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DESIGN OF PARTIALLY RESTRAINED FRAMES FOR SEISMIC LOADS

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ABSTRACT

Analyses and design of steel frames are usually carried out under the assumption that connections are either fully rigid or pinned. However in the vast majority of cases the pinned connections actually show partially-restrained (PR) behavior, in particular when the composite action of the floor system is taken into account. While the monotonic behavior of frames with PR connections has been investigated by many researchers, the dynamic response of these frames has not received much attention. The results of a combined analytical/experimental investigation into the behavior of these structures were used to (1) determine the applicability of this structural system to seismic forces, and (b) assess the current state-of-the-art on the design of partially restrained frames in seismic areas. The frames with PR connections showed good seismic performance for ground motions expected in zones of low to moderate seismicity. In particular they showed less problems with buckling of lower-story members and equal or better energy dissipation capacity than rigid frames. The global response factors (R and C_d) for the PR frames are not significantly different from those of the rigid frames, but the PR frames showed more dependable weak beam-strong column mechanisms. Four main areas are identified as needing development of design provisions: calculation of natural periods, development of rational force reduction factors, simplified computations for drift, and stability criteria.

KEYWORDS

Partially restrained connections; PR connections; semi-rigid connections; semi-continuous construction; frame stability; natural periods.

INTRODUCTION

Traditional approaches to frame design overlook the actual response of joints and adopt ideal behavioral models, i.e. the "hinge" model in simple, braced frames and the "fully rigid" (FR) model in continuous construction. In reality most connections exhibit partially restrained (PR) behavior, and recently attention has been focused on this type of framing in areas of low to moderate seismicity for the following reasons:

(1) Large areas of the eastern and midwestern North America have been upgraded to seismic zones with PGA values for design as high as 0.2g (FEMA, 1994), with most areas ranging between 0.05g and 0.10g. In

these areas, where lateral load design was traditionally governed by wind, new construction will have to comply with some minimum level of seismic detailing to insure safety during an earthquake. Thus it is imperative to develop connections that can provide continuity and ductility at economical costs, and PR connections seem to be the best choice.

(2) For the vast majority of low to medium rise buildings, composite floors have become the preferred structural systems for gravity loads. Since their design is most economical when based on ultimate strength limits (AISC, 1994), the economical span-to-depth ratios have increased from about 20 to 24 in non-composite steel construction to 28 to 32 in composite construction. This has led to slender floors prone to problems with both short- and long-term deflection and vibrations. Many of these problems can be ameliorated with the use of PR connections, which significantly reduce deflections and increase the frequency of vibration. This improvement in the stiffness characteristics of the connections for gravity loads will also have an effect for lateral loads, resulting in a more efficient design for seismic forces.

(3) Since connection fabrication and erection represent a significant portion of a structure's cost, the introduction of radically new connection technology will result in significant cost increases. The most logical solution is to modify common connections in use today to increase their strength and stiffness. Since PR connections already possess some flexural strength and rigidity, it is logical to try to improve their performance rather than to promote a whole new technology. This is particularly valid for the eastern and midwestern parts of the US because the seismic demands are lower than in the western US for the type of structure under consideration here, and thus the needed increases in strength and stiffness are easily achievable.

(4) Recent damage assessments from the 1994 Northridge and 1995 Kobe earthquakes indicates that the traditional FR connection (AISC, 1992) used in the western US to resist seismic forces can have unexpected performance problems unless great care is taken in the field welding operations (SAC, 1994). In many cases buildings suffered damage to a large numbers of their FR connections but showed little if any of the non-structural damage that would be expected if excessive drifts had occurred. Many researchers attribute the good performance of the buildings to the action of both non-structural elements and the remaining non-seismic connections. The latter did not possess great strength and stiffness individually, but their large numbers managed to provide a good backup structural system when the primary FR connections failed.

Over the past ten years the author and his co-workers at the U. of Minnesota have developed the concept of partially restrained composite connections (PR-CC)[1]. These connections utilize the additional strength and stiffness provided by the floor slab which is activated by adding shear studs and slab reinforcement in the negative moment regions adjacent to the columns (Leon, 1990; Leon and Ammerman, 1990; Ammerman and Leon, 1990; Leon, 1994). Typically these connections consist of a seat angle, a double angle shear connection to the web, and continuous slab reinforcement across column lines (Fig. 1).

