PARAMETRIC STUDY in THE SEMI-CONTINUOUS DESIGN of MULTI-STOREY BRACED STEEL FRAME USING TRAPEZOIDAL WEB PROFILED (TWP) SECTION

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ABSTRACT: In recent development, British Standard BS 5950:2000 and Eurocode 3 offer the opportunity to design steel frames as 'semi-continuous' by including the moment resistance of 'partial strength' connections in plastic hinge analysis of the frame. Such design method offers various benefits for braced frames such as shallower and lighter beams, standardized connections with less complicated geometry, and more robust frames compared to simple construction. It is also expected to give significant savings in frame weight. This paper presents parametric study findings on a series of two-bay, four-bay and six-bay braced frames of two-, four-, six- and eight-storey with span ranging from 6 m to 9 m, by comparing between Hot-rolled (HR) steel beams designed using simple construction and Trapezoidal Web Profiled (TWP) steel beams designed using the semi-continuous construction method. Flush end-plate and extended end-plate connections were used as partial strength joints whereas for the simple construction, partial depth flexible end-plate connections were used as pin joints. The semi-continuous design method can reduce the frame weight between 13.4% and 20.5% compared to simple construction.

KEYWORDS: Multi-storey Frame, Trapezoidal Web Profiled (TWP), Semi-Continuous Construction.

1. INTRODUCTION

In Malaysia, build-up plate girder is gaining more interest in construction compared to the hot-rolled sections which are limited in size and quite expensive to produce. Economic design of steel plate girders require thin web. However, the web must be strong enough to resist shear forces and local buckling. Besides using stiffeners, one of the innovative ways is to make the web corrugated in shape. Steel sections with such profile are called trapezoidal web profiled (TWP) section. It is locally manufactured by TWP Sdn. Bhd. based in Johor, Malaysia (Hussein, 2001).

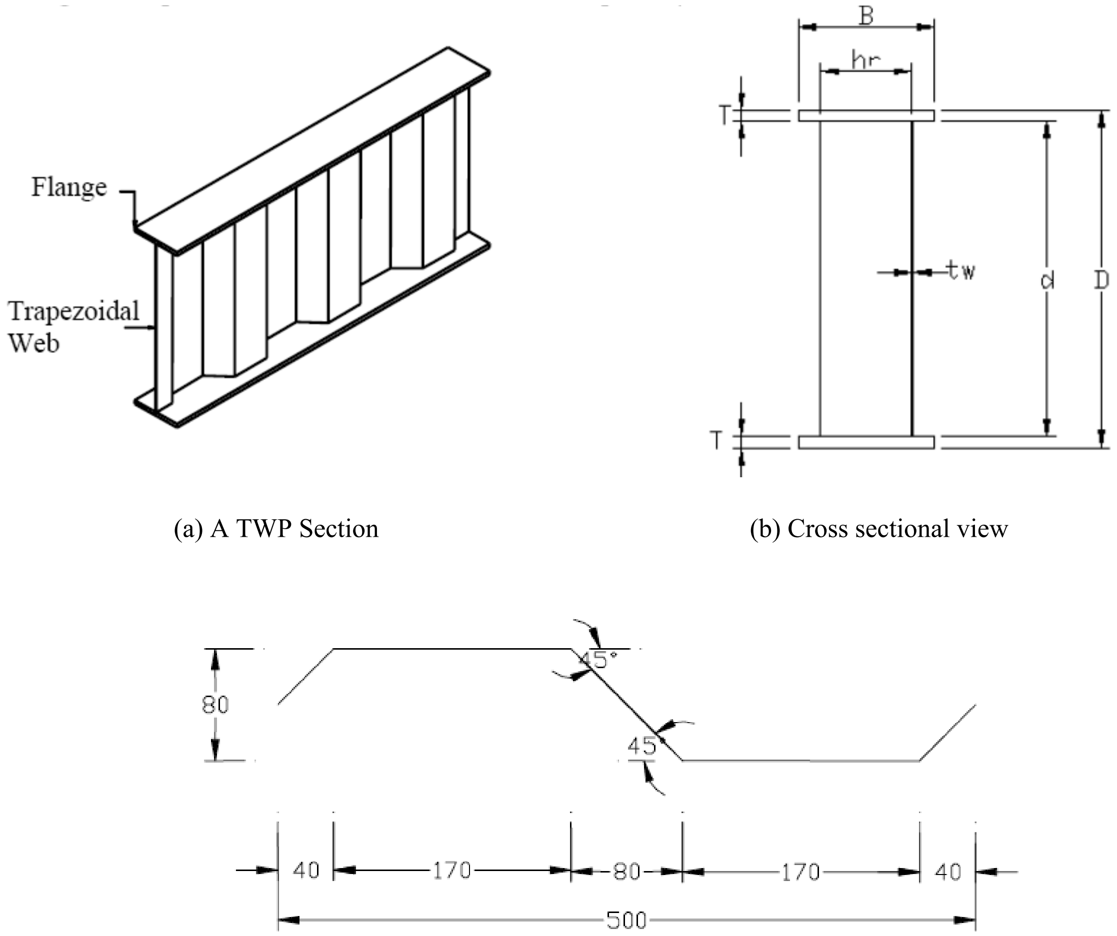
The design of steel frames for most buildings in Malaysia usually assumed that the bolted connections between the beam and column elements are either rigid with associated bending moment or "simple" where the connection resists shear and axial forces only. For buildings higher than three-storeys, some form of shear wall or bracing systems are assumed to be provided and the structures are designed as 'non-sway' or braced frames under vertical loads. In such circumstances, the connections need to be designed to resist shear only. However, many connections, although termed as simple, are in fact relatively stiff and are able to resist significant moment. There is a transfer of moment from the beams to the columns, resulting in a reduction in the maximum beam sagging moment. The method of frame design that takes into account the moment-rotation characteristics of the connections is known as semi-rigid or partial strength design.

