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# STEEL WEIGHT SAVING DEVELOPED FROM SEMI-CONTINUOUS CONSTRUCTION IN MULTI-STOREY BRACED STEEL FRAME BASED ON EURO-CODE 3

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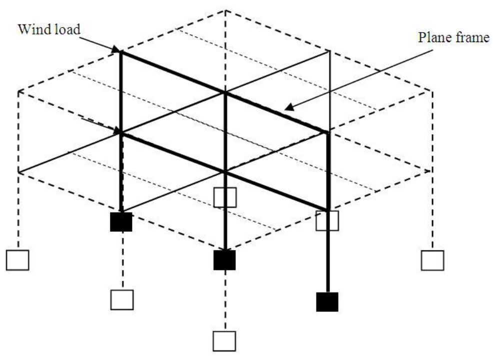


**Abstract**

Steel frames can be designed as simple, semi-continuous, and continuous construction. However, these types of constructions depend on the type of connections used. Connections are usually classified in design as pinned which is associated with simple construction or rigid which is associated with continuous construction. However, the actual behaviour in most cases is classified as semi-rigid connections or partial strength. The semi-rigid connections usually associated with the stiffness of the connection while the strength of this connection usually associated with partial strength. The use of semi-rigid connection has been encouraged by Euro-code 3 and studies on the matter known as semi-continuous construction have proven that substantial savings in steel weight of the overall construction. A series of parametric studies on two bays of two, four, six, and eight storey of multi-storey braced steel frame are presented in this paper. All frames are designed using S275 steel and flush end-plate connection was used as connection for semi-continuous construction whereas fin plate connection was used for simple construction. The frames are designed both as simple construction and semi-continuous construction and the steel weight of the frames was calculated and compared. From the parametric study it was found that by using partial strength connection the saving in steel weight of the frames is in the range of 11.5% to 22.5% of the total steel weight of the frames.

*Keywords*: Beam-to-column connection, Euro-code 3, partial strength, moment resistance



## 1.0 INTRODUCTION

Multi-storey steel frame is classified as braced when the bracing system reduces the horizontal displacement by at least 80% [1]. Typical braced steel frames for buildings can be designed as either "simple" or "rigid", depending on the assumed behaviour of the joints [2]. In designing braced frames, nominally-pinned joints are most commonly used because they are easy to fabricate and save time; they cut the construction cost and manuals on standardised nominally-pinned joints [3] are available to ease the design. Another method of designing a braced frame is to use rigid joints. This method may be used to design beams with a lighter or less deep section. The use of rigid joints in a braced frame contributes a significant amount of moment to the column which results in heavy column sections [4-6]. Rigid joints are difficult and time consuming to fabricate, and usually require substantial stiffening to the column web to resist the large forces arising from the beam end moments; stiffening may also be judged necessary to realise the assumption of rigid behaviour. Overall, rigid joints are not economical and not commonly used in multi-storey construction [4-6]. The most recent approach of designing steel frame and becoming popular is partial strength approach. The advantage of the partial strength approach is that it utilises the moment resistance of connections to reduce beam sizes, while avoiding the use of stiffening in the joints. The potential benefits of using this approach can be listed as lighter beams, shallower beams, greater stiffness, more robust structure, and lower overall cost as compared with the steel frames designed with pinned joint or rigid joint.

A study conducted by J.M. Cabrero and E. Bayo [7] with pinned and semi-rigid connections with steel grade of S275 only using EC3 had been presented. The study showed that weight of semi-rigid frames was 15.7% and 17.3% lighter than pinned frames for (2-storey, 3-bay) regular frame and (2-storey, 4-bay) for irregular frame respectively. A study has been conducted by Nizar *et al*. [8] on a multi-stages design method for steel frames with semi-rigid connection with optimum steel weight. A genetic algorithm was used to optimize on connection, beam and column with the least cost of production were collected from many manufacturers. EC3 are used in design with I and H-cross sections with different span length (5, 6, 7 and 8) m, while steel grade was S275, S235. The research showed that by using semi-rigid connection (flush end plate), a percentage between 14% and 7% of steel weight saving can be achieved as compared with pinned joints. E.S. Kameshki and M.P.Saka [9] presented a research to study the weight saving of multi-storey steel frame with rigid and semi-rigid connections. The study adopted wide flange section from American Institute of Steel Construction (AISC) and UB form BS (British Standard) to the same purpose. The results showed that weight of semi-rigid frames is 11.2% and 15.2% lighter than rigid frame for (3-storey, 2-bay) frame and (10-storey, 1-bay) frame respectively.

