A SIMPLIFIED PROCEDURE FOR ESTIMATING THE INELASTIC DRIFT DEMANDS ON FRAME STRUCTURES

B.Ö. Ay[1] and S. Akkar[2]

[1] *Research Assistant, Earthquake Engineering Research Center, Dept. of Civil Engineering, Middle East Technical University, 06531 Ankara, Turkey*

[2] *Professor, Earthquake Engineering Research Center, Dept. of Civil Engineering, Middle East Technical University, 06531 Ankara, Turkey*

Email: ozer@metu.edu.tr, sakkar@metu.edu.tr

ABSTRACT:

This study presents a simple model for estimating the inelastic maximum interstory drift ratio (MIDR) for frame type structural systems. The proposed model is a modified version of a previously derived empirical equation that yields fairly reliable MIDR estimations for moment–resisting frame systems responding in the elastic range. This study modifies the former version to estimate inelastic MIDR by observing the MIDR demands on inelastic buildings and the peak inelastic displacements of the corresponding equivalent single–degree–of–freedom (SDOF) systems. Inherently, these observations presume a dominant fundamental mode behavior in the proposed model. A total of 12 model frames with fundamental periods ranging from 0.4 s to 1.6 s are used to evaluate the accuracy of the proposed model. The chosen frame models are capable of simulating non–degrading to severely degrading (in terms of stiffness and strength) hysteretic behavior. The model buildings are subjected to a suite of dense–to–stiff site ground–motion recordings with source–to–site distances (R_{rup}) less than 25 km. Using different combinations of the 60 ground–motion records assembled for this study, the results derived from the 2880 response history analyses suggest that the proposed model yields fairly accurate inelastic MIDR estimations. Given the simplicity of the proposed model, these MIDR estimations can be considered as quite promising for the implementation of this model in the preliminary seismic performance assessment of large building stocks in earthquake prone regions.

KEYWORDS: inelastic maximum interstory drift ratio, non–degrading to severely degrading hysteretic behavior, nonlinear response history analysis, preliminary seismic performance assessment

1. INTRODUCTION

Maximum interstory drift demand is one of the most preferred global deformation parameters for seismic performance assessment of building systems. Past earthquakes have shown that MIDR can be correlated to the structural damage in a quantitative manner. For this reason both probabilistic and deterministic seismic performance assessment procedures frequently employ MIDR while implementing their methodologies. Owing to its wide range of use, the literature is abundant in empirical expressions that estimate MIDR to a certain level of accuracy (Miranda, 1999; Heidebrecht and Rutenberg, 2000; Gülkan and Akkar, 2002; Miranda and Reyes, 2002; Akkar et al., 2005). Most of these empirical equations estimate MIDR for linear structural behavior that may fail to represent the actual MIDR demands on structures responding beyond their elastic limits.

In this study a useful approach for estimating the inelastic MIDR ($MIDR_{ie}$) of frame type structures from the corresponding equivalent SDOF system deformation is proposed. Essentially, the procedure improves the methodology of Akkar et al. (2005) by observing the variations in the MIDR of inelastic building systems and the peak inelastic displacements of the corresponding equivalent SDOF systems.

1.1. Ground Motion Data Set and Generic Frame Models Used in This Study

To characterize different levels of seismic hazard, three different ground–motion sets are selected. Each set contains 20 ground–motion records. Near–fault records with dominant pulse waveforms and recordings of very soft soil sites are not included in the data set. The mean values of moment magnitude (M_w), closest distance to fault (D), peak ground acceleration (PGA), peak ground velocity (PGV), and corresponding coefficient of variation (COV) values as a measure of dispersion are listed in Table 1.1. Except for the distance, the mean values of the presented ground–motion parameters increase gradually from Set I to Set III. This also advocates a gradual increase in the seismic hazard level from Set I to Set III.