Efforts have been carried out in the Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM) to achieve economic benefits from the use of TWP sections in steel frame design. The Steel Technology Centre as a centre of excellence is given the task to spearhead the research aimed at applying advanced steel frame design and to reduce steel weight, which would leads to cost saving and time efficiency in construction..

This paper presents the design approach in integrating partial strength connection with TWP section for the design of semi-continuous construction. It discusses on an innovative development that combining the application of semi-continuous frame design with the utilization of locally produced TWP sections. A comparison between the conventional simple construction and semi-continuous construction design is discussed and analyzed. The objective of this study is to compare the difference of steel weight for braced frame design using hot-rolled sections and Trapezoidal Web Profiled (TWP) sections.

2. TRAPEZOIDAL WEB PROFILED (TWP) SECTIONS

A trapezoid web profile plate girder is a built up section made up of two flanges connected to a corrugated slender web (Osman, 2001). The web is corrugated at regular intervals into trapezoidal shape along the length of the beam. The web and the flanges can be made from different steel grade depending on design requirements. The flanges width ranging from 200mm to 600mm and thickness ranging from 8mm to 50mm are determined based on the depth of the section. The flange is designed for resisting the flexural capacity of the steel structure. The design strength of the flange is usually taken as 355 N/mm^2. The web thickness is in the range of 3mm to 8mm thick. The web is designed for resisting shear and bearing capacity of any point load. The design strength of the web is usually taken as 275 N/mm^2. The web is connected to the flanges by automated welding machine which control the quality of welding. The geometrical aspects of the TWP section are shown in Figure 1. The combination of high strength steel (S355) for flange and mild steel (S275) for web improves the ratio of girder weight to capacity of the section if compared with conventional hot-rolled sections. By using TWP section with otherwise identical dimensions, substantially less material is required and much greater span can be achieved with the same quantity of steel used.



