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FLANGE COMPACTNESS EFFECTS ON THE BEHAVIOR OF STEEL BEAMS WITH CORRUGATED WEBS

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ABSTRACT– *In this paper, the effects of the flange compactness on the behavior of steel beams with corrugated webs are experimentally and analytically studied. The experimental program consists of four simply supported beams with different web configurations (Flat or Corrugated) and different flange compactness (non-compact or compact). Nonlinear finite element technique was used to model the tested specimens and to carry out the parametric study. The variables of the parametric study were the thickness and the width of the flange transversal stiffeners (FTS), and the flange thickness (FT). The results obtained from the finite element were compared with the corresponding experimental ones that show a reasonable degree of accuracy. Finally, comparison between beams with corrugated webs and those with flat webs was carried to exhibit the advantages and disadvantages of using web corrugation. The results indicate that; the flange transversal stiffeners enhances the beam yield load by 21% and the flange thickness can increase the yield load by 56%, where if both of them are used (FTS and FT) the beam yield load can achieved 72% more than beam without these enhancement.*

KEYWORDS: *Uniform moment – Simply Supported Beam – Corrugated webs – Nonlinear Finite Element Analysis – Flange compactness*

1- INTRODUCTION

The corrugated steel sheets are introduced as beam webs to allow the use of thin plates without stiffeners for use in buildings and bridges. This contributes to the reduction in the beam weight and fabrication cost. **Figure 1** shows the trapezoidal corrugated sheets, which will be used in this study. This configuration is the most common one used as beam web in the majority of previous works. In this study, four simply supported beams were tested experimentally, two of them have flat webs and the rest have corrugated webs. One of the flat web beams has non-compact flange with C/t_f ratio of 12.5, and the other beam has a compact flange with C/t_f ratio of 5. For the second type of beams, the flange restrained by corrugated web, it is evident that there are different values of the outstanding in both side of web, this leads to that the maximum outstand may govern the buckling behavior of compression flange consequently will govern the C/t_f ratio. Finite element model is developed and a nonlinear analysis was performed using COSMOS (2000) program package [2]. The results obtained are compared with the results of experimental work results and gave a reasonable accuracy. This model is used to conduct an analytical investigation that will study the effect of using different flange thickness and flange transversal stiffeners with different width and thickness. A comparison between the behavior of non-compact beams with flat webs and beams with corrugated webs are made before and after enhanced the flanges of the corrugated webs beams by increasing FT or adding FTS.

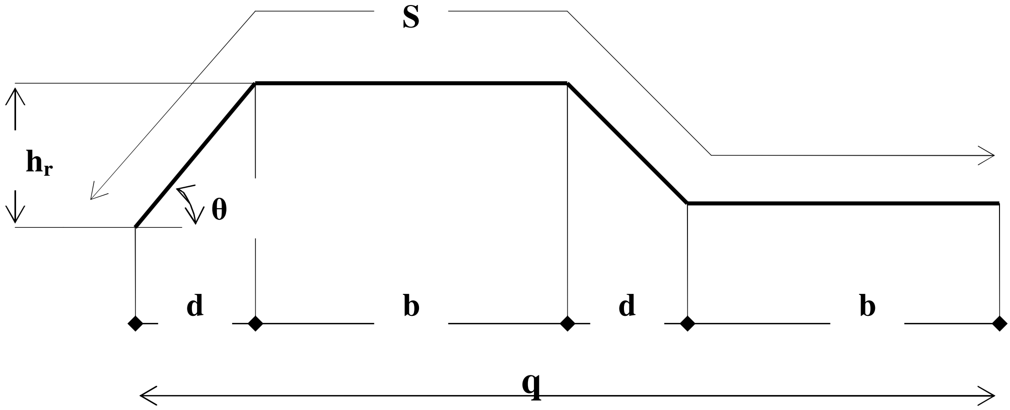

Fig. 1: Configuration of one Profile.

2- BACKGROUND AND PREVIOUS WORK

Abbas [1] studied the influence of shear, bending and fatigue on corrugated steel beams using High Performance Steel as the most recently research concerned with corrugated web beams. Results from his study, showed that flange transverse bending must be taken into consideration. It was also found that, the shear capacity could be sensitive to initial imperfection and finally he suggested a formula for global shear calculation. Recently, several experimental and finite element tests were carried out by Kalid and Chan [10]. Their models include vertical and horizontal waves of web corrugations. Results showed that, the vertical corrugation type of web stand the highest uniform moment. It was also found that, the vertical channel type of corrugation could stand the highest bending load (concentrated load). Elgally [4, 5] studied the behavior of corrugated web beams with hollow flange under different types of loads.

3- TEST SPECIMENS

Four specimens were tested at the heavy structures lab, Faculty of Engineering, Tanta University. The component plates were cut from larger plates by burning them mechanically (oxygen cut), so that the direction of applied stress was parallel to the direction of rolling. The flange plates were welded to the web plate using two side fillet weld, while these plates, flange and web plates, were welded to the end plates using groove welds. A convex fillet welds are made between plate surfaces at right angel forming built up sections. The size of weld for connecting built up section and end connecting plates is taken according to the Egyptian Code of Practice for Steel Construction and Bridges No. 205. Careful procedures of welding were followed to avoid distortion of the girder result from the high temperature from welding process especially for slender parts. To determine the mechanical properties of the steel, three standard tension coupons were cut from each specimen; one from the compression flange, one from tension flange and one from the web. The coupons were cut as far as possible from the flame cut side and machined to the nearest 0.01mm.