Table 1.1 Statistical properties of ground motion sets

	Set I		Set II		Set III	
	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
M_w	6.2	7	6.6	6	6.9	6
D (km)	12.3	38	10.4	67	10.4	56
PGA (g)	0.16	35	0.34	31	0.44	38
PGV (cm/s)	11.17	49	29.14	22	48	13

Number of stories is considered as the major parameter that affects structural response in this study. Hence 3, 5, 7, and 9–story planar frame models with three bays are developed. Story height of 3 meters and bay width of 5 meters are assumed in the model frames. The generic frame models are classified into three subclasses named as poor, typical and superior according to the inherent characteristics and deficiencies of construction practice. To obtain the structural response of these buildings, the analysis program IDARC–2D (Valles et al., 1996) is used. To simulate the cyclic response, piece–wise linear hysteretic model of IDARC–2D that incorporates stiffness and strength degradation characteristics is used in this study. For superior building subclass that is assumed to have good material quality, the structural members do not exhibit degradation. Thus, there is a stable behavior with high energy dissipation characteristics and members exhibit degradation neither in stiffness nor in strength. In case of typical building subclass with moderate material quality, the structural members are assumed to exhibit slight–to–moderate degradation. The strength at the maximum displacement slightly decreases with the number of cycles as similar as the area enclosed by the hysteresis loops. Finally, for poor building subclass that represents systems with low material quality, the structural members are assumed to exhibit severe strength degradation and there is a considerable amount of pinching in the analytical model, which narrows the area enclosed by the loops and reduces the dissipated energy significantly. Representative hysteresis behavior of superior, typical and poor subclass generic frames are given in Figure 1.1.

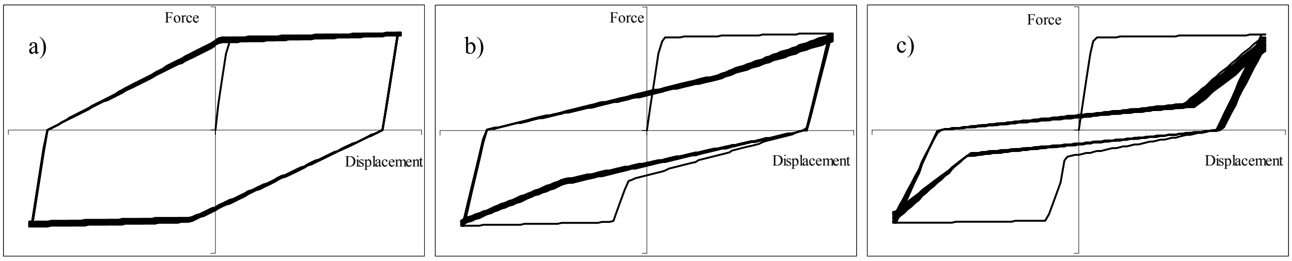

Figure 1.1 Representative hysteresis behavior of (a) superior, (b) typical and (c) poor subclass generic frames

2. BRIEF INFORMATION ON THE ELASTIC MIDR ESTIMATION PROCEDURE

Akkar et al. (2005) proposed a simple procedure to estimate elastic MIDR ($MIDR_e$) of regular moment resisting frame type structures by using elastic spectral displacement and beam–to–column stiffness ratio, ρ, proposed by Blume (1968). The ground story drift ratio estimation of shear frames proposed by Gülkan and Akkar (2002) is generalized by correction factors as functions of fundamental period, T, and ρ to estimate $MIDR_e$. The expression of Gülkan and Akkar (2002) for maximum ground story drift ratio (GSDR) of shear frame behaving in the fundamental mode is given below in Eqn. 2.1, whereas the general form of the equation proposed by Akkar et al. (2005) is given in Eqn. 2.2. In essence, the procedure simply modifies the elastic SDOF peak response ($S_{d,e}$) for certain structural properties to estimate $MIDR_e$. That is, the procedure grossly assumes a linear relationship between $MIDR_e$ and $S_{d,e}$.