## 2.0 SCOPE OF STUDIES

A series of two-bay of two, four, six, and eight storeys, was used to compare the simple construction design and semi-continuous construction design. Comparisons were made with the aim of designing the beam for the lightest section. The structure was assumed to comprise a series of plane frames at 6 m centres. Floors and roof were assumed to span this distance between the plane frames, and therefore the longitudinal beams were designed only to tie the frames together and to provide lateral restraint to the columns at each floor level. Figure 1 shows a general arrangement for a typical plane frame of two bays, within a two-storey structure. Figure 2(a) and Figure 2(b) show typical arrangements for the two contrasting types of connection considered. The first type of pinned connection known as fin plate (see Figure 2(a)) [3] was used in simple construction design. The second type of partial strength connection known flush end plate (see Figure 2(b)) [10] was used in semi-continuous design. To achieve economy in the semi-continuous design, the columns were not stiffened at the joints, the forces transmitted to the columns being limited by the partial-strength nature of the connections. Beams' span was taken as 6m. The column height per storey was fixed at 5m for the bottom storey and 4m for each storey above.

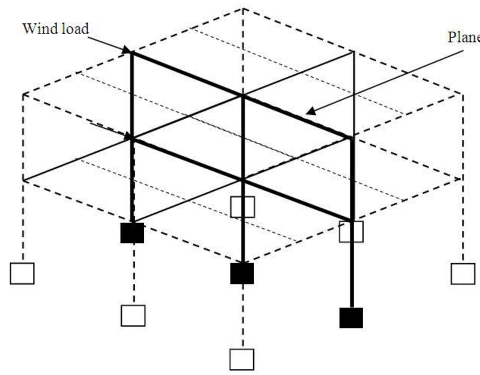


**Figure 1** Layout of a 2-bays and 2-storeys braced plane frame

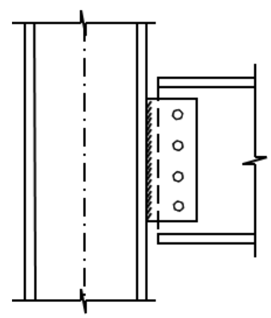

**Figure 2(a)** Fin plate connection

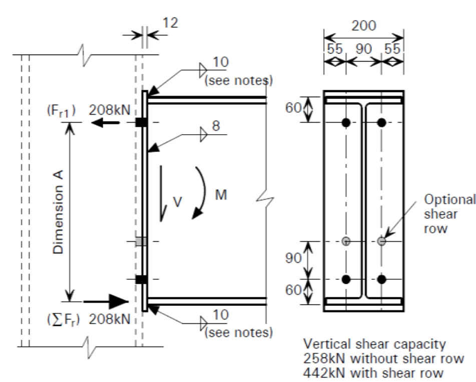


**Figure 2(b)** Flush End- Plate connection

# 3.0 LOADING

## 3.1 Loading on Beams

Permanent load was derived from precast floors and imposed load for office building was taken from BS6399 Part 1[1]. The permanent load was assumed to be of 4.00 kN/m² for both roof and floor levels. The variables load was taken as 4 kN/m² for floor level (including partitions) and as 1.5 kN/m² for roof level. Reduction in live load is made when a column supported more than one level, according to BS 6399 [11].

# 4.0 DESIGN APPROACH

Computer software was prepared by the authors to analyse and design both simple and semi-continuous construction [12]. Two sets of computer programming were prepared. The first set was prepared to analyse and design simple construction frames with pinned joint. The second set was prepared to analyse and design semi-continuous construction frames with partial strength joint.

## 4.1 Simple Construction Design

### *4.1.1 Design of Beams*

The frame is designed based on usual practice according to EC3 [1]. 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 100mm from the face of the column. If a beam was not a roof beam, the moment was divided equally between the columns above and below. All beams were subjected to uniformly distributed load, and the design moment in simple construction was therefore $wL^2/8$. The effective span for beams in simple construction was taken from centre of column to centre of column. Details of the analysis and design are presented elsewhere [12].

