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TOWARDS PERFORMANCE-BASED SEISMIC DESIGN OF MDOF STRUCTURES WITH EXPLICIT CONSIDERATION OF RESIDUAL DEFORMATIONS

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ABSTRACT

Most structures designed according to current code provisions will sustain residual deformations in the event of a design-level earthquake, even if they perform exactly as expected. Despite this reality, little consideration is currently given to residual deformations when assessing the seismic performance or in the design of seismic resistant structures. Parameters influencing residual deformations are first identified and a framework for evaluating performance based on a combination of maximum and residual response indices is proposed. Non-linear residual displacement spectra are computed for a number of SDOF hysteretic systems and design spectra, based on residual/maximum displacement ratios, are suggested as a function of effective secant period. Analyses are then extended to the response of MDOF systems through a series of non-linear time history analyses. The direct displacement based design method is then modified to include an explicit consideration of residual deformations in the early stages of the design procedure. A discussion on design decisions affecting residual deformations is also presented.

KEYWORDS: Residual Deformations, Performance-Based Seismic Design, Displacement-Based Design, Frame Structure, Inelastic Spectra

INTRODUCTION

Current advances in earthquake engineering favor performance based approaches for the seismic design of new structures and for the assessment and rehabilitation of existing structures located in active seismic zones (ASCE, 2000). Typically, a performance objective is defined when a set of structural and non-structural performance levels, representing losses and repair costs, are coupled with different intensities of seismic input. Current seismic design philosophies emphasize the importance of designing ductile structural systems to undergo inelastic cycles during earthquake events while sustaining their integrity, recognizing the economic disadvantages of designing buildings to withstand earthquakes elastically. The performance of a structure is typically assessed on the basis of the maximum deformation and/or cumulative inelastic energy absorbed during the earthquake. Reports from past earthquake reconnaissance observations, from shake table tests, as well as results from analytical studies, indicate 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. Residual deformations can result in the partial or total loss of a building if static incipient collapse is reached, the structure appears unsafe to occupants or if the response of the system to a subsequent earthquake is impaired by the new at rest position of the structure. Furthermore, they can also result in increased cost of repair or replacement of non-structural elements as the new at rest position of the building is altered. These aspects are not reflected in current performance assessment approaches.

Recognizing the importance of controlling residual deformations, or completely eliminating them, recent developments in precast concrete moment resisting frames (MRF) or jointed shear walls (Priestley et al., 1999) as well as steel MRFs (Christopoulos et al., 2002b) making use of unbonded high strength tendons, have resulted in structural systems which can undergo inelastic displacements similar to their traditional counterparts, while limiting the damage to the structural system and assuring full re-centering capability. However, for more traditional systems, which count for the vast majority of buildings, residual deformations are currently considered an unavoidable result of structural inelastic response under severe seismic shaking, even for new-designed structures.

Priestley (1993) as well as MacRae and Kawashima (1997) discussed the importance of residual deformations when assessing the performance of structures by emphasizing the difficulty and cost associated with straightening structures after a major earthquake before repairs could be carried out. A number of researchers (MacRae and Kawashima, 1997; Borzi et al., 2001; Christopoulos et al., 2003) have identified the post-yielding stiffness as the main parameter influencing the residual deformations of non-linear SDOF oscillators. MacRae and Kawashima (1997) also provided a physical explanation for this dependence based on the concept of the Hysteresis Center Curve. As reported by Kawashima (1997), the 1996 Japanese seismic design specifications for highway bridges imposes a design check on residual deformations for important bridges. In this design specification, residual deformations are computed using:

$$\delta_r = c_r(\mu_r - 1)(1 - r)\delta_y \tag{1}$$

where *r* is the ratio of the post-yielding stiffness to the initial stiffness, μ_r is the response ductility, δ_y is the yield displacement, and c_r is a factor depending on *r*. The computed residual displacement must be smaller than 1% of the bridge height.

A residual deformation damage index (RDDI), which measures the degree of permanent deformations and drifts of SDOF or MDOF structures, has also recently been proposed as an additional indicator to fully quantify the performance level of buildings under seismic loading (Christopoulos et al., 2003; Pampanin et al., 2003).

In this paper, the parameters influencing residual deformations of SDOF systems exhibiting bilinear hysteresis and stiffness-degrading behavior (i.e. Takeda hysteresis rule) are first summarized. The proposed framework for considering residual deformations in performance assessment, by defining a performance matrix which combines both maximum and residual response indices, is then presented. Inelastic residual displacement spectra are then derived for both maximum and residual deformations and for a number of hysteretic models and for effective secant periods. The extension of these results from SDOF systems to the expected residual deformations of MDOF frame structures is then carried out and a method for explicitly accounting for residual deformations in design is suggested.

RESIDUAL DEFORMATIONS IN PERFORMANCE-BASED SEISMIC DESIGN

A performance-based seismic design procedure requires a quantification of “performance” based on one or multiple structural response indices. Traditionally, ductility, energy dissipation, or a combination of both, have been identified as the parameters that best evaluate the performance level of structural elements. A number of well known damage indices (Park and Ang, 1985, 1987; Fajfar, 1992; Cosenza et al., 1993) propose methods to carry through such an evaluation by one of these parameters, or weighted sums of both. These parameters are usually calibrated against experimental data to result in a value of 1 corresponding to failure of the structural system. The basic idea behind these approaches is a low-cycle fatigue type failure of the structural system, where the number of available cycles before failure reduces as the amplitude increases. As reported by Kappos (1997), the energy dissipation term accounts for a very small portion of the damage indices for well designed structures and thus the ductility-based term of damage assessment is probably the most representative. Although this approach is very effective in characterizing the different performance levels for systems where the main concern is to avoid failure, or where large levels of ductility are not reached, it seems that it is unable to fully characterize the performance level of structures where the structural integrity is not at risk during the seismic attack. Nonetheless, considering the important developments in earthquake engineering in the past 30 years, as well as code imposed drift limitations, it is more likely that structures will fall in this latter category in the future. In light of this, the final state of a structure subjected to an earthquake, as described by its final permanent deformation state, becomes increasingly significant in the assessment of structural performance, since repair and rehabilitation of well designed structures are directly associated with the performance level achieved. Furthermore, current investigations on the global performance of buildings during earthquakes have revealed that a large portion of the sustained damage is due to non-structural elements and contents, rather than to the main structural system. This is especially true for low to moderate earthquakes. Although a portion of this damage is acceleration dependent, a considerable amount is due to deformations imposed upon non-structural elements by the main structural system’s deformations. Obviously, it is the maximum deformations that cause damage to these elements, but, when the damage is assessed, based on the cost of replacement, residual deformations must also be considered. The cost of replacement can be highly dependent on the final geometry of the main structural system, and may even require restoring or modifying the main system, if possible, before it can be carried out correctly. This also emphasizes the need for an additional performance assessment parameter directly dependent on residual deformations.

1. Damage Index Based on Residual Deformation

A new damage index based on residual deformations was suggested by Christopoulos et al. (2003). The residual deformation damage index *RDDI*, ranging from 0 to 1, is defined as:

$$RDDI = \begin{cases} \phi.RDDI_S + \chi.RDDI_{NS} & \text{for} \quad RDDI_S < 1 \\ 1 & \text{for} \quad RDDI_S = 1 \end{cases} \tag{2}$$

where $RDDI_S$ and $RDDI_{NS}$, ranging from 0 to 1, are the residual deformation damage indices, for the main structure and for non-structural elements, respectively, and ϕ and χ are positive weighting factors with:

$$\phi + \chi = 1 \tag{3}$$

The values of ϕ and χ are defined to reflect the relative importance given to each of the two components of the *RDDI*. In Equation (2), the *RDDI* is set to 1 if $RDDI_S$ reaches 1 to reflect the fact that if there is a total loss of the structure, the performance of non-structural elements is irrelevant. Discrete performance levels were also defined to evaluate the values of $RDDI_S$ and $RDDI_{NS}$. For the main structural elements, to evaluate $RDDI_S$, three performance ranges are delimited by three performance limits RD-PLS1,S2,S3:

- low residual deformations (RD<RD-PLS1): no consideration needed; residual deformations are neglected, and no intervention is required
- intermediate residual deformations (RD-PLS1<RD<RD-PLS2): intervention is required, in the form of repair, primarily to address concerns about future performance of the structure from a new at rest position
- large residual deformations (RD-PLS2<RD<RD-PLS3): major repair requiring repositioning, strengthening or replacement of portions of the structure

The ultimate limit, RD-PLS3 represents the structural state where the building is statically at imminent collapse under *P-Δ* effects and is, therefore, representative of the total loss of the building. Note that when the structure is at rest after an earthquake, the second order effects corresponding to the entire factored gravity load (corresponding to the mass associated to the lateral load resisting system) must be taken into account. The static incipient collapse may be reached after the earthquake, even if at the maximum transient displacement the structure did not collapse as a result of dynamic instability during the earthquake. Similar performance levels are derived for non-structural elements, but are not discussed in this paper. Additional information on the definition of these performance levels can be found in Christopoulos et al. (2003).

The *RDDI* was proposed as an additional indicator to structural performance rather than a complete replacement to performance indices based on maximum and/or cumulative response. In fact, it is possible that a structure highly damaged by a large maximum displacement may sustain limited residual displacements. It is also of interest to note that performance levels based on maximum and/or cumulative response indices are in reality related to strain levels in structural components. From strain-based performance levels, which represent the true basis of performance-based approaches, other indices such as plastic rotations or interstorey drifts can be derived by means of simple geometric calculations. In the case of performance levels, defined on residual deformations, this approach is not as straightforward. A portion of the performance level can still be assessed based on residual strains, but global indices such residual plastic rotations or residual drifts, which better describe the final geometry of the structure, may be a more appropriate starting point.

