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Recentering requirements for the seismic design of self-centering systems

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ABSTRACT: To achieve the full benefits of a self-centering seismic resilient system, the designer must ensure that the entire structure does indeed self-center following an earthquake. An idealised flag-shaped cyclic hysteresis response is typically used to define the residual drift behaviour of a self-centering member. However, such an idealised cyclic hysteresis response seldom exists and the residual drift of a building subjected to an earthquake is dependent on the actual shape of the cyclic hysteresis response as well as the dynamic loading. To accurately capture the cyclic hysteresis response, the design must consider the inelastic strain in the compression toe of the member and the resulting stiffness degradation of the hysteresis loops.

This paper summarises the current methods that are used to ensure that a self-centering response is achieved during the design of seismic resilient structures. A simple lumped plasticity model was used to demonstrate the inaccuracies of these current procedures and highlight the need to accurately capture the structures dynamic hysteresis response. Additionally, the results were presented for time-history analysis that was performed to investigate the expected residual drift of an example self-centering concrete wall system during an earthquake. Time-history analyses indicated that due to dynamic shake-down the final residual drifts were less than 35% of the maximum possible residual drifts that were observed from the cyclic hysteresis response.

1 INTRODUCTION

The main objective when designing seismic resilient building systems is to safely dissipate the energy imparted to a structure during an earthquake, with minimal structural damage. Given the difficulty in straightening a building which is left with a significant residual drift following an earthquake, self-centering behaviour is a critical aspect of seismic resilient design. Since their inception during the PRESSS research program (Priestley 1991), self-centering structural components that utilise unbonded post-tensioning have been developed using concrete, steel and timber members (Priestley et al. 1999; Christopoulos et al. 2002; Newcombe et al. 2008). The behaviour of self-centering structures is typically characterised by a flag-shaped hysteresis response. However, when a flag-shaped cyclic hysteresis response is used to define the self-centering behaviour of post-tensioned (PT) structure, three major factors are ignored. First, in reality the response of a member with unbonded PT does not follow a perfect bilinear-elastic hysteresis rule, and so an imperfect flag-shape is often observed. Second, the influence that other structural and non-structural elements have on the hysteresis response is ignored. Third, investigation of the cyclic hysteresis response does not account for the dynamic shake-down that occurs following the structure experiencing the peak lateral displacement. This paper summarises the current self-centering design procedures and demonstrates what additional factors must be considered to obtain a realistic estimate of the residual displacement for a structure subjected to an earthquake loading.

2 BACKGROUND

2.1 *Static Self-centering*

The response of a self-centering system is typically characterised by a flag-shaped hysteresis loop. For a member with unbonded PT, the hysteresis response is typically assumed to be bi-linear elastic, with zero residual displacement. The combination of the bi-linear elastic response and the elasto-plastic response of the energy dissipating components results in the idealised flag-shape response, as shown in Figure 1.

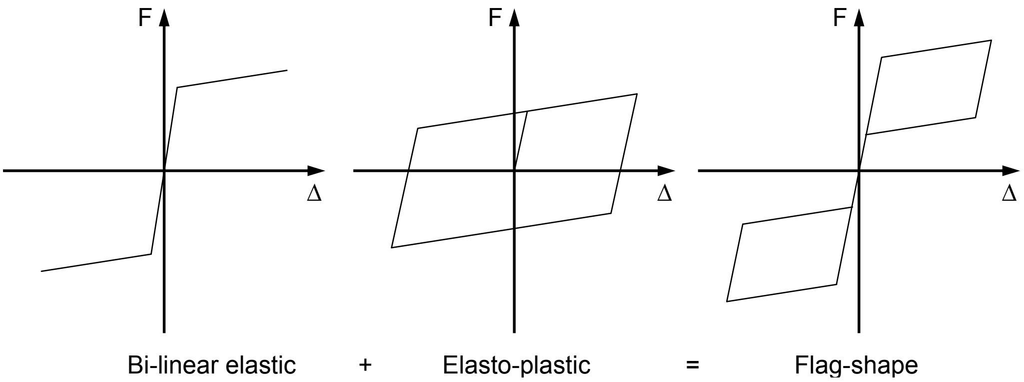


Figure 1 – Idealised flag-shape hysteresis response typically assumed for self-centering systems

Based on the ideal flag-shape shown in Figure 1, the common perception during the PRESSS program and subsequent studies was that self-centering would be achieved if the moment provided by the energy dissipating elements was less than the moment provided by the PT (Stanton et al. 1997). This concept is referred to as “static self-centering”, were the hysteresis response is assumed to return to zero displacement when the lateral load is slowly released to zero.

