EVALUATION OF FEMA440 EQUIVALENT NONLINEAR STATIC SEISMIC ANALYSIS FOR IRREGULAR STEEL MOMENT RESISTING FRAMES

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ABSTRACT

It is well established that for seismic evaluation, design, and retrofitting of building structures, a simplified design-oriented modeling procedure is more practical. One of well-established procedures is the equivalent nonlinear static procedure summarized in FEMA356 based on nonlinear static pushover analysis using the target displacement predicted by the Coefficient Method (CM). CM utilizes a displacement modification procedure in which several empirically derived factors are used to modify the response of a single-degree-of freedom model of the structure assuming that it remains elastic. FEMA440 has suggested some recommendations for improving the performance of CM leading to a Modified Coefficient Method (MCM).

This paper presents a detailed investigation on performance of FEMA440 MCM for estimating frame maximum roof displacement, base shear, and median story drifts of steel moment resisting frames with irregularities in elevation. Results of nonlinear dynamic analyses of 22 irregular frames subjected to a family of 14 ground motions and nonlinear equivalent static analyses of all frames up to the target roof displacement computed by MCM are compared to evaluate the accuracy and conservatism of FEMA440 MCM.

KEYWORDS: FEMA440 Modified Coefficient Method, Equivalent Nonlinear Static Analysis, Irregular Moment Resisting Steel Frames, Target Displacement

1. INTRODUCTION

Reduction of seismic irreparable structural damages has been the main goal of structural engineering. It is well known that structural members commonly behave in the inelastic range during intermediate and sever earthquakes. Therefore nonlinear analyses methods are needed to assess the actual structural behavior in order to retrofit existing structures or design new ones. Nonlinear time history analysis (NL-THA) provides the most accurate modeling for prediction of seismic demands. However its high computational cost and its complexity and sensitivity to nonlinear member models lead to development of simpler method such as equivalent nonlinear static procedures (NSP) for estimating seismic demands. Previous researches [1] have shown that nonlinear static procedures give reasonable estimation for displacement demands for regular frames and frames with base weak story. Currently these NSP methods are restricted to regular buildings with low or medium rise height. Hence evaluation of NSP methods for irregular buildings seems to be necessary.

One of the well-established nonlinear static procedures is the equivalent nonlinear static procedure summarized in FEMA356 [2] based on nonlinear static pushover analysis using the target displacement predicted by the Coefficient Method (CM). CM utilizes a displacement modification procedure in which several empirically derived factors are used to modify the response of a single-degree-of freedom model of the structure assuming that it remains elastic. FEMA440 [3] has suggested some recommendations for improving the performance of CM leading to a Modified Coefficient Method (MCM).

FEMA440 MCM suggests that the maximum demands (displacements and forces) for a nonlinear time history analysis can be estimated from a nonlinear static analysis where roof displacement is the same as maximum roof displacement estimated by the nonlinear time history analysis. The structure layout, boundary conditions, and nonlinearities are the same in both analyses. The lateral loading pattern for the nonlinear static analysis is limited to recommendation in Chapter 3 of FEMA356. In order to make the nonlinear static analysis independent from the nonlinear time history analysis, FEMA440 MCM estimates the target roof displacement (δ_t) using the following formula:

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g \qquad \& \qquad R < R_{\max} \tag{1.1}$$

Where the modification factor C_0 relates the spectral displacement of an equivalent SDOF system to the roof displacement of the MDOF building, the modification C_1 relates expected maximum inelastic displacements to displacements calculated for linear elastic response, the modification factor C_2 represents the effect of pinched hysteretic degradation on displacement response and is recommended to be 1.0, T_e is the effective fundamental period, S_a is the response spectrum acceleration at T_e and damping ratio of the building, g is the acceleration of gravity, R is the ratio of elastic strength demand to calculated yield strength coefficient at the target displacement δ_t, and R_{max} is the recommended maximum R value for limiting plastic P-Δ instability.

