SEISMIC PERFORMANCE OF STEEL FRAMES WITH POST-TENSIONED CONNECTIONS

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SUMMARY:
The aim of this paper is to study the seismic performance of self-centering moment resisting frames for better understanding the advantages of this type of structure. Alternatively, the paper compares the seismic performance of traditional structures with rigid connections with an equivalent structure but with post-tensioned connections. For this aim, thirty long duration ground motion records obtained from the soft soil of Mexico City are used. Non-linear time history analyses are developed for both types of structural systems to obtain the maximum and residual interstory drifts, where the maximum drift is the main parameter used in the seismic design codes to evaluate the seismic performance of structures. It is concluded that the structural response of steel buildings with post-tensioned connections subjected to strong ground motions is reduced compared with the seismic response of building with rigid connections. Moreover, residual drift demands are reduced considerably for the system with post-tensioned connecction.

Keywords: Maximum inter-story drift, residual drift, self-centering.

1. INTRODUCTION

Moment resisting frames (MRF) with post-tensioned connections (PT) represent a viable alternative to conventional MRF with welded beam-column connection (FWC). The post-tensioned frames with semi-rigid connection (FPT) have been proposed recently as an alternative for controlling the structural damage and to improve the behavior of steel structures in seismic areas (Ricles et al. 2001, Ricles et al. 2002 Christopoulos et al. 2002a, 2002b, Garlock et al. 2005, 2007, 2008). The system is designed to prevent brittle fractures in the nodes areas of steel frames, which may cause reduction in the ductility capacity of the frame (as occurred in many cases during the 1994 Northridge earthquake). The beams are post-tensioned to the columns by high strength post-tensioning strands oriented parallel to the axis of the beam, which provides capacity of self-centering of the frame, reducing the residual drift and at the same time providing energy dissipation through special devices placed in the connections. The control of maximum inter-story drift is very important because is one of the main parameters recommended by seismic design codes to evaluate the performance of structures.

Structural damage measures are related to story drift, residual drift and inelastic deformation. Moreover, residual drift is an important index to make the decision if the structure is repaired or demolished after the occurrence of an earthquake. MacRae and Kawashima (1997) studied residual displacements of inelastic single-degree-of-freedom (SDOF) systems and illustrated their significant dependence on the post-yield stiffness ratio. Christopoulos et al. (2003) studied residual displacements of five SDOF systems using different hysteretic rules and suggest that residual displacements decrease when increasing the post-yielding stiffness ratio. Ruiz-Garcia and Miranda (2006) showed that residual displacements are more sensitive to changes in local site conditions, earthquake magnitude, distance to the source range and hysteretic behavior than peak displacements. Pampanin et al. (2003) studied the seismic response of multi-degree-of-freedom (MDOF) systems and highlighted a significant sensitivity of residual drifts to the hysteretic rule, post-yield stiffness ratio and global plastic mechanism. McCormick et al. (2008) addressed the issue of discomfort of the occupants of the building due to residual deformations; they reported that significant discomfort is felt by occupants of building with residual inclination above 0.8%. Based on past experiences from building that have undergone differential settlement they propose a residual drift limit of 0.5% to be considered in performance-based seismic design. They also reported that repairing damaged structures with residual story drifts greater than 0.5% after the 1995 Hyogoken-Nanbu earthquake was not financially viable.

In this study, eight steel frame models with different stories have been subjected to a set of thirty narrow-band earthquake ground motions taken from the soft soil of Mexico City. Four frames correspond to traditional MRF and the others to equivalent frames but post-tensioned. It will be observed that the posttensioned structural systems can reduce considerably the maximum and residual inter-story drift.

