Accounting for the Effects on Residual Deformations due to Torsional Response

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ABSTRACT: Recent developments in performance-based seismic design and assessment approaches have emphasised the importance of properly assessing and limiting the residual (permanent) deformations typically sustained by a structure after a seismic event, even when designed according to current code provisions.

In this contribution, the performance-based design framework for residual deformations, previously developed by the authors for 2-D regular structures, is further extended to the behaviour of 3-D irregular (asymmetric in-plan) buildings. The seismic response of a set single storey systems, comprising of seismic resisting frames, and made of alternative materials (concrete or steel), is investigated under uni-directional earthquake loading excitations. Different layouts in plan, leading to either torsionally unrestrained or restrained systems, are considered.

Sensitivity analyses are carried out in order to identify the influence of varying levels of torsional restraint on the residual deformations/displacements in the response of a 3-D irregular building, the irregularity being given by an imposed mass eccentricity.

1 INTRODUCTION

As part of the development of performance-based seismic design procedures, it is becoming increasingly recognised that such approaches should take into account the likely residual deformations of structures. A number of researchers (MacRae et al. 1993a & 1993b, Priestley 1993, Kawashima 1997, Borzi et al. 2001, Christopoulos et al. 2003) have investigated the residual deformation behaviour of structures, however to date these studies have been limited to SDOF oscillators or simple 2-D frame systems. Contrary to this, extensive studies on the maximum torsional response of buildings have been carried out, with significant advances made in recent years to develop approaches that act to control twist induced displacement demands for a wide range of building forms. There remains however no explicit mention of residual deformations due to torsional response.

A need therefore remains for a simple but comprehensive design procedure accounting for residual deformations that accounts for second-order effects (i.e. P-Δ) and irregularities both in plan and elevation. Such an approach should be flexible such that it can be applied in both force-based (FBD) and displacement-based design (DBD) contexts, using some form of simplified 2-D approximation to the full 3-D system.

A comprehensive research program has been initiated with the intent to further investigate the role of residual deformations within performance-based design and assessment approaches, extending the conceptual outline presented by the authors (Christopoulos et al. 2003, Pampanin et al. 2002 & 2003) to the 3-D response of irregular buildings. This contribution will focus on the behaviour of simple frame structures; however the results are also representative of similar structural wall systems. Some basic comparisons are drawn between different construction forms with models representative of reinforced concrete and steel materials.

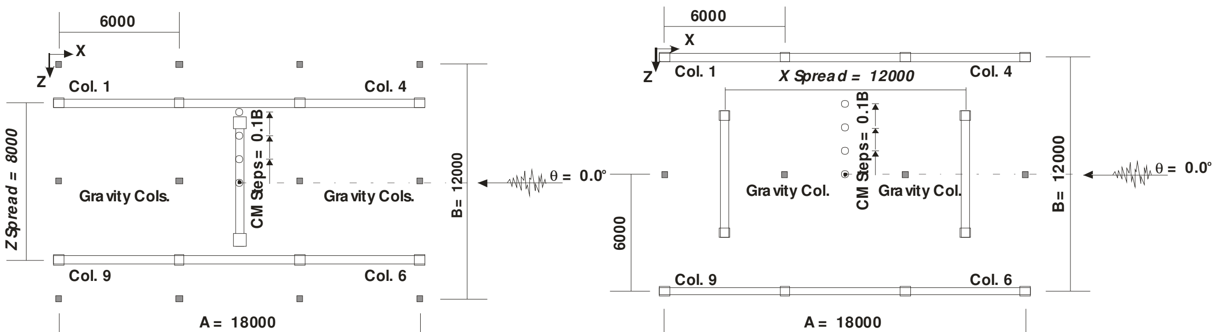
2 INVESTIGATION OUTLINE

A series of single storey 3-D structures consisting of frames or walls have been considered, and their response to earthquake excitation assessed using inelastic time-history analyses. Both torsionally restrained and unrestrained configurations, according to definitions promoted by Paulay (1996 & 2000) and Castillo (2002 & 2004), of seismic resistance are included.

Systems with mass eccentricity or strength and stiffness eccentricity were considered in the study, however only results for the mass eccentric frames are shown in the following sections. A recent study by Peruš & Fajfar (2005) has shown that maximum torsional response due to mass or combined strength and stiffness eccentricity is generally similar; the residual deformation results for both types of eccentricity generally reflect this finding. The findings presented below are primarily related to the response of unrestrained and restrained frame buildings, however the general trends are also applicable for similar wall systems. Further background information and results are given by Pettinga et al. (2005).