(a) A TWP Section

(b) Cross sectional view

(c) Typical profile of the trapezoidal web

Figure 1 Cross Section of Trapezoid Web Profiled Section

3. SEMI-CONTINUOUS CONSTRUCTION USING STANDARDIZED JOINTS

In a semi-continuous construction, the degree of continuity between the beams and columns is greater than that assumed in simple design, but is less than that assumed in continuous design, as shown in Figure 2. The degree of continuity can be chosen to produce the most economic balance between the primary benefits associated with the two traditional design alternatives (Lawson, 1988; Dhillon, 1999). Couchman (1997) presented a method of analysis and design which permits semi-continuous braced steel frames to be designed by hand calculation. The method was only marginally more complex than the simple design, and the connection details were more straightforward, and therefore inexpensive. Connection forces and moments could be chosen so that column stiffening is not required. The use of partial strength connection leads to the reduction in beam depths and beam weights.

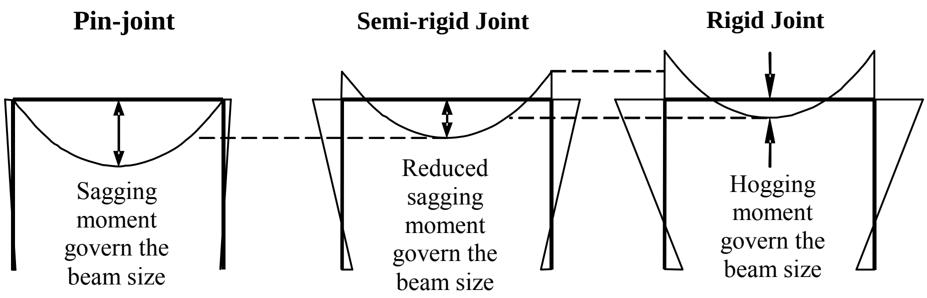


Figure 2 Comparison of Bending Moment at Simple Construction (Pin Joint), Semi-Continuous Construction (Semi-rigid Joint) and Continuous Construction (Rigid Joint)

Flush end-plate and extended end-plate (See Figures 3) are proposed in the standard connections table. The design checking is based on the criteria mentioned in SCI (1995). The connections must achieve three important characteristics, that are the stiffness, strength and ductility. Figure 4 shows a moment-rotation graph of a connection suitable for semi-continuous construction.

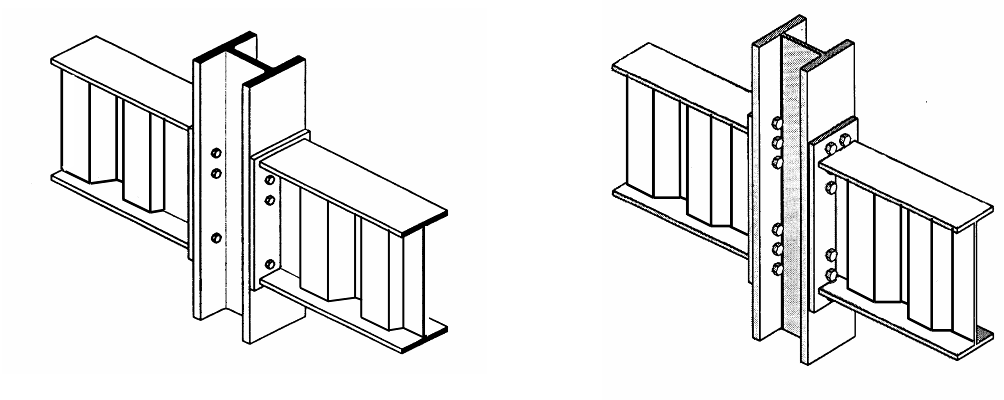


Figure 3 Flush End-plate (Left) and Extended End-plate (Right) Joints for TWP Section

