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BEHAVIOR OF STEEL GIRDERS WITH CORRUGATED WEBS WITH AND WITHOUT OPENINGS

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ABSTRACT

This paper presents the results of the theoretical and finite element analyses of the lateral torsional buckling behavior of I-girders with corrugated webs with and without openings. Previous studies on the behavior of the I-girders with corrugated webs are first discussed. Then, the elastic lateral torsional buckling moment M_{cr} of all analayzed girders are determined numerically by using Euro-code equations by the three methods suggested by Lindner, Zhang et al. and Moon et al. Finally, the effect of different parameters such as (web thickness, web height, flange thickness, flange width and corrugation shape) on lateral torsional buckling resistance using finite element analysis are studied and verify the results with Euro-code equations.

KEYWORDS : Corrugated Web, I-Girders, Warping Constant, Lateral Torsional Buckling, Finite Element Model

سلوك الكمرات المعدنية ذات العصب المموج بوجود أوعدم وجود فتحات

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ملخص البحث

يعتبراستخدام الكمرات المعدنية ذات العصب المعرج من التطبيقات الحديثة والتي تستخدم علي نطاق واسع فى العديد من مجالات استخدام المنشات المعدنية بسبب خصائصها المتعددة. و قد بدا الاستخدام المتزايد لهذا النوع من الكمرات علي مدي السنوات العشرون الماضية في مجال الجسور. تم دراسة الكمرات المعدنية ذات العصب المعرج في الابحاث العلمية عن طريق استخدام برامج تحليل العناصر المحددة وعن طريق التجارب العملية. الكمرات المعدنية ذات العصب المعرج ذات الفتحات تسمح بمرورالانابيب ومتطلبات الاعمال الكهروميكانيكية من خلالها وذلك يعد حلا جيدا بدلا من تغيير مسارات الاعمال الكهروميكانيكية داخل المنشأ او زيادة ارتفاع الادوار بالمنشأ مما يؤدي لزيادة التكلفة. هناك العديد من العوامل التي تؤثر علي سلوك الكمرات المعدنية ذات العصب المعرج بوجود فتحات مثل تغيرالأبعاد للقطاع وشكل العصب المعرج واماكن واشكال الفتحات.

تم دراسة سلوك وتاثير انبعاج الالتواء الجانبي للكمرات المعدنية ذات العصب المعرج وتاثير تغيرابعاد وسمك القطاعات المكونة للكمرات المعدنية ذات العصب المعرج وكذلك تم دراسة تاثير تغير شكل العصب المعرج عن طرق استخدام عدة اشكال مختلفة للعصب المعرج والمقارنة بينها. تم عمل مقارنة بين سلوك الكمرات المعدنية ذات العصب المعرج بوجود فتحات وكمرات معدنية اخري بدون فتحات مع تغير شكل وموقع الفتحات داخل العصب المعرج.

الكلمات المفتاحية : الكمرات المعدنية ذات العصب المعرج ، انبعاج الالتواء الجانبي للكمرات المعدنية ، برامج تحليل العناصر المحددة

1. INTRODUCTION

Built-up steel sections with corrugated webs have been used for years in some countries, particularly to increase the out of plane stiffness and shear buckling strength without the use of vertical stiffeners. Lindner.[1] proposes a method for calculating the critical moment of girders with corrugated webs based on analytical derivations, verified by experimental testing. Lindner states that the moment of inertia about the weak axis I_z and the torsion constant I_t can be calculated using the same, expressions as for girders with flat webs. The extra capacity in terms of critical lateral-torsional buckling moment obtained for girders with corrugated webs is attributed to an increased warping constant I_z. Moon etal. [2] performed analytical models to investigate the lateral–torsional buckling strength of the I-girder with corrugated webs under uniform bending and also suggested an approximated method for estimating the warping constant $C_{(w,co)}$ by using a numerical method. Zhang et al [3] performed analytical models as Moon, etal.[2]. According Zhang etal[3] approach the warping constant of a girder with corrugated web is based on the expression for the warping constant of a prismatic girder with a flat, eccentric web. H.R. Kazemi et.al [4] performed analytical study to determine lateral torsional buckling moment for simply supported girders with corrugated webs subjected to end moments and they found that the lateral torsional buckling moment of girders increased up to 40% by using corrugation profiles of the web. Fatimah De'nan [5] performed analytical study to investigate the effect of web corrugation angle for triangular web on the bending behavior in minor and major axes and compare results with flat girders and they concluded that the value of moment of inertia about major axis I_X for the corrugated web is in a range from 0.754 to 0.818 times of that for flat web. The value of moment of inertia about minor axis I_y for corrugated web is in a range from 1.523 to 1.686 times of that for flat web. Elgaaly et.al.[6] have investigated the bending strength of beams with corrugated webs and they concluded that the contribution of the web to the ultimate moment capacity of a beam with corrugated webs is negligible. The design procedure of Euro-code[7] is used to determine the elastic lateral torsional buckling moment as shown in Equ.(1).

$$M_{cr} = \frac{\pi^2 E I_z}{L^2} \sqrt{\frac{I_w}{I_z} + \frac{L^2 G I_t}{\pi^2 E I_z}} \qquad \text{………} \ (1)$$

Where, I_w is the warping constant for steel girder with corrugated web and it can be calculated by the three methods suggested by Lindner, Zhang et al. and Moon et al, I_t is the torsion constant, G is the shear modulus, E is the modulus of elasticity, I_z is the second moment of area about minor axis and L is the unsupported length of compression flange.

The aims of this paper are comparing between the critical lateral torsional buckling moments for steel girders with corrugated web, which are obtained from proposed finite element model, with those calculated from the Euro-code equations (EC3). The effect of the variations in the dimensions and corrugation shape of the steel girders with corrugated web on lateral torsional buckling behavior are also studied.

