 | 186.4 | 0.98 |
| | | 7.20 | 20 | 178.1 | 186.4 | 0.96 |
| | | 8.70 | 25 | 171.8 | 186.4 | 0.92 |
| | | 10.20 | 30 | 162.2 | 186.4 | 0.87 |
| | PGCWs | 3.00 | 6 | 178.2 | 186.4 | 0.96 |
| | | 3.60 | 8 | 172.6 | 186.4 | 0.93 |
| | | 4.20 | 10 | 167.8 | 186.4 | 0.90 |
| | | 4.80 | 12 | 152.6 | 186.4 | 0.82 |
| | | 5.70 | 15 | 148.2 | 186.4 | 0.80 |
| | | 7.20 | 20 | 121.8 | 186.4 | 0.65 |
| | | 8.70 | 25 | 96.2 | 186.4 | 0.52 |
| | | 10.20 | 30 | 79.4 | 186.4 | 0.43 |
| G-300-80 | PGDCWs | 3.00 | 6 | 114.8 | 113.25 | 1.01 |
| | | 3.60 | 8 | 114.1 | 113.25 | 1.01 |

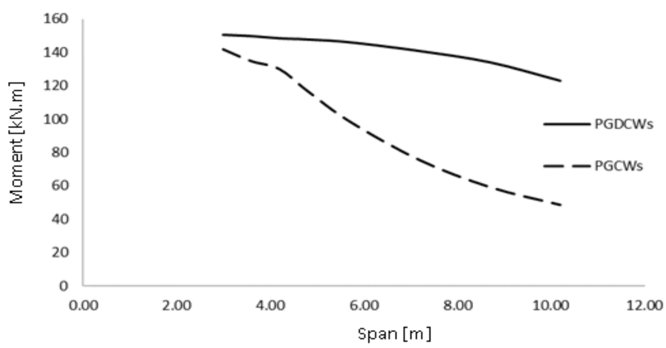


**Fig. 14. Moment versus Span of G-400-80.**

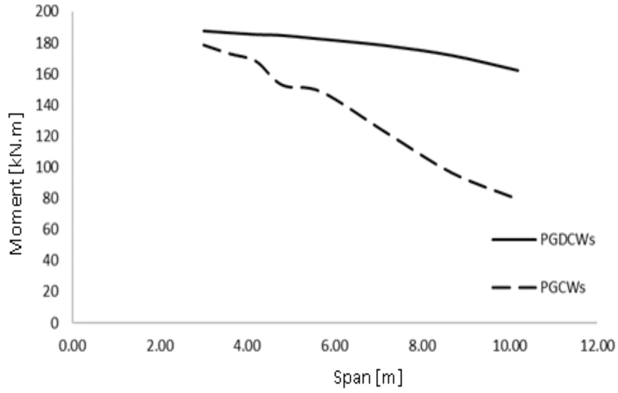


**Fig. 15. Moment versus Span of G-400-100.**

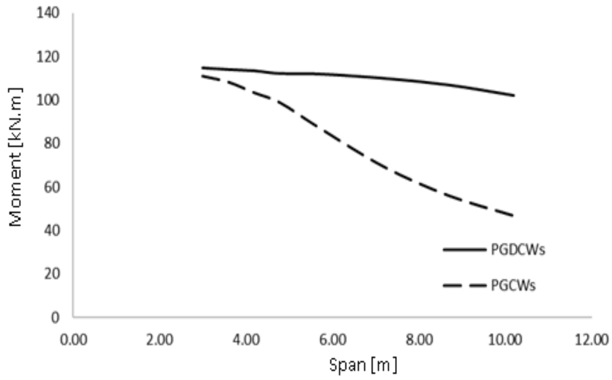


**Fig. 16. Moment versus Span of G-300-80.**

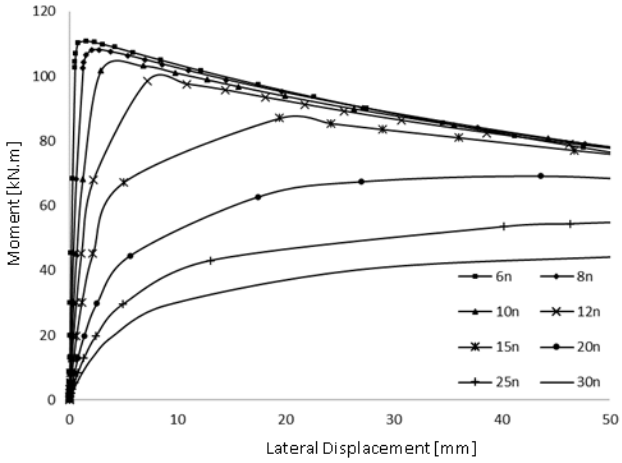


**Fig. 17. Moment versus Lateral Displacement of G-300-80 (PGCWs).**

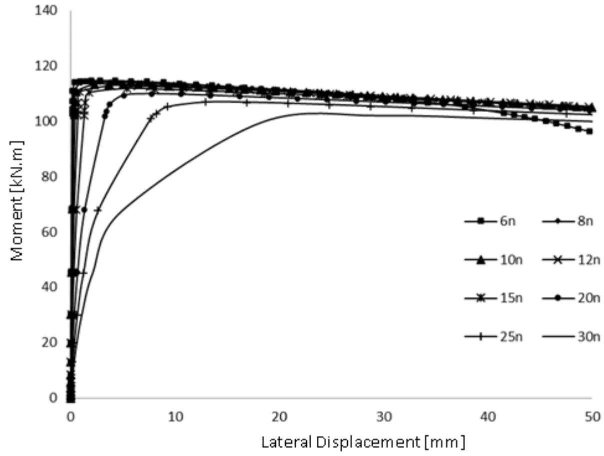


