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STRUCTURAL PERFORMANCE OF COMPOSITE BEAM WITH TRAPEZOID WEB STEEL SECTION

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Abstract: An experimental work on a composite beam with trapezoidally corrugated web steel section has been carried out to study its structural performance. A full scale composite beam test specimen with trapezoid steel section was tested under bending moment. For comparison, a specimen of composite beam with flat web section was also tested in the same way. Deflections, position of neutral axis, distribution of strain across the depth of the composite section were measured and analysed. The results show that the composite beam with trapezoid web has no significant difference in its structural performance compared to the composite beam with normal flat web.

Keywords: *Trapezoid web; composite beam; bending capacity; shear capacity; strain distribution*

Abstrak: Satu ujian keatas rasuk komposit dengan keratan keluli yang mempunyai web yang berkerut secara trapezoid telah dijalankan untuk mengkaji prestasi strukturnya. Satu spesimen rasuk komposit dengan web trapezoid berskala penuh telah diuji dengan mengenakan tindakan momen lentur. Sebagai perbandingan, satu spesimen rasuk komposit dengan keratan keluli yang mempunyai web rata telah juga diuji dengan cara yang sama. Pesongan, kedudukan paksi neutral, taburan terikan disepanjang ukurdalam rasuk komposit telah diukur dan dianalisis. Keputusan ujian menunjukkan rasuk komposit dengan web trapezoid tiada mempunyai perbezaan ketara didalam prestasi struktur berbanding dengan rasuk komposit dengan web rata.

Kata kunci: *Web trapezoid; rasuk komposit; keupayaan lenturan; keupayaan riceh; taburan terikan*

1.0 Introduction

Steel beams with trapezoid web profile (Figure 1) have been widely used in recent years. It allows the use of thin plates without the need for stiffeners due to its high web shear capacity (Osman et.al,1999). Beams with steel-concrete composite action are one of the most commonly used structural elements because they considerably increase flexural strength and stiffness of steel beams. The use of trapezoid web has also found to lower the stress concentration at the web-flange welded connection and hence increase the fatigue strength (Izni,2001). However, there are only few experimental test data available to study the performance of TWP steel section acting compositely with concrete. The search for this experimental data has been the main concern in this project and the experiment is described and discussed in this paper. The objective of this project was to study the performance of composite beam with TWP steel section in elastic and plastic stage, in comparison with the composite beam with flat web. Two specimens span 5 meter in length with steel section of 300 $\times$ 120 mm and concrete section of 110 $\times$ 1000 mm were tested under bending moment. Sufficient stud connectors were provided to give full interaction between the steel and concrete. Analysis was carried out on the deflection behaviour under loading, the position of neutral axis, distribution of strain across the depth of the composite section and the crack development in the concrete section.

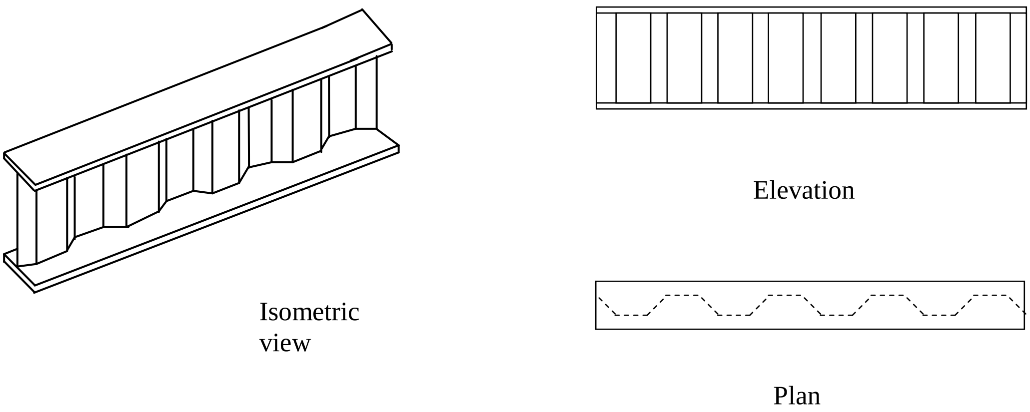


Figure 1: A typical shape of trapezoid web section

2.0 Design Capacity of Steel Section

In the design of bare steel section, trapezoid web steel section is known as having higher shear capacity as compared to the normal section with flat web. The corrugation in trapezoidal profile contributes to the higher shear strength of the web because each cycle of the corrugation acts as a partial intermediate stiffener to the web. The critical buckling shear capacity of the section is given by,

$$V_{cr} = \tau_{cr}\, d.t \qquad (1)$$

where τ_{cr} is the critical shear buckling strength. For web with slenderness ratio d/t of less than 63ε, $\tau_{cr} = \tau_y = 0.6p_y$, where p_y is the design strength, d and t are the depth and thickness of web respectively, and τ_y is the von Mises yield shear strength.

