

Finite Element Analysis of the Loading Position Effects to the Bending Behaviour of Triangular Web Profile Steel Section



F. De'nan, K. K. Shoong and N. S. Hashim

Abstract Loading position effect on the bending behaviour of triangular web profile ($T_{RI}WP$) steel section is presented in this paper. A $T_{RI}WP$ steel section was made by the connection two flanges to a web plate triangular profile, which were analysed using LUSAS finite element software. The study involved 3000, 4000 and 4800 mm span of $T_{RI}WP$ steel sections with size $200 \times 100 \times 6 \times 3$ mm and $180 \times 75 \times 5 \times 2$ mm, respectively. Three types of loading positions were studied: the middle of the slanting part, the upper corner and the lower corner (of the corrugation profile). It was observed that the middle of the inclined part loading position contributes lower deflection compared to the others loading position. This was true for both deflection in major axis of $T_{RI}WP1$ and $T_{RI}WP2$ steel section. This was due to the middle position (inclined part) of the web section, which is more stiffen between the upper and lower positions of the web. Meanwhile, for the minor axis, the deflection value of inclined part is nearly close to the upper and lower loading position results, although the deflection value of the inclined part is the highest compared to the other loading positions.

Keywords Finite element analysis · Bending behaviour · Triangular web profile

1 Introduction

Economic design is achieved by changing the web into a corrugation profile. Through web corrugation profile, it is increased the stability against buckling. Besides that, corrugation web profile possible to reduce the raw material and cost of

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web stiffeners. It is estimated more than 30% compared with standard I-beams and about 10–30% compared with conventional built-up sections. By comparing with a truss system, high strength-to-weight ratio section is achieved and reduces the cost and steel, as the clear spans increase. In addition, it is reduced the erection cost. Lifting equipment are not required when lifting and unloading the beam because over the weak axis bending and rotation, the corrugation in the web makes the section high on bending resistance. The necessity for brace angles or tubes against rotation resistance is reduced, further erection cost and time also reduced [1].

Bending behaviour almost the mainly structural action for each section. Other effects such as bearing and shear are also presented. Therefore, it is important that the stiffness properties of the section are adequate to avoid any excessive deflection.

Previous researchers had conducted several tests to investigate structural properties of the vertically trapezoidal corrugation such as bending and shear mode and including compressive patch loads. It was found that local buckling on the web for coarse corrugation and global buckling on the web for dense corrugation was the main failure effects under shear loading [2]. Since early 60s, the studies on the behaviour of trapezoid web profile beam are conducted and only on 1980, the full capacity of trapezoid web profile has been explored in detail [3–5].

According to the previous study, when the trapezoidal web girder is loaded at the centre of the oblique corrugation part, the highest strength value is achieved. Meanwhile, when it is applied at the centre of the flat corrugation part, the girder has the lowest strength value [6, 7]. With a Ramberg–Osgood strain-hardening model for webs, the ultimate strength of girder is about 8–12%, which was higher than the ultimate strength of an elastic-perfectly plastic analysis. Through block distribution analysis, it was found that the degree of strain hardening and yield stress for the small region material at the corner of the web profile is higher than in other regions. However, the ultimate and the shear capacity post-buckling increase by the increment of web thickness. The corrugation depth did not affect the ultimate shear capacity but affected the buckling mode localization degree. Thus, in order to increase the bending behaviour of corrugated steel section, a new shape of steel section known as triangular web profile ($T_{RI}WP$) steel section has been studied in this paper.

This triangular web profile ($T_{RI}WP$) steel section eliminated the eccentric stiffeners as in trapezoidal web steel section. The transition model from trapezoidal web steel section to triangular web profile ($T_{RI}WP$) steel section are clearly figured in Fig. 1. This type of steel section was used to study the effect of the loading position to the bending behaviour in major (I_x) and minor (I_y) axes of $T_{RI}WP$ by finite element analysis.