The coupons were prepared and tested according to the Egyptians Standard Codes No 76 for Tensile Test of Metals, having a gauge length of 160 mm (including embedded distance of each jaw of the testing machine). The tension coupons were tested in a 300 kN capacity displacement controlled testing machine using friction grips to apply the loading. The stress strain curve was obtained and plotted as shown in **Fig. 2**. The results such as Modulus of Elasticity, Elongation percentage, Ultimate and Yield stresses obtained from these tests are listed in **Table 1.** The tested ***Beams*** have 185 cm approximate length with an effective span of 175 cm. The beams consist of two stiffened panels and central slender panel. As can be noted from **Fig. 3**, only the central panel is subjected to pure bending moment. The panels adjacent the supports were made of 10 mm flat web and 14 mm flange plates and stiffened in the middle to ensure that failure will occur in the central panel due to bending. The central test panel was made either flat web panel or corrugated web panel, a brief description for each case of beams configurations may be as follows.

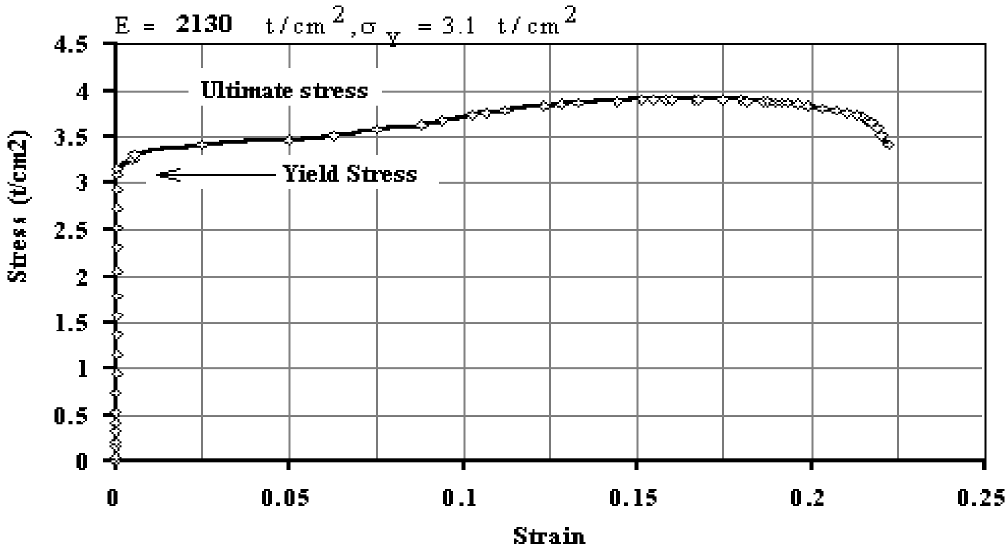

Fig. 2: Typical Stress strain curve of a tested coupon.

Table 1: Modulus of Elasticity, Elongation percentage, Ultimate and Yield stresses .

Coupon Type	F_Y (t/cm^2)	F_u (t/cm^2)	E (t/cm^2)	δ %
Compact Flange	3	3.75	2000	28
Non-compact Flange	3.2	3.9	2130	25
Web	3.1	3.9	2050	24

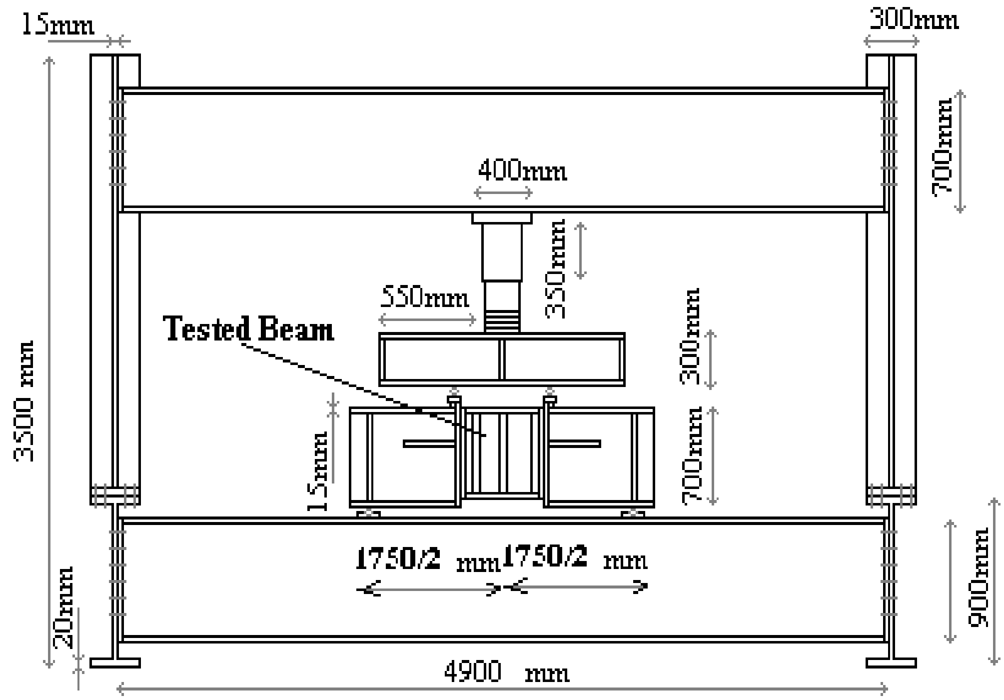

Fig. 3: Test setup.

