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Linear Investigation on Tapered Steel Isolated Plates with Zigzag Corrugated Web

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Abstract: **Owing to the benefits of corrugated steel webs, they are frequently utilized in a variety of buildings, particularly bridges. They have good and beautiful appearance, Secondly, they exhibit large out of plane stiffness, so they have a high ability to resist shear buckling which is known as accordion effect. There are many profiles of corrugation such as trapezoidal, curved and zigzag shapes, many researchers studied the trapezoidal profile as prismatic and tapered but zigzag profile was studied as a prismatic only, so it was focused on this research to examine the behavior of the elastic buckling stress τ_{cr} on tapered corrugated webs with zigzag profile for case I exposed to shear load. The ABAQUS Program is utilized here to make a series of finite element (FE) simulations to investigate the factors which affect the behavior of the elastic buckling stress and to modify the equation of $\tau_{cr,T}$ to be suitable for zigzag profile.**

Keywords: **Zigzag corrugation, Elastic, Tapered plates, Case I.**

I. INTRODUCTION

Recently, civil engineers have used Corrugated steel plate girder in bridges instead of normal plate girders. As it has multi benefits, First its good and beautiful appearance, Secondly, it exhibits large out of plane stiffness so it has a high ability to resist shear buckling which is known as accordion effect [1]. According to this effect the number of stiffeners in the girders are reduced which lead to saving in weight and cost [2]. These girders are typically made of two flange plates and a corrugated web that is joined to the flanges by welding. In general, trapezoidal and sinusoidal corrugations are used in bridges and structures; respectively. Furthermore, the shear strength of such girders is provided by their webs, whereas the flexural strength is totally provided by their flanges. Hence, there is no interaction between flexural and shear actions. Local, global, and interactive buckling are the three categories under which the shear buckling mechanism in steel corrugated webs are described see Fig. 2. It is common practice to utilize tapered plate girders with corrugated webs (TPGCWs) because of their added benefits, including efficient stress distribution and a pleasing look Fig. 1. According to the direction of the tension field long or short diagonal and the type of axial force tension or compression in the inclined flange, the webs of these TPGCWs can be divided into four categories in accordance with the distributions of the bending moment and shear force, Fig. 3 illustrates how to classify the webs of two distinct bridges into the four typologies [3].This would be based on a typical loading example that takes into account a load that is distributed uniformly. As seen in Fig. 3, the regions of zero moment and zero shear, if they occur within the tapering portion of the girder, separate the web into various typologies.

As observed, three of them can be found in different locations on a bridge span with a tapered cross section, while the fourth type may be present in another bridge system. In this bridge, the end of the tapered part of the girder under the negative bending moment occurring close to the intermediate support immediately determines the web typology III. When compared to other tapered typologies and prismatic webs, the axial force in the inclined flange results in a vertical component that affects the shear behavior and strength of the panel in tapered web panels. This phenomenon is known as the Resal Effect [4] and it can be positive or negative depending on the tapered typology. In their investigation of the behavior of tapered plate girders with flat web, Bedynek et al. [4] proposed a unique equation for determining the stress by combining the results of prismatic plate girders and tapered plate girders.

(A) Prismatic Girder

(B) Tapered Girder

Figure 1. Types of Girders.

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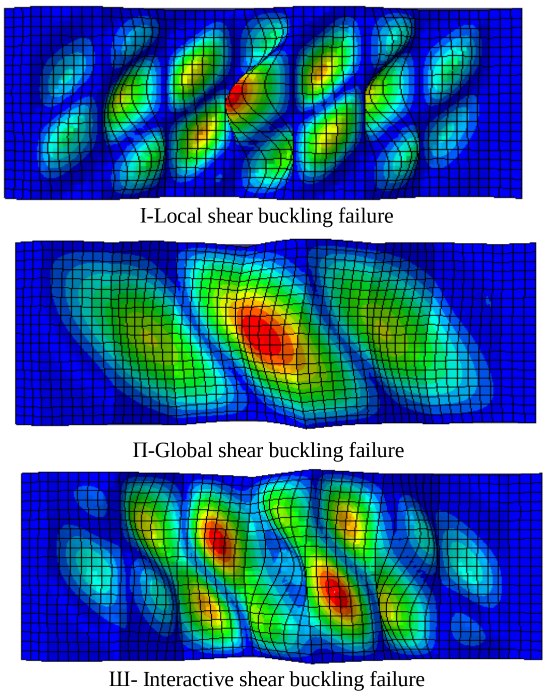

Figure 2. Corrugated web failure due to shear buckling.