2. MODELLING

Shell element 181 with 4 node and 6 degree of freedom per node was used to model all analyzed girders using the computer package ANSYS vr.18 [8]. The studied girders are considered simply supported in flexure and torsion. Displacements in Y direction (U_y) at lines (c, d) are restrained and displacement in Z direction (U_z) at lines (a, b) are restrained. Point (A) is considered as a hinge joint, where the translations in X, Y and Z directions and the rotation about X-axis are restrained. While point (B) is considered as a roller joint, where the translations in Y and Z directions and the rotation about X-axis are restrained. All boundary conditions for analyzed girders are shown in Fig.(1). Eigenvalue buckling analysis was performed on all analyzed girders to evaluate the theoretical buckling loads where girders become unstable. All analyzed girders were subjected to equal two-end moment to study lateral torsional buckling under pure moment without any shear force acting on girders. These cases of loading are represented as tension and compression forces at the ends of the top and lower flanges.

All analyzed girders have yield strength F_y and ultimate strength F_u of 250 MPa and 400 MPa, respectively and Poison's ratio υ equals to 0.3. The behavior of the material is set as multi linear isotropic hardening rule with von Mises yield criterion. It is assumed to behave linear elastic until reaching the yield strength by Young's modulus E of 210 GPa. After it, the material is assumed to follow linear hardening with a reduced hardening modulus E_r equal to 0.01E. The general case of the analyzed girder is a simply supported beam with span (L=9500mm), consists of two flange plates with width and thickness equal 200mm and 12mm, respectively. The web is considered as corrugated web with height and thickness equal 700mm and 2mm, respectively. The corrugation angle assumed equal to 45°. The width (b) and depth of corrugation (d) are taken equal 140mm and 100mm, respectively, as shown in Fig.(2).

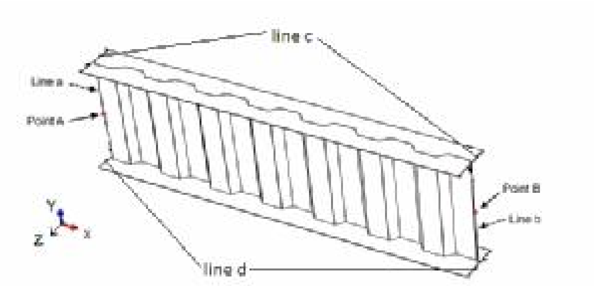

Figure 1: Boundary conditions of the analyzed girders.

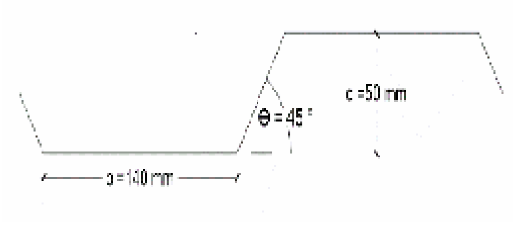

Figure 2: Web corrugation profile.

3. METHODS OF CALCULATING THE WARPING CONSTANT:

3.1 Approach suggested by lindner[1]:

Lindner proposes a method for calculating the critical moment of girders with corrugated webs based on analytical derivations, verified by experimental testing. Lindner states that the moment of inertia about the weak axis I_z and the torsion constant I_t can be calculated using the same expressions as for girders with flat webs. The extra capacity in terms of critical lateral-torsional buckling moment obtained for girders with corrugated webs is attributed to an increased warping constant I_w. The critical moment is calculated using the expression stated in **Equ.(1)**, with the torsion and warping constants I_t^* and I_w^* calculated according to Equ.(2a) and **Equ.(2b)**.

$$I_t^* = I_t \qquad \text{.........(2a)}$$

$$I_w = I_w + C_w \frac{l^2}{Ep^2} \qquad \text{....... (2b)}$$

I_t and I_w are the torsion and warping constants of a girder with flat web and c_w is defined according to **Equ.(3)**.

$$C_W = \frac{(2d)^2 h_w^2}{8U_x (a+b)} \qquad \text{......... (3a)}$$

$$u_x = \frac{h_w}{2Gat_w} + \frac{{h_w}^2 (a+b)^3 (I_{y1} + I_{y2})}{600a^2 E(I_{y1} I_{y2})} \qquad \text{.........(3b)}$$

I_{y1} and I_{y2} in **Equ.(3b)** are the moment of inertia about the strong axis of the girder of the upper and lower flange respectively. For girders with equal flanges the expression for u_x can be simplified according to **Equ.(4).**

$$u_x = \frac{h_w}{2Gat_w} + \frac{{h_w}^2 (a+b)^3}{25a^2 E b_f {t_f}^3} \qquad \text{………… (4)}$$

3.2 Approach suggested by Moon et al [2]:

Moon et al. establish a method for calculating the critical buckling moment of girders with corrugated webs using the same assumptions as Lindner, i.e. that all sectional properties, except the warping constant, of a girder with corrugated web are equal to those of a prismatic girder. In contrast to the expressions for calculating the warping constant presented by Lindner, the expressions presented by Moon et al. are derived analytically based on the theory presented by Galambos. These expressions are quite complex, but can be simplified by considering the geometry of the cross-section. By doing so, numerical formulas for warping constants of open thin-walled members can be obtained as explained by Lue et al. [9]. The warping constant of an open, thin-walled prismatic member can be calculated by considering the cross section to be a series of thin, interconnected plates. The cross-section is divided at discrete points, nodes, defining the end points of these plate elements. The nodes are labelled 1 to n , and the geometry of each plate element is defined by its thickness t_{ij} and length L_{ij}. The warping constant I_w for the cross-section is calculated according to **Equ.(5)**.