3-1 Beams With Flat Webs

The two flat web beams studied experimentally had 10 cm flange plates width while the flange thickness varied from one specimen to another. The flanges thickness was 0.4 cm in the first beam and 1cm in the second beam; where the C/t_f ratios were 12.5 (Non-compact) and 5 (Compact), respectively. Also, the web height of these specimens was 40cm and the thickness was 0.21 cm which equivalent to h/t_w ratio equals 200 (slenderness) as indicated in **Table 2.**

3-2 Beams With Corrugated Web

The tested beams with corrugated webs had 10 cm flange plates width, while the flange thickness varied from one specimen to another. The flange thickness was 0.4 cm in the first beam and 1cm in the second one, which equivalent to C/t_f ratio of 18.75 (Slenderness) in the first beam and 7.5 (Compact) in the second beam. Also, the web height of these specimens was 40 cm and the thickness was 0.21 cm which equivalent to h/t_w ratio of 200 (slenderness). The web profile used for each beam has a length **q** equal to 30 cm in the horizontal projection (i.e. **b** = 10 cm & **d** = 5 cm& $\theta = 45°$) as illustrated in **Fig.1**. From previous, the specified dimensions and the slenderness ratios of the component plates of the specimens are classified according to the Egyptian Code of Practice for Steel Construction and Bridges“, No. 205 which are listed in **Tables 2** and **3.**

Table 2: Average dimensions of cross-section.

Average dimension of cross Sections and width-to-thickness ratios of specimens						
Specimen	h (cm)	t_w (cm)	b_f (cm)	t_f (cm)	h/t_w	C/t_f
1 (F.W)	40	0.21	10	0.4	200	12.5
2(F.W.)	40	0.21	10	1.0	200	5
3 (C.W.)	40	0.21	10	0.4	200	18.75
4 (C.W.)	40	0.21	10	1.0	200	7.5

Table 3: Comparison between the experimental and theoretical results.

Load (ton)								
F.W. exp.	Theor. Comparsion of yield load of C.W. beam and Non-Compact Flange							
	Exp.	Theo.	t_{st} =0.2 & C/t_f= 18.75			t_f		
			Stiffener width			0.4 cm	0.5 cm	0.6 cm
			b_{st} = 0.25 b_f	b_{st} = 0.5 b_f	b_{st} = 0.75 b_f	C/t_f=18.75	C/t_f= 15	C/t_f= 12.5
11	10	9.7	9.76 0.62%	10.1 4.12%	10.15 4.64%	9.7 0.00%	12.57 29.59%	15.2 56.70%
			t_{st} =0.4 & C/t_f= 18.75					
			Stiffener width					
			b_{st} = 0.25 b_f	b_{st} = 0.5 b_f	b_{st} = 0.75 b_f			
			10.8 11.34%	11.4 17.53%	11.76 21.24%			

3-3 Test Loads

In Tanta University, faculty of engineering, laboratory of heavy equipments tests, the specimens were loaded in 1000 kN capacity testing machine which attached to a computer control system. The load was applied to the specimens as two equal concentrated loads across the top flange over the intermediate stiffeners at approximately the third points of the span by using the rollers, as shown in **Fig. 3**.

3-4 Test Results

Figure 4 shows the specimens of beams with F.W. or C.W. and with non-compact or compact flanges under test and after failure. The corrugated web beam with non-compact flange, **Fig. (4-c),** shows a flange local buckling in the maximum outstands in earlier stage of loading. Where the flat web beam, **Fig. (4-d),** shows a flange buckling followed by web crippling. Finally, in case of compact flange is used the buckling occurred in both cases (F.W. or C.W.) in the web panel and at higher stage of test load as shown in **Fig. (4g & 4i)**.

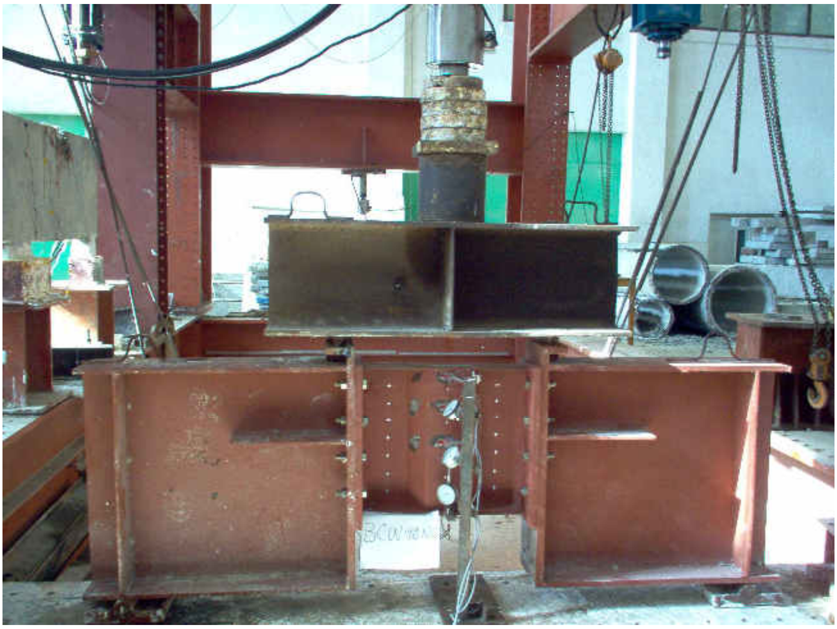

Fig. 4a: N.CF. C.W. under test.