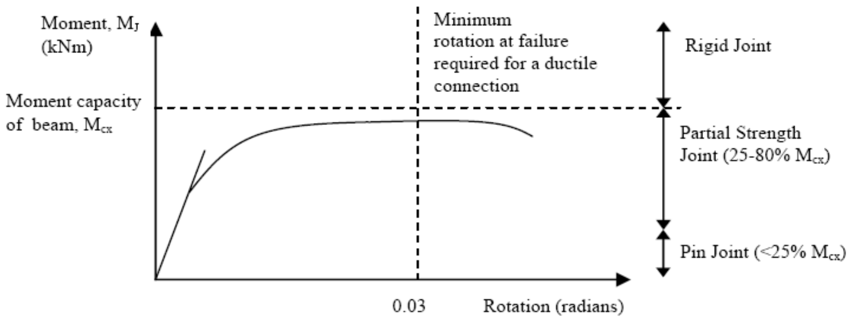


Figure 4 Moment-rotation Character of Partial Strength Joints

4. PARAMETRIC STUDY ON THE DESIGN OF BRACED STEEL FRAME

Parametric study for the design of multi-storey braced frames was carried out. The loadings and frame layout are listed in Table 1 and Figure 5. The frames are assumed laterally braced, where no wind load is taken into the design consideration. The top flange of beams are designed as effectively restrained against the lateral torsional buckling. Two cases of frame design were identified for the parametric study:

i) Design in simple construction, using hot-rolled section as beam.

ii)Design in semi-continuous construction, using TWP section as beam.

Table 1 Loadings and Frame Layout

Loading: Roof: Dead Load, G_k Live load, Q_k Floor: Dead Load, G_k Live load, Q_k	 4.0kN/m^2 1.5kN/m^2 4.0kN/m^2 4.0kN/m^2
Number of Storey	2, 4, 6 and 8 storeys
Number of Bay	2, 4 and 6 bays
Storey height: First Floor Other Floors	5m 4m
Bay width	6m and 9m
Frame's longitudinal width	6m

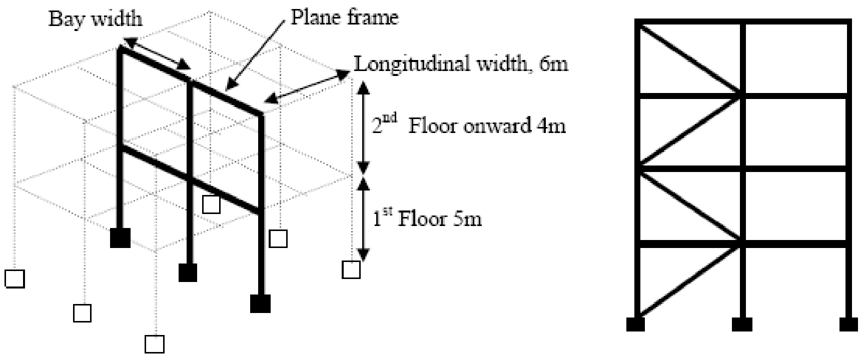


Figure 5 Frame Layout (Left) and Typical Bracing System Against Wind Load (Right)

Manual calculations have been made to track the design steps. An excel design worksheet was later established to support faster analysis and design. All designs were based on BS5950-1:2000 (BSI, 2001). The method of semi-continuous braced frames design was based on the work example drawn by Couchman (1997). Design capacities of flush end-plate and extended end-plate connection were based on the methods mentioned in SCI (1995).

The design in simple construction followed the usual practice according to BS 5950-1:2000 (BSI, 2001). Hence, although the connections were designed for shear only, external columns were designed for a nominal moment due to an assumed eccentricity in the application of beam end reactions. This was taken as 100 mm from the face of the column. If the beam was not a roof beam, the moment was divided equally between the columns above and below. Hot-rolled beam sizes were selected from the list of Universal Beams (SCI, 2003) to provide adequate resistance and stiffness. All beams were subjected to uniformly distributed load, and the design moment in simple construction was therefore $wL^2/8$. The flexible end plate connections were selected to resist the design shears (SCI 1992). According to the code, the following stability check needs to be satisfied in 'simple' construction:

$$\frac{F}{P_c} + \frac{M_x}{M_b} + \frac{M_y}{p_y Z_y} \leq 1.0 \qquad (1)$$

where F is the axial force in column, P_c is the compression resistance of column, M is the maximum end moment transfer to the column on x or y axis, M_b is the buckling resistance moment, p_y is the design strength of steel, and Z_y is the elastic modulus.