$$GSDR_{sh}(T_1,\xi)=1.27\sin\left(\frac{\Pi h}{2H}\right)\frac{S_{d,e}(T_1,\xi)}{h} \tag{2.1}$$

$$MIDR_e=\gamma_1(\rho,T_1)\gamma_2(\rho,T_1)GSDR_{sh}(T_1,\xi) \tag{2.2}$$

For detailed information about correction factors, variables, error statistics and accuracy comparisons with similar expressions proposed by other researchers, the reader is referred to Akkar et al. (2005). To evaluate the validity of Akkar et al. (2005) with using the frame models and ground motions, $MIDR_e$ estimations ($MIDR_e^{EST}$) are compared with the ones computed from elastic response history analyses ($MIDR_e^{RHA}$).MIDR results computed from response history analysis of buildings are accepted as exact in this study. Figure 2.1 presents the scatters obtained from residual analysis; log ($MIDR_e^{RHA}/MIDR_e^{EST}$) as a function of fundamental building period.

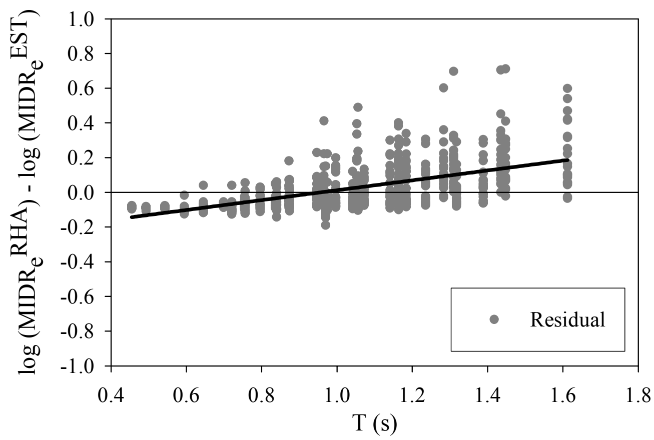

Figure 2.1 Residuals of elastic MIDR results with respect to fundamental period

The straight line superimposed on the scatter points (Figure 2.1) indicates that, for period values less than 1 s, the procedure proposed by Akkar et al. (2005) overestimates $MIDR_e$, whereas for period values larger than 1 s, Akkar et al. (2005) underestimates $MIDR_e$ values. The evaluations of $MIDR_e$ presented in this study reveal a significant similarity to those of Akkar et al. (2005). This simple case study advocates the generality of the Akkar et al. (2005) procedure for elastic MIDR estimations of frame systems. Based on this fact, this study modifies the Akkar et al. (2005) procedure for $MIDR_{ie}$ estimations.

3. COMPARISONS OF SDOF AND MDOF RESPONSES

The linear and nonlinear MDOF responses obtained from response history analyses are compared with the corresponding equivalent SDOF results to assess the correlation between the MDOF and SDOF deformation demands in the elastic and post–elastic ranges. The results highlighted from these observations are further used in the proposed procedure. To obtain equivalent SDOF systems, conventional pushover analyses are performed using IDARC–2D. Pushover analyses are conducted using inverted triangular load pattern in accordance with the high fundamental mode mass participation of the generic frames. The pushover curves of building models are idealized using the procedure described in FEMA 356 (ASCE, 2000).

Idealized pushover curves are converted into acceleration–displacement response spectrum curves to conduct linear and nonlinear SDOF response history analyses. The procedure presented in ATC–40 (ATC, 1996) is used for this purpose that assumes first–mode dominant structural behavior as well as negligible changes in the elastic fundamental modal properties when the structure behaves in the post–elastic range.

The comparisons of MDOF response and corresponding equivalent SDOF response are performed by plotting the elastic and inelastic MIDR results against the corresponding elastic ($S_{d,e}$) and inelastic ($S_{d,ie}$) peak SDOF displacements. The scatter plots for all building models as well as in terms of number of stories are given in Figure 3.1.