A combination of maximum drift and residual drift (RD), in the format of a RD-Based performance matrix, is therefore suggested as a more comprehensive tool to evaluate the actual performance of frame structures. The independent scale of performance based on residual deformations can thus be adequately combined with existing performance levels based on maximum response or cumulative damage, commonly used, to form a more general performance domain. For different seismic intensity levels, this results in a full 3-dimensional performance domain (see Figure 1, left side). This three-dimensional performance domain should be evaluated for both the structural and non-structural elements in order to obtain a full evaluation of a building's performance.

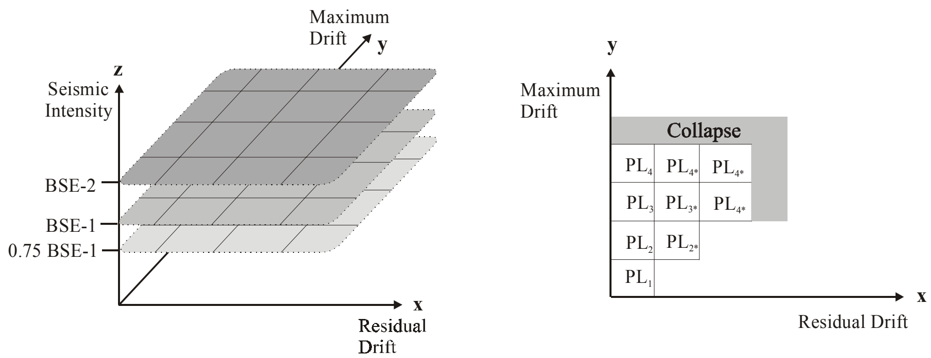

Fig. 1 RD-based performance matrix for different intensity levels

For a given seismic intensity, the RD-based performance matrix consists of a mask of pre-defined performance domains (Figure 1, right side) that can then be compared to plots with maximum and residual indices from seismic response. For a given maximum response index, the resultant performance limits would result in a poorer combined performance level for higher level of residual deformations: the main performance levels PL_i, based on maximum limits, are extended in sub-domains PL_i* depending on the associated residual drift values. When, for example, combining a maximum drift level corresponding to PL_2 with a large residual drift, the actual performance level is shifted to level PL_3*. This performance level can also be reached with higher maximum drifts (PL_3) associated with lower residual drifts. Note that the highest performance level PL_1 is limited to a single square, as the elastic response of any structural system should not result in any residual drift. Thus, although being subjected to similar interstorey drift demands, the frame systems can be assigned substantially different levels of performance, depending on the value of the residual response indices. Following the proposed performance assessment approach, the enhanced performance of self-centering systems would, therefore, be directly captured while a more detailed case-by-case assessment of structures which exhibit more traditional hysteresis behaviour (i.e. modified-Takeda for RC structures and elasto-plastic for steel structures) would be required. This framework can be applied to global indices, as well as local indices, depending on which is more pertinent for the performance evaluation. Note that, in certain cases, local maximum indices can be combined with global residual indices, or vice-versa, if deemed more effective in characterizing the performance level.

2. Evaluation of Global Damage

A global damage indicator for MDOF structures can be defined as the weighted sum of the individual member performance within the entire structure, or as an array of floor performance levels.

The performance level at storey i, PL_i can be evaluated by:

$$PL_i = f(\text{Maximum Storey Drift}_i, \text{ Residual Storey Drift}_i) \tag{4}$$

where $f(.)$ represents the RD-based performance matrix.

The aforementioned approach would lead to a vector of n (storey number) performance levels representing the damage distribution along the elevation of the frame system:

$$PL = \begin{Bmatrix} PL_1 \\ PL_2 \\ .... \\ .... \\ PL_n \end{Bmatrix} \tag{5}$$

In Figure 2, the responses of the three new-designed 5-storey frame structures exhibiting the Takeda (TK), elasto-plastic (EP) and flag-shaped (FS) hysteresis with similar backbone curves were subjected to the 1987 Superstition Hills record are shown in the framework of a RD-Based performance matrix where the maximum interstorey drifts and residual drifts are used as response indices. Details on the design of these structures can be found in Pampanin et al. (2003). Note how, for the EP frame, the 5th floor sustains the largest maximum drift and lowest residual drift and how the performance level of the 1st storey, which sustains very low maximum drift, would be significantly affected because of its substantial residual drift. The FS frame does not sustain any residual deformations.

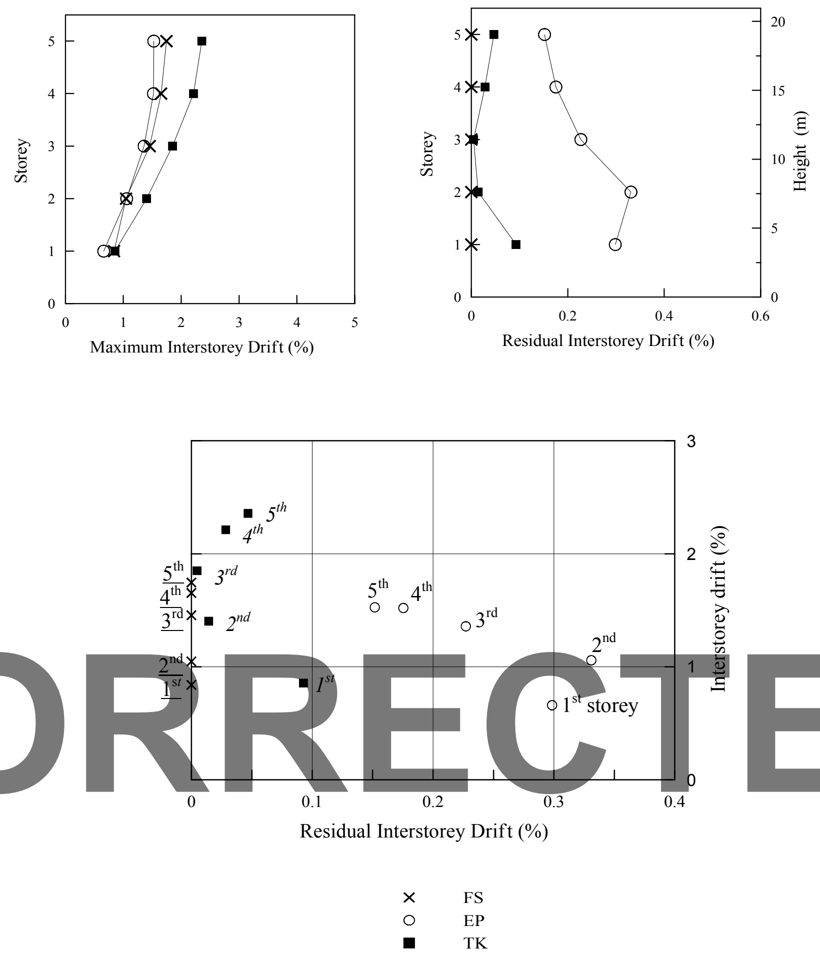

Fig. 2 RD-based performance matrix with interstorey drifts: response of new-designed frame systems under 1987 Superstition Hills record

Although it is preferable to assess the performance of a MDOF structure by having a complete understanding of the spread along the height of the performance levels as well as the contribution to this performance level of the two indices (maximum and residual), a general single performance level of the structure, PL_{global}, can also be defined by adequately weighting the individual storey contributions.

Limits between repairable and un-repairable domains can be well established within the RD-Based performance matrix using a combination of maximum drifts (information on inelastic strain demand in the material, i.e. steel yielding or failing, concrete crushing and spalling, shear cracking, etc.) and residual drifts (direct consequence of residual crack widths and local damage as well as global off-set of the structure) limits.

In the presence of an un-repairable storey, the global performance index would be governed by this storey alone independently of the higher performances of the other storeys. Soft storey behaviour (more likely to occur in existing building response) represents an extreme example of this. In such cases, the maximum storey performance level $\left(PL_{\max} = \max\left(PL_i\right)\right)$ should be taken as the global damage indicator.

Inversely, when dealing with a storey performance vector with all its elements beneath the reparable limit, a weighted average would be more appropriate to represent the total repair costs, including straightening of the structure.

The global performance level PL_{global} can be expressed in equation form by:

$$PL_{\text{global}} = \begin{cases} PL_{\max} & \text{for } PL_{\max} \geq PL^* \\ \sum_{1}^{n} \pi_i PL_i & \text{for } PL_{\max} < PL^* \end{cases} \tag{6}$$

where PL^* is the reparability limit of a storey, n is the number of stories and π_i is the weighting factor of the i^{th} floor contributing to the global performance evaluation of the structure.

The individual storey weighting factors, π_i, should distinguish between types of damaged structural elements (beams, columns or joints) based on:

- *structural considerations*: the same residual drift might occur with alternative local mechanisms and different contribution of beams, columns and joints.
- *difficulties and costs of repairing*: accessibility problems and repair costs for structural/non-structural elements might significantly vary.
- *different damage distributions*, i.e. severity of damage and repair costs as well as number of damaged elements. A given storey or frame damage level could derive from numerous combinations of number, type and damage levels of single elements.

RESIDUAL DEFORMATIONS OF INELASTIC SDOF SYSTEMS

1. Previous Results

Permanent displacements of elasto-plastic single-degree-of-freedom (SDOF) oscillators with variable post-yielding stiffness coefficient have been studied by MacRae and Kawashima (1997). The ratio of the residual displacement to the maximum possible residual displacement was found to be almost entirely dependent on the post-yielding stiffness and independent of the type of earthquake, natural period of the oscillator or peak ductility. Note that in this context the post-yielding stiffness is largely dependent on P-Δ effects and may be negative. The maximum possible residual displacement was defined as the residual displacement obtained by slowly unloading the structure from its maximum deformation state. Large residual displacement ratios were obtained for oscillators with negative post-yielding stiffness coefficient. Another study by Borzi et al. (2001) on SDOF oscillators of different hysteretic characteristics also identified the post-yielding stiffness as the main parameter influencing residual displacements. Ductility is also mentioned in this study as a parameter affecting residual displacements. In Christopoulos et al. (2003), the ratio of residual deformations over the maximum deformations of SDOF systems representing frame structures ranging from 4 to 20 stories were also found to be dependent on the post-yielding stiffness ratio, α, and displacement ductility level for EP and TK hysteretic systems. Significantly, lower residual deformation ratio was observed for the TK systems when compared to the EP systems. It was also found, in this study, that increasing the intensity of the seismic input from the BSE-1 level to BSE-2 levels (see ASCE (2000)) also increased the ratio of residual deformations to maximum deformations (see Figure 3). Details on the definition of the earthquake ensembles used to derive results in Figure 3 can be found in Christopoulos et al. (2003).

