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Seismic Design Study of P-Δ Effect on Steel Frames with Various Connections

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ABSTRACT

This paper presents a study for P-Δ effect on steel frames with various connections. A spectrum method is used to design two semi-rigid sample frames with 5-stories and 10-stories, on which inelastic dynamic time history analysis is carried out for three representative ground motions. The results are presented in the forms of maximum displacement, drift ratio, shear force, and energy input.

INTRODUCTION

Seismic design study on steel frames has shown that a steel frame with more flexible beam-to-column connections has less energy input during an earthquake excitation, and therefore has a potential to cost less in construction. It is a common sense, however, that a flexible steel frame is susceptible to P- Δ effect, which has to be considered in design. It can be shown from static viewpoint that reducing stiffness by introducing flexible connections would increase the P- Δ effect. In seismic design case, the issue becomes complicated because all steel frames are expected to suffer large inelastic deformation to dissipate energy during a strong ground motion. Development of design consideration for steel frames with less rigid connections has been carried out by authors and others, during which it was felt that a complete investigation of P- Δ effect on steel frames with various connection configurations would enhance our knowledge about the issue, and provide very needed information for design of rational design frames. This paper is intended to present an analytic investigation of steel frames with beam-to-column connections with different stiffness, strength and ductility capacity. Two steel frames, with 5 stories and 10 stories respectively, are designed with different beam-to-column connections commonly used in steel construction. Behavior-specific connection computer models have been under development for different connections, and incorporation into general purpose inelastic dynamic analysis programs. The scope of this investigation includes: envelopes of displacement, story drift ratio, shear force, and energy input. Recommendations are made regarding the consideration of P- Δ effect in seismic design of steel frames, particularly with non-rigid construction.

SEISMIC DESIGN STUDY OF SEMI-RIGID STEEL FRAMES

AISC design code allows to design steel frames with semi-rigid beam-to-column connections. However, current seismic code provisions do not provide needed information