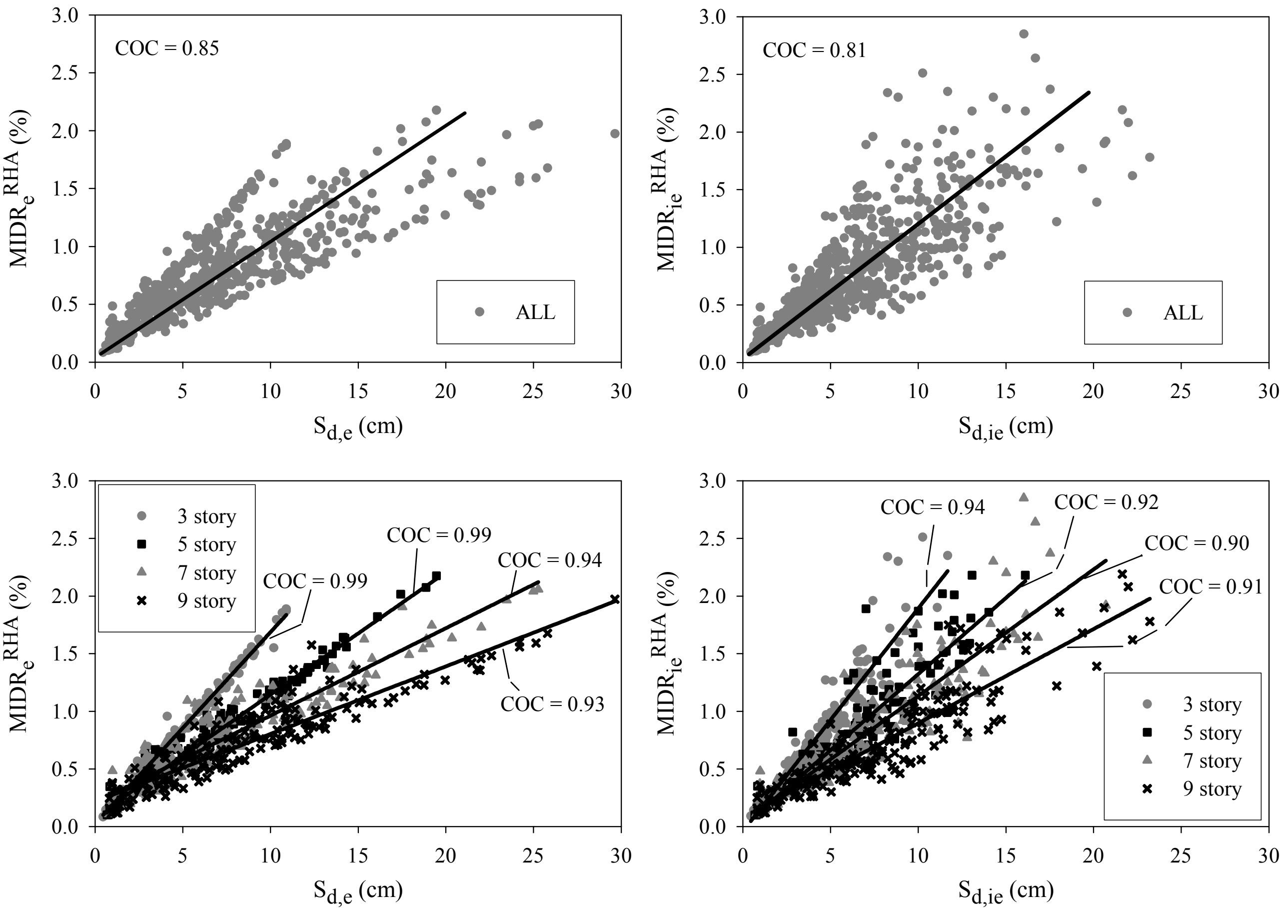

Figure 3.1 Elastic and inelastic MIDR results versus the corresponding peak SDOF displacements

The comparisons between the scatter plots for MIDR and spectral displacements reveal that there is a fairly well linear correlation between these two parameters. The correlation coefficient (COC) values of the entire response history analyses (first row scatters) are found as 0.85 for elastic and 0.81 for inelastic behavior. This indicates that the linearity assumption made in the elastic structural behavior can be extended to inelastic response. The COC values presented in terms of number of stories (second row scatters) also exhibit a similar conclusion.