However, Hassanein and Kharoob [5] only examined the behavior of the TPGCWs when standard mild steels were used (NMSs). In 2015 EL hadidy et al [6] studied the behavior of the corrugated web with zigzag profile under shear for prismatic girder. So, it was in this paper to study the behavior of tapered corrugated web for zigzag corrugation. The ABAQUS Program was used in this research to conduct a series of finite element (FE) simulations to investigate the factors which affect the behavior of the elastic buckling stress and to modify the equation of $\tau_{cr,T}$ to be suitable for zigzag profile for case I.

II. FINITE ELEMENT ANALYSIS ON ISOLATED TAPERED PLATE

2.1 Overview

The elastic buckling of zigzag corrugated tapered webs for case I was simulated using the FE program ABAQUS [7]. The Eigenvalue analysis was used to estimate the buckling mode. The load was applied within the step of a linear elastic simulation using the (BUCKLE) state from the ABAQUS library [7]. In order to determine the FE critical shear stress $\tau_{cr,FE}$ the first eigenvalue buckling mode was used. According to [2,3] ,the 8-node shell element S8R5 was employed in the current models[10]. The steel material is represented by a von Mises material with isotropic hardening. It has a Poisson's ratio of 0.3 and a Young's modulus of 210 GPa.

2.2 Boundary condition and applied load.

Table 1 demonstrates how the first one handled the outer edges of the isolated corrugated plates as Fixed. The symbols R and F in the table represent restrained and free boundary conditions; respectively. In order to confirm that the plate is in pure shear as shown in Fig. 4, the load in that case is transmitted to the long depth h_{w1} edge (BC).

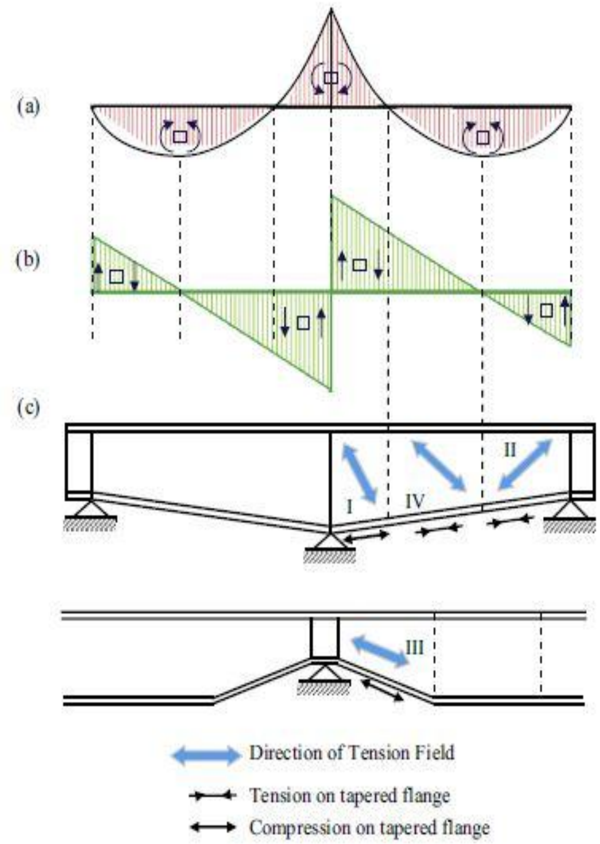

Figure 3. (a) Bending moment diagram, (b) Shear force diagram and (c) Web typology for tapered plates in continuous steel bridges.

