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Seismic Design of Composite Semi-Continuous Frames

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Summary

The poor performance of fully restrained frames during the Northridge and Kobe earthquakes has led to a reassessment of the required ductility in steel frames subjected to seismic loads. From the ductility standpoint, one possible alternative to FR frames is the use of semi-continuous or partially restrained (PR) frames. PR connections can undergo large cyclic rotations, exhibit excellent hysteretic behavior, and result in highly redundant, tough structures. However, PR connections are generally not full strength (FS), and their satisfactory performance depends on understanding their cyclic behavior and careful detailing during the design process.

1. Introduction

Although American steel design codes have recognized the use of partially restrained (PR or semi-continuous) construction since 1946, the codes do not provide any specific guidance for their design. However, there has always been extensive use made of these connections in low-rise construction in areas where wind force govern the lateral load design of the structure. For this situation the code has allowed a two-step analysis, where the connections are assumed as pinned for gravity loads and rigid for gravity loads. Extensive parametric studies have shown that under a allowable stress design (ASD) format, this approach provides a safe and economical design [Ackroyd 1987]. In the past few years there has been a trend towards ultimate strength design spurred by the increasing recognition both that seismic design criteria need to be implemented in large areas of the US and that this format has been adopted in codes worldwide. Although under the Load and Resistance Factor Design (LRFD or ultimate strength design) approach the two-step approach has been maintained, there is increasing recognition that more advanced design techniques need to be implemented for the design of structures with PR connections.

The 1994 Northridge earthquake, which severely damaged modern fully rigid (FR) steel moment frames, indicated that there is a need to provide redundancy and toughness to steel frames. Inspections after this earthquake showed that numerous buildings, in which a large number of rigid connections fractured, performed well because of the resistance of the gravity connections. The latter are PR, partial strength connections whose interaction with the slab provided adequate strength and stiffness to resist the lower base shear demand resulting from the increased flexibility of the structural system. While the composite interaction observed during the Northridge earthquake was unintentional, the concept of a partially-restrained composite connection (PR-CC) has been around for many years. Recently, Leon et al. [Leon 1990] among others have shown that these connections possess enough strength, stiffness, and ductility to resist wind and moderate seismic loads. The concept of PR-CCs is currently being applied in the Eastern US to low-rise, commercial structures with large footprints where numerous column lines allow the cumulative effect of the connections to provide the required lateral resistance. Recently two design documents have been developed [Leon et al. 1996; ASCE Design Guide to appear in print in early 1998] to give detailed, step-by-step design procedures. More importantly, the new drafts of both the AISC Seismic Specification [AISC 1997] and the model code promulgated by the National Earthquake Hazard Research Program (NEHRP) [NEHRP 1997] explicitly include this system and assign it specific force reduction, displacement amplification, and system redundancy factors. In this short paper the key aspects of PR-CC design will be discussed and its implementation in codes explained.

2. Partially Restrained Composite Connections and Frames

Partially restrained, or semi-rigid, composite connections (PR-CC) are modified steel frame connections in which additional strength and stiffness are provided by the floor slab. These connections require the addition of shear studs and slab reinforcement in the negative moment regions adjacent to the columns, and utilize the slab reinforcement as the top element of the connection (Fig. 1).

