APPLICATION OF PARTIAL STRENGTH CONNECTION IN THE DESIGN OF MULTI-STOREY BRACED STEEL FRAME USING TRAPEZOIDAL WEB PROFILED SECTION

Mahmood Md Tahir[1], Tan Cher Siang[2], Thong Chin Mun[2]
[1]*Steel Technology Centre, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor.*
[2] *Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor*

Abstract: Eurocode 3 offers 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. Semi-continuous construction with partial strength connections offers many benefits for braced frames such as shallower and lighter beams, standardized connections with less complicated geometry, and more robust frames than simple construction. It is expected to give significant savings in frame weight. This paper presents 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: *Braced Frame, Trapezoidal Web Profiled (TWP), Partial Strength Connection, Semi-Continuous Construction.*

Abstrak: Eurocode 3 menawarkan peluang untuk merekabentuk kerangka sebagai 'separa-lanjar' dengan mengambilkira keupayaan momen sambungan separa kekuatan dalam analisis sendi plastik kerangka. Pembinaan separa-selanjar dengan menggunakan sambungan separa kekuatan adalah menguntungkan dalam kerangka terembat seperti menghasilkan rasuk yang kurang dalam dan lebih ringan, sambungan piagam yang geometrinya kurang rumit, dan kerangka yang lebih lasak daripada kerangka pembinaan mudah. Penjimatan yang ketara dalam berat kerangka juga dijangkakan dengan menggunakan kaedah pembinaan ini. Penulisan ini membentangkan pemerhatian dalam satu siri kerangka 2 bay, 4 bay, dan 6 bay dengan 2, 4, 6 dan 8 tingkat, di mana rentangnya merangkumi 6 m hingga 9 m dari perbandingan antara rasuk semesta dan rasuk *Trapezoidal Web Profiled* (TWP) dengan menggunakan rekabentuk mudah dan rekabentuk separa selanjar. Plat hujung tidak terjulur dan plat hujung terjulur telah digunakan sebagai sambungan separa kekuatan di mana sambungan plat hujung separa dalam digunakan sebagai sambungan pin. Rekabentuk separa selanjar dapat mengurangkan berat kerangka antara 13.4% ke 20.5% berbanding dengan pembinaan mudah.

Katakunci: *Kerangka Terembat, Trapezoidal Web Profiled (TWP), Sambungan Separa Kekuatan, Pembinaan Separa Selanjar*

1. Introduction

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.

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 Pasir Gudang, Johor.

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 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 analysed. The objectives of this study are:

i) To present the design approach in integrating partial strength connection with TWP section for the design of semi-continuous construction

ii) To compare the difference of steel weight for braced frame design using hot-rolled sections and Trapezoidal Web Profiled (TWP) sections.

2. Conventional Braced Steel Frame Design

A braced steel frame is designed to resist vertical loads only, where the possible lateral loads caused by wind are assumed to be resisted by the bracing system or shear wall. Traditionally, engineers assume that the connections between the beams and columns are pin-jointed, for it is the simplest way of analysis and design. The beam is designed based on the maximum sagging moment, whereas the column is designed to carry axial load with nominal moment caused by eccentric loading (see Figure 1a). Simple beam-column joints are used where the connections are designed to resist shear only.

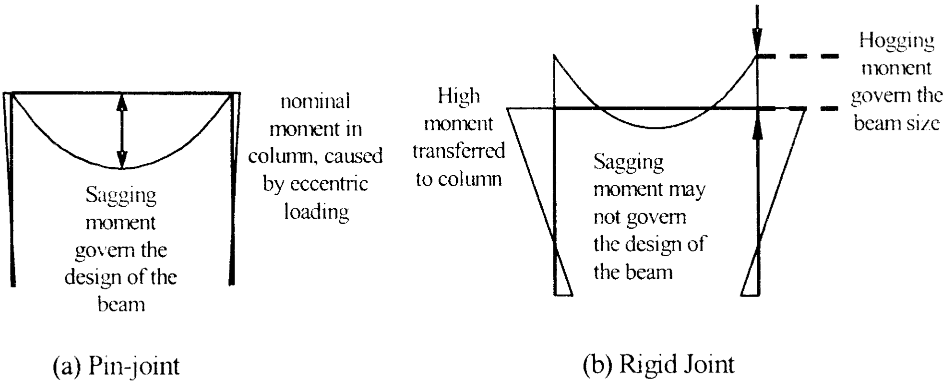


Figure 1: Bending moments of braced frame in simple and continuous construction

Another conventional steel frame design method is to assume that rigid joints are rigid between the columns and beams. This method is named continuous construction design. The design method involves more complicated procedures. The design of beam is governed by hogging moments at both ends, and such moments will increase the size of column (see Figure 1b). The analysis procedure involves matrix conversion and usually a computer program is needed to solve the problems. The rigid connection used is quite complex which will lead to the increase in cost of fabrication.