4. PROPOSED PROCEDURE

The results presented in the previous section indicate that the linear relationship assumption between $MIDR_{ie}$ and the inelastic SDOF peak response ($S_{d,ie}$) holds fairly well provided that the structure deforms predominantly under the first mode behavior. Therefore, this study modifies the procedure of Akkar et al. (2005) by replacing $S_{d,e}$ with $S_{d,ie}$ in Eqn. 2.1 and estimating $MIDR_{ie}$ via Eqn. 2.2. This way, the possible changes in the first mode dynamic properties due to nonlinear structural behavior are overlooked and a linear relationship between $MIDR_{ie}$ and $S_{d,ie}$ assumption is utilized as discussed above. Although these assumptions are gross, similar simplifications are also done by many researchers (e.g. Miranda, 1999; Medina and Krawinkler, 2005). Note that $S_{d,ie}$ can be computed from the equivalent SDOF systems of the buildings using either the nonlinear response history analysis or modifying factors that estimate $S_{d,ie}$ from the corresponding $S_{d,e}$. Such modifying factors are abundant in the literature (e.g. Newmark and Hall, 1982; Vidic et al., 1994; Miranda, 2000; Ruiz–García and Miranda, 2003; Chopra and Chintanapakdee, 2004). For the sake of further simplification in the proposed procedure, the modifying factor proposed by Chopra and Chintanapakdee (2004) is used for approximating the $S_{d,ie}$. Chopra and Chintanapakdee (2004) investigated the relation between inelastic and elastic SDOF responses for bilinear non–degrading systems and proposed modifying functions for $S_{d,ie}$ for constant ductility (μ) and normalized lateral strength (elastic to yield strength ratio, R_y). In this study, the modifying factor of constant strength (C_R) is used for $S_{d,ie}$ estimations because the pushover curves reveal explicit information only about the yield strength of the model buildings. C_R is defined in Eqn. 4.1 and its functional form proposed by Chopra and Chintanapakdee (2004) is given in Eqns. 4.2 and 4.3.

$$C_R = \frac{S_{d,ie}}{S_{d,e}} \tag{4.1}$$

$$C_R = 1 + \left[(L_R - 1)^{-1} + \left(\frac{a}{R_y{}^b} + c \right) \left(\frac{T_n}{T_c} \right)^d \right]^{-1} \tag{4.2}$$

$$L_R = \frac{1}{R_y} \left(1 + \frac{R_y - 1}{\alpha} \right) \tag{4.3}$$

In Eqn. 4.2, a=63, b=2.3, c=1.7, and d=2.3. These coefficients are independent of post–yield stiffness ratio, α. On the other hand, the effect of post–yield stiffness ratio is accompanied by L_R presented by Eqn. 4.3. In Eqn. 4.2, T_n is the elastic vibration period and T_c is the period that separates acceleration and velocity sensitive regions. (T_c is suggested as 0.43 by Chopra and Chintanapakdee (2004) for large magnitude and short distance records that are similar to the ground motions used here. The reader is referred to Chopra and Chintanapakdee (2003) for further information.) By using the normalized lateral strength values, R_y, and post–yield stiffness ratios, C_R can be found for each particular case from Eqn. 4.2.

The linear relationship assumption between the elastic and inelastic SDOF and MDOF deformation demands can be further generalized as given below.

$$C_R = \frac{S_{d,ie}}{S_{d,e}} \cong \frac{MIDR_{ie}}{MIDR_e} \tag{4.4}$$

Accordingly, $MIDR_{ie}$ can be simply estimated by using Eqn 4.5 as follows.

$$MIDR_{ie} = C_R \times MIDR_e \tag{4.5}$$

At this stage, the validity of linear relationship assumption between the MDOF and SDOF deformation demands are verified once again from residual analysis presented in Figure 4.1. The residual plots represent the logarithmic differences between the exact $MIDR_{ie}$ obtained from the response history analyses and the estimations obtained from Eqn. 4.5. The C_R value in Eqn. 4.5 is computed from Eqns. 4.2 and 4.3, whereas $MIDR_e$ values are derived from the elastic response history analysis of the models. The linear line fitted to the residuals does not show any trend indicating that the approximation in Eqn. 4.4 is unbiased. Therefore, this simple case study once again shows the validity of linear relationship assumption between the MDOF and SDOF deformation demands both in the elastic and inelastic ranges.

