IDA Capacity Curves: The Need for Alternative Intensity Factors

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Abstract

Incremental dynamic analysis (IDA) has recently emerged as an alternative approach to investigate inelastic limit states in performance-based seismic engineering. IDA requires a series of nonlinear-time history analyses at increasing intensity levels of the same ground motion. The intensity of the earthquake load is typically expressed in terms of the first mode spectral acceleration. In this study the validity of such an intensity measure is investigated. IDA is applied to an existing six-story steel moment-frame building. Two sets of ground motions representing far-fault and near-fault records are considered separately to study the influence of different seismic source characteristics on the outcomes of the IDA. The study reveals that first mode spectral acceleration, $S_a(T_1,5\%)$, is an inadequate and incomplete measure of seismic intensity in the context of generating IDA capacity curves. It is concluded that alternative intensity measures are needed to make IDA more meaningful in seismic assessment. A preliminary investigation utilizing spectral magnitudes from constant-ductility inelastic spectra as a measure of seismic intensity is reported in this paper.

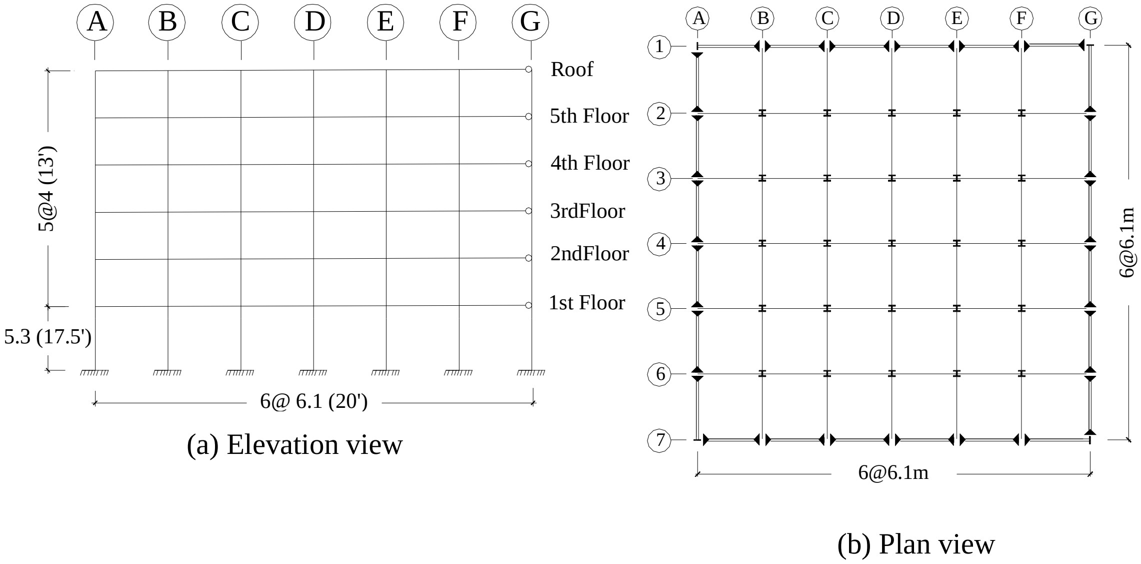
Introduction

It has been long recognized that the current nonlinear static procedures (NSP) based on invariant loading vectors such as those recommended in FEMA-356 (2000) possess inherent drawbacks in adequately representing the effects of varying dynamic characteristics during the inelastic response of structures. Although some improved NSPs have been developed over the past few years, their validity for a variety of structural systems and a range of ground motion characteristic have yet to be demonstrated. The results of nonlinear time history (NTH) analyses based on actual earthquake recordings serve as the only reliable benchmark solutions against which the NSP results can be compared. In that respect, incremental dynamic analysis has emerged as a potential tool for seismic evaluation since it involves a series of time history analyses. Originally proposed by Vamvatsikos and Cornell (2002), an IDA involves increasing the severity of the record till a collapse limit state is reached. Hence the term “dynamic” pushover has often been used to describe the conceptual framework of IDA. The approach has the potential to provide dynamic capacity curves for different ground motion levels and describe the variation of seismic demand parameters with changes in ground motion intensity measures.