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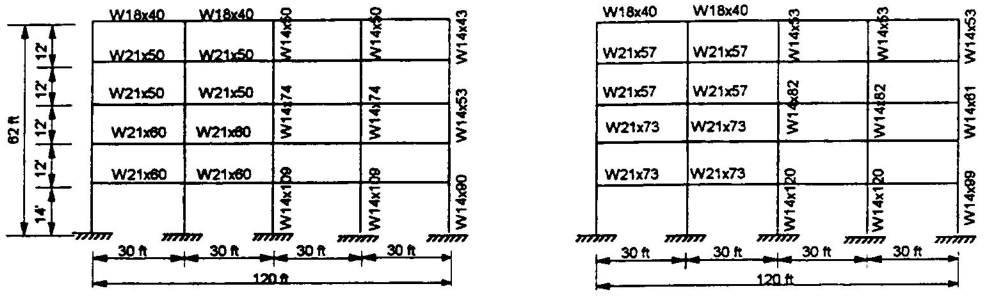
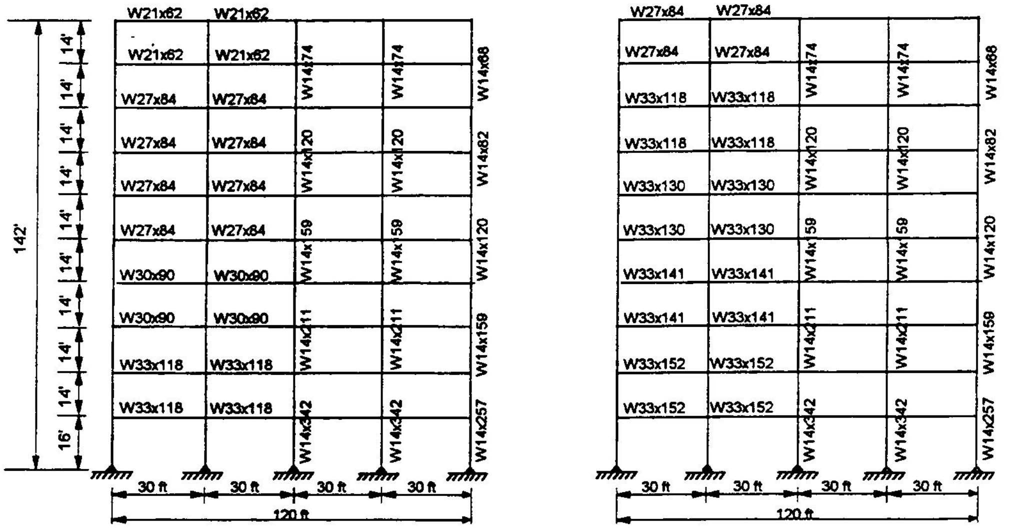
to design a semi-rigid steel frame. For instance, what is fundamental period that will be used in establishment of base shear force? what is the reduction factor, R_w, for a semi-rigid steel frame? What is the drift limit for a semi-rigid steel frame if a static approach is used? These questions will remain until our understanding on seismic response of semi-rigid steel frames is further developed. Furthermore, as more and more powerful computers appear on the desks of design engineers, computer-aided seismic design will soon become a common practice, which requires only rational procedure, not simplification made for classical design practice. In the process towards the development of computer-integrated design in this study, a rational design method is introduced to construct modal semi-rigid frames to be studied on the basis of practice in steel structures and principles of structural dynamics [Shen, Akbas, and Demirtas, 94]. The method consists of a set of iterative steps. An accompanying rigid steel frame is designed based on well-known static procedure as well as spectrum method described in UBC,94. Peak ground acceleration in the spectrum is selected so that the dynamic base shear is comparable to the base shear based on the static procedure. Starting with the rigid steel frame, one can design a semi-rigid frame by introducing semi-rigid connections at beam ends with targeting connection-to-beam stiffness ratio, α (α = K_0/ (EI/L) of beam, where K_0 is initial stiffness of connection, E Young's modules, I moment of inertia, L the span of a beam) under factored gravity and specified earthquake load in the form of response spectrum. The method tends to be rational rather than simple to serve as a specific purpose of designing analytic semi-rigid frame models under study. A semi-rigid frame so designed has same design ground motion as its counterpart of the rigid frame, but lighter sections due to the fact that flexibility of connections elongates vibration periods of the frames. Drift limitation is not considered in the design because stiffness-controlled design may loss the generosity of the study. Two sets of frames, 5 stories and 10 stories, are given in Figure 1. The planes of the buildings are symmetrical, and have two perimeter frames in both directions with four 30-ft bays. Dead load of 100 psf and live load of 50 psf are used in the load combination of 1.2 DL + 0.5 LL + 1.5 E for all members, except the roof floor, at which dead load of 80 psf and live load of 20 psf were used in the combination. Design response spectrum on stiff soil (UBC-S_1) with peak acceleration of 10% gravity was found to generate similar base shear in both 5- story and 10-story rigid frames to what the static method predicted with 5 and 10% percent differences. LRFD code provisions were used in the design with A36 steel. The semi-rigid frames were designed with α = 15 for both 5-story and 10-story buildings (Figure 1.(a) and (c)). Also listed in the figure are the associated rigid frames (Figure 1.(b) and (c)). Strong column and week beam requirement is released in the design of rigid frame .