**Fig. 18. Moment versus Lateral Displacement of G-300-80 (PGDCWs).**

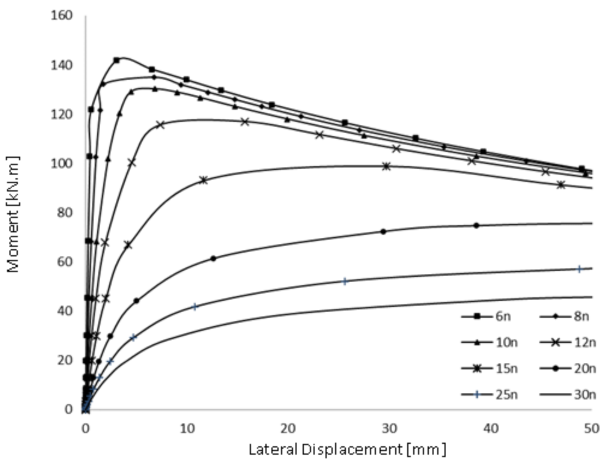


**Fig. 19. Moment versus Lateral Displacement of G-400-80 (PGCWs).**

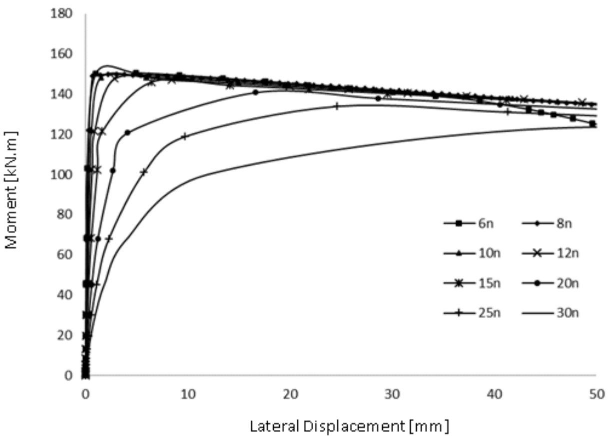


**Fig. 20. Moment versus Lateral Displacement of G-400-80 (PGDCWs).**

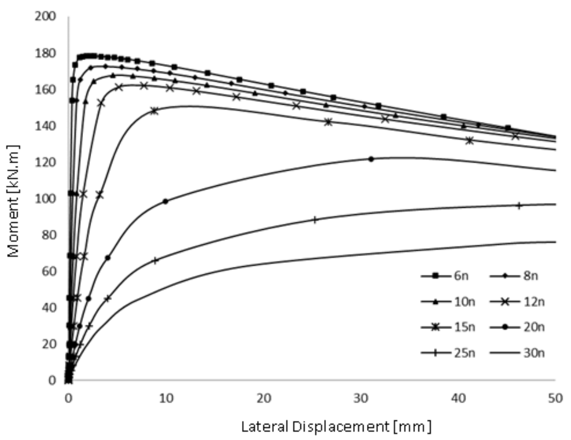


**Fig. 21. Moment versus Lateral Displacement of G-400-100 (PGCWs).**

As for the PGCWs, increasing the span reduced the section efficiency from 95% to 33% for girder (G-400-80) and from 96% to 43% for girder (G-400-100) and 98% to 41% for girder (G-300-80). Also, Figs. (17, to 22) show significant improvement in resisting lateral torsional buckling and reducing the lateral displacement that occur at the ultimate moment of the girder. This can be explained by the fact that using two webs instead of one, increased the torsional resistance of the girder and increased the out-of plane stiffness, thus reducing the lateral displacement.