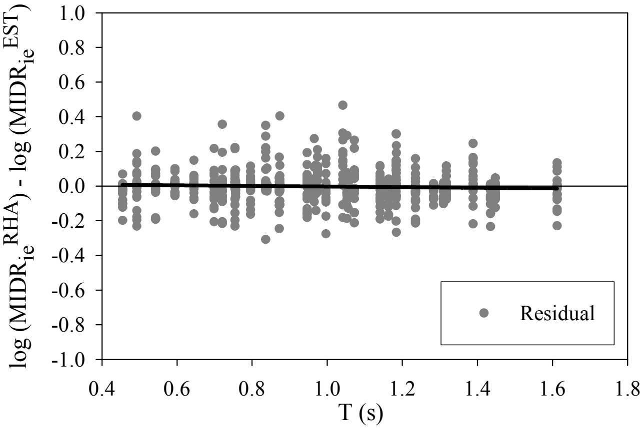

Figure 4.1 Residuals of inelastic MIDR results found by Eqn 4.5

Eqn. 4.6 shows the final form of the modified Akkar et al. (2005) procedure for estimating inelastic MIDR. In brief, the expression makes use of a modifying factor for $S_{d,ie}$ estimation from its elastic counterpart ($S_{d,e}$) and overlooks the changes in the fundamental mode features when the system behaves in the post–elastic range. Note that, one can use a modifying factor as a function of displacement ductility (i.e. C_μ), if this structural parameter is known *apriori*. For the sake of completeness, this expression is given in Eqn. 4.7.

$$MIDR_{ie} = C_R \times \gamma_1(\rho, T_1) \times \gamma_2(\rho, T_1) \times 1.27 \sin\left(\frac{\Pi h}{2H}\right) \frac{S_{d,e}(T_1, \xi)}{h} \tag{4.6}$$

$$MIDR_{ie} = C_\mu \times \gamma_1(\rho, T_1) \times \gamma_2(\rho, T_1) \times 1.27 \sin\left(\frac{\Pi h}{2H}\right) \frac{S_{d,e}(T_1, \xi)}{h} \tag{4.7}$$

5. INELASTIC MIDR ESTIMATIONS

The $MIDR_{ie}$ estimations are computed using Eqn. 4.6 for each building subclass and for a total of 60 ground motions. These estimations are then compared with the ones obtained from the nonlinear response history analyses. Figure 5.1 shows the overall residual scatter for the proposed expression, whereas Figure 5.2 presents the correlation between the nonlinear response history analyses and the estimations computed from Eqn 4.6 in terms of number of stories. The common observation from these figures is that the proposed empirical relationship tends to overestimate the $MIDR_{ie}$ for short period (low–rise) frame systems, whereas for relatively long–period buildings (fundamental periods greater than 1.0 s), Eqn. 4.6 tends to underestimate $MIDR_{ie}$.

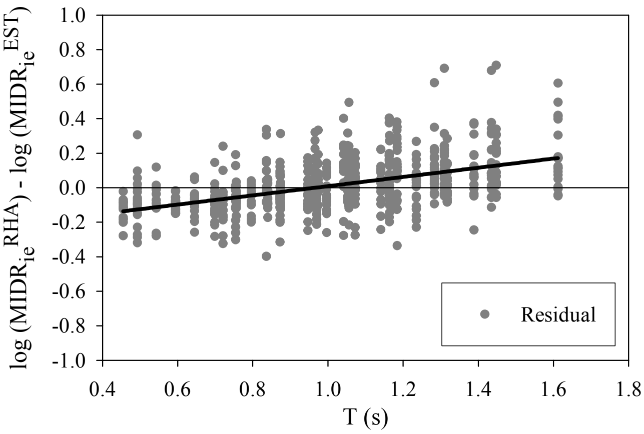

Figure 5.1 Residuals of inelastic MIDR results with respect to period values

When the information revealed from Figure 5.1 and Figure 5.2 is combined with the conclusion derived from Figure 4.1, one can state that neglecting the changes in the fundamental mode dynamic properties due to post–elastic structural behavior results in biased estimations. Nonetheless, the biased estimations can be tolerated given the simplicity of the proposed method.