For trapezoid web which normally has very slender web, τ_{cr} is given by Fathoni (2003) and simplified by Hanim et.al.(2004) as,

$$\tau_{cr} = k\, \frac{1.6\pi^2 E}{12(1-\nu^2)(d/t)^2} \qquad (2)$$

where $k = 1.8/(a/d)^2 - (a/d)^3 + 8(a/d) + 9$.

a/d is the aspect ratio of each sub-panel web, where a is the width of the flat subpanel. v is the poison's ratio taken as 0.3. In this study, mild steel (design strength p_y = 275 N/mm^2) sections with the overall depth of 300 mm, flange width and thickness of 120 mm and 10 mm respectively and web thickness of 2 mm were selected and used for both flat web and corrugated web. The sub-panel of the corrugating shape was 100 mm. With a = 100 mm and d = 280 mm, it gives τ_{cr} = 158 N/mm^2, and V_{cr} = 88.4 kN.

For flat web section with slender web, τ_{cr} is as given by BSI (2000) in BS 5950:Part 1:

$$\tau_{cr} = 0.9\sqrt{\tau_y.\tau_e} \qquad (3)$$

$$\tau_e = \left[1 + \frac{0.75}{(a/d)^2}\right]\left[\frac{1000}{(d/t)}\right]^2 \qquad (4)$$

For a section with only bearing stiffener at both supports, a is taken as equal to the distance between supports. For the beam tested in this study, the length was 5 m and this give τ_{cr} = 83.0 N/mm^2, giving V_{cr} = 49.8 kN.

In bending capacity, due to the slenderness of the web for both beam sections, the web is neglected and therefore the bending capacity is given by the formula,

$$M_c = A_f . p_y . h \quad (5)$$

Where A_f is the area of each flange and h is the lever arm between the top and bottom flange.

When the section is acting compositely with concrete at the top flange, the whole cross section area of steel is normally in tension. The tension strength of section with trapezoid web has not been well established. Analytical study (Ihsan, 2001) and experimental study (Tan, 2003) have shown that the major axis deflection of beam with trapezoid web is higher than that with flat web. It gives an indication that the contribution of the corrugated web to the tension strength of the section is less than the flat web. This will be taken into consideration in the analysis of the experimental results.

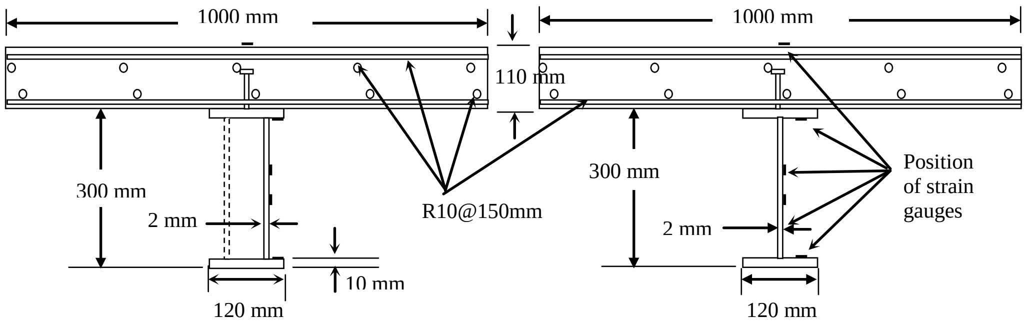
3.0 Testing procedures

3.1 Test Specimens

A steel-concrete composite beam, with trapezoidal web steel section, was designed based on BS5950: Part 3: Section 3.1(BSI, 1995). The ultimate bending strength was taken as the plastic moment capacity of steel and concrete acting compositely, given as the function of their plastic section modulus and their material yield strength (Oehler *et.al*, 1995). From the design, the test specimen with steel cross section of 300 $\times$ 120 mm and concrete flanges of 1000 mm breadth and 110 mm thickness was proposed, as is shown in Figure 2. As a control, a similar set of composite beam with flat web was also tested. From the tensile test results, the yield strength of the steel material for both flat and corrugated section was 315 N/mm^2.

