The Effect of Web Corrugation Angle on Bending Performance of Triangular Web Profile Steel Beam Section

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***Abstract*–The structural action of a beam is predominantly bending, with other effects such as shear, bearing and buckling also being presented. Due to the more application of corrugated section in steel design, this paper develops a three-dimensional finite element model using LUSAS 14.3 to investigate the effects of web corrugation angle on bending behavior of Triangular Web Profile (*$T_{RI}WP$*) steel sections. A triangular web profile (*$T_{RI}WP$*) steel section is a built-up steel section made up of two flanges connected to a web plate of triangular profile. Thin shell element was chosen to represent the element type of the model. Two sizes of flat webs (FW) as control specimens and two sizes of *$T_{RI}WP$* which are 200×100×6×3 mm and 180×75×5×2 mm section were used. Each of beam section was modeled using several spans such as 3 m, 4 m and 4.8 m and different corrugation angles (15^0,30^0,45^0,60^0 and 75^0). It was noted that deflection of 45^0 and 75^0 web corrugations angle be the lowest deflection value either in minor or major axis of *$T_{RI}WP$* steel section. It means that the *$T_{RI}WP$* steel section is stiffer when the web corrugation angle is 45^0 or 75^0. In other word, *$T_{RI}WP$* steel section has a higher resistance to bending in minor and major axis when the web is used in both corrugation angles.**

Keywords-Finite Element Model; Bending; Triangular Web Profile

I. INTRODUCTION

The early studies have been done by Elgaaly which are focused on the vertically trapezoidal corrugation. It was found that the failure of beams under shear loading is due to local buckling on the web for coarse corrugation and global buckling on the web for dense corrugation [1]. They also found that the contribution of the web profile could be neglected in the calculation of the second moment of area of the TWP section, due to its insignificant contribution towards the beam load-carrying capability [2]. However, it was found that the web might have a contribution towards increasing the second moment of area, Atan [3] and Tan [4]. Later, Jamali [13] investigated on the torsional properties, that is torsional constant and warping constant that could influence the lateral torsion capacity of trapezoid web profile section. She also performed lateral torsional buckling tests on two beams with normal flat web and two beams with trapezoid web profile. The experimental results of both tests indicated a greater resistance in lateral buckling provided by beams with trapezoid web profile. In 2008, De'nan [5] presented the result of an experimental and finite element analysis investigation to find the value of second moment of area on the minor and major axes for a TWP section and she found that the TWP section has a higher stiffness in minor axis and has lower stiffness in major axis compared to the flat web steel section. While, under compressive patch loads, the failure were dependent on the loading position and corrugation parameters where it can be a combination of the aforementioned modes [6]. Besides that, the two distinct modes of failure under the effect of patch loading were dependent on the loading position and the corrugation parameters was investigated by Johnson and Cafolla [7, 8] and were further discussed in their writings. While, Luo and Edlund [9, 10] addressed the differences in results between experimental and analytical analyses, was due to a consideration adopted in modeling. The ability of a wholly corrugated web (WCW) H-beam to resist buckling have been studied quantitatively by Zhang, Li, Zhou and Widera [11, 12] which involves the influence of the corrugation parameters and developed a set of optimized parameters for the wholly corrugated web beams (WCW) based on the basic optimization on the plane web beams.

Therefore, a new type of steel section namely triangular web profile (*$T_{RI}WP$*) has been studied in this paper to know the significant effect to bending strength. The objective of this paper is to present the results of finite element analysis investigation to know the effects of web corrugation angle on bending behavior in minor and major axes for a *$T_{RI}WP$* steel section (see Fig. 1).