2. STRUCTURAL MODELS

2.1 Frame models

Eight steel structural frames were analyzed in the study: four FWC and four FPT. The first group was designed according to the seismic requirements of RCDF. The buildings are assumed to be for office occupancy. They have 6, 8, 10 and 14-stories, 3 bays, hereafter identified as F6WC, F8WC, F10WC and F14WC, respectively. The dimensions of the frames are shown in Fig. 1. The beams and columns are A36 steel W sections, a bilinear hysteretic model behavior with 3% of post-yielding stiffness was considered for the analyses, and the damping used was 3% of critical. The fundamental periods of vibration (T_1) are 1.07, 1.20, 1.37 and 1.91s respectively. On the other hand, the FPT frames were designed according to the recommendations proposed by Garlock et al. (2007), which basically start with the design of the steel frames as usually is done (considering rigid connections), then, the semi-rigid post-tensioned connections are designed to satisfy the requirements of the serviceability and resistance conditions. The beam-column connection consists of two angles bolted to the flanges of the beam and to the column flange (top and seat). The four FPT models are identified here as F6PT, F8PT, F10PT and F14PT, for the frames with 6, 8, 10 and 14 stories. They have fundamental periods of vibration of 1.03, 1.25, 1.37 and 2.1 s, respectively. It is noticed that the mechanical characteristics and dimensions of beams and columns are the same for both FWC and FPT. Fig. 2 shows a typical assembly of a post-tensioned steel frame, where the post-tensioned strands can be identified. Also, the energy-dissipating elements (bolted angles) can be observed.

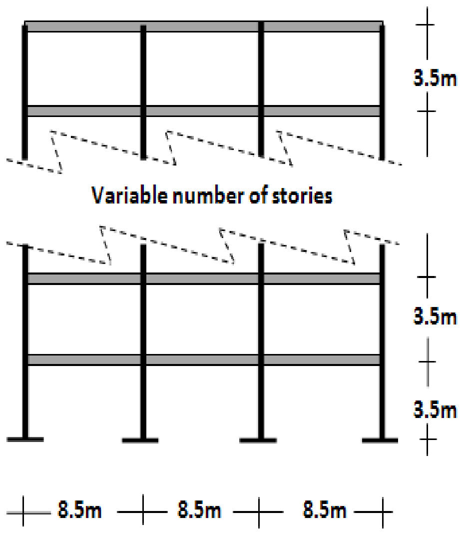


Figure 2.1. Overall dimensions the frames

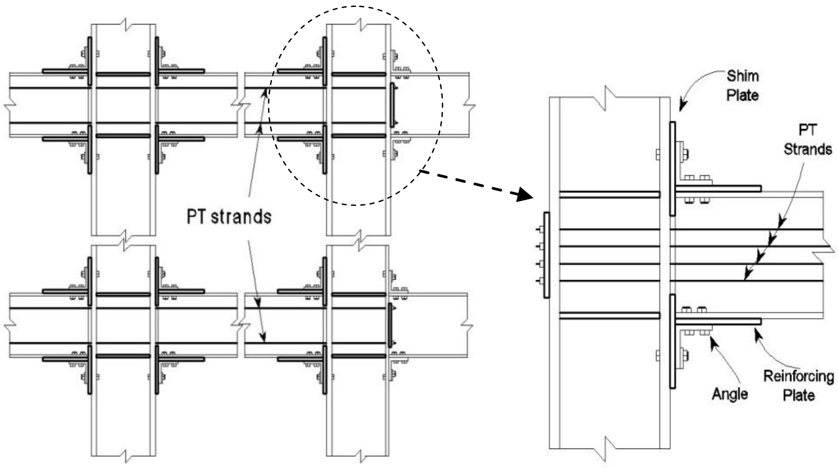


Figure 2.2. Angles and post-tensioned strands in FPT

2.2 Connection model

The hysteretic rules that represent the cyclic behavior of the semi-rigid connections of the post-tensioned frames are characterized by moment-rotation curves (M-θr), which usually present shapes similar to a flag. This representation characterizes the nonlinearity, self-centering capability and energy dissipation capacity of the connection. Experimental tests with isolated angles, subjected to cyclic and monotonic loads conducted by Shen and Astaneh-Asl (1999) showed a stable cyclic response and good capability of hysteretic energy dissipation. Ultimate strength exceeds 3 times the yield strength and ductility reached values between 8 and 10.The strength and stiffness in bending of the post-tensioned connection, is coming from the contribution of the angles of the TS connection and by post-tensioned strands. Wires and angles work as springs in parallel. In the system post-tensioned strands exhibit linear behavior, while connecting angles behave non-linear from the start of the deformation. Fig. 2.3 shows a typical example of a hysteretic curve corresponding to a post-tensioned connection. The mathematical expressions of the curves were obtained from the superposition of the exponential equation proposed by Richard (1987) for semi-rigid connections and the linear contribution of the strands, as well as decompression moments (Md) and the closing moment (Mc) of the connection. The curves obtained with the equations were compared with experimental results published by Ricles et al. (2002) and Garlock et al. (2005) exhibiting a good accuracy.