Although it is possible to utilize a single record for IDA, it is essential to consider variations in ground motion content when utilizing IDA in performance-based assessment. Therefore, the selection of ground motion records taking into consideration site characteristics and source mechanisms is critical. Consequently, near-fault and far-fault ground motions are treated separately in this study. All near-fault records compiled in this investigation have the forward-directivity effects and contain coherent long-period velocity pulses. Such a feature does not exist in the ordinary far-fault records.

Description of Six-Story Steel Moment-Frame Building

An existing six-story moment frame for which instrumented data is available and previous calibration studies (Kunnath et al., 2004) have been conducted is considered in this study. The primary lateral load resisting system is a moment frame around the perimeter of the building. Interior frames are designed to carry only gravity loads. The plan view and elevation of a typical frame are shown in Fig. 1. Additional building details are reported in Kunnath et al. (2004).



(a) Elevation view

(b) Plan view

Figure 1. Building configuration

Ground Motions

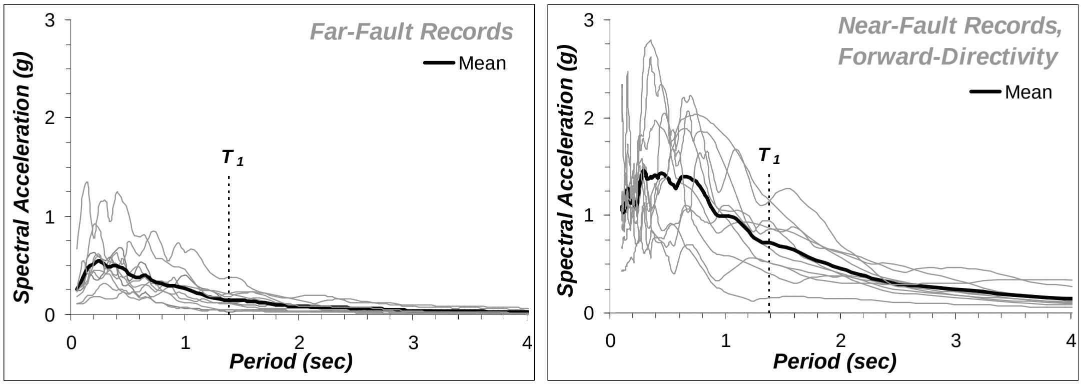
The seismic excitations used for the nonlinear time history evaluations are defined by two sets of records. The first set constitutes ten far-fault motions from earthquakes having a magnitude range of 6.4 to 7.5 at soil and stiff-soil sites. In the second set ten near-fault records having forward-directivity effects are compiled. These near-fault motions are recorded at a distance less than 15 km to the seismogenic rupture from earthquakes having magnitude of 6.4 to 7.3. Details of the records are listed in Table 1, and their 5% damped pseudo-acceleration spectra along with their mean spectrum for near-fault and far-fault records are exhibited in Fig. 2.

Table 1. Details of ground motion recordings

No.	Year	Earthquake	M_W	Mech. *	Station	Component	Site Class	PGA (g)	Data Source **
(a) Far-Fault Recordings									
1	1952	Kern county	7.5	TH/REV	Taft	111	Soil	0.18	1
2	1979	Imperial-Valley	6.5	SS	Calexico	225	Soil	0.27	1
3	1989	Loma Prieta	7.0	OB	Cliff House	90	Stiff soil	0.11	1
4	1989	Loma Prieta	7.0	OB	Presido	0	Soil	0.01	1
5	1992	Big Bear	6.4	SS	Desert Hot	90	Soil	0.23	2
6	1994	Northridge	6.7	TH	Century	90	Soil	0.26	2
7	1994	Northridge	6.7	TH	Montebello	206	Soil	0.18	1
8	1994	Northridge	6.7	TH	Terminal Island	330	Soil	0.19	1
9	1994	Northridge	6.7	TH	SantaFE Spr.	30	Soil	0.14	1
10	1994	Northridge	6.7	TH	Saturn	S70E	Soil	0.43	2
(b) Near Fault Recordings (Forward-Rupture Directivity)									
1	1989	Landers	7.3	SS	Lucerne	275	Stiff soil	0.721	1
2	1989	Loma Prieta	7.0	OB	Lexington Dam	90	Stiff soil	0.41	2
3	1989	Loma Prieta	7.0	OB	LGPC	0	Stiff soil	0.56	1
4	1992	Cape Mendocino	7.1	TH	Petrolia	90	Stiff soil	0.66	1
5	1992	Erzincan	6.7	SS	Erzincan	EW	Soil	0.50	1
6	1994	Northridge	6.7	TH	Rinaldi	275	Soil	0.84	2
7	1994	Northridge	6.7	TH	Olive View	360	Soil	0.84	1
8	1994	Northridge	6.7	TH	Slymar Converter	018	Soil	0.83	1
9	1995	Kobe	6.9	SS	KJMA	0	Stiff soil	0.82	1
10	2003	Bingol	6.4	SS	Bingol	NS	Soil	0.56	3