$$\bar{I}_w = \frac{1}{3} \Sigma ({W_{ni}}^2 + W_{nj} W_{ni} + {W_{nj}}^2) t_{ij} L_{ij} \qquad \text{..……….(5)}$$

The normalized unit warping w_{ni} and w_{nj} for the nodes at the ends of each element i-j are defined by **Equ.(6)**.

$$W_{ni} = \frac{1}{2A} \sum_{0}^{n} (W_{oi} + w_{oj}) t_{ij} L_{ij} - w_{oi} \qquad \text{…..……(6a)}$$

$$W_{ni} = \frac{1}{2A} \sum_{0}^{n} (W_{oi} + w_{oj}) t_{ij} L_{ij} - w_{oj} \qquad \text{…………(6b)}$$

Where A is the area of the cross-section, $= \sum t_{ij} l_{ij}$, and ρ_{0i} is the distance from the centroid of each element to the shear center of the cross-section, defined perpendicular to the plate element. The unit warping with respect to the centroid at point i and j respectively, w_{0i} and w_{0j}, are defined according to **Equ.(7)**.

$$W_{oi} = r_{oij} L_{ij} \qquad \text{……… (7a)}$$

$$W_{oi} = W_{oi} + r_{oij} L_{ij} \qquad \text{……… (7b)}$$

Fig. (3) and Equ.(5) show an example of how the warping constant is calculated for an I-girder with eccentric web, indicating how the division into thin plate elements has been performed and what nodes define each element. The normalised unit warping for each node can be calculated according to **Equ.(8)**, and is used in **Equ.(5)**. For further reading, Lue et al.[9] perform a very clear step-by-step example of how the warping constant of an arbitrary open thin-walled cross-section can be calculated.

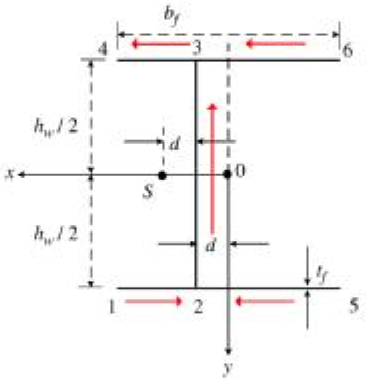

Figure 3: Definition of nodes and geometry used when calculating the warping constant of an I-girder with eccentric web. Figure courtesy of Moon et al.

$$W_{n1} = \frac{2b_f^2 h_w t_f + b_f h_w^2 t_w}{8b_f t_f + 4h_w t_w} \qquad \text{……… (8a)}$$

$$W_{n2} = \frac{2b_f^2 h_w t_f + b_f h_w^2 t_w}{8b_f t_f + 4h_w t_w} - (\frac{b_f}{4} - \frac{d}{2}) * h_w \qquad \text{……… (8b)}$$

$$W_{n3} = \frac{2b_f^2 h_w t_f + b_f h_w^2 t_w}{8b_f t_f + 4h_w t_w} - (\frac{b_f}{4} + \frac{d}{2}) * h_w \qquad \text{……… (8c)}$$

$$W_{n4} = \frac{2b_f^2 h_w t_f + b_f h_w^2 t_w}{8b_f t_f + 4h_w t_w} - \frac{1}{2} b_f h_w \qquad \text{……… (8d)}$$

$$W_{n5} = W_{n4} \qquad \text{……… (8e)}$$

$$W_{n6} = W_{n1} \qquad \text{……… (8f)}$$

The method presented by L_{ue} et al.[9] for finding the warping constant is valid for an arbitrary open, thin-walled prismatic girder. For I-shaped girders with corrugated webs, the eccentricity of the web d, which is included in **Equ.(8b)** and **Equ.(8c)**, is not constant but varies periodically. In order to overcome this, Moon et al. suggest using an average eccentricity d_{avg}, calculated according to **Equ.(9)**. By doing so, the girder is now mathematically considered to be a prismatic member with a constant web eccentricity.

$$d_{avg} = \frac{(2a+b)d_{\max}}{2(a+b)} \qquad \text{……….(9)}$$

Moon et al. calculate the elastic critical buckling moment according to **Equ.(10)** which is an alternative way of writing **Equ(1)**.

$$M_{cr} = \frac{p}{L}\sqrt{EI_z G_{co} I_t}\sqrt{1+w^2} \qquad \text{……… (10)}$$

Where, $$W = \frac{p}{L}\sqrt{\frac{E\bar{I}_w}{G_{co} I}} \qquad \text{……… (11)}$$

With $\bar{I}_w$ defined according to **Equ.(5)**, and where G_{co} is the reduced shear modulus for girders with corrugated webs. The reduced shear modulus is obtained by multiplying the regular shear modulus by a reduction factor, defined as the ratio between the projected length of the corrugated web plates in the longitudinal direction of the girder and the actual length of the web plates according to **Equ.(12)**.

$$G_{co} = \frac{a+b}{a+c}G \qquad \text{………} (12)$$

Finally, it should be noted that Moon et al.[2] suggest that the reduced shear modulus G_{co} should be applied at all instances where the shear modulus is used in **Equ.(10)** and **Equ.(11)**, not only at the terms that relate the web. It could be argued that the reduced shear modulus should be applied only to the terms that refer to the web, and not the terms that refer to the flanges.

Moon et al, also investigate how the geometry of the corrugation influences the elastic critical buckling moment by changing the corrugation angle α. By increasing the angle between the longitudinal panels and the inclined panels of the corrugated webs, the shear modulus G_{co} decreases while the warping $\bar{I}_w$ increases. The reduced shear modulus decrease the gain from the corrugated web in the terms of the critical buckling moment. The results presented by Moon et al, indicate that the lateral-torsional buckling resistance of the girders with corrugated webs increases with an increases with an increase angle α, with a maximum increase of approximately 10 percent for an angle α of 60°.

