# A Relationship between the Energy Demands of MDOF and Equivalent SDOF Systems under Pulse-Type Near-Fault Earthquakes

**Seyed Abdonnabi Razavi[1], Navid Siahpolo[2*], Mehdi Mahdavi Adeli[1]**

[1]Department of Civil Engineering, Islamic Azad University, Ahvaz Branch, Ahvaz, Iran
[2] Department of Civil Engineering, ACECR Institute for higher education, Khouzestan Branch, Ahvaz, Iran



## ABSTRACT

The main purpose of the paper is qualitative and quantitative study of the relationship between the energy demand of multi-degree-of-freedom systems, MDOF, and equivalent-single-degree-of-freedom systems to calculate the total energy demand of the MDOF system using the ESDOF energy demand. For this purpose, multi-story special steel moment frames designed and analyzed under the influence of 10 near-fault earthquake with forward-directivity effects. Moreover, the process done for the ESDOF system considering specified values of *R* (degree of nonlinearity). Accordingly, linear and nonlinear total dissipated energy (*TDE*), hysteretic energy (*HE*), and damping energy (*DE*) ratios were introduced to estimate the relationship of the ESDOF and MDOF energy. Results shows that ratio of nonlinear to linear *TDE* and *HE/TDE* is affected by period and *R* in ESDOF system. However, as the period and *R* increase, the ratio converges to one. The same result was observed between the nonlinear *TDE* of the MDOF system and the linear *TDE* of the ESDOF system. In other words, ESDOF linear *TDE* can be used instead of MDOF for long periods. In addition, the nonlinear *TDE* of the MDOF system to the nonlinear *TDE* of the ESDOF system ratio is affected by higher modes and period, by increasing the period the ratio is generally greater than one for the constant *R*. Also the effect of higher modes on the ratio of total story dissipated energy to total structure dissipated energy was significant for low *R* values. With increasing *R*, the structure tends to damp all the dissipated energy in the first mode.

## KEYWORDS

**Energy demand, MDOF systems, SDOF systems, Pulse-type near-fault earthquake, higher modes effects.**

[*] Corresponding Author: Email: siahpolo@acecr.ac.ir

## 1 Introduction

Goel *et al.* proposed a performance-based-plastic design (PBPD) method with the energy factor of elastic-plastic SDOF systems quantifying the seismic demand [1]. Effectiveness of this method has been examined by applying the procedure in steel moment resisting frames [2], steel frame with buckling restrained braces [3], braced truss moment frames [4, 5] and steel frames with steel shear walls [6].

Hall *et al.* indicated that the displacement caused by the pulses of near-fault earthquakes imposes considerable seismic demand on structures [7]. Krawinkler *et al.* assessed a steel moment-resisting frame under the effect of a near-fault earthquake and stated that the structural response to the continuation of the acceleration pulse, which matches the fundamental period, is critical [8]. On the other hand, many researchers have investigated the effects of this pulse-type ground motion on the linear and nonlinear behavior of SDOF systems [9].

## 2 Material and Method

### 2.1 Description of Frames

In this study, 4-, 10-, 15-, 20-, and 30-story 2D steel MRFs with three bays are considered. Gravity and seismic loads are applied models in accordance with the Iranian National Building Code-Part 6 [10]. Gravity load consists of dead load, equivalent partitioning load and live load on the beams of the frames of this study equal to 1.75, 1 and 1.25 kN/m respectively. The DBE is expressed by the Iranian Code of Practice for Seismic Resistant Design of Buildings - 4$^{th}$ edition (also known as Standard 2800) [11] design spectrum for peak ground acceleration equal to 0.35g, behavior factor R equal to 7, importance factor I, and soil type III.

### 2.2 Research Methodology

Following the initial analysis, design, and determining the sections, the models introduced in Section 3.1 are used to generate the practical ratios through analysis. To this end, initially, the target behavior coefficient ($R_{t,i}$) is set to 0.25, 0.5, 0.75, and 1 in the elastic analyses. This coefficient is considered equal to 1.5-6 in the inelastic analyses (with 0.5 increments). The yield base shear coefficient ($C_y$) is calculated using the ASCE/SEI 41-13 through pushover analysis of the MDOF structure. It is noteworthy that the coefficient introduced as the behavior coefficient in this study ($R_{exist,i}$) is the ratio of the elastic spectral acceleration to the yield strength of the MDOF structure (with damping ratio 5%).