Due to the slenderness of web, intermediate stiffener was supposed to be used to stiffen the flat web section. However, if intermediate stiffeners were provided in the flat web section, the advantage of TWP section would not be apparent in the experiment. It was thus decided not to improve the shear buckling capacity of the web with intermediate stiffeners so that the true performance of composite beam with TWP section can be compared.

With the span of beam of 5.0 m, the estimated maximum effective breadth was 1.25 m (SCI, 1990). In this project, 1.0 m have been used as the effective breadth for the concrete flange of the composite beam. This value has been chosen to enable full plasticity to develop in the steel section. The concrete used in the test was of Grade 30.



(a) Composite beam with TWP section

(b) Composite beam with I-plate girder (Control specimen)

Figure 2 : The test specimens

(a) Plastic Moment Capacity of Composite Beam

The plastic moment capacity of a symmetrical composite section, M_c, depends on the relative magnitudes of R_s and R_c, which determines the position of the plastic neutral axis (PNA). Design equations were provided in BS5950: Part 3 Appendix B, which assume that the web is compact. Due to slenderness of web, plastic neutral axis was predicted to lie in the concrete. The plastic moment capacity is calculated as:

$$M_c = R_s\left[\frac{D}{2} + D_s - \frac{R_s}{R_c}\frac{D_s}{2}\right] \qquad (6)$$

where D is the depth of the steel beam, D_s is the depth of slab, R_s is the tensile capacity of steel section, R_c is the compressive design capacity of the concrete slab over its effective breadth. For the composite section used in this study, R_s = 660 kN, R_c = 1485 kN and therefore M_c = 156 kNm. It is to be noted that due to the lower tension resistance of the corrugated web, R_s for the composite section with corrugated web may be less than that of the section with flat web.

b) Capacity of Shear Resistance

Headed stud shear connectors have been selected in this project. In calculating the capacity of shear resistance, the two parameters considered were the capacity of shear connectors, and the longitudinal force transferred for full shear connection. Characteristic resistances of stud in normal weight concrete were given in clause 5.4.6 of the standard. The design capacities of shear connectors were taken as 80% of the characteristic resistances in sagging or positive moment regions. The shear connector used were 19 mm diameter and 80 mm length and were manually welded to the top flange. Each headed stud shear connector was expected to have the maximum capacity of resisting 69 kN (Goh, 2004).

In order to develop full composite action, the longitudinal force to be transferred by the shear connectors, R_q should exceed the smaller of R_c or R_s. The design capacity of the shear connectors was to be multiplied by the number of shear connectors between the points of zero and maximum moment to obtain R_q. However, back calculation was used to determine the number of shear connectors so that $R_q > R_s$. Eventually, 40 shear studs were provided for each specimen with the studs spacing of 125 mm center to center. Such number was sufficient to maintain full shear interaction between steel and concrete until the ultimate failure of the composite beam.

Sufficient transverse reinforcement at 150 mm spacing in the concrete flange was provided to enable the concrete flange to resist the longitudinal shear transmitted by the shear connectors. Figure 3 shows the arrangement of shear studs and transverse reinforcement in the formwork.

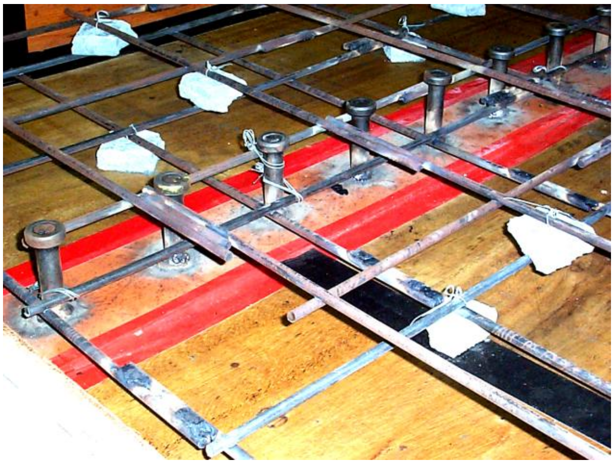


Figure 3: The shear studs and reinforcements

3.2 Loading frame and measurement

Frictional forces developed at the loading and reaction points were reduced through the use of rollers at the reaction and loading points. Lateral restraint was provided at the loading points by adjustable torsion restraints. Two point loads at 1 m spacing were applied through a load actuator in the middle of the span (Figures 4 and 5). This loading arrangement resulted in pure bending moment (zero shear) between the loading points.