Under gravity loads the slab reinforcement provides the tension part of the couple, while the angle in bearing acts as the compression member. Because of the increase in steel strength (Grade 60 vs. A36 or A572) and lever arm, this detailing adds significant moment capacity to the connection over a typical top and seat angle one. There are also significant stiffness gains because the slab steel yields in almost pure tension and at a higher stress than a top angle. Additional stiffness gains accrue from the use of friction bolts and, at large rotations, from the presence of web angles. Under seismic loading, however, the bottom angle will pull out at relatively low loads resulting in unsymmetrical hysteretic behavior. In addition, the slab will crack and the yielding of the slab reinforcement will localize around the major cracks near the column. This results in a degrading behavior for the system since cracks have to close before the system regains its stiffness.

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[1] The term partially restrained (PR) is equivalent to the terms semi-rigid or semi-continuous used in the literature.

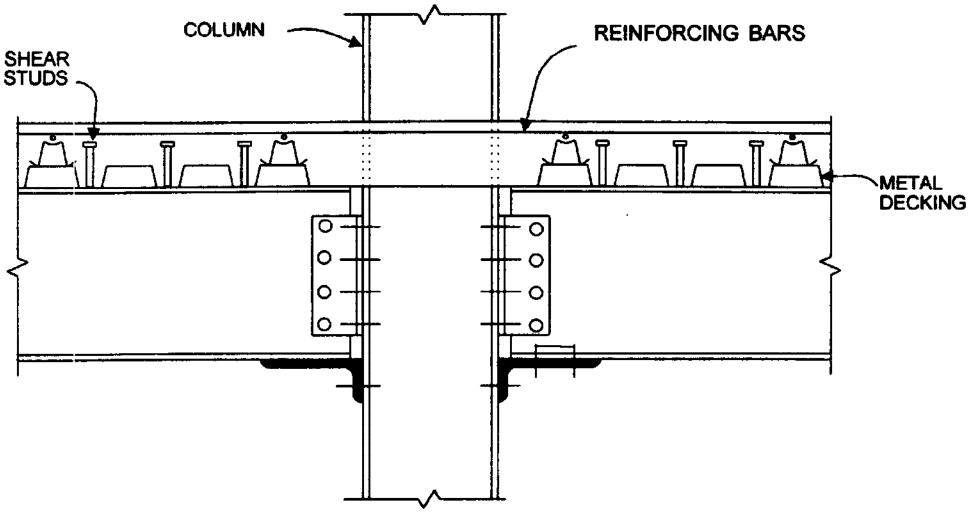

Fig. 1 - Typical PR composite connection (PR-CC).

Figure 2 shows a typical moment-rotation curve for this type of connection, indicating very good initial stiffness, excellent energy dissipation capacity, only minor pinching of the loops as rotations exceed 10 milliradians, and hardening behavior to rotations in excess of 30 milliradians.