3.3 - Approach suggested by Zhang et al [3]:

Zhang et al.[3], presents a method for calculating the critical buckling moment in a way similar to that presented by Moon et al[2], Zhang et al, also rely on the assumptions first presented by lindner, stating that moment of inertia about the weak axis Iz and the torsion constant It of the girders with a corrugated web can be assumed to be equal to those of a girder with a flat web, and that the increased critical buckling moment is caused only by an increased warping constant Iw. The approach suggested by Zhang et al, for obtaining the warping constant of a girder with corrugated web is based on the expression for the warping constant of a prismatic girder with a flat, eccentric web. That expression is defined in **Equ.(13)**.

$$I_W^{ecc} = \frac{t_f b_f^{\,3} h_w^{\,2}}{24} + \frac{t_w h_w^{\,3} e^2}{12} \qquad \text{…………}(\ 13)$$

The first term in Equ.(13) can be identified as the expression commonly used for calculating the warping constant of adoubly symmetric I-profile, I_w , and the second term is an addition due to the eccentricity of the web. In order to account for the varying eccentricity of the corrugated web, **Equ.(13)** is integrated over one corrugation wave length, q and divided by this length as shown in **Equ.(14)**. $\bar{I}_w$ is the equivalent warping constant, suggested by Zhang et al[3], accounting for the effect of the corrugated web.

$$\bar{I}_w = \frac{1}{q}.\int_0^q \frac{t_f b_f^{\,3} h_m^{\,2}}{24} + \frac{t_w h_m^{\,3} e^2}{12}\,dx = I_w + \frac{t_w h_m^{\,3} d^2}{12}\,\frac{(a+\frac{b}{3})}{2q} \qquad \text{……….…}(14)$$

4. LATERAL TORSIONAL BUCKLING BEHAVIOR OF CORRUGATED WEB GIRDERS WITHOUT OPENINGS USING THE PROPOSED FINITE ELEMENT MODEL

Lateral torsional buckling of corrugated steel web girders still need to be investigated. In this paper, the critical moment causing lateral buckling was determined using a numerical model based on the finite element technique. The applicability of the equations developed for I-girders with flat webs in Euro-code to determine elastic critical moment to girders with corrugated webs was examined.

The considered parameters in this paper are: the thickness and height of the corrugated web (t_w , h_w), corrugation angle (Ɵ), width of corrugation (a) and corrugation shape. The thickness of the web is considered from 1 mm to 10 mm, while its height is ranged from 300 mm to 1200 mm. The thickness of the flange is considered from 4 mm to 24 mm, while its width is ranged from 100 mm to 400 mm. Finally, the corrugation shape is presented in three types as trapezoidal, triangular and rectangular corrugated web. Figures (4) to (9) illustrate influence of each parameter on lateral torsional buckling moment.

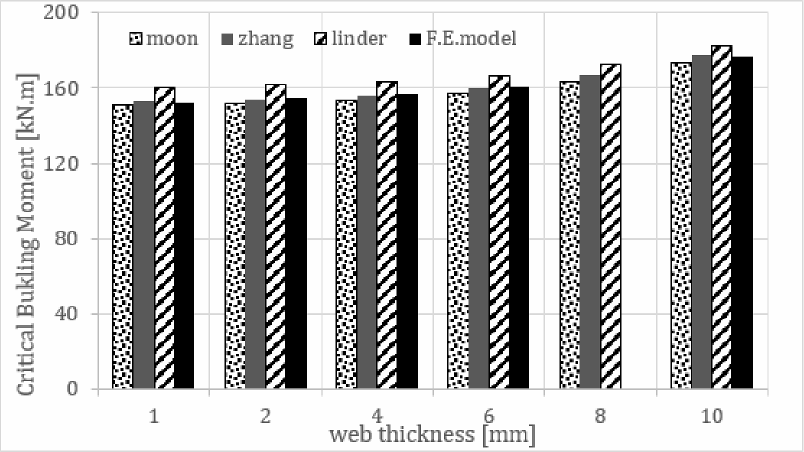

Figure 4: Influence of web thickness on lateral torsional buckling moment (h_w = 700 mm)

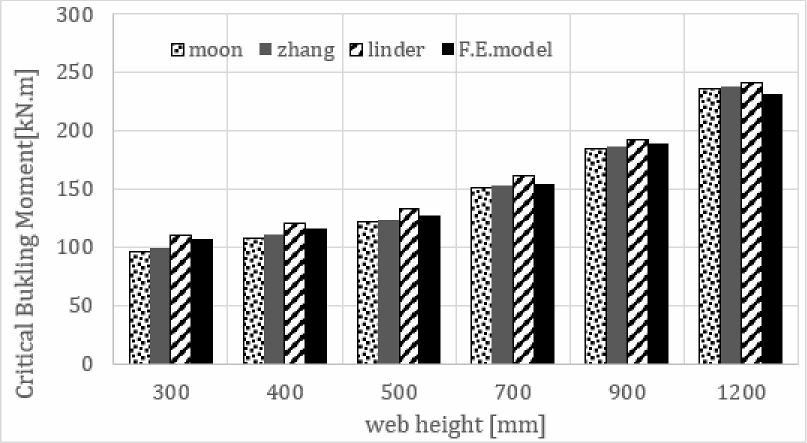

Figure 5: Influence of web height on lateral torsional buckling moment (t_w = 2 mm)