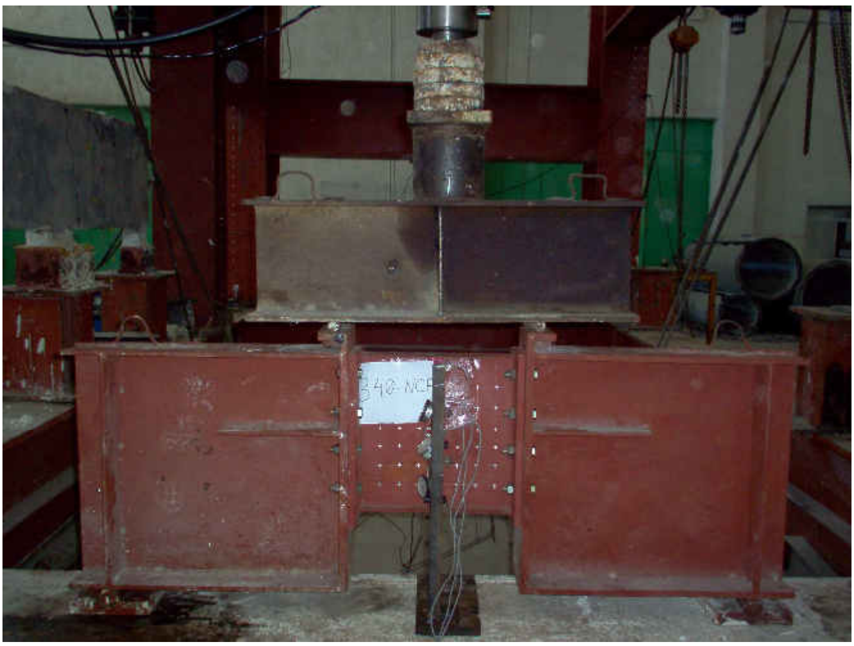

Fig. 4b: N.CF. F.W. under test.

Fig. 4c: N.CF. C.W. specimen after failure.

Fig. 4d: N.CF. F.W. specimen after failure.

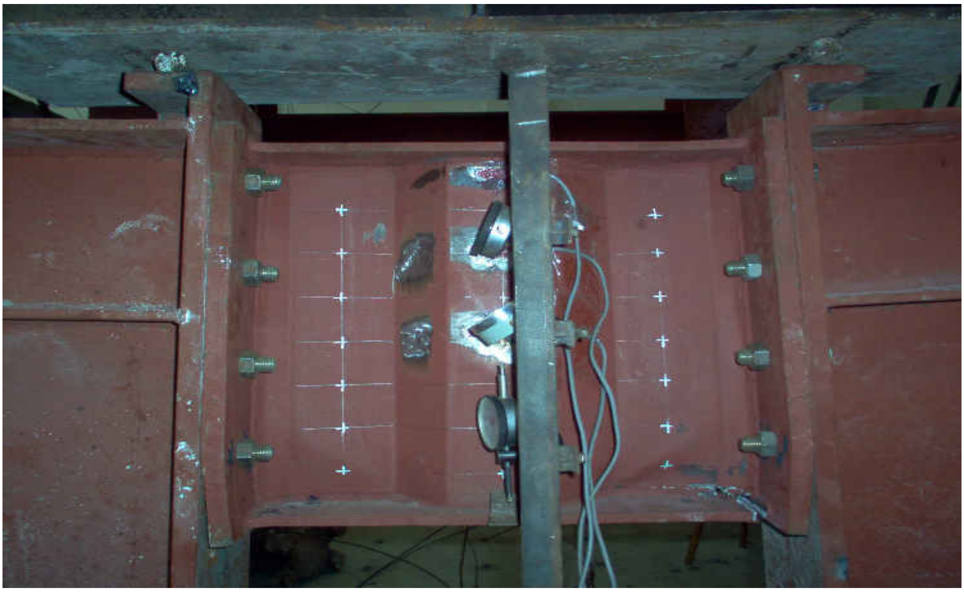

Fig. 4f: C.F. C.W. under test.

Fig. 4g: C.F. F.W. specimen after failure.

Fig. 4h: Comparison F.W.& C.W. with NCF.

Fig. 4i: Comparison F.W.& C.W. with C.F.

4- FINITE ELEMENT MODEL

The finite element program COSMOS/M (2000) [2] was used to perform parametrical studies and investigate the effect of flange compactness and transversal stiffeners on yield load of beam with corrugated webs. The cross sections of the beams were built up with four-node thick shell elements; each node has six degree of freedom to model the flanges, web and stiffeners. The thick shell element can capture the essential features of bending and membrane stresses of the beams and gives all buckling modes whether global or local. Common nodes between flanges, web and stiffeners are merged together to perform rigid connections at these nodes. As shown in **Fig. 5** only one half of the girder was modeled using the advantage of the symmetry about the mid-span section. Three degrees of freedom were restrained for all nodes at that section, the translations in the longitudinal direction Z (Uz=0) and the rotations about both X and Y axes (Rotx=0 and Roty=0). The translation in the Y direction was restrained along a line at the end support section to simulate the vertical support of the girder. Finally, the applied loads are simulate by a serial of point loads on nodes above the end connecting plate.

