MODELING SENSITIVITY IN COMMONLY USED COMPUTER PROGRAMS – CASE STUDIES OF INSTRUMENTED STEEL MOMENT-FRAME BUILDINGS

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Abstract

There are various nonlinear analysis programs in use today, and an even greater number of modeling choices within and between computer programs. It is essential for engineers to understand the nuances of nonlinear modeling so as to construct a reliable simulation model and analyze its seismic behavior. As a step towards such an understanding, the suitability of three widely used computer programs (SAP2000, Perform3D, and OpenSees) for seismic evaluation are investigated in terms of their response sensitivity to nonlinear modeling choices. Selected results from a set of nonlinear response history analyses of a 9-story steel moment frame building are reported in this paper.

Introduction

This paper presents some findings from a nonlinear sensitivity study of instrumented steel moment frame buildings. The study involved three instrumented steel moment frame buildings of varying height, however only select results from the 9-story building will be highlighted in this paper. The development of the 9-story elastic models in OpenSees, Perform3D, and SAP2000, as well as the subsequent calibration and validation of the models to recorded data is discussed in Swensen and Kunnath (2012). Nonlinear models were developed in OpenSees, Perform3D, and SAP2000 using moment-rotation hinges, moment-curvature hinges, and fiber hinges. Numerous nonlinear response history analyses were performed using both near fault and far fault ground motions. Response sensitivity to various modeling choices, including post-yield stiffness and hinge length, was investigated.

Case Study: 9-Story Steel Moment Frame Building

The building considered in this paper is the Aliso Viejo 9-story office building (CSMIP Station No. 13364). This 9-story office building located in Aliso Viejo, California was designed in 2006 according to the 2001 California Building Code, and constructed in 2008. The building is rectangular in plan with dimensions of approximately 220 ft. x 120 ft. The first floor story height is 17 ft. while the remaining story heights are 13.5 ft. for a total building height of 125 ft. There is a helistop located near the center of the building about 11 ft. above the roof level. Lateral forces are resisted in each direction by steel special moment resisting frames located at the perimeter of the building. The connection used in the moment frames is SSDA's proprietary slotted beam connection. Figure 1 shows the typical floor plan and moment frame elevation of the building.

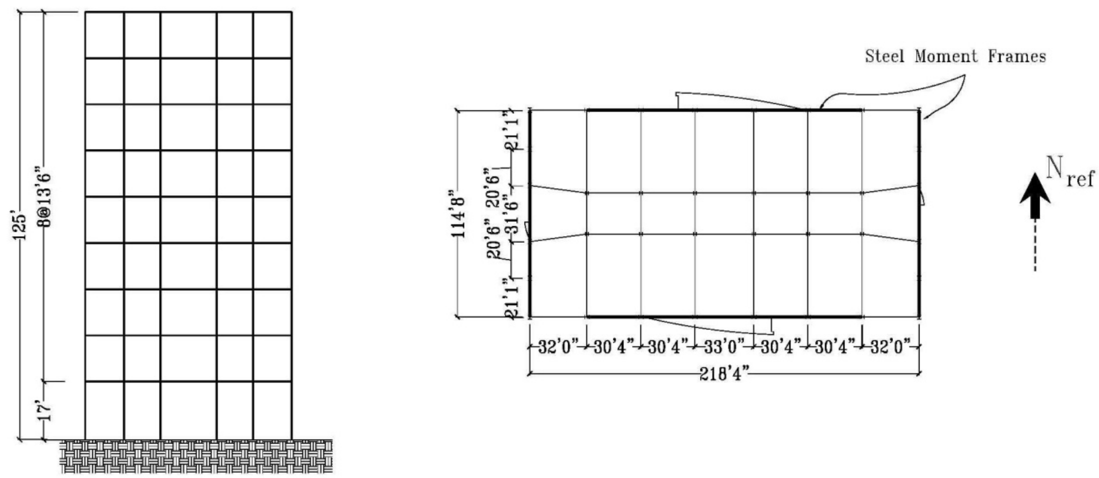

Figure 1: Elevation of typical steel moment frame (N-S Direction) and floor plan of the building

Ground Motion Selection

Seven time histories representing far fault ground motions and seven time histories representing near fault ground motions with forward directivity effects were selected from the PEER-NGA database to be used in performing nonlinear response history analyses of the calibrated SAP2000, Perform-3D, and OpenSEES models of the Aliso Viejo 9-story office building.