3. Innovative Development of Braced Frame Design

3.1 Semi-continuous Construction

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).

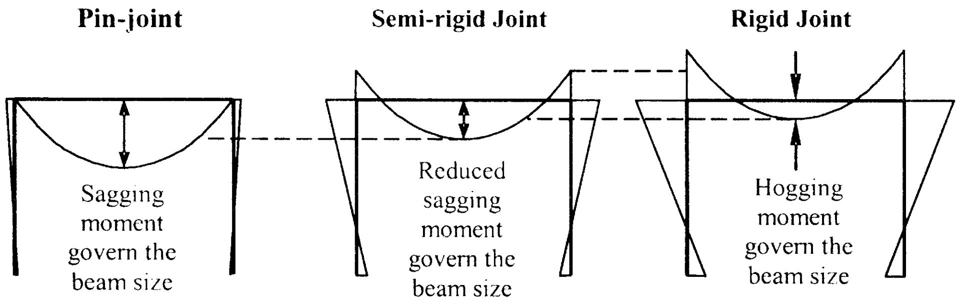


Figure 2: Bending moment diagram for semi-rigid joints.

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.

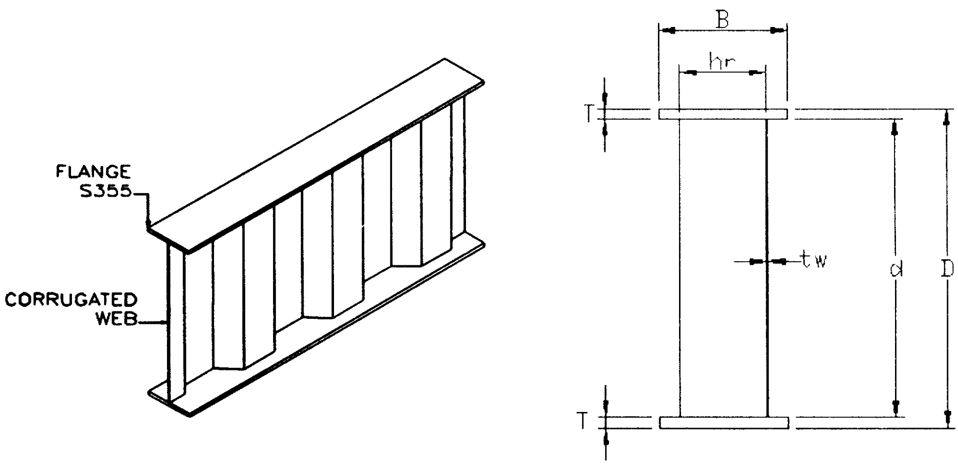
3.2 Application of TWP Sections

Trapezoid web profile (TWP) (Figure 3) is a built up section made up of two flanges connected by a corrugated thin web. In the current practice, the flanges are made from steel grade S355 and the web from steel grade S275. This construction considerably improves the ratio of girder weight to performance compared to conventional hot-rolled girders. By using TWP girders with otherwise identical dimensions, substantially less material is required and much greater span can be achieved with the same quantity of steel used.

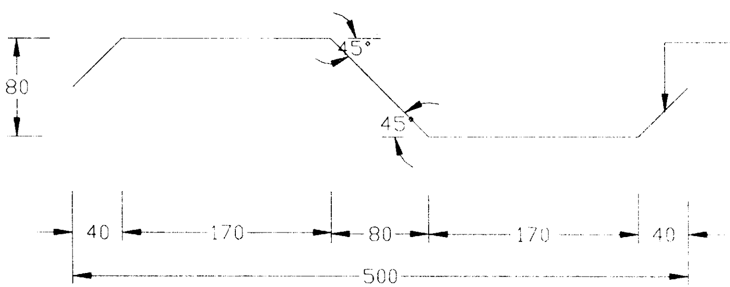
The characteristics and design guidance of TWP sections has been presented by Hussein (2001) and Osman (2001). Here, some of the sections' properties and capacities that would influence the frame design are being highlighted. Conservatively, only the flanges are taken into account in the section properties. As an example, the gross area of a TWP section is equal to:

$$A_g = 2(B \times T) \quad (1)$$

From the same assumption, the other properties of section such as second moment of area (I), plastic modulus (S), elastic modulus (Z) and radius of gyration (r) are calculated.