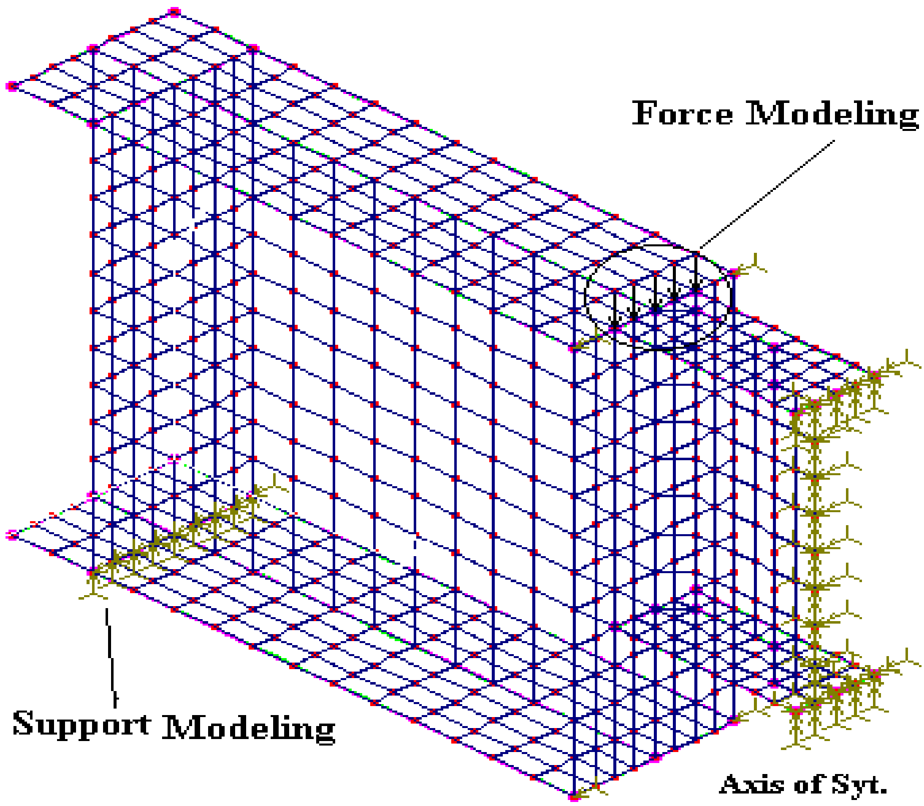

Fig. 5: Beams Boundary Conditions and Global axes directions.

4-1 Validation Of COSMOS Simulations

Under two concentrated loads, pilot runs have been performed for two simply supported beams with corrugated webs and having the same span and flange dimensions of the two beams with corrugated webs studied experimentally. **Figures 7** and **8** show comparisons between experimental results of non-compact and compact flanged beams with flat or corrugated web, respectively. The vertical deflection of the central point of bottom flange has been plotted against vertical load applied as mentioned in **Table 2** and shown in **Figures 9** and **10**. **Figure 9** shows the results of experimental works versus analytical model in case of beam with non-compact flange, where, **Fig. 10** shows the case if compact flange used. The results were found to be in good agreement which indicated the validity of the method of modeling and solving beams with corrugated webs and it were taken as a datum for studying the effect of each variable on beam capacity. The same models are analyzed under the effect of flange transversal stiffeners and thickness in the behavior of corrugated web beams up to failure as will be discussed in the upcoming sections.

5- PARAMETRIC STUDIES AND RESULTS

The proposed investigation embraced a range of parameters that influence the compression flange buckling which including the flange restrains and the flange thickness. To investigate the effect of these parameters, the corrugated web beam with slenderness flange model has been solved with different combinations of values for these parameters. The values of such parameters in each model are given in **Table 2**. Comparisons between critical yielding load for corrugated web beam with non compact flange after and before the effect of these parameters are listed in **Tables 3, 4** and plotted from **Fig. 11** to **Fig. 18**. These results will be discussed individually in the following sections.

5-1 Effect Of Flange Transversal Stiffeners Width

The stiffeners are positioned in the maximum outstand width as shown in **Fig. 6.** In **Fig. 11** load deflection relationships between beam with and without flange transversal stiffeners are shown. These stiffeners have thickness equal to web thickness and variable width ranged from 0.25 to 0.75 of the flange width. From that figure it can be seen that, the deflection load curves where the stiffeners width (b_{st}=0.25b_f) equal 0.25 of flange width has no great effect and the percentage of increase which can be reached is 0.62% as stated in **Table 3**. Also, it can be noticed that when the stiffeners with thickness equal web thickness and width varied from 0.5 to 0.75 of flange width the percentage of increase in beam yield load can varied from 4.12% to 4.64%, respectively as mentioned in **Table 3. Figure 12** shows load deflection relationships between beam with and without flange transversal stiffeners which have variable width and thickness equal to flange thickness. From that figure it can be seen that, the beam yield load increased by 11.34%, 17.53% and 21.24% when the stiffeners widths are 0.25, 0.5 and 0.75 from flange width, respectively.

5-2 Effect Of Flange Thickness

The flange thickness is varied from 0.40 cm to 0.60 cm and the equivalent C/t_f values varied from 18.75 to 12.5, respectively. In **Fig. 13** a comparison between beam with C/t_f = 18.75 and beam with a flange slenderness ratio varied from C/t_f =15 and C/t_f = 12.5 load deflection relationships is illustrated. From that figure it can be noticed that when the beam flange has slenderness ratio 18.75 (slender flange) the beam capacity is less than beam with flat web by 12%, where if the flange slenderness ratio equal to 15 (slenderness flange) the beam capacity increased by 14%, and finally if the slenderness ratio equal 12.5 (non-compact flange) the same as flat web beam the beam capacity increased by 38% as shown in **Fig. 14**.