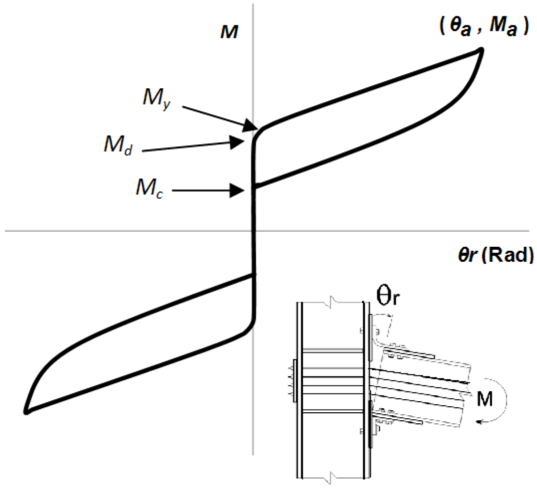


Figure 2.3. Moment-relative rotation curve of the connecting post-tensioned

3. SEISMIC GROUND MOTION

The structural models described above were subjected to 30 long-duration narrow-band seismic records. The narrow-band ground motions have a special feature that significantly affects specific structures within a short interval periods (especially that suffer from softening structures or with structural periods near the period of the soil). In fact, these records demand large amounts of energy to structures compared to movements of broadband (Terán-Gilmore and Jirsa, 2007). The records were previously used by Bojorquez et al. (2008), and they correspond to the subduction seismic events. They were taken where the period of the soil was close to two seconds in sities where most of the damage during the México earthquake of september 19, 1985 occurred.

4. METHODOLOGY

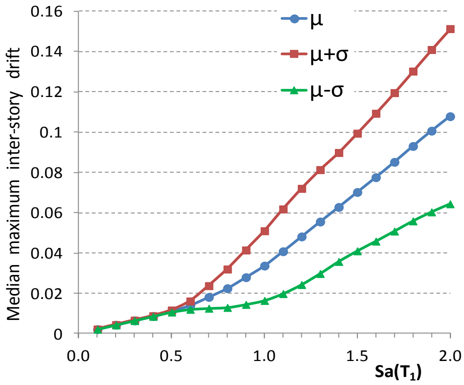
The comparison of maximum inter-story drift (γ) and residual drift (γ_R) of the traditional and post-tensioned steel frames was estimated using incremental nonlinear dynamic analysis (Vamvatsikos and Cornell 2002). For this aim, the building frame models were subjected to the set of 30 narrow-band earthquake ground motions, which were scaled at different values of the seismic intensity in terms of spectral acceleration at first mode of vibration of the structure $Sa(T_1)$. The selected seismic intensity values were from 0.1g to 2.0g with increments of 0.1g. The RUAUMOKO program (Carr 2011) was used for the step by step nonlinear dynamic analysis. The results are expressed in terms of maximum inter-story drift and residual drift at the end of the earthquakes for each scaling levels in terms of the spectral acceleration.

4.1 Maximum inter-story drift results

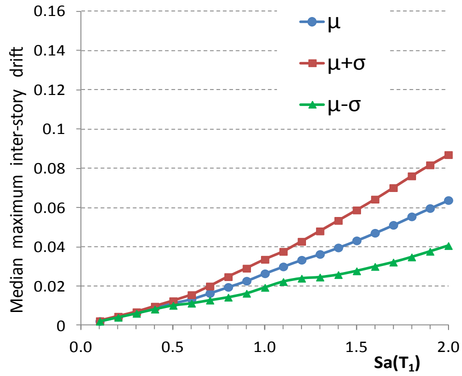
The median (μ) and standard deviation (σ) of γ for each frame, and seismic intensity level are determined. Fig. 4.1 shows the values of γ at different seismic intensities for frames F6WC, F10WC, F6PT and F10PT. It is observed for frames of the same height and is the same ground motion intensity, the median values of γ are lower for the FPT. This difference increases when increasing the spectral acceleration. Results also indicate that the demands of γ decrease as height increases while the dispersion grows when $Sa(T_1)$ tend to increase. For FPT models, γ lineally increases with $Sa(T_1)$. The reason for this is that the strands remain elastic contributing significantly to the stiffness of the connection.

