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 (TRIWP) steel sections. A triangular web profile (TRIWP) 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 TRIWP 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°, 30°, 45°, 60° and 75°). It was noted that deflection of 45° and 75° web corrugations angle be the lowest deflection value either in minor or major axis of TRIWP steel section. It means that the TRIWP steel section is stiffer when the web corrugation angle is 45° or 75°. In other word, TRIWP 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 (TRIWP) 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 TRIWP steel section (see Fig. 1).

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

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

(1)

Where,

$I$ = Second moment of area
$E$ = Elastic modulus of steel
$P$ = Applied point load
$\delta$ = Vertical deflection at mid span
$L$ = Span of beam

A linear relationship between the load ($P$) versus deflection ($\delta$) 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 TRIWP 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 TRIWP and FW steel sections are performed, the second moment of area, $I$, for a TRIWP 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 ($P/\delta$) 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].

$$I_{TRIWP} = \frac{E}{\delta_{TRIWP}} \times I_{FW} \quad (2)$$

![Isometric view of TRIWP section](image)

![Plan view of TRIWP section](image)

![Side view of TRIWP section](image)

![Section view of TRIWP section](image)

Figure 1 Shape and dimensions of a typical TRIWP section (all units are in mm)

II. FINITE ELEMENT ANALYSIS

Finite element study was carried out on the TRIWP steel section using LUSAS 14.3. This section discusses the numerical approach to obtain the flexural stiffness through elastic load-deflection behavior for TRIWP and FW steel sections. For the TRIWP 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, TRIWP and FW steel sections have been modeled using the criteria as tabulated in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of section</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW1</td>
<td>L=3 m, 4 m, 4.8 m</td>
<td>200×100×6×3</td>
</tr>
<tr>
<td>TRIWP1</td>
<td>L=3 m, 4 m, 4.8 m</td>
<td>180×75×5×2</td>
</tr>
<tr>
<td>FW2</td>
<td>L=3 m, 4 m, 4.8 m</td>
<td>180×75×5×2</td>
</tr>
<tr>
<td>TRIWP2</td>
<td>L=3 m, 4 m, 4.8 m</td>
<td>180×75×5×2</td>
</tr>
</tbody>
</table>

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 $209\times10^3$ N/mm$^2$, shear modulus, $G$, of $79\times10^3$ 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 TRIWP1 and 340 for TRIWP2. 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, $\theta$:

Among the many factors that may influence the bending performance of the TRIWP 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 ($\theta$). 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 TRIWP steel section models with corrugation angle, \( \theta \) varies from 15° to 75° were considered for both TRIWP steel sections. Other geometric parameters which were kept constant are \( D=200 \text{ mm}, B=100 \text{ mm}, t_w=3 \text{ mm} \) and \( t_f=6 \text{ mm} \). For other section, geometric parameters which were kept constant are \( D=180 \text{ mm}, B=75 \text{ mm}, t_w=2 \text{ mm} \) and \( t_f=5 \text{ mm} \). All data of maximum deflection results were tabulated in Table 2.

<table>
<thead>
<tr>
<th>Span (m)</th>
<th>( \theta ) (°)</th>
<th>( \delta ) (mm) minor</th>
<th>( \delta ) (mm) major</th>
<th>( \delta ) (mm) minor</th>
<th>( \delta ) (mm) major</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>15</td>
<td>5.941</td>
<td>31.72</td>
<td>7.557</td>
<td>29.75</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>15.28</td>
<td>116.16</td>
<td>15.40</td>
<td>83.30</td>
</tr>
<tr>
<td>4.8</td>
<td>15</td>
<td>30.16</td>
<td>111.71</td>
<td>20.96</td>
<td>34.11</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>7.372</td>
<td>420.3</td>
<td>5.566</td>
<td>6.680</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>18.57</td>
<td>77.37</td>
<td>19.26</td>
<td>8.593</td>
</tr>
<tr>
<td>4.8</td>
<td>30</td>
<td>27.98</td>
<td>10.98</td>
<td>18.84</td>
<td>13.68</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>5.540</td>
<td>8.032</td>
<td>3.899</td>
<td>4.951</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>11.79</td>
<td>11.63</td>
<td>12.36</td>
<td>8.811</td>
</tr>
<tr>
<td>4.8</td>
<td>45</td>
<td>22.02</td>
<td>12.62</td>
<td>19.39</td>
<td>13.75</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>4.506</td>
<td>3.516</td>
<td>7.119</td>
<td>3.574</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>16.89</td>
<td>6.626</td>
<td>16.71</td>
<td>6.960</td>
</tr>
<tr>
<td>4.8</td>
<td>60</td>
<td>25.25</td>
<td>10.03</td>
<td>15.53</td>
<td>12.10</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>4.879</td>
<td>3.382</td>
<td>6.251</td>
<td>3.536</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>8.556</td>
<td>6.127</td>
<td>10.66</td>
<td>6.731</td>
</tr>
<tr>
<td>4.8</td>
<td>75</td>
<td>21.97</td>
<td>9.980</td>
<td>13.85</td>
<td>10.87</td>
</tr>
</tbody>
</table>

In this numerical study, it was noted that deflection of 45° and 75° web corrugations angle are the lowest deflection value either in minor or major axis of \( T_RWP \) steel section. This is because, as the corrugation angle is more than 45°, 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°, a \( T_RWP \) steel section tends to behave similarly as a flat web steel section. When the \( \theta \) is close to 0°, the \( T_RWP \) 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 \( T_RWP \) steel section is stiffer when the web corrugation angle is 45° or 75°. In other word, \( T_RWP \) 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° web corrugation angles were then used for the calculation of flexural stiffness of \( T_RWP \) to compare with the FW steel section. 45° of web corrugation angle were then used to calculate the flexural stiffness in terms of flat web.