### *4.1.2 Design of Columns*

For design of the columns the effective length factor about the minor axis was taken as 1.0, as for simple design. The moment applied to a column was taken as the moment resistance of the connection plus the additional eccentric moment arising from the presence of the joint at the face of the column. The latter moment was therefore determined using an eccentricity of half the depth of the column section. The external columns thereby carried axial load and end moment whereas the internal columns in the studies carried only axial load. The buckling resistance moment for the column section was calculated in accordance with the formula given in Eurocode 3[1]. In EC3-1-1, clause 6.3.3(4) gives two expressions that should be satisfied for member with combined bending and compression. However for column in simple construction, the two expressions may be replaced by a single equation as shown in Equation 1 where details of the terminology used can be referred in EC3-1-1.

$$\frac{N_{Ed}}{N_{\min,b,Rd}} + \frac{M_{y.Ed}}{M_{y,b,Rd}} + 1.5\frac{M_{z,Ed}}{M_{z,cb,Rd}} \leq 1.0 \qquad \text{Eqn. (1)}$$

## 4.2 Design Procedure in Semi-Continuous Construction

### *4.3.1 Design of Beams*

In semi-continuous construction members were designed for a local plastic hinge mechanism, taking into account the design moment resistance of the joints. Beams were assumed laterally restrained by the floor or roof units. The total load on the beam was not reduced though in comparison with simple design. The end moments were selected from tables originally provided in wind-moment joints [10], because it is these configurations that have the assured ductility. The beam section selected had to be at least "compact" to enable its plastic moment to be developed; a restriction to only "plastic" sections was unnecessary as the plastic hinge in the beam section is always the last to form due to the limited resistance of the connections. Beam sizes were selected from the list of Universal Beams to provide adequate resistance and stiffness.

### *4.3.2 Design of the Columns*

For partial strength connections, columns were checked against overall buckling using the simplified approach outlined in EC3-1-1 clause 6.3.3(4) where two expressions should be satisfied for member with combined bending and compression. Bending moment diagrams are assumed to form at least partial double curvature on the column. The beam end moment $M_{beam}$ is assumed to be divided equally between the upper and lower column lengths. All column members were Universal Columns of British Steel sections.

# 5.0 PARTIAL STRENGTH CONNECTIONS

As previously mentioned, beams were designed for a local plastic hinge mechanism taking into account of the moment resistance in connections, with ductility assured by testing [10]. For the partial-strength connections, failure of the end-plate, or the column flanges to which it is attached, can be modelled as an equivalent T-stub flanges as illustrated in Eurocode 3: Part 1:1. The resistance of a beam-to-column connection may also depend on the strength of the beam's flanges, the bolts in the connections, the welds between the beam and end plate, and the resistance of the column web. There are three possible modes of failure for the end plate and the column flange:

Mode 1 Yielding of column flange and/or end plate only.
Mode 2 Combination of yielding of column flange and/or end plate with bolt failure.
Mode 3 Bolt failure only.

To ensure sufficient ductility, strictly only Mode 1 or, with calculation, Mode 2 failure is permitted [10], leading generally to the use of thin end plates. The use of thin end plates also ensures that usually it is the resistance of this component that governs the resistance of the entire connection, provided that Grade 275 steel is used in conjunction with M20 grade 8.8 bolts and suitably robust welds. This permits the moment resistance of standardised connections to be tabulated in a form which is dependent only on the depth of the beam. This greatly eases the task of design. Only flush end plate was used in this study. The standard connection table used in the study are available in SCI publication [10].

## 6.0 APPROACH USED TO CALCULATE TOTAL WEIGHT

The total weight calculated for both simple and semi-continuous construction takes into account all beams, columns, and fittings. The beam's weight was calculated as mass of beam per metre multiplied by the clear span; the latter is defined as the length between the column supports. Typical calculations of total weight are given in tabular form in Table 1 for simple construction and Table 2 for semi-continuous construction of two-storey two-bay frame, designed with beams spanning at 6 metre between column centres. The number of columns determined in Table 3 is counted as column designed for each floor level grouped together as external and internal columns. Percentage weight savings were determined by dividing the total mass difference with the total mass of frame designed for simple construction. The total mass for each frame was calculated by including the mass of the beam section and column section. The mass of beam and column sections were calculated by multiplying the length with the number of designed sections.