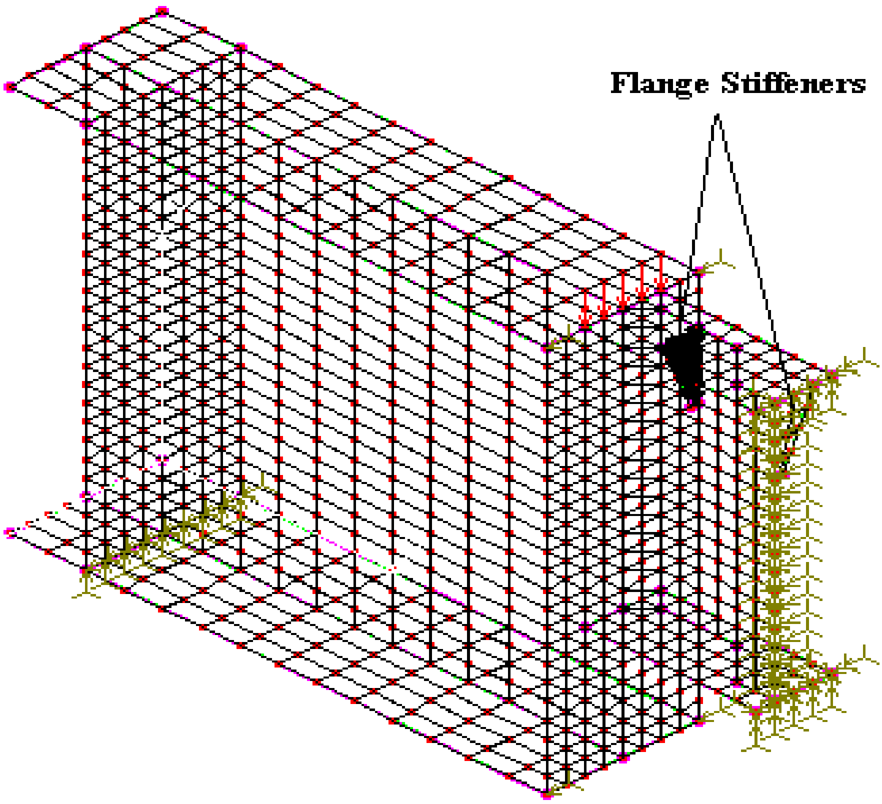

Fig. 6: Flange transversal stiffeners.

5-3 Effect Of Both Flange Stiffeners And Thickness

In this part of study, the two enhancement of flange stiffness stated above are performed together as follows, flange transversal stiffeners with thickness equal flange thickness and width varied from 0.25 to 0.5 of flange width are used while the flange thickness are varied from 0.50 cm to 0.60 cm and the equivalent C/t_f values varied from 15 to 12.5 respectively. **Figure 15** compares load deflection relationships between beam flange with ((b_{st}=0.25b_f) & C/t_f = 15) and beam with flat web and non-compact flange with (C/t_f = 12.5). From that figure it can be noticed that, the beam capacity is increased by 39.69 % if it is compared with the same beam but non-stiffened flange, which means 10% more than the same beam but with (C/t_f = 15) and without transversal stiffeners, finally the percentage of increase from flat web beam is about 23%.

Also from the same figure and **Table 4,** it can be noticed that, if the beam flange has ((b_{st}=0.25b_f) & C/t_f = 12.5) the beam capacity is increased by 69.59 % if it is compared with the same beam but non-stiffened flange, which means 12.9% more than the same beam but with (C/t_f = 12.5) and without transversal stiffeners. Finally the percentage of increase from flat web beam is about 49.5% as illustrated in **Fig. 17**.

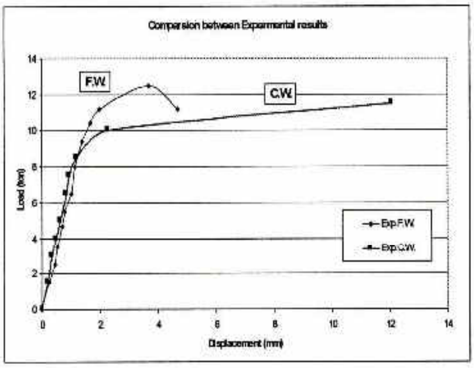

Fig. 7 Comparison between experimental results of non-compact flange beams with flat or corrugated web.

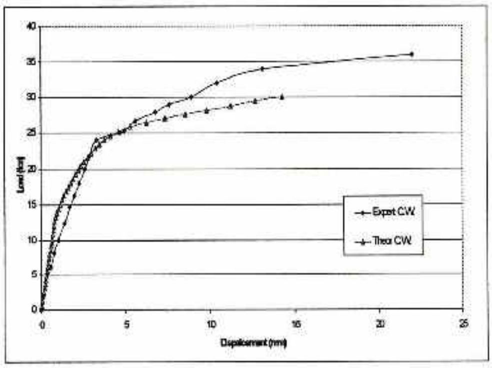

Fig.10. Comparison between experimental and theoretical results of Compact Flange beams with corrugated web.

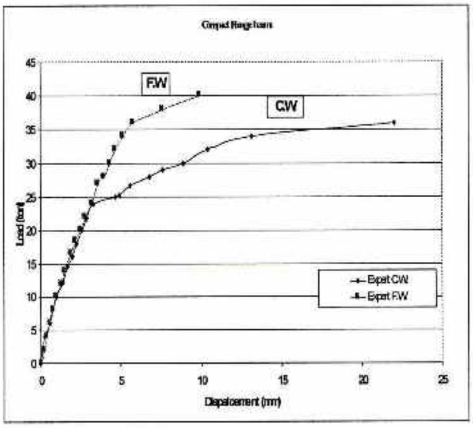

Fig. 8.Comparison between experimental results of Compact Flange beams with flat or corrugated web.

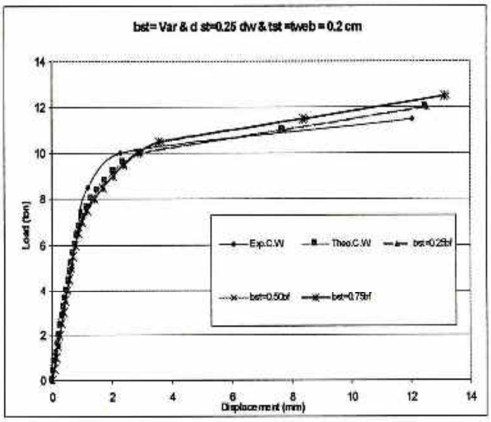

Fig.11 Effects of transversal flange stiffeners width with thickness t_{st} = 0.2 cm on beam behavior.