Generally, without carrying any axial stresses due to flexure, prestressing, creep, the corrugated webs can withstand shearing forces. Thus, only pure shear stresses appear in the corrugated webs. As a result, by using corrugated webs, alternative attractive to composite bridges girder is obtained [8–11].

Ordinary plane web I-beam was tested experimentally to analyse the strength effects on a beam web corrugation. The comparison between the results obtained from both methods, for the plane web type, shows 3.1–7.1% differences and for the

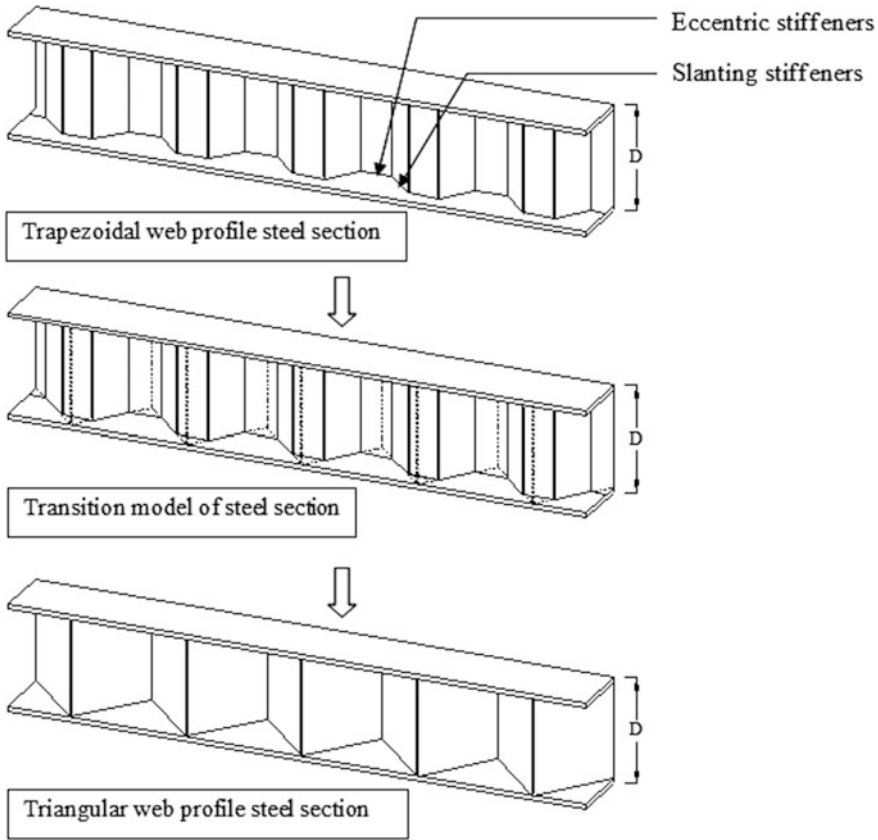


Fig. 1 The transition model from TWP steel section to $T_{RI}WP$ steel section

beams with vertical corrugated web, 38.8–54.4% able to stand higher moments than the horizontal type. The vertical corrugated web provides a more resistance to the flange buckling, between the plane and horizontal corrugated web types and the same results for the other three radiuses. Moreover, corrugated web beams with larger corrugation radius could resist higher bending moment, and it is true for the sizes used. 10.6% reduction in weight for the vertical corrugated web compared to the FW beam [12]. However, the compression flange yielded and vertically buckled into the crippled web [13]. Besides that, larger radius corrugation was able to resist high bending until the yielding stage. This affected the increment of the second moment of area (I) that controls the bending stresses (σ_{zz}).

In addition, the panel width had the most significant effect on the mode of buckling. An ideal ratio between the inclined panel width and the horizontal panel width for a trapezoidal corrugation profile is proposed to be 1.0 [14]. Besides that, global buckling mode governs the instability behaviour for significantly small corrugation width b (dense corrugation), and the local buckling mode governs the

behaviour for significantly large values of b . The corrugation angle also affects the interactive critical stress for small panel widths, b where the behaviour is controlled by either pure global buckling or interaction between global buckling and steel yielding. The numerical analysis reveals that after web buckling has occurred, corrugated web girders still continue carrying the load. The width of panel clearly affected the post-buckling strength. For corrugated webs with bigger panel widths, the strength of post-buckling reached 53% for a 400 mm panel width. For such girders, the lateral torsion-flexure buckling resistance is 12–37% higher than the traditional plane webs plate girders [15].