Across the middle of the beam, 5 strain gauges were fixed, one strain gauge on top of concrete surface, one under the top flange, one on the bottom flange and two on the surface of web of steel section. Concrete and steel surfaces where gauges were fixed were grinded to remove paint and rust as well as to provide a smooth surface for effective bonding. The deflection of the beam was measured using displacement transducers positioned under the middle of the beam.

3.3 Test procedure

Loading was increased at 10 kN increment, in which measurement of deflection and strain were recorded in each increment. The loading was stopped when excessive deflection of the beam, or cracking in concrete or shear buckling in web were observed.

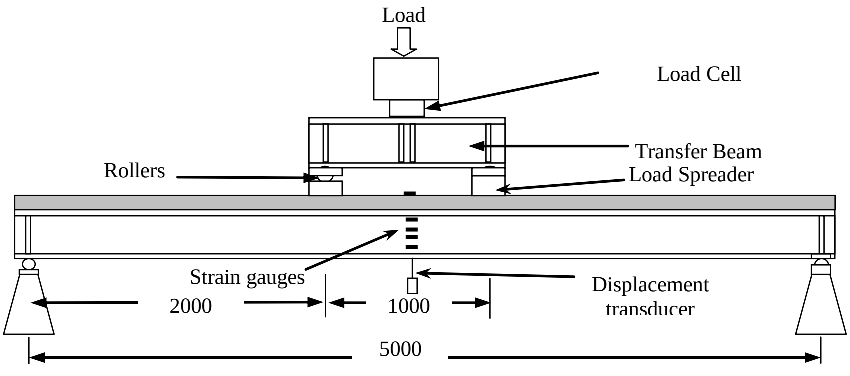


Figure 4: Elevation of the test arrangement, with strain gauges and displacement transducer

Figure 5 : Free roller used at loading point and rollers for line load spreaders

4.0 Results and Discussion

4.1 Strain

Typical plots of strain readings at the bottom flange and top of concrete slab, are shown in Figure 6. The compressive strain readings at the top of concrete (negative sign means compression) for both specimens are almost equal. In the other hand, the tension strains at the bottom flange of trapezoid composite are consistently higher than that of the composite beam with flat web.

(a) Strain distribution in the composite beam with trapezoid web steel section

The strain distribution across the depth of the composite beam under various loading is shown in Figure 7. As expected, due to the web corrugation, there is no linearity of strain distribution across the depth of the web. This effect is particularly obvious when taking strain reading at the diagonal web as has been done in this experiment. This is also due to the previous research findings that the corrugated web has no significant contribution to the axial tensile capacity of the section. Therefore, in the calculation of the strength of the composite section, the web is to be neglected.

The result shows that the web contributes much lesser to the tensile strength of the steel section. For this reason, the flanges of the TWP specimen will have to resist the additional tension force that is not taken by the trapezoidal web. It explains the reason of slightly higher elastic neutral axis. The neutral axis is determined from the interpolation between the top of concrete and the top flange of the steel section. The elastic neutral axis (E.N.A.) is 81 mm from the top whereas elastic-plastic neutral axis is 69 mm.

(b) Strain distribution in the composite beam with flat web steel section

The normal specimen gives a set of satisfying plots of strain distribution across the section depth. As is shown in Figure 8, the value of positive strains (tensile stresses) increase almost linearly with the distance from the neutral axis. It is shown that the neutral axis gradually shifted upwards from elastic condition to plastic condition. From the experiment, the elastic neutral axis (E.N.A.) is 88 mm from concrete top surface whereas plastic neutral axis (P.N.A.) is 67 mm from the top.

(c) Position of neutral axis

The neutral axis, theoretically and experimentally, in both specimens are summarised in Table 1.