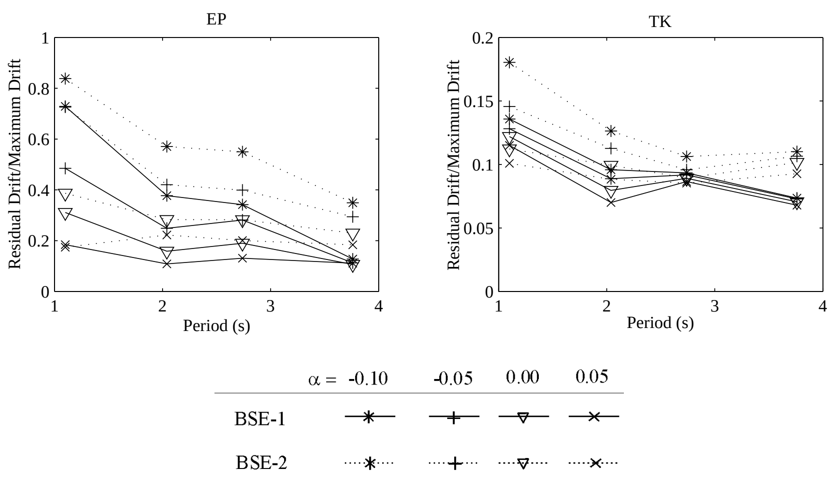

Fig. 3 Ratio of residual drift/maximum drift in SDOF systems (elasto-plastic and Takeda hysteresis rules)

In Table 1, results from this study on the maximum ductility, residual drift and residual/maximum drift ratios are reported in terms of average values over 20 earthquake records as well as the corresponding standard deviations. The effect of post-yield stiffness and hysteresis rule can be clearly seen in this table. It can also be seen that the standard deviations are large for both the residual drifts and the residual/maximum ratio values.

2. Residual Displacement Spectra

In Kawashima et al. (1998), equal-ductility residual displacement spectra were computed and converted to residual displacement ratio spectra by normalization with respect to the maximum possible residual deformation. These were derived for bilinear elasto-plastic hysteretic systems with different post-yielding stiffness and were suggested as a design tool for accounting for residual deformations in bridge peers. In this study, 63 ground motions, recorded on stiff, medium and soft soils and with peak ground accelerations ranging from 0.02*g* to 0.2*g*, were considered. Although most records were recorded for seismic events with magnitudes greater than 7, only three records had peak ground accelerations above 0.2*g*. It was also suggested that an equivalent bilinear representation can be used for approximating the residual displacements of systems exhibiting a Takeda hysteresis behavior.

Table 1: Mean Values and Standard Deviations of Maximum Ductility and Residual Drift for BSE-1 Level Earthquakes

No. of	Hysteretic		Maximum Ductility					Residual Drift (%)				Residual Drift/Maximum Drift			
Storeys	Model	α =	-0.10	-0.05	0.00	0.05	0.10	-0.10	-0.05	0.00	0.05	-0.10	-0.05	0.00	0.05
4	EP	MEAN	2.85	1.87	1.63	1.57	-	2.08	0.91	0.51	0.29	0.398	0.312	0.220	0.143
		STDV	3.27	1.33	0.93	0.82	-	3.56	1.32	0.65	0.33	0.357	0.283	0.206	0.145
	TK	MEAN	1.57	1.55	1.55	1.54	-	0.21	0.20	0.19	0.18	0.100	0.095	0.090	0.084
		STDV	0.77	0.75	0.74	0.73	-	0.26	0.24	0.22	0.20	0.095	0.086	0.080	0.076
	FS	MEAN	1.68	1.63	1.60	1.59	1.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		STDV	0.88	0.79	0.76	0.75	0.75	-	-	-	-	-	-	-	-
8	EP	MEAN	1.30	1.16	1.12	1.10	-	0.54	0.32	0.19	0.13	0.179	0.143	0.106	0.081
		STDV	1.24	0.76	0.65	0.59	-	1.36	0.66	0.33	0.19	0.244	0.197	0.133	0.098
	TK	MEAN	1.12	1.13	1.13	1.14	-	0.12	0.11	0.10	0.09	0.069	0.065	0.059	0.053
		STDV	0.62	0.64	0.66	0.68	-	0.15	0.14	0.12	0.11	0.063	0.057	0.051	0.045
	FS	MEAN	1.18	1.18	1.19	1.20	1.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		STDV	0.75	0.76	0.78	0.79	0.80	-	-	-	-	-	-	-	-
12	EP	MEAN	1.10	1.03	0.97	0.95	-	0.39	0.30	0.19	0.13	0.171	0.159	0.130	0.105
		STDV	0.94	0.75	0.61	0.56	-	0.89	0.63	0.32	0.17	0.233	0.200	0.137	0.090
	TK	MEAN	0.92	0.92	0.93	0.94	-	0.09	0.09	0.09	0.08	0.083	0.083	0.081	0.080
		STDV	0.51	0.52	0.53	0.54	-	0.09	0.09	0.09	0.08	0.057	0.057	0.057	0.056
	FS	MEAN	0.95	0.95	0.96	0.96	0.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		STDV	0.56	0.57	0.57	0.58	0.59	-	-	-	-	-	-	-	-
20	EP	MEAN	0.75	0.74	0.74	0.74	-	0.10	0.09	0.08	0.08	0.110	0.103	0.100	0.102
		STDV	0.47	0.47	0.46	0.46	-	0.14	0.12	0.12	0.12	0.103	0.099	0.099	0.098
	TK	MEAN	0.76	0.76	0.76	0.76	-	0.06	0.06	0.06	0.05	0.078	0.078	0.077	0.076
		STDV	0.49	0.49	0.49	0.49	-	0.06	0.06	0.06	0.06	0.063	0.064	0.065	0.065
	FS	MEAN	0.78	0.78	0.78	0.78	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		STDV	0.53	0.53	0.53	0.53	0.53	-	-	-	-	-	-	-	-

3. Current Analytical Investigations

To further investigate the parameters influencing residual deformations of SDOF systems, inelastic residual spectra were derived for a set of 20 earthquakes scaled to match the code spectra. These spectra are derived for equal displacement ductility values of 2, 3, 4, and 5.

3.1 Hysteretic Rules

The Takeda degrading stiffness (TK) and bilinear elasto-plastic (EP) hysteresis (see Figure 4) were considered to derive the inelastic spectra. Three values of the post-yield stiffness, α = −0.05, 0.00 and 0.05, were considered for both the TK and EP hysteretic systems, while the loading and unloading parameters for the TK hysteresis were set to the typical values of γ = 0.3 and δ = 0.2.

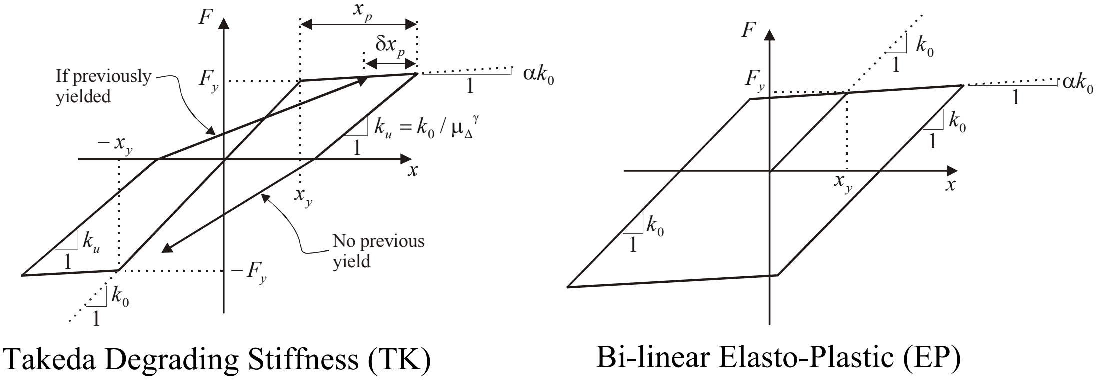

Fig. 4 Hysteretic models used in the analyses

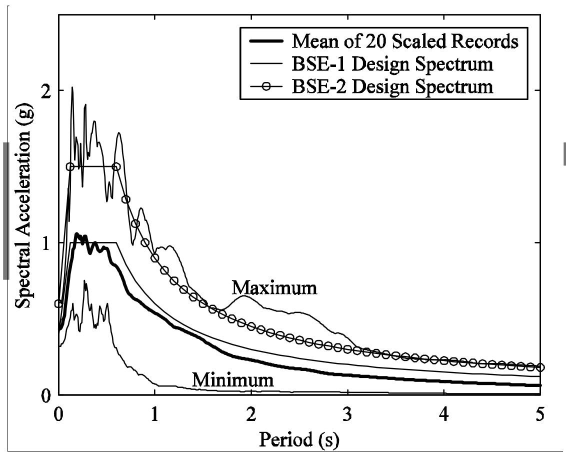

Fig. 5 Elastic acceleration response spectra (5% elastic damping) of the considered ground motions

3.2 Ground Motions Considered in this Study

An ensemble of 20 earthquakes scaled to match the design response spectrum of the UBC 97, zone 4 spectrum for soil types C or D is used for the analyses. Details on the characteristics of the earthquake records, as well as scaling factors, can be found elsewhere (Christopoulos et al., 2002a). This target response spectrum also corresponds to the design spectrum defined by the International Building Code (ICBO, 2000) for a soil class C, defined as two thirds of the maximum considered event (MCE) spectrum for accelerations of S_s = 1.5g for the short period range and S_1 = 0.10g for a period of one second. The MCE scaled down by two thirds represents a probability of exceedance of 10% in 50 years, while the MCE response spectrum corresponds to a probability of exceedance of 2% in 50 years. These levels also correspond to the BSE-1 (Basic Safety Earthquake) and BSE-2, respectively (ASCE, 2000). The basic safety objective (BSO) is attained when a structure achieves both the Life Safety Performance level under the BSE-1 level earthquake and the Collapse Prevention Performance level under the BSE-2 level earthquake. Other seismic intensity levels can be defined and used to define a multitude of performance levels. In this study, the two levels used to define the BSO, namely BSE-1 and BSE-2, are used for the analyses.

