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Elastic Behavior of Corrugated Web Girders with Square Opening

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المخلص: في هذا البحث تمت الدراسة النظرية على الكمرات اللوحية المعرجة ذات الفتحة المربعة المعرضة لأحمال قص. وقد تم ذلك التحليل عن طريق استخدام برنامج الأيكوس. حيث تم دراسة عدد من المتغيرات وذلك لبحث تأثير هذه المتغيرات على معامل انبعاج القص (k_t). وشملت هذه المتغيرات ارتفاع الكمر، عرض اللوح المعدني المسطح، عمق الكمر، النسبة بين اللوح المعدني المسطح الي اللوح المعدني المائل، مكان وحجم الفتحة المربعة. وللتأكد من دقة النتائج في هذا البحث تم مقارنة بعض النتائج مع النظريات المتاحة والتي اظهرت توافقا جيدا في النتائج. وقد اظهرت النتائج ان الزيادة في ارتفاع الكمره يؤدي الي نقص في معامل انبعاج القص (k_t). ايضا وجد ان التغير في عمق الكمره اظهر تأثير واضح في معامل انبعاج القص (k_t). بالاضافة وجد ان تأثير تغير مركزية الفتحة كبيرة الابعاد في الاتحاة الافقي لا يملك تأثير كبير علي معامل انبعاج القص (k_t) بينما في الفتحة ذات الابعاد الصغيرة لا يوجد تأثير ملحوظ علي معامل انبعاج القص (k_t). علي الجانب الاخر وجد انه لا يوجد تأثير في معامل انبعاج القص في حالة تغير مركزية الفتحة في الاتحاة الراسي. في نهاية البحث تم عرض منحنيات للحصول علي قيمة مقاومة انبعاج القص في حالة $4 < \alpha \leq 8$ و في حالة $\alpha > 8$ مع اختلاف المركزية في الاتحاة الافقي للفتحة وقد تم التوصية في حالة ($\alpha < 4$) علي التعامل مع الكمره كأنها ليس بها فتحة وذلك للحصول علي معامل انبعاج القص (k_t).

ABSTRACT- This paper presents an elastic parametric study for the trapezoidal corrugated web with a square opening subjected to a shear load. A series of finite element (FE) analyses using the ABAQUS program is carried out to study the influence of square opening on trapezoidal corrugated webs. A parametric study is conducted in this paper to investigate the effect of key parameters on the shear buckling coefficient (k_t) including the height of the web, width of the flat fold, depth of corrugation, the ratio between the flat fold and inclined fold, eccentricity and size of the square opening. By using the finite element model, the eigenvalue buckling analysis is obtained and verified using theoretical models. The results have shown that the increase in the height of the web plate leads to a decrease in the value of the shear buckling coefficient k_t . Also, it is found that the changing in the corrugated depth shown a clear influence on the shear buckling coefficient. Also, it is concluded that the effect of horizontal eccentricity in a big opening has a small influence on the shear buckling coefficient while in a small opening no changes are found in the shear buckling coefficient. On the other hand, it is found that there is no effect of changing the vertical eccentricity on the values of the shear buckling coefficient. Finally, design curves are proposed to obtain the shear buckling coefficient for $4 < \alpha \leq 8$ and $\alpha > 8$ with different values of horizontal eccentricity. Also, for ($\alpha < 4$) it is recommended to determine the shear buckling coefficient according to a corrugated web without opening.

I. INTRODUCTION

Trapezoidal corrugated steel web plate is composed of

sequences of a plane and inclined folds as shown in Fig. (1). The corrugated webs increase the stability of steel girders against buckling and weight savings due to the elimination of the need for transverse stiffeners. Moreover, previous research points towards that the weight of the plate girders with corrugated webs can be 10.6% less than the weight of the plate girders with the flat web [1]. The girder is subjected to shear force and bending moment the web carries shear forces due to the accordion effect [2], while the moment is carried by the flanges.

Several researchers have studied expansively on the shear strength of trapezoidal corrugated webs. For example, in the 1988s, Lindner and Aschinger [3] presented test results for the shear strength of steel trapezoidal corrugated webs and suggest using 70% of shear buckling stress as the nominal shear strength for design. In the 1996s, Elgaaly et al. [4] presented experimental and analytical results for the buckling characteristics and strength of trapezoidal corrugated webs loaded in shear. In 1998s, El-Metwally [5] investigated the behavior of girders with steel trapezoidal corrugated webs and prestressed concrete flange and develops a formula for guessing the nominal shear strength.

In the 2006s, Driver et al. [6] presented experimental and analytical results on the shear strength of large scale steel girders with trapezoidal corrugated webs and suggested shear design criteria for corrugated webs that are appropriate for bridge design specification. In the 2008s, Yi et al. [7] presented a formula for the nominal shear strength of trapezoidal corrugated webs and compare this formula with 15 test results and with FE analysis results. In the 2008s, Moon et al. [8] presented results from 3 tests, described the shear strength formula previously presented by Yi et al. [7] and compared the proposed formula and several other formulas with results from 17 tests. Recently, In the 2013s, Hassanein and Kharoob [9] proposed to use $n=0.60$ of the interactive equation, but in case fixed junctures between the flanges and the webs.