When comparing the elastic neutral axis of trapezoid web composite beam with flat web composite beam, higher position of neutral axis was indicated based on the interpolation between the strain at the top of concrete slab and the strain in the top flange. This should be explained through the tension strain that is concentrated in the flanges of TWP steel section. A slightly rise in concrete strength might as well be the reason because the concrete ages are different in the two experiment.

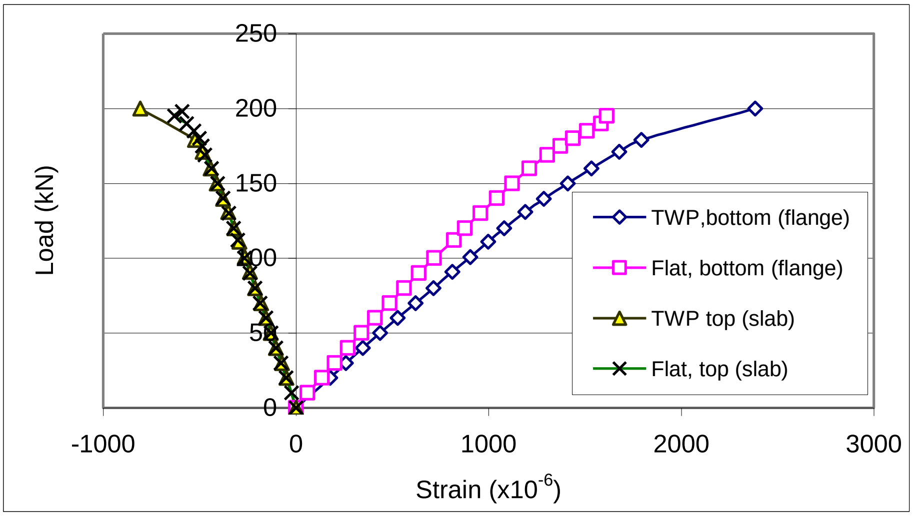


Figure 6: Strains readings at the bottom flanges and top of concrete slab at midspan of both test specimens

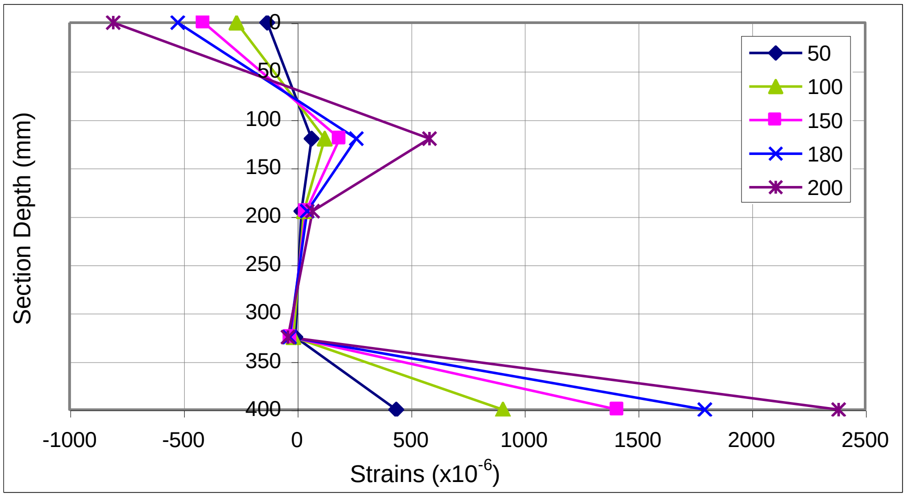


Figure 7: Strains variation across the depth at section A for various loadings for TWP composite beam