The BSE-1 ensemble comprises the twenty records scaled to match the design spectrum, while the BSE-2 ensemble comprises these records, with their amplitude scaled up by a factor of 1.5. Figure 5 shows the mean, maximum and minimum spectra of the twenty scaled records along with the BSE-1 and BSE-2 design response spectra. The BSE-1 design spectrum is in reasonable agreement with the mean spectrum of the 20 records, although for the longer period range (above 2 s), it is slightly above the mean spectrum. Note also that the BSE-2 spectrum is in reasonable agreement with the envelope of maximum spectral ordinates of the twenty records. Table 2 lists the earthquake records considered along with the magnitude, distance to the fault soil type, scaling factor and scaled peak ground acceleration (PGA).

Table 2: Time-Histories Considered in the Study

Name	Earthquake Event	Year	M_w	Station	$R_{closest}$ (km)	Soil Type (NEHRP)	Duration (s)	Scaling Factor	Scaled PGA (g)
EQ 1	Superstition Hills	1987	6.7	Brawley	18.2	D	22.0	2.7	0.313
EQ 2	Superstition Hills	1987	6.7	El Centro Imp. Co. Cent.	13.9	D	40.0	1.9	0.490
EQ 3	Superstition Hills	1987	6.7	Plaster City	21.0	D	22.2	2.2	0.409
EQ 4	Northridge	1994	6.7	Beverly Hills 14145 Mulhol	19.6	C	30.0	0.9	0.374
EQ 5	Northridge	1994	6.7	Canoga Park - Topanga Can	15.8	D	25.0	1.2	0.427
EQ 6	Northridge	1994	6.7	Glendale - Las Palmas	25.4	D	30.0	1.1	0.393
EQ 7	Northridge	1994	6.7	LA - Hollywood Stor FF	25.5	D	40.0	1.9	0.439
EQ 8	Northridge	1994	6.7	LA - N Faring Rd	23.9	D	30.0	2.2	0.601
EQ 9	Northridge	1994	6.7	N. Hollywood - Coldwater Can	14.6	C	21.9	1.7	0.461
EQ 10	Northridge	1994	6.7	Sunland - Mt Gleason Ave	17.7	C	30.0	2.2	0.345
EQ 11	Loma Prieta	1989	6.9	Capitola	14.5	D	40.0	0.9	0.476
EQ 12	Loma Prieta	1989	6.9	Gilroy Array # 3	14.4	D	39.9	0.7	0.386
EQ 13	Loma Prieta	1989	6.9	Gilroy Array # 4	16.1	D	40.0	1.3	0.542
EQ 14	Loma Prieta	1989	6.9	Gilroy Array # 7	24.2	D	40.0	2.0	0.452
EQ 15	Loma Prieta	1989	6.9	Hollister Diff. Array	25.8	D	39.6	1.3	0.363
EQ 16	Loma Prieta	1989	6.9	Saratoga - W Valley Coll.	13.7	C	40.0	1.4	0.465
EQ 17	Cape Mendocino	1992	7.1	Fortuna Fortuna Blvd	23.6	C	44.0	3.8	0.441
EQ 18	Cape Mendocino	1992	7.1	Rio Dell Overpass - FF	18.5	C	36.0	1.2	0.462
EQ 19	Landers	1992	7.3	Desert Hot Springs	23.3	C	50.0	2.7	0.416
EQ 20	Landers	1992	7.3	Yermo Fire Station	24.9	D	44.0	2.2	0.334

3.3 Inelastic Residual Displacement Spectra

Figure 6 presents the mean values over the 20 BSE-1 level records of the equal ductility maximum and residual displacement spectra for both the TK and EP hysteresis, and for all values of the post-yield stiffness α. These spectra were computed with the INSPECT module of the RUAUMOKO program (Carr, 2003). It can be seen by comparing the plots for the TK and EP hysteresis that although similar maximum deformations are sustained by systems of equal values of α for both hysteretic rules, larger values of residual displacements are observed for the EP systems. Lower values of post-yield stiffness, especially the case of $\alpha = -0.05$, result in increased values of residual displacements. Lower values of α also increase the sensitivity of the residual and maximum displacements to the level of ductility. This trend is especially true for the EP hysteresis. For values of α larger than 0, the effect of the ductility level is negligible. For the case of $\alpha = -0.05$ for the EP system, an increase of both maximum and residual deformations for larger levels of ductility can also be observed.

The ratio of residual/maximum deformations was found to be generally unaffected by the target ductility with a slightly increased sensitivity for the $\alpha = -0.05$ case and more so for the EP system. A displacement ductility of 4, commonly used in design, was therefore selected as representative for all ductility levels.

Figure 7 shows the mean values of the residual/maximum displacement ratio as a function of the effective period of the system at the target maximum displacement for displacement ductility of 4 and for both BSE-1 and BSE-2 level earthquakes. The effect of intensity on this ratio is negligible.

Based on Figure 7 and for all ductility levels ranging from 2 to 5, the values presented below are suggested for estimating the mean residual/maximum ratio for design purposes. The values of the standard deviation (STDV) are also given in {} and may be added to the suggested mean values if a higher level of confidence is required on the estimation of residual deformations.

For the TK hysteresis, for all effective periods

0.10 {0.10} for $\alpha = 0.05$

0.15 {0.10} for $\alpha = 0.00$

0.20 {0.10} for $\alpha = -0.05$

For the EP hysteresis, for effective periods lower than 3 seconds:

0.20 {0.15} for $\alpha = 0.05$

0.35 {0.20} for $\alpha = 0.00$

0.40 {0.20} for $\alpha = -0.05$

For the EP hysteresis, for effective periods from 3 to 8 s:

0.20 + 0.030 (T_{eff} -3) {0.15} for $\alpha = 0.05$

0.35 + 0.015 (T_{eff} -3) {0.20} for $\alpha = 0.00$

0.40 + 0.010 (T_{eff} -3) {0.20} for $\alpha = -0.05$

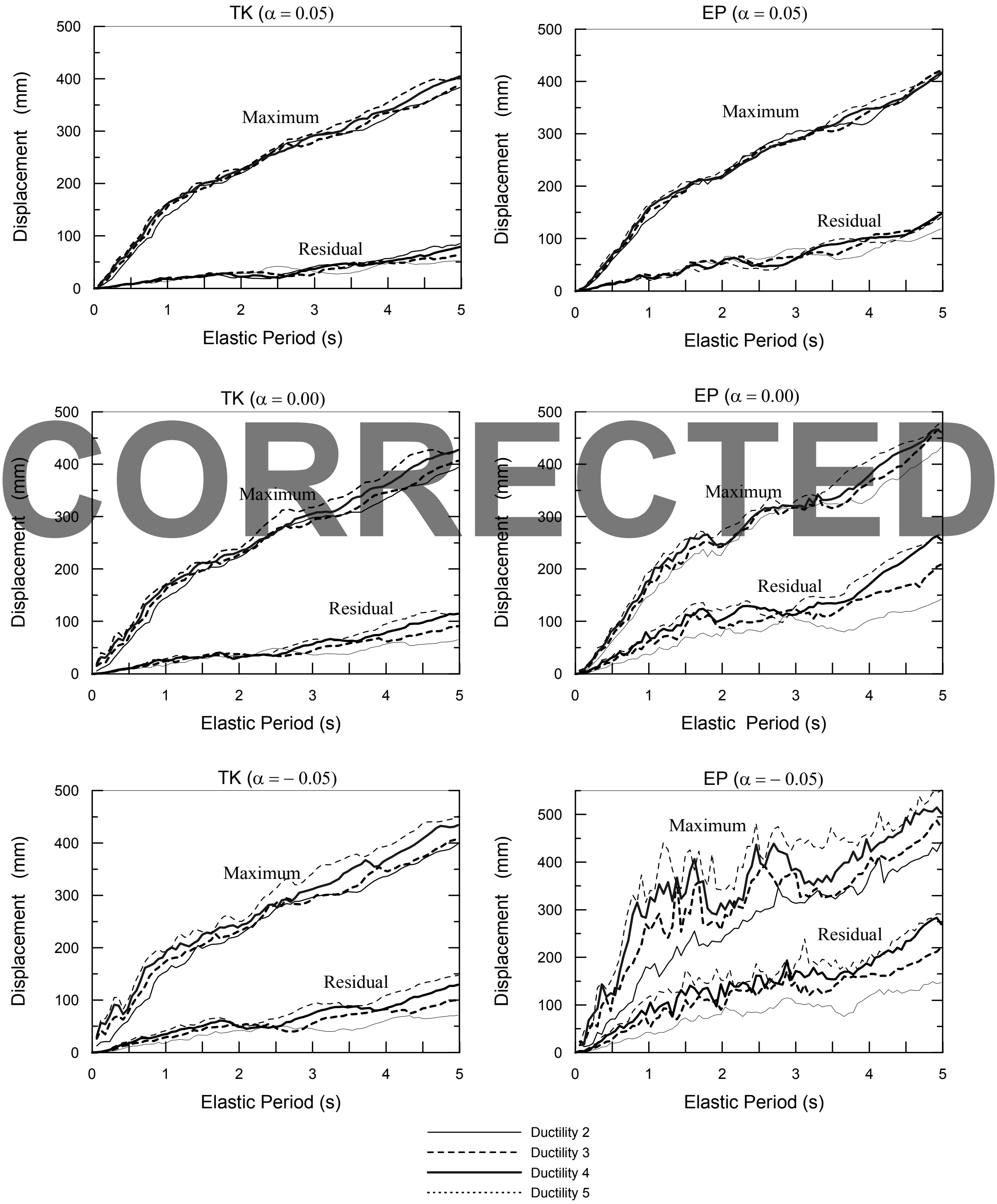

Fig. 6 Mean over 20 BSE-1 records of maximum and residual displacement spectra for all systems considered