The response spectra for the selected motions and the mean spectra for each set are shown in Figure 2. In order to generate a robust set of nonlinear results from the time history analyses it was determined that the intensity for each of the selected ground motions should be sufficient to produce, at a minimum, 2% inter-story drift ratios along the height of the structure. This would guarantee sufficient nonlinearity in the models and make the results of the sensitivity study more meaningful. The intensity of each of the ground motions from the near fault set was sufficient, without scaling, to produce the desired inter-story drift ratios. The set of far fault ground motions however, required some scaling. The scale factor for each of the far fault motions was determined by uniformly scaling each far fault response spectrum to approximately 0.9 g at 2.2 seconds, the first modal period of the models used in the time history analyses.

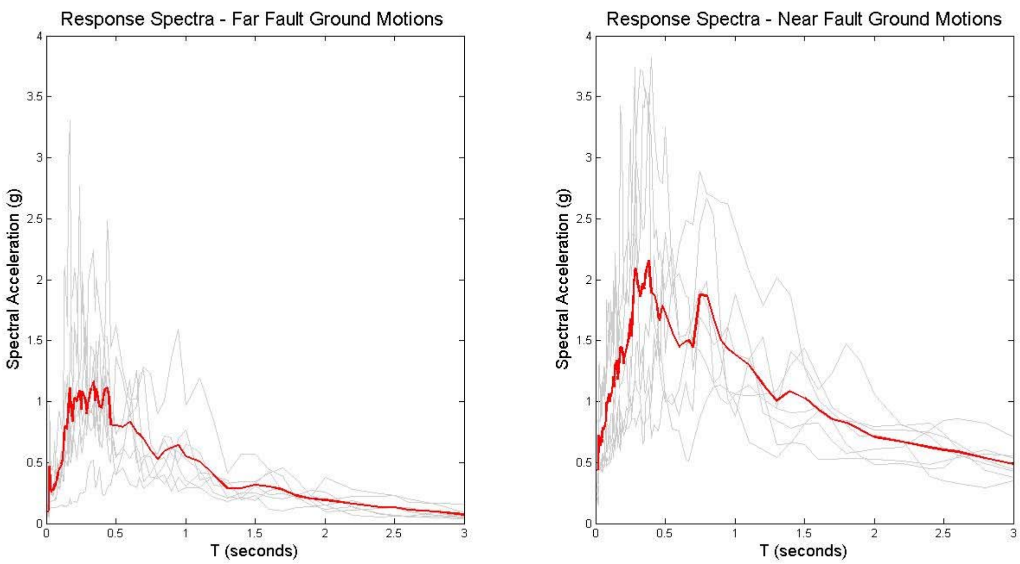

Figure 2: Individual (light lines) and mean spectra (bold line) of selected ground motions.

Nonlinear Simulations: Moment-Rotation Hinge Model

Two dimensional nonlinear models using moment-rotation hinges were completed in OpenSees, Perform3D, and SAP2000. The hinges were located at each end of each beam and column of the moment frame. The moment-rotation relationship for each hinge was assumed to be bilinear with the following variations in post-yield stiffness: 0.05%, 2%, and 5%.

Nonlinear response history analyses using the seven far fault and seven near fault ground motions were performed on a total of nine different moment-rotation models: three models from each of the three software, reflecting the variations in post-yield stiffness mentioned above. The following assumptions were made for the nonlinear response history analyses for each of the nine models:

- No dummy columns included
- Include the effects of P-delta
- 5% Rayleigh damping anchored at the first and third modes and proportional to mass and *initial* stiffness (no modal damping)

The dummy columns represent stiffness contributed by various non-structural components which is assumed effective at only low amplitude shaking; as the intention is to shake these models well into the nonlinear range it makes sense to exclude the dummy columns from the nonlinear models.