(a) a TWP section (b) crossed-sectional view



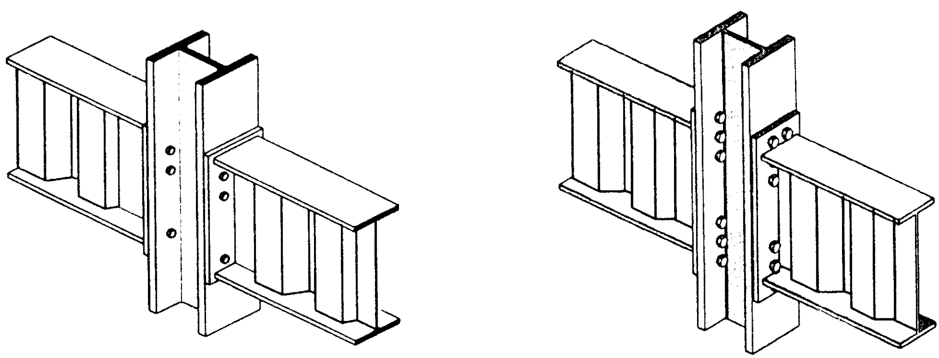
(c) a standard corrugated web profile

Figure 3: Trapezoidal web profiled (TWP) section

The size of the TWP section is basically determined as in plate girder design. However, in order to standardise with the connection design, a series of 'standard' TWP sections are proposed in this study. The sizes of the sections are taken as an equivalent to British Standard Hot-rolled UB section. The member capacities are more or less the same as those of the UB sections, but the weights are relatively lower.

3.3 Application of Standard Connection Tables

Flush end-plate and extended end-plate (See Figures 4(a) and 4(b)) are proposed in the standard connections table. The design checking is based on the criteria mentioned in SCI (1995). The connections must have three important characteristics i.e. the stiffness, strength and ductility. Figure 5 shows a moment-rotation graph of a connection suitable for semi-continuous construction. A total of 14 design tables (see Figure 6) were proposed, where an example involving the flush end-plate connection type was reproduced here as shown in Table 1.



(a) Flush end plate (b) Extended end plate

Figure 4: Two types of bolted end plate of partial strength connections

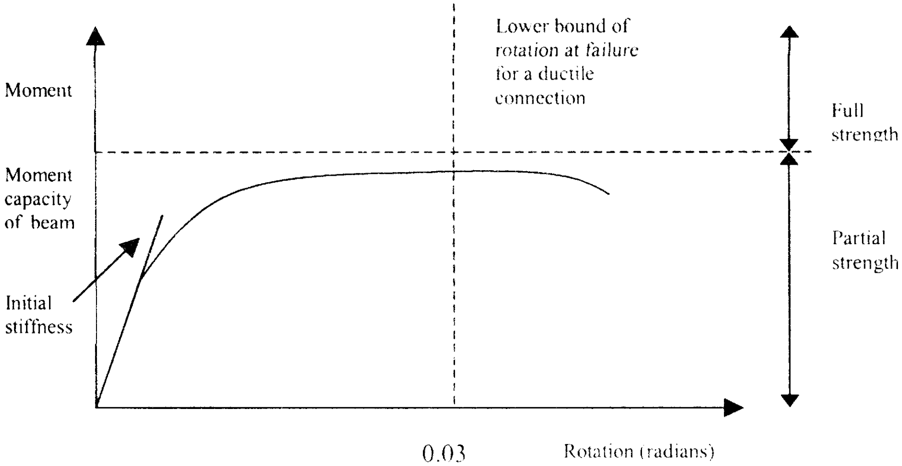


Figure 5: Moment-rotation relationship of a partial strength connection.

