Performance levels and acceptance criteria for joints with rigid semi-rigid and flexible connections
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ABSTRACT

Beams, columns and beam-to-column connections are considered to be the basic structural elements in moment-resisting steel frames. These elements are expected to undergo large inelastic deformations and significant number of inelastic cycles when subject to severe earthquake ground motion. In seismic evaluation procedure, the performance of these elements in the inelastic range is required to be assessed. The element or structure will collapse when the earthquake induced inelastic deformations are larger than the element or structure can tolerate. This paper presents an analytical procedure developed to estimate the inelastic deformations of rigid, semi-rigid and flexible connections in Indian context. The performance levels and acceptance criteria are discussed.

Keywords: Inelastic deformation, rigid-connection, semi-rigid connection, flexible connection.

1. Introduction

Beams, columns and beam-to-column connections are considered to be the basic structural elements in moment-resisting steel frames. Appropriate model requires the determination of the nonlinear properties of each component in the structure that are quantified by strength and deformation capacities. An analytical procedure is developed to estimate the inelastic deformations of beams, columns and connections in Indian context. Bjorhovde and Brozzetti developed a scheme to classify the connections in terms of strength, stiffness, and ductility, using tests and theoretical data. The special cases considered were connections with softening and stiffening characteristics, connections with low ductility, and connections with properties that vary as a function of the applied load sense. The classification system is arranged such that new connection types can easily fit into the current database. Gioncu and Pectu studied numerically and experimentally the available rotation capacity of wide flange steel beams and beam-columns using plastic mechanism. Goto and Miyashita proposed a new classification system for beam-to-column connections, in terms of the boundary between rigid and semi-rigid connections. The connection model used for the classification was the power model proposed by Kishi and Chen. The connection curves for the respective connection types are determined by the initial stiffness and ultimate moment capacity. Mitsuru et al. studied the moment-inelastic rotation behaviour with respect to interior pier sections of steel girder bridges. Yongjiu et al. derived a new theoretical model to evaluate the moment-rotation relationship for stiffened and extended steel beam-to-column end plate connection. They decomposed the connection into several components, including the panel zone, bolt, end-plate and column flange. The complete loading-deformation process of each component is then analysed. Finally the loading-deformation process for the whole connection is obtained.
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by superimposing the behaviour of each component. Ihaddoudene et al.\(^8\) presented a mechanical model in order to take into account the influence of the joints on the behaviour of steel frames. The mechanical model is based on the analogy of three springs, and a non deformable element of nodes describing relative displacements and rotations between the nodes and the elements of the structure. They had drawn the conclusion that the flexibility of joints affects both the internal force distribution and the elements deformation. This paper investigates on the deformation characteristics and acceptance criteria for rigid, semi-rigid and flexible connections by correlating connection rotation with reference length. To assess seismic performance of structure, the connection details and moment–rotation characteristics with well defined performance levels are useful for practicing engineers. The paper presents an analytical procedure developed to estimate the inelastic deformations of rigid, semi-rigid and flexible connections.

2. Beam-to-column connections and behaviour

Beam-to-column connections can be classified as rigid, semi-rigid and flexible depending on the amount of moment transfer taking place between the beam- to - column. The flexible connections are assumed to transfer only shear at some nominal eccentricity. These connections can be used only in non-sway frames where the lateral loads are resisted by alternative arrangement such as bracings or shear walls. On the other hand, rigid connections are necessary in sway frames for stability and also contribute in resisting lateral loads. In high-rise and slender structures, stiffness requirements may warrant the use of rigid connections. The recognised fact that most of structural connections do have some degree of rotational rigidity and efforts to utilise it led to the development of the semi-rigid connections. They are used in conjunction with other lateral load resisting systems for increased safety and performance. Use of semi-rigid connections makes the analysis somewhat difficult but leads to economy in member designs. The analysis of semi-rigid connections is usually done by assuming linear rotational springs at the supports or by advanced analysis methods, which account for non-linear moment-rotation characteristics.