In the following sections we present a detailed investigation on performance of FEMA440 MCM for estimating frame target roof displacement, base shear, and story drifts of steel moment resisting frames with irregularities in elevation.

2. FRAME MODELS AND ANALYSES

The developed irregular moment resisting frames are schematically shown in Fig. 1. These frames are designed as intermediate moment resisting frame (IMRF) using AISC-LRFD-99 steel design code [4] and load combinations in UBC-97 [5]. Each frame has three 10-meter spans and five stories. All story heights are 3.6m except the first story height is 3.4m. All IPB beams and columns are laid out to bend about their major axis in the frame plane and are rigidly connected to one another. Column sections are typically IPB800 to IPB1100 for first story and IPB260 to IPB320 for top story. Beams are typically IPB320 to IPB600. The design base shear coefficient is 0.165g using response reduction factor R=5. Frame weights including dead load and effective live load vary from 1465 Ton to 2379 Ton.

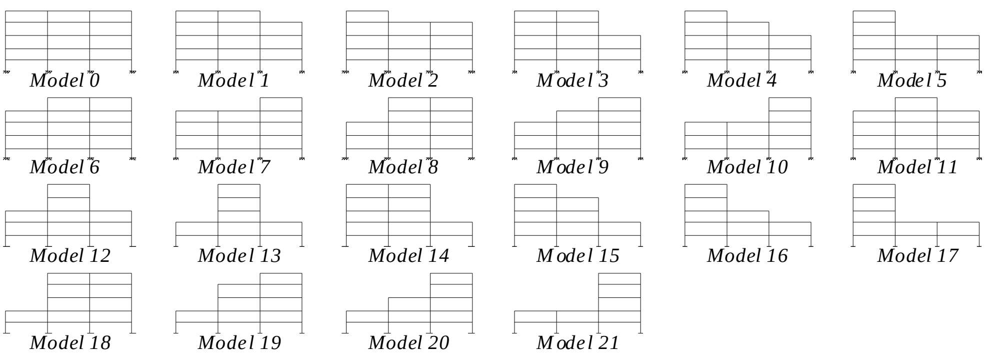

Fig. 1 Selected frame models

The inelastic static and dynamic analyses have been performed using the Inelastic Damage Analysis of Reinforced Concrete software (IDARC6.1) [6] for planar frames. IDARC6.1 uses fiber element approach for modeling nonlinear hysteretic behaviors. For nonlinear time history analyses fourteen (7 pairs) of recorded ground motions are used as listed in Table 1. These ground motions are all for soil type C using USCGS categories and have similar earthquake magnitude and distance to the fault. The selected ground motions are scaled using procedure suggested in Chapter 1 of FEMA356 while design spectrum is as recommended in the Iranian Seismic Code 2800 [7] for site type C. The computed scale factor for each ground motion is shown in Table 1 and scaled spectra are shown in Fig. 2.

Table 1 Selected ground motions

W	Earthquake	Identifier	Magnitude	Dist. "Km"	PGA "g"	Scaled PGA "g"
1	Chi-Chi, Taiwan	CHY101W	Ms= 7.6	11.14	0.353	0.596
2	Chi-Chi, Taiwan	CHY101N	Ms= 7.6	11.14	0.44	0.596
3	Imperial Valley	E11230	Ms= 6.9	12.6	0.38	1.154
4	Imperial Valley	E11140	Ms= 6.9	12.6	0.364	1.154
5	Loma Prieta	G03000	Ms= 7.1	14.4	0.555	0.813
6	Loma Prieta	G03090	Ms= 7.1	14.4	0.367	0.813
7	Northridge	CNP106	Ms= 6.7	15.8	0.356	0.562
8	Northridge	CNP196	Ms= 6.7	15.8	0.42	0.562
9	Superstitn	ICC000	Ms= 6.6	13.9	0.358	0.750
10	Superstitn	ICC090	Ms= 6.6	13.9	0.258	0.750
11	Northridge	LOS000	Ms= 6.7	13	0.41	0.664
12	Northridge	LOS270	Ms= 6.7	13	0.482	0.664
13	Loma Prieta	G02000	Ms= 7.1	12.7	0.367	0.705
14	Loma Prieta	G02090	Ms= 7.1	12.7	0.322	0.705