** TH: Thrust; REV: Reverse; SS: Strike-slip; OB: Obligue*

** 1: PEER, http://peer.berkeley.edu/smcat/, 2: COSMOS, http://db.cosmos-eq.org, 3: ERD, http://angora.deprem.gov.tr/



(a) (b)

Figure 2. Pseudo-spectral acceleration spectra and mean spectrum of original records: (a) Far-fault motions; (b) Near-fault forward directivity motions

Calibration of Simulation Model

For numerical simulations, a two-dimensional finite element (FE) model of the EW exterior frames was developed. OpenSees (2005) is used as the finite element platform. The program utilizes the layered 'fiber' element for inelastic frame analysis and incorporates the spread of inelasticity along the member length using a force-based formulation. Since the building was instrumented, the recorded base motion during the 1994 Northridge earthquake was used as input for the model validation study. The simulated time history is compared to the recorded response in Figure 3.

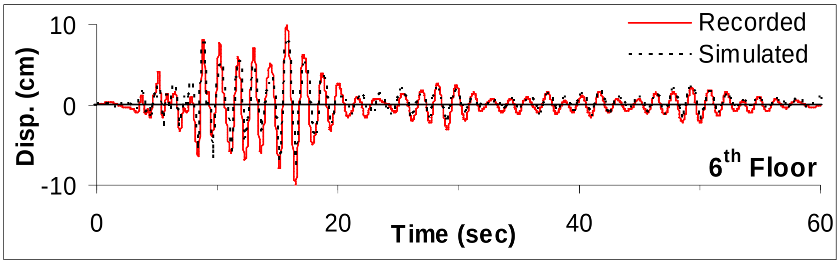


Figure 3. Comparison of recorded and computed response (a) at channel 2 (EW direction) at 6th storey level

Details of Evaluation Procedure

Since IDA is based on the NTH analysis, the resulting response is ground motion dependent. This is demonstrated in Figure 4 wherein the demands resulting from two near-fault records are projected. The *Olive V.* record generates a large concentrated demand at the first-story which implies a dominant first-mode response while the response of building when subjected to *KJMA* record is a clear indication of higher mode effects resulting in significant demands at the 5th story level.