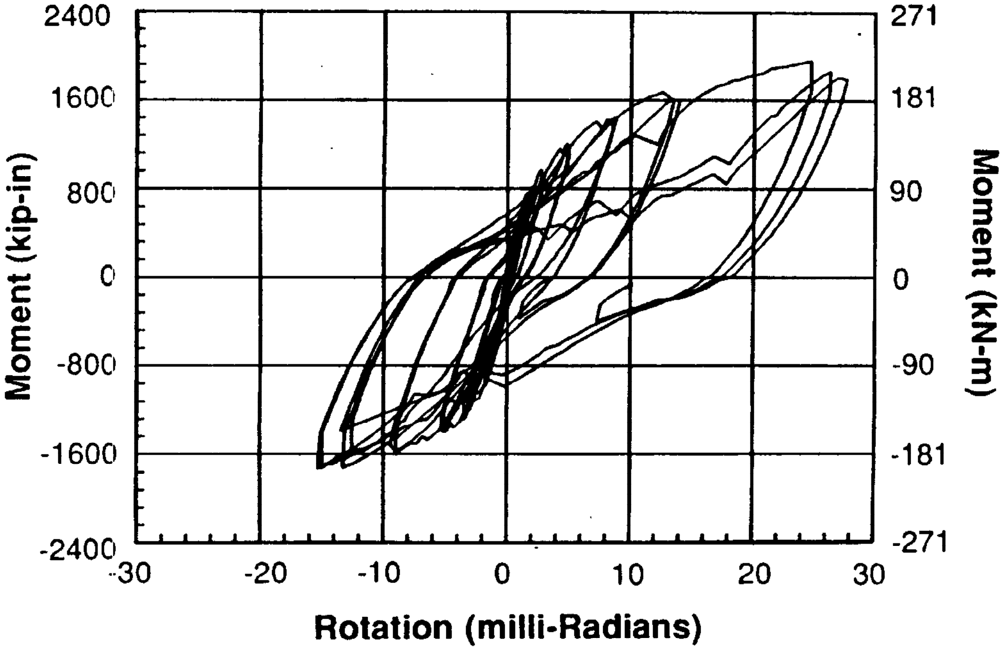

Fig. 2 - Typical cyclic moment-rotation curves for a PR-CC.

PREVIOUS RESEARCH

The concept of a partially-restrained (semi-rigid or semi-continuous) composite system for gravity load applications was outlined first by Barnard (1970) and Johnson and Hope-Gill (1972). A summary of the work in this area up to 1986 can be found in Zandonini (1989), and an updated version in Leon and Zandonini (1992). Until about 1986 most of the work was not very systematic and could be categorized as pilot studies

(Echeta and Owen, 1981[2]). Much of it was carried out on scale specimens under gravity loads (Van Dalen and Godoy, 1982) and was aimed at proving the feasibility of the system rather than at developing behavioral models or design recommendations. More recently, more systematic and comprehensive approaches have been proposed for the design for these connections under gravity loads based on extensive experimental and analytical work (Jaspart et al., 1991; Xiao, 1994; Li, 1994), and this experimental work has been complemented by exhaustive analytical studies for steel PR frames. The few full-scale specimens tested under cyclic loads (Leon and Ammerman, 1987, Leon et al, 1987; Leon 1990; Benussi et al. 1989; Puhali et al, 1990; Schleich and Pepin, 1992) have shown that composite connections possessed excellent strength and ductility characteristics, and that their performance justifies their use in areas of low to moderate seismic risk.

DYNAMIC PERFORMANCE OF PR FRAMES

The issue of dynamic performance of frames with partially-restrained connections has also reached some maturity with the work of Nader and Astaneh (1991, 1992), Deierlein and Zhao (199x), Leon and Shin (1995), and Forcier (1995) to name a few. Only the latter two works, however, include the effect of the slab by modeling the non-symmetric moment-rotation characteristics of the connections and the degradation due to the slab cracking. The work by Forcier (Leon et al., 1995) was for older riveted, encased connections that show very similar behavioral characteristics as PR-CCs, but that work will not be described here.

The work by Leon and Shin (1995) centered on performing second-order, inelastic, time-history analysis utilizing elasto-plastic connection models for all-steel rigid (FR) frames and two unsymmetrical, degrading models for partially-restrained composite (PR-CC) frames. The studies included three frames (4, 6, and 8 stories) designed to the older LRFD Specification (AISC, 1986) and subjected to the El Centro, Pacoima, and Taft ground motions scaled up to 0.4g. A typical result of this work is shown in Fig. 3, which compares the behavior of a six-story PR and a FR frame subjected to the first 20 seconds of the Taft record (PGA = 0.16g).