The bi-linear elastic hysteresis assumption may be valid for steel and timber members, but it is seldom achieved for PT concrete members. Cyclic tests on both unbonded PT concrete frames (Palmieri et al. 1997) and concrete walls (Perez et al. 2003) have indicated that the response of the PT concrete member included noticeable stiffness degradation and cyclic hysteresis area. This imperfect bi-linear elastic hysteresis response, which is caused by inelastic strains in the compression toe of the concrete member, significantly increases the residual drift observed in the cyclic hysteresis response. This deviation from the idealised behaviour was further highlighted during tests of self-centering concrete systems (Stanton et al. 1997; Priestley et al. 1999; Restrepo and Rahman 2007; Sritharan et al. 2008).

In addition to using an idealised flag shape response for the self centering system, its interaction with other structural and/or non-structural elements in the system is not given any consideration. It has been shown that the inclusion of additional structural and non-structural elements, such as the wall-to-floor interaction, will drastically alter the system’s hysteresis behaviour, with an increase in strength, energy dissipation and residual drift (Henry et al. 2009). Therefore, even if the main lateral load resisting structure has the self-centering ability, the entire structure may not recenter.

2.2 *Current Design Procedures*

Despite the experimentally observed behaviour of PT concrete members, current design procedures that are used to ensure that self-centering is achieved are predominantly based upon the ideal flag-shaped hysteresis response. As a result of the PRESSS research program, ACI design guidelines for self-centering concrete frames included the expression shown in Eq. 1, which states that the moment contribution from energy-dissipating reinforcement, M_s, must equate to less than 50% of the probable flexural strength of the member, M_{pr}. In accordance with capacity design procedures, the New Zealand concrete design standard adopted a similar expression that also included the overstrength factor of the energy dissipating components. The equation included in Appendix B of NZS 3101:2006 is shown in Eq. 2, where the moment contribution ratio, λ, must be greater than the overstrength factor of the energy dissipating components, α_o. In New Zealand, the overstrength factor for mild steel is typically 1.15 or greater (NZS 3101:2006), which implies that the moment contribution from the energy dissipating components should be less than 46% of the total flexural strength. The design guidelines for self-centering concrete systems published by the New Zealand Concrete Society (Pampanin et al. 2010) also includes Eq. 2, but it is further recommended that the moment provided by the energy dissipating components should not exceed 40% of the total moment resistance.

$$\frac{M_s}{M_{pr}} \leq 0.5 \tag{1}$$

$$\lambda = \frac{M_{pt} + M_N}{M_s} \geq \alpha_o \tag{2}$$

where M_{pt} is the moment provided by the unbonded PT and M_N is the moment provided by additional axial load (including self-weight).

The ACI Innovation Task Group 5 (ITG-5) that established the code requirements for the development and design of unbonded post-tensioned concrete walls did not include a specific procedure to ensure that self-centering was achieved. However, ITG-5.1 (ACI Innovation *Task* Group 5 2007) states that studies by Kurama (Kurama 2002) indicated that the self-centering capability following a major earthquake may be lost if more than 40% of the flexural capacity was provided by energy dissipating mild steel.

Both Eqns. 1 and 2 are intended to be calculated at the design lateral drift, or ultimate moment resistance, which is not sufficient to ensure static self-centering of the cyclic hysteresis loops, as demonstrated later in Section 3. Additionally, Eqns. 1 and 2 do not account for the realistic cyclic hysteresis behaviour, or the dynamic response, when considering the self-centering capability of a structure during an earthquake.

2.3 *Dynamic Self-centering*

A residual displacement observed from a cyclic hysteresis loop does not necessarily guarantee poor building performance. This is because the residual drift of a structure subjected to an earthquake depends on the peak drift that the structure experiences as well as its dynamic response during the remainder of the earthquake duration and the free vibration phase following the earthquake excitation. This post-peak behaviour, referred to as the “shake-down” phenomenon (Macrae and Kawashima 1997), is illustrated in Figure 2. As a result, the residual drift at the end of dynamic response, d_r, will typically be less than the maximum residual drift immediately following the peak lateral drift, $d_{r,\,max}$.