The equivalent gravity frame originally included in the elastic model was included in the nonlinear time history analyses, and a P-delta geometric transformation was used for the columns in both the moment frame and equivalent gravity frame for each of the models. Thus, the effects of P-delta should be sufficiently captured in the results of the nonlinear response history analyses.

For each of the nonlinear models the expected yield stress of the steel wide flange framing (55 ksi) was used instead of the design yield stress (50 ksi) for establishing the associated strengths of the force-deformation relationships. In the equivalent gravity frames for each of these models, moment-rotation hinges were used at each end of the gravity beams with an assumed elastic-perfectly plastic force-deformation relationship. The plastic moment capacities for these partially-rigid connections were determined in a manner similar to one outlined in Foutch and Yun (2002).

A comparison of the computed peak inter-story drift ratios of each model using 0.05% post-yield stiffness from the set of seven near fault ground motions and the set of seven far fault ground motions can be seen in Figure 3 and Figure 4, respectively. Figure 3 shows that each model produced very similar results with some minor variations, most notably in GM #3 and GM #4. There is greater dispersion in the far fault ground motion results, especially with SAP2000, as can be seen in Figure 4.

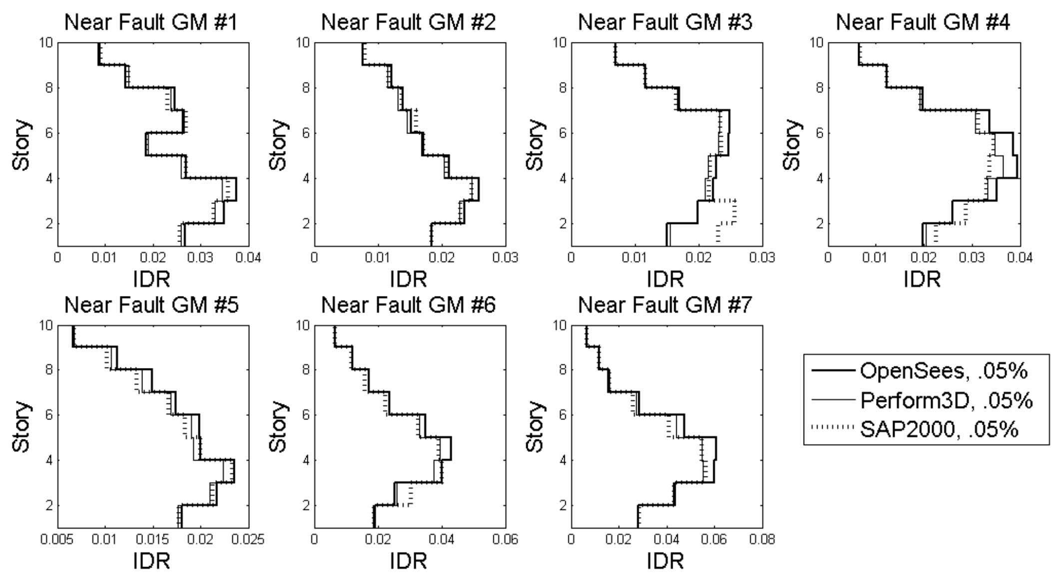

Figure 3: Comparison of computed peak inter-story drift ratios using moment-rotation hinges with 0.05% post-yield stiffness in OpenSees, Perform3D and SAP2000 from seven near fault ground motions with forward directivity effects