In the 2013s, Hassanein and Kharoob [10] proposed results of the comparison indicated that among the strengths utilizing the proposed interactive shear buckling strength formula ($\tau_{cr,1,0.6}$), the modified one which adopts Sause and Braxtan's [11] formula was found to be the best. More

recently, In the 2017s, Elkawas and El-Baghdadi [12] generated a generalized critical shear buckling stresses, based on the (b/h_w) . In the 2018s, Aggarwal et al. [13] investigated the local shear buckling behavior of beam with trapezoidal corrugated webs by using the program ABAQUS and presented an equation to approximate the local shear buckling coefficient in corrugated web beams.

In the 2018, El Hadidy et al. [14] studied the effect of using tubular flanges in bridge girders with corrugated steel webs on their shear behavior. Results this study showed the importance of using flange steel tubes with a large depth of flange to increase the shear strength of the girders. In the 2019s, wang et al. [15] studied shear behavior of steel I-girder with the stiffened corrugated web which showed that the loading capacity of corrugated steel web girders with vertical stiffeners, horizontal stiffeners, and hybrid stiffeners is increased by 57%, 8%, and 59%, respectively in comparison to pure corrugated web girder. Also, In the 2019s, He et al. [16] showed that the calculation methods proposed by Hassanein and Kharoob [9] and Leblouba et al. [17] can be used to predict the shear strength of corrugated steel web more accurately. All of the existing methods underestimate the shear strength of vertical stiffened corrugated steel web. A calculation method to accurately predict the shear capacity of stiffened corrugated steel web needs to be developed in further study.

To provide ducts and pipes beneath beams and girders of structural steel framing in building structures may produce unacceptably large construction depths. A solution often used is to provide openings in the webs of the beams and girders. In highway bridge structure, web holes on such girders are used to give space for service, checkup, and maintenance.

In the 1970s, Hoglund [18] researched the effects of circular holes on the shear of plate girders with thin webs. Then describe the shear buckling coefficient by a corrected shear buckling coefficient:

$$k_t^0 = \left(1 - \frac{D}{h_w}\right) \cdot k_t \quad (1)$$

Where: D is the diameter of opening; h_w is the web height and k_t is the shear buckling coefficient.

In the 1994s, Lindner and Huang [19] at the Technical University of Berlin, carried out extensive studies on the local buckling behavior of trapezoidal web girder with an opening. They described the correction factor as:

$$k_t^0 = \left(1 - 0.88 \frac{D}{b}\right) \cdot k_t \quad (2)$$

Where the correction factor is determined for specific dimensions.

Recently, Romeijn (2009) [20] studied the effect of the circular opening on the corrugated web plate. He found that

the influence of diameter of the opening on the shear buckling coefficient can be modeled by the following function:

$$k_t(0) = 6.77 - 5.15 \frac{D}{b} \quad (3)$$

Shear buckling mechanism in corrugated web plate is classified as local, global or interactive buckling. Local buckling happens when a flat fold between vertical edges has large width to thickness ratio. On the opposite, the global buckling mode involves multiple folds and the buckled shape extends diagonally over the depth of the web. However, the interactive shear buckling is resulting in the interaction between local and global shear buckling and governs the shear buckling strength. When the local buckling occurs, the buckling stress can be calculated by using the classical plate buckling theory [21] as follows:

$$\tau_{cr,L} = k_t \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t_w}{a_{max}}\right)^2 \quad (4)$$

Where E is Young's modulus of elasticity; ν is Poisson's ratio; a_{max} is the maximum of b (flat fold) and c (inclined fold) and t_w is the web thickness. k_t is the local shear buckling coefficient. Assuming that the panel has simply supported edges, k_t is given by:

$$k_t = 4.0 + \frac{5.35}{\alpha^2} \quad \text{For: } \alpha \leq 1 \quad (5)$$

$$k_t = 5.35 + \frac{4.0}{\alpha^2} \quad \text{For: } \alpha > 1 \quad (6)$$

$$\alpha = h_w/a_{max} \quad (7)$$

Several researchers presented FE modeling procedures to investigate the shear buckling behavior of the trapezoidal corrugated steel web plate. However, there is still no information about the shear buckling behavior of steel trapezoidal corrugated webs with a square opening. Hence this research focuses on obtaining the shear buckling coefficient of steel trapezoidal corrugated webs with square opening.

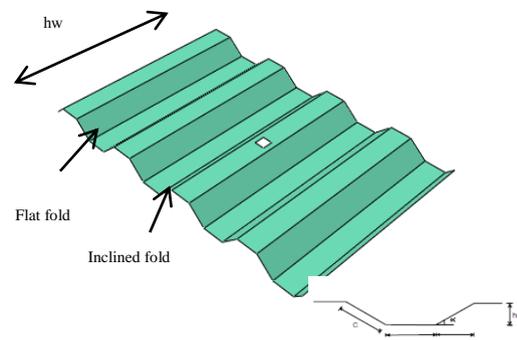


Fig. 1. Trapezoidal corrugated web

II. FINITE ELEMENT ANALYSIS WEB

2.1 Scope

The FE program ABAQUS [22] was used to simulate the elastic buckling of the corrugated webs with an opening. The buckling mode was estimated done the Eigenvalue analysis. This was a linear elastic analysis done using the (BUCKLE) system existing in the ABAQUS library [22] with the load applied within the step. The first buckling mode occurred in the eigenvalue analysis was used to estimate the FE critical shear stress ($\tau_{cr,FE}$). The S8R5 element was used in the current FE model following Ref. [4,7]. This element was a reduced integration thin shell element that suits the structure applications failing by shear buckling. The elastic properties of the steel material included a Young’s modulus of 210 GPa and the Poisson’s ratio of 0.3 are used.