Table 3 show the flexural stiffness in major and minor axis bending respectively results for \( T_RWP \) 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 \( T_RWP \) higher than FW steel section. The value of \( I_y \) for the \( T_RWP \) 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 \( T_RWP \) steel section. Summary of finding for finite element analysis were tabulated in Table 4.

<table>
<thead>
<tr>
<th>Model (mm) Position</th>
<th>Length (mm)</th>
<th>Flexural stiffness (kN/mm)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \frac{P}{\delta} ) ( T_RWP )</td>
<td>( \frac{P}{\delta} ) ( FW )</td>
</tr>
<tr>
<td>200×100×6×3 (( T_RWP )) Major axis</td>
<td>4800</td>
<td>1.109</td>
<td>1.178</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>1.590</td>
<td>2.031</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>2.591</td>
<td>4.824</td>
</tr>
<tr>
<td></td>
<td>Minor axis</td>
<td>4800</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>0.254</td>
<td>0.157</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>0.542</td>
<td>0.372</td>
</tr>
<tr>
<td>180×75×5×2 (( T_RWP )) Major axis</td>
<td>4800</td>
<td>0.582</td>
<td>0.597</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>0.908</td>
<td>1.110</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>1.616</td>
<td>2.441</td>
</tr>
<tr>
<td></td>
<td>Minor axis</td>
<td>4800</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>0.081</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>0.256</td>
<td>1.131</td>
</tr>
</tbody>
</table>
that deflection of 45° and 75° web corrugations angle be the
Observation form the finite element simulations, it was noted
the value of TRIWP
which has been analyzed by De’nan [5]. It means that the
than FW and trapezoidal web profile (TWP) steel section
strength of the stiffeners to slanting stiffeners is significant to the bending
section. It can be concluded that the changes of eccentric
steel section is stiffer compared to FW and TWP steel
section is more than FW but less than TWP steel
section. However, the deflections in major axis for
that the deflection in minor axis for
TRIWP steel section is in a range 1.523 to
Iw
Iw
strength analysis of the web of a WCW H-beam: Part 2. Development
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C.L. Chan, Y.A. Khalid, B.B. Sahari and A.M.S. Hamouda, “Finite
Y.A. Khalid, C.L. Chan and B.B. Sahari, “Bending behaviour of
M. Elgaaly and A. Seshadri, “Depicting the behavior of girders with

IV. SUMMARY

Finite element models of TRIWP 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 TRIWP steel section from FEA under bending were compared. The effect of web corrugation angle of
TRIWP steel section for both models was reported. Observation form the finite element simulations, it was noted
that deflection of 45° and 75° web corrugations angle be the
lowest deflection value either in minor or major axis of TRIWP steel section. It means that the TRIWP steel section is stiffer when the corrugation angle of the web is 45° or 75°. Obviously, TRIWP steel section has a higher resistance to bending in minor and major axis when the web is constructed in both corrugation angles.

Besides, the value of I, for the TRIWP steel section is in a
range 0.754 to 0.818 times the I, of FW steel section. While, the value of I, for the TRIWP steel section is in a range 1.523 to
1.686 times the I, of FW. This numerical analysis indicated that the deflection in minor axis for TRIWP 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 TRIWP steel section is stiffer compared to FW and TWP steel section in minor axis. In this regard, TRIWP steel section has a higher resistance to bending in minor axis than FW and TWP steel section. However, the deflections in major axis for TRIWP 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 TRIWP steel section. The introduction to slanting stiffeners shows a greater bending strength compare to corrugated section by using trapezoidal web.

ACKNOWLEDGMENT

The author wishes to thank University Sains Malaysia (USM) for the financial support during the course of research.

TABLE 4 SUMMARY OF FINDING

<table>
<thead>
<tr>
<th>Section (mm)</th>
<th>Specimen no</th>
<th>ITRIWP = ratio of flexural stiffness × Iww</th>
</tr>
</thead>
<tbody>
<tr>
<td>200×100×6×3</td>
<td>TRIWP1</td>
<td>Iw = 0.754 Iww, Iy = 0.818 Iww, Ix = 1.686 Iww</td>
</tr>
<tr>
<td>180×75×5×2</td>
<td>TRIWP2</td>
<td>Iw = 1.523 Iww, Iy = 0.754 Iww</td>
</tr>
</tbody>
</table>

REFERENCES

strength analysis of the web of a WCW H-beam: Part 2. Development
[16] M. Elgaaly and A. Seshadri, “Depicting the behavior of girders with