After recognising that the residual drift of a structure was a function of the hysteresis behaviour and the earthquake ground motion, MacRae and Kawashima (1997) conducted a series of dynamic analyses to investigate the behaviour of single-degree-of-freedom oscillators. MacRae and Kawashima found that even for oscillators with elasto-plastic hysteresis rules, significant reduction in the residual displacement was observed due to the shake-down effect. The residual displacement at the end of the ground motion was normalised by the maximum possible residual displacement to define the “residual displacement ratio”, or d_{rr}.

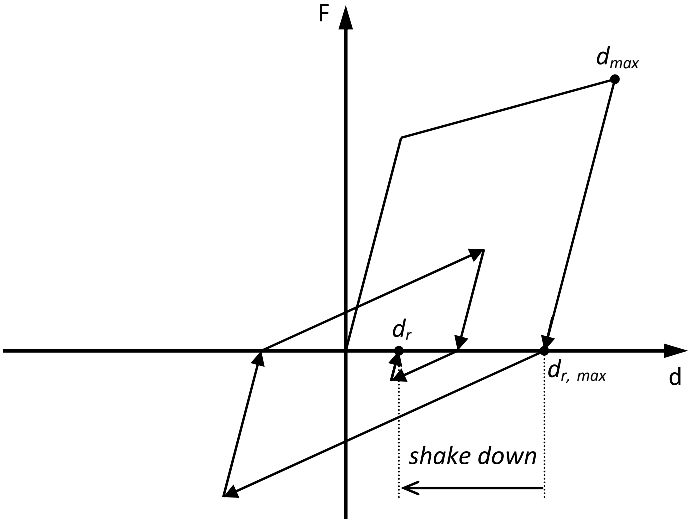


Figure 2 – An illustration of dynamic shake-down behaviour expected for seismic load resisting systems

3 STATIC ANALYSIS OF FLAG-SHAPE RESPONSE

Although self-centering members exhibit a response that appears flag-shaped, the idealised flag-shape representation shown in Figure 1 does not typically exist for two reasons. First, the responses of the PT member and energy dissipating components cannot be simply added together because energy dissipating elements are only engaged after decompression occurs at the tension toe and uplift occurs at the joint. Second, an imperfect flag-shape is achieved when realistic hysteresis responses are used for both the PT member and the energy dissipating elements. This section investigates the flag-shaped hysteresis response of a more realistic self-centering wall model. The inaccuracy of the current procedures for ensuring self-centering is demonstrated, even when the residual drift caused by non-linear member deformations and the dynamic shake-down effects were ignored.

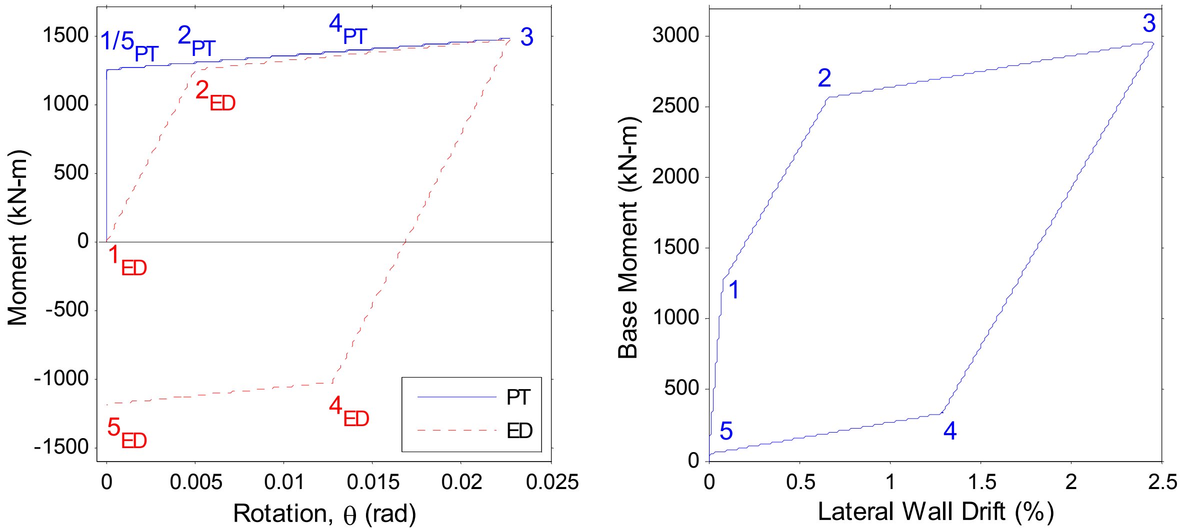
3.1 *Lumped Plasticity Model*

A realistic representation of the response of a self-centering structural member can be achieved using a lumped plasticity model, such as the two-spring model that was used by Palermo et al. (2007) to analyse the response of self-centering bridge piers. The structural member (wall, column, or beam) can be represented by an elastic beam member, with the non-linear behaviour lumped into two rotational springs at the base of the member. The two rotational springs represent the base moment-rotation behaviour of the PT member and energy dissipating components, respectively. The moment-rotation response at the base of a PT member is idealised as non-linear elastic, with a high initial stiffness and non-linear behaviour initiating when the wall begins to uplift. The energy dissipating components are idealised using an elasto-plastic moment-rotation response.