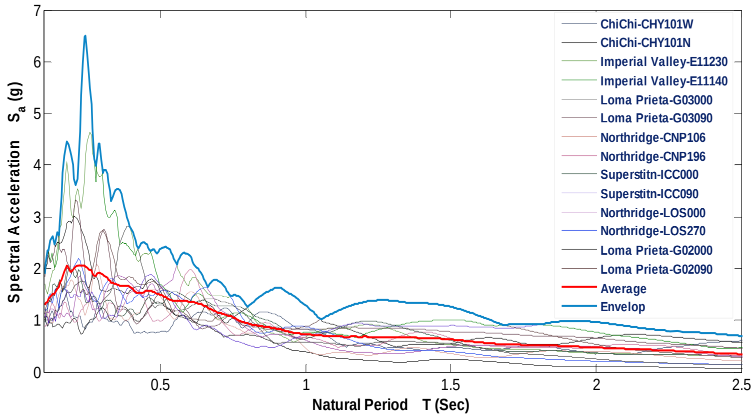

Fig. 2 Scaled ground motion spectra

3. NONLLINEAR STATIC AND DYNAMIC RESULTS

For each of selected 22 frames, two nonlinear static analysis (using uniform and triangular lateral loading patterns) and one nonlinear time history analysis are performed for each of 14 selected scaled ground motions. Figure 3 compares the estimated roof displacement for these analyses for the regular frame model number 0. In Fig. 3 if the nonlinear time history displacement is greater than the FEMA440 MCM estimated target displacement then the bar connecting these results is solid otherwise it is hatched. The height of connected bar represents the estimation error for a given ground motion. It can be observed that FEAM440 MCM reasonably estimates the roof maximum displacement for a regular frame. Similar analyses and results are developed for all 22 selected frames. Such results are summarized in following sections.

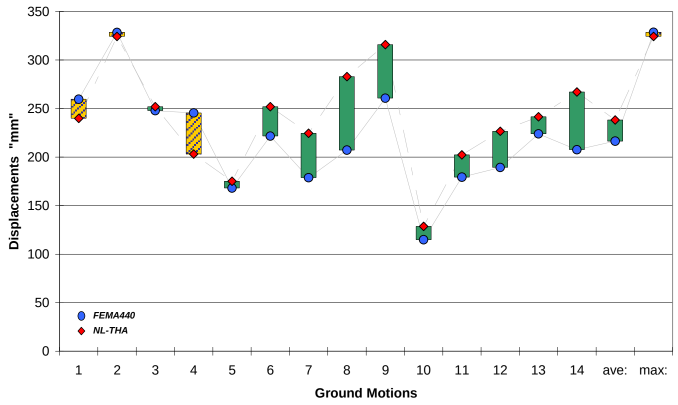

Fig. 3 Estimated maximum roof displacements for frame model 0

3.1. Error Indices and Correlation Factors

Since there are 14 nonlinear time history analyses for each frame, the accuracy and conservatism of FEMA440 MCM are represented by 14 error values computed for a given response measure such as roof displacement, frame base shear, and frame maximum story drift. Therefore each response measure and its associated error index have a distribution which can be represented by its minimum, median, and maximum values. In this study relative error ($error_r$) is determined as follows:

$$error_r^i = \frac{Q_i^{NL-THA} - Q_i^{FEMA440}}{Q_i^{NL-THA}} \times 100 \tag{3.1}$$

Where Q_i^{NL-THA} is the nonlinear time history response (such as target displacement, base shear, drift) for the i^{th} ground motion and $Q_i^{FEMA\,440}$ is the associated FEMA440 MCM estimated response.