When a point load, *P*, is applied at the mid span of a simply supported beam, the maximum deflection, δ_{max} for elastic condition, of the span can be calculated as:

$$\delta_{max} = \frac{PL^3}{48EI} \tag{1}$$

Where,

I = Second moment of area

E = Elastic modulus of steel

P = Applied point load

δ = Vertical deflection at mid span

L = Span of beam

A linear relationship between the load (P) versus deflection (δ) graph will represent the value of constant containing I. Since the length (L) and Young Modulus (E) for all models are known, the I value for the $T_{RI}WP$ steel section can be obtained from the slope of $P\!-\!\delta$ plot obtained from finite element analysis investigation. Thus, if finite element analysis for the $T_{RI}WP$ and FW steel sections are performed, the second moment of area, I, for a $T_{RI}WP$ steel section about any axis can be determined provided the second moment of area, I, of FW section of that axis is known, using equation 2. The values of the flexural stiffness (P/δ) for the corrugated steel section such as trapezoidal web profile and FW steel sections can be obtained from the $P\!-\!\delta$ graphs plotted from appropriate bending analysis De'nan [5].

$$I_{TWP} = \frac{\left(\frac{P}{\delta}\right)_{TRIWP}}{\left(\frac{P}{\delta}\right)_{FW}} \times I_{FW} \qquad (2)$$

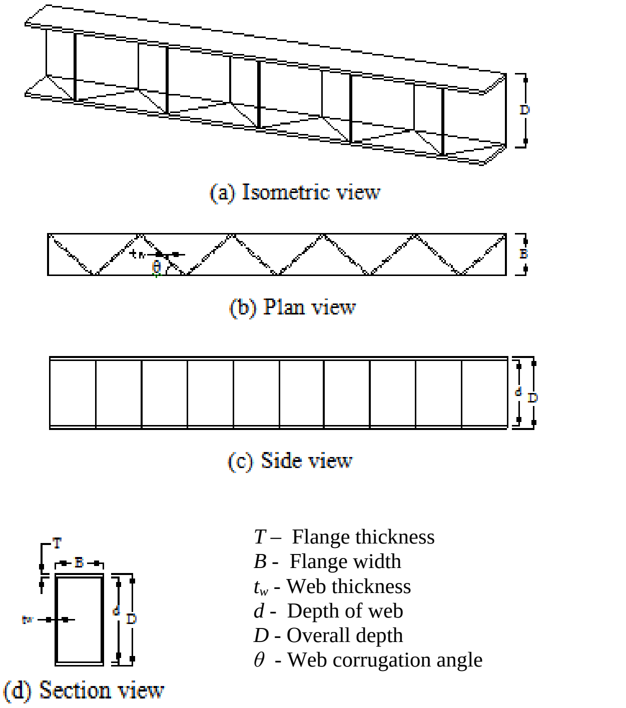
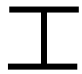
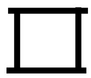
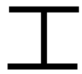
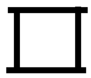


Figure 1 Shape and dimensions of a typical $T_{RI}WP$ section (all units are in mm)

II. FINITE ELEMENT ANALYSIS

Finite element study was carried out on the $T_{RI}WP$ steel section using LUSAS 14.3. This section discusses the numerical approach to obtain the flexural stiffness through elastic load-deflection behavior for $T_{RI}WP$ and FW steel sections. For the $T_{RI}WP$ steel section models in this study, each surface is formed of 4 nodal lines. Thin shell element was chosen to represent the element type of the model. In LUSAS there are two types of thin shell elements which are quadrilateral thin shell element (QSL8) and triangular thin shell element (TSL6). As required by thin shell theory, transverse shearing deformations are excluded. This element type was being able to cater for both membrane and bending effects simultaneously on the element. For this research, element shape as the quadrilateral and interpolation order in quadratic is selected. Chan, Khalid, Sahari and Hamouda [14, 15] and Elgaaly and Seshadri [16] also used this element type for their thin-walled FE models. In this study, $T_{RI}WP$ and FW steel sections have been modeled using the criteria as tabulated in Table 1.