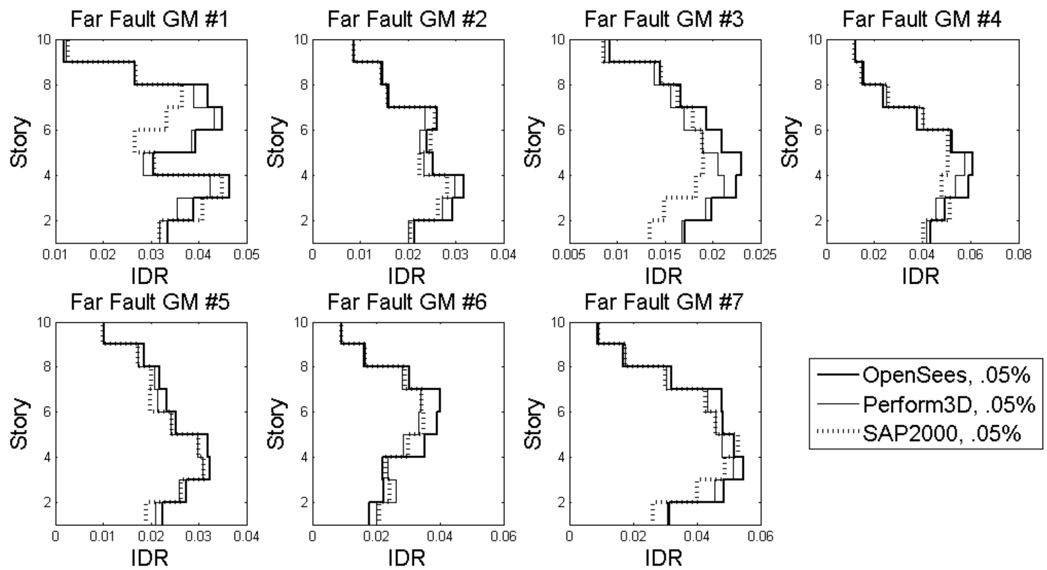

Figure 4: Comparison of computed peak inter-story drift ratios using moment-rotation hinges with 0.05% post-yield stiffness in OpenSees, Perform3D and SAP2000 from seven far fault ground motions

A comparison of the probability distributions of the maximum computed peak inter-story drift ratios of the seven near fault ground motions and seven far fault ground motions for the case of 0.05% post-yield stiffness can be seen in Figure 5. It can be noted that the median values and dispersions of the near fault results are quite similar, whereas the far fault results show more noticeable variation in both median value and dispersion.

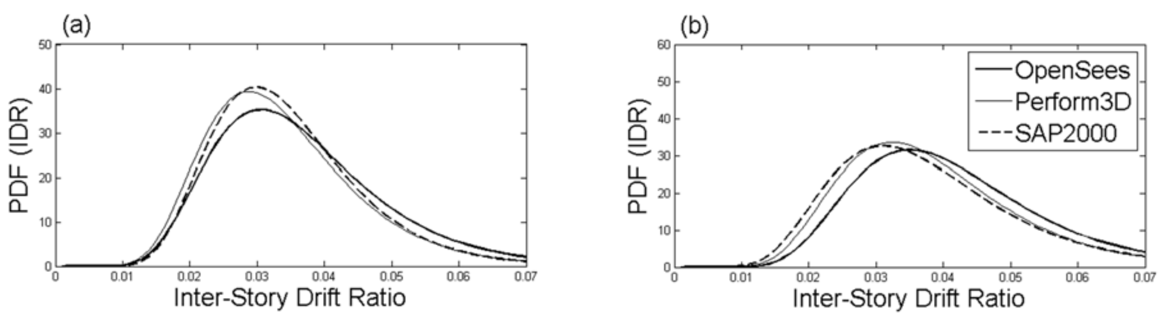

Figure 5: Probability distributions of the maximum computed peak inter-story drift ratios using moment-rotation hinges in OpenSees, Perform3D, and SAP2000: (a) 0.05% post-yield stiffness, near fault records; (b) 0.05% post-yield stiffness, far fault records

Nonlinear Simulations: Moment-Curvature Hinge Model

Two dimensional nonlinear models using moment-curvature hinges were completed in OpenSees, Perform3D, and SAP2000. The hinges were located at each end of each beam and column of the moment frame. Three different hinge length values were assumed, each expressed as a multiple of the beam depth (D): 1.0*D, 0.75*D and 0.50*D.