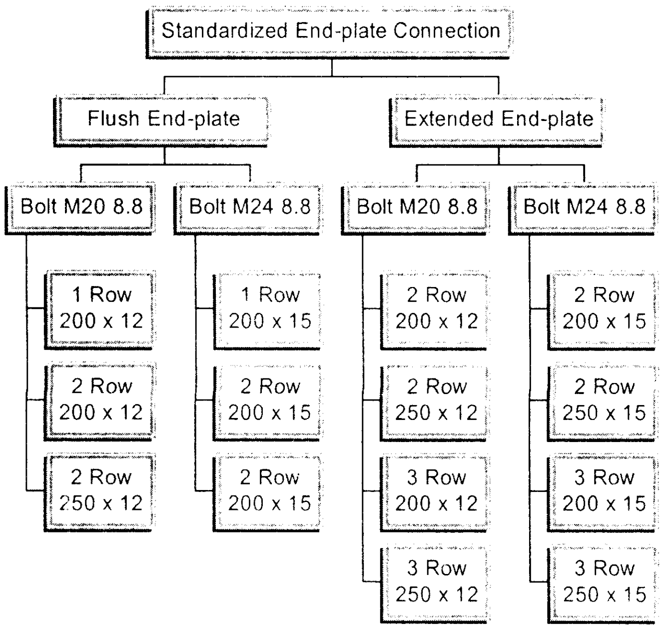


Figure 6: Types of standard connection design tables

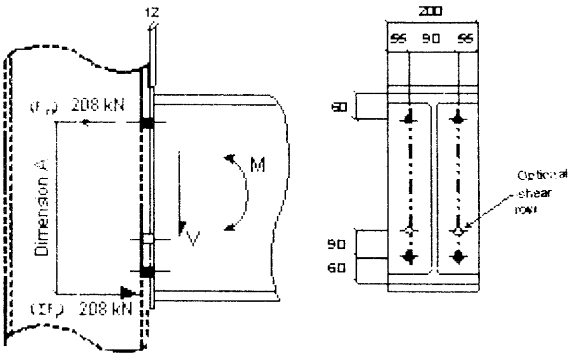
Table1: Flush End Plate Connection Design Capacities

1 Row M20 8.8 Bolts

200 x 12 Design Grade S275 Flush End Plate

TWP STANDARD BEAM

Beam Serial Size	Demension A' (mm)	Moment Capacity (kNm)
460 x 185	393	82
450 x 150	384	80
410 x 175	344	72
400 x 140	335	70
360 x 170	295	61
350 x 125	285	59
310 x 165	244	51
310 x 120	244	51
310 x 100	246	51
260 x 145	195	41
260 x 100	196	41



Vertical Shear Capacity
258kN without shear row
442kN with shear row

4. Parametric Study on the Braced Steel Frame Design

Parametric study for the design of multi-storey braced frames was carried out. The loadings and frame layout are listed in Table 2. 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.

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).

Table 2: Loadings and Frame Layout

Number of Storey	2, 4, 6 and 8 storeys
Number of Bay	2, 4 and 6 bays
Storey height: First Floor	5m
Other Floors	4m
Bay width	6m and 9m
Frame's longitudinal width	6m
Frame bracing	Assumed laterally braced, no wind load is taken into account.
Beam restraint	Top flange of beams are effectively restrained against lateral torsional buckling.
Loading:	
Roof: Dead Load, *DL*	4.0kN/m^2 @ 24.0kN/m
Live load, *LL*	1.5kN/m^2 @ 9.0kN/m
Floor: Dead Load, *DL*	4.0kN/m^2 @ 24.0kN/m
Live load, *LL*	4.0kN/m^2 @ 24.0kN/m

4.1 Simple Construction

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:

$$\frac{F}{P_c} + \frac{M_x}{M_b} + \frac{M_y}{p_y Z_y} \leq 1.0 \qquad (2)$$

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.

4.2 Design of Semi-Continuous Construction

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:

$$\frac{F}{P_c} + \frac{m_x M_x}{p_y Z_x} \leq 1.0 \qquad (3)$$

$$\frac{F}{P_{cy}} + \frac{m_{LT} M_{LT}}{M_b} \leq 1.0 \qquad (4)$$

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:

$$\frac{F_c}{A_{eff} p_y} + \frac{M_x}{M_{cx}} \leq 1.0 \qquad (5)$$

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

5. Discussion

The results of the parametric study on the two cases of braced frame design are recorded in detail, with two examples of the result tables are reproduced here as shown in Tables 3 and 4. 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 5. Comparison of the percentage steel-weight savings between simple construction and semi-continuous construction are given in Table 6.