Fig. 4.2 shows the maximum inter-story drift for all frames and ground motion intensities of 0.8g, 1.2g and 1.5g. Results indicate that the drift of the FPT models are lower than those of the corresponding FWC models, this difference increases as the number of floors increases.

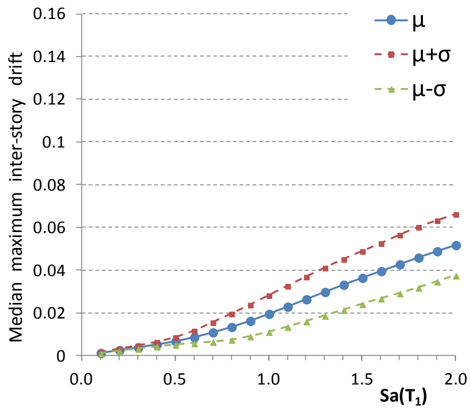
The ratio of the maximum inter-story drift of FPT and FWC model (RMD) is showed in Fig. 4.3 for different levels of intensities. It is observed that RMD in all cases is smaller than unity, indicating that the γ values of the FPT systems are lower than those of the FWC system. Moreover, the ratio is constant for small values of the earthquake intensity and for a specific frame (both types of frames FPT and FWC remain elastic). Furthermore, for larger values of nonlinear behavior, the ratio is almost the same for all the frames analyzed with a value about 50%, which represent a important reduction compared with the tradiotional structural steel frame models.