Nonlinear response history analyses using the seven far fault and seven near fault ground motions were performed on a total of nine different moment-curvature models: three models from each of the three software, reflecting the variations in hinge length mentioned above. The following assumptions were made for the nonlinear response history analyses for each of the nine models:

- Bilinear moment-curvature relationship with 0.05% post-yield stiffness
- No dummy columns included
- Include the effects of gravity columns and P-delta
- 5% Rayleigh damping anchored at the first and third modes and proportional to mass and *initial* stiffness (no modal damping)

A comparison of the computed peak inter-story drift ratios of each model, using a hinge length equal to the beam depth, from the set of seven near fault ground motions and the set of seven far fault ground motions can be seen in Figure 6 and Figure 7, respectively. Figure 6 shows very close agreement between the three models in most cases, with some significant variation at the lower levels in GM #3 with SAP2000. Figure 7 shows significant variation between the three models in most cases; GM #2 and GM #5 match fairly closely.

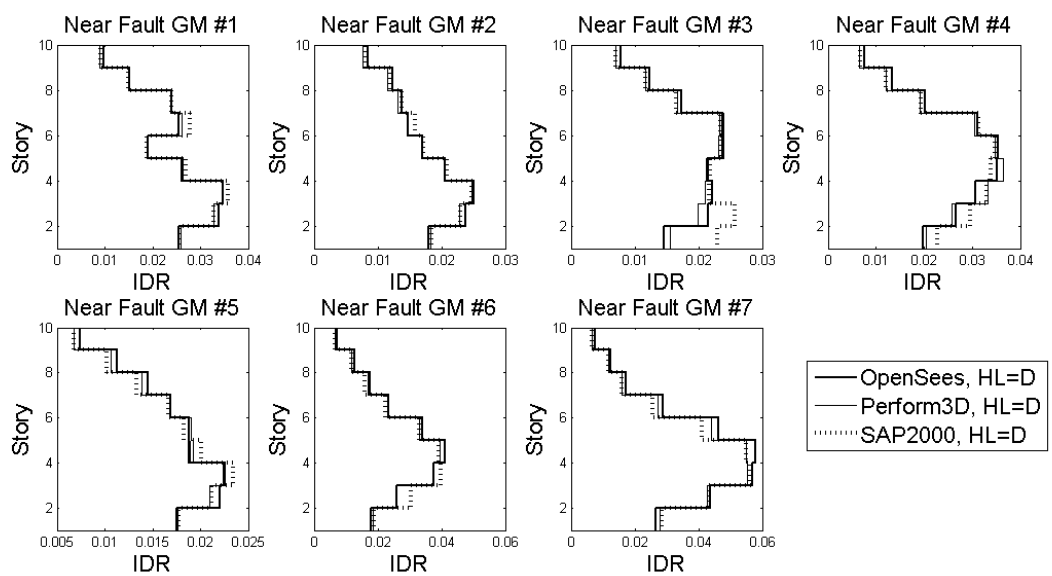

Figure 6: Comparison of computed peak inter-story drift ratios using moment-curvature hinges with hinge length (HL) equal to beam depth (D) in OpenSees, Perform3D and SAP2000 from seven near fault ground motions with forward directivity effects