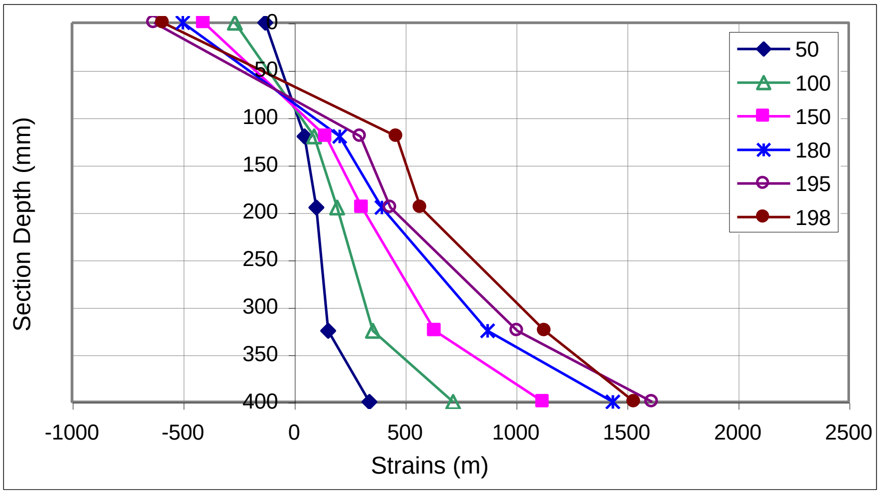


Figure 8: Strains variation across the depth at section A for various loadings for flat web composite beam

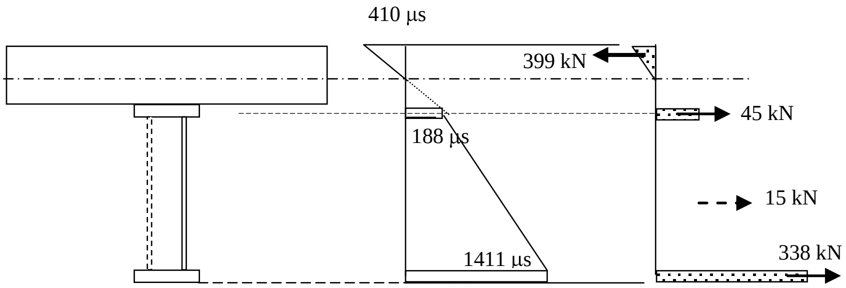
The higher neutral axis in trapezoid web composite beam also means that the compressive force in the concrete is less. This is probably because the trapezoid web has no tension strength, i.e. all the tension forces are carried by the flanges only. This confirms the earlier assumption that the web in trapezoid section is neglected in the calculation of tension force in composite section.

It can be explained by taking for instance the reaction forces in the steel and concrete area under the load of 150 kN. As shown in Figure 9, the reaction force in the web of trapezoid composite (shown by dotted arrow) is too small. The reaction force in the concrete slab is assumed to be equal to the sum of the reaction force in the flanges and web.

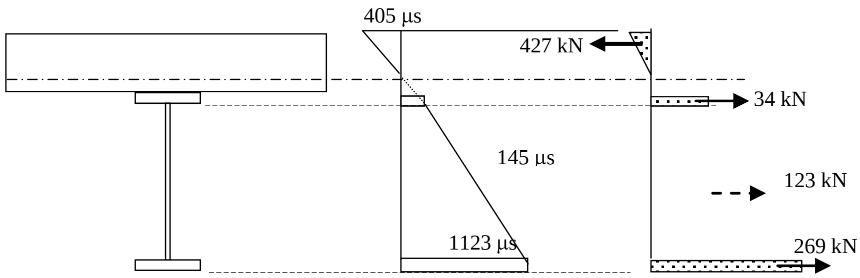
Table 1: Comparison of the Position of Elastic Neutral Axis and Plastic Neutral Axis

Specimen	**Neutral Axis**	**Theoretical (mm)**	**Design (mm)**	**Experimental (mm)**
Composite Beam with flat web section	Elastic (E.N.A.)	88.6	86.5	88
	Plastic (P.N.A.)	35.1	56.3	67
Composite beam with TWP steel section	Elastic (E.N.A.)	83.1	79.5	81
	Plastic (P.N.A.)	29.1	46.8	69

In elastic state, the contribution of trapezoidal web in TWP-composite beam in resisting tension is too small and can be neglected. For this reason, tension force resistance concentrated at the flanges of TWP steel section, causing the bottom flange to yield earlier than the normal flat web beam. It is also found that the position of neutral axis of the composite beam with trapezoid web is higher that TWP steel section in composite beam.



(a) Composite beam with trapezoid web steel section



(b) Composite beam with flat web steel section

Figure : Reaction forces in the concrete and steel area

Since full plastic section did not achieved in both of the specimens, it was unable to locate the position of plastic neutral axis from the experiment. The plastic neutral axis is much greater than the expected value. This can be explained through several reasons. It should be noted that the difference of theoretical and design value is due to the introduced partial safety factor of concrete material.