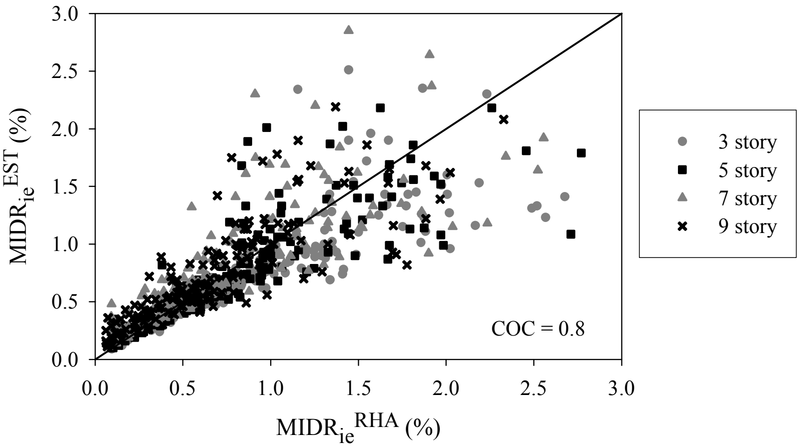

Figure 5.2 Comparison of exact (response history analyses) and estimated (Eqn. 4.6) MIDR$_{ie}$ values. Note the high correlation coefficient suggesting a fairly well performance of the proposed procedure.

Figure 5.3 compares the MIDR$_{ie}$ estimations (left panel) with the actual MIDR$_{ie}$ scatters (right panel) in terms of story numbers. The plots also present the mean and ± sigma curves computed at each story level. Although the mean curves of estimated and actual MIDR$_{ie}$ follow each other closely, the discrepancy in ± sigma curves is notable in particular for low–rise models. On the other hand, ± sigma plots also reveal that the dispersion about the mean of actual and estimated MIDR$_{ie}$ is inevitable. This fact emphasizes the significance of record–to–record variability as well as complex nonlinear structural response.

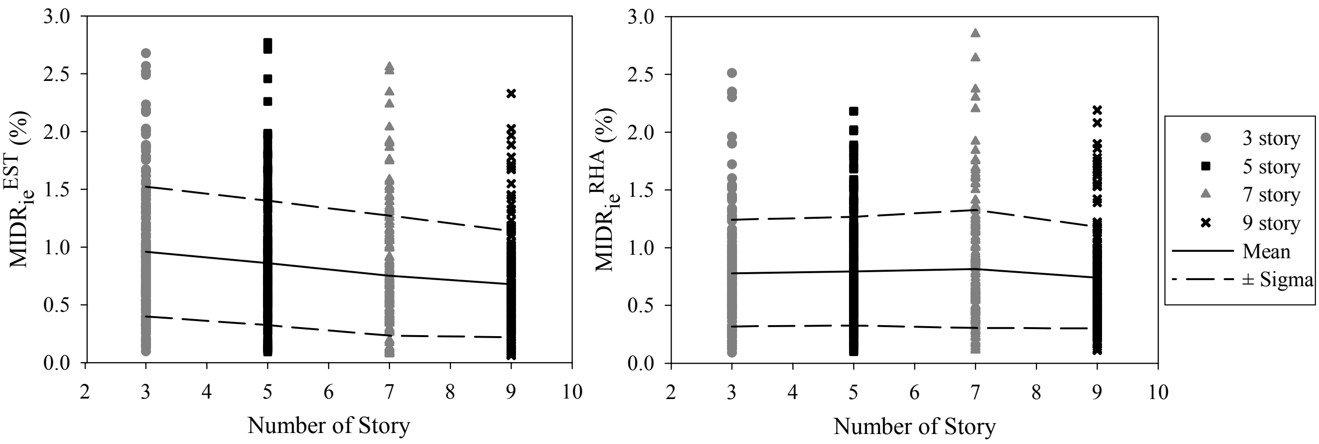

Figure 5.3 Comparisons of estimated and actual MIDR$_{ie}$ values with respect to number of stories

