Evaluation of Residual Drift of Steel Frames Designed with Direct Displacement-Based Design Method

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ABSTRACT: The current study evaluates residual response of near-fault steel frames designed based on a well-established performance based design procedure called the Direct Displacement-Based Design method. Residual deformation is one of the most important parameters which influence the reconstruction or repair feasibility of a structure. It is very useful to determine the residual capacity of structures and to evaluate real level of seismic performance. Nonlinear time-history analyses of steel frames designed with DDBD have been carried out under near-fault ground motions. The study showed that height wise distribution of residual drift of the structures have been left in more uniform condition than the other methods. Also, the method provides very adequate control of residual story drifts even for tall buildings. Structures designed with the DDBD design procedure using near-fault displacement spectra, are able to undergo the severe pulse of near-fault motions very appropriately. It is, therefore, believed that the DDBD design procedure could be an alternative to traditional force-based design methods

1 INTRODUCTION

Current advances in earthquake engineering favor performance based approaches for the design of new structures and for the assessment and rehabilitation of existing structures in seismic zone NERHRP (1997). It has been widely recognized that the earthquake response and performance of a building depends on the stiffness, strength, deformation capacity of a building. These performance levels of structures are typically assessed based on maximum deformation and/ or cumulative inelastic energy absorbed during the earthquake. Reports and reconnaissance observation from past earthquakes indicates that most structures designed according to current codes will sustain residual deformations in the event of a design level earthquake, even if they perform exactly as expected. This aspect of design in not reflected in current performance assessment. It seems a combination of maximum and residual response of system can help to define the system global performance level of structures. It highlights the key role of evaluating of residual deformations in structures.

A relatively new performance-based seismic design procedure called the Direct Displacement-Based Design (DDBD) proposed by Priestley (2000) has recently received notable acceptance among researchers. It seems that the methods could be a rational alternative to traditional erroneous force-based seismic design and an approach to control the amplitude of residual deformation in structures. Due to the importance of severe pulse-type displacement demands on near-fault structures, on one hand, and the key role of displacement in DDBD procedure, on the other, it is argued that the method would be appropriate for seismic design of near-fault type structures.

2 PERIVIOUS STUDIES ON RESIDUAL DISPLACEMENT

Several observations on the amplitude of residual displacement demands have been obtained from non-linear dynamic response of single degree of freedom (SDOF) systems, although very little systematic studies have been carried out up to date. For instance, permanent displacements of elsato-palstic single degree of freedom oscillators with variable post- yielding stiffness coefficient have been studied by Mac Rae (1997). They pointed out that post yielding stiffness ratio of bilinear SDOF systems has a significant influence on the amplitude of residual displacements, while Christopoulos (2003) recognized the influence of the hysteretic behavior on the amplitude of residual displacement demands. Although both studies provided useful information, their analyses assumed that the displacement ductility demand on the system is known (e.g. constant-ductility approach) and their results are not directly applied to the assessment of existing structure. Later, Pampanin (2003) evaluated residual drift demands of four frame building models. In particular author noted that the mean residual drift demands are sensitive to hysteresis modeling of the structural component. Therefore, comprehensive studies aimed at evaluating several residual parameters of MDOF systems are needed.

The primary objective of this paper is to gain further understanding on residual displacement and performance of DDBD steel frame designed. It should noted that this study is related to MDOF systems subjected to earthquake ground motions that show pulse-type features in the velocity time-history representative near fault ground motions.

3 GENERIC BUILDING FRAMES MODELS USED IN THIS STUDY

3.1 *Building frame design and modeling*

The characteristic of maximum and residual deformation are first investigated by examining the response of MDOF systems. For this purpose, regular 4-bay frame building models having four different number of stories (N=4, 8, 12, 16) were considered here. The properties of these models described in Table 1 represents SDOF idealization of buildings designed following a direct displacement-based design procedure, for a target maximum inter-story drift 2.5% under a displacement design spectrum corresponding to peak ground acceleration of 0.5g. A damping-ductility relationship corresponding to steel frames with beam plastic hinges exhibiting the Elasto-plastic hysteresis was used in the design process.