2.2 Verification of the model

To verify the ability of the FE model to predicted the shear buckling of the trapezoidal web plate with a square opening, it was necessary to compare the FE model with the theoretical method. The FE model tests had been carried out on a flat square plate without opening (125x125mm) and rectangular plate without opening (125x375mm) with $\alpha=3$ and (125x1250mm) with $\alpha=10$. The result of the shear buckling coefficient from FE is 9.317 for a square plate, and the rectangular plate with ($\alpha=3$ and $\alpha=10$) was (5.880 and 5.378), respectively. Hence, the results of FE were predicted well the values of Euro-code [23] using Eq. (5) and (6), see Table (1). The mean value of the ratio between the FE results and the results of the Euro code is (0.99) with a coefficient of stander deviation (0.005).

The equation of the shear buckling coefficient obtained by Hoglund [18]; Eqs. (1) was used to verify the FE model in the case of a trapezoidal corrugated web plate with an opening. The steel corrugated web with ($\alpha = 3$) and circular opening with the diameter (D) was used. The comparison between the FE results and the Equation proposed by Hoglund [18] was described in Fig. (2) and Table (1). It can be seen from the Figure that FE results were closed to th results of Hoglund [18]. The average value between the FE results and the results of Hoglund [18] is (1.0) with a coefficient of stander deviation of (0.070); see Table (1). Accordingly, the FE model is predicted well with the theoretical methods.

2.3 Mesh analysis

The meshing analysis of simply supported edges of corrugated steel web plate of ($h_w=500$ mm, $b= 125$ mm, $c=125$ mm, $t_w=3$ mm and $h_r=75$ mm) with the square opening of ($b=45$ mm) was carried out. The convergence test aims at finding the best number of elements per horizontal

single fold which provides accurate results accompanied with good solution timing.

TABLE 1
THE RESULT OF FE

h_w	t_w	b	D	$k_{t,FE}$	$k_{t,L}$	$k_{t,FE}/k_{t,L}$
125	3	125	-	9.317	9.350	.99
375			-	5.880	5.794	1.0
1250			-	5.378	5.390	.99
375			10	5.821	5.4096	1.1
			20	5.451	4.939	1.1
			30	4.975	4.468	1.1
			40	4.4	3.998	1.1
			50	3.7	3.528	1.0
			60	3.2	3.057	1.0
			70	2.769	2.587	1.0
			80	2.3	2.116	1.0
			90	2.0	1.646	1.2

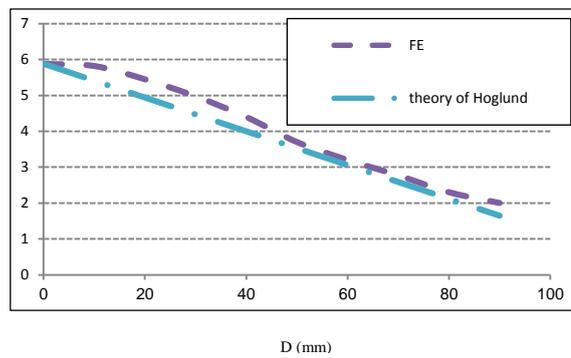


Fig. 2. Shear buckling coefficient as a function of opening

Fig. (3) shows the relationships between the shear-buckling stress (τ_{FE}) of FE and the number of elements per single fold. It can be noticed that the stress stabilizes from about using 6 elements per single fold and refine the mesh size around the opening to be 11x11 mm. Hence, each fold was divided into six elements and mesh size around the opening was taken as 11x11 mm in the current FE models.

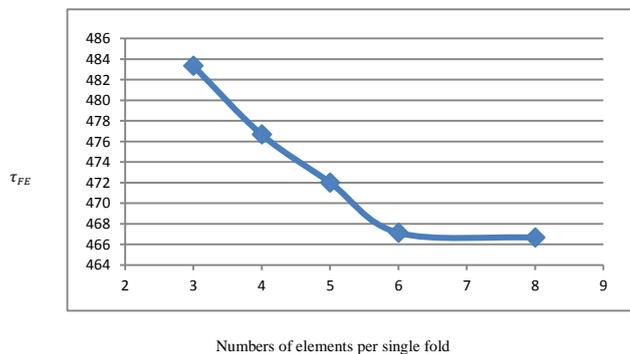


Fig. 3. Results of the convergence test

2.4 Boundary condition and load application

All four edges of the corrugated steel web plate with square opening were considered simple, as can be seen in Fig. (4). The translations and rotations are shown in the same figure, where the (R) represents a restrained boundary condition,

while (F) represents a free boundary condition. The web plate is subjected to a shear load plotted in Fig. (4). Fig. (4) also shows the location of the square opening where the square opening was placed approximately in the middle of the plate.