6. RESULTS AND CONCLUSION

A simplified procedure to estimate MIDR$_{ie}$ by using SDOF response is proposed for low– to mid–rise frame buildings. The procedure is based on a) linear relationship between SDOF and MDOF global deformation demand parameters, b) invariability of the first mode dynamic properties both in the elastic and inelastic structural behavior. A total of 2880 nonlinear and linear response history analyses are conducted to validate the proposed procedure. The case studies show that the first assumption is fairly acceptable as long as the structural behavior is dominated by the fundamental mode. However, the same case studies show that the second assumption may result in bias in the overall structural response covered in this study. This bias is tolerable considering the simplicity of the method.

ACKNOWLEDGEMENTS

This study is conducted as part of the project entitled "Compilation of Turkish strong ground–motion database in accordance with international standards" that is funded by the Scientific and Technological Research Council of Turkey under the Award No. 105G016.

REFERENCES

Akkar, S., Yazgan, U., and Gülkan, P. (2005). Drift estimates in frame buildings subjected to near–fault ground motions. *Journal of Structural Engineering, ASCE*, **131:7**, 1014-1024.

American Society of Civil Engineers (ASCE). (2000). Prestandard and commentary for the seismic rehabilitation of buildings, FEMA–356, Washington, D.C.

Applied Technology Council (ATC). (1996). Seismic evaluation and retrofit of concrete buildings, ATC–40, California.

Blume, J. A. (1968). Dynamic characteristics of multi–story buildings. *Journal of Structural Division ASCE*, **94:2**, 377-402.

Chopra, A. K. and Chintanapakdee, C. (2003). Inelastic deformation ratios for design and evaluation of structures. Rep. No. EERC-2003-09, Earthquake Engineering Research Center, University of California at Berkeley, Berkeley, California.

Chopra, A. K. and Chintanapakdee, C. (2004). Inelastic deformation ratios for design and evaluation of structures: Single-degree-of-freedom bilinear systems. *Journal of Structural Engineering, ASCE,* **130:9**, 1309-1319.

Gülkan, P. and Akkar, S. (2002). A simple replacement for the drift spectrum. *Engineering Structures*, **24:11**, 1477-1484.

Heidebrecht, A. C. and Rutenberg, A. (2000). Applications of drift spectra in seismic design. Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, Paper No. 209.

Medina, R. A. and Krawinkler, H. (2005). Evaluation of drift demands for the seismic performance assessment of frames. *Journal of Structural Engineering, ASCE*, **131:7**, 1003-1013.

Miranda, E. (1999). Approximate seismic lateral deformation demands in multistory buildings. *Journal of Structural Engineering, ASCE*, **125:4**, 417-425.

Miranda, E. (2000). Inelastic displacement ratios for structures on firm sites. *Journal of Structural Engineering*, **126:10**, 1150–1159.

Miranda, E. and Reyes, C. J. (2002). Approximate lateral drift demands in multistory buildings with non–uniform stiffness. *Journal of Structural Engineering*, **128:7**, 840-849.

Newmark, N. M. and Hall, W. J. (1982), *Earthquake Spectra and Design*, Earthquake Engineering Research Institute, Oakland, CA.

Ruiz–García, J. and Miranda, E. (2003). Inelastic displacement ratios for evaluation of existing structures. *Earthquake Engineering and Structural Dynamics*, **32:8**, 1237-1258.

Valles, R. E., Reinhorn, A. M., Kunnath, S. K., Li, C., and Madan, A. (1996). IDARC–2D Version 4.0: A Program for the Inelastic Damage Analysis of Buildings. Technical Report NCEER–96–0010, Buffalo, NY.

Vidic, T., Fajfar, P., and Fischinger, M. (1994). Consistent inelastic design spectra: strength and displacement. *Earthquake Engineering and Structural Dynamics*, **23:5**, 507-521.