3. Connection response considerations

To facilitate the classification of the responses of the connections to external loading, it must be recognized that since it is necessary to use a specific beam length to correlate the connection rotation and the beam slope, it is also essential that the connection responses can be grouped according to broad ranges of flexural behaviour. Thus, the grouping must reflect the primary connection characteristics. This leads naturally to the overall response types that have traditionally been associated with rigid, semi- rigid, and flexible connections.

The classification system useful to a structural designer, categories the connection behaviour as realistic and practical types of joints. The proposed system achieves this by incorporating simultaneously the three basic response groups, as follows: (1) Flexible connections (pinned); (2) rigid connections (fixed); and (3) semi- rigid connections. The first two of these are currently used in numerous analysis and design programs, and it is not necessary to take into account the semi-rigid connection response characteristics. Thus, the idealized approximation of the moment-rotation behaviour, as perfectly pinned and fully fixed, is sufficiently accurate to represent a small range of connection responses. It is only necessary to consider the connection flexibility for the third category, although it is clear that most realistic connections can fit into this group in some fashion. For this case, the structural analysis must take into account the actual connection response, because it will lead to a more
accurate representation of the behaviour of the structure itself, as well as the fact that it may lead itself to economy for the final product. It is also important to recognize that the increased connection flexibility can produce significantly larger second-order \((P-\Delta)\) effects in the structure, which must be accounted in the design. Since the connection response is nonlinear, it would be logical to have this reflected in the classification system ranges of behaviour. In other words, it is realistic from a strict moment-rotation standpoint to have the regions in the \(M-\Phi\) diagram be bounded by nonlinear curves. This approach also will facilitate using the classification system both for ultimate and serviceability limit states design.

4. Connection performance criteria

The rotation is the essential measure of deformability in the evaluation of the various types of connections, as shown in Figure 1. This was one of the reasons that it was decided to use specific beam element lengths in the development of the classification criteria.

![Connection rotation](image)

**Figure 1: Connection rotation**

Since the reference length concept is based on the need to correlate connection rotation, beam curvature, initial moment-rotation curve slope, and beam stiffness, it is particularly useful in conjunction with serviceability limit states analysis. Outlined the basic principles, whereby the initial stiffness, \(C = EI/L\), defines a straight line that is tangential to the \(M-\Phi\) curve at its origin. The straight line intersects the horizontal line that is defined by the level of the plastic moment of the beam \(M_p\), for a rotation equal to \(\Phi_p\).

The length of the beam is chosen such that the initial stiffness of the beam matches that of the connection. A typical connection \(M-\Phi\) curve is shown in Figure 2. Since connection stiffness vary significantly, it is necessary to use different reference lengths for different connection behaviours. For the same reason that the classification system was conceived in the first place, it is consequently important to categorize the connections with respect to the beam lengths, such that a given length can represent a range of structural joints. In this way, all connection responses can be compared to the single beam curve, and the non-dimensional rotation for the actual connection can be obtained by dividing the \(\Phi\)-values by the \(\Phi_p\) of the beam with the given length. The solution that is presented is a practical one that resolves the complexity of the issue, specifically by recognizing that a representative value of the reference length can be developed on the basis of available test data. Some measure of accuracy is therefore sacrificed for the convenience of a simpler system, acknowledging that the majority of semi-rigid connections will have response parameters that fit the "average" of
the chosen reference length. The ultimate moment capacities for the connection categories also need to be provided along with the rotation capacities. The limits used for connection classification as per IS: 800-2007⁹ is as shown in Table 1 and in Figure 3.