Table 1. Properties of SDOF oscillator

No.Stories	T_{eff}	T_0	H_{eff}	ζ_{eq}	dr_{design}	μ
	s	s	m	kN	-	-
4	1.80	C	9	23.681	0.025	0.042
8	2.40	C	17	22.973	0.022	0.038
12	2.70	C	25	20.495	0.02	0.031
16	3.10	C	41	19.950	0.015	0.029

The initial (first-yield) natural periods, T_0 , effective natural periods at maximum displacement response, T_{eff}, effective height H_{eff}, total damping, ζ_{eq} and design ductility, μ are listed in Table 1.

Also listed in Table 1 are the values of the equivalent design drift dr_{design} , which corresponds to the maximum drift of 0.025 for assumed deflected shape of building. Note how this value decreases with increasing height.

The flexure yielding moment capacity in the element was determined from story shear forces using the lateral static force distribution obtained from current seismic provision in Iranian building code 2800.

As to allow for accurate estimation of structural damage distribution, the spread of material inelasticity along the member length and across the section area is explicitly represented through the employment of a fiber modeling approach, implicit in the formulation of inelastic beam-column frame element. It should be mentioned that main discussion of results is based on assuming an elastoplastic moment curvature relationship. Main observation in this study is related to generic frame model which are accepted to develop a 'strong-column weak-beam' mechanism. In current seismic provisions, this mechanism is fomented by specifying a beam-to-column moment ratio. For instance, in the AISC (1997) seismic provision for the design of new steel structure it is required that $\Sigma M^*_{pc} > \Sigma M^*_{pb}$, where ΣM^*_{pc} is the sum of the moment in the column centerlines and ΣM^*_{pb} is the sum of the moments in beams at the intersection of beam and column centerlines. These seismic provisions encourages the use of improved connections (e.g. reduced-beam section connection commonly known as ‘dog-bone’) that force the plastic hinges to develop in the beams.

Each generic building was modeled as a two-dimensional centerline frame using the computer software SEISMOSTRUCT.

3.2 *Design displacement spectra and ground motions used in study*

As mentioned before, an essential material for DDBD methodology is the design displacement spectra. For the aim of this study, design displacement spectra have been selected as the mean spectra of six displacement spectra derived from six near-fault (pulse-type) records which contain severe directivity effects. Some records contain high frequency components; therefore, both short and long period structures can be affected quite well. Table 2 summarizes some important characteristics of the selected records. Among various definitions for near-fault region founded in many references, the “nearest distance to the causative fault” was considered. All records were downloaded from http:\\www.peerberkeley.edu. [Peer strong ground motion database] Each record showed its own interesting characteristics in terms of intensity, frequency content and duration.

Table 2. Characteristics of the selected near-fault records

Name	Year	Magnitude	Soil Type	Closest Distance
		M_S	(USGS)	Km
Chi-Chi	1992	7.63	C	0.91
Northridge	1994	6.8	C	12
Erzincan	1992	6.69	C	4.38
Imperial Valley	1979	6.53	C	4
Kobe	1986	6.9	C	8.34
Tabas	1970	6.3	C	6.12

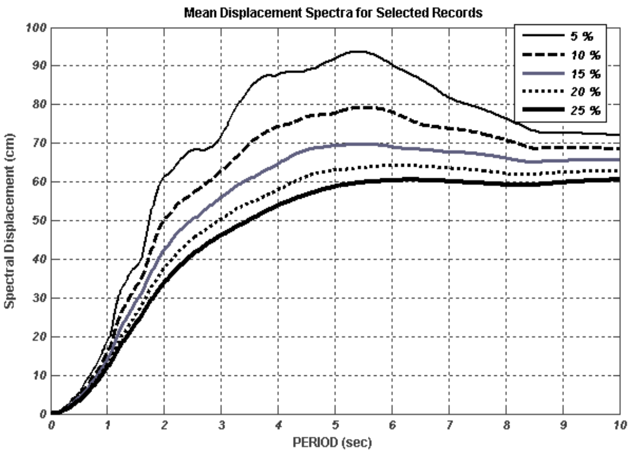

Figure 1. Mean displacement spectra for selected records.

Figure 1 shows the design displacement spectra for five levels of damping used in this study. Each spectral displacement ordinate in Figure 1 has been calculated as the mean of six spectral displacement ordinates corresponding to each record for a specific level of viscous damping. As the performance and residual response of the designed frames have been verified using non-linear time-history analysis, it is needed that the original time-histories of all ground motions be modified so that their new spectral ordinates match the design spectral ordinates for different levels of damping. Such "massaging procedure" has been implemented using frequency domain analysis by RASCAL computer program, Silva (1999).