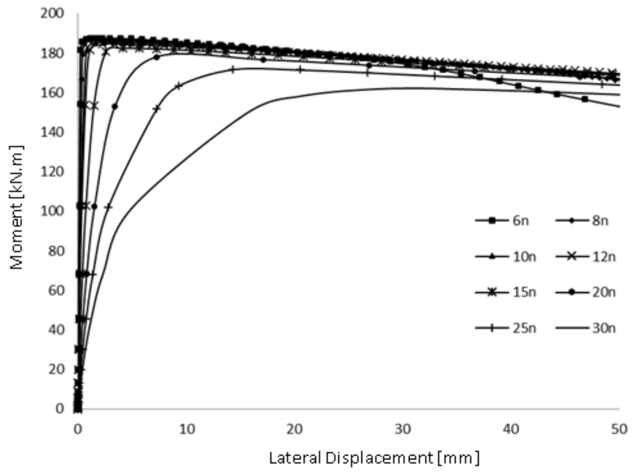


**Fig. 22. Moment versus Lateral Displacement of G-400-100 (PGDCWs).**

## V. SUMMARY AND CONCLUSIONS

From the above FE modelling and validation, the following results may be concluded:

- The finite element method is a numerical procedure that can be applied to obtain solutions to various engineering problems.
- The FE program ABAQUS was used to simulate the plate girders with corrugated webs (PGCWs). The model used the actual measured geometric and material properties.
- The FE program ABAQUS was then used to simulate the plate girders with double corrugated webs (PGDCWs). The difference in behaviour between both types of girders was then studied.
- Finite element analysis for buckling requires two steps of analysis. The buckling modes of girders are estimated, first, through the Eigenvalue analysis. This is a linear elastic analysis performed using the (*BUCKLE) procedure available in the ABAQUS library with the load applied within the step. The first buckling mode predicted from the Eigenvalue analysis is used. A load-displacement nonlinear analysis is, then, carried out. In this analysis, the initial imperfections and material nonlinearity are included. From this analysis, failure modes, load-deformation responses and ultimate loads are determined.
- The finite element results are in good agreement with the experimental results.
- From the previous results it can be noted that using two webs instead of only one web greatly improved the girder resistance to lateral torsional buckling.
- Using double webs increased the efficiency of the whole section at resisting pure bending moment compared to that of PGCWs with the same weight.
- Increasing the girder span doesn't significantly reduce the PGDCWs capacity compared to that of the normal PGCWs.

## REFRENCES

[1] Fraser, A. F., "Experimental investigation of the strength of multiweb beams with corrugated webs", NACA Technical note 3801, Washington, 1956.

Vol. 6, No. 1 – 2022 Journal of Engineering Research (ERJ)

[2] Jáger, B., Dunai, L., Kövesdi, B., "Flange buckling behavior of girders with corrugated web Part I: Experimental study", Thin-walled structures, Vol. 118, pp. 181-195, 2017.

[3] Shimada, S., "Shearing Strength of Steel Plate Girder with Folded Web Plate (Ripple Web Girders)", Journals of the Japan Society of Civil Engineers, No.12412, pp. 1-10, 1965.

[4] Tagawa, K., Okamoto, H. and Nakata, K., "Studies on Corrugated Web Girders", Technical Report of NKK Corporation (Japan), No.71, pp. 25-33, 1976.

[5] Ibrahim S. A., El-Dakhakhni W. W., Elgaaly M., "Fatigue of corrugated-web plate girders: analytical study", Journal of Structural Engineering, ASCE, Vol. 132, No. 9, pp. 1381–1392, 2006.

[6] Ibrahim S. A., El-Dakhakhni W. W., Elgaaly M., "Behavior of bridge girders with corrugated webs under monotonic and cyclic loading", Engineering Structures, Vol. 28, No. 4. 1941–1955, 2006.

[7] Sause, R., "Corrugated Web Girder Fabrication", ATLSS Report No. 03-19, Lehigh University, 2003.

[8] Moon J., Yi J. W., Choi B. H., Lee H. E., "Lateral– torsional buckling of I-girder with corrugated webs under uniform bending", Thin-walled Structures, Vol. 47, pp. 21–30, 2009.

[9] Hamada, M., Nakayama, K., Kakihara, M., Satoh, K. and Ohtake, F., "Development of welded I-beam with corrugated web", The Sumitomo Search, No. 29, pp. 75-90, 1984.

[10] ABAQUS Standard User's Manual. Hibbitt, Karlsson and Sorensen, Inc. Vol. 1, 2 and 3, Version 6.6, USA, 2007.

[11] Elgaaly M., Seshadri A., Hamilton R. W., "Bending strength of steel beams with corrugated webs", Journal of Structural Engineering, ASCE, Vol. 123, No. 6, pp. 772–782, 1997.

[12] Elkawas A. A., Hassanein M. F, El Hadidy A. M., El-Boghdadi M. H., Elchalakani M., "Behaviour of corrugated web girders subjected to lateral-torsional buckling", Structures, Vol. 33, pp.152-168, 2021.