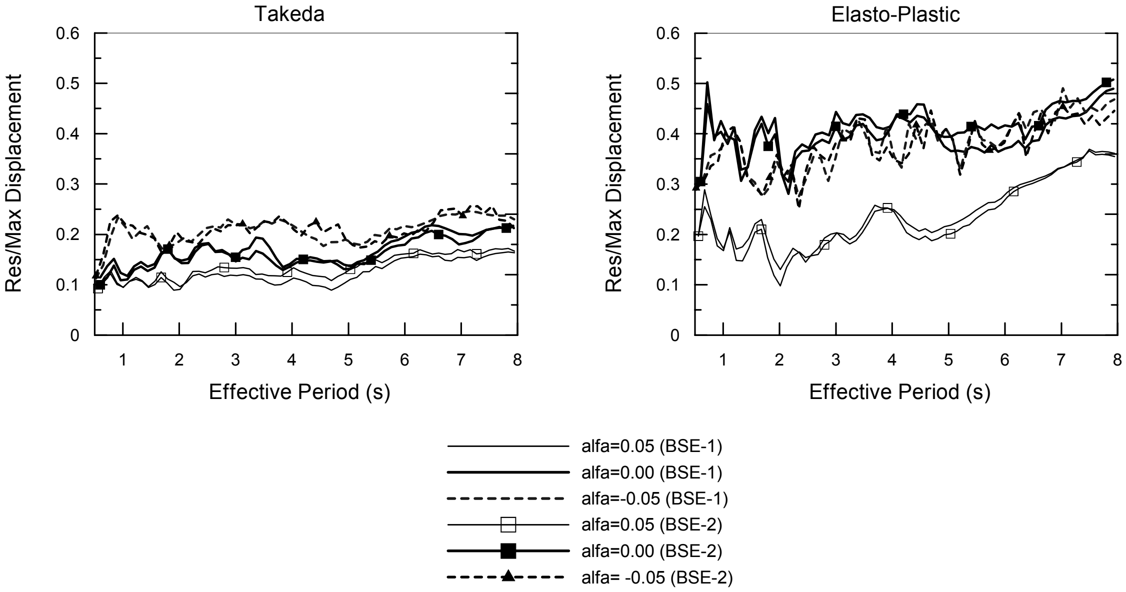

Fig. 7 Mean of residual/maximum displacement ratios as a function of effective structural period for ductility = 4, for BSE-1 level records

RESIDUAL DEFORMATIONS OF MDOF SYSTEMS

While a number of studies in the literature have reported analytical investigations on permanent/residual deformations of SDOF systems (see previous paragraphs), little information is currently available on the response of MDOF systems in terms of residual deformations at both local and global levels. Considering that most design procedures use some form of equivalent SDOF representation, in the following paragraphs the relationship between MDOF response and SDOF representations for both maximum and residual response quantities are discussed.

1. Amplification Factors

Several procedures have been proposed in the literature for the estimation of maximum seismic deformation demands for MDOF systems, typically based on the use of either simplified elastic/inelastic SDOFs, coupled pushover analyses, or approximate equations for different simplified systems and loading conditions (Fajfar and Gaspersic, 1996; Krawinkler and Seneviratna, 1998; Chopra and Goel, 1999; Gupta and Krawinkler, 2000). The evaluation of residual drift for MDOF frame systems can conceptually follow approaches similar to those adopted for the evaluation of maximum deformations/drifts (Gupta and Krawinkler, 2000). The residual drift of a MDOF system, RD_{MDOF}, can be evaluated, starting from the effective residual drift of an equivalent SDOF system, RD_{SDOF}, using amplification factors to account for higher modes, f_{MDOF}, and for P-Δ effects, $f_{P\text{-}\Delta}$.

This can be expressed as:

$$RD_{\mathrm{MDOF}} = RD_{\mathrm{SDOF}} . f_{\mathrm{MDOF}} . f_{P\text{-}\Delta} \tag{7}$$

Once the residual drift of a given storey or the maximum residual drift along the height of the structure have been derived, additional geometric amplification factors, f_{geom}, are used to derive the corresponding local (member) residual deformations, $R\Phi_i$:

$$R\Phi_i = RD_{\mathrm{MDOF}} \cdot f_{\mathrm{geom}} \tag{8}$$

The total amplification of residual displacements, when comparing MDOF systems with their equivalent SDOF systems, is also dependent on the geometric characteristics (i.e. multi-span frames of uneven span lengths) and on the type of local and global inelastic mechanisms (weak-beam/strong-column, weak-column/strong-beam or combination of the above, including joint damage and failure). Similar considerations regarding the effects on maximum drift demand have been presented in Seneviratna and Krawinkler (1996). Appropriate amplification factors of local residual deformations,

$R\Phi_i$, either representing a residual rotation, curvature or strain, can be defined for each element. When evaluating the performance of a structure based on residual deformations, both local residual strain values and global drift values are necessary. For a frame system with an expected inelastic behaviour based on a weak-beam strong-column mechanism, the local residual rotation $R\theta_b$ is, for example, given by:

$$R\theta_b = \mathrm{RD} \cdot \left(\frac{L}{L - h_c} \right) = \mathrm{RD} \cdot f_{\mathrm{geom}} \tag{9}$$

where L is the length of the beam from centre to centre of the columns, h_c is the column depth, and RD is the residual interstorey drift.

1.1 Numerical Investigation and Observed Trends

To investigate the relationship between amplification factors for maximum deformations and those for residual deformations, the response of different multi-storey frame systems, either representing new-designed structures or existing buildings designed for gravity-loads-only, were investigated in Pampanin et al. (2002, 2003). Effects of the hysteresis behavior at member connections, the inelastic mechanism and the seismic intensity were considered to capture simplified trends on the aforementioned maximum and residual drift amplification factors. Given the focus of this paper on design aspects, only the results pertaining to new-designed frame systems are discussed. It is, however, of interest to note that in Pampanin et al. (2003), where existing non-seismically designed structures were also considered, it was found that the amplification factors applied to maximum and residual deformations were highly dependent on the inelastic mechanism of the system. Notably, weak-column/strong-beam mechanism, typical of existing poorly designed structures, leads to considerable increases of residual deformations even when strength degradation characteristics associated to local brittle failure or extensive flexural damage are not considered. This dependency is also relevant for new designed structures where weak-column mechanisms are permitted for low-rise construction (i.e. NZS (1995), where weak-column mechanisms are accepted for one or two-storey frame systems).

The response of three five-storey "new-designed" buildings were investigated under a set of 10 records chosen within the ensemble of accelerograms, described above (see Pampanin et al., 2003), and scaled to the BSE-1 and BSE-2 levels. The members were first sized based on the assumption that the building was made of reinforced concrete using a direct displacement-based design procedure (Pampanin et al., 2003). Members in all the three systems were then assigned the same monotonic strength characteristics. However, each system was assigned a different hysteretic rule in the beam-column and column-to-foundation connections respectively the elasto-plastic (EP), Takeda (TK), and flag-shape (FS) (see Figure 8). The corresponding cyclic push-pull over responses of the three buildings are shown in Figure 8 (left), where similar backbone curves (monotonic behavior) are observed for all three systems. Details on the design procedure, the analytical model (based on a plasticity concentrated approach), the definition of the effective SDOF oscillators (see Figure 8 - right) as well as a full report on the results can be found in Pampanin et al. (2003). The analyses were carried out using the non-linear dynamic analysis program RUAUMOKO (Carr, 2003).

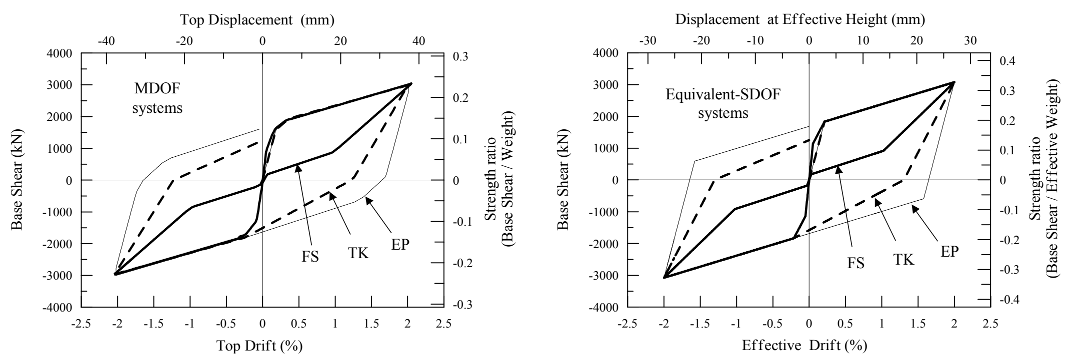

Fig. 8 Hysteresis loops of the 5-storey new-designed frames and of the equivalent inelastic SDOF systems

The seismic responses of these three frame systems (EP, TK and FS) were compared in terms of top floor displacement time-histories, maximum and residual interstorey drift distributions, residual deformed shapes, maximum floor displacements envelopes and residual storey moment ratios. In Figure 9, the response under the EQ3 record (BSE-1 level), without *P-Δ* effects, is shown as an example.