In semi-continuous construction, members were designed by taking into account the design moment resistance of the joints. Beams were assumed to be laterally restrained by the floor or roof units. Unlike conventional simple design, the beam was taken to span between the flanges of the columns, assuming that the column sections were obtained in simple design. This was because accurate account was being taken of the moment developed in the partial-strength connection at the face of the column. The total load on the beam was not reduced though, in comparison with simple design. The end moments were selected from tables provided in reference (SCI, 1995) for wind-moment joints, because it is these configurations that have the assured ductility. TWP sections were chosen from the proposed design table. A few iterations were carried out until optimum beam size with adequate connection capacity is chosen. The deflections of the beams were calculated by taking into account the partial restraint of the connection; the limit was checked according to BS 5950: Part 1(BSI, 2001).

For partial strength connections, the columns were checked against overall buckling using the simplified approach outlined in BS 5950: Part 1 clause 4.8.3.3.1:

$$\frac{F}{P_c} + \frac{m_x M_x}{p_y Z_x} \leq 1.0 \tag{2}$$

$$\frac{F}{P_{cy}} + \frac{m_{LT} M_{LT}}{M_b} \leq 1.0 \tag{3}$$

with moment factor, taken to be 0.43. The beam end moment M_{beam} is assumed to be divided equally between the upper and lower column lengths. A further check on the local capacity was made using the equations in BS 5950: Part 1 clause 4.8.3.2:

$$\frac{F_c}{A_{eff}\, p_y} + \frac{M_x}{M_{cx}} \leq 1.0 \tag{4}$$

All column members were Universal Columns of British Steel sections (SCI 2003).

5. RESULT AND DISCUSSION

The results of the parametric study on the two cases of braced frame design are recorded in detail, with an example of the result tables are reproduced here as shown in Tables 2. Summary of the total steel weight for the two design methods, as well as the percentage weight saving of TWP section, are listed in Table 3. Comparison of the percentage steel-weight savings between simple construction and semi-continuous construction are given in Table 4.

As Shown in Table 4, all frame types and beam spans, semi-continuous construction using TWP section offer significant weight savings. The percentage saving ranged from 13.4% to 20.5%. The percentage savings for braced steel frame with 9 m beam span is higher than those of the 6 m beam span, because deep, large hot-rolled section is required for moment capacity as well as to provide adequate stiffness against deflection. TWP sections can offer significant weight savings compared to the large hot-rolled sections. According to Md Tahir (1997), the weight savings in semi-continuous design using Universal Beam (UB) were in the range of 2.38% to 11.95%. Hence by adopting TWP section, the weight saving is even increased up to 9%.

The columns in both simple and semi-continuous designed frames are of the same height and they carried the same axial force. However, due to the partially rigid behaviour, the effective lengths of columns in semi-continuous frame are less than those in the simple construction. It indirectly allowed smaller sections to be chosen for certain columns. For simple construction, steel bracing is needed in multi-storey frame design. However, the weight of steel bracing have not been taken account into this study. Thus it is expected that more percentage of weight-saving can be achieved.

Table 2 Design of multi-storey braced frames in semi-continuous construction using TWP Section

Model No	Frame Type	Dimensions (m)				Gravity Load (kN/m^2)				Frame Analysis Results						Section Designation					
		Width of Bay	Height of columns		Width of Longitudinal Bays	Floor		Roof		Moment (kNm)			Axial Load (kN)			TWP Beam Sections		Universal Columns			Total Steel Weight (tonne)
			Ground	Elevated		DL	LL	DL	LL		Floor	Roof		Internal	External	Floor	Roof		External	Internal	
1	2 Bay	6								1	243	162	1	288	144	450/150/43.4	360/125/35.5	Up to 2nd	203x203x46	203x203x46	2.189
	2 Storey																	Storey			
2	2 Bay	6								1	243	162	1	1584	792	450/150/43.4	360/125/35.5	Up to 2nd	203x203x46	203x203x71	4.559
	4 Storey									2	243		2	1152	576			Storey			
										3	243		3	720	360			2 - 4th	203x203x46	203x203x46	
													4	288	144			Storey			
3	2 Bay	6								1	243	162	1	2448	1224	450/150/43.4	360/125/35.5	Up to 2nd	203x203x71	254x254x107	7.680
	6 Storey									2	243		2	2016	1008			Storey			
										3	243		3	1584	792			2 - 4th	203x203x46	203x203x71	
			5	4	6	4	4	4	1.5	4	243		4	1152	576			Storey			
										5	243		5	720	360			4 - 6th	203x203x46	203x203x46	
													6	288	144			Storey			
4	2 Bay	6								1	243	162	1	3312	1656	450/150/43.4	360/125/35.5	Up to 2nd	254x254x89	305x305x137	11.307
	8 Storey									2	243		2	2880	1440			Storey			
										3	243		3	2448	1224			2 - 4th	203x203x71	254x254x107	
										4	243		4	2016	1008			Storey			
										5	243		5	1584	792			4 - 6th	203x203x46	203x203x71	
										6	243		6	1152	576			Storey			
										7	243		7	720	360			6 - 8th	203x203x46	203x203x46	
													8	288	144			Storey			