Another practical measure for estimating the accuracy of FEAM440 MCM is the correlation factor for results estimated by nonlinear time history analyses and FEMA440 MCM and is computed as follows:

$$\rho = \frac{\sum_{i=1}^{m}(Q_i^{NL-THA} - \overline{Q}^{NL-THA})(Q_i^{FEMA440} - \overline{Q}^{FEMA440})}{\sqrt{\sum_{i=1}^{m}(Q_i^{NL-THA} - \overline{Q}^{NL-THA})^2} \times \sqrt{\sum_{i=1}^{m}(Q_i^{FEMA440} - \overline{Q}^{FEMA440})^2}} \tag{3.2}$$

Where Q_i^{NL-THA} and $Q_i^{FEMA\,440}$ are the same as in Equation 3.1, $\overline{Q}^{NL-THA}$ is the average of nonlinear time history results for 14 ground motions and 22 models, $\overline{Q}^{FEMA440}$ is the average of FEMA440 MCM results, and *m*=22x14=308 is the total number of results. The correlation factor can be determined for each individual frame model setting *m*=14. For fully correlated matched results ρ is equal to one.

3.2. Frame Roof Displacement Results

By scatter plotting target roof displacements estimated by FEMA440 MCM versus maximum roof displacement estimated by the nonlinear time history analyses, as shown in Fig. 4, the accuracy and conservatism of FEMA440 MCM for estimating roof displacement can be presented. The correlation factor using 308 nonlinear time history results and 308 results obtained from 616 nonlinear static analyses (using two lateral load patterns) is equal to 0.6911 showing reasonable correlation between FEMA440 MCM estimated roof displacements and actual maximum roof displacements. Figure 5 shows the relative error distribution (minimum, maximum, and median) for each selected frame model. In this figure each bar shows the relative error range for 14 and the median value of relative error is written for each bar. The correlation factor for each frame model is shown in Table 2.

It can be observed that for frame models 1, 3, 6, 8, 13, 14, and 18 the relative errors and correlation factors are close to the values for the regular frame model 0. Such observations are being used in ongoing research for defining an irregularity measure for each frame and a correction factor for FEMA440 MCM target displacement formula, as shown in Eqn. 1.1. The relative error for the regular frame model 0 is maximum 27% on the unsafe side. Therefore a magnification factor of 1.37 can make FEMA440 MCM conservative for all ground motions for this given frame model. In order to make FEMA440 MCM conservative for estimating maximum roof displacement for all selected irregular frame models, the magnification factor should be 2.0. By using the median estimated roof displacements, the required magnification factor can be reduced to 1.4.