TABLE I DIMENSIONS OF TRIWP AND FW STEEL SECTION IN FINITE ELEMENT ANALYSIS

Case		Type of section	Size (mm)
FW1	L=3 m, 4 m, 4.8 m		200×100×6×3
T_{RI}WP1	L=3 m, 4 m, 4.8 m		200×100×6×3
FW2	L=3 m, 4 m, 4.8 m		180×75×5×2
T_{RI}WP2	L=3 m, 4 m, 4.8 m		180×75×5×2

Every part of a finite element model should be assigned a material property dataset. For this study, the whole specimens was assigned ungraded mild steel for its material property with Young's modulus, E, of 209×10^3 N/mm^2, shear modulus, G, of 79×10^3 N/mm^2 and Poisson ratio of 0.3. These material properties remain constant throughout the analysis. The assignment of loadings and boundary condition can significantly affect the results. For this study, loading conditions will be assigned to the model by applying concentrated load in the centre of the span. To ensure the load is applied through the web, the nodes for the support will be constrained in its x, y, and z translation at the both sides of support.

A. Convergence Study

Convergence criteria were defined to determine the suitable mesh for the model. The convergence of the mesh was established by independently increasing the mesh density in each part of the model beam section. The model was given increased mesh density in all parts of the section simultaneously, and with higher-order elements (QSL8). The results clearly indicate that a convergence solution has been obtained when the number of elements is 234 for T_{RI}WP1 and 340 for $T_{RI}WP2$. From the results of the mesh ratio investigation, elements size 20 is selected for both types of steel sections. This meshing was adapted to all models of triangular web profile steel section throughout this study.

1) Parametric Study on the Effect of Web Corrugation Angle, θ:

Among the many factors that may influence the bending performance of the $T_{RI}WP$ steel section are the geometric parameters which are the most governing factors such as the effect of the web thickness (t_w), depth of web (D) and corrugation angle (θ). In order to limit this paper and make it brief and clear, this section mainly focused only on the effects of the web corrugation angle.

III. RESULTS AND DISCUSSION

To investigate the effect of the corrugation angle to the bending performance, a few $T_{RI}WP$ steel section models with corrugation angle, θ varies from 15° to 75° were considered for both $T_{RI}WP$ steel sections. Other geometric parameters which were kept constant are D=200 mm, B=100 mm, t_w=3 mm and t_f=6 mm. For other section, geometric parameters which were kept constant are D=180 mm, B=75 mm, t_w=2 mm and t_f=5 mm. All data of maximum deflection results were tabulated in Table 2.

TABLE 2 DEFLECTION RESULTS OF THE BENDING IN MINOR AND MAJOR AXIS DUE TO THE EFFECTS OF WEB CORRUGATION ABGLE

Span (m)	θ (°)	δ (mm) minor	δ (mm) major	δ (mm) minor	δ (mm) major
		(Section 200×100×6×3) mm		(Section 180×75×5×2) mm	
3	15	5.941	31.72	7.557	29.75
4	15	15.28	14.68	15.40	8.330
4.8	15	30.11	11.71	20.96	34.11
3	30	7.372	4.203	5.566	6.680
4	30	18.57	7.737	19.26	8.593
4.8	30	27.98	10.98	18.84	13.68
3	45	5.540	5.403	3.899	4.951
4	45	11.79	8.806	12.36	8.811
4.8	45	22.02	12.62	19.39	13.75
3	60	4.506	3.516	7.119	3.574
4	60	16.89	6.626	16.71	6.960
4.8	60	25.25	10.03	15.53	12.10
3	75	4.879	3.338	6.251	3.536
4	75	8.556	6.127	10.66	6.731
4.8	75	21.97	9.980	13.85	10.87

In this numerical study, it was noted that deflection of 45^0 and 75^0 web corrugations angle are the lowest deflection value either in minor or major axis of $T_{RI}WP$ steel section. This is because, as the corrugation angle is more than 45^0, the number of slanting web increased throughout the length. This will lead to minimum deflection occurred. While for the corrugation angle which is less than 45^0, a $T_{RI}WP$ steel section tends to behave similarly as a flat web steel section. When the θ is close to 0^0, the $T_{RI}WP$ steel section will become slightly such as FW steel section. The reason is that, extremely lower value of corrugation angle causes the steel section to be very slender for slanting web and the steel section will deflect easily. This kind of geometrical profile does not take the advantages of corrugated profile in minor and major axis of bending and may lead to uneconomical design. It means that the $T_{RI}WP$ steel section is stiffer when the web corrugation angle is 45^0 or 75^0. In other word, $T_{RI}WP$ steel section has a higher resistance to bending in minor and major axis when the web is constructed in both corrugation angles. The results of 45^0 web corrugation angles were then used for the calculation of flexural stiffness of $T_{RI}WP$ to compare with the FW steel section. 45^0 of web corrugation angle were then used to calculate the flexural stiffness of minor and major axis in terms of flat web.