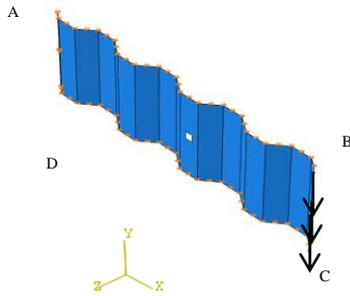


Fig. 4 The boundary conditions and the applied loads

III. PARAMETRIC STUDY

The parametric study in this paper includes the effect of the height of web (h_w), the width of a flat fold (b), the depth of corrugation (h_r), the β -ratio between the flat fold to the inclined fold of corrugated web, the eccentricity of square opening and the size of the square opening ($\frac{b_0}{b}$).

Deformation	Symbols	Simple isolate 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	F	F	F	F
	θ_y	F	F	F	F
	θ_z	F	F	F	F

A Height of web ($\alpha = \frac{h_w}{b}$)

The influence of the height of the web (h_w) was investigated on the value of shear buckling coefficient (k_t) for the web dimension of ($b=125$ mm, $c=125$ mm, and $h_r=75$ mm). It can be observed that for the solid web plate the increasing in the height of the web plate leads to a decrease of the shear buckling coefficient k_t value as shown in Fig. (5). The effect of changing the web height on the shear buckling coefficient for the existing square opening was investigated in Fig. (6). It can be concluded that, for a small opening, the increase of the height of the web plate leads to

clear decreases in the shear buckling coefficient value compare to the big square opening where this change may be neglected; see Fig. (6-a) and Fig. (6-b), respectively.

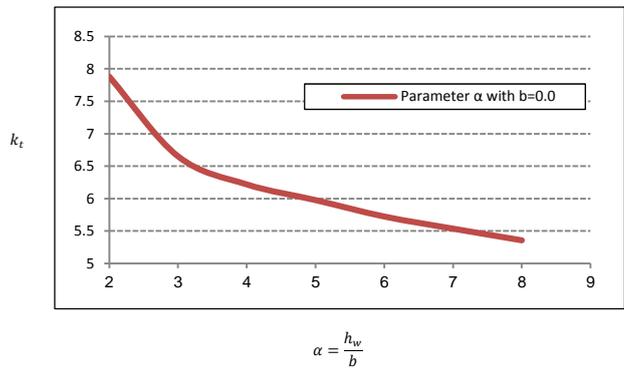


Fig. 5 Influence of α on shear buckling coefficients

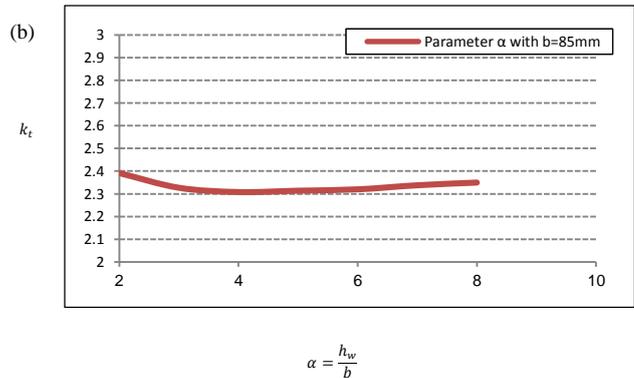
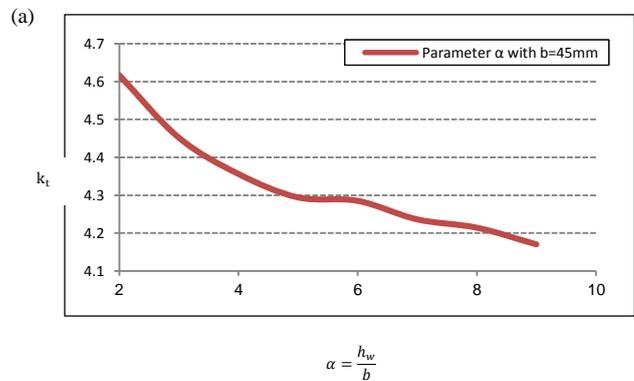


Fig. 6 Influence of $\alpha = \frac{h_w}{b}$ on shear buckling coefficients for square opening

B. Width of the flat fold (b)

Fig. (7) shows the effect of the width of a flat fold (b) on the value of shear buckling coefficient (k_t) for web dimension of ($h_w=500$ mm, $c=125$ mm, $h_r=75$ mm and $b_0=45$ mm). It can be obtained from the figure that the increase in the value of width fold (b) causes an increase in the value of shear buckling coefficient k_t .

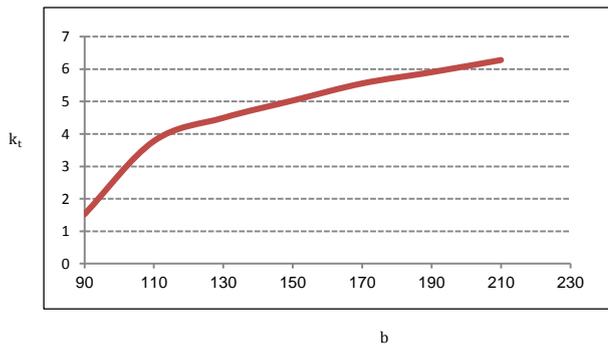


Fig. 7 Influence of the width of the flat fold on shear buckling coefficients

C. Depth of corrugation (h_r)

The relationships between the depth of corrugation (h_r) and the shear buckling coefficient (k_t) were investigated for a trapezoidal corrugated web with a central square opening of size $b_0 = 45$ mm; see Fig. (8). This investigation was made on a certain dimension of the corrugated web ($b = 125$ mm, $h_w = 500$ mm, $\alpha = 4$ and $c = 125$ mm). It can be concluded that the increase in corrugated depth causes an increase in the value of the shear buckling coefficient (k_t) until $h_r = 30$ mm. The shear buckling coefficient decreases for the depth of corrugation more than 30 mm and this decreases is high after $h_r=120$ mm.