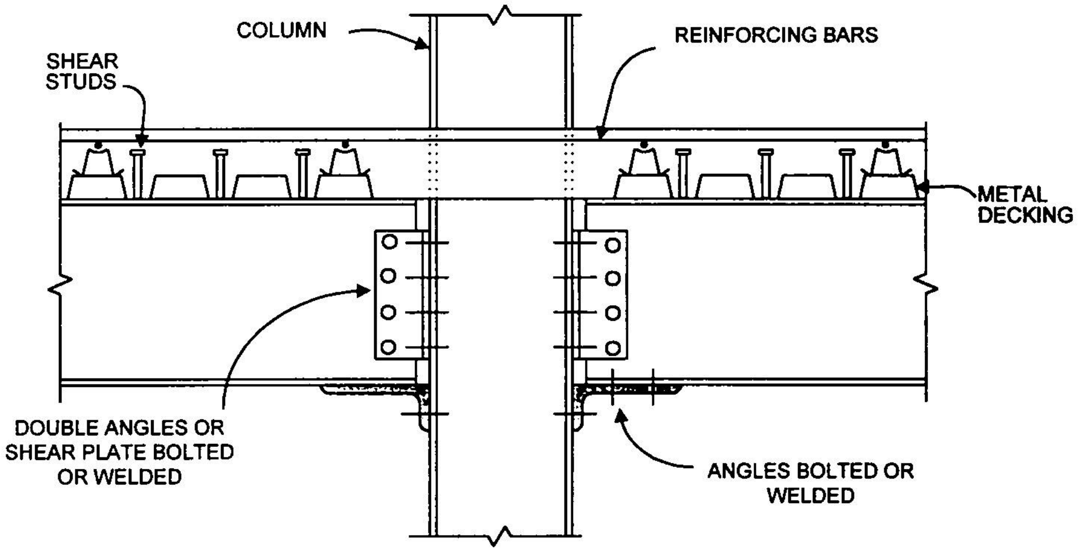

Figure 1 - Typical partially-restrained composite connection (PR-CC).

Several important characteristics of PR-CC design, with particular emphasis on their effect on design procedures and the dynamic performance of the frame, need to be understood:

1. PR-CC connections are typically partially restrained insofar as stiffness and partial strength insofar as ultimate capacity. The designer is free to choose an optimal combination of strength and stiffness for the particular application. Parametric studies indicate that the most efficient connections are those that provide around 70% to 80% of the bare steel beam plastic resistance and have a service stiffness of 10 to 15 time that of the beam [Leon and Forcier 1992].

2. Connection flexibility has a significant impact on the serviceability limit state, and trial designs indicate that the required connection stiffness for drift control under wind loads is the governing parameter in the design. Because of the non-linear characteristics of the moment-rotation curves for PR-CCs, conventional analysis and design procedures, based on rigid, full-strength connections cannot be utilized directly to obtain the forces and deformations in these structures. For the service load level, the use of linear springs in the analysis can be justified if a conservative secant stiffness, rather than the initial tangent stiffness, is used.
3. As the ultimate strength of the connections is reached, plastic hinges will form at the ends of beams. Under increasing monotonic lateral loads, a stable frame-sway mechanism will result only if the connections provide large ductility and a dependable hardening regime. In addition, under cyclic load reversals, the losses of strength and stiffness with cycling have to be controlled so the system provides adequate energy dissipation capacity. For gravity loads, it is recommended that the rotational capacity be at least 0.05 radian. For lateral loads the cyclic rotational capacity must exceed 0.03 radian with less than 20% loss of strength. These stringent requirements mean that careful attention must be paid to the connection detailing.
4. Composite action will resist only loads applied after the concrete has hardened (live, wind, and earthquake loads). Thus the beams need to be checked for construction and dead loads as either simply supported beams or beams with weak PR connections.
5. The effect of the flexibility of the connections on the dynamic performance of the structure is to lengthen its period, and thus reduce its base shear demand. The change in period is very susceptible to the assumption of initial stiffness for the connection. The use of a complete non-linear moment-rotation curve, with the period computed based on the initial stiffness, will result in very small changes in period vs. that of a FR frame. On the other hand, periods computed based on a secant or tangent stiffness near initial yield, can produce large period shifts. It is not clear yet which definition of stiffness should be used for code-type calculations.
6. Analytical studies have shown that structures with PR connections do not necessarily drift more than similar structures with FR connections. In general, the drift of frames with PR connections is within ±20% of that of similar FR frames. The results are sensitive to ground motion amplitude, frequency content,
7. duration, and distribution of energy input with time.
8. The problem of dynamic stability of a frame with PR connections is fundamentally different from that of a frame under monotonically increasing loads. Because the loads are inertial and random, the temporary formation of a mechanism does not imply the collapse of the structure. The study of plastic hinge distribution in PR frames subjected to ground motions indicate that local mechanisms disappear within a few time steps (a typical step is 0.02 sec. or smaller).
9. It is unlikely that the number of frames required to resist lateral loads in a PR frame will remain the same as in a similar FR one. More frames, and in fact all frames if possible, should be used to resist lateral loads in a frame with PR-CCs. This results in a highly redundant and tough structural system.
10. PR-CC connections use continuity and strength that is already built in into many existing structures. Some empirical code provisions and long-established criteria already take the effects of floor slabs and partial restraint into account indirectly. Examples of this include code provisions for calculation of natural periods and the traditional limits for service deflections and drift. Thus, designers need to exercise care when assessing the impact of PR-CC in their designs.