Table 1. Fixed Isolated Plates Boundary conditions

Deformation	Symbols	Fixed isolated plate			
		AB	BC	CD	DA
Translation	δ_x	R	R	R	R
	δ_y	F	F	F	R
	δ_z	R	R	R	R
Rotation	θ_x	R	F	R	F
	θ_y	R	F	R	F
	θ_z	R	F	R	F

R and F stand for restrained and free boundary condition

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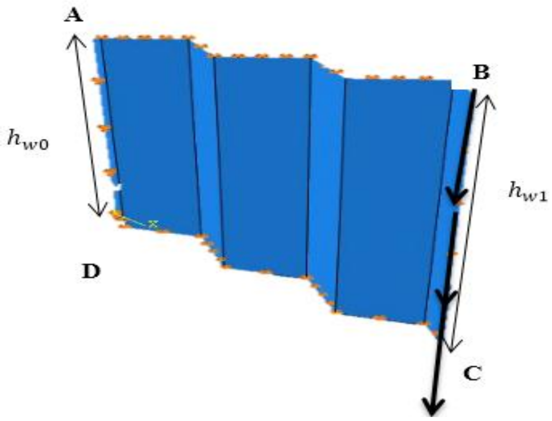

Figure 4. Boundary conditions and load requirement of a standard corrugated web.

III. PARAMETRIC STUDY

The ABAQUS FE software [7] was used to create 120 FE models of zigzag steel tapered web plates . Six groups of 20 models each were formed from the 120 models. The configurations of these groups were derived from the listed existing bridges in Table **1** [10]. The width (b) was taken as the width of the Shinkai, Matsnoki, Dole, Hondani, Maupre, and IIsun bridges. Each group composed of three waves of zigzag corrugated tapered web. Height of corrugations h_r measurements are (150, 200 and 220 mm). The corrugation of the existing bridges was trapezoidal, whereas this study's corrugation is zigzag, therefore the angles of the corrugation were different from those in the existing bridges and were 30.9, 26.5, 27.1, 36.5, 37.7, and 31.2; respectively.

The web's thickness was assumed to support Easley's conclusions [11] to achieve the geometric rigidity of (h_r/t_w) >10 which is necessary for bridge construction for the current Matsnoki, Hondani, and IIsun, The web- heights of control prismatic corrugated webs were taken as 1,700 mm, 1,500 mm, and 1,900 mm; respectively, instead of the web depth in the existing bridges [10] to ensure that the aspect ratio of the web panel (a/h_{w1}) is larger than unity and in order to obtain the required geometric rigidity of $b/h_{w1} \leq 0.2$ for bridge construction [7, 8]. The current study is represented in Table 2 by 120 isolated webs covering four critical parameters: the corrugation configuration, the web thickness (t_w) and the angle of inclination of the upper edges.

A. *Effect of web thickness (t_w)*

As can be obvious in Fig. 5 there is a relationship between critical shear stresses $\tau_{cr,FE}$ and the web thickness t_w for the set 1 which have the same profile corrugation, it can be concluded that the critical shear stress $\tau_{cr,FE}$ rises with increasing the web thickness t_w. In addition, it shows that they nearly have the same value of the critical shear stress $\tau_{cr,FE}$ at the small thickness.

B. *Inclination angle of the top flanges and its effects*

From Fig. 6, it can be seen that, in case I, the critical shear buckling stress $\tau_{cr,FE}$ values increase with the increase of the value of inclination angles γ for zigzag corrugation.

C. *Effect of corrugation depth-to-web thickness ratio (h_r/t_w)*

The correlations between the FE critical shear stresses $\tau_{cr,FE}$ and the depth-to-web thickness ratios (h_r/t_w) for various inclination angles are shown in **Fig.7**. It can be said that the critical shear stress$\tau_{cr,FE}$ is decreased by increasing the (h_r/t_w) ratio. Additionally, it is found that for any analysed inclination angles, the critical shear stress $\tau_{cr,FE}$ becomes nearly quite similar as the (h_r/t_w) ratio reaches 66.67.