3 SYSTEM AND ANALYSIS DEFINITION

Figure 1 shows the plan views for the torsionally (a) unrestrained and (b) restrained frame buildings considered for the restraint studies. Included are the incremental positions of the CM and the applied earthquake angle of attack with respect to the CG. The wall systems considered have the same overall dimensions and layout, with elements sized and reinforced to satisfy NZS3101:1995 code requirements.



(a) (b)

Figure 1. Plan configuration of (a) torsionally unrestrained (b) torsionally restrained frame buildings used to investigate the interaction effects of varying radii of gyration of strength and/or mass.

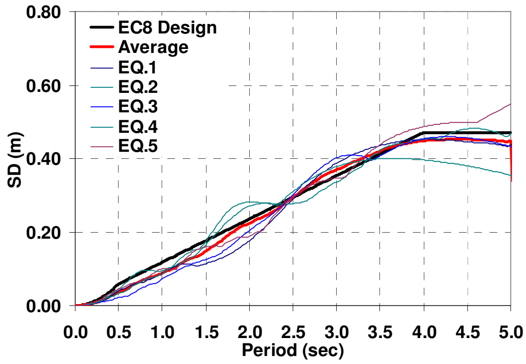
3.1 Structural Design and Modelling

The structures were designed in each principal direction using a Direct Displacement-Based Design approach (Priestley & Kowalsky 2000, Pettinga & Priestley 2005) with a 2.5% target drift and equivalent viscous damping values typical of reinforced concrete connections ($\xi \approx 20\%$). When comparing the response of alternative (material-wise) structures, the same design strengths and overall monotonic behaviour of the connections were considering, while alternative hysteretic rules, more appropriate for steel or concrete (i.e. Elasto-Plastic, EP or Takeda, TK), were implemented for the inelastic time-history models. A lumped plasticity approach was adopted for the numerical model, implemented in

Ruaumoko 3-D (Carr 2005), consisting of Giberson one-component frame elements for both beams and columns (with an additional moment-axial load interaction yield surface). At this stage of the investigation, for simplicity, no interaction between the flexural capacities in the column element principal directions under bi-axial demand has been considered.

3.2 **Time-history Analysis Excitations**

The time-history analyses were carried out using a suite of five accelerogram pairs that included four real earthquakes and one artificial pair (created from two random seeds in *SIMQKE*). The real records were scaled to match a modified Eurocode 8 (CEN 2002) pseudo-displacement design spectrum (0.5g PGA; Soil Type B) with an assumed damping of $\xi = 20\%$ (Figure 2). The principal component, selected based on the maximum area under the 20% damped pseudo-displacement spectrum for each direction, was scaled to minimise the average root-mean-square of the observed 20% damped spectrum from the target design displacement spectrum (adapted from Bommer & Acevedo 2004) over the period range zero to four seconds. It is worth noting that the selection of such a wide period range for spectrum compatibility was due to the intent to extend the investigation herein presented to the response of multi-storey frame systems. In the following results only the principal components were applied along the X-axis of the buildings ($\theta = 0^o$), thus allowing the actual variation of rotation to be clearly identified without inertial interaction due to secondary excitation (the influence of the orthogonal earthquake component has been considered in further parametric studies not present here).



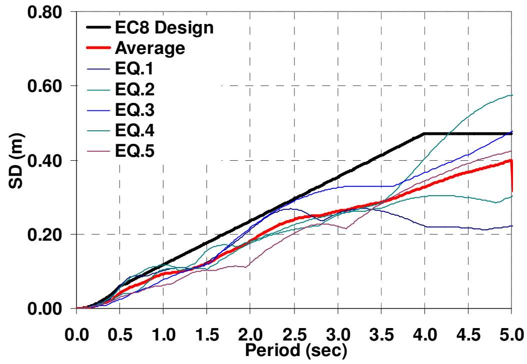


Figure 2. Elastic earthquake displacement spectra ($\xi = 20\%$) (a) principal components (b) secondary components.