**Table 1** Total mass of beams and columns for simple construction for 2 bay 2 storey 6m span

| | **UB section** | **Beam span (m)** | **Total mass of beam (kg)** | **Position** | **UC section** | **Effective Length (m)** | **Total mass of each column (kg)** |
|---|---|---|---|---|---|---|---|
| Roof | 356x171x45 | 6.0 | 270.0 | External<br>Internal<br>External | 152x152x44<br>203x203x52<br>152x152x44 | 4.0 | 176<br>208<br>176 |
| 1st. Floor | 457x152x60 | 6.0 | 360.0 | External<br>Internal<br>External | 152x152x44<br>203x203x52<br>152x152x44 | 5.0 | 220<br>260<br>220 |
| Total mass | 630 x 2 = 1260 | | | 1260 | | | |

**Table 2** Total mass of beams and columns for semi-continuous construction for 2 bay 2 storey 6m span

| | **UB section** | **Beam span (m)** | **Total mass of beam (kg)** | **Position** | **UC section** | **Effective Length (m)** | **Total mass of each column (kg)** |
|---|---|---|---|---|---|---|---|
| Roof | 356x127x39 | 6.0 | 234.0 | External<br>Internal<br>External | 152x152x37<br>203x203x46<br>152x152x37 | 4.0 | 148<br>184<br>148 |
| 1st. Floor | 457x152x52 | 6.0 | 312.0 | External<br>Internal<br>External | 152x152x37<br>203x203x46<br>152x152x37 | 5.0 | 185<br>230<br>185 |
| Total mass | 546 x 2 = 1260 | | | 1080 | | | |

**Table 3** Percentage difference between simple and semi-continuous construction

| **Simple construction design** | | | **Weight in (kg) for number of component required** | **Semi-continuous construction design** | | | **Weight in (kg) for number of component required** |
|---|---|---|---|---|---|---|---|
| Component | Section | Length | Total | Component | Section | Length | Total |
| Roof beam | 356x171x45 | 12 | 540 | Roof beam | 356x127x39 | 12 | 468 |
| Floor beam | 457x152x60 | 12 | 720 | Floor beam | 457x152x52 | 12 | 624 |
| External column | 152x152x44 | 18 | 792 | External column | 152x152x37 | 18 | 666 |
| Internal column | 203x203x52 | 9 | 468 | Internal column | 203x203x46 | 9 | 414 |
| Total | | | 2520 | | | | 2172 |
| Percentage difference | | | | | 13.8% | | |

## 7.0 DISCUSSIONS AND ANALYSIS OF RESULTS

The results of the percentage weight savings are shown in Table 1, 2, and 3 for a plane frame designed for S275 steel. The designed sections of beams and columns for frames studied are listed in Table 4 and Table 5. Table 4 was designed for simple construction approach whereas Table 5 was designed for semi-continuous construction approach. In comparing the two forms of construction, the moment resistance of flush end plate connections shows that beams with partial-strength connections were of lighter section. Although moment is transferred to the external column due to beam end moments, there was no increase in weight of external columns. Within the scope of the study, the percentage savings focus on the span of 6m only. The overall percentage of weight savings in steel ranging between 9.7% to 13.8% for S275 steel as shown in Table 6.

**Table 4** Simple construction design using flexible end-plate connections

| Simple Design for EC 3 with S275 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basic frame type ( 3 panels and 2 bays ) | Span width (m) | Hight of the Column (m) | | Width of Longitudinal Bays (m) | Gravity Load (kN/m²) | | | | Storey NO. | Simple Design | | | | Total Wieght |
| | | | | | Roof | | Floor | | | Universal Beam | | Universal Column | | |
| | | Ground | Elevated | | D.L | L.L | D.L | L.L | | Roof | Floors | External | Internal | |
| 2-Storey | 6 | 5 | 4 | 6 | 4 | 1.5 | 4 | 4 | 1st-2nd storey | 356x171x45 | 457x152x60 | 152x152x44 | 203x203x52 | 2520 |
| 4-Storey | | | | | | | | | 3rd - 4th storey | 356x171x45 | 457x152x60 | 152x152x37 | 152x152x44 | 5237.0 |
| | | | | | | | | | 1st-2nd storey | | | 203x203x52 | 254x254x73 | |
| 6-Storey | | | | | | | | | 5th - 6th storey | 356x171x45 | 457x152x60 | 152x152x37 | 152x152x44 | 8539 |
| | | | | | | | | | 3rd - 4th storey | | | 203x203x46 | 203x203x71 | |
| | | | | | | | | | 1st-2nd storey | | | 203x203x71 | 305x305x97 | |
| 8-Storey | | | | | | | | | 7th - 8th storey | 356x171x45 | 457x152x60 | 152x152x37 | 152x152x44 | 11876 |
| | | | | | | | | | 5th - 6th storey | | | 203x203x46 | 203x203x71 | |
| | | | | | | | | | 3rd - 4th storey | | | 203x203x60 | 254x254x89 | |
| | | | | | | | | | 1st-2nd storey | | | 254x254x73 | 305x305x118 | |