The first reason for such difference is that the experimental value is obtained when the steel section is not fully yielded. In the rigid plastic theory of composite beam, in order to maintain equilibrium, the whole steel element must yield and only part of the concrete element will be fully yielded (Byfield, et.al, 1998). The second reason is the possible slip strain (Chapman,1994) which is hardly avoided although full interaction shear connectors have been provided.

4.2 Deflection

The plots of loading versus deflection at midspan for both specimens are shown in Figure 10. Within the elastic behaviour of the beams, the composite effect with the concrete material has brought to the common deflection for both types of steel section. Previous test (Tan, 2003) and analytical study (Ihsan, 2001) on the deflection of bare steel sections has shown that TWP section generally deflect more than flat web section. However, within the elastic-plastic region, the composite beam with trapezoid web section deflects less than the control specimen of flat web section, in contrary with the previous finding.

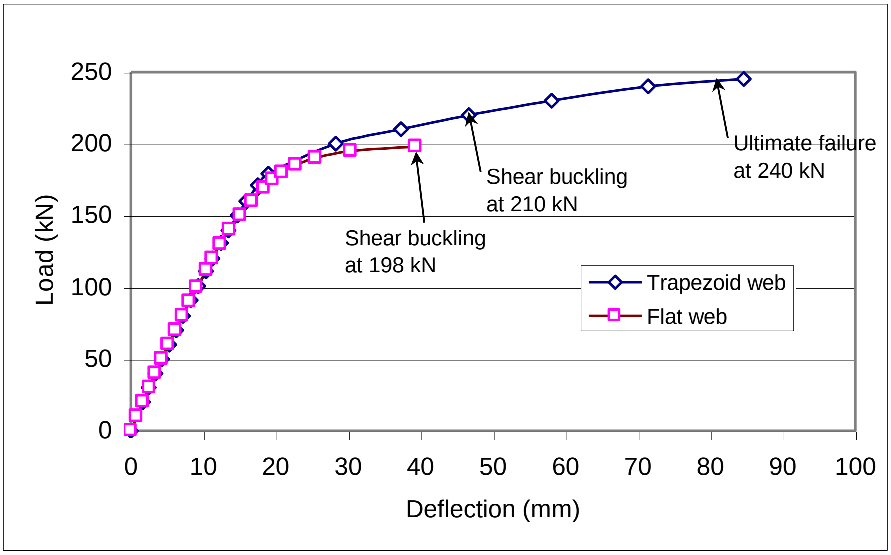


Figure 10 : Plot of loading versus deflection at midspan

From Figures 7 and 8, a contradicting phenomenon is observed where TWP-composite beam suffers greater strain than flat web composite beam whilst it deflects less within the elastic-plastic condition.

Higher strain values can be explained through stress concentration at steel flanges of TWP-composite because the trapezoidal shape of web did not give significant contribution to resist the tensile force, particularly in the elastic range. In this elastic stage, the deflections of both specimens were almost equal. It may be due to the fact that when combined with concrete slab, both composite sections have an equal moment of inertia. This also shows that full steel-concrete interaction has been achieved in the composite beams.

In the elastic-plastic condition, the bottom flanges of the specimens reached their yield strength; TWP-composite beam deflects less than control specimen. There were mainly two possible reasons. First, the roller supports at both ends allowed horizontal movement to the beam. Therefore the trapezoidal shape of web enabled the bottom part of web to spread open in horizontal direction when the bottom flange has became weak after yielding, i.e. when the stress values were greater than 315 N/mm^2. If the loading effect in steel is more significant in horizontal movement than vertical movement, which is always limited by the steel-concrete interaction, then the rate of deflection for TWP-composite beam should be less than flat web composite beam.

Second, stiffness of material governs in elastic stage whereas strength of material governs in plastic stage. After the yield at bottom flange, the yielding of web in flat web composite beam follows. However in TWP-composite beam, the trapezoidal web is still under elastic mode and its stiffness contribution grows when the spreading effect of web slows down, this has more or less limit the vertical displacement of the TWP-composite beam.

In the elastic-plastic stage, particularly after the yielding of bottom flange, composite beam of TWP steel section is able to enhance greater force and deflects less before the web buckles when compared to control specimen of flat web section.