4 **RESULTS**

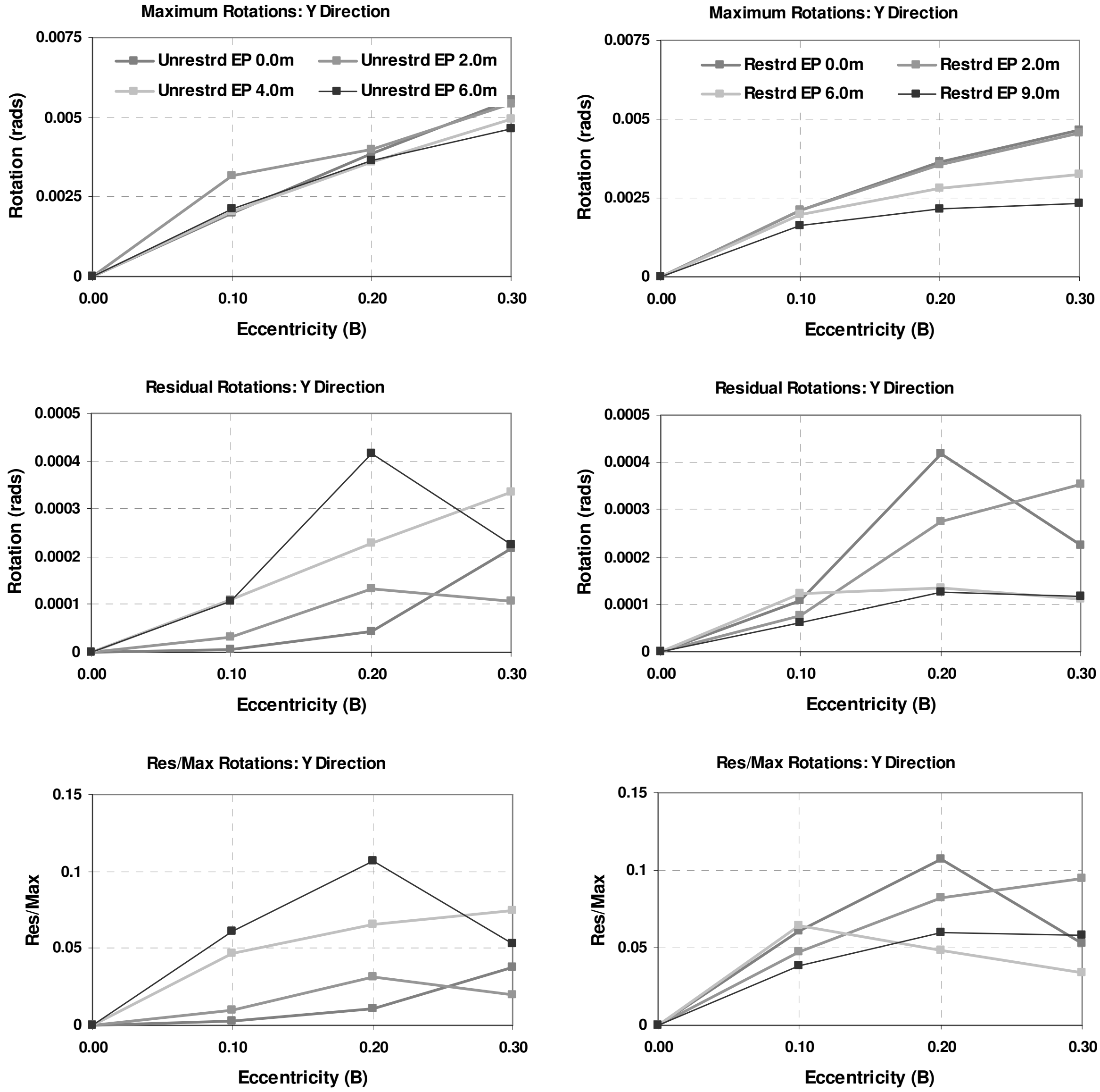
The inelastic time-history results from the set of frame systems described in the previous section are summarised below. Basic indications of the response in terms of maximum and residual rotations are provided with the intent to identify, at this stage, qualitative trends to be used in subsequent investigations that can define the design issues and more appropriate quantitative values.

4.1 **Influence of System Restraint Conditions**

In the work presented by Castillo (2004), the influence of the translational elements (quantified by the ratio of radius of gyration of strength to radius of gyration of mass r_{vx}/r_m of the elements parallel to the principal direction of excitation) was investigated (by keeping the strength distribution constant while changing the distribution of mass) and identified as the basic factor in limiting system rotations. The degree of torsional restraint provided by the transverse elements (r_{vz}/r_{vx}) was also considered, however variations in transverse restraint were relatively insignficant.