D. *FE critical stress comparison with the existing formula*

Specifically, Hassanein and Kharoob [13] suggested calculating the critical shear buckling stress $\tau_{cr,T}$ for tapered corrugated webs by connecting them to the critical values of prismatic webs $\tau_{cr,P}$ in Eq (1), were compared to the zigzag corrugated webs' critical shear stress $\tau_{cr,FE}$ for fixed junctures.

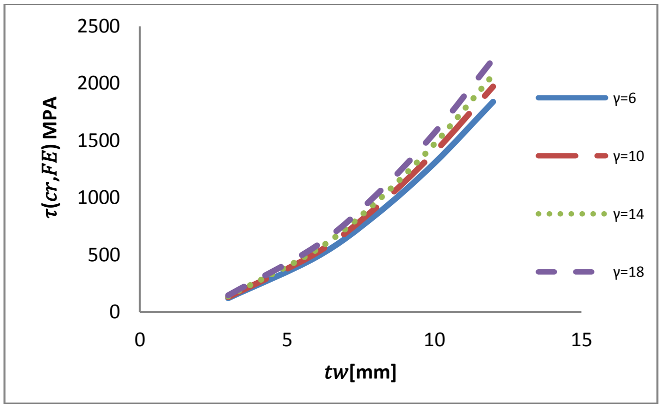

Figure 5. FE critical stress for tapered corrugated webs with Set 1 configuration.

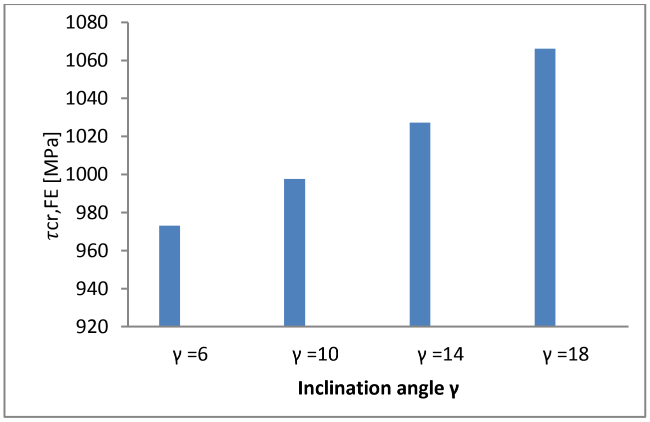

Figure 6. F critical stress for tapered corrugated webs with Set 2 configuration.

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Table 2: Details of Analysed Models

Corrugation configuration	h_{w1} [mm]	(γ) [°]	t_w [mm]	α [°]	Boundary Condition	No.of models
Set 1	1,183	6-10-14-18	3-6-8-10-12	30.9	F	20
Set 2	1,700	6-10-14-18	3-6-8-10-12	26.5	F	20
Set 3	2,546	6-10-14-18	3-6-8-10-12	27.1	F	20
Set 4	1,500	6-10-14-18	3-6-8-10-12	36.5	F	20
Set 5	2,650	6-10-14-18	3-6-8-10-12	37.7	F	20
Set 6	1,900	6-10-14-18	3-6-8-10-12	31.2	F	20
Total No .of models						120

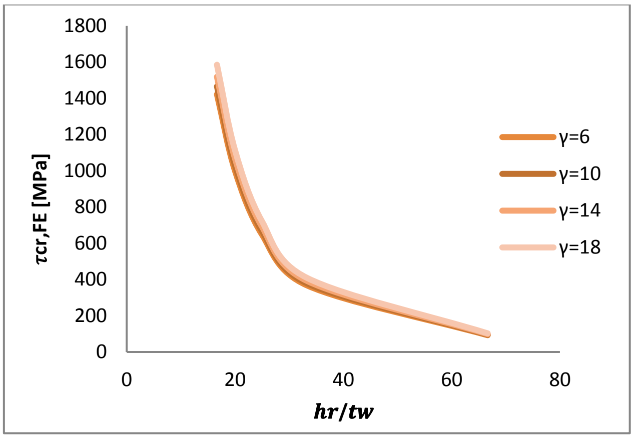

Figure 7. FE critical stress for tapered corrugated webs with Set 4 configuration with (h_r/t_w) ratios

$$\tau_{cr,T} = \tau_P/(1 + Tan\gamma) \tag{1}$$

The critical buckling stress for PPGCWs is $\tau_{cr,P}$ while Hassanein and Kharoob's [13] recommended value for TPGCWs is $\tau_{cr,T}$, As per EL Hadedy et al [6] in the fixed situation, the second order 2nd interactive shear buckling stress was taken to equal $\tau_{cr,P}$ for zigzag corrugated web.