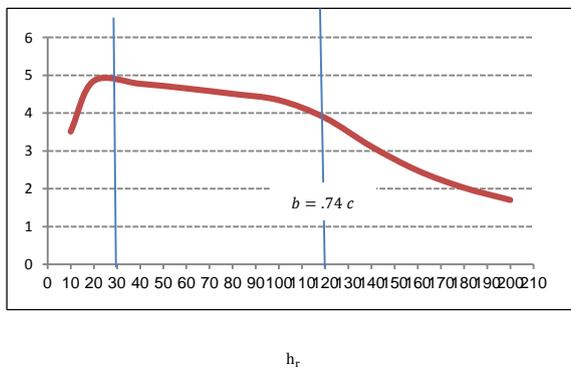


Fig. 8 Influence of depth of corrugation on shear buckling coefficient

D. Ratio between the flat fold to the inclined fold of the corrugated web (β)

Based on the FE model analysis results the influence of the ratio between the flat fold and inclined fold was studied for a corrugated web plate with height $h_w = 500$ mm, $b=125$ mm ($\alpha = 4$). Fig. (9) illustrate the relationships between the shear buckling coefficient of the corrugated web without square opening and with a square opening ($b_0 = 45$ and 85 mm) versus β -ratio. It can be noticed that in solid web the shear buckling coefficient (k_t) increases linearly with increasing β -

ratio until $\beta=1.0$. After that, the shear buckling coefficient slightly increases and then decreases. On the other hand, for the corrugated web with a square opening, the shear buckling coefficient increases linearly with increasing β -ratio until the value of $\beta=0.85$ and then the increases may be neglected.

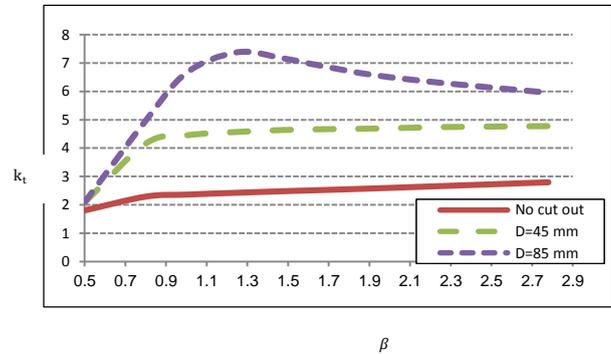


Fig. 9 Influence of β on shear buckling coefficient

E. Eccentricity of square opening

Fig. (10) shows the variables e_x and e_z where e_x is horizontal eccentricity of square opening and e_z is vertical eccentricity of square opening. The influence of the horizontal eccentricity e_x on the shear buckling coefficient was investigated on the corrugated web with square opening with the size of $b_0=20, 45$ and 90 mm; plotted in Fig. (11). In this section a certain dimension of the corrugated web was used; ($b = 125$ mm, $c = 125$ and $h_r = 75$ mm). From Fig. (11) it can be observed that the shear buckling coefficient is nearly constant for all values of horizontal eccentricity in the case of the small opening. While in big opening small changes are observed in the values of k_t . Also, the influence of the vertical eccentricity (e_z) on the shear buckling coefficient is shown in Fig. (12) for the corrugated web with $\beta = 1$ where $b = 125$ mm and $h_r = 75$ mm. It can be concluded that there no effect of changing the vertical eccentricity on the value of the shear buckling coefficient.