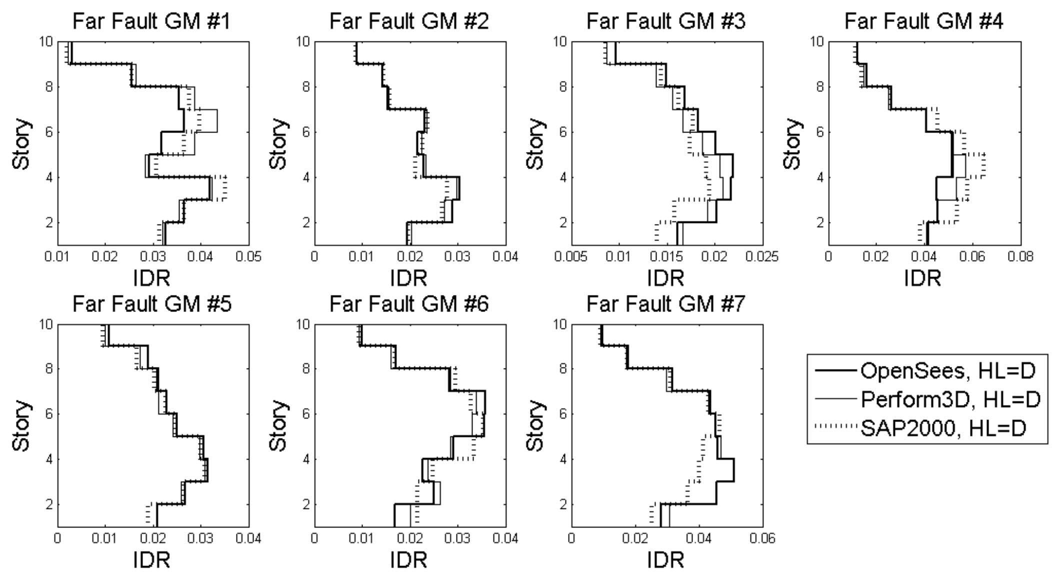

Figure 7: Comparison of computed peak inter-story drift ratios using moment-curvature hinges with hinge length (HL) equal to beam depth (D) in OpenSees, Perform3D and SAP2000 from seven far fault ground motions

A comparison of the probability distributions of the maximum computed peak inter-story drift ratios of the seven near fault ground motions and seven far fault ground motions for the case when the hinge length is set equal to the beam depth can be seen in Figure 8. It can be noted from the figure that in most every case the median values and dispersions are quite similar; Figure 8(b) shows some significant variation in both median value and dispersion.

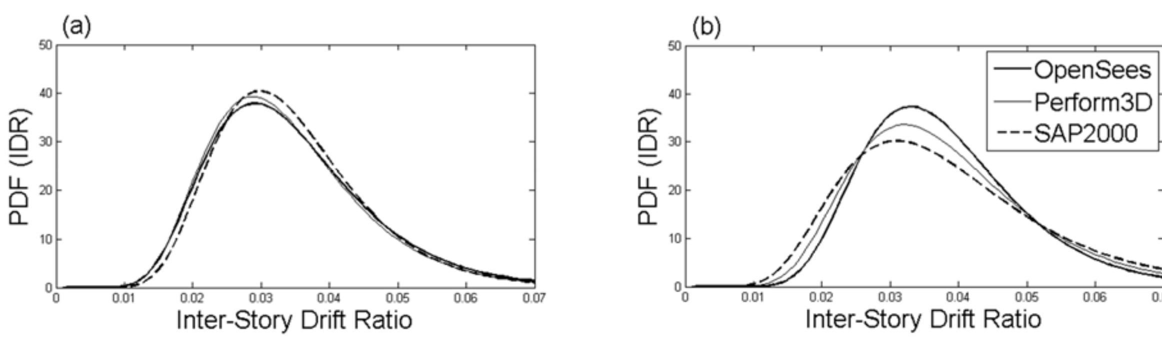

Figure 8: Probability distributions of the maximum computed peak inter-story drift ratios using moment-curvature hinges in OpenSees, Perform3D, and SAP2000:
(a) hinge length equal to beam depth, near fault records; (b) hinge length equal to beam depth, far fault records

Nonlinear Simulations: Fiber Hinge Model

Two dimensional nonlinear models using fiber hinges were completed in OpenSees, Perform3D, and SAP2000. The hinges were located at each end of each beam and column of the moment frame. Three different hinge length values were assumed, each expressed as a multiple of the beam depth (D): 1.0*D, 0.75*D and 0.50*D.

Nonlinear response history analyses using the seven far fault and seven near fault ground motions were performed on a total of nine different fiber hinge models: three models from each of the three software, reflecting the variations in hinge length mentioned above. The following assumptions were made for the nonlinear response history analyses for each of the nine models:

- Bilinear stress-strain relationship with 0.05% post-yield stiffness
- No dummy columns included
- Include the effects of gravity frames and P-delta
- 5% Rayleigh damping anchored at the first and third modes and proportional to mass and *initial* stiffness (no modal damping)

For each of the models in OpenSees, Perform3D and SAP2000 fiber hinges were located at the ends of the moment frame beams and columns. Nonlinear material relationships were confined to the hinge regions at the ends of these framing members, with the interior portion of the member set to perform in a linear-elastic manner. Each fiber hinge required a length and section definition be assigned to it. The section was defined by a combination of individual fibers, each with an associated cross-sectional area, location and bilinear stress-strain relationship.