$$\tau_{cr,I} = \frac{\tau_{cr,L} * \tau_{cr,G}}{\left((\tau_{cr,L})^2 + (\tau_{cr,G})^2\right)^{1/2}} \tag{2}$$

The local shear buckling is denoted by $\tau_{cr,L}$, and the global shear buckling is denoted by $\tau_{cr,G}$. Use Eq. (3) to Eq. (7) to calculate them.

$$\tau_{cr,L} = k_L \frac{\pi^2 E}{12(1-\upsilon^2)} \left(\frac{t_w}{w}\right)^2 \tag{3}$$

where E is the Young's modulus of elasticity υ is the ratio of Poisson; w is the width of fold. For the buckling of an inclined fold w is the maximum value of (b) or (c), While k_L is computed from the Eq. (4), $h_w$in this equation relates to the long depth, h_{w1}.

$$k_L = 5.34 + 4\left(\frac{w}{h_w}\right)^2 \tag{4}$$

$$\tau_{cr,G} = 36\beta \frac{D_y^{0.25} D_x^{0.75}}{t_w h_w^2} \tag{5}$$

in which the corrugated web's transverse and longitudinal bending stiffness (D_x and D_y; respectively) are calculated in respect to Sayed Ahmed [14].

$$D_x = \frac{E t_w^3}{12} \cdot \left(\frac{h_r}{t_w}\right)^2 \tag{6}$$

$$D_y = \frac{E t_w^3}{12(1-\mu^2)} \tag{7}$$

while the global buckling coefficient β ranges from 1 to 1.9 relating to the web's boundary conditions for simple or fixed supported. Table **3** demonstrates that the equation developed by Hassanein and Kharoob [13] is not appropriate for determining the critical shear stress for zigzag corrugated web. The standard deviation and mean variation are shown in the tables below as 0.08 and 0.73, respectively. In order to fit the equation with the FE critical stresses, it is changed. The improved equation is displayed in Eq (8). For the plates, the average and standard deviation are 0.99 and 0.11, respectively, after applying the modifying equation.

$$\tau_{cr,mod} = {1.36\tau_{cr,P}}\Big/{(1 + tan\gamma)} \tag{8}$$

Table 3: Comparison to the existing formula (Fixed case)

	Model No	t_w [mm]	h_{w1} [mm]	$\tau_{cr,T}$ / $\tau_{cr,FE}$ Hassanein&Kh-aroob [13]	$\tau_{cr,mod}$ / $\tau_{cr,FE}$
Set 1	1	3		0.84	1.14
	2	6		0.85	1.16
	3	8		0.86	1.17
	4	10		0.86	1.18
	5	12		0.87	1.19
	6	3		0.74	1
	7	6		0.75	1.01
	8	8		0.75	1.02
	9	10		0.76	1.03