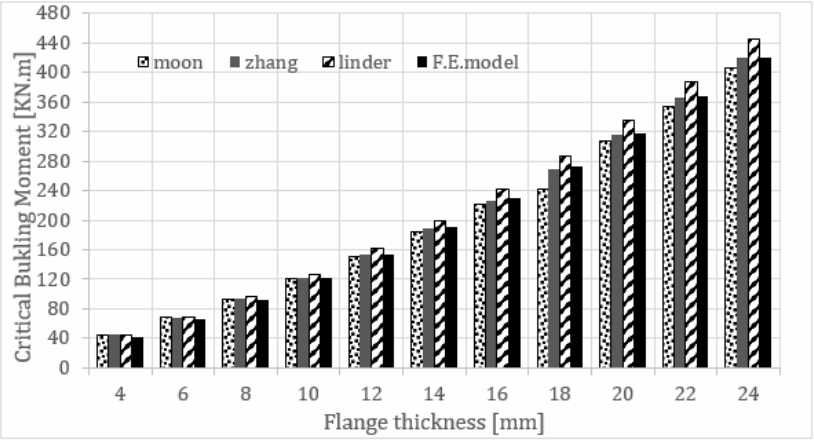

Figure 6: Influence of flange thickness on lateral torsional buckling moment

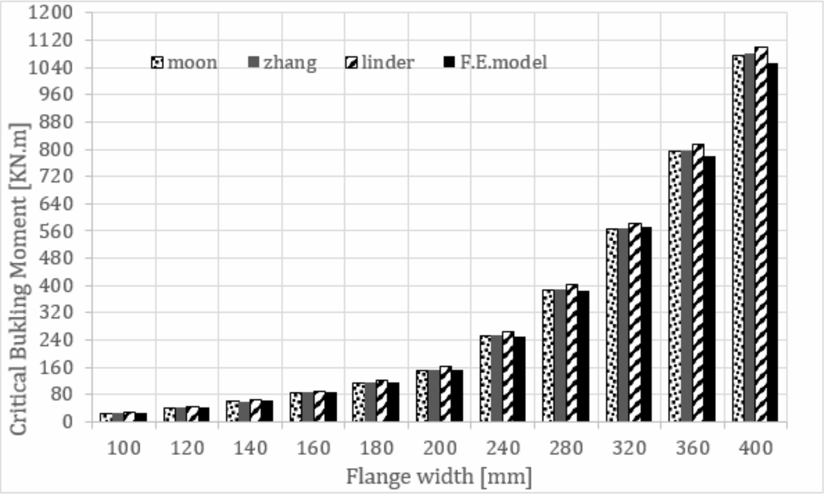

Figure 7: Influence of flange width on lateral torsional buckling moment

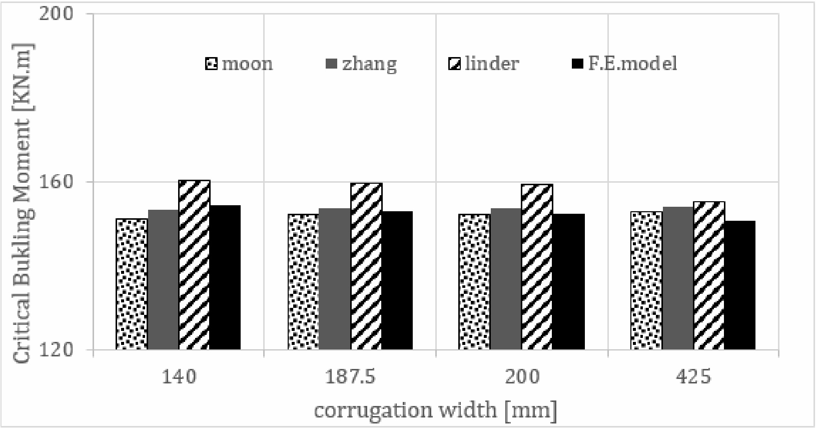

Figure 8: Influence of corrugation width on lateral torsional buckling moment (b)

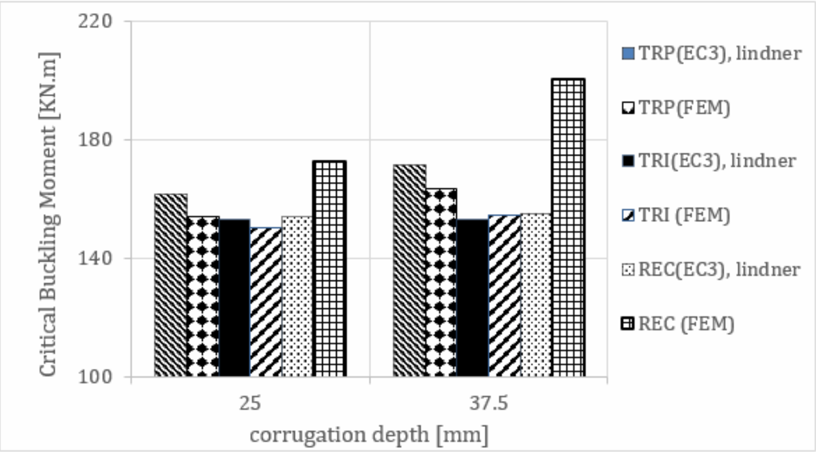

Figure 9: Influence of corrugation shape on lateral torsional buckling moment

After careful inspection of these figures, it can be observed from Fig.(4) that the results of finite element analysis and the lateral torsional buckling moment which had been calculated by the three approaches are in a good agreement and the increasing of web thickness leads to increase the elastic lateral torsional buckling moment. It is obvious from Fig.(5) that the increasing of web height leads to increase the elastic lateral torsional buckling moment M_{cr}

where the moment of inertia about minor axis increased by increasing web height.

Additionally, the results from F.E.M are in a good agreement with the Euro-code (EC3).

It can be observed from Fig.(6) that the results of finite element analysis and the lateral torsional buckling moment which had been calculated by the three approaches are in a good agreement and the increasing of flange thickness leads to increase the elastic lateral torsional buckling moment. Also, the critical buckling moment varies approximately linearly with the flange thickness for thicknesses in the range 4 to 24 mm.