In web, the shear force caused some varying buckling modes such as local, global and interactive shear buckling. However, the shear force due to accordion effects was overcome by using corrugated web [16]. In particular, the interactive shear buckling among local and global modes was clearly discussed [17].

It was found that the critical moment increases from constant web to corrugation web [18]. About 21–29% the elastic lateral-torsional buckling strength of the I-girder with trapezoidal web corrugations higher than the I-girder with flat webs [19].

For I-girder with corrugated webs in a plastic and elastic stage, as the section became elastic section, the effect of bracing stiffness decreased and increased as the lateral unbraced length increases [20]. It means modified slenderness of I-girder is one of the factors that affected the stiffness of the restraint. Moreover, numerical simulations indicated that when the loading length increases, the load carrying capacities increased linearly. However, the load carrying capacity decreases for the high web or fold ratios. Besides that, when the corrugation angle increases, the patch loading resistance increases and the failure mode in the parameter range of bridges is mainly local buckling [21].

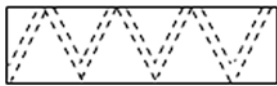
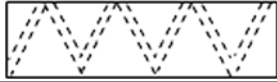
Throughout this investigation, a triangular web profile ($T_{RI}WP$) steel section was selected. Parametric studies were carried out on $T_{RI}WP$ to investigate the loading position effects to the bending behaviour.

2 Parametric Study

Two types of mild sections were studied, namely, $T_{RI}WP1$ ($200 \times 100 \times 6 \times 3$ mm) and $T_{RI}WP2$ ($180 \times 75 \times 5 \times 2$ mm). A parametric study by FEA on the $T_{RI}WP$ was analysed to obtain the loading position–deflection graphs of the bending behaviour for $T_{RI}WP$ steel sections. For this analysis, no initial imperfectness and load eccentricity occurred were assumed. Table 1 shown the dimensions for each type of section.

The maximum deflection, δ for elastic condition of a simply supported beam as shown in Fig. 1, can be calculated by using Eq. 1, if a point load, P , is applied at the mid-span:

Table 1 The detail properties of T_{RI}WP and FW specimens

Case		Plan view	Size
T _{RI} WP1	L = 3000, 4000, 4800 mm		200 × 100 × 6 × 3 mm
T _{RI} WP2	L = 3000, 4000, 4800 mm		180 × 75 × 5 × 2 mm

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

where I = second moment of area, P = applied point load, L = length of span, E = elastic modulus of steel, and δ = vertical deflection at midspan.

A linear relationship between the load (P) and deflection (δ) can be obtained from a load–deflection graph [22]. In this study, each surface of T_{RI}WP models is formed by 4 nodal lines. Thin shell element in 3D dimension was selected to represent the model element type. Each of T_{RI}WP steel section was assigned ungraded mild steel with Young’s modulus, E , of $209 \times 10^3 \text{ N/mm}^2$, shear modulus, G , of $79 \times 10^3 \text{ N/mm}^2$ and Poisson ratio of 0.3. Throughout the analysis, the material properties remain constant.

The boundary and loadings situation have to represent the actual situation of triangular web profile for its application. Throughout this analysis, the total global distributed load is assigned in the middle of the span. The nodes at the support are constrained in its x , y and z translation at both sides of the support to make sure the load is applied entirely the whole web. The boundary and loading conditions assigned to the model in the minor and major axis are shown in Fig. 2. The support condition enlargement to the model was shown in the respective figure.

3 Convergence Study

Increased mesh density and higher order elements were inputted in each part of the model simultaneously to get the suitable mesh for T_{RI}WP steel section model. It is clearly indicated that from the Model 1 to Model 6, the displacement increment becomes smaller. It is observed that a convergence mesh is obtained when the number of elements is 234. Therefore, elements size 20 is used in following analyses.