3.2 *Ruaumoko Analysis*

To analyse the flag-shaped hysteresis behaviour, a two-spring lumped plasticity model was constructed using the non-linear structural analysis program Ruaumoko. The model properties were approximately defined to match a self-centering concrete wall test specimen known as PreWEC (Sritharan et al. 2008), and the top of the beam member was then subjected to a single lateral displacement cycle to 2.5% drift.

The first analysis was conducted using idealised hysteresis models for the rotational springs, including a bi-linear elastic definition for the PT spring and a bi-linear elasto-plastic definition for the energy dissipation (ED) spring. As shown in Figure 3a, both rotational springs had equal yield moments of 1250 kN-m and ultimate moments of 1500 kN-m (corresponding to approximately 2.5% lateral wall drift). The moment-drift response of the model, shown in Figure 3b, indicated that the flag-shaped response consisted of five distinct segments. When compared to the idealised flag-shape that was shown in Figure 1, the initial stiffness consisted of two segments. Initially, the stiffness of the system is controlled by the elastic response of the wall, but once decompression occurs at the wall toe and the PT spring becomes non-linear (point 1 in Figure 3), the stiffness is also influenced by the second slope of the PT spring and the initial stiffness of the energy dissipating spring. Upon unloading, the hysteresis response returned to the origin with zero residual drift. Using current self-centering procedures described previously, a zero residual drift would be expected because the moment attributed to the energy dissipating components did not exceed the moment attributed to the PT.

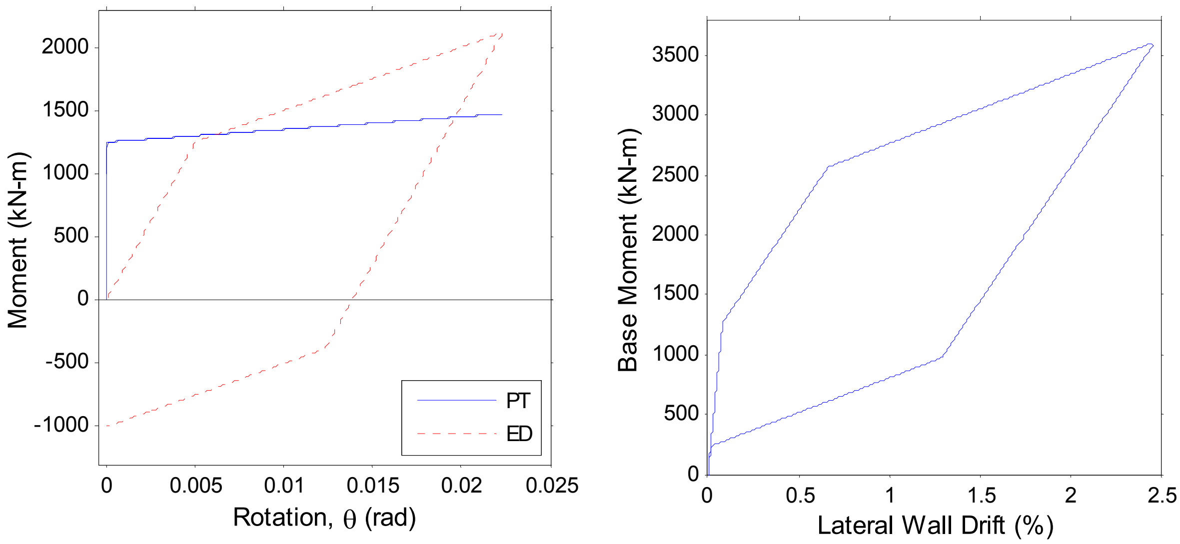


(a) Rotational spring definitions (b) Total system hysteresis response

Figure 3 – Two spring lumped plasticity model with idealised hysteresis and equal moment resistance