Matching is quite well, especially in the period range needed for the designed frames.

Also, an additional 20 to 30 second of zero ground motion was added to the end of each earthquake record to enable the models to settle down to elastic vibration for accurate assessment of residual displacement.

4 RESULTS

All analysis were carried out using a New mark-beta integration scheme with a time step of 0.005 and assuming an elastic viscous damping coefficient of 5% of critical based on the initial elastic stiffness. All earthquake records were padded trailing free vibration time to allow the structure to come to a complete rest before recording the residual displacement. Throughout this investigation, some types of residual drift demands were recorded and processed.

Displacement ductility μ_Δ defines as:

$$\mu_\Delta = \frac{d_{\max}}{d_y} \qquad (1)$$

Where d_{max} is the maximum transient displacement and d_y is the yield displacement.

Maximum inter story drift ratio IDR_{max} (e.g. story drift with normalized with respect to the height of story);

Maximum residual inter story drift ratio $RIDR_{max}$ (e.g. residual story drift with normalized with respect to the story height of story);

In order to provide a context to following results, it should be mentioned that recent recommended seismic provisions for the assessment and rehabilitation of existing building in U.S. specify limiting value on residual drift demand linked to system performance levels, FEMA (2000). For instance, RIDRmax should not exceed 1% for life safety and 5%for Collapse Prevention performance level.

Figure 5 shows a typical displacement time-history of 4-story frame under the Erzincan record. The severe effect of the directivity pulse is clear from the figure. Indeed, the directivity pulse is responsible for the early nonlinear behavior of the structure at the beginning of the response. As expected, the maximum displacement demand occurs during the imposition of the directivity pulse. As shown later, all other demands including inter-story drifts and ductility demands are at their maximum during the pulse. The structure experiences a shift to a new equilibrium position, as expected. Upon the imposition of the pulse, displacement amplitudes reduce significantly until the end of the motion. One of the very interesting findings of this study is that in all displacement time-histories the displacement amplitudes after the pulse are "trapped" between two specific limits. This behavior was observed in all time-histories. It is, thus, argued that the DDBD methodology has the ability to design structures with "controlled residual displacement" characteristics; a very important factor in seismic performance of buildings.

4.1 *Effect of number of story*

Of particular interest to this investigation was to obtain information about amplitude and distribution of residual inter-story drift demands along the height of the building. It can be seen that for all model building distribution of residual drift demands changes as the number of story increases. In general, the distribution of *RIDR* along the height become non-uniform and it tends to concentrate at specific stories. This tendency of residual drift to concentrate in certain stories is more evident for model with high number of stories. The larger increment in maximum residual drift demands in lower stories of tall frames is attributed to *P-Δ* effects.

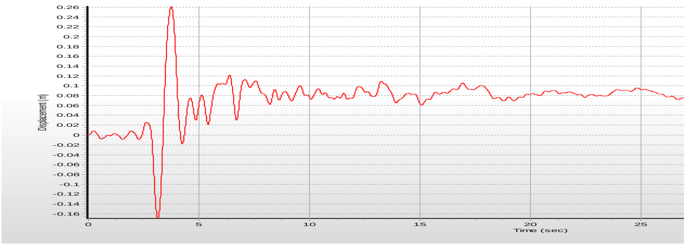

Figure 2 Displacement response history for 4-story model under Erzinjan record

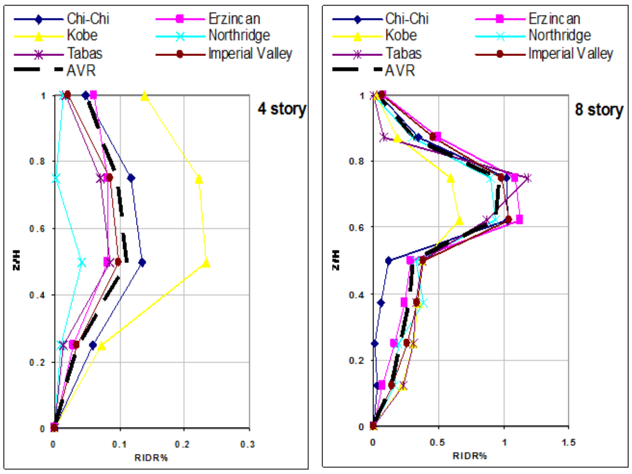

Figure 3. Effect of number of stories on residual drift demands for generic building frames with 4 and 8 stories.