In this study the X-direction elements (for the unrestrained systems, see Figure 1) and Z-direction elements (for the restrained systems) were shifted such that the radii of gyration of strength in either direction were set at r_{vx} = 6m, 4m, 2m and 0m for the unrestrained systems (a) and r_{vz} = 9m, 6m, 4m and 0m for the restrained systems (b). For each structure the same mass eccentricities were applied for each variation of restraint level. It should be noted that P-Δ effects were not included in these analyses as this would be included as an additional factor in the explicit design approach proposed by Christopoulos et al. (2004a & b).

The dynamic behaviour of these two building typologies provides some interesting comparisons to the traditionally accepted trends of torsional response. Shown in Figure 3 are results in terms of the average maximum, residual and residual/maximum diaphragm rotation for each building type as a function of eccentricity. When considering the maximum rotations, the behaviour is generally as expected with the unrestrained systems exhibiting larger rotations than the restrained counterparts.



(a) (b)

Figure 3. Results indicating the effect of variations in radii of gyration of strength (a) Bilinear Unrestrained frame r_{vx} (b) Bilinear Restrained frame r_{vz} (No P-Δ effects included in analyses)

Attention is now given to the differentiation between restrained and unrestrained buildings (i.e. type (a) or (b)). In the case of the restrained buildings, both column and beam hysteretic action is developed in the global Z-direction frames due to the diaphragm rotations, whereas the unrestrained buildings only exhibit column hysteresis. With the presence of axial loads (both gravity and seismic) in the columns the hysteretic loops will tend to be narrower or smaller. In the case of reinforced concrete inelastic behaviour (represented by a Modified Takeda hysteresis rule) the unloading stiffness will be significantly reduced leading to narrower loops that have an inherent re-centring ability.

Considering columns 1, 4, 6 and 9 (at the ends of the X-axis in the resisting frames) it is evident that the unrestrained systems only develop out-of-plane hysteretic action in the columns, as there are no resisting beams present. These systems can exhibit lower residual deformations or re-centre to a greater extent than the restrained counterparts, even though the unrestrained maximum rotations are clearly larger.

The implication of these observations is that while higher maximum diaphragm rotations are typically expected from torsionally unrestrained and asymmetric buildings, residual deformations might not follow the same amplification trend. From the results presented here it is suggested that for non-perimeter frame (or wall) systems the residual/maximum rotation ratio for unrestrained structures tends to be lower than that for the restrained systems. It is possible that such systems can in fact produce lower residual/maximum plan rotations due to the interaction of low amplitude diaphragm rotation cycles and degrading column stiffness response (in the case of Takeda hysteresis), as well as the lack of beam hysteresis which generally produces greater residual deformations.

Figure 4 shows the average Res/Max results as a function of mass eccentricity and restraint for RC frame behaviour. Clearly the Res/Max ratio results are significantly lower than those seen for EP systems in Figure 3 and for most levels of eccentricity these average values could be neglected, although the scatter as shown in Figure 5a suggests this may be not be satisfactory. It is interesting to note the difference in curve shapes between Figure 4 and Figure 3, with the TK results tending to grow as eccentricity increases, whereas the EP curves exhibit more of a plateau with increasing eccentricity.

A more significant consideration comes from the comparative response between systems with decreasing levels of torsional restraint. As the separation between restraining elements decreases (i.e. lowering the level of torsional restraint or radius of gyration of strength) the displacement demands on the seismic resisting members due to twist are reduced, therefore the resisting elements have lower inelastic demands. Thus, while the extreme corner maximum displacements are amplified by the twist during the excitation, the structural members (now situated closer to the GC of the building) are not subjected to high ductility levels, therefore the final diaphragm rotation is reduced as these control the residual response. Hence even though a system with lower restraint will undergo greater maximum rotational response, the residual response will not necessarily maintain the same proportionality with the increased maximum.