3. Code Implementation

It is important to understand that although many design methods have been proposed for PR frames, there is not yet a consensus in the profession on how to analyze and design PR, partial strength structures. The most important differences between analyses of PR frames and traditional FR steel frames are the need to include both the non-linear behavior and partial strength characteristics of the connections into the analysis of the former. Proposed code language enabling the use of PR-CC construction [AISC 1997, NEHRP 1997] does not contain any specific suggestions for the analysis of PR frames. The references cited by these codes suggest that for preliminary design of regular frames for gravity and wind loads, a two-step approach (service level and ultimate strength) is reasonable. Regular frames are defined as those meeting strict requirements insofar as distribution of strength and stiffness in both plan and elevation. In addition, both codes limit the use of the system to structures under 40 m in height, and to structures not housing critical facilities. The force reduction and displacement amplification factors used for design are equivalent to those permitted for intermediate steel frames. The latter are a class of structures where only minimum seismic detailing is required. Both codes [AISC 1997, NEHRP 1997] set the force reduction factor at 6.0, the displacement amplification factor (inelastic/elastic displacement) at 5.5, and its horizontal overstrength factor is 2.75. Because these new codes have significantly larger design base shears built-in, it is not possible to directly compare them with those given in other seismic codes.

For the service level, an elastic analysis with linear springs can give reasonable values for the required connection stiffness. However, as noted earlier, because the connections have non-linear moment-rotation characteristics, it is necessary for preliminary design to utilize a conservative secant stiffness rather than the initial tangent stiffness for the connections. For the ultimate strength limit state, a simplified second-order plastic analysis [Horne and Morris 1982], based on empirical factors derived from extensive parametric studies [Leon et al. 1996], can provide a conservative estimate of the collapse strength of the frames if the regularity and detailing criteria are met. For final design, a complete non-linear analysis under both proportional and non-proportional loading is suggested. For the case of seismic forces, both proposed codes [AISC 1997, NEHRP 1997] require that non-linear, time-history analyses be run to determine the overall performance of the system.

Because PR-CCs incorporate the floor slab into the frame action, it is important to model this behavior in the analysis and design of PR-CC frames. For analyses using an equivalent static load, it is suggested that an equivalent prismatic moment of inertia (I_{eq}) be used for the beam members. This moment of inertia can be taken as [Leon et al., 1996]:

$$I_{eq} = 0.6 I_{LB+} + 0.4 I_{LB-} \tag{1}$$

where I_{LB+} and I_{LB-} are the lower bound moments of inertia in positive and negative bending respectively.

Preliminary column stability checks should be carried out by assuming that the effective length factor includes the effect of the spring (ASCE 1997). This can be accomplished by assuming a modified I_{eff} for the girder as given by Eq. (2).

$$I_{eff} = I_{eq} \left(\frac{1}{1+3\alpha}\right) \quad \text{where} \quad \alpha = \frac{2\ E\ I_{eq}}{L_g\ k_{conn}} \tag{2}$$

Because for an unbraced frame under lateral loads one connection will be loading and one unloading, the values of the connection stiffness (k_{conn}) on either side of the connection vary. For initial calculations, k_{conn} should be taken as equal to the secant stiffness at the service load level for the unloading side, and as the hardening stiffness of the connection for the loading side.

The force transfer mechanism for this type of connection is shown in Fig. 2. The tensile forces produced on the left side of the connection (sagging or negative moment) are transferred by bearing on the column flange on the other side of the connection through a strut-and-tie mechanism.