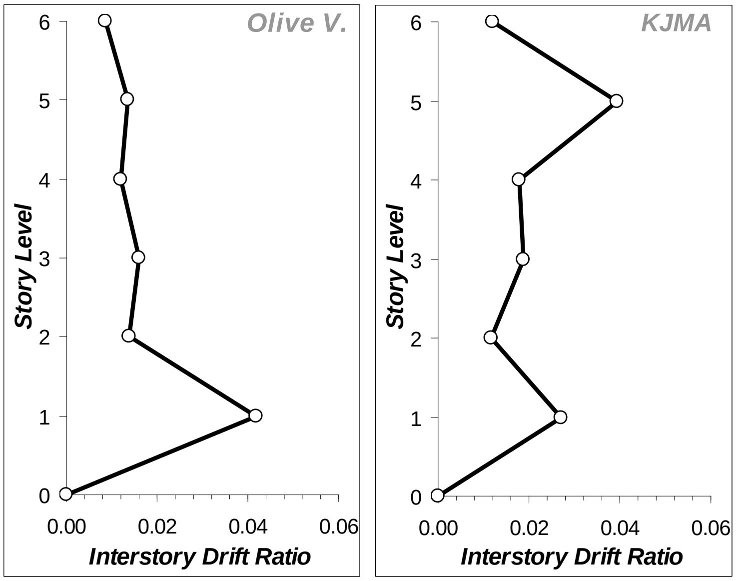
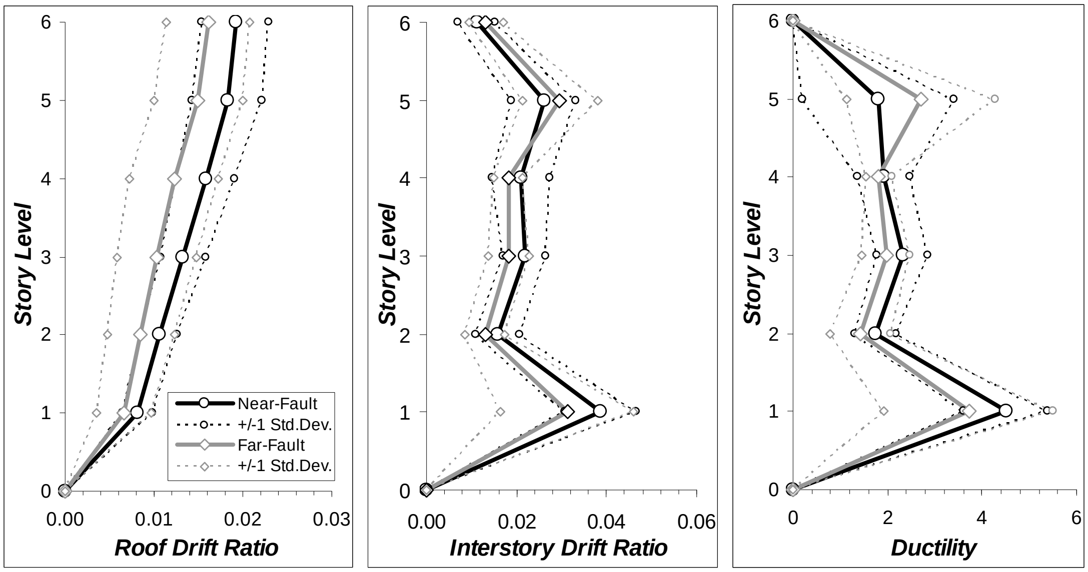


Figure 4. Peak interstory drift ratio profiles obtained using *Olive V.* and *KJMA* records scaled to their maximum intensity level

Figure 5 shows the mean and 84 percentile plots of the peak demand parameters, namely roof-drift ratio, inter-story drift ratio and story ductility, obtained from nonlinear time history analyses of twenty ground motions (when scaled to their maximum intensity). Story ductility is defined as the ratio of peak interstory drift to yield drift. In general, the mean curves produced by near-fault and far-fault records show significant similarities. The near-fault record creates the largest mean roof drift, but most importantly the dispersion of response at the upper and lower levels is remarkably larger in the case of far-fault records.