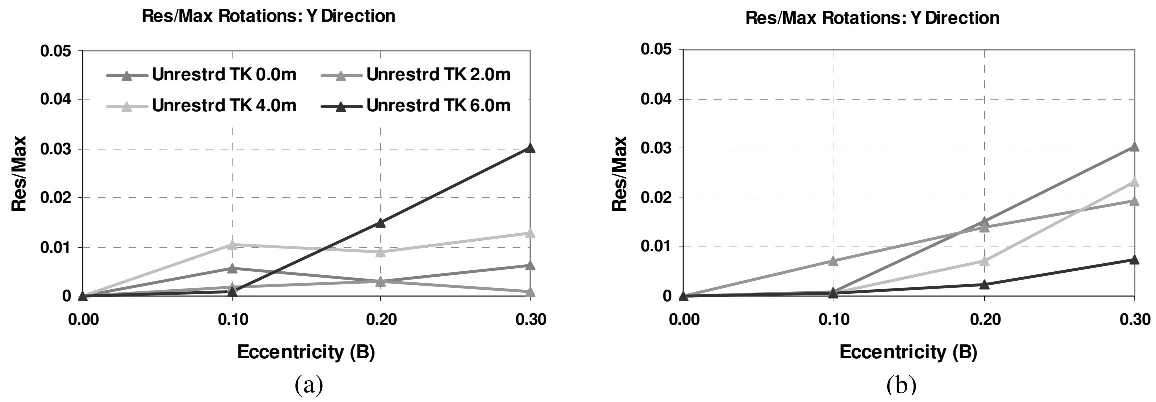


Figure 4. Results indicating the effect of variations in radii of gyration of strength (a) Modified Takeda Unrestrained frame r_{vx} (b) Modified Takeda Restrained frame r_{vz} (No P-Δ effects included in analyses)

4.2 Explicit Design for Residual Deformations due to Torsional Response

While the designs used in this investigation were developed using DDBD (Priestley & Kowalsky 2000), the form of any proposed method for estimating residual deformations due to torsion must be compatible with both DBD and FBD approaches. The explicit residual deformation design procedure proposed by Christopoulos et al. (2004a & b) fulfils this requirement by utilising either elastic or equivalent periods for the translational residual/maximum spectra.

It is tentatively proposed here that the complete equation describing the residual deformation (*RD*) would take the following general form for single-storey structures:

$$RD_{SDOF} \cdot f_{P-\Delta} + \Gamma \cdot RD_{Torsion} \cdot f'_{P-\Delta} = RD_{Total} \quad (1)$$

which can be further defined as:

$$\theta_{SDOF,Max} \cdot \left(\mathrm{Res}/_{Max} \right)_{2D} \cdot f_{P-\Delta} + \Gamma \cdot \varphi_{Tors,Max} \cdot \left(\mathrm{Res}/_{Max} \right)_{3D} \cdot \psi \cdot f'_{P-\Delta} = RD_{Total} \quad (2)$$

where the first component of the design equation represents the residual drift due to translational response as defined in previous studies (Christopoulos et al. 2003, Pampanin et al. 2003, Christopoulos et al. 2004a & b), while the second part defines the additional residual drift due to diaphragm rotations. The reader is referred to the previous studies for further information on the complete design procedure. In this equation $\varphi_{Tors,Max}$ is the expected maximum diaphragm rotation determined by some means (for example Sommer & Bachmann 2005 or Trombetti et al. 2002), which must also indicate whether inelastic torsional response occurs, something which available methods do not currently achieve. ψ is a geometric ratio (in-plan distance from the CM/inter-storey height) that converts the diaphragm rotation to lateral drift at the element in the structure under consideration. To account for the varying level of concurrency between the observed maximum translational and rotational responses (a phenomenon that is highly dependent on the type of system considered), a "Phase Coupling Coefficient" Γ, is introduced. It should be noted that the two P-Δ amplification terms $f_{P-\Delta}$ and $f_{P-\Delta}'$ are defined separately for translation and rotation respectively.

As has been shown above, the value of the Res/Max ratio for diaphragm rotation is effectively dependent on the level of torsional restraint provided. The ratio of pure rotational circular frequency (ω_θ) to pure translational circular frequency (ω_L) provides a simple and efficient way of quantifying the torsional restraint in a dynamic sense. This ratio is defined as γ by Trombetti et al. (2002).

$$\gamma = \frac{\omega_\theta}{\omega_L} \quad (3)$$

By plotting the individual column results, shown as averages in Figure 3 and Figure 4, against the corresponding value of γ for each system (Figure 5) it can be seen that, in torsional systems with $1.0 \leq \gamma \leq 1.25$, the residual/maximum rotation ratios reach a peak, at which point restrained and unrestrained systems have similar results.

If the plots in Figure 5 are termed "Residual/Maximum Rotation Spectra" it is possible to enter the appropriate chart with a calculated value of γ and retrieve the design value of rotational Res/Max, using an appropriately fitted design curve (as suggested by the smoothed mean + 1 standard deviation curve in Figure 5). With this ratio defined, and the maximum rotational response also calculated, the total residual deformation (storey drift) can be found from Equation 2 and compared with the target residual drift (Christopoulos et al. 2004).