No meaningful results were obtained from the SAP2000 fiber hinge models for either the near fault or far fault set of ground motions. The analysis for each of the ground motions in SAP2000 typically failed (convergence could not be achieved) within the first 10 seconds of the record.

A comparison of the computed peak inter-story drift ratios of each model, using a hinge length equal to the beam depth, from the set of seven near fault ground motions and the set of seven far fault ground motions can be seen in Figure 9 and Figure 10, respectively. Figure 9 shows close agreement between the two models in most cases, with some significant variation in GM #3. Figure 10 shows significant variation between the two models in most cases; GM #2, GM #5 and GM #7 match more closely.

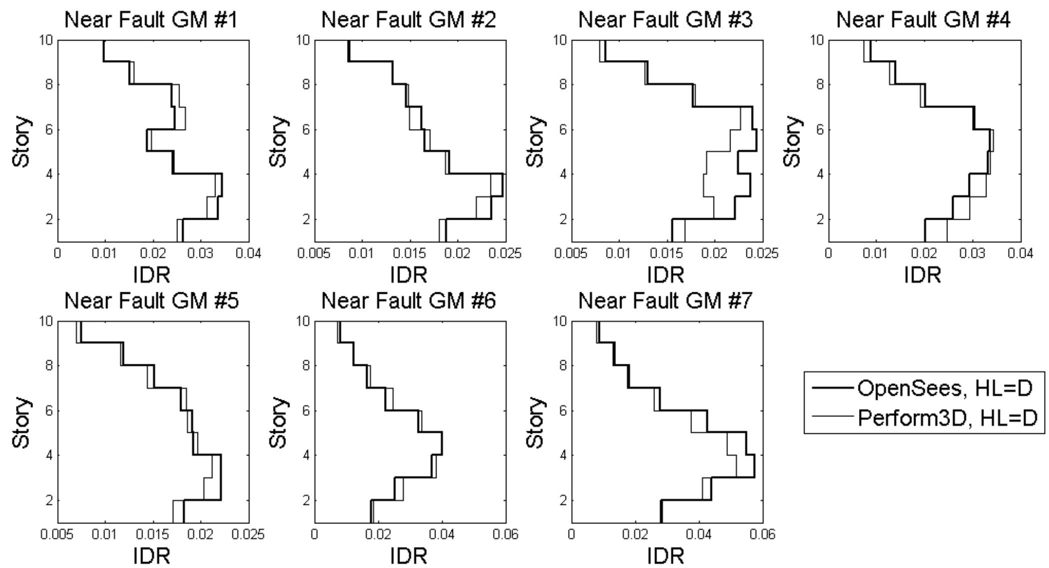

Figure 9: Comparison of computed peak inter-story drift ratios using fiber hinges with hinge length (HL) equal to beam depth (D) in OpenSees and Perform3D from seven near fault ground motions with forward directivity effects