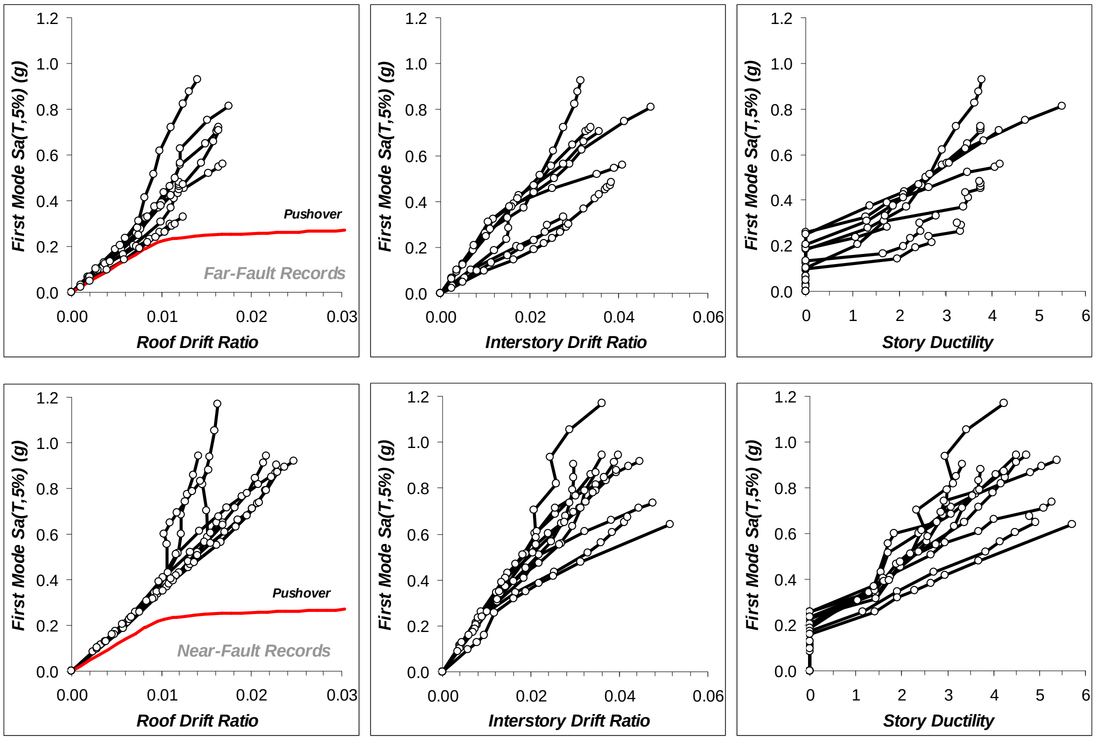


(a) (b) (c)

Figure 5. Nonlinear time history analysis results for each set of record when they scaled to their maximum intensity level: Mean and 84 percentile curves of (a) Roof drift ratio; (b) Inter-story drift ratio; (c) Story ductility

It is of interest to investigate the correlation between IDA and conventional NSP capacity curves. A monotonically increasing invariant load pattern representing the elastic first-mode shape is utilized for NSP in this investigation. This is generally consistent with the intensity measure used in IDA.

In Figure 6, each plot illustrates the imposed demands by each ground motion record at different intensities. The results indicate that the initial stiffness in the case of far-fault records is generally well represented by the first-mode force pattern in pushover analysis, yet there is a significant difference in the case of near-fault records. Examining post-yield behavior, IDA curves when plotted against $S_a(T_1,5\%)$ do not convey any useful information related to failure limit states. In the present study, it was not possible to obtain convergence for larger intensities than those shown in the plots.