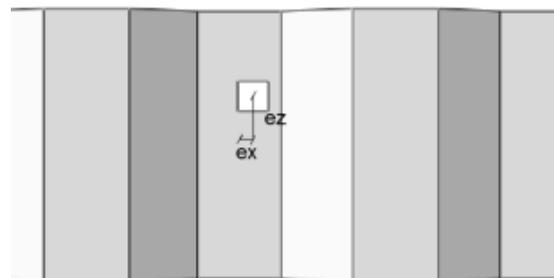


Fig. 10 Description of the variable e_x and e_z

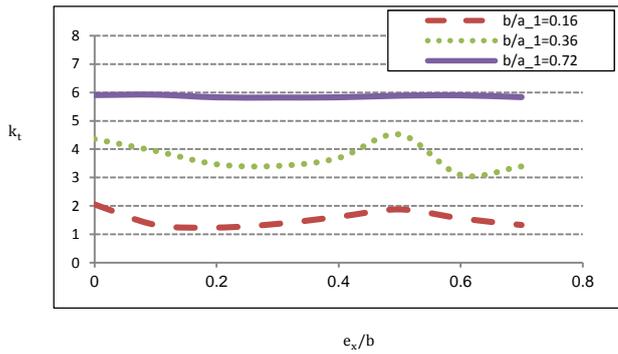


Fig. 11 Influence of e_x on shear buckling coefficient

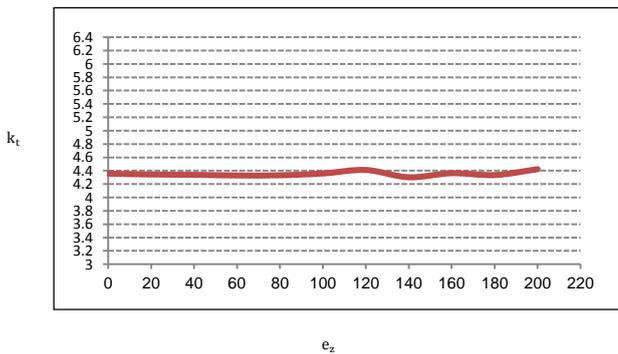


Fig. 12 Influence of e_z on shear buckling coefficient

F. Size of square opening

Fig. (13) shows the effect of the size of the central square opening on the shear buckling coefficient for the corrugated web with a dimension of ($b = 500$ mm, $c = 125$ mm, $h_r = 75$ mm, and $h_w = 500$ mm). It can be noticed that increasing the size of the square opening causes decreases in the values of the shear buckling coefficient. The relationships between the shear buckling coefficient and the ratio of b_0/b may be given by an approximate equation as following.

$$k_t(\delta) = 3(\delta)^2 - 7.8(\delta) + 6.2 \quad (8)$$

where $\delta = b_0/b$

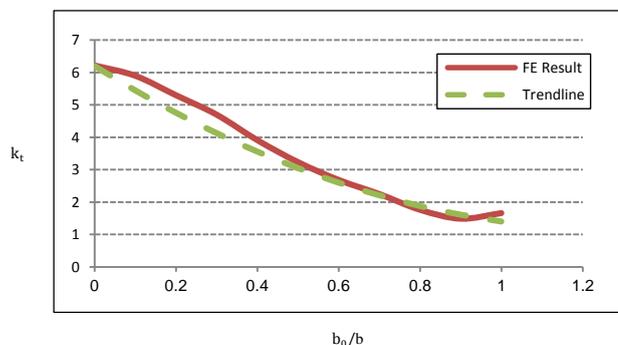


Fig. 13 Influence of opening on the shear buckling coefficient

IV. RESULTS AND DISCUSSION

The study presented in this paper had covered an investigation on the shear buckling behavior of trapezoidal corrugated web with square opening. A general-purpose FE model was determined for several heights of the web and a wide range of the horizontal eccentricity of the square opening. About section (IV.E), it can be noticed that the effect of horizontal eccentricity may be accounted for in consideration for calculating the shear buckling coefficient of steel corrugated web with a square opening. Moreover, it can be seen that the vertical eccentricity of square opening did not influence the obtained shear buckling coefficient (k_t). The influence of the size of the square opening on the shear buckling coefficient for central opening ($e_x = 0$) taking the account of several values of α -ratios is shown in Fig. (14). It can be seen that the shear buckling coefficient decreases with increasing the size of opening until the values of ($\frac{b_0}{b} = 0.85$) then the value is increased. The increase in the shear buckling coefficient is probably not caused by problems in the results of the FE model because using small elements shows the same results as the original model.

The better buckling behavior could be caused by a more favorable shear buckling mode. Fig. (15) shows the shear buckling modes of the corrugated web with a central square opening with small and big sizes. It can be seen that the shear buckling mechanism of the web with a big opening does not give a favorable mode of failure. However, the shear buckling behavior of the web with a big size opening is only seen for the central square opening. It can be recommended to avoid using a very big square opening located in the center point of the flat fold. Fig. (16) shows corrected curves of shear buckling coefficient for central square opening with big size.

Fig. (17) shows that it is not useful to generate different diagrams with many values of α -ratios for different horizontal eccentricity (e_x). For this reason Fig. (18) to Fig. (21) took the α -ratios equal to 4.0, 6.0, 8.0, and 10.0, respectively. For every α -ratio, 14 curves were given to take the horizontal eccentricity of the square opening into account. It can see that smaller horizontal eccentricity leads to a high buckling coefficient, the opposite is true. With the help of previously proposed curves, it can be recommended to use the diagrams described in Fig. (22) for obtaining the shear buckling coefficient used in the shear strength of steel trapezoidal corrugated web with square opening. On the other hand, in the case of ($\alpha < 4$), the shear buckling coefficient can be determined according to a corrugated web without opening.