4.3 Ultimate strength

(a) Composite beam with trapezoid web section

At the load of 160 kN, corresponding to a bending moment of 160 kNm at mid-span, the bottom steel flange of the specimen reaches its yield strength at the mid span. Excessive deflection occurs when the load reached 200 kN, where the section change from elastic condition to lower bound of plastic condition. Vertical hairline cracks were observed along both slab edges and there is sign of shear buckling in the flat portion of web near the supports. As the load increased, more minor cracks observed along both of the concrete edges at the mid span region. The cracks include the longitudinal splitting cracks on top of the concrete surface which indicates a compressive failure. From the experimental data, both steel flanges and concrete material reached their tensile and compressive strength respectively at 230 kN (corresponding to 230 kNm), meaning that full plastic section was developed. The web shear buckling was also initiated between loading point and support as shown in Figure 11. The maximum loading on the composite beam was 240 kN.

The shear capacity of bare steel section with trapezoid web is τ_{cr} = 158 N/mm^2, which give the shear capacity of 88.4 kN. The shear buckling of the composite beam specimen was occurred at the load of 210 kN, i.e. 105 kN shear force, an increase of only 11.8 %.

(b) Composite beam with flat web section

For the composite section with flat web, the bottom steel flange of composite beam starts to yield when the load was about 185 kN. The yielding effects continued and spread towards the neutral axis at mid span, as shown in Figure 12. However, premature web buckling was then occurred at the area under loading point, at the load of 198 kN, which prevents the development of full bending strength. The concrete did not reach its maximum compression stress at the maximum load. As concrete is known for its weak in tension resistance, hairline cracks were observed at mid span of the beam at the bottom edge of concrete and along the longitudinal direction at middle of the beam, which is believed to be resulted from longitudinal splitting forces. It indicates that there is a combined failure of bending and shear in the beam.

The objective of loading to ultimate failure in bending was not achieved in flat web composite beam due to earlier occurrence of shear failure before the whole steel section at mid span yield. No stiffeners have been provided to stiffen the web at the shear area is the main reason to this. However, stiffeners are not proposed in this experiment because that will eliminate the advantage of using TWP.

The shear strength of the bare steel section with flat web without intermediate stiffeners is τ_{cr} = 83 N/mm^2. which give V_{cr} = 46.5 kN. The shear buckling was occurred at the load of 198 kN, which resulted in 99 kN shear force along the beam between the loading and support. It means that the composite action of the section has increased the shear capacity more than 100%.

Figure 11 : Failure of TWP-composite specimen due to web buckling near support

Figure 12 : Failure of flat web composite beam specimen due to global web buckling

The comparison of the design and experimental values are shown in Table 2. In bending capacity, it is shown that for both sections, the experimental values exceed the design values. The trapezoid web composite shows a higher bending capacity compared to the flat web composite which was failed prematurely due to shear buckling in its web. Although the ultimate bending moment has not been reached in the flat web composite beam, it seems that, should intermediate stiffeners were provided in the flat web, the shear capacity would increase significantly higher. This may lead to a better performance of composite beam with flat web.

Table 2 : Summary of the ultimate capacity of the composite specimens.

Composite beam with different types of steel section	Shear force		Bending moment	
	Design capacity (kN)	Shear buckling (experiment) (kN)	Design capacity (kNm)	Bending moment at shear buckling (experiment) (kN)
Flat web	46.5	99.0	156.0	198.0
Trapezoid web	88.4	105.0	156.0	210.0

5.0 Conclusions

Bending tests on full scale composite beams have been carried out, one with trapezoid steel section and another one with flat web steel section. Deflections, distribution of strain across the depth of the composite section, and the position of neutral axis, were measured and analysed. In elastic state, the contribution of trapezoidal web in TWP-composite beam in resisting tension is too small and can be neglected. Tension force resistance is concentrated at the flanges of TWP steel section, causing the bottom flange to yield earlier than the normal flat web beam. This is based on the analysis of strain distribution and the position of the neutral axis in both beam specimens. In the elastic-plastic region, especially after the bottom flange reached its yield strength, TWP section shows a better performance with less deflection as well as stiffer web from buckling.

In general, the results show that the composite beam with trapezoid web has no significant advantage in structural performance at elastic stage compared to the composite beam with normal flat web.

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