In applying Equation 2 consideration should be given to whether it is applicable to augment the residual deformation on one or both sides of the structure (taken to be either side of the CM). This decision will depend on whether the building is expected to develop inelastic action on both sides under coupled response. Force-based design methods would suggest that buildings will generally achieve ductile response in all resisting elements due to the generally high values of design ductility allowed in current design codes. Under displacement-based approaches it has been shown (Pettinga & Priestley 2005) that drift limits will often dictate the maximum allowable ductility developed under a design earthquake. Therefore it is possible that in many cases the design system ductility μ_Δ will be between 2 and 3. In the study by Peruš and Fajfar (2005) it was demonstrated that maximum rotational response will occur when one side of a structure remains within or close to its linear-elastic limit as this induces a significant shift of the centre of stiffness (or rotation) therefore increasing the eccentric distance from the centre of mass.

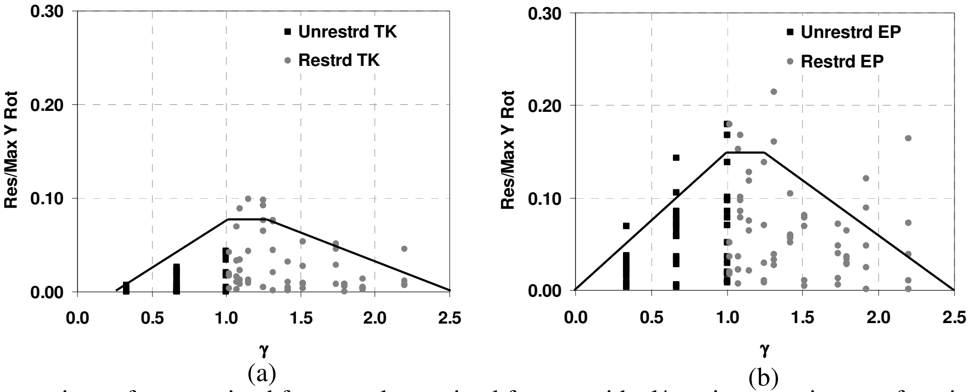


Figure 5. Comparison of unrestrained frame and restrained frame residual/maximum ratios as a function of $\gamma = \omega_\theta/\omega_L$: (a) Takeda hysteresis (b) Bilinear hysteresis.

Thus if the system ductility is limited to low values as suggested above it is expected that elements on one side of the structure may not yield or would not be negatively influenced by the coupled response, while those on the first-yielding side could suffer further inelastic cycles (however not necessarily greater displacements) due the significant rotations induced. It is assumed here that the increased number of inelastic cycles (rather than simply increased maximum ductility achieved) can be more significant in terms of residual drifts.

5 CONCLUSIONS

The preliminary results from an ongoing investigation into the residual deformation response of 3-D structures are presented. The comparative effects of varying torsional restraint in simple prototype mass eccentric frame systems have been highlighted. It has been shown that residual diaphragm rotations can be reduced for systems with a lowered level of torsional restraint due to the reduced demand induced in the resisting elements under coupled response. Further to this the position of potential plastic hinge zones can also play a role in determining the level of residual deformation, with beam plastic hinging tending to exhibit larger hysteretic loops that dominate the system residual deformation behaviour.

Based on these preliminary results and further parametric studies (not included here) a general design approach is suggested that can be included within the explicit design procedure already presented in earlier work. Principally this 3-D component utilises an estimation of the maximum system rotation and a value of residual/maximum rotation determined from a "Residual/Maximum Rotation Spectrum". This value of Res/Max rotation is found as a function of γ, the ratio of elastic fictional pure rotational frequency to pure translational frequency. In a similar manner to the determination of translational residual drift, the additional drift due to P-Δ effects is accounted for by including a scaling factor that amplifies the basic value of residual drift.

Finally an important point is highlighted regarding the development of inelastic action in parallel resisting elements in an asymmetric structure. It is noted that for buildings in which maximum allowable drift demand controls the ductility to be developed, certain systems may not exhibit inelastic action in all elements either side of the centre-of-mass, giving potential for a significant shift of the centre-of-stiffness that can lead to increases in the system eccentricity, and thus diaphragm rotations.

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