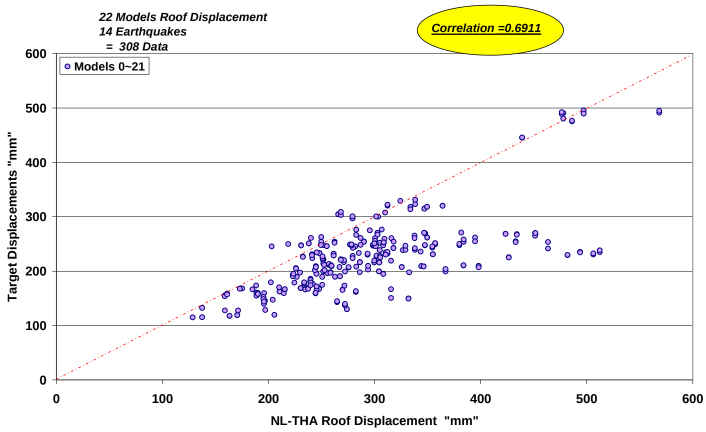

Fig. 4 Scatter plot of estimated maximum roof displacements

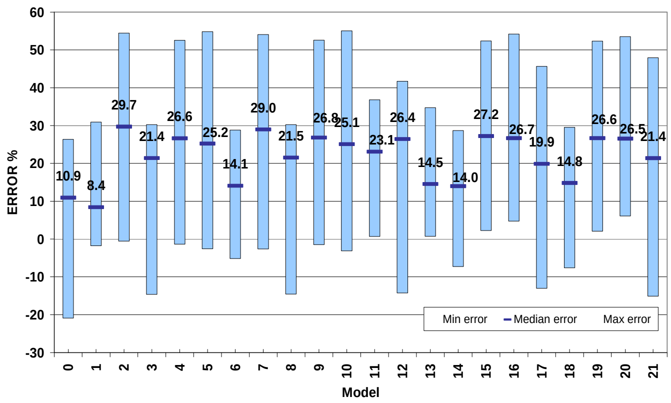

Fig. 5 Relative errors of estimated maximum roof displacements

Table 2 Correlation factors for estimated maximum roof displacements

Model	Corr.	Model	Corr.	Model	Corr.
0	0.808	8	0.783	16	0.719
1	0.782	9	0.684	17	0.688
2	0.649	10	0.579	18	0.834
3	0.782	11	0.727	19	0.695
4	0.684	12	0.665	20	0.725
5	0.582	13	0.915	21	0.673
6	0.799	14	0.837		
7	0.657	15	0.691		

3.3. Frame Base Shear Results

Similar to presentations for roof displacement results, scatter plots of all estimated frame base shears are shown in Fig. 6 and relative errors for each frame model are shown in Fig. 7. The correlation factor for each frame model is shown in Table 3. The correlation factor using all 308 base shear results is equal to 0.8614 showing good correlation between FEMA440 MCM estimated frame base shears and actual base shears.

It can be observed that for frame models 1, 3, 6, 8, 14, and 18 the relative errors and correlation factors are close to the values for the regular frame model 0. The relative error for the regular frame model 0 is maximum 3% on the unsafe side. Therefore FEMA440 MCM is conservative for estimating frame base shear for a regular frame and no magnification factor is needed. However, in order to make FEMA440 MCM conservative for estimating frame base shear for all selected irregular frame models, the magnification factor should be 2.0. By using median estimated frame base shear, the required magnification factor can be reduced to 1.5. FEMA440 MCM has low correlation factor of less than 0.5 for irregular frame models 2, 4, 5, 7, 9, 10, 15, 16, 17, 19, 20, and 21. Irregularities represented by these frames should be considered sever and FEMA440 MCM may not be conservative for estimating frame base shears for these frames.