(a) Semi-rigid Frame - 5SRF

(b) Rigid Frame - 5RF



(c) Semi-rigid Frame - 10SRF

(d) Rigid Frame - 10RF

Figure 1. Semi-rigid frames and associated rigid frames

SEISMIC ANALYSIS OF THE FRAMES

The two-dimensional models of frames were built for nonlinear time history analysis using a general purpose inelastic dynamic analysis program, DRAIN-2DX [Prakash, Powell, and Campbell, 93]. Semi-rigid connection elements were arranged at each beam-to-column joint. Three inelastic beam elements were used in each span of girders. P-M interaction relation, suggested by LRFD, was used as yielding surface of column elements. The beam-column elements have two bi-linear lumped plastic hinges and an elastic beam segment. 5 % of initial stiffness was assumed for the post-yielding stiffness of connections, beams and columns. Second-order effect (P-Δ effect) was introduced approximately by adding additional vertical trusses introducing constant geometric term in the tangent stiffness. Three representative earthquakes, El Centro, Taft, and Miyagi-Ken-Oki, were factored to 0.35g as seismic excitations. The dynamic analysis of the frames included the dead load and each of the excitations. A step-by-step time integration with constant acceleration assumption was used in the dynamic analysis. Mass was lumped at joints, and 2% viscous damping was included.

SEISMIC RESPONSE OF THE FRAMES

Results from nonlinear time history analyses are presented in the forms of envelope of displacement, drift ratio, and shear force, and energy input as the average values of three representative earthquakes.

Envelopes of Displacement and Story Drift Ratio

The envelopes of the maximum values for displacement and drift ratio obtained from the inelastic analysis are presented in Figures 3 and 4, respectively. From the analyses of the results shown in these plots, the following can be observed.

1. For 5-story building, P-Δ effect is not much significant on displacement but on drift ratio. By decreasing stiffness, P-Δ effect becomes less important..
2. For 10-story building, except for rigid case, P-Δ is quite significant with varying α and β values at top stories, but has less effect at lower stories.

Shear Force Envelopes

Figure 5a and 5b show the distribution of maximum shear forces. The following can be observed.

1. For 5-story building, the shear force decreases when P-Δ is included compared with standard analysis for all cases.
2. For 10-story building, P-Δ effect becomes very significant.
3. High mode participation is significant in semi-rigid frames for both standard analysis and P-Δ analysis.

Energy Input

Total energy input for different cases for both structures is plotted in Figure 6a and 6b. The following can be seen.

1. The energy input is not very sensitive to the variation of α and β.
2. In most cases, semi-rigid frames attract less energy than rigid frames do.
3. In general, when P-Δ is included, 5-story building attracts less energy compared with standard analysis, but more energy for 10-story building.

CONCLUSIONS

From the investigation carried out in this study, the following conclusions can be drawn:

1. P-Δ effect is insignificant in the seismic response of low-rise semi-rigid frames;
2. P-Δ effect has significant effect on seismic response of high-rise frames no matter what types of connections are used.