## 3 Results and Discussion

### 3.1 Hysteretic Energy Demand in MDOF Systems

On the basis of a study conducted by Gerami and Abdollahzadeh, the Hysteretic Energy (*HE*) can be considered as a key factor to minimize expected structural damages [12]. Hence, the mean HE energy of the 2D steel MRFs of the present study are depicted and discussed. Fig. 1 shows the ratio of hysteretic energy dissipated energy in MDOF system to the corresponding values obtained from an E-SDOF system considering various *R* values (level of nonlinearity).

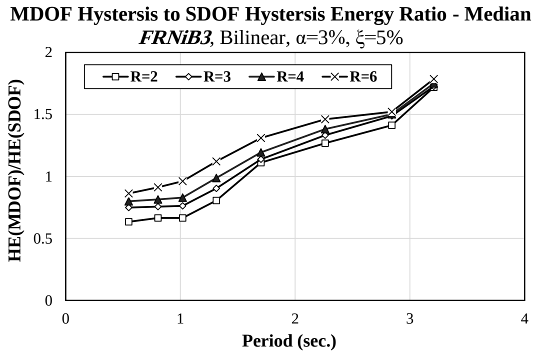


Fig. 1 **Higher mode effects (MDOF effects) on *HE* demand**

### 3.2 Height wise Distribution of Hysteretic Energy Demand (HE)

Results obtained in these sections fails to give an accurate insight into the hysteretic energy demands (*HE*) over the height of structure. Hence, the concept of the story hysteretic energy demand ($HE_{s,i}$) is introduced. In order to gain a better statistical understanding of the accumulation of the story hysteretic energy, the story *HE* demand is normalized by the total dissipated hysteretic energy ($HE_t$).

Figs. 2 shows the mean values of the normalized story hysteretic energy over the height. Due to space limitation graphs are shown only for *R*=2.0, 3.0, 4.0 and 6.0. The following observation can be made from the presented graphs:

- In the structures, in which there is a high possibility of plastic hinges formation, accumulation of maximum energy demands is observed at the lower stories.
- In low- and mid-rise frames, the peak $HE_{s,i}/HE_t$ ratio is influenced by the higher modes and locates at the upper stories for *R*=2.0 and 3.0.

However, in high-rise frames (15 stories and more), the peak $HE_{s,i}/HE_t$ ratio occurs at the lower floors due to the nature of near field motions and dynamic instability.

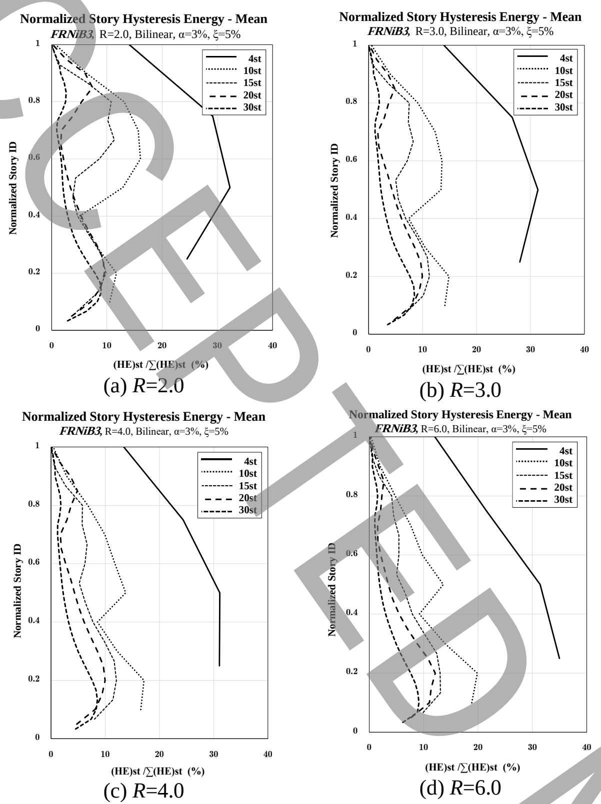


Fig. 2 **The story hysteretic energy distributed at height, $HE_{st,i}$ normalized by the total hysteretic energy for *R*=2, 3, 4, 6 and 4-, 10-, 15-, 20-, and 30-story frames**