It can be observed from Fig.(7) that when varying the flange width within the range of 100 to 400 mm, the critical buckling moment is strongly dependent on the flange width. All examined methods are reasonably accurate for calculating the critical buckling moment. Also, it is hard to distinguish any differences but, by studying the exact values, it appears that Moon et al.[2] and Zhang et al[3]. underestimate the critical buckling moment for girders with a small flange width.

From Fig.(8), it can be observed that the results of finite element models reveal that the lateral torsional moment of girders with corrugated webs is decreased by increasing the corrugation width because the increasing corrugation width leads to decrease the number of corrugation in span and get partially constraint compression flange.

From Fig.(9) It can be observed that girders with rectangular corrugated web have lateral torsional buckling resistance more than that of girders with triangular or trapezoidal corrugated web with average ratio 22 % and 17 %, respectively. This is due to the compression flange restrained against the lateral deformation in the case of rectangular corrugation is more than that for the two other cases because the existence of vertical panels.

On the other hand, lateral torsional buckling resistance of models using the three approaches (Moon et al approach and Zhang approach) are increased with a small ratio by increasing the corrugation width because the warping constant is also increased. But the lateral torsional buckling resistance of models using (Lindner approach) decreased by increasing the corrugation width. Finally, by comparing results of finite elements models and the lateral torsional buckling moment which had been calculated by the three approaches, the difference between them is very small.
From the results of FEM, it was found that the lateral torsional buckling moment which had been calculated by the three approaches are in a good agreement with the results from the finite model analysis for triangular and trapezoidal webs. On the other hand for rectangular web, the results of the finite element model is higher than the values of lateral torsional buckling moment which had been calculated by the three approaches because the moment on inertia about minor axis for the rectangular corrugated web at section (a-a) depends on web thickness ,while is section (b-b) depends on the corrugation depth as shown in Fig(10) and this is not taken into account in the calculation of moment of inertia about minor axis in Euro-code equations. Therefore, the difference between the values of the lateral torsional buckling moment for the rectangular corrugated web, which are obtained from finite element analysis and according to EC3, is increased due to the increasing in corrugation depth.

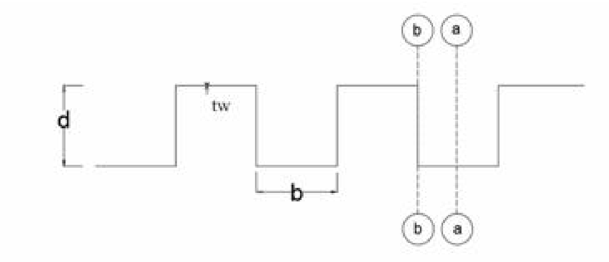

Figure 10: Corrugation profile for rectangular corrugated web girder

5. LATERAL TORSIONAL BUCKLING BEHAVIOR OF CORRUGATED WEB GIRDERS WITH OPENINGS.

Using the corrugated web beam with openings will reduce the material volume without affecting the structural strength or serviceability requirements, allowing the passage of large pipes and ducts through the web of beam instead of re-routing of services or increasing the floor height at the design.

Shell element (181) with 4 node and 6 degree of freedom per node were used to model all analyzed girders using the computer package ANSYS ver18[8]. All the analyzed girders are a simply supported beam .The dimensions of the analyzed girders as mention before but, the width (b) and depth of corrugation (d) are taken equal 200 mm and 50 mm respectively.

Two cases of openings had been studied: the first case is that the opening is located in the flat part of the corrugated web with two positions, first the opening is near the compression flange and the other position is near the tension flange and the ratio between the openings size to the height of the web is 0.22, as shown in Fig.(11). The second case study is studying the circular and square openings which located in the flat part and also in the inclined panel of the corrugated web and the ratio between the openings size to the web height is 0.3, 0.5 and 0.7. Also, the number of openings is changing along the span (5 openings – 10 openings – 20 openings), as shown from Figures (12) to (17).

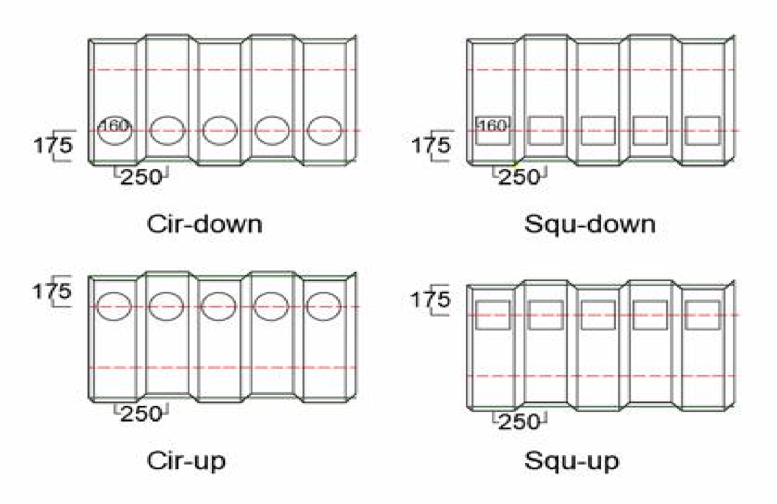

Figure 11: Case study (1) : The openings locations and dimensions

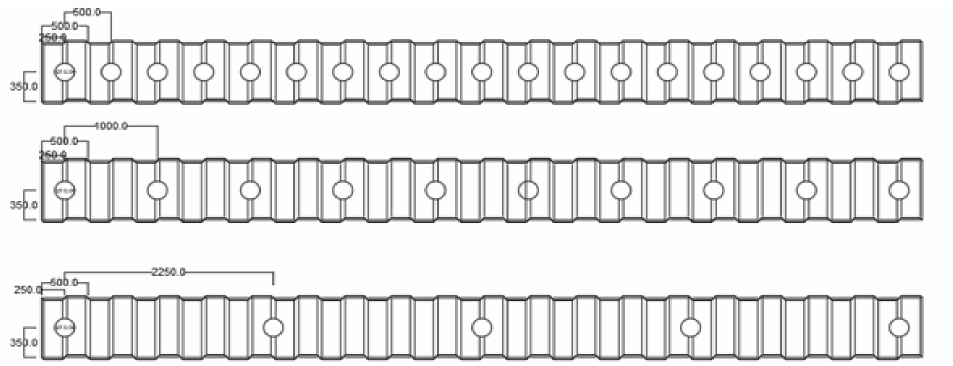

Figure 12: Case study (2): Girders with circular opening (d/hw=0.3) with number of openings (5-10-20)