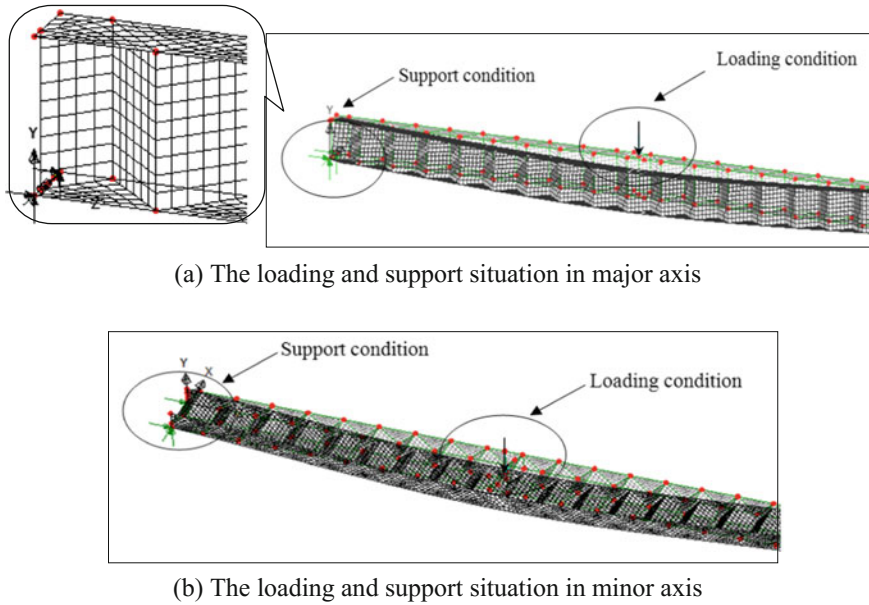


Fig. 2 Mode of deflection of a $T_{RI}WP$ model

4 Results and Discussion

The effects of the stated three loading positions on bending behaviour as shown in Fig. 3 were investigated. The aim of this analysis is to know the best loading point for use in design work.

The results of analysis due to the loading position effects under point load 14 kN in major axis and 3 kN in minor axis are listed in Table 2 for the $T_{RI}WP1$ steel section and Table 3 under point load 8 kN in major axis and 1 kN in minor axis for the $T_{RI}WP2$ steel section, and are shown in Figs. 4 and 5. From Figs. 4a and 5a, it was noted that the loading position at the middle of the inclined part gives minimum deflection compared to the others loading position. This was true for both

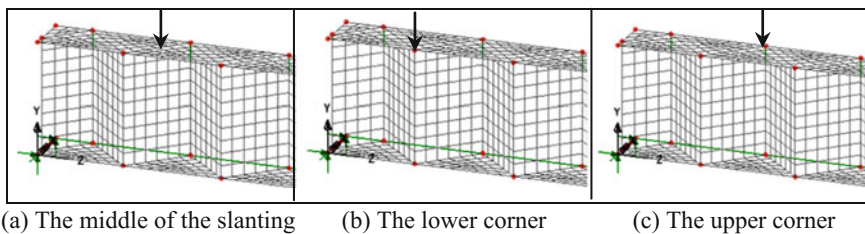


Fig. 3 Types of loading position

Table 2 Deflection in minor and major axis for section $200 \times 100 \times 6 \times 3$ mm

Loading position	Span (mm)	Deflection in major axis, δ_{major} (mm)	Deflection in minor axis, δ_{minor} (mm)
At the upper corner	3000	10.47	3.74
	4000	19.04	11.70
	4800	26.95	21.93
At the lower corner	3000	20.76	3.72
	4000	28.19	11.75
	4800	35.38	21.99
At the middle of the slanting part	3000	5.40	5.54
	4000	8.81	11.79
	4800	12.62	22.02