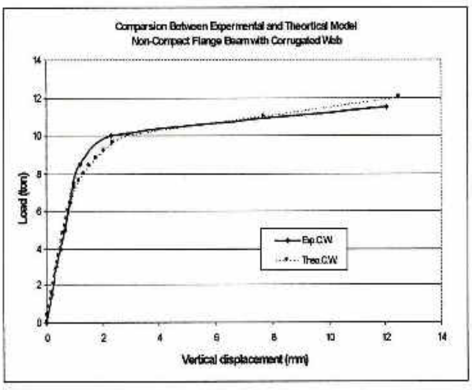

Fig.9.Comparison between experimental and theoretical results of Non-compact Flange beams with corrugated web.

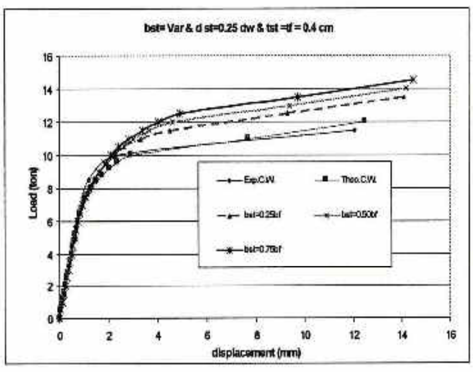

Fig.12 Effects of transversal flange stiffeners width with thickness t_{st} = 0.4 cm on beam behavior.

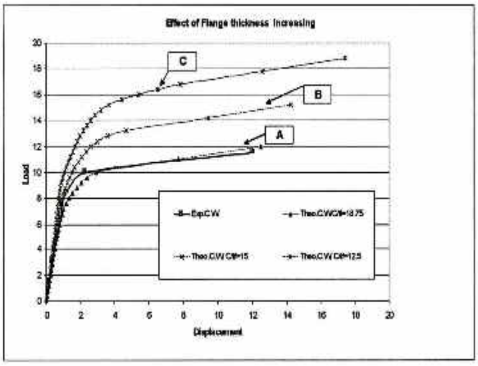

Fig. 13 Effects of flange slenderness ratio on beam behavior.

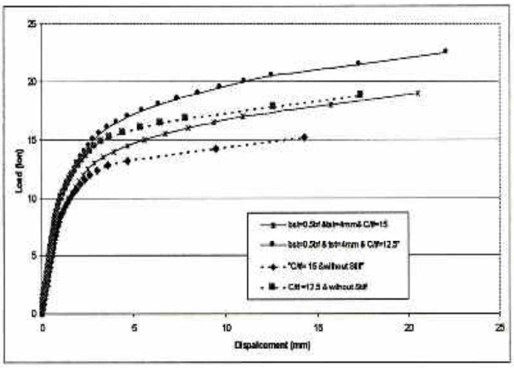

Fig. 16 Effects of transversal flange stiffeners (b_{st}=0.5b_f) on the behavior of beams with corrugated web and flange has different slenderness ratio.

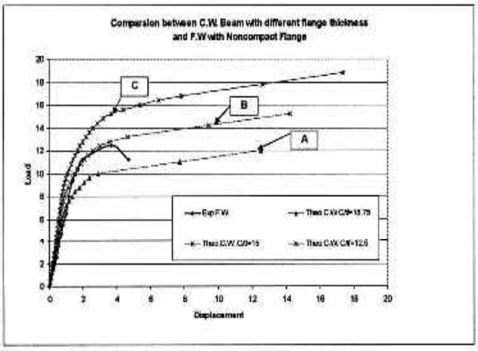

Fig. 14 Comparison between flat web beam with non-compact flange, and corrugated web beam with flange has different slenderness ratio.

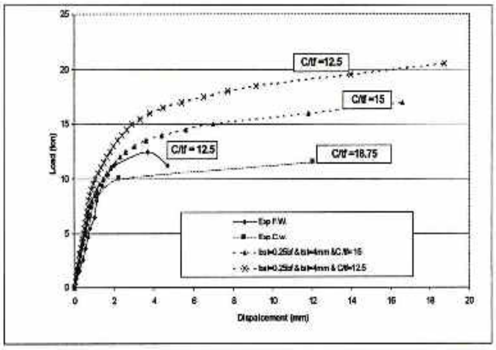

Fig. 17 Effect of both transversal flange stiffeners (b_{st}=0.25b_f) and flange thickness on the behavior of beams with corrugated web.

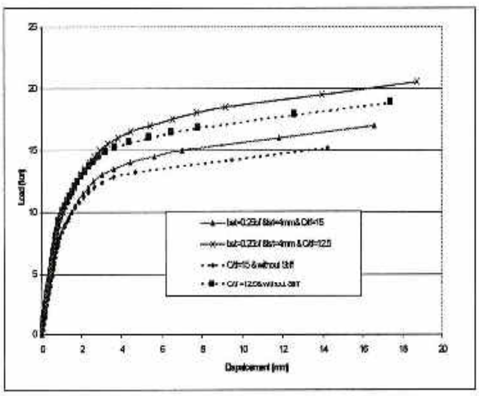

Fig. 15 Effects of transversal flange stiffeners (b_{st}=0.25b_f) on the behavior of beams with corrugated web and flange has different slenderness ratio.

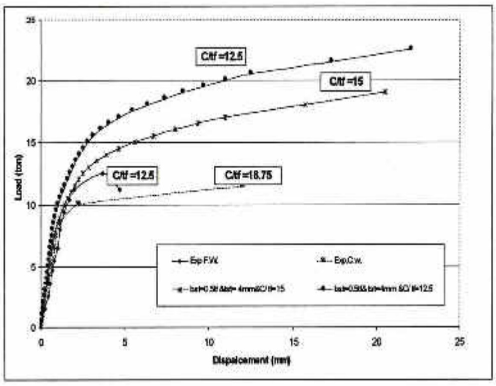

Fig. 18 Effects of transversal flange stiffeners (b_{st}=0.5b_f) together with increasing flange thickness on the behavior of beams with corrugated web.