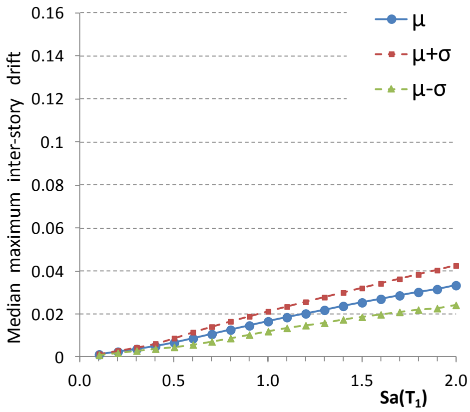
a) F6WC



b) F10WC



c) F6PT



c) F10PT

Figure 4.1. Drift maximun median and standar desviation for FWC and FPT

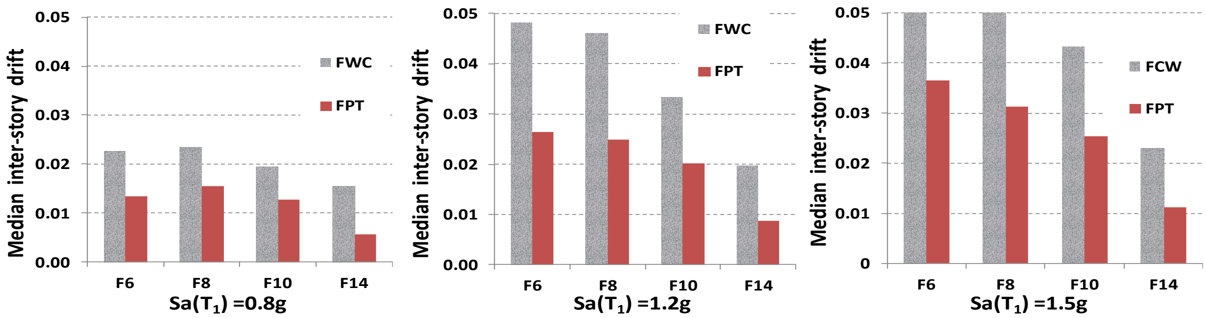


Figure 4.2. Median maximum drift of the frames FWC and FPT

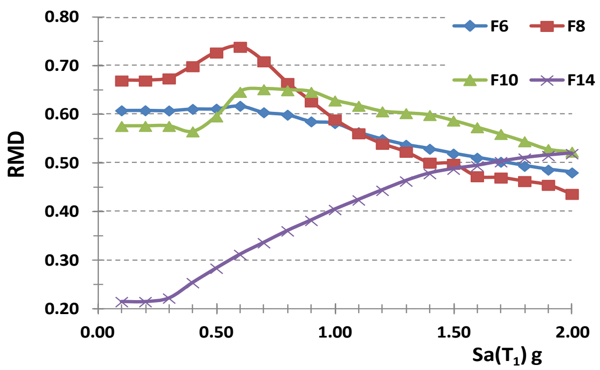
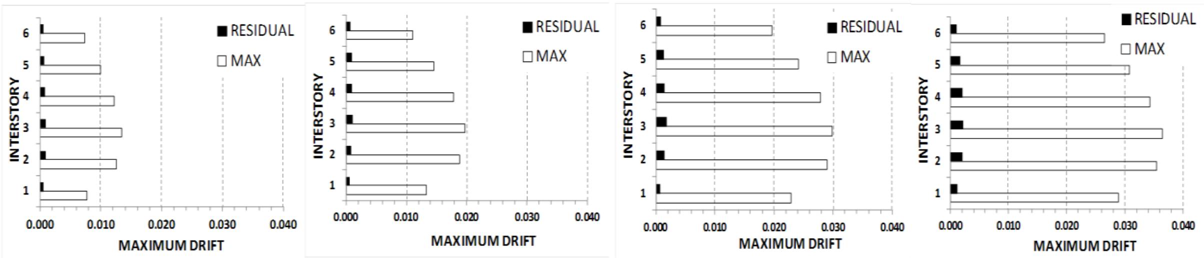


Figure 4.3. Ratio of maximum inter-story drift between FPT and FWC

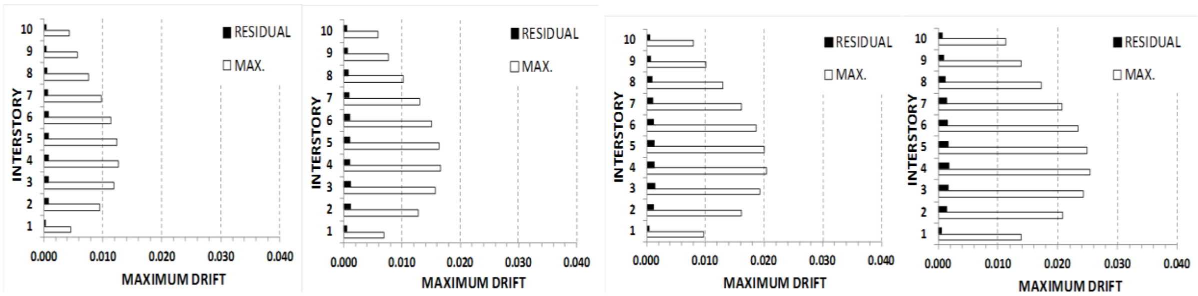
4.2 Residual inter-story drift results

The results of median values of maximum and residual inter-story drift demands are compared in Figs. 4.4 and 4.5. For ground motion intensities of 0.8g, 1.0g, 1.2g and 1.5g, and for structural models F6PT and F6PT. As it is expected, the magnitudes of γ grows when increasing spectral acceleration (see Fig. 4,4 from a up to d), while the residual drift slightly increase with increasing $Sa(T_1)$, remaining lower than 0.005 Rad. for $Sa(T_1)$.equals 1.5g. Note that this value for residual drift was proposed by McCormick et al. (2008) as the limit for feasible financially structures. The higher demands of γ occur in the intermediate stories (between 0.3 and 0.6 of the height).



a) b) c) d)

Figure 4.4. Maximum interstory drift F6PT for: a) 0.8g, b) 1.0g, c) 1.2g and d) 1.5g



a) b) c) d)

Figure 4.5. Maximum interstory drift F10PT for: a) 0.8g, b) 1.0g, c) 1.2g and d) 1.5g

Fig. 4.6 shows the median residuals drift for frames with 6, 8 and 10 story level and different spectral acceleration values from 0.1 to 2.0g. It can be seen that the residual drift increases with increasing $Sa(T_1)$. For $Sa(T_1) \geq 0.5$g the residual drift of the models FPT are lower than those of the FWC models, this difference increases with increasing $Sa(T_1)$. In the case of FWC, the residual drift depends on the height of the frames being smaller for low-rise frames. There is a linear variation of the residual drift with $Sa(T_1)$ for the three FPT models. The dispersion is small, so that it can be concluded that the height has little influence on the magnitude of the residual drifts in this type of structuration. To measure the difference of the residual drift for the FWC and FPT structural system, the RDR parameter is introduced. It is defined as the ratio of residual drift of the FPT and the FWC models. Fig. 4.7 shows the RDR values for the frames with 6, 8 and 10 story levels. Note that for a specific frame the ratio tend to be constant for all the intensity values under consideration; also, the ratio increases with the number of stories of the frames increase. This can be summarized in Table 4.1, where the mean ( ) and standard deviation (σ) of RDR are presented for all frames. Results indicate that increases and σ decreases, as the number of levels increases, this implies a greater difference and dispersion of the results in the frames with lower levels. For the 6 story levels frame RDR=0.49, this means that the average of the residual drift for F6PT is about 51% lower that the FWC residual drift. In the same manner, the reductions are of 36% and 28% for the 8 and 10 story levels frames, respectively.