As Shown in Table 6, 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 3: Design of multi-storey braced frames in semi-continuous construction using TWP Section

Model No	Frame Type	Dimensions (m)				Gravity Load (kN/m²)				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 2 Storey	6	5	4	6	4	4	4	1.5	1	243	162	1	288	144	450/150/43.4	360/125/35.5	Up to 2nd Storey	203x203x46	203x203x46	2.189
2	2 Bay 4 Storey	6								1	243	162	1	1584	792	450/150/43.4	360/125/35.5	Up to 2nd Storey	203x203x46	203x203x71	4.559
										2	243		2	1152	576						
										3	243		3	720	360			2 - 4th Storey	203x203x46	203x203x46	
													4	288	144						
3	2 Bay 6 Storey	6								1	243	162	1	2448	1224	450/150/43.4	360/125/35.5	Up to 2nd Storey	203x203x71	254x254x107	7.680
										2	243		2	2016	1008						
										3	243		3	1584	792			2 - 4th Storey	203x203x46	203x203x71	
										4	243		4	1152	576						
										5	243		5	720	360			4 - 6th Storey	203x203x46	203x203x46	
													6	288	144						
4	2 Bay 8 Storey	6								1	243	162	1	3312	1656	450/150/43.4	360/125/35.5	Up to 2nd Storey	254x254x89	305x305x137	11.307
										2	243		2	2880	1440						
										3	243		3	2448	1224			2 - 4th Storey	203x203x71	254x254x107	
										4	243		4	2016	1008						
										5	243		5	1584	792			4 - 6th Storey	203x203x46	203x203x71	
										6	243		6	1152	576						
										7	243		7	720	360			6 - 8th Storey	203x203x46	203x203x46	
													8	288	144						

Table 4: Design of Multi-storey Braced Frames in Simple Construction using Hot-rolled (Universal Beam, UB) 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)			Univesal Beams		Universal Columns			Total Steel Weight (tonne)
			Ground	Elevated		DL	LL	DL	LL		Floor	Roof		Internal	External	Floor	Roof		External	Internal	
1	2 Bay 2 Storey	6	5	4	6	4	4	4	1.5	1	324	216	1	288	144	406x178x60	356x171x51	Up to 2nd Storey	203x203x46	203x203x46	2.574
2	2 Bay 4 Storey	6								1	324	216	1	1584	792	406x178x60	356x171x51	Up to 2nd Storey	203x203x46	254x254x73	5.361
										2	324		2	1152	576						
										3	324		3	720	360			2 - 4th Storey	203x203x46	203x203x46	
													4	288	144						
3	2 Bay 6 Storey	6								1	324	216	1	2448	1224	406x178x60	356x171x51	Up to 2nd Storey	203x203x71	254x254x107	8.877
										2	324		2	2016	1008						
										3	324		3	1584	792			2 - 4th Storey	203x203x46	254x254x73	
										4	324		4	1152	576						
										5	324		5	720	360			4 - 6th Storey	203x203x46	203x203x46	
													6	288	144						
4	2 Bay 8 Storey	6								1	324	216	1	3312	1656	406x178x60	356x171x51	Up to 2nd Storey	254x254x89	305x305x158	13.092
										2	324		2	2880	1440						
										3	324		3	2448	1224			2 - 4th Storey	203x203x71	254x254x107	
										4	324		4	2016	1008						
										5	324		5	1584	792			4 - 6th Storey	203x203x46	254x254x73	
										6	324		6	1152	576						
										7	324		7	720	360			6 - 8th Storey	203x203x46	203x203x46	
													8	288	144						

Table 5: Total steel weight for the multi-storey braced frame design

Types of Frame	Bay Width	Total Steel Weight (ton)	
		Simple Construction	Semi-continuous Construction
	Beams:	Hot-rolled	TWP*
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

*TWP - Trapezoidal web profiled section

Table 6: Percentage difference of steel weight (ton) between the semi-continuous construction and the simple construction

	6m Span			9m Span		
Frame	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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