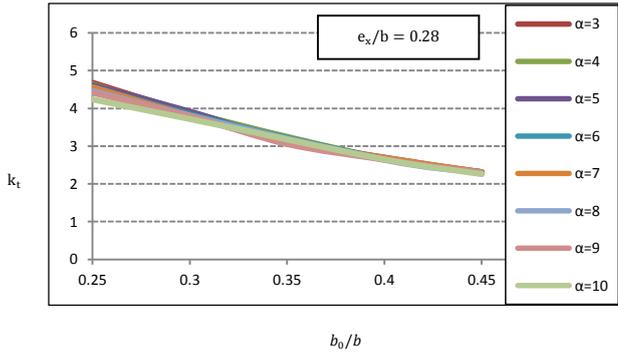
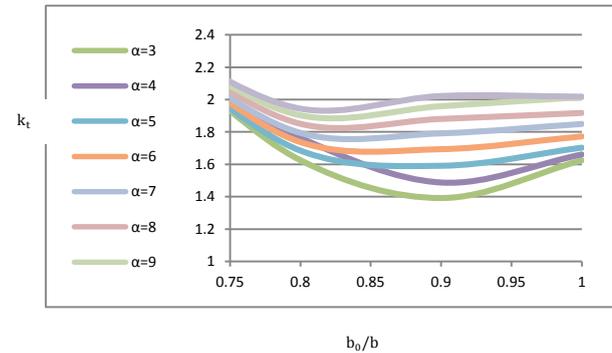
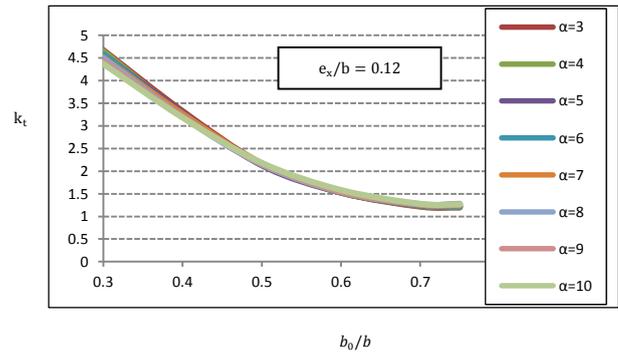
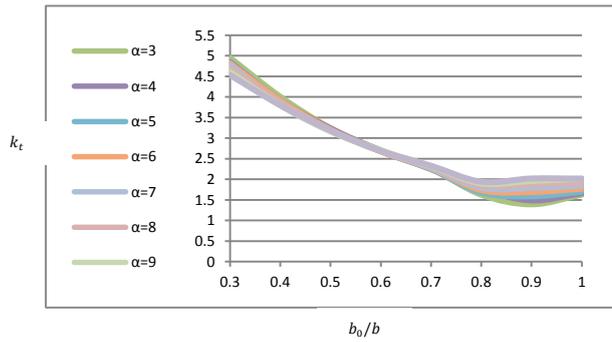


Fig. 14 Influence of b_0/b on the shear buckling coefficient for center opening ($e_x = 0$).

Fig. 17 Influence of b_0/b on shear buckling coefficient for $e_x/b = 0.12$ and $e_x/b = 0.28$

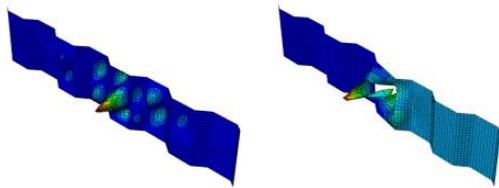


Fig. 15 Failure modes of central cutouts with small (left) and big diameter (right)

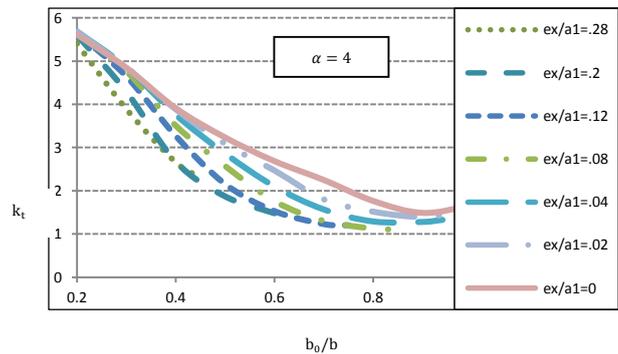


Fig. 18 Shear buckling coefficients for $\alpha=4$

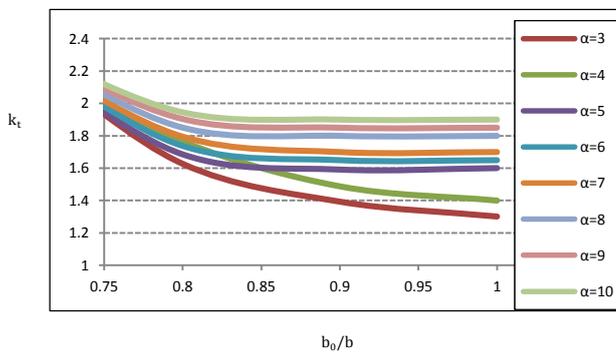


Fig. 16 Corrected shear buckling coefficients for central opening with big dimension (without rising near $b_0 = b$)