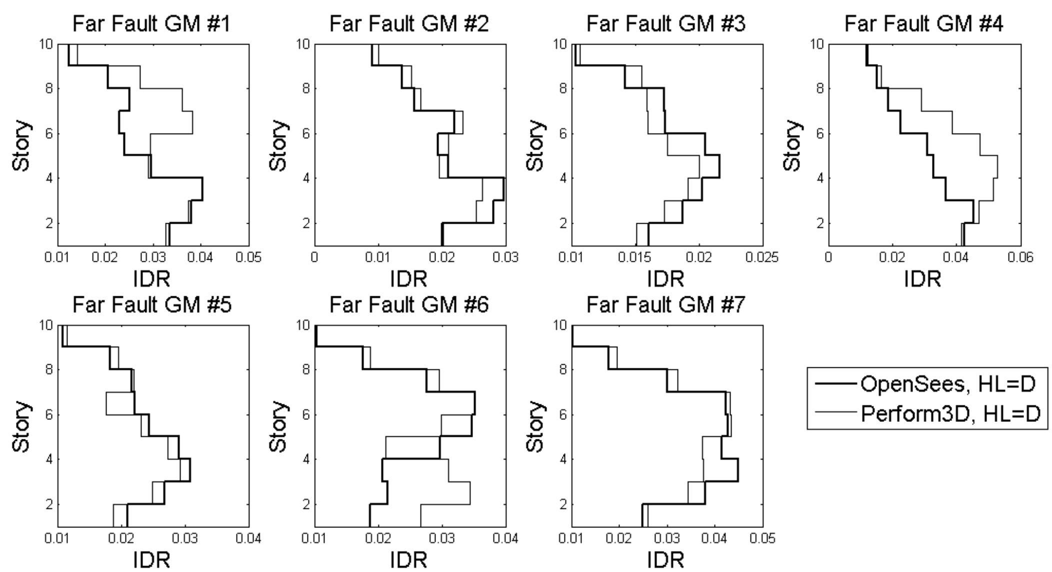

Figure 10: Comparison of computed peak inter-story drift ratios using fiber hinges with hinge length (HL) equal to beam depth (D) in OpenSees and Perform3D from seven far fault ground motions

A comparison of the probability distributions of the maximum computed peak inter-story drift ratios of the seven near fault ground motions and seven far fault ground motions for the case when the hinge length is set equal to the beam depth can be seen in Figure 11. It can be noted from the figure that in the case of the near fault records the median values and dispersions are quite similar between the models, while the results from the far fault records show greater variation in both median value and dispersion.

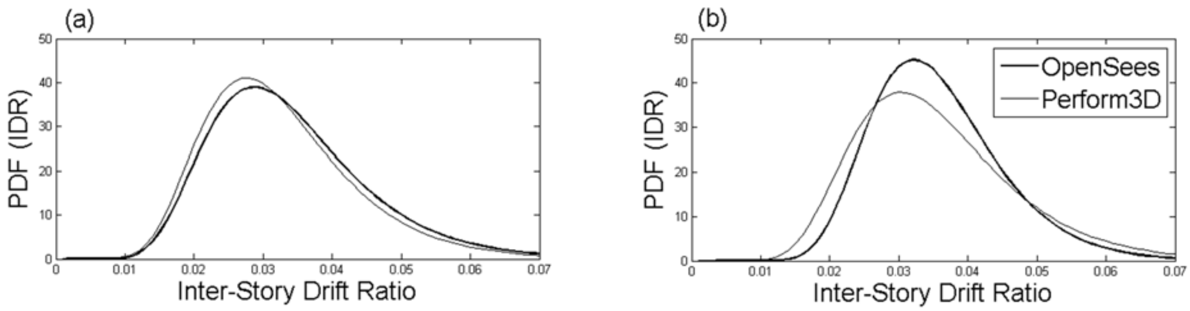

Figure 11: Probability distributions of the maximum computed peak inter-story drift ratios using fiber hinges in OpenSees and Perform3D: (a) hinge length equal to beam depth, near fault records; (b) hinge length equal to beam depth, far fault records

Concluding Remarks

For the case of moment-rotation hinges, the inter-story drift ratios resulting from the near fault ground motions compared fairly well both statistically and over the height of the building. The results from the far fault set of ground motions did not compare quite as well as those of the near fault set; the statistical results showed some variation in median value and there was greater variation over the height of the building (most notably with SAP2000). The inter-story drift results for the case of moment-curvature hinges mirror those obtained using moment-rotation hinges; the near fault results compare well both statistically and over the height of the building while the far fault results show slightly greater variation.

As mentioned previously, no SAP2000 results were obtained for the case of fiber hinges as convergence could never be achieved with either ground motion set. Significant variation can be seen in the far fault set of results between OpenSees and Perform3D over the height of the structure, and some modest differences in the statistical results. The near fault results show improvement over those from the far fault set.

Acknowledgements

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References

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