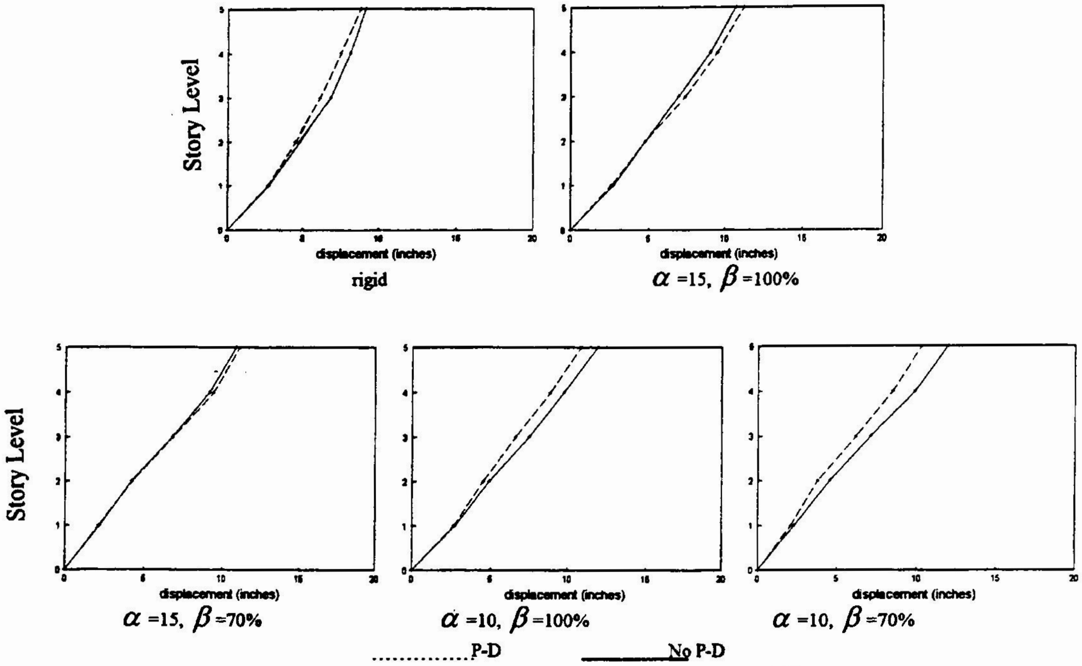


Figure 3a. Envelope of Displacements - 5S

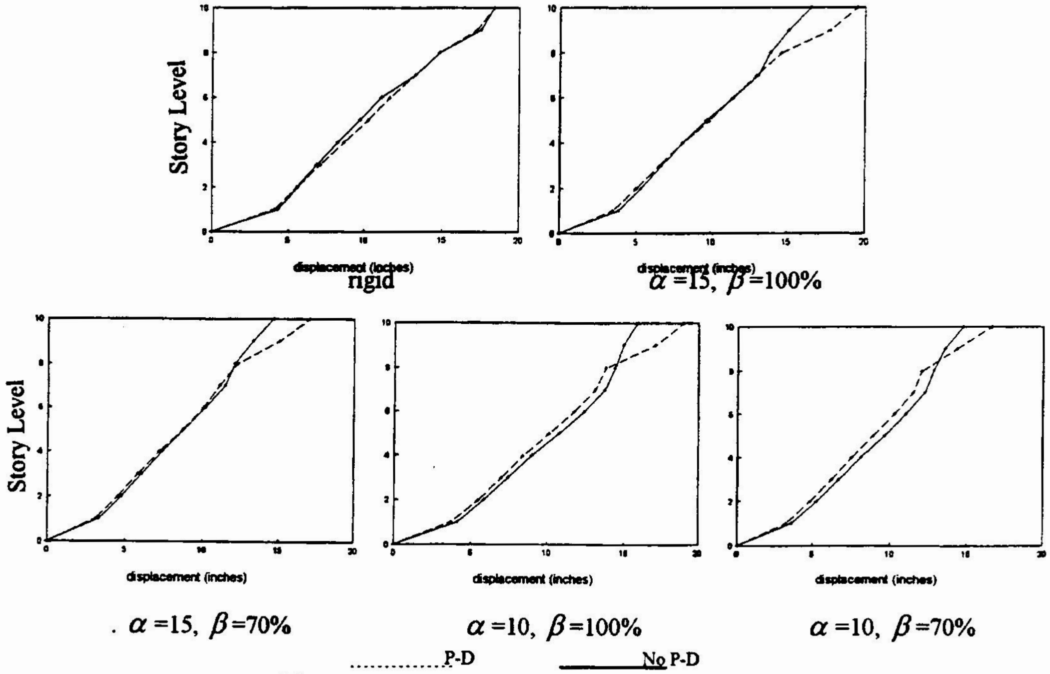
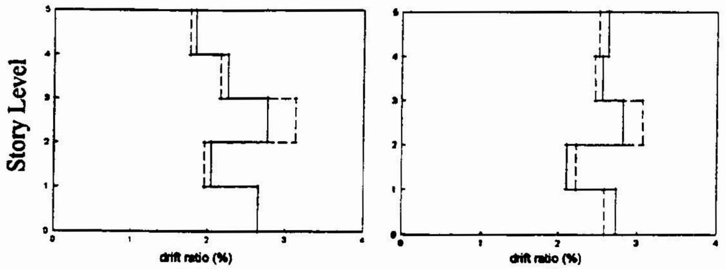
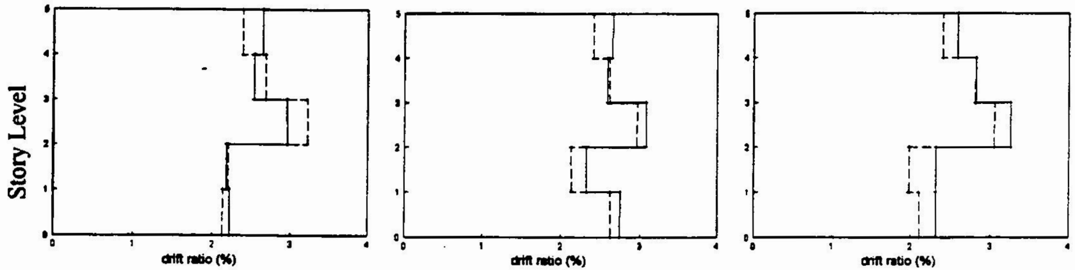