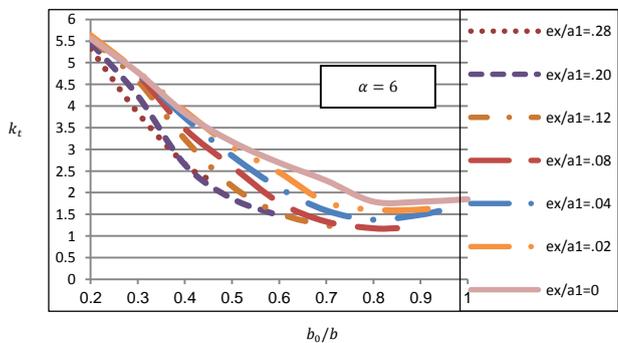
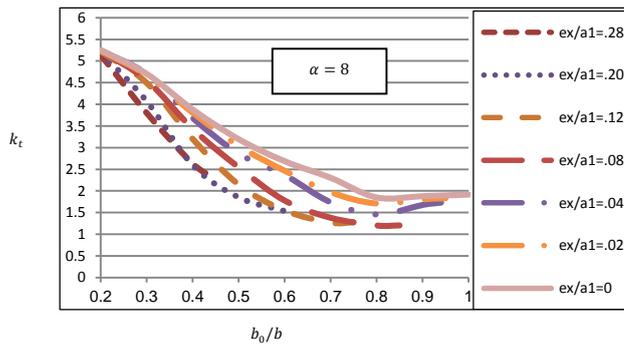
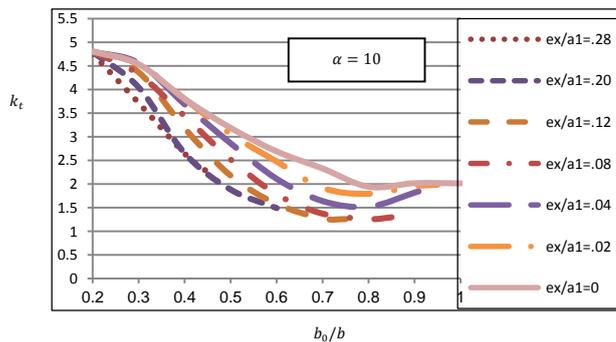
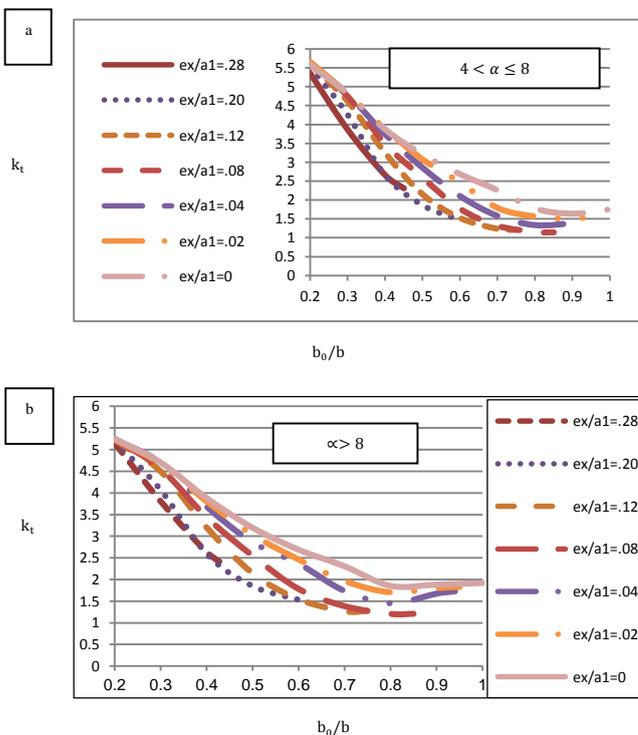


Fig. 19 Shear buckling coefficients for $\alpha=6$

Fig. 20 Shear buckling coefficients for $\alpha=8$ Fig. 21 Shear buckling coefficients for $\alpha=10$ Fig. 22 Shear buckling coefficients for $4 < \alpha \leq 8$ and $\alpha > 8$

V. CONCLUSIONS

In the current paper, elastic bifurcation buckling analysis

was carried out on a corrugated web with a square opening. Based on the current FE results using ABAQUS, the following points were obtained:

- For the solid web plate, the increase in the height of the web plate leads to a decrease in the shear buckling coefficient k_t value. On the other hand, for a small opening, the increase of the height of the web plate leads to clear decreases in the shear buckling coefficient value compare to the big square opening where this change may be neglected.
- The increase in the value of width fold (b) causes an increase in the value of shear buckling coefficient k_t .
- The increasing in corrugated depth causes an increase in the value of the shear buckling coefficient (k_t) until $h_r = 30\text{mm}$. The shear buckling coefficient decreases for the depth of corrugation more than 30mm and this decreases is high after $h_r=120\text{mm}$.
- In solid web, the shear buckling coefficient (k_t) increases linearly with increasing β -ratio until $\beta=1.0$. After that, the shear buckling coefficient slightly increases and then decreases. On the other hand, for the corrugated web with a square opening, the shear buckling coefficient increases linearly with increasing β -ratio until the value of $\beta=0.85$ and then the increases may be neglected.
- The shear buckling coefficient is nearly constant for all values of horizontal eccentricity in the case of the small opening. While in big opening small changes are observed in the values of k_t . On the other hand, it was found that there is no effect of changing the vertical eccentricity on the values of the shear buckling coefficient.
- The increase in the size of the square opening causes decreases in the values of the shear buckling coefficient. It was proposed an approximate equation between the shear buckling coefficient and the ratio of b_0/b .
- Design curves were proposed to obtain the shear buckling coefficient for $4 < \alpha \leq 8$ and $\alpha > 8$ with different values of horizontal eccentricity. For ($\alpha < 4$) it was recommended to determine the shear buckling coefficient according to a corrugated web without opening.

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