Table 3 show the flexural stiffness in major and minor axis bending respectively results for $T_{RI}WP$ compared to FW steel sections. The value of I_x is in a range 0.754 to 0.818 times the I_x of FW steel section. On the other hand, the deflections in minor axis for $T_{RI}WP$ higher than FW steel section. The value of I_y for the $T_{RI}WP$ is in a range 1.523 to 1.686 times the I_y of FW steel section. Finite element analysis on bending indicates that the changes of eccentric stiffeners to slanting stiffeners bring contribution to the bending strength of the $T_{RI}WP$ steel section. Summary of finding for finite element analysis were tabulated in Table 4.

TABLE 3 PERCENTAGE DIFFERENCES OF FLEXURAL STIFFNESS FOR TRIWP1&2 AND FW1&2

Model (mm)	Position	Length (mm)	Flexural stiffness (kN/mm) $(P/\delta)_{T_{RI}WP}$	Flexural stiffness (kN/mm) $(P/\delta)_{FW}$	$\left(P/\delta\right)_{T_{RI}WP} / \left(P/\delta\right)_{FW}$	Average
200×100×6×3 (T_{RI}WP1)	Major axis	4800	1.109	1.178	0.9992	0.754
		4000	1.590	2.031	0.7758	
		3000	2.591	4.824	0.4294	
	Minor axis	4800	0.136	0.091	2.1402	1.523
		4000	0.254	0.157	2.0784	
		3000	0.542	0.372	1.8820	
180×75×5×2 (T_{RI}WP2)	Major axis	4800	0.582	0.597	1.1748	0.818
		4000	0.908	1.110	1.2312	
		3000	1.616	2.441	0.6474	
	Minor axis	4800	0.052	0.033	2.1719	1.686
		4000	0.081	0.053	1.4577	
		3000	0.256	1.131	1.9595	

TABLE 4 SUMMARY OF FINDING

Section (mm)	Specimen no	$I_{TRI\ WP}$ = ratio of flexural stiffness × I_{FW}
200×100×6×3	T_{RI}WP1	I_x = 0.754 $I_{x\ FW}$ I_y = 1.523 $I_{y\ W}$
180×75×5×2	T_{RI}WP2	I_x = 0.818 $I_{x\ FW}$ I_y = 1.686 $I_{y\ W}$

IV. SUMMARY

Finite element models of $T_{RI}WP$ and FW steel section were developed using thin shell elements. Linear finite elements analysis, which considers both geometric and linearity was performed. The computer program LUSAS version 14.3 was used throughout the analysis. The numerical results of FW and $T_{RI}WP$ steel section from FEA under bending were compared. The effect of web corrugation angle of $T_{RI}WP$ steel section for both models was reported. Observation form the finite element simulations, it was noted that deflection of 45^0 and 75^0 web corrugations angle be the lowest deflection value either in minor or major axis of $T_{RI}WP$ steel section. It means that the $T_{RI}WP$ steel section is stiffer when the corrugation angle of the web is 45^0 or 75^0. Obviously, $T_{RI}WP$ steel section has a higher resistance to bending in minor and major axis when the web is constructed in both corrugation angles.