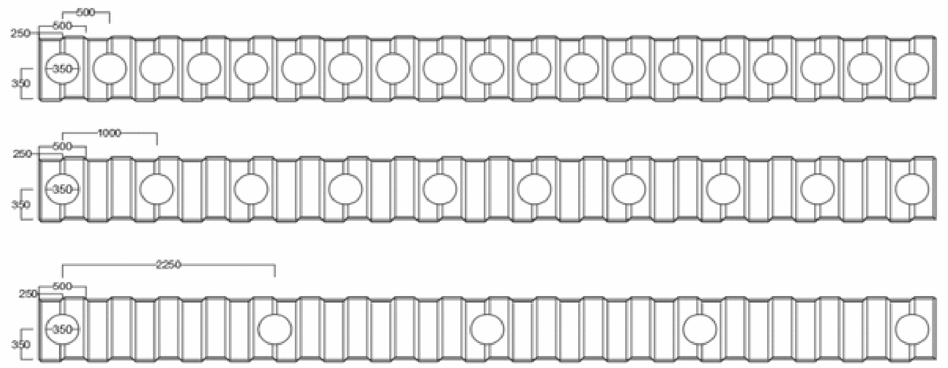

Figure 13: Case study (2): Girders with circular opening (d/hw=0.5) with number of openings (5-10-20)

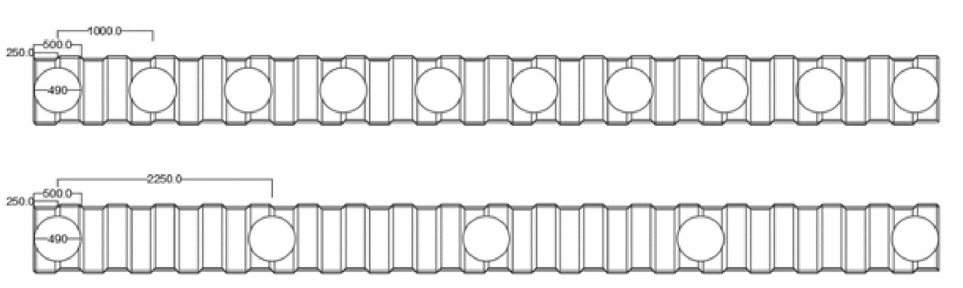

Figure 14: Case study (2): Girders with circular opening (d/hw=0.7) with number of openings (5-10)

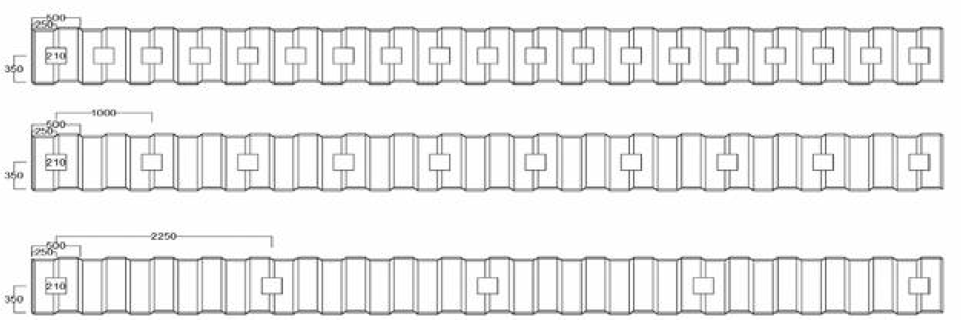

Figure 15: Case study (2): Girders with square opening (d/hw=0.3) with number of openings (5-10-20)

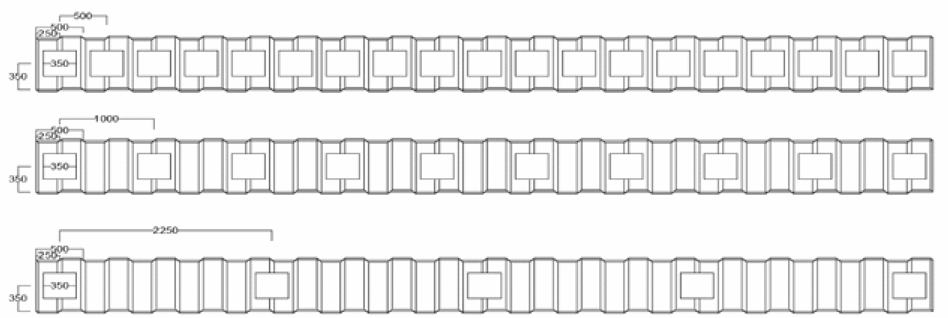

Figure 16: Case study (2): Girders with square opening (d/hw=0.5) with number of openings (5-10-20)