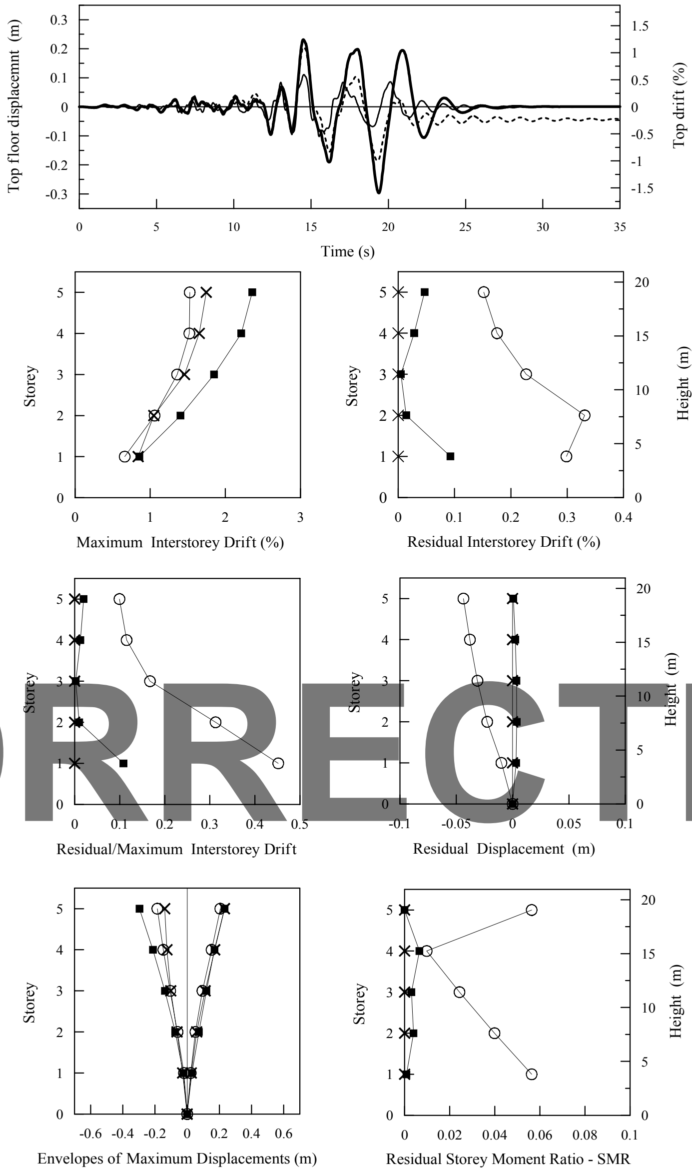

Fig. 9 New-designed frames: Comparison of response under EQ3 (BSE-1) record

Mean and STDV of maximum drift, residual drift and the ratio of the above are presented in Table 3. A summary of the response of all three systems to all ten records is presented using the RD-based performance matrix format, discussed in a previous paragraph, in Figure 10. The residual drift plotted on the horizontal axes of these figures corresponds to the maximum value over the height of the structure.

The following qualitative trends can be observed:

- Despite having similar maximum drifts to the EP and TK systems, the FS system sustains no residual deformations due to its self-centering property.
- As was the case for SDOF systems, current performance-based seismic design procedures would not reflect the enhanced performance of self-centering FS systems.
- The TK system undergoes similar to higher maximum interstorey drifts when compared to the EP system. As discussed for SDOF systems, when similar maximum interstorey drifts are obtained, the TK system generally sustains considerably lower levels of residual interstorey drifts due to its hysteretic characteristics (i.e. difference in loading and unloading stiffness with a tendency to “shake

down" and reduce the residual displacement after the maximum displacement has been reached). However, when the TK system sustains significantly higher maximum interstorey drifts than the EP system, higher levels of residual interstorey drifts and residual/maximum interstorey drift ratios are observed for the TK system.

- A clear trend in the ratio of the residual interstorey drift to the maximum interstorey drift ratio at each storey could not be observed. However, the ratio of the maximum residual interstorey drift along the height of the building to the maximum interstorey drift along the height of the building yielded nearly constant mean values for both the EP and TK systems, independent of the seismic intensity or the inclusion of *P-Δ* effects in the analyses (see Table 3).

Table 3: Mean Values and Standard Deviations of Maximum Drift, Residual Drift and Residual/Maximum Drift Ratio for New-Designed Five-Storey Frame Systems

Hysteretic Model	Level	Maximum Drift (%) BSE-1 (no P-Δ)	(P-Δ)	BSE-2 (no P-Δ)	(P-Δ)	Residual Drift (%) BSE-1 (no P-Δ)	(P-Δ)	BSE-2 (no P-Δ)	(P-Δ)	Residual/Maximum Drift BSE-1 (no P-Δ)	(P-Δ)	BSE-2 (no P-Δ)	(P-Δ)
EP	MEAN	1.70	2.11	2.63	3.12	0.17	0.22	0.25	0.35	0.11	0.13	0.10	0.11
	STDV	0.40	0.58	0.97	1.10	0.11	0.13	0.12	0.22	0.08	0.08	0.04	0.05
TK	MEAN	2.20	2.52	3.26	3.90	0.19	0.29	0.28	0.53	0.09	0.10	0.10	0.11
	STDV	0.50	0.72	0.99	1.50	0.18	0.24	0.17	0.58	0.07	0.07	0.08	0.10
FS	MEAN	1.73	1.72	2.31	2.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	STDV	0.40	0.39	0.48	0.80	-	-	-	-	-	-	-	-

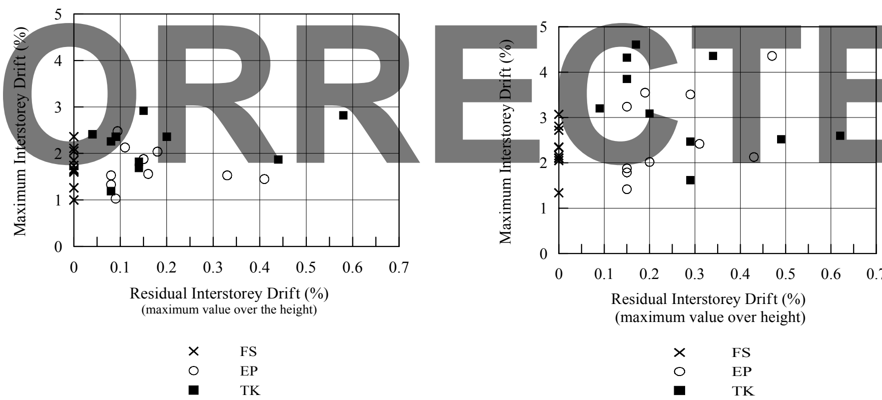

Fig. 10 New-designed frame systems response (without *P-Δ* effects) at BSE-1 (left side) and BSE-2 (right side) levels: RD-based performance matrix

1.2 Amplification Factor due to Higher Modes

In order to evaluate the amplification factors, relating the response of the MDOF systems to those of their equivalent-SDOF systems, both in terms of maximum and residual drifts, results from non-linear time-history analyses on equivalent-inelastic-SDOF systems, whose hysteretic properties were assumed to match the cyclic behavior of the original frame systems, were compared to results obtained on the MDOF systems without *P-Δ* effects. A summary of the results from each earthquake record (both BSE-1 and BSE-2 levels, without *P-Δ* effects) is shown in Figure 11, while results in terms of mean and standard deviations are provided in Table 4. It can be noted that the amplification factors of maximum drift, α_{MDOF}, show smaller mean values and scatter (e.g. mean values of 1.86, 2.26 and 1.83 and STDV values of 0.53, 0.43 and 0.61 for the EP, TK and FS systems, respectively, for the BSE-1 level records) than the amplification factors of residual drift, f_{MDOF} (e.g. mean values of 3.17 and 2.37 and STDV values of 3.47 and 1.94 for the EP and TK systems, respectively, at BSE-1 level). More scatter is also observed for the EP frame than for the TK system. The SDOF FS frames do not sustain residual drifts. The amplification factors of residual drift due to higher modes show also higher sensitivity to the intensity level than the amplification factors of maximum drift.

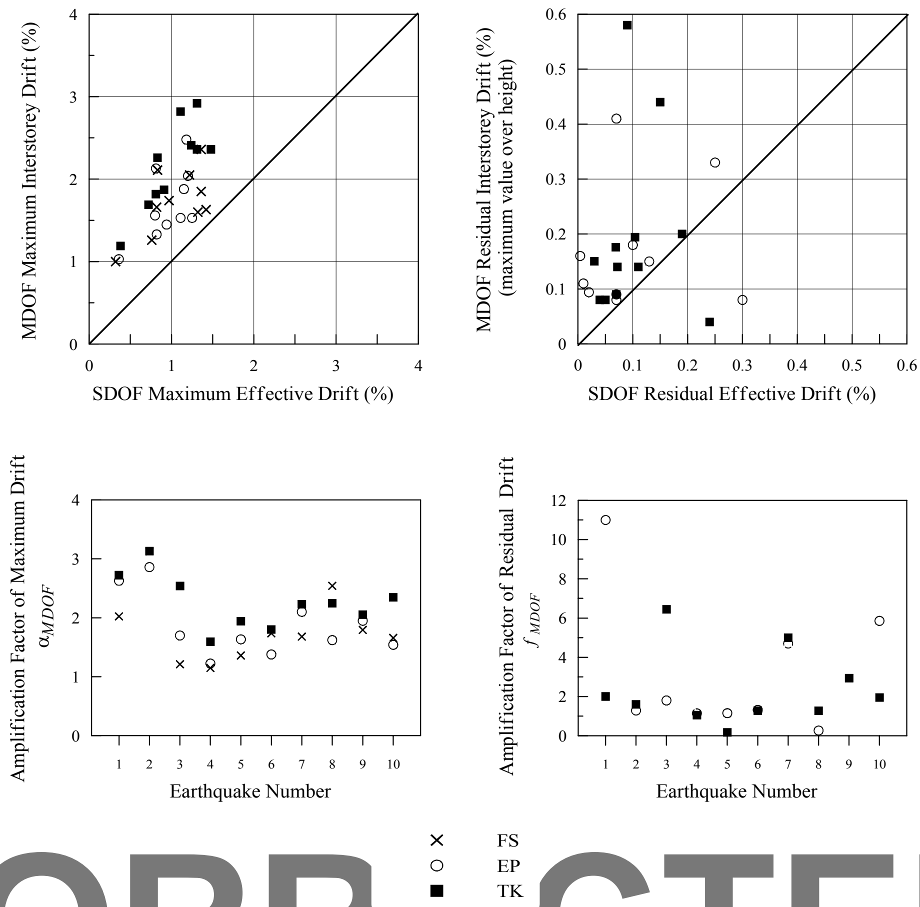

Fig. 11 New-designed frame systems response at BSE-1 level (without *P-Δ* effects): Maximum drift and residual drift amplification factors due to higher modes