## 4 Conclusion

The energy demand of the MDOF system was normalized with the corresponding energy demand of the E-SDOF system to consider the effects of higher modes and degrees of freedom. According to the results of the analyses, the following findings can be concluded:

- The $TDE^{in}/TDE^{el}$ ratio resulted for ESDOF system is weakly dependent on period and nonlinearity, except for period shorter than 1 Sec. The same finding is available for *HE/TDE* ratio. The trend of *HE/TDE* ratio for long period systems depends on the earthquake energy content substantially.
- *TDE* of the elastic MDOF structure is equal to 80% of the *TDE* demand of the corresponding elastic E-SDOF system. With an increase in the period, due to MDOF effect, TDE ratio $(TDE^{el}_{MDOF}/TDE^{el}_{SDOF})$ increases rastically.
- Evaluation of $(TDE^{in}_{MDOF}/TDE^{el}_{MDOF})$ ratio demonstrates that dissipated energy in the nonlinear structure is equal to dissipation of energy due to damping in the elastic system, except for short period frames.
- The ratio of $(TDE^{in}_{MDOF}/TDE^{el}_{SDOF})$ shows the effect of MDOF increases the corresponding *TDE* of inelastic MDOF system. But for short period models, elastic *TDE* of E-SDOF is an acceptable estimation.
- The trend of *HE/TDE* ratio resulted in MDOF structure is similar to corresponding E-SDOF ratio. Hence, the E-SDOF system ratio is practical for MDOF system.

## References


[1] Goel, S. C., Liao, W. C., Bayat, MR., Chao, SH., "Performance-based plastic design (PBPD) method for earthquake-resistant structures: an overview", Struct Des Tall Spec, 19(1–2), pp. 115–37

[2] Banihashemi, MR., Mirzagoltabar, AR., Tavakoli, HR., "Development of the performance based plastic design for steel moment resistant frame", Int J Steel Struct, 15(1), pp. 51–62, 2015.

[3] Sahoo, DR., Chao, S., "Performance-based plastic design method for buckling-restrained braced frames", Eng Struct, 32(9), pp. 2950–2958, 2013.

[4] Wongpakdee, N., Leelataviwat. S., Goel. SC., Liao, WC., "Performance-based design and collapse evaluation of buckling restrained knee braced truss moment frames", Eng Struct, 60, pp. 23–31, 2014.

[5] Heidari, A., Gharehbaghi, S., "Seismic performance improvement of special truss moment frames using damage and energy concepts", Earthq Eng Struct Dyn, 44(7), pp. 1055–1073, 2015.

[6] Kharmale, SB., Ghosh, S., "Performance-based plastic design of steel plate shear walls", J Constr Steel Res, 90, pp. 85–97, 2013.

[7] Hall, J. F., Heaton, T. H., Halling, M. W., Wald, D. J., "Near-source ground motion and its effects on flexible buildings", Earthquake spectra, 11(4), pp.569-605. 1995.

[8] Krawinkler, H., Anderson, J., Bertero, V., Holmes, W., Theil, Jr. C., "Steel buildings", Earthquake Spectra, 12(S1), pp. 25-47, 1996.

[9] Makris, N., Black, C. J., "Dimensional analysis of bilinear oscillators under pulse-type excitations", Journal of engineering mechanics, 130(9), pp. 1019-1031, 2004.

[10] Corporate author "DHUD-Part6: Applied loads on buildings", Department of Housing and Urban Development, "Iranian National Building Code-Part 6", third edition, (in Persian), Iran, 2014.

[11] Corporate author "BHRC–PN 253: Iranian code of practice for seismic resistant design of building", Iranian building codes and standards, forth revision, (in Persian), Iran, 2014.

[12] Gerami, M., Abdollahzadeh, D., "Estimation of forward directivity effect on design spectra in near field of fault", Journal of Basic and Applied Scientific Research, 2(9), pp. 8670-8678, 2012.