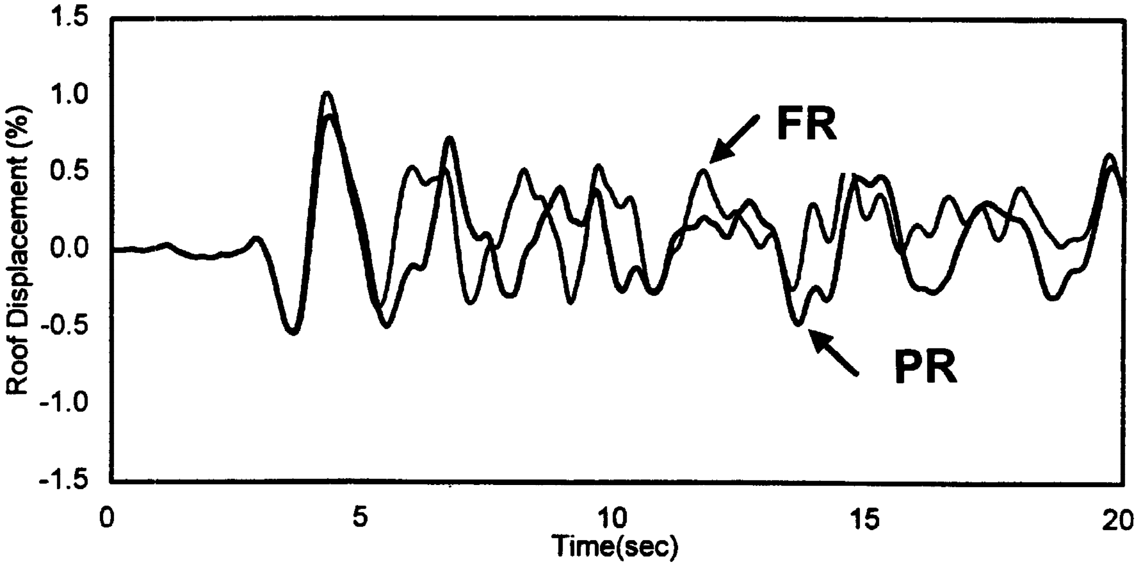

Fig. 3 - Comparison of the top drift for a six-story frame subjected to the Taft accelerogram (Shin, 1992).

The work concentrated on determining the periods, base shears, ductilities and failure mechanisms for the frames. Initially, the four-story PR frame showed only a 6.5% (1.44 sec./1.36 sec.) longer period than the FR frame. For the six- and eight-story frame the periods of vibration of both the rigid and semi-rigid frames were almost identical. This appears to be due to the fact that both the initial slope of the PR-CC is very high, and the moment of inertia of the composite girder used in the PR-CC frames is considerably larger than that of the bare steel girders used in the FR frames. In order to evaluate the change of period after damage, the results of

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[2] Only a few selected references are given for each topic in this section since this is not intended to be a complete literature review.

top story drift of each frame for the Pacoima earthquake were used. These results may give a good approximate period after damage because the amplitude of the Pacoima accelerogram after 12 seconds was nearly negligible. After the damage for the Pacoima earthquake, the vibration period of the composite semi-rigid frames increased 6% (1.54 sec./1.44 sec.), 25%, and 14% for the four-, six-, and eight-story frames, respectively, while the periods for the rigid frames remained unchanged. The computed periods are about 1.9 times longer than the estimation given by the usual code equations. If the actual periods were used in the seismic design, the forces would have been considerably lower than those used.

Given the space limitations, only the results of the six-story frame will be described in detail. The frame had three 31.5 ft. bays and 14 ft. story heights. Typical floor beams were W24x68 with a 3 in. slab on a 2 in. deck. The interior columns ranged from W14x120 at the base to W12x45 at the top two floors; exterior columns ranged from W12x79 to W12x53. All members were A36 steel. For this frame, the maximum drift responses of the FR and PR-CC frames for the El Centro record were obtained at 5.5 and 5.7 second respectively, and that the PR-CC frame drifted significantly more (up to 44%). From the response plots, clear differences could also be seen in amplitudes, waveform, and frequency contents. For the Pacoima record, however, the FR drifted 22% more than the PR-CC. The runs for the Pacoima record indicated that after the maximum response, around 3.8 sec., the amplitude of the drift for the PR-CC decreased rapidly. In contrast, for the FR frame the Pacoima record resulted in a large residual deformation. For the Taft record the FR frame had more story drift (20%), and also a large permanent drift in the positive direction. In general the FR frame experienced response with some high frequency content at moderate amplitudes, while the PR-CC frames seemed to have less high frequency content.

As expected the PR frame attracted less story shear forces than the rigid one for all story levels, with the force at the first story for the PR frame being 71%, 61%, and 84% of that of the rigid one for the El Centro, Pacoima, and Taft records respectively. The interstory drifts showed little correlation between the PR-CC and the FR frames. For the El Centro record, for example, the PR-CC frame exceeded the design limit of 1.5% at the fifth story, while the FR frame exceeded it at the third and fourth levels. It was clear from looking at all the records, however, that the PR-CC frames exhibited a more even distribution of story drifts than the FR frames. In many of the latter the interstory drift seemed to concentrate in a few stories.

The parametric studies indicated that for rock or very stiff soil sites the performance of the PR frames, both in terms of displacement and ductility demands, was superior to that of rigid ones. As the soil conditions approach those of deep cohesionless deposits the frequency content becomes more important, and the critical parameter seems to be the period shift undergone by the structure during the ground motion due to internal damage. For designs in the eastern US this is a critical issue since the expected ground motions are very different from those in the western US which were used in this study (Toro and McGuire, 1987).