![Figure 2: M-Φ Curves for Beam Elements for Different Lengths (Bjorhvode et al¹)](image)

**Table 1: Connection classification limit as per IS: 800-2007**

<table>
<thead>
<tr>
<th>SL.NO</th>
<th>Nature of the connection</th>
<th>In terms of strength</th>
<th>In terms of stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rigid connection</td>
<td>m₁ ≥ 0.7</td>
<td>m₁ &gt; 2.5θ¹</td>
</tr>
<tr>
<td>2</td>
<td>Semi-rigid connection</td>
<td>0.7 &gt; m₁&gt;0.2</td>
<td>2.5θ¹ &gt; m₁&gt;0.5θ¹</td>
</tr>
<tr>
<td>3</td>
<td>Flexible connection</td>
<td>m₁ ≤ 0.2</td>
<td>m₁ &lt; 0.5θ¹</td>
</tr>
</tbody>
</table>

Note: m₁ = ratio of ultimate moment to plastic moment, θ¹ = Normalized rotation with respect to plastic rotation

![Figure 3: Classification of Connections (Bjorhvode et al¹)](image)

**4.1 Acceptance criteria**
Acceptance criteria are indicators of whether the predicted performance is adequate. An acceptance criteria is a specified indicator in assessing the ability of component to perform its intended function. The acceptability of force and deformation actions shall be evaluated for each component. All structural and non-structural components shall be capable of resisting force and deformation actions within the applicable acceptance criteria of the selected performance level in a structure.

4.1.1 Acceptance criteria for Indian rolled steel sections

The inelastic capacity of members are modelled by defining the performance levels corresponding to the acceptance criteria. The structural performance levels are defined as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). For the acceptable limit values of IO, LS and CP, the values of performance levels recommended by FEMA356 is followed: for performance within the damage control performance range. IO=0.2 Δ, LS=0.6 Δ, CP= 0.8 Δ, where, Δ is length of plastic hinge. The rotation capacity of connections plays a vital role in predicting the plastic hinge formation under seismic condition. An approach is proposed for moment-rotation behaviour of rigid, semi-rigid and flexible connection with Indian standard rolled steel sections as beam members. This appears to hold a promise for a more rational approach to dealing with different type of connections.

The salient moment and rotation characteristics are modelled by following the equations given below in Table 2. Figure 4 shows pictorial representation of performance levels. The inelastic deformation capacities are modelled with yield, plastic and ultimate moment and rotation values of sections. The ultimate moment is taken as 3% of ultimate stiffness of elastic slope and a residual strength ratio of 0.6 is assumed in absence of test data. The yield, plastic and ultimate rotation capacities in terms of non-dimensional numbers is estimated with the developed expressions (conceptually based on IS:800 and Ginocu and Pectu. The expressions are proposed for moment gradient and quasi-constant moment conditions.

![Figure 4: Typical moment vs rotation curve with performance levels](image)
The moment-rotation characteristic behaviour of Indian Standard rolled sections with typical rigid, semi-rigid and flexible connections are shown in Figures 5-7. The performances levels are discrete damage states identified from a continuous spectrum of possible damage states. The generally adopted structural performance levels, immediate occupancy (IO), life safety (LS) and collapse prevention (CP) are defined as follows

### 5.1.1 Immediate Occupancy (IO)

The Immediate Occupancy structural performance level is defined as the post earthquake damage state in which only limited structural damage has occurred. Damage is anticipated to be so slight that it would not be necessary to inspect the building for damage following the earthquake, and such little damage as may be present would not require repair. The beam-to-column connections/elements meeting this performance level ensure that the structure is safe for immediate post-earthquake occupancy, presuming that damage to nonstructural components is suitably light and utility services are available.

### 5.1.2 Life Safety (LS)

The structural performance level, life safety, means the post-earthquake damage state in which significant structural damage has occurred, but some margin against either partial or total structural collapse remains. Some structural elements and components (beam-to-column connections) are severely damaged, but this has not resulted in large falling debris hazards, either within or outside the building. Injuries may occur during earthquake; however, the overall risk of life-threatening injury as a result of structural damage is expected to be low. It should be possible to repair the structure; however, for economic reasons this may not be practical. While the damaged structure is not an imminent collapse risk, it would be prudent to implement structural repairs or install temporary bracing prior to re-occupancy.