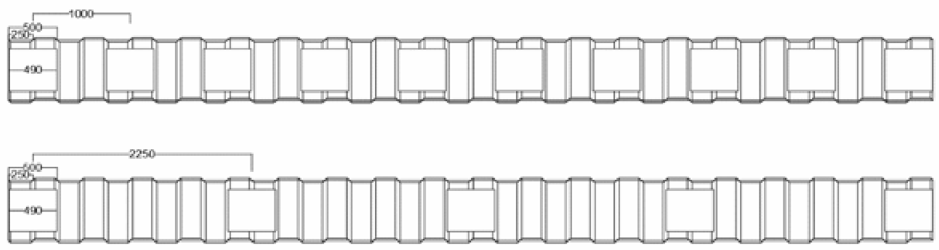

Figure 17: Case study (2): Girders with square opening (d/hw=0.7) with number of openings (5-10)

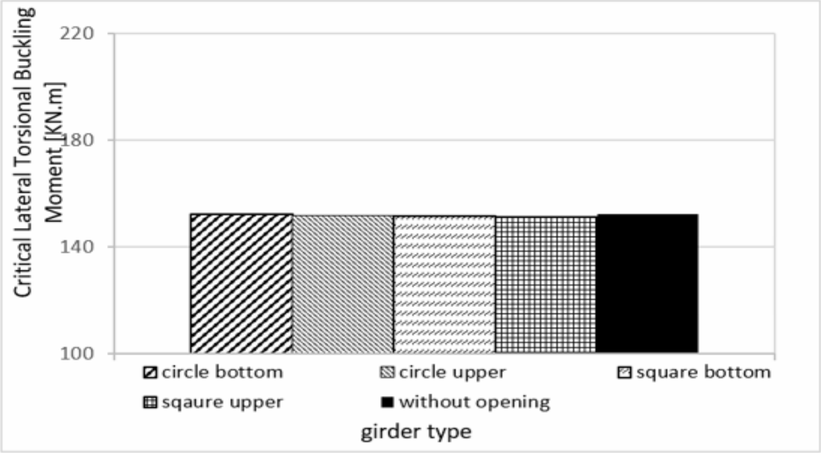

Figure 18 **Lateral torsional buckling moment mode for all analyzed girders for case study (1)**

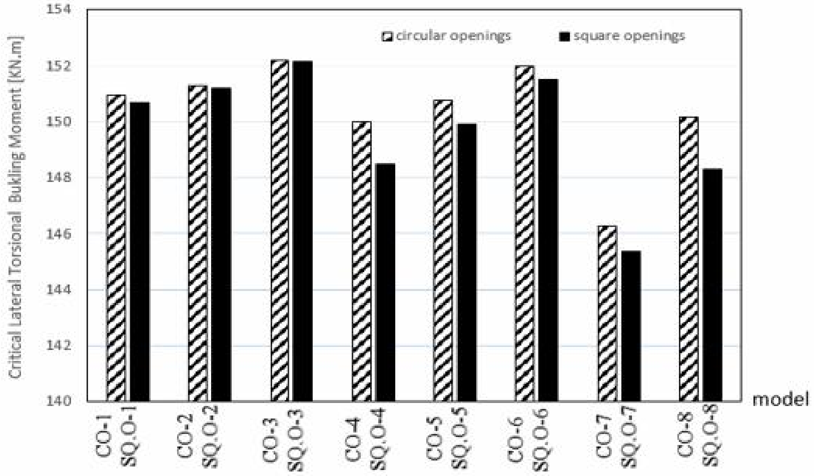

Figure 19 **Lateral torsional buckling moment mode of analyzed girders for case study (2)**

From the previous results of the finite element models for the case study (1) which plotted in Fig.(18), it is evident that the critical lateral torsional buckling moment for the corrugated web girders without openings is very close to the those girders with openings and the reason for these results is that the critical lateral torsional buckling moment are strongly dependent on the flange of the girders not on the web of the girders and also it can be noted that the values of the critical lateral torsional buckling moment for corrugated web girders with openings which have the openings near the tension flange is a bit higher than other girders which have the openings near the compression flange. Also From the finite element models results for the case study (2) which plotted in Fig(19), the critical lateral torsional buckling moment for the corrugated web girders with circular opening is higher than the other girders which have square openings. At the same number of openings along the span of the girder the value of the critical lateral torsional buckling moment for girders decreases with a ratio about 1% when the opening depth to the web height increases from 0.3 to 0.7. In addition, the difference between the critical lateral torsional buckling moments for the corrugated web girders without openings to the other girders of the case study (2) is not high values that also because the critical lateral torsional buckling moment are strongly dependent on the flange of the girders not on the web.

6. CONCLUSIONS.

From analytical study on the behavior of steel girders with corrugated web, it can be concluded the following:

1-From finite element analysis, the lateral torsional buckling resistance for girders with the corrugated web are increased by increasing in web thickness, web height, flange thickness and flange width, but they are decreased by increasing the corrugation width.

2-The strength of plate girders against lateral torsional buckling increased by increasing in corrugation depth.

3-Girders with rectangular webs have lateral torsional buckling resistance more than that of girders with triangular or trapezoidal webs with average ratios 22% and 17%, respectively.

4-Euro-code equations of lateral torsional buckling resistance gives convergent results to that of the finite element models for girders with triangular or trapezoidal web. But for girders with rectangular web, the results of the Euro-code are far away from the finite element model.

5-The critical lateral torsional buckling moment for the corrugated web girders without openings is very close to the other girders which have openings in all studied cases because that the critical lateral torsional buckling moment are strongly dependant on the flange of the girders not on the web of the girders.

6-The values of the critical lateral torsional buckling moment for corrugated web girders with openings which have the openings near the tension flange is higher than other girders which have the openings near the compression flange.

7-Lateral torsional buckling moment for the corrugated web girders with circular opening is higher than those with square openings.

8-The value of the critical lateral torsional buckling moment for girders decreases when the opening depth to the web height increases.

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