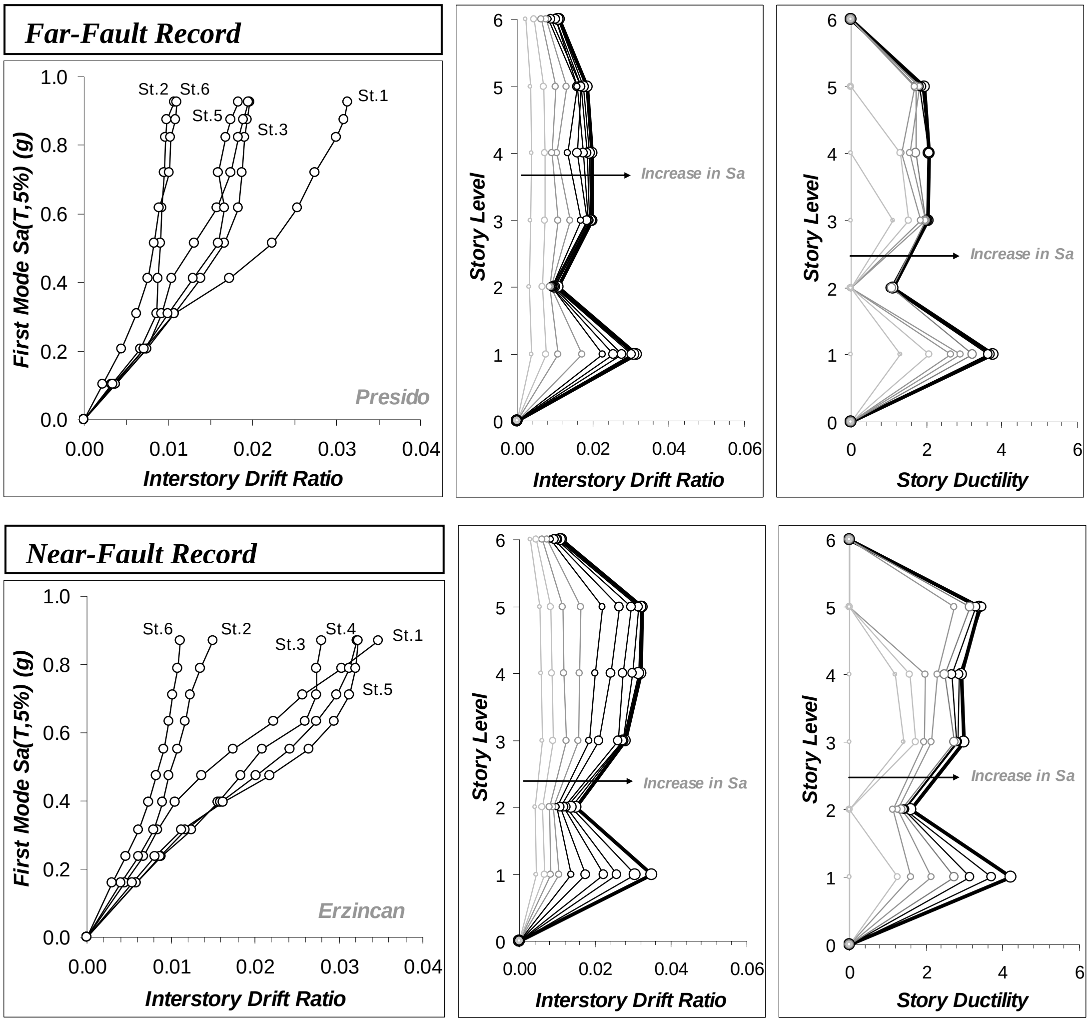


(a) (b) (c)

Figure 6. IDA curves plotted against $S_a(T_1, 5\%)$

In Figure 7, the building response from elastic to inelastic stage is plotted with increasing seismic intensity for a selected far-fault and near-fault record. Examining the IDA curves of the far-fault record (Erzincan), the softening of the first story and the hardening of other stories (Figure 7a) is seen. Similarly for the selected near-fault record (Presido) it is possible to observe softening and hardening at the different story levels for increasing levels of PGA. However, the concepts of softening and hardening, as defined in the conceptual framework of IDA, are not fully correlated with observed story drifts.

In fact, the first mode spectral acceleration is only an indication of the elastic first mode response which is valid only during the initial pre-yield phase of the response. Since an IDA curve is supposed to represent behavior from elastic to post-yield range, it is necessary to go beyond the first-mode spectral acceleration to adequately quantify the seismic intensity causing damage in the structure.



(a) (b) (c)

Figure 7. (a) IDA curves of peak interstory drift for each floor; (b) Progressive interstory drift demands, (c) Progressive story ductility demands with an increase in amplitude of base motion

In Figure 8 the variation of the base shear coefficient with increase in the first mode spectral acceleration $S_a(T_1,5\%)$ is shown. Clearly the relationship between the base shear coefficient and first mode spectral acceleration is nonlinear. In Figure 9, IDA curves corresponding to variation of roof drift ratio, interstory drift ratio and story ductility are plotted against the base shear coefficient. Also shown in this figure is the capacity curve obtained from the pushover analysis. A closer investigation of these findings is underway to develop improved intensity measures to enable utilization of IDA capacity curves in performance-based evaluation.