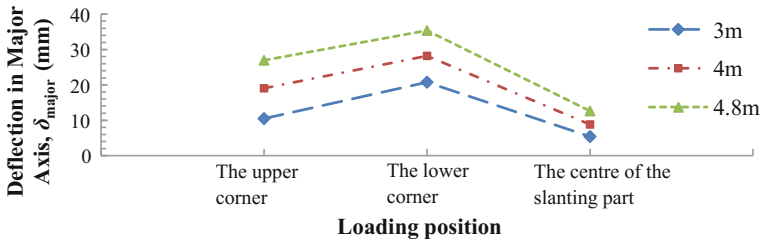
Table 3 Deflection in minor and major axis for section $180 \times 75 \times 5 \times 2$ mm

Loading position	Span (mm)	Deflection in major axis, δ_{major} (mm)	Deflection in minor axis, δ_{minor} (mm)
At the upper corner	3000	11.52	3.47
	4000	22.05	11.97
	4800	27.36	18.98
At the lower corner	3000	17.87	3.50
	4000	21.97	11.95
	4800	32.32	19.01
At the middle of the slanting part	3000	4.95	3.90
	4000	8.81	12.36
	4800	13.75	19.23

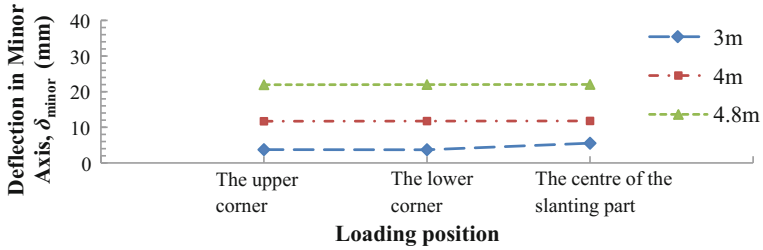
deflections in the major axis of $T_{RI}WP1$ and $T_{RI}WP2$ steel section. This was due to the middle position (inclined part) of the web section, which is more stiffen between the upper and lower positions of the web. Meanwhile, for the minor axis, the deflection value of inclined part is nearly close to the upper and lower loading position results, although the deflection value of the inclined part is the highest compared to the other loading positions (see Figs. 4b and 5b).

In this section, parametric studies were presented to investigate how loading position influences the bending behaviour in minor and major axis of $T_{RI}WP$ steel section. For conclusion, the best loading point in bending about the major axis is in the middle of the slanting part. Deflection due to bending in minor axis is found more or less same of each loading point.

The comparison between maximum deflection results of the experimental and theoretical analysis for FW and $T_{RI}WP$ steel section was presented [22] and tabulated in Tables 4 and 5. It was found that the deflections in major axis for $T_{RI}WP$ steel section is higher compared to that of FW steel section. However, deflection in minor axis for $T_{RI}WP$ steel section is lesser compared to that of FW steel section.

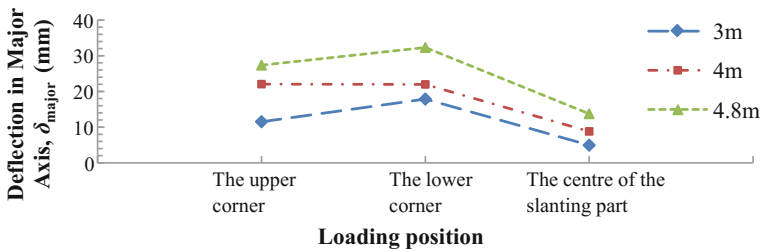


(a) Major axis (I_x) under point load 14 kN

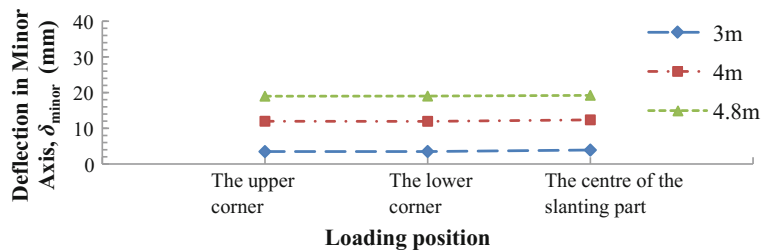


(b) Minor axis (I_y) under point load 3 kN

Fig. 4 Deflection, δ versus loading position (section $200 \times 100 \times 6 \times 3$ mm)