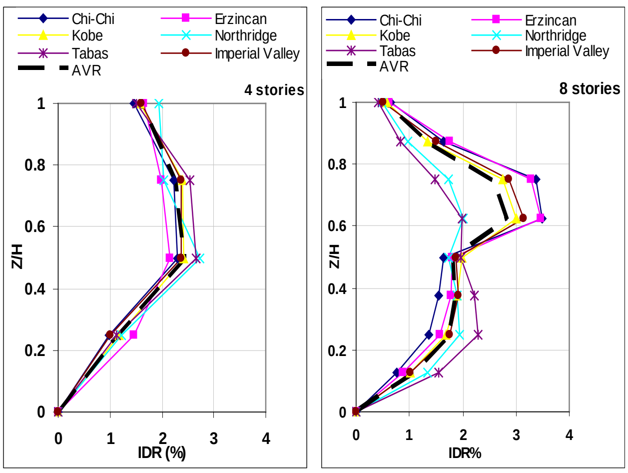

Figure 4. Effect of number of stories on maximum drift demands for generic building frames with 4 and 8 stories.

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It should be mentioned that *RIDR* pattern tends to mimic the same trend observed for maximum inter-story drift (*IDR$_{max}$*). This observation means that once structural damage is trigged by large inter-story drifts demands, maximum drift demands tend to concentrate at specific stories and building adopts a non-recoverable configuration until end of the earthquake excitation. Results indicates that inter-story drift and residual drift concentration has also been observed for generic frames models designed to exhibit ideal BH mechanism

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Figure 3 illustrates the distribution of residual drift demands (*RIDR*) along the height of stories for 4 and 8 number stories models. These profiles indicate that distribution of residual drift over the height of story become non-uniform by incrimination of total height of buildings and number of stories.

As mentioned earlier, a value of 2.5% was selected for this study. Figure 4 represents the inter-story drift (*IDR*) profiles of same frames under the selected pulse-type records. Referring to these diagrams, the *DDBD* method performs quite satisfactorily. The overall profile shapes are similar to those expected for rigid frames. It is also interesting to note that a secondary residual drift concentration tends to occur in upper stories of tall frame models. This secondary residual drift concentration as the frame building becomes taller and more flexible reflects the effect of higher mode of vibration (mainly second mode of vibration) on the seismic response of regular frame building

An indirect measure of amplitude of residual drift demands is obtained from normalizing residual (permanent) drift demands with respect to the maximum (transient) drift demands at each story. This ratio was named residual deformation ratio γ. It is illustrated for 4 and 8 story models. It can be seen the residual deformation ratio is not constant along the height and, for a specific story, it grows at a different rate. It should be noted that the location of the maximum residual deformation ratio over the height changes with the variation of building height and number of story. For example this ratio is rather constant for models with low number of story (4 story), but it become non-uniform for other models.

4.2 *Effect of fundamental and pulse period of vibration*

The influence of fundamental period of vibration on *RIDR$_{max}$* (maximum *RIDR* over the height) in all records is evaluated here. First it can be seen that *RIDR$_{max}$* increases as the fundamental period of vibration increase up to 2.5 seconds. It is worth noting that the spectral shape of this profile follows in a good manner as displacement design spectra, presented before.

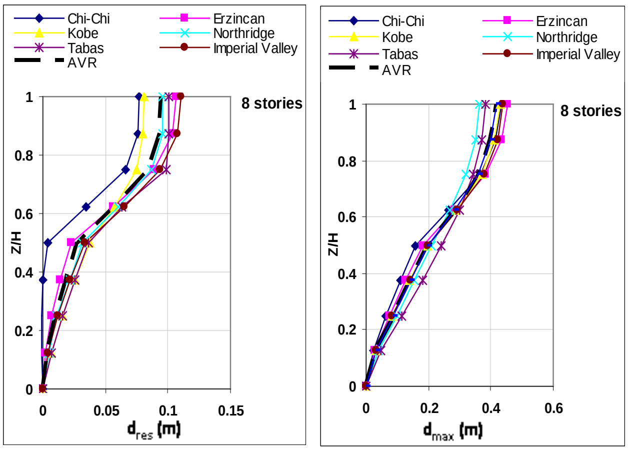

Figure 5. Residual and maximum displacement distribution over the height for generic building frames with 8 stories