1.3 Amplification Factor due to P-Δ Effects

The *P-Δ* effects on both maximum and residual drifts are shown, for each earthquake record, in Figure 12. Results in terms of mean and standard deviations are provided in Table 4. While the amplification factors of maximum drift, $\alpha_{P-\Delta}$, show a more regular trend and are limited within well-defined upper and lower bounds (e.g. mean values of 1.25, 1.15 and 1.01 and STDV values of 0.25, 0.12 and 0.14 for the EP, TK and FS systems, respectively), the amplification factors of residual drift, $f_{P-\Delta}$, show significant higher values as well as a wider scatter (e.g. mean values of 1.57 and 2.30 and STDV values of 0.94 and 2.57, for the EP and TK systems, respectively).

For the 5-storey structures, analyzed in this study, the summary of the mean values of the amplification factors as well as the standard deviations are shown in Table 4. Although these results are indicative of the types of values that can be expected, extensive analyses are still needed to fully characterize these factors for different structural systems.

PROPOSED SEISMIC DESIGN PROCEDURE FOR MDOF FRAME STRUCTURES WITH EXPLICIT CONSIDERATION ON RESIDUAL DEFORMATIONS

Residual deformations can be included in any design procedure in the form of a final check once the design of a structure has been completed. In fact, the SDOF response estimates, based either on the elastic period or effective periods, can be obtained from the inelastic design spectra presented in the previous paragraphs and a suitable amplification of this SDOF residual deformation can then be extended to the maximum residual deformation along the height of a structure and compared to predefined acceptable limits. Although, as discussed previously, interstorey residual drifts represent a good measure of the implications of residual deformations on the final state of a structure, local residual deformations such as residual plastic rotations, residual crack widths or residual strains in the materials can also be used.

Table 4: Mean Values and Standard Deviations of Amplification Factors due to Higher Modes and *P-Δ* Effects for New-Designed Frame Systems

Hysteretic Model	Level	Higher Modes Amplification – Max Drift α_{MDOF} BSE-1	Higher Modes Amplification – Res Drift f_{MDOF} BSE-1	P-Δ Effects Amplification – Max Drift $\alpha_{P-\Delta}$ BSE-1	P-Δ Effects Amplification – Res Drift $f_{P-\Delta}$ BSE-1
EP	MEAN	1.86	3.17	1.25	1.57
	STDV	0.53	3.47	0.25	0.94
TK	MEAN	2.26	2.37	1.15	2.30
	STDV	0.43	1.94	0.12	2.57
FS	MEAN	1.83	-	1.01	-
	STDV	0.61	-	0.14	-

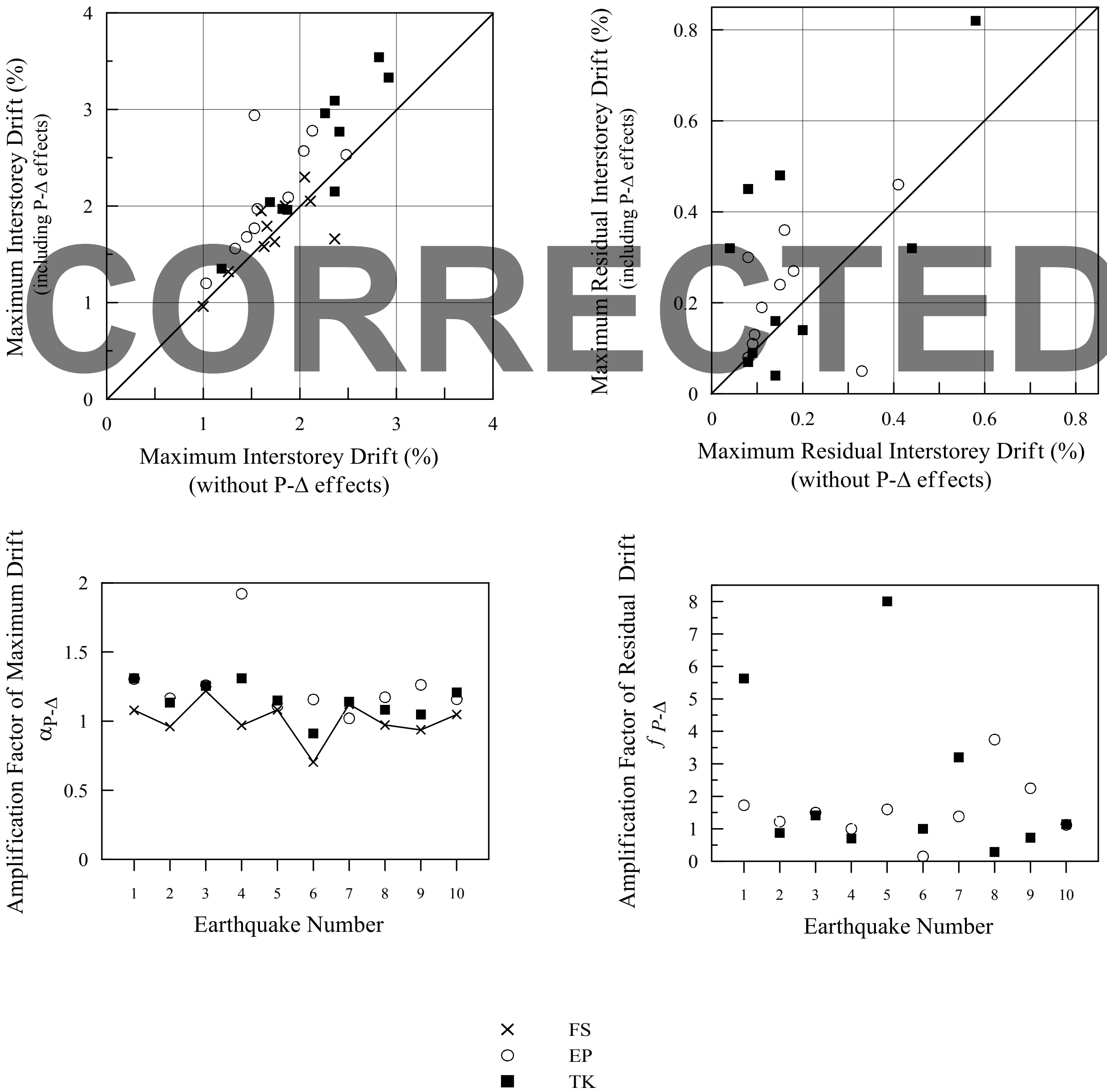

Fig. 12 New-designed frame systems response at BSE-1 level: Maximum drift and residual drift amplification factors due to *P-Δ* effects

The inclusion of residual deformations in the design process is given a more central role in the method, herein proposed, by including it at the earliest stage of the design procedure (i.e. before the complete sizing of members). Considering that results from previous paragraphs indicate that residual deformations can be suitably determined based on the maximum deformation, the hysteretic rule, the expected post yield-stiffness, and, in the case of the EP hysteresis, on the effective structural period, consideration of residual deformations in the design process is most suitably included in a displacement-based design procedure.

It is beyond the scope of this paper to discuss, in detail, direct displacement-based design procedures. Details on the development of these procedures, both for assessment and design purposes as well as complete discussions and comparisons of these methods to traditional force-based design methods, can be found elsewhere (Priestley, 1993, 1998; Calvi and Kingsley, 1995; Kowalsky et al., 1995; Priestley and Kowalsky, 2000; Sullivan et al., 2003).

1. Proposed Direct Displacement-Based Design (DBD) Procedure with Explicit Consideration on Residual Deformations

A direct DBD procedure differs fundamentally from traditional design procedures in that the maximum target displacement is a predetermined goal to be achieved under the design level earthquake. As noted by Priestley (1998), a design approach that attempts to design a structure to achieve rather than not exceed a given limit state under a given seismic input level would result in an inventory of uniform-risk structures, philosophically compatible with the uniform-risk seismic intensity incorporated in most codes. Since this target displacement is set and the effective period is determined within the first portion of the first iteration, before the final dimensioning of the members is carried out, the check on the expected residual deformations is imposed at that stage.

Figure 13 shows the proposed flow chart for the DBD procedure with explicit consideration on residual deformations. Steps 1, 2 and 3 correspond to the direct DBD procedure (Priestley, 1998). Step 2R is the additional step that is added for the check on the residual deformations. The steps are summarized below:

- *Step 1*: The target performance level is set, including both maximum and residual deformation response, from an RD-based performance matrix (see Figure 1). The structural system is then transformed into an equivalent-elastic SDOF oscillator with effective height, h_e, and effective mass, m_e, by assuming a deflected shape at maximum displacement of the system. Once the maximum design drift is set, the target displacement can be computed.

- *Step 2*: The target ductility level of the structure is estimated by first determining the yield displacement of the SDOF based on the geometry and layout of the structure. The corresponding equivalent viscous damping is then evaluated (either based on a ductility damping chart or other relationships proposed in the literature) and finally the required effective period is read on an elastic displacement spectrum for the computed value of damping.