Table 3 Total Steel Weight from Parametric Study

Types of Frame	Bay Width	Total Steel Weight (ton)	
		Simple Construction using Hot-rolled Steel Section	Semi-continuous Construction using TWP Section
2Bay 2Storey	6m	2.574	2.189
2Bay 4Storey		5.361	4.560
2Bay 6Storey		8.877	7.680
2Bay 8Storey		13.092	11.307
4Bay 2Storey		4.734	3.964
4Bay 4Storey		10.183	8.563
4Bay 6Storey		16.919	14.508
4Bay 8Storey		25.204	21.430
6Bay 2Storey		6.894	5.738
6Bay 4Storey		15.005	12.564
6Bay 6Storey		24.961	21.335
6Bay 8Storey		37.316	31.550
2Bay 2Storey	9m	4.590	3.735
2Bay 4Storey		10.233	8.506
2Bay 6Storey		16.393	14.083
2Bay 8Storey		23.664	20.488
4Bay 2Storey		8.820	7.056
4Bay 4Storey		19.741	16.166
4Bay 6Storey		31.665	26.861
4Bay 8Storey		45.950	39.386
6Bay 2Storey		13.050	10.377
6Bay 4Storey		29.249	23.827
6Bay 6Storey		46.937	39.640
6Bay 8Storey		68.236	58.283

Table 4 Percentage difference of steel weight (ton) between the semi-continuous construction and the simple construction

Frame	6m Span			9m Span		
	Semi-con	Simple	%	Semi-con	Simple	%
2Bay 2Storey	2.189	2.574	14.96	3.735	4.590	18.63
2Bay 4Storey	4.560	5.361	14.94	8.506	10.233	16.88
2Bay 6Storey	7.680	8.877	13.48	14.083	16.393	14.09
2Bay 8Storey	11.307	13.092	13.63	20.488	23.664	13.42
4Bay 2Storey	3.964	4.734	16.27	7.056	8.820	20.00
4Bay 4Storey	8.563	10.183	15.91	16.166	19.741	18.11
4Bay 6Storey	14.508	16.919	14.25	26.861	31.665	15.17
4Bay 8Storey	21.430	25.204	14.97	39.386	45.950	14.29
6Bay 2Storey	5.738	6.894	16.77	10.377	13.050	20.48
6Bay 4Storey	12.564	15.005	16.27	23.827	29.249	18.54
6Bay 6Storey	21.335	24.961	14.53	39.640	46.937	15.55
6Bay 8Storey	31.550	37.316	15.45	58.283	68.236	14.59

6. CONCLUSIONS

It is concluded that semi-continuous design of braced frames using TWP section is more economical compared to the conventional simple construction. A weight-saving of up to 20.48% can be achieved. For future studies, it is suggested to include the economic aspects of unbraced frame design because more advantages are expected for the use of semi-continuous design method in unbraced frame. Full-scale testing can be performed to study the performance of partial strength connections using TWP beam sections. Further development in the standard design tables for TWP sections using the flush end-plate and extended end-plate connections, as well as the use of computer analysis and design spreadsheet can be done in order to make the new proposed method be more acceptable in the construction industry.

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