### 5.1.3 Collapse Prevention (CP)

The Collapse Prevention structural performance level is defined as the post-earthquake damage state in which the structure is on the verge of experiencing partial or total collapse. Substantial damage to the structure has occurred, potentially including significant degradation in the stiffness and strength of the lateral-force-resisting system, large permanent lateral deformation of the structure, and, to a more limited extent, degradation in the vertical load carrying capacity. However, all significant components of the gravity-load-resisting system must continue to carry their gravity-load demands. The structure may not be technically or economically practical to repair and is not safe for re-occupancy; aftershock activity could credibly induce collapse.

For most steel structural connections, the axial and shearing deformations are usually low compared to the rotational deformation. Consequently, for practical design, it is essential to determine the connections rotational deformations. Hence, with this per view an attempt has been tried to compare the earlier proposed analytical moment-rotation behaviour of typical semi-rigid connections with experimental results Arul et al.11. During the experimental programme, eight specimens of endplate connections which have end plates extended in the tension side alone are studied by stiffening the column webs at the beam flange column interface. The comparison is shown in Figure 8. The results show that proposed expressions provides better understanding of the key behavioural characteristics.
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Figure 5: Moment- Rotation Characteristic behaviour of Rigid Connection

Figure 6: Moment- Rotation characteristic behaviour of semi-rigid connection

Figure 7: Moment rotation characteristic behaviour of flexible connection
Table 2: Proposed expressions for moment-rotation characteristics of beam-to-column connection

<table>
<thead>
<tr>
<th></th>
<th>Moment Gradient</th>
<th>Quasi–Constant Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_p$</td>
<td>$f_y \alpha$</td>
<td>$Z_e \frac{f_y}{1.1}$</td>
</tr>
<tr>
<td>$\theta_0$</td>
<td>$Z_e \frac{f_y}{1.1}$</td>
<td>$Z_e \frac{f_y}{3.3f_y}$</td>
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<td>$M_p$</td>
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</tr>
</tbody>
</table>

Note: For rigid connection $L = 1d$ to $2d$, semi-rigid $L = 2d$ to $5d$ and flexible $L = 10d$ to $15d$, where $d$ is the depth of cross section of beam member meeting at that particular joint/connection, and $\alpha$ is a multiplication factor, $\alpha = 1$ to 0.9 for rigid connection and $\alpha = 0.7$ to 0.45 for semi-rigid connection and $\alpha = 0.2$ to 0.15 for flexible connections.

Moment Gradient: Inelastic behaviour of a simply supported beam loaded by a concentrated force in the midspan.

Quasi–Constant Moment: Inelastic behaviour of a simply supported beam loaded by a uniformly distributed load through out the span.

**Figure 8: Validation of connection behaviour with Arul et al.**

5. Conclusion

The connections are the critical points in any moment–resisting steel frames. The connections are classified according to their strength and stiffness as rigid, semi-rigid and flexible.
paper presents analytical procedure developed to estimate the inelastic deformations of various beam-to-column connections. The rotation capacity of beam-to-column connections plays a vital role in predicting the plastic hinge formation in nonlinear static analysis, which provides an estimate of capacity and performance of the structure under an earthquake. Simplified expressions are proposed to simulate the moment-rotation behaviour of connections using plastic mechanism and validated with published works of Arul et al.\(^\text{11}\). The proposed expressions achieves this by incorporating simultaneously the three basic response groups as rigid, semi-rigid and flexible by correlating connection rotation with reference length. Suggested criteria indicate that an acceptable level of confidence and promises more rational approach for practicing engineers to deal with different type of beam-to-column connections. The moment-rotation characteristic behaviour of typical Indian standard rolled sections under different connection responses are discussed.

**Acknowledgement**

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**6. References**