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	10	12		0.77	1.04
	11	3		0.66	0.9
	12	6		0.67	0.91
	13	8		0.68	0.92
	14	10		0.68	0.93
	15	12	1,183	0.69	0.94
	16	3		0.59	0.8
	17	6		0.6	0.81
	18	8		0.6	0.82
	19	10		0.61	0.83
	20	12		0.61	0.83
	1	3		0.83	1.13
	2	6		0.82	1.12
	3	8		0.81	1.1
	4	10		0.78	1.06
	5	12		0.75	1.02
	6	3		0.76	1.04
	7	6		0.76	1.03
	8	8		0.74	1.01
	9	10		0.72	0.98
Set 2	10	12		0.69	0.93
	11	3	1,700	0.7	0.95
	12	6		0.69	0.94
	13	8		0.68	0.92
	14	10		0.66	0.89
	15	12		0.63	0.85
	16	3		0.64	0.87
	17	6		0.63	0.86
	18	8		0.62	0.84
	19	10		0.6	0.81
	20	12		0.57	0.78
	1	3		1.13	0.83
	2	6		1.14	0.84
	3	8		1.14	0.84
	4	10		1.15	0.84
	5	12		1.15	0.85
	6	3		1.04	0.76
	7	6		1.04	0.77
	8	8		1.05	0.77
	9	10		1.05	0.77
Set 3	10	12		1.06	0.78
	11	3	1,500	0.87	0.64
	12	6		0.87	0.64
	13	8		0.88	0.64
	14	10		0.88	0.65
	15	12		0.88	0.65
	16	3		0.87	0.64
	17	6		0.87	0.64
	18	8		0.88	0.64
	19	10		0.88	0.65
	20	12		0.88	0.65
	1	3		0.83	1.12
	2	6		0.83	1.13
	3	8		0.84	1.14
	4	10		0.84	1.15
	5	12		0.85	1.16
	6	3		0.75	1.03
	7	6		0.76	1.03
	8	8		0.76	1.04
	9	10		0.77	1.05
Set 4	10	12	1,900	0.78	1.06
	11	3		0.69	0.94
	12	6		0.69	0.94
	13	8		0.7	0.95
	14	10		0.7	0.95
	15	12		0.71	0.96
	16	3		0.62	0.85
	17	6		0.63	0.85
	18	8		0.63	0.86
	19	10		0.64	0.87
	20	12		0.64	0.87
	1	3		0.84	1.14
	2	6		0.84	1.14
	3	8		0.84	1.15
	4	10		0.85	1.16
	5	12		0.86	1.17
	6	3		0.77	1.05
	7	6		0.77	1.05
	8	8		0.78	1.06
	9	10		0.78	1.06
	10	12		0.79	1.07
Set 5	11	3	2,546	0.71	0.96
	12	6		0.71	0.97
	13	8		0.71	0.97
	14	10		0.72	0.98
	15	12		0.72	0.99
	16	3		0.65	0.88
	17	6		0.65	0.89
	18	8		0.65	0.89
	19	10		0.66	0.90
	20	12		0.66	0.90
	1	3		0.86	1.17
	2	6		0.86	1.17
	3	8		0.87	1.18
	4	10		0.87	1.19
	5	12		0.88	1.2
	6	3		0.8	1.09
	7	6		0.81	1.1
Set 6	8	8	2,650	0.81	1.1
	9	10		0.82	1.11
	10	12		0.82	1.12
	11	3		0.75	1.02
	12	6		0.76	1.03
	13	8		0.76	1.03
	14	10		0.77	1.04
	15	12		0.77	1.05
	16	3		0.71	0.96
	17	6		0.71	0.97
	18	8		0.71	0.97
	19	10		0.72	0.98
	20	12		0.72	0.98
AVE				0.74	0.99
SD				0.08	0.11

IV. CONCLUSIONS

The primary objective of this research is to investigate the elastic behavior of tapered corrugated plates with zigzag section for case I and to modify the equation of FE critical shear stress$\tau_{cr,T}$, the outcomes that followed were as follows:

1. The critical shear stress $\tau_{cr,FE}$ increases with increasing the web thickness t_w.
2. The values of the critical shear buckling stress $\tau_{cr,FE}$ increase with the increase of the value of inclination angles γ for zigzag corrugation.
3. It can be concluded that raising the (h_r/t_w) ratio will reduce the critical shear stress $\tau_{cr,FE}$ The equation developed by Hassanein and Kharoob [13] is not appropriate for determining the critical shear stress for zigzag corrugated web, So the equation was modified to fit with the results.

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Conflicts of Interest: There is no conflict of interest, according to the Authors understanding.