The frames with PR connections showed good seismic performance for ground motions expected in zones of low to moderate seismicity (up to 0.4g). In particular they showed less problems with buckling of lower story members and equal or better energy dissipation capacity than rigid frames. However, it was observed in some case that as the PGA increase above the 0.4g limit, the analysis of the tallest frame (eight stories) presented numerical problems. In some case these dealt with the inability to rapidly converge to a unique solution when numerous connections were in the inelastic range, while in others it was associated with the formation of local mechanisms. The latter were due to the fact that the strong column-weak beam design was satisfied at the design level (around connection rotations of 0.01 radian), while the connections model included infinite hardening behavior. Thus when the connection rotations became large (>0.05 radian) on either side of a column, it was possible to exceed the Mp of the columns resulting in a local collapse mechanism which the algorithm used in the program could not handle. A complete design procedure for semi-rigid composite frames, based on current American LRFD specifications, has also been developed [Ammerman and Leon 1990], and design provisions for these frames are now included in the new chapter for composite structures in the latest version of the NEHRP/BSSC design provisions (FEMA, 1994).

DESIGN ISSUES

The brief previous discussion implies that much work has been done on the performance of PR composite connections and frames. While this impression is correct, much work remains to be done if these systems are to be allowed under our current codes as equivalent to the more established FR frames. This is because code-type provisions for PR frames cannot be derived from previous experience and performance in past earthquakes. These systems are "new" and require careful analytical and experimental work before they can be implemented in areas where seismic concerns govern. The four main problems that need to be addressed are the determination of a "design" period, the development of force reduction factors, the development of simplified calculations for ultimate drift, and the assessment of the importance of stability effects in PR frames subjected to cyclic loads. In addition to these four main items, there are numerous secondary issues that need to be resolved.

The issue of the determination of a "design" period is important because the design forces in an equivalent lateral load approach are dependent on this parameter. The use of an equivalent lateral load approach for PR frames was verified by Leon and Forcier (1992) for a large class of regular PR frames under proportional and non-proportional loading. The economical design of PR frames for seismic loads depends on a trade-off between the lower design forces expected and the additional flexibility (drift) implied by the lower connection stiffness. Expressions for the change in natural period due to the presence of PR elastic connections have been proposed by Nader and Astaneh (1992) and Mazzolani and Piluso (1994). Figure 4 shows the ratio of the PR to FR periods as the connection stiffness (K_{conn}) changes.

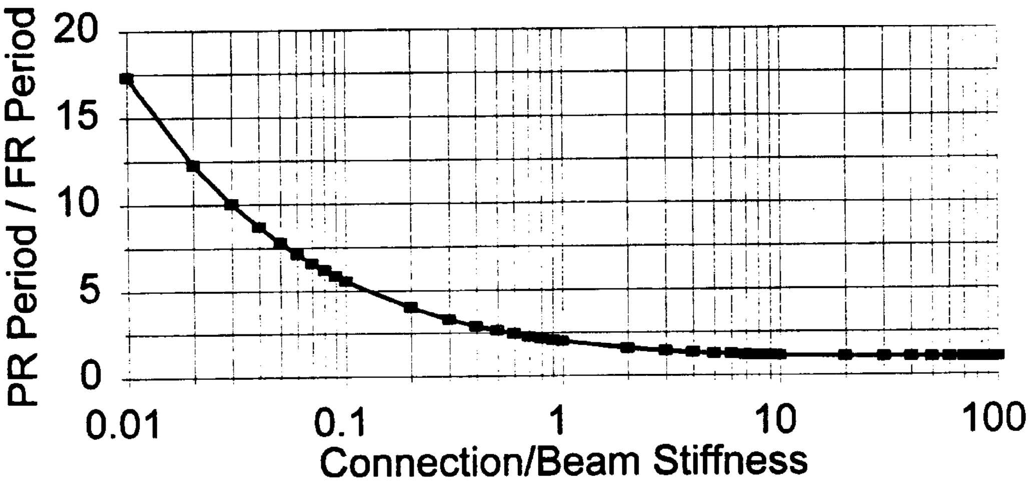

Fig. 4 - Ratio of PR/FR periods with changing connection stiffness for a story subssamblage with equal column and beam stiffnesses ($(EI/L)_{beam} = (EI/H)_{col}$, after Mazzolani and Piluso, 1994).