Table 4: Effects of transversal stiffeners and flanges slenderness on beam capacity.

Theor. Comparsion of yield load of C.W. beam (ton)					
Exp.	Theo.	$b_{st}=0.25\ b_f$		$b_{st}=0.25\ b_f$	
		$t_f=0.50$ cm	$t_{st}=0.4\&\ t_f=0.5$	$t_f=0.60$ cm	$t_{st}=0.4\&\ t_f=0.6$
		without Stiff	With Stiff	without Stiff	With Stiff
10	9.7	12.57 29.59%	13.55 39.69%	15.2 56.70%	16.45 69.59%
		$b_{st}=0.5\ b_f$		$b_{st}=0.5\ b_f$	
		$t_f=0.50$ cm	$t_{st}=0.4\&\ t_f=0.5$	$t_f=0.60$ cm	$t_{st}=0.4\&\ t_f=0.6$
		without Stiff	With Stiff	without Stiff	With Stiff
		12.57 29.59%	13.87 42.99%	15.2 56.70%	16.77 72.89%

Figure 16 shows a comparison between load deflection relationships for beam flange with ((b_{st}=0.5b_f) & C/t_f = 15) and beam with flat web and non-compact flange with (C/t_f = 12.5). From that figure it can be noticed that, the beam capacity is increased by 42.99 % if it is compared with the same beam but non-stiffened flange, which means 13.4% more than the same beam but with (C/t_f = 12.5) and without transversal stiffeners, and finally the percentage of increased from flat web beam is about 26%.

Also from the same figure and **Table 4,** it can be noticed that, if the beam flange has ((b_{st}=0.5b_f) & C/t_f = 12.5) the beam capacity is increased by 72.89 % if it is compared with the same beam but non-stiffened flange, which means 16.19% more than the same beam but with (C/t_f = 12.5) and without transversal stiffeners, and finally the percentage of increased from flat web beam is about 52.5% as illustrated in **Fig. 18**.

6- SUMMARY AND CONCLUSIONS

In this investigation, four beams with different flange compactness and web configurations were studied experimentally and theoretically under the effect of bending moment. The experimental work shows that, if the beams have non-compact flanges, failure will be occurred suddenly and due to buckling in compression flanges followed by web crippling. Finite element model was performed, using COSMOS package, to simulate the behavior of such beam theoretically. The results obtained from finite element compared with the experimental ones; it was found that, it is represent the experimental results to good degree of accuracy. Parametric investigation was performed to investigate the effect of variables such that width and thickness of flange transversal stiffeners and/or flange thickness on the behavior of non-compact beam with corrugated webs. The results were collected and tabulated. Based on these results the following conclusion can be drawn:

1. When flange transversal stiffeners with thickness equal web thickness and width varied from 0.25 to 0.5 of flange width the percentage of increase in yield load more than 12%.
2. Beam yield load increased by 11.34%, 17.53% and 21.24% when the stiffeners widths are 0.25, 0.5 and 0.75 from flange width respectively.
3. The corrugated web beam with flange compactness at the lowest limit of non-compact can increase the beam capacity by 38% comparing with flat web beam has the same C/t_f value.
4. The capacity of corrugated web beams with C/t_f at the ceiling of slenderness and with flange transversal stiffeners has width b_{st} = 0.5 b_f and t_{st} = t_f will be increased by 52% if it compared with flat web beam has the same C/t_f ratio.

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SYMBOLS

The following symbols are used in this paper:

b_f	=	*Width of flange*
b_{st}	=	*Width of stiffeners*
C.W.	=	*Corrugated web*
C.F.	=	*Compact Flange*
E	=	*Young's Modulus*
F_y	=	*Yield stress*
F_u	=	*Ultimate stress*
F.W	=	*Flat Web*
H	=	*Depth of web*
N.C.F.	=	*Non compact flange*
t_f	=	*Flange thickness*
t_{st}	=	*Transversal stiffeners thickness*
t_w	=	*Web thickness*

تأثير درجة تدامج شفه الكمرات الحديدية ذات الأعصاب المعرجة على سلوكها

في هذا البحث تم عمل دراسة عملية تحليلية لتأثير درجة التدامج في شفه الكمرات الحديدية ذات الأعصاب المعرجة على سلوك تلك الكمرات حتى حمل الانهيار. حيث تم عمل تجارب عملية على مجموعتين من الكمرات المجموعة الاولى عبارة عن كمرتين ذات عصب معرج ولكن الكمرة الاولى له شفه مدمجة والثانية لها شفه غير مدمجة. أما المجموعة الثانية فلها نفس مواصفات الاولى ولكن عصب الكمرات مسطح وليس معرج. ثم تم عمل نموذج تحليلي للكمرات باستخدام طريقة العناصر المحددة للوصول إلى نموذج تحليلي يعطى نتائج تمثل لدرجه قريبه من العملي. ثم تم إجراء دراسة على المتغيرات التي يمكن ان تؤثر على سلوك الكمرات ذات الأعصاب المعرجة وذات شفه غير مدمجه وشملت هذه المتغيرات سمك الشفة وسمك وعرض الدعمات أسفل الشفة ثم الاثنين معا (زيادة السمك ووضع الدعمات). وقد أظهرت النتائج التأثير الكبير لسلوك الكمرات وزيادة فاعليتها باستخدام اى من الحالتين السابقتين أو استخدامهما معا لكي تعطى نتائج تزيد من 20% إلى 70% عن حمل الخضوع بدون تلك الدعمات وزيادة سمك الشفة.