Connections and Frame Design for Economy

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Both BS 5950 and Eurocode 3 permit semi-rigid design, in which only a limited degree of stiffness and moment capacity is provided by the connections. This article explains the benefits of this approach and outlines how these may be achieved. Application in practice is demonstrated.

What is Semi-Rigid Design?
Steel frames for buildings have usually been designed on the basis that beam-to-column connections are either pinned or rigid. The actual stiffness though will fall somewhere between these extremes, giving what is generally termed 'semi-rigid' behaviour. In practice, a connection may also have a resistance which is less than that of the connected beam; such a behaviour is termed 'partial-strength'.

Clearly, the stiffness of the connections, and their resistance, will influence the response of the frame as a whole. It is now more widely recognised that steel frames can be deliberately designed as 'semi-continuous', on the basis of semi-rigid and/or partial strength behaviour. This approach provides greater freedom than the usual procedures, with the connections being chosen by the designer to meet the particular requirements of the structure. The resulting benefits are now explained. So that these can be realised, later sections give guidance on sources of connection data and introduce design procedures for semi-continuous framing.

What are the Benefits of Semi-Rigid Design?
The benefits depend on the type of frame and the usual basis of design. For braced frames this is simple construction, assuming pinned connections. Unpinned frames are usually designed as continuous structures, assuming rigid joints.

**BRACED FRAMES**
- reduction in beam depth
- reduction in frame cost

**UNBRACED FRAMES**
- reduction in complexity of detailing by avoidance of stiffened connections
- reduction in frame cost

The reasons for these benefits are now explained.

Braced Frames
The effect of semi-rigid connections on beam design can be seen by examining the behaviour of a single span member. Fig. 1a shows a simply supported beam, with a uniformly distributed load; the maximum bending moment occurs at mid-span. In Fig. 1b the simple supports have been replaced by fixed supports. The maximum elastic bending moment now occurs at the supports, but is only two-thirds of the former value.

Fig. 1c shows a beam with semi-rigid end connections. Depending on the stiffness of the connection, the maximum elastic moment occurs at the supports or at mid-span, but will always be less than that for a simple beam. Fig. 2 shows that by an appropriate choice of connection stiffness, $S_e$, relative to the beam, the moment at the supports can be made equal to the value at mid-span, thereby minimizing the design moment.

There may well be practical difficulties however in providing such a precise value of stiffness. Also, unless minimising beam depth is the overriding concern, such a solution may not be the optimum. This is because of the additional cost of providing connections with the required stiffness. Fig. 2 shows that the design moment is significantly reduced even if the stiffness of the connections is only modest. A similar pattern occurs when the elastic deflection of the beam is considered, as can be seen from Fig. 3. This suggests that reduced beam depth can be obtained economically by either:
- recognising the inherent stiffness of some types of simple connection, or
- modifying simple connections to a limited extent to provide increased stiffness.
properties. With reference to Fig. 10 these are:

\[ M_{Rd} \quad \text{design moment resistance} \]

\[ S_1 \quad \text{secant stiffness at } M_{Rd} \]

\[ \phi_{cd} \quad \text{design rotation capacity} \]

Methods to determine these properties are given in Annex J of Eurocode 3, for connections with end plates (Fig. 6). Worked examples have been published by the European Convention for Constructional Steelwork (ECCS) and PC-based programs are available.

Formulae to predict the characteristics of several forms of connection not covered by Annex J are also available. ECCS Publication 67 lists the original papers. A forthcoming ECCS publication will treat such connections more fully. This will include formulae for flange cleated connections.

The connection properties relevant to a particular design will depend upon the method to be adopted for global analysis.

For elastic analysis stiffness \( S_1 \)

For rigid-plastic analysis moment resistance \( M_{Rd} \)

Although iteration is often necessary to achieve a safe but economical design, it is desirable that this is minimised by good initial estimates of the relevant connection properties. For braced frames, the beam-line concept (Fig. 11) provides a convenient method to determine the influence of semi-rigid connections on the behaviour of an elastic beam. This approach in effect combines characterisation of connection response, analysis for internal moments and evaluation of performance in one interactive process. Using this method, connection characteristics may be tested by being superimposed on the beam-line (Fig. 11a) to determine the corresponding values of end moment, and thereby the beam design moment. Alternatively, the minimum connection stiffness needed to justify a particular beam section can be determined (Fig. 11b). This

leads directly to the minimum connection resistance \( M_{Rd} \) needed to achieve the elastic connection behaviour assumed in the analysis.