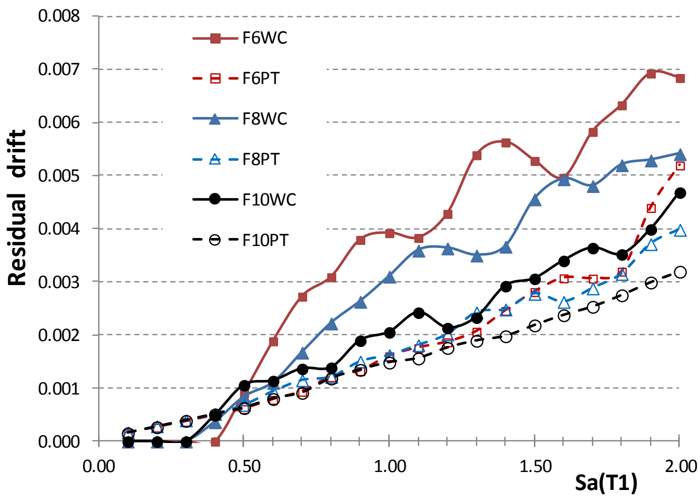


Figure 4.6. Residual drift of the frames FWC and FPT

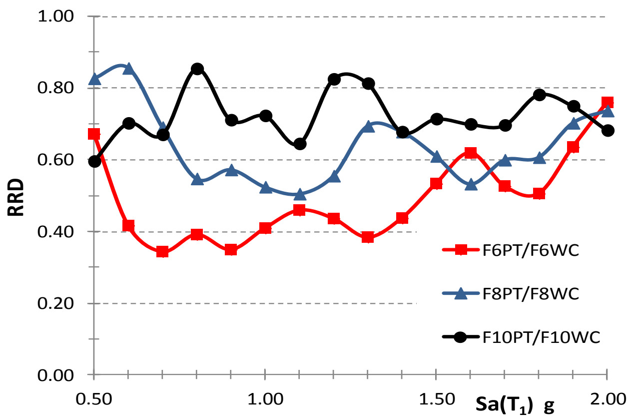


Figure 4.7. Ratio of FPT γ_R and FWC γ_R

Table 4.1. Mean and standard desviation of RDR

Ratio		σ
F6PT γ_R /F6WC γ_R	0.49	0.123
F8PT γ_R /F8WC γ_R	0.64	0.106
F10PT γ_R /F10WC γ_R	0.72	0.069

CONCLUSIONS

In order to compare the performance in terms of maximum and residual inter-story drifts of post-tensioned self-centering MRF with welded connection MRF, incremental nonlinear analysis was carried out for eight frames. Thirty long-duration ground motion records scaled at different values of $Sa(T_1)$ were used for the analyses. The M-θr curve of the post-tensioned connections was modeled by using equations proposed by the authors who were validated with experimental results. The numerical study indicates that; in all cases, the maximum drifts of the FPT are smaller than those of the FWC; the difference is for low-rise frames, on the average the reduction is of 47%.

For spectra acceleraration larger or equals than 0.5g, residual drifts of the FPT are smaller than those of FWC, the difference increases with increasing the intensity of the ground motion.

The residual drifts of FPT are smaller than 0.005 which is the limit for an operating structure.
The greatest reduction in terms of residual drift was 51% for the 6-level frame. In general, considering all the frames and levels of seismic intensity ranging from 0.5 to 2.0g, an average reduction of 38% occurs.

The reduction of the maximum drift implies less damage to structural and non-structural elements. Moreover, the reduction of the residual drift implies significant saving in repairing and in interruption of the use of the building.

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