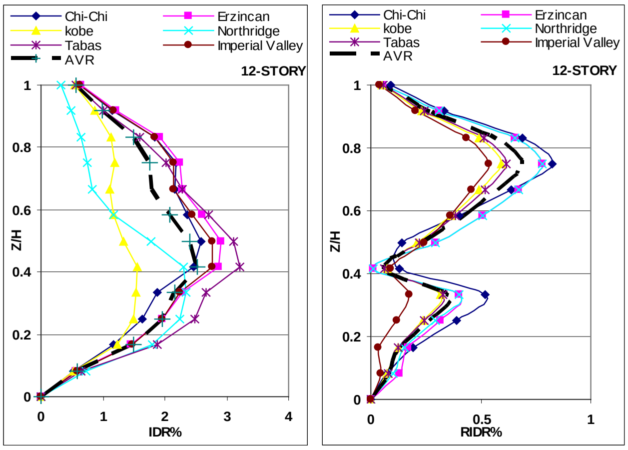

Figure 6. Effect of number of stories on residual and maximum drift demands for generic building frames with 12 stories.

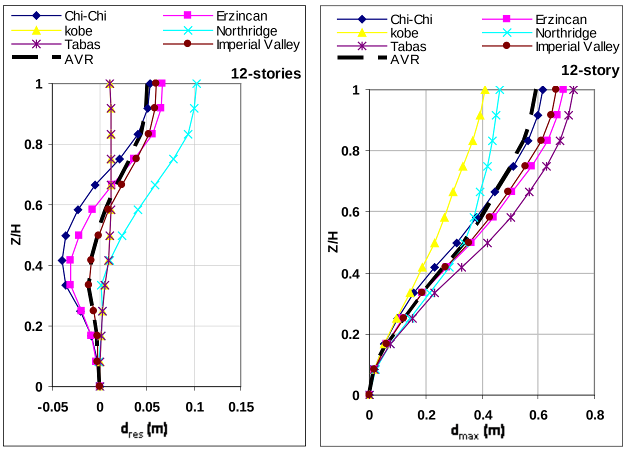

Figure 7. Residual and maximum displacement distribution over the height of generic building frames with 12 stories.

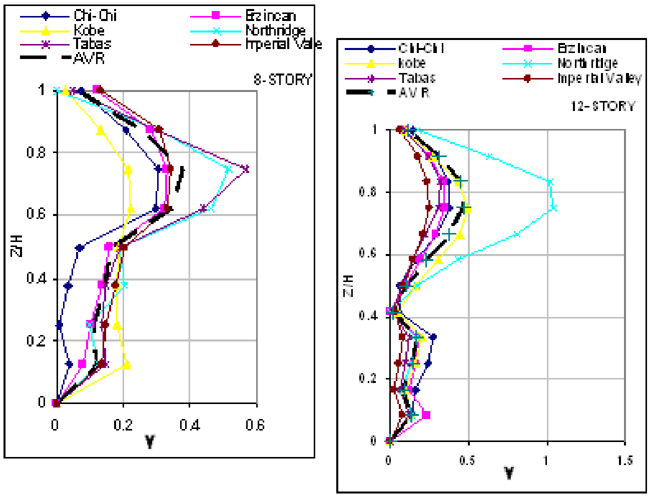

Figure 8. Height wise distribution of residual drift ratio for 8 and 12 stories frame

As indicated before, most of frames left in residual condition after earthquake excitation due to inelastic response of them. Displacement time histories of models under near fault ground motion show earlier inelastic response after pulse period. The effect of T/T_p on maximum residual drift demand over the height is illustrated in Figure 10 for 4 story model. It can be observed that the amount of T/T_p have an important influence on spectral shape and amplitude of residual displacement particularly for periods of vibration smaller than pulse period ($T/T_p<1$).