In most cases PR connections exhibit inelastic behavior from the onset of loading and the determination of the appropriate K_{conn} to use in entering Fig. 4 is problematic. The use of an initial tangent stiffness, which is generally very large, results in periods that are almost equal to those of similar frames with rigid connections. For the frames studied by Shin (1991) discussed above this approach resulted in a period shift of 6.5% for the 4-story frame and no increase at all for the six- and eight-story ones. On the other hand, the use of a secant stiffness to the rotations expected at the seismic design load level results in an unrealistically flexible structure, with increases in period larger than 100% not being uncommon for this assumption. Comparison of the maximum base shears for the PR frames versus those on the FR ones indicates that reductions are on the order of 15% to 25% are to be expected for the ground motions used. This represents increases in natural period of roughly between 25% and 50%. In the design of these frames the use of current design provisions resulted in the need for large stiffnesses to control drift. The ratio of the connection stiffness (K_{conn}) , based on a secant stiffness at the service load rotation of 0.0025 radian, to the beam stiffness (EI/L) was generally in the range of 15 to 25, which puts them close to the rigid classification (i.e., most connection stiffness classifications assume that for $K_{conn}L/EI > 25$ the behavior is similar to that of a rigid connection.) Only Nader and Astaneh (1992) have proposed comprehensive rules for determining the period of a PR frame and the results by Shin (1991) seem to support those proposals. A simplistic proposal that appears to be conservative is to change the 0.0035 constant currently used in calculating the period for steel special moment frames (FEMA, 1994) to 0.0045 and not permit additional increases in the design phase.

The second problem, the determination of force reduction (R) factors, is an area where there has been relative little rigorous work done for PR frames. This is not surprising since even the factors used for well-established structural systems have not been appropriately documented or justified. In most cases the current R factors are justified based on "past performance" and "back-calibration". This is not possible for most PR and PR-CC frames and thus these structures will constitute a challenging problem for the proposed procedures to determine R-factors.

The third problem, the determination of an appropriate displacement amplification factor for frames with PR connections would seem at first even more difficult than the period one. This is because the use of an equivalent lateral load procedure will by necessity result in larger displacement being calculated for a PR frame than for a FR one. Non-linear dynamic analysis, however, indicate that in general the drifts calculated for PR frames subjected to real accelorograms are within +/- 20% of those computed for similar FR frames. No consistent pattern has been found for when the drifts of the PR frames are larger or smaller than those of the FR ones (Shin, 1991), and it is reasonable to conclude for design purposes that the PR frames will not drift more than the PR ones. Thus the use of displacement amplification factors for PR frames similar to those currently used for FR steel frames seems justified. It should be remembered that in areas of low to moderate seismicity it is very likely that the drift due to wind at service loads will actually control the design. Thus the designer will need to use more frames and connections in a PR frame than in a FR one to meet the drift requirements. This provides the structure with significant advantages under seismic loading since there is additional toughness, redundancy, damping, and ability to retain non-structural element participation though a larger portion of the load history.

The issue of stability is one that requires much study and not just for PR frames. Current codes do not provide any in-depth guidance for calculating the stability of steel frames under seismic loads. In particular the issue of the effect of higher modes, which seems of importance in PR frames, is not included in the current equations which are the result of analysis on inelastic SDOF systems. The stability of PR frames is complicated by the use of effective length factors, which require that the effect of the connection stiffness be incorporated into the calculations. The selection of a stiffness, whether a secant or tangent one, and the level at which this is to be computed, factored loads or at collapse, are difficult from the design standpoint. A recent thorough review of the stability of PR under static lateral loads (ASCE, 1996) indicates that the work necessary to arrive at realistic provisions for seismic loads is in its infant stages.

Conclusions

The studies described included three PR-CC frames designed to the current LRFD Specification and subjected to several levels of three different ground motions. They have shown that for rock or very stiff soil sites the performance of the semi-rigid frames is equivalent or superior to that of rigid ones. As the soil conditions approach those of deep cohesionless deposits the frequency content becomes more important, and the critical parameter seems to be the period shift undergone by the structure during the ground motion due to internal damage. The frames with PR connections showed good seismic performance for ground motions expected in zones of low to moderate seismicity.

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