Besides that, the value of I_x for the $T_{RI}WP$ steel section is in a range 0.754 to 0.818 times the I_x of FW steel section. While, the value of I_y for the $T_{RI}WP$ steel section is in a range 1.523 to 1.686 times the I_y of FW. This numerical analysis indicated that the deflection in minor axis for $T_{RI}WP$ steel section is less than FW and trapezoidal web profile (TWP) steel section which has been analyzed by De'nan [5]. It means that the $T_{RI}WP$ steel section is stiffer compared to FW and TWP steel section in minor axis. In this regard, $T_{RI}WP$ steel section has a higher resistance to bending in minor axis than FW and TWP steel section. However, the deflections in major axis for T_{RI}WP steel section is more than FW but less than TWP steel section. It can be concluded that the changes of eccentric stiffeners to slanting stiffeners is significant to the bending strength of the $T_{RI}WP$ steel section. The introduction to slanting stiffeners shows a greater bending strength compare to corrugated section by using trapezoidal web.

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REFERENCES

[1] M. Elgaaly, R.W. Hamilton, and A. Seshadri, "Shear strength of beams with corrugated webs," Journal of Structural Engineering. ASCE, vol. 122, pp. 390-398 (4) 1996.

[2] M. Elgaaly, A. Seshadri, and R.W. Hamilton, "Bending strength of steel beams with corrugated webs," Journal of Structural Engineering ASCE, vol. 123, pp. 772-782 (6) 1997.

[3] H. Atan, "Flexural Behaviour of Trapezoidal web Profile," MSc Thesis. Universiti Teknologi Malaysia (2001).

[4] C.S. Tan, "Buckling Analysis of Compression member with Trapezoid Web Profile," MSc. Thesis. Universiti Teknologi Malaysia (2004).

[5] F. Denan,"Lateral Torsional Buckling Behaviour of Trapezoidal Web Profile," PhD Thesis. Universiti Teknologi Malaysia (2008).

[6] M. Elgaaly and A. Seshadri, "Girders with corrugated webs under partial compressive edge loading," Journal of Structural Engineering ASCE, vol. 123 pp. 783-791 (6) 1997.

[7] R.P. Johnson and J. Cafolla, "Local flange buckling in plate girders with corrugated webs," Proceedings of the Institution of Civil Engineers, Structures and Buildings, vol. 122, pp. 148-156 (2) 1997.

[8] R.P. Johnson and J. Cafolla, "Corrugated webs in plate girders for bridges," Proceedings of the Institution of Civil Engineers, Structures and Buildings, vol. 122, pp. 157-164 (2) 1997.

[9] R. Luo and B. Edlund, "Ultimate strength of girders with trapezoidally corrugated webs under patch loading," Journal of Thin-Walled Structures, vol. 24, pp. 135-156 (2) (1996).

[10] R. Luo and B. Edlund, "Shear capacity of plate girders with trapezoidally corrugated webs," Journal of Thin-Walled Structures, vol. 26, pp. 19-44 (1) 1996.

[11] W. Zhang, Y. Li, Q. Zhou, X. Qi and G.E.O. Widera, "Optimization of the structure of an H- beam with either a flat or a corrugated web: Part 3. Development and research on H-beams with wholly corrugated webs," Journal of Materials Processing Technology, vol. 101, pp. 119-123, 2000.

[12] Y. Li, W. Zhang, Q. Zhou, X. Qi and G. E. O. Widera, "Buckling strength analysis of the web of a WCW H-beam: Part 2. Development and research on H-beams with wholly corrugated webs (WCW)," Journal of Materials Processing Technology, vol. 101, pp. 115-118, 2000.

[13] S. Jamali, "Lateral Torsional Buckling of Trapezoid Web Profile," MSc. Thesis, Universiti Teknologi Malaysia (2004).

[14] C.L. Chan, Y.A. Khalid, B.B. Sahari and A.M.S. Hamouda, "Finite element analysis of corrugated web beams under bending," Journal of constructions steel research, vol. 58, pp. 1391-1406, 2002.

[15] Y.A. Khalid, C.L. Chan and B.B. Sahari, "Bending behaviour of corrugated web beam," Journal of materials processing technology, vol. 150, pp. 242-254, 2004.

[16] M. Elgaaly and A. Seshadri, "Depicting the behavior of girders with corrugated webs up to failure using non-linear finite element analysis," Journal of advances in engineering software, vol. 29, pp. 195-208, 1998.