**Table 5** Semi-continuous construction design using flush end-plate connections

| Semi-continuous Design for EC 3 with S275 ( 1 row M20 8.8 bolts 200 × 12 S275 flush end plate ) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basic frame type ( 3 panels and 2 bays ) | Span width (m) | Hight of the Column (m) | | Width of Longitudinal Bays (m) | Gravity Load (kN/m²) | | | | Storey NO. | Simple Design | | | | Total Wieght |
| | | | | | Roof | | Floor | | | Universal Beam | | Universal Column | | |
| | | Ground | Elevated | | D.L | L.L | D.L | L.L | | Roof | Floors | External | Internal | |
| 2-Storey | | | | | | | | | 1st-2nd storey | 406x140x39 | 457x152x52 | 152x152x37 | 203x203x46 | 2172 |
| 4-Storey | | | | | | | | | 3rd - 4th storey | 356x127x39 | 457x152x52 | 152x152x30 | 152x152x37 | 4549.0 |
| | | | | | | | | | 1st-2nd storey | | | 203x203x52 | 203x203x71 | |
| 6-Storey | | | | | | | | | 5th - 6th storey | | | 152x152x30 | 152x152x37 | |
| | 6 | 5 | 4 | 6 | 4 | 1.5 | 4 | 4 | 3rd - 4th storey | 356x127x39 | 457x152x52 | 152x152x51 | 203x203x60 | 7541 |
| | | | | | | | | | 1st-2nd storey | | | 203x203x60 | 254x254x89 | |
| 8-Storey | | | | | | | | | 7th - 8th storey | | | 152x152x30 | 152x152x37 | |
| | | | | | | | | | 5th - 6th storey | | | 203x203x46 | 203x203x60 | |
| | | | | | | | | | 3rd - 4th storey | 356x127x39 | 457x152x52 | 203x203x52 | 203x203x86 | 10724 |
| | | | | | | | | | 1st-2nd storey | | | 254x254x73 | 305x305x118 | |

**Table 6** Braced frames; S275 steel; flush end plate partial-strength joints; 6m span

| | **Flush end plate Beam span 6 metre** |
|---|---|
| | 2 bay |
| 2 storey | 13.8% |
| 4 storey | 13.1% |
| 6 storey | 11.7% |
| 8 storey | 9.7% |

### 7.1 Effect of Changing Connection from Pinned to Flush End-Plate Connection

Table 6 shows the effect to the design of beam as the connection of beam-to-column connection is changed from pinned to flush end-plate connection. The results show that the percentage of savings tends to increase. This is due to the partial restraint provided by the flush end-plate connection that has reduced the design moment of the beam. The determination of maximum design moment in the semi-continuous frame is calculated as $wL^2/8$ minus the moment resistance of the connection. Therefore, the higher the ratio the lesser the maximum design moment of the beam for semi-continuous construction, which results in a smaller section.

## 8.0 CONCLUSIONS

The benefits of semi-continuous construction are difficult to quantify because they depend upon what practice is followed in "simple" construction, and on the range of available sections. Partial-depth end plates with only web welds provide a very economical form of connection for "simple" design. Even so, studies shows an average overall weight saving for a planar frame up to 13.8%. This was achieved using plastic design methods in conjunction with published resistance tables for standard connections. With experience, design calculations therefore take a little longer than those for “simple” design. The flush end plate connections used for the semi-continuous designs were of limited moment resistance, with the result that the same column sections could be used for the two design approaches. The use of partial-strength connections results in shallower beams and worthwhile reductions in the cost of the structure. The increase in the number of storey has not contributed significantly to the steel weight saving as the reduction in steel weight on column is not as significant as beam. Therefore, as the storey height increases the steel weight of the frame tend to reduce.

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