4.3 *Effect of earthquake magnitude*

In order to study if residual deformations are modified by earthquake magnitude, $RIDR_{max}$ were computed from all records corresponding to a range of surface wave magnitude. This range contains 6 earthquake ground motions recorded in same site condition (site class C). Then amplitudes of $RIDR_{max}$ corresponding to different magnitudes are shown in figure 11. It can be seen that amplitude of maximum residual drift demand is not significantly affected by earthquake magnitude for models with less stories (e.g. 4 and 8 stories models). However, magnitude seems to influence more on $RIDR_{max}$ as the number of stories increases.

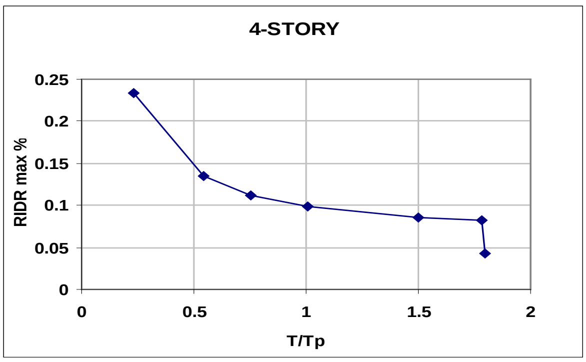

Figure 9. Effect of T/T_p on $RIDR_{max}$. for 4 stories frame model

The present study focuses on evaluating residual displacements of near-fault steel structures design with a new performance-based design tool called the direct displacement-based design. This method provides very adequate control of residual displacement even for tall buildings.

On the other hand, residual displacement of structures is function of structural and ground motion characteristics. Therefore, further understanding of parameters that influence the amplitude and height wise distribution of residual drift demands is provided in this study.

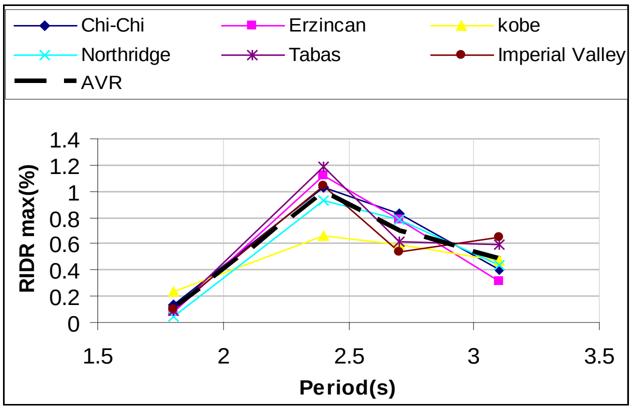

Figure 10. Effect of period on RIDR

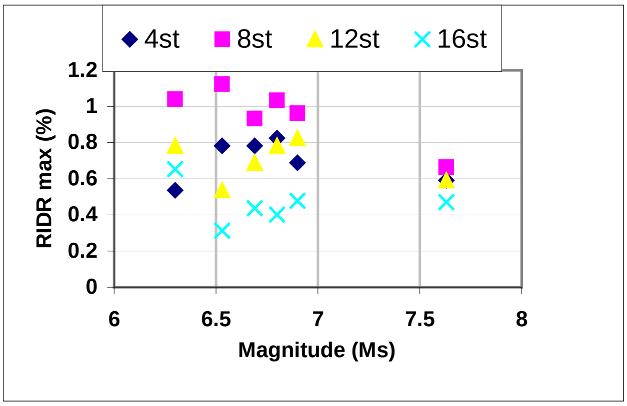

Figure 11. Residual and maximum displacement distribution over the height of generic building frames with 12 stories

5 CONCLUSIONS

Results of current study indicates that amplitude and distribution of residual drift demands over the height of models become non-uniform as the number of stories increase.

Concentrations of residual drift demand observed for buildings, is mainly due to *P-Δ* effects and the secondary one is due to the higher mode effects.

Dispersion of residual drift demands in DDBD design method is less than the other design procedures.

It can be seen that $RIDR_{max}$ increases as the fundamental period of vibration increase.

Ratio of fundamental period of vibration to pulse period of each ground motion make an important changes in amplitude of this parameter especially for the ratios less than 1.

Observed amplitude of residual drift demands are less affected by magnitude of ground motions particularly in strong systems.

Given results of time history displacement analysis under scaled records, show a residual displacement at the end of displacement time history.

Direct displacement based design method proposed here result in controlling residual displacements.

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