Figure 3b. Envelope of Displacements - 10S



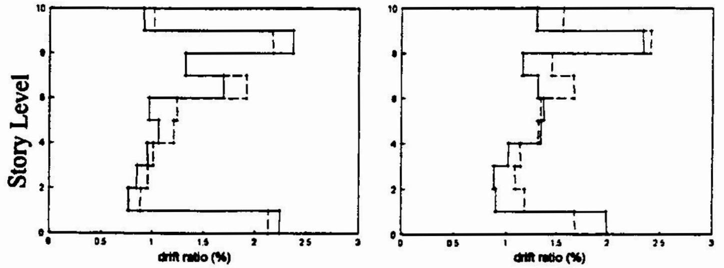
rigid α =15, β=100%



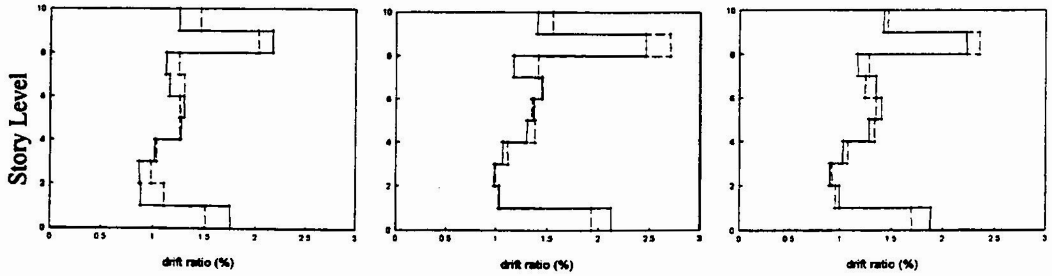
α =15, β=70% α =10, β=100% α =10, β=70%

..............P-D ________No P-D

Figure 4a. Envelope of Drift Ratios (%)-5S



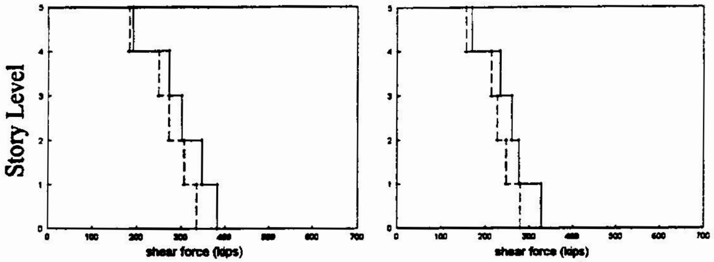
rigid α =15, β=100%



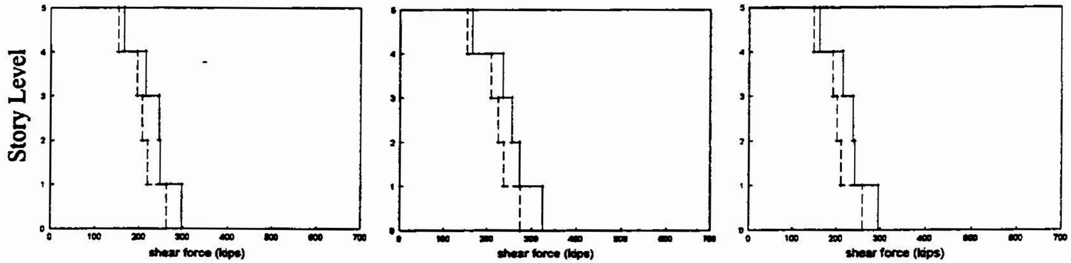
α =15, β=70% α =10, β=100% α =10, β=70

..............P-D ________No P-D

Figure 4b. Envelope of Drift Ratios (%)-10S