- *Step 2R*: With the target maximum displacement and the effective period, the residual displacement at the effective height can be estimated through the Res/Max displacement spectra. The residual displacement is then converted to an effective residual drift (SDOF oscillator). The maximum residual drift of the structural (MDOF) system is then obtained by multiplying the effective residual drift by the corresponding amplification factors, f_{MDOF} and $f_{P\text{-}\Delta}$ (see Equation (8)). If required, maximum local residuals can be obtained by using geometric transformations (see Equation (9)). Residual deformations, either at the interstorey drift level or the local level, are then compared to acceptable limits. If these limits are exceeded, before carrying through the design, the characteristics of the structural system are appropriately modified and the procedure is repeated.

- *Step 3*: Once the residual deformations computed in Step 2 are acceptable, the direct DBD procedure is completed by computing the corresponding base shear, distributing it along the height of the structure and finally designing the structural members.

2. Reducing Residual Deformations

As stated in Step 2R, if the residual deformations are found to be excessive, the design returns to Step 1. However, since residual deformations are primarily a function of the post-yield stiffness and the hysteretic rule exhibited by the inelastic members, the following design decisions can be made to affect residual deformations:

- If the structural system is fixed and cannot be altered (for example use of RC frame system), a reduction in the maximum target displacement (accepted maximum drift) can directly lead to a reduction of residual deformations. It is of interest to note, that similar limitations on the maximum interstorey drift are currently imposed in codes for limiting *P-Δ* effects (no collapse limit state) and damage to non-structural elements (damage control limit state).

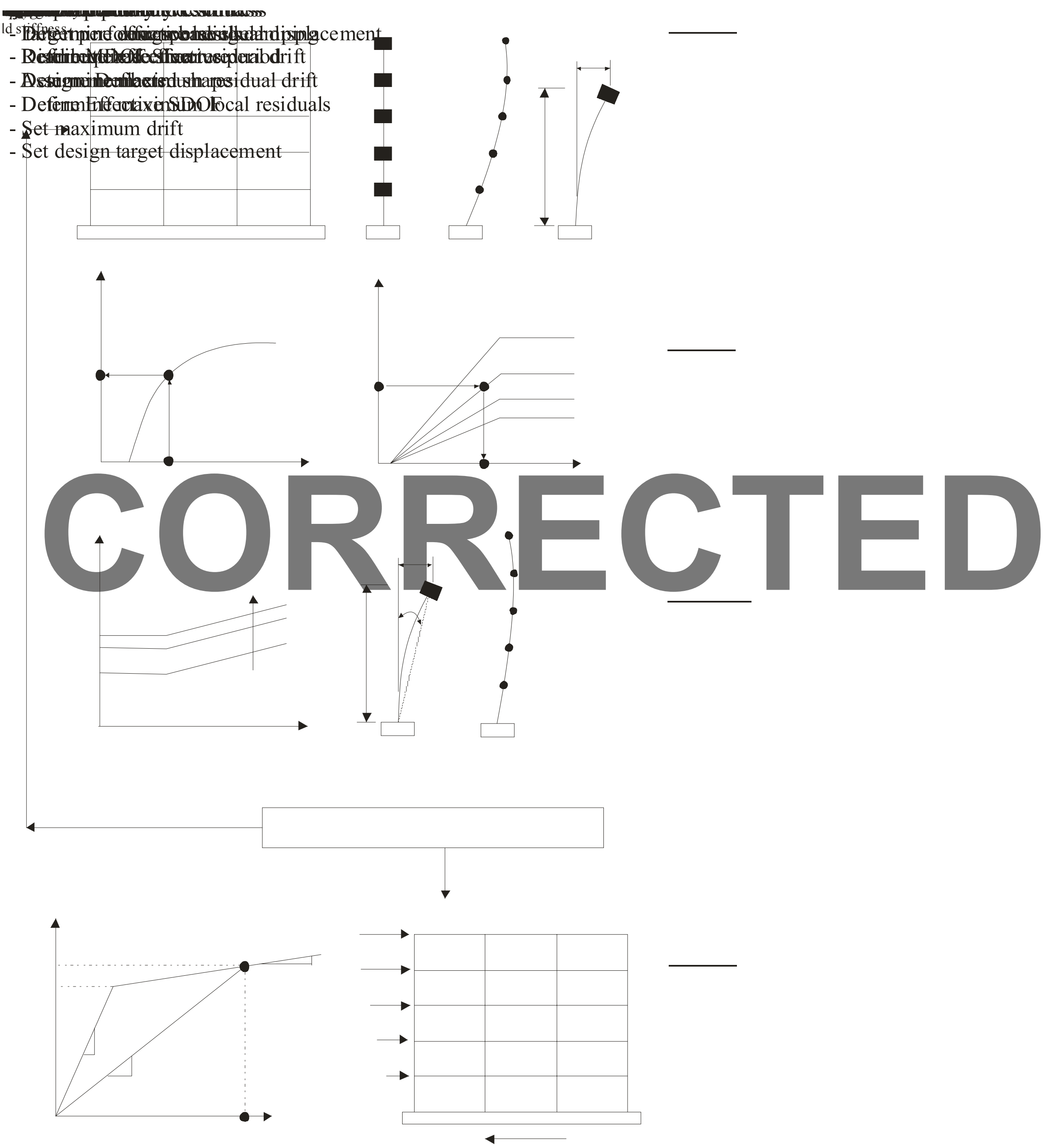

Fig. 13 Flowchart of DBD procedure with explicit consideration of residual deformations

- Alternative solutions to increase the post-yield lateral stiffness of the structure can also be envisaged:
  - o coupling the main structural system with a more flexible secondary system. The secondary system is designed to undergo elastic deformations while the main system undergoes inelastic deformations, and, therefore, provides supplemental post-yielding stiffness.

- o appropriately changing material properties (e.g. steel with high strain hardening), reinforcement properties and section design in order to increase the post-yielding stiffness at a section level. MacRae and Kawashima (1997) suggest that additional confinement of the core concrete of bridge piers leads to an increased post-yield stiffness of members in flexure. Similarly, in a concrete section, the use of distributed reinforcement along section depths as well as low ratios of longitudinal reinforcement can lead to earlier onsets of steel strain hardening effects.

- Considering that a notable difference exists in the residual deformations for different hysteretic rules, an alternative option, consisting of penalizing a type of system by imposing lower allowable maximum drifts based on its propensity to produce higher residual deformations could also be considered. In fact, “fatter” hysteretic rules that are commonly perceived as more efficient seismic resistant systems because of the higher energy dissipation capacity are most likely to produce the highest residual deformations, especially if the response is affected significantly by *P-Δ* effects.
- The use of new self-centering systems that achieve similar maximum deflections as their traditional counterparts while eliminating all residual deformations can also be envisaged for the highest performance level with respect to residual deformations.

3. Future Challenges towards Implementing Explicit Considerations of Residual Deformations in the Design of MDOF Structures

The proposed procedure includes all parameters that have been found to influence residual deformations for both SDOF and MDOF systems through extensive numerical analyses. However, at the current stage of development, the amplification factors discussed earlier for five-storey buildings with alternative hysteresis behavior cannot be extended to all types of structures. Results on amplification factors for non-seismically designed structures also indicated the sensitivity of these parameters to the assumed inelastic mechanisms. These topics are currently the subject of further extensive numerical investigations to better understand and characterize these factors for a larger family of systems.

Although important trends on residual deformations of SDOF and MDOF systems have been established, an important aspect of implementing design procedures to include this response parameter is to address the large scatter, that is observed when assessing residual deformations of inelastic systems. The scatter was found to be more significant for systems, exhibiting the fuller EP hysteretic rule and for systems with low post-yield stiffness, which coincide also with the systems that exhibit the largest residual deformations.

Also central to fully including residual deformations in design is the elaboration of well defined limits on global and local residual deformations. Extensive experimental investigations, including a full assessment of the implications of different levels of residual deformations to the serviceability of the structure as well as to the cost of repair, are needed to achieve this.

CONCLUSIONS

The need for consideration of residual deformations in the performance based seismic design and assessment of structures has been discussed. Indices, similar to those currently used for maximum response characterization, were suggested for defining performance levels based on residual deformations and a framework, which combines both residual and maximum performance levels, was defined. Residual deformations of SDOF systems were then investigated to define residual/maximum deformation ratios for design purposes. Post-yielding stiffness, as well as hysteretic rule were found to mostly influence residual deformations and the residual/maximum deformation ratio. The ductility level was found to influence the response of EP systems in terms of residual displacements more than the TK systems and more so for systems with low post-yield stiffness. Tentative values of residual/maximum displacement ratios, based on the mean + 1 STD results from 20 records with spectrum-compatible mean, were suggested for use in design.

Generally, the TK systems exhibited constant residual/maximum ratios for all effective design periods, while the EP system exhibited a linear increase for larger effective design periods. The extension of SDOF residual deformations to maximum residual deformations in MDOF systems was discussed and amplification factors, taking into account *P-Δ* effects and higher mode effects, were suggested. The values of such amplification parameters were investigated numerically for a 5-storey new-designed frame structure with different hysteresis behavior. It was primarily found that residual displacements are significantly more sensitive to both higher mode effects and *P-Δ* effects than maximum displacements. Elasto-plastic systems exhibit amplification factors with higher mean values and scatter. Adequate amplification factors for residual deformations cannot, thus, be neglected and should be considered in a design or assessment procedure.

Based on results on residual deformations of both SDOF and MDOF, the direct DBD procedure was modified to include an explicit step where residual deformations are controlled. This step can be done before completely sizing structural members and, therefore, provides a quick and effective way of changing the initial design assumptions to assure acceptable residual deformations in the final design. The main challenges, for further developing and implementing the proposed method, were identified as being the elaboration of residual deformation amplification factors for a wider range of structures, the definition of residual deformation performance levels and the quantification of uncertainties when computing residual deformations.

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