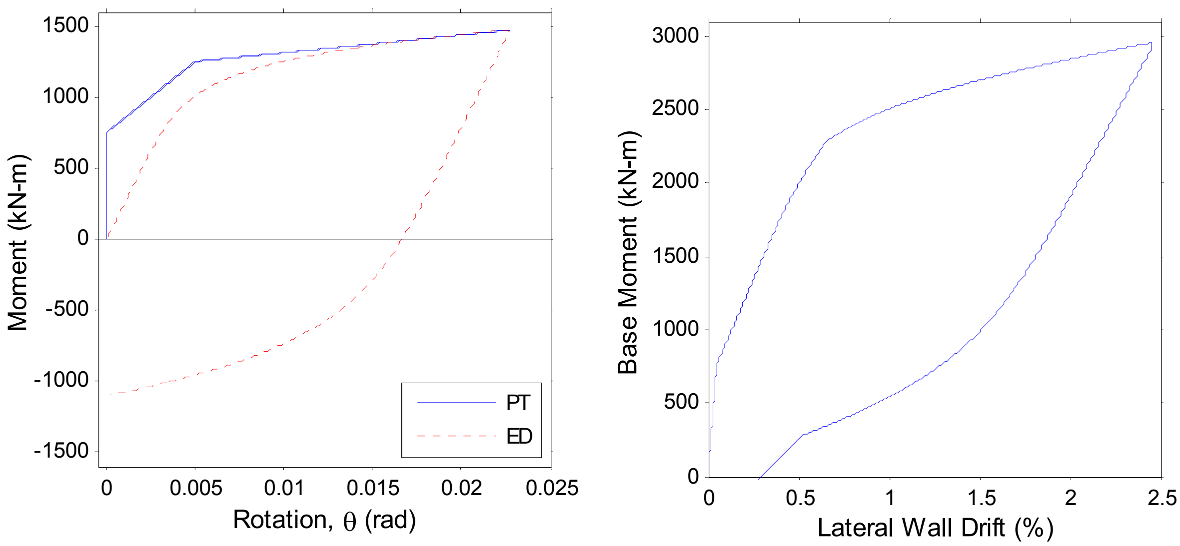
For the second analysis, the post-yield stiffness of the ED spring was increased, so that the ultimate moment of the ED spring exceeded that of the PT spring, as shown in Figure 4a. Interestingly, as observed from Figure 4b, the resulting moment-drift hysteresis response of the system exhibited perfect self-centering with zero residual drift after unloading. This observation demonstrated that the traditional criterion that was used to ensure self-centering occurred was inaccurate and ambiguous, as perfect static self-centering was achieved even when the energy dissipating components provided more than 50% of the total moment. Although there is some correctness to the 50% ED moment criteria, the point at which this calculation is performed during the response is critical. The proportion of the moment provided by the energy dissipating components at the maximum lateral drift is not relevant, and instead the moment balance calculation should be performed when the member is unloaded to zero displacement.

For realistic self-centering members, the hysteresis definitions of the PT and ED rotational springs do not perfectly follow the bi-linear elastic and bi-linear elasto-plastic rules. The response of an undamaged PT member can be more accurately approximated using a tri-linear elastic hysteresis (ignoring the wall hysteresis energy dissipation) and the energy dissipating components typically display a smoother elasto-plastic hysteresis response. For the third analysis, a tri-linear elastic definition was used for the PT spring and a Ramberg-Osgood definition was used for the ED spring, as shown in Figure 5a, and the yield moments and ultimate moments of the PT and ED springs were approximately equal. As shown in Figure 5b, the resulting hysteresis response deviated from the ideal flag-shape behaviour, with a more realistic smooth form. Although the moment provided by the energy dissipating components did not exceed the moment provided by the PT, perfect self-centering was not achieved and a small residual drift was observed. Again, this analysis highlighted that the PT and ED moment contributions to the self-centering feature are only critical when the member is unloaded to zero displacement. In this case, the unloaded moment in the ED spring of -1100 kN-m exceeded the 750 kN-m yield moment of the PT spring and thus perfect static self-centering was not achieved.