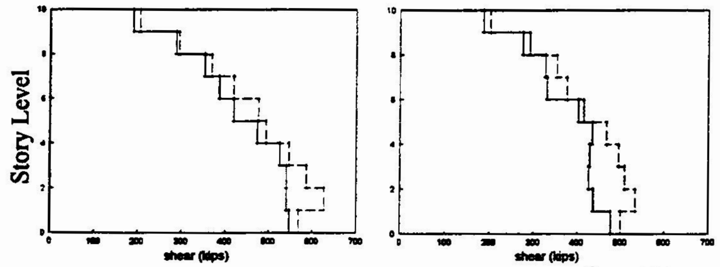
rigid α =15, β=100%



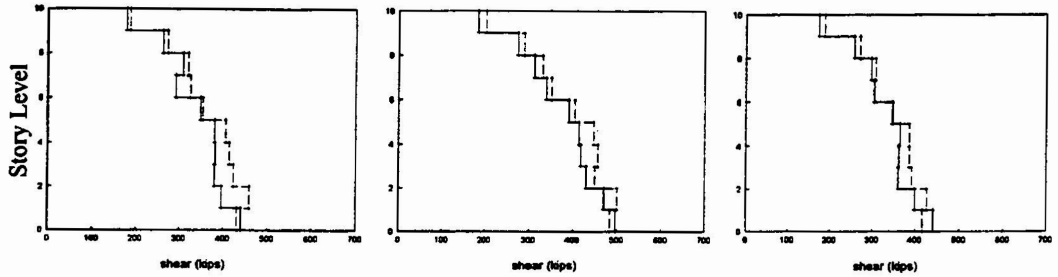
α =15, β=70% α =10, β=100% α =10, β=70%

.............P-D ________No P-D

Figure 5a. Envelope of Shear Forces-5S



rigid α =15, β=100%



α =15, β=70% α =10, β=100% α =10, β=70%

.............P-D ________No P-D

Figure 5b. Envelope of Shear Forces-10S

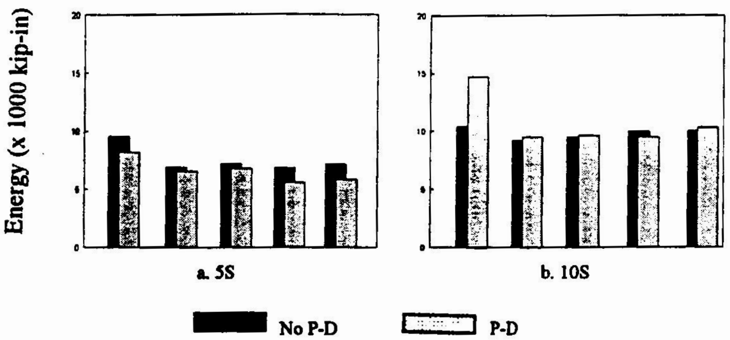


Figure 6. Energy Input

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