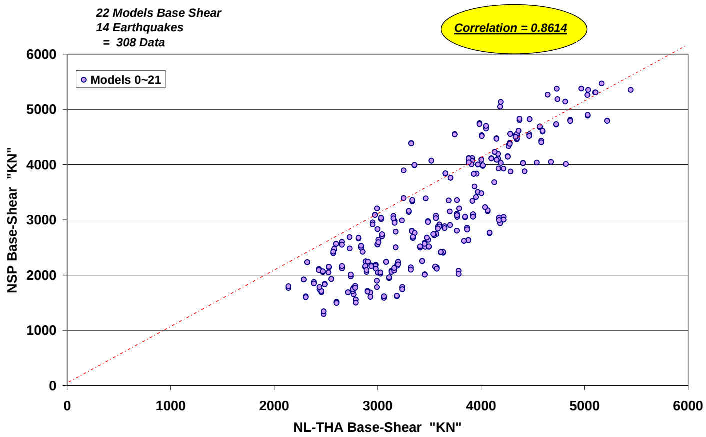

Fig. 6 Scatter plot of estimated frame base shears

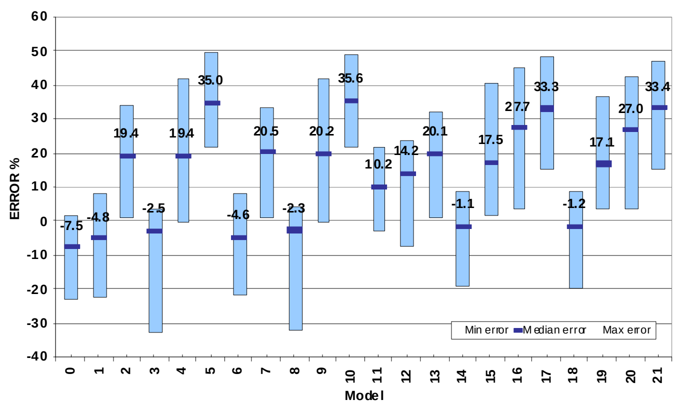

Fig. 7 Relative errors of estimated frame base shears

Table 3 Correlation factors for estimated frame base shears

Model	Corr.	Model	Corr.	Model	Corr.
0	0.849	8	0.655	16	0.090
1	0.767	9	0.185	17	-0.307
2	0.316	10	0.207	18	0.789
3	0.667	11	0.672	19	0.230
4	0.208	12	0.649	20	0.126
5	0.163	13	0.550	21	-0.371
6	0.741	14	0.792		
7	0.301	15	0.202		

3.4. Frame Story Drift Results

By scatter plotting median story drifts estimated by FEMA440 MCM versus median story drifts estimated by the nonlinear time history analyses, as shown in Fig. 8, the accuracy and conservatism of FEMA440 MCM for estimating story drifts can be presented. Median story drift is the median of story drifts estimated for 14 ground motions for a given story. The correlation factor using all 110 median story drifts is equal to 0.8827 showing good correlation between FEMA440 MCM estimated median story drifts and actual drifts. The relative errors for each frame model are shown in Fig. 9. The relative errors for median story drifts are greater than relative errors for estimated roof displacement and frame base shear. The correlation factor for 5 estimated median story drifts for each frame model is shown in Table 4. These model correlation factors represent how well estimated median drifts follow the median of drifts estimated by the nonlinear analyses along the height of a given frame model.

It can be observed that for frame models 1, 3, 6, 8, 14, and 18 the relative errors and correlation factors are close to the values for the regular frame model 0. However the correlation factor for these models and the regular frame model 0 are less than the correlation factors for remaining irregular frames. The scatter plot of all story drifts estimated by FEMA440 MCM versus story drifts estimated by nonlinear time history analyses is shown in Fig. 10. The overall correlation factor is 0.6983 which is fair and similar to the correlation factor for estimated roof displacements but not as good as the correlation factor for estimated frame base shears.

The relative error for the regular frame model 0 is maximum 50% on the unsafe side. Therefore a magnification factor of 2.0 can make FEMA440 MCM conservative for all ground motions for this regular frame model. In order to make FEMA440 MCM conservative for estimating median story drifts for all selected irregular frame models, the magnification factor should be 3.0. Therefore FEMA440 MCM is not reasonably accurate for estimating maximum story drift. It should be noted that by moving from global response measures such as target displacements and base shears toward local response measures like story drifts and plastic hinge rotations, the estimation accuracy of equivalent nonlinear static procedures decreases.