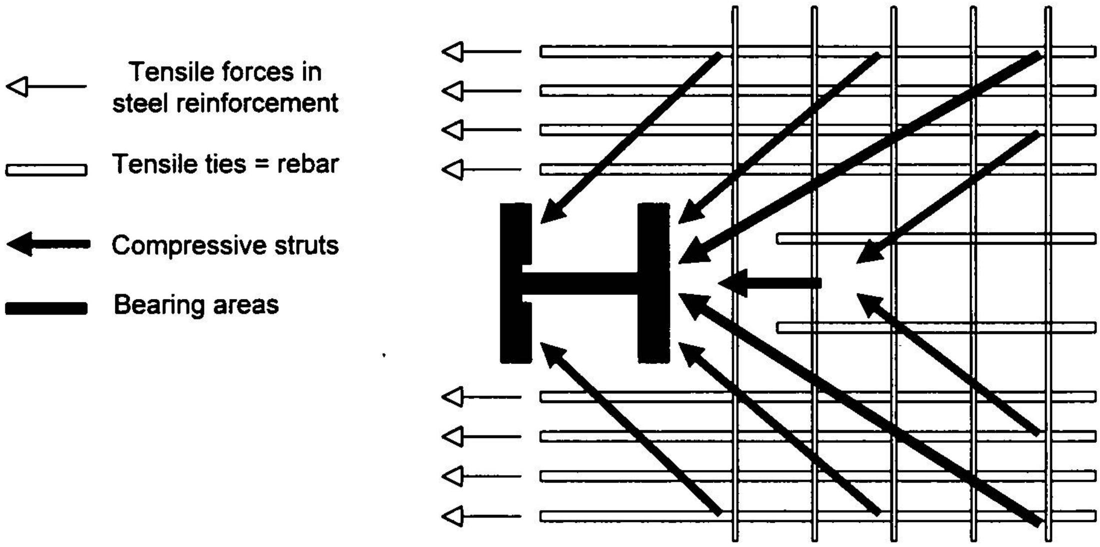

Figure 2 - Force transfer mechanism (simplified strut-and-tie model).

The design of the connections is predicated on achieving a ductile, reliable limit state (yielding of the slab steel under negative moments, for example) well before any brittle failure mechanism (buckling of the bottom beam flange or shearing of the bolts in the seat angle, for example) can occur. The design procedure requires that the following limit states be checked:

1. Shear strength for bolts attaching the seat angle to the beam.
2. Bearing strength at the bolt holes.
3. Tension yield and rupture of the seat angle.
4. Tension strength, including prying action, for the bolts connecting the beam to the column.
5. Shear capacity of the web angles.
6. Block shear capacity of the web angles.
7. Number and distribution of slab bars, including transverse reinforcement, to insure a proper strut-and-tie action at ultimate.
8. Concrete bearing stresses
9. Number and distribution of shear studs to provide adequate composite action.
10. Column panel zone (check the need for column stiffeners).

Design tables for PR-CC connections that meet all of these criteria are available (Leon et al. 1996).

The following detailing rules for the slab steel for structures subjected to seismic forces intend to insure a smooth transfer of forces into the columns, and delay strength degradation with cycling:

1. The slab reinforcement should consist of at least six longitudinal bars, not welded wire fabric, placed symmetrically within a total effective width of seven column flange widths.
2. Transverse reinforcement, consistent with a strut-and-tie model, shall be provided. In the limit this amount will be equal to that of the longitudinal reinforcement.
3. The maximum bar size allowed is 19 mm and the transverse reinforcement should be placed below the top of the studs whenever possible.
4. The slab steel should extend for a distance given by the longest of $L_b/4$ or 24 bar diameters past the assumed inflection point. At least two bars should be carried continuously across the span.
5. All splices shall be designed in accordance with seismic requirements for concrete structures.
6. Whenever possible the space between the column flanges shall be filled with concrete. This aids in transferring the forces and reduces stability problems in the column flanges and web.

4. Conclusions

While the recognition by design codes of the potential of PR-CC connections is encouraging, several important practical issues still need to be clarified. The first is the need for advanced analysis techniques, which is necessary at this stage because little is known about the system behavior for this type of frame. The second is the development of simplified procedures to take into account the strengthening and stiffening effect of the slab on the whole system and not just the connections. A third important practical issue is the development of simplified formulae for the calculation of the natural period of these structures. Finally, it is necessary to investigate the effect of higher modes on the dynamic performance of these frames since non-linear dynamic analysis indicate that this phenomenon may be of greater importance for PR than for FR frames.

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