(a) Major axis (I_x) under point load 8 kN



(b) Minor axis (I_y) under 1 kN point load

Fig. 5 Deflection, δ versus loading position (section $180 \times 75 \times 5 \times 2$ mm)

Table 4 Deflections for $T_{RI}WP1$ and $FW1$ steel section ($200 \times 100 \times 6 \times 3$ mm)

Span (mm)	Major axis			Minor axis		
	$\delta_{T_{RI}WP}$ (mm)	δ_{FW} (mm)	δ_{THEORY} (mm) Equation 1	$\delta_{T_{RI}WP}$ (mm)	δ_{FW} (mm)	δ_{THEORY} (mm) Equation 1
3000	5.403	3.088	2.908	5.536	8.057	8.071
4000	8.806	6.924	6.894	11.789	17.283	19.130
4800	12.616	13.100	11.913	22.015	32.776	33.060

Table 5 Deflections for $T_{RI}WP2$ and $FW2$ ($180 \times 75 \times 5 \times 2$ mm)

Span (mm)	Major axis			Minor axis		
	$\delta_{T_{RI}WP}$ (mm)	δ_{FW} (mm)	δ_{THEORY} (mm) Equation 1	$\delta_{T_{RI}WP}$ (mm)	δ_{FW} (mm)	δ_{THEORY} (mm) Equation 1
3000	4.951	3.636	3.281	3.900	7.710	7.654
4000	8.811	7.856	7.777	12.362	18.343	18.140
4800	13.754	13.502	13.440	19.230	30.858	31.346

It means in minor axis, the $T_{RI}WP$ steel section is stiffer compared to that of FW steel section. Therefore, in minor axis, $T_{RI}WP$ steel section has a higher bending resistance than FW steel section.

The load versus deflection of experimental and analytical study for both types of steel section was plotted. It was observed the entire data is returned to zero when the applied load being unloaded. It means the section returns to the original shape after the loading being unloaded. This proved that bending tests were carried in elastic condition only.

In major axis, the maximum deflection of $T_{RI}WP$ was higher than that of the FW steel section. The web section with triangular profile acted as stiffeners was not effected the bending behaviour in major axis. However, in minor axis, the maximum deflection of $T_{RI}WP$ steel section was lower than that of the FW steel section.

In summary, the deflection in minor axis for $T_{RI}WP$ for both sizes is lower than FW steel section. It shows that $T_{RI}WP$ steel section is stiffer compared to FW steel section in minor axis. Meanwhile, the deflections in major axis for $T_{RI}WP$ is higher than that of FW steel section.

5 Conclusions

In general, the study of corrugated steel section and literature on the previous research were reviewed in this paper. It was concluded that the bending behaviour of FW and TWP sections research is early discussed. However, the bending

behaviour research of $T_{RI}WP$ steel section is not available yet. From the previous analysis, it was identified that bending behaviour of trapezoidal web girder is dependent on loading position. Therefore, investigation of the effects of loading position was studied in detail because it may influence the bending behaviour of $T_{RI}WP$ steel section.

A parametric study was done by using LUSAS software. Bending behaviour for both sizes of $T_{RI}WP$ due to the effects of section properties was observed and investigated. It was observed from the parametric study results that the best loading point in bending about major axis is at the middle of the slanting corrugation part. Deflection due to bending about minor axis is found to be approximately the same regardless of position of the loading point. For economic design consideration in bending, appropriate loading position should be early considered.

Acknowledgements The authors thankfully acknowledge the financial support from Universiti Sains Malaysia (USM) within this research course. This research was supported by the Research University Grant-RUI (Account Number: 1001/PAWAM/814222).

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