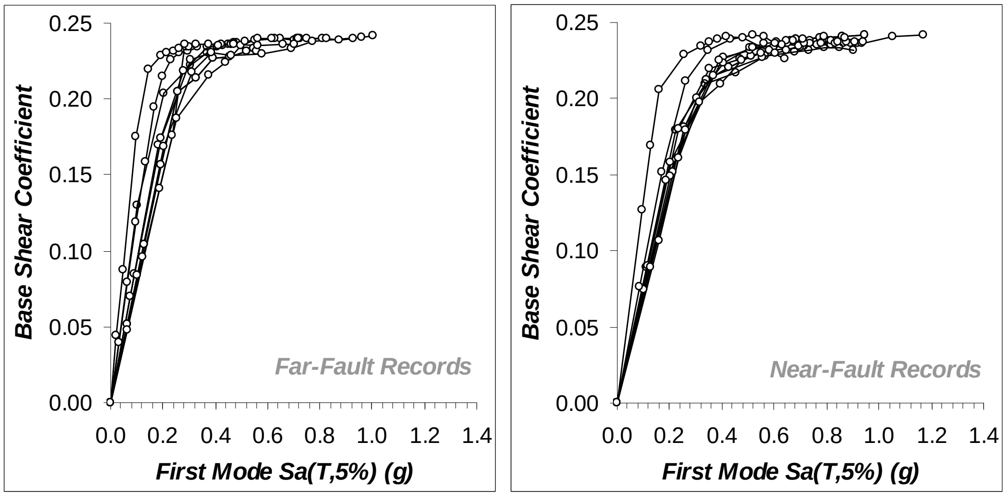
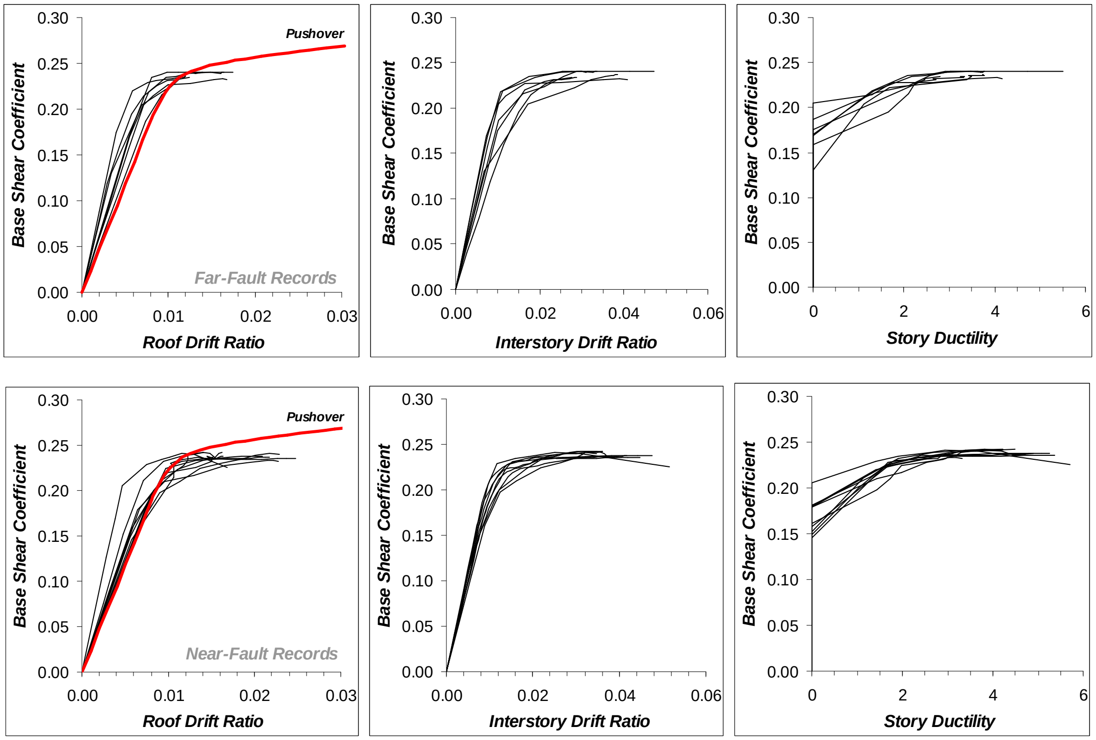


Figure 8. Variation of base shear coefficient with increase in the first mode spectral acceleration $S_a(T_1,5\%)$



(a) (b) (c)

Figure 9. IDA curves plotted as a function of base shear coefficient

Conclusions

The IDA procedure was applied to a calibrated simulation model of an existing six-story steel building. It is shown that the first mode spectral acceleration, $S_a(T_1,5\%)$, a commonly used parameter in the IDA representation of seismic intensity is not a reliable parameter to assess inelastic limit states. A comprehensive study is underway examining other intensity parameters, including inelastic spectral demands, as alternative measures for use in generating IDA capacity curves.

Acknowledgement

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