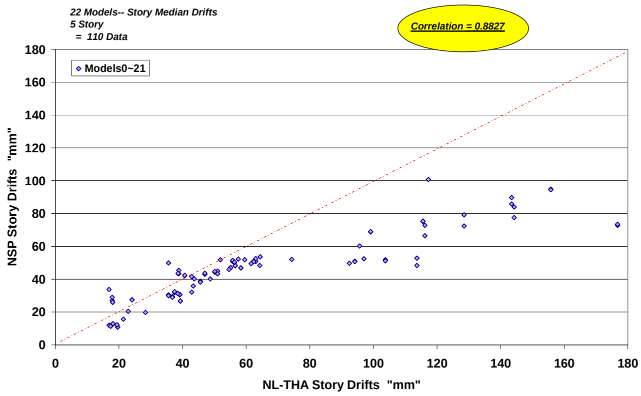

Fig. 8 Scatter plot of estimated median story drifts

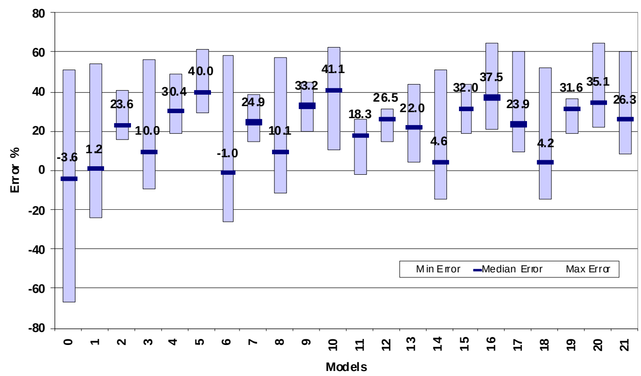

Fig. 9 Relative errors of estimated median story drifts

Table 4 Correlation factors for estimated median story drifts

Model	Corr.	Model	Corr.	Model	Corr.
0	0.728	8	0.814	16	0.911
1	0.791	9	0.991	17	0.879
2	0.960	10	0.922	18	0.840
3	0.837	11	0.992	19	0.990
4	0.983	12	0.953	20	0.908
5	0.938	13	0.361	21	0.881
6	0.619	14	0.846		
7	0.969	15	0.983		

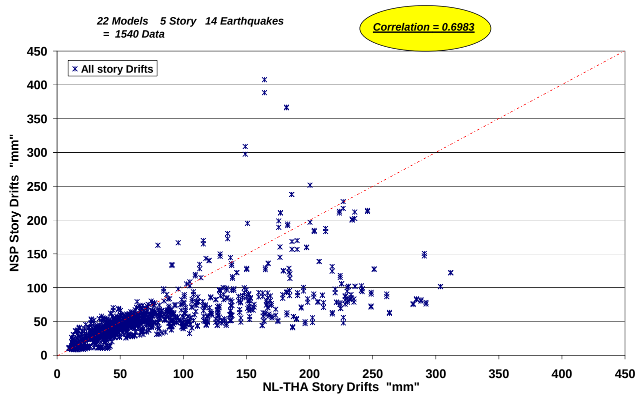

Fig. 10 Scatter plot of estimated story drifts

4. CONCLUSIONS

Summary of a detailed investigation on performance of FEMA440 Modified Coefficient Method (MCM) for equivalent nonlinear static analysis for estimating frame maximum roof displacement, base shear, and median story drifts is presented for steel moment resisting frames with irregularities in elevation. Results of nonlinear dynamic analyses of 22 irregular frames subjected to a family of 14 ground motions and nonlinear equivalent static analyses of all frames up to the target roof displacement computed by MCM are compared to evaluate the accuracy and conservatism of FEMA440 MCM.

Following trends and results are observed:

- The correlation factors for estimated roof maximum displacements and story drifts are about 0.69 which a fair correlation but not as good as the correlation factor for estimated frame base shears of 0.86.
- The correlation factor for story drifts is improved to 0.88 by using median of story drifts estimated for 14 ground motions.
- For the regular frame, the maximum relative errors for estimated roof displacements, frame base shears, and median story drifts are 27%, 3%, and 50%, respectively.
- For the irregular frame, the maximum relative errors for estimated roof displacements, frame base shears, and median story drifts are 55%, 50%, and 65%, respectively.
- FEMA440 MCM better estimates frame roof displacement and base shear than story drifts for regular and irregular frames.
- The main sources of approximation errors are formation of local partial plastic mechanisms instead of complete plastic mechanisms and equivalency of damping value between static and dynamic nonlinear analyses.
- There are frame irregularities (setbacks) which not cause significant decrease in accuracy and conservatism of FEMA440 MCM when compared to a regular frame. Such irregularities need to be classified and measured.
- The conservatism of FEMA440 MCM target displacement formula can be improved by introducing a magnification factor representing irregularity measure.

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