Using a rigid-plastic approach for a braced frame, the moment resistance \( M_{Rd} \) required at the connection is readily determined from consideration of the plastic hinge mechanism (Fig. 4). This approach is particularly recommended because the calculation of a connection’s moment resistance is already an established procedure in design offices. For serviceability, it is not necessary to calculate \( S_1 \) if simplifying procedures are adopted. For example, a conservative value may be assumed for either \( S_1 \) or the end moment under serviceability loading, or reliance may be placed on limiting span : depth ratios.

For an unbraced frame, initial estimates of the moment resistance required at each connection can be determined by a rigid frame analysis. Preliminary connection details can then be determined by designing connections to resist the rigid frame moments, but omitting any stiffeners.

Clearly, for both braced and unbraced frames the use of standard connections enables the designer to refer to predetermined connection properties, as is common for simple connections, thereby reducing the calculations for a particular project.

**Evaluation of Performance**

When an elastic method is used for global analysis, a check is necessary on the resistance of the connection. For unbraced frames the flexibility of the connections will have increased the sway deflections. If these are excessive, the extent of the deflection due to joint flexibility can be determined if a rigid frame analysis has been performed previously, as proposed above.

For end plate connections designed by Eurocode 3, the contribution of each component i.e. end plate, column flange, column web, bolts, welds, to the properties of the connection is readily apparent from the calculations. The connection details can be easily revised therefore to provide a more appropriate resistance or stiffness. A similar approach will be provided for flange cleated connections in the forthcoming ECCS publication.

For braced frames, rigid-plastic analysis has been recommended as an alternative to elastic methods. It will then be necessary to ensure that the connection has appropriate rotation capacity. For bolted end plate and cleated connections, adequate rotation capacity will be available if the moment resistance is governed by the shear zone (Fig. 6) or if deformation capacity is available through yielding of the end plate, the cleats or the column flange. The connections should...
be detailed to provide such behaviour if possible, because otherwise elastic-plastic analysis is needed to determine the rotation capacity required from the connections.

**Practical Application**

Some of the benefits available with semi-continuous framing are illustrated in Figs. 12-13. Further examples of design calculations are presented in ECCS Publication 67.

The structures are load-bearing frames within a braced building, the floor and roof spanning 6m between these frames. All steelwork is in Grade 43 material. The unfactored loads are:

- **Roof**  Permanent 4.5 kN/m² Variable 1.5 kN/m²
- **Floor**  Permanent 5.0 kN/m² Variable 5.0 kN/m²

Calculations to determine suitable member sections are in accordance with BS 5950.

The design shown in Fig. 12 is for simple construction, the beam-to-column connections being made for example by partial-depth or full-depth flexible end plates bolted to the flanges of the columns.

The semi-continuous design shown in Fig. 13 illustrates that worthwhile reductions in beam size can be obtained without increasing column sections. Internal moments are determined by rigid-plastic analysis. Moment-resisting connections are provided by using full-depth end plates. These connections are 'partial-strength'; their design resistances being between 13% and 35% of the connected beams. As this is comparatively low, unbalanced moment due to partial loading does not become critical for the design of the internal columns. The resistances of the connections were determined using formulas based on Annex J of Eurocode 3.

For external columns, the resistance of the column web panel in shear may limit the moment resistance of the connection. In view of this, the most economical arrangement in this example is to provide only one row of tension bolts in the external connections.

The semi-continuous design shows significant reductions in beam sections, leading to a worthwhile saving in cost, fabrication included. Reduction in the depth of floor beam is achieved, without using haunched or stiffened connections.

**Conclusion**

The semi-rigid approach provides greater freedom than simple or fully-continuous design. This is because the properties of the connections are treated as variables in design, to be chosen to meet the individual requirements of each project.

For braced frames, semi-rigid design allows shallower beams and a reduction in the cost of the structural frame. The use of such beams leads to a reduction in the overall height of the structure with consequent additional savings in the total building cost.

For unbraced frames, semi-rigid design reduces the complexity of the connections, resulting in significant savings in the cost of fabrication.

Worked examples demonstrate the practical application of semi-rigid design. Further information is provided in ECCS Publications.

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**Further Reading**