REFERENCES

[1] J. Y. Oh, D. H. Lee, and K. S. Kim, "Accordion effect of prestressed steel beams with corrugated webs, "*Thin-Walled Struct.*, vol. 57, pp. 49–61, 2012, doi: 10.1016/j.tws.2012.04.005.

[2] R. G. Driver, H. H. Abbas, and R. Sause, "Shear Behavior of Corrugated Web Bridge Girders," *J. Struct. Eng.*, vol. 132, no. 2, pp. 195–203, 2006, doi: 10.1061/(asce)0733-9445(2006)132:2(195).

[3] A. A. Elkawas, M. F. Hassanein, and M. H. El-Boghdadi, "Numerical investigation on the nonlinear shear behaviour of high-strength steel tapered corrugated web bridge girders," *Eng. Struct.*, vol. 134, pp. 358–375, 2017, doi:10.1016/j.engstruct.2016.12.044.

[4] A. Bedynek, E. Real, and E. Mirambell, "Tapered plate girders under shear: Tests and numerical research," *Eng. Struct.*, vol. 46, pp. 350–358, 2013, doi: 10.1016/j.engstruct.2012.07.023.

[5] M. F. Hassanein and O. F. Kharoob, "Linearly tapered bridge girder panels with steel corrugated webs near intermediate supports of continuous bridges," *Thin-Walled Struct.*, vol. 88, pp. 119–128, 2015, doi: 10.1016/j.tws.2014.11.021.

[6] Dabaon, M.A., El-Boghdadi, M.H., El Hadidy, A.M., "Non-Linear Finite Element Modelling of plate Girders with Zigzag corrugated Webs" International Conference on Advances in structural and Geotechnical Engineering (ICASGE'17), Hurgada, Egypt, 2015

[7] Michael Smith, "ABAQUS / CAE User's Manual," *ABAQUS/CAE User's Man.*, pp. 1–847, 2001.

[8] M. Elgaaly, R. W. Hamilton, and A. Seshadri, "Shear Strength of Beams with Corrugated Webs," *J. Struct. Eng.*, vol. 122, no. 4, pp. 390–398, 1996, doi: 10.1061/(asce)0733-9445(1996)122:4(390).

[9] J. Yi, H. Gil, K. Youm, and H. Lee, "Interactive shear buckling behavior of trapezoidally corrugated steel webs," *Eng. Struct.*, vol. 30, no. 6, pp. 1659–1666, 2008, doi: 10.1016/j.engstruct.2007.11.009.

[10] M. F. Hassanein and O. F. Kharoob, "Behavior of bridge girders with corrugated webs: (I) Real boundary condition at the juncture of the web and flanges," *Eng. Struct.*, vol. 57, pp. 554–564, 2013, doi: 10.1016/j.engstruct.2013.03.004.

[11] A. Bakr Saddek, H. Gomaa Kotb, and S. Abdullah Tohamy, "Shear Buckling Strength of Plate Girder with Trapezoidal Corrugated Steel Webs 53 Shear Buckling Strength of Plate Girder with Trapezoidal Corrugated Steel Webs," *Minia J. Eng. Technol.*, vol. 35, no. 2, 2016, [Online]. Available: https://www.researchgate.net/publication/333311208

[12] K. H. Jung, J. W. Yi, and J. H. J. Kim, "Structural safety and serviceability evaluations of prestressed concrete hybrid bridge girders with corrugated or steel truss web members," *Eng. Struct.*, vol. 32, no. 12, pp. 3866–3878, 2010, doi: 10.1016/j.engstruct.2010.08.029.

[13] M. F. Hassanein and O. F. Kharoob, "Shear buckling behavior of tapered bridge girders with steel corrugated webs," *Eng. Struct.*, vol. 74, pp. 157–169, 2014, doi: 10.1016/j.engstruct.2014.05.021.

[14] E. Y. Sayed-Ahmed, "Behaviour of steel and (or) composite girders with corrugated steel webs," *Can. J. Civ. Eng.*, vol. 28, no. 4, pp. 656–672, 2001, doi: 10.1139/cjce-28-4-656.

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