(a) Rotational spring definitions (b) Total system hysteresis response

Figure 4 – Two spring lumped plasticity model with idealised hysteresis and unbalanced moment resistance



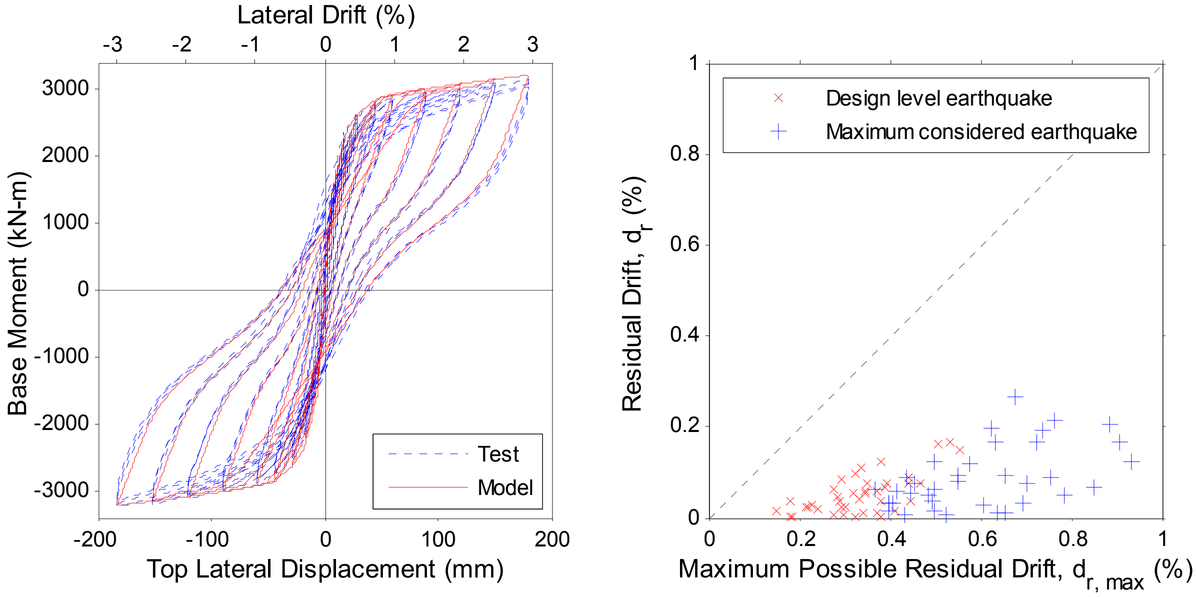
(a) Rotational spring definitions (b) Total system hysteresis response

Figure 5 – Two spring lumped plasticity model with realistic hysteresis and equal moment resistance

4 TIME-HISTORY ANALYSIS

To accurately assess the residual drifts that would be expected for a self-centering system during an earthquake, both the realistic cyclic hysteresis response and the dynamic shake-down need to be considered. A recent study was conducted to assess the self-centering behaviour of a PreWEC system (Henry 2011). A parametric study was conducted using a lumped plasticity model that represented the cyclic hysteresis behaviour observed during the experimental test and a range of fundamental periods, earthquake ground motions, and earthquake intensities. The model used a combination of rotational springs to accurately capture the imperfect flag-shaped hysteresis response and static residual drift that was observed for the PreWEC test specimen, as shown in Figure 6a.

As shown in Figure 6b, it was found that the dynamic shake down reduced the residual drifts to less than 35% of the maximum possible residual drift observed from the cyclic hysteresis loops. The residual drifts at the end of the analysis were less than 0.2% for the design level intensity earthquake and less than 0.25% for the maximum considered earthquake intensity. These residual drifts were considered to be within acceptable limits for realistic self-centering structures, and would result in only minor cosmetic repairs following a major earthquake.



(a) Cyclic hysteresis response for the test and model

(b) Residual drift results

Figure 6 – Time-history analysis of lumped mass models with PreWEC hysteresis response

5 CONCLUSIONS

Self-centering systems that utilise unbonded PT can be used to construct seismic resilient structures. This paper investigates how self-centering is defined during the design of such structures and what factors influence the ability of a real structure to self-center following an earthquake.

Current procedures that are used to ensure that self-centering would occur are based on an ideal flag-shaped cyclic hysteresis response, ignoring the realistic cyclic hysteresis of the PT member, the additional cyclic hysteresis due to other elements, and the dynamic response.

Using a two-spring lumped plasticity model, a series of simple analyses showed that prefect self-centering could still be observed from the cyclic load response even when the energy dissipating elements contribute to over 50% of the total moment resistance. Additionally, the analysis showed that even when the PT wall response followed a multi-linear elastic response, a small residual drift can occur when the moment contributions from the PT and energy dissipating elements are balanced.

For PT concrete members, the hysteresis response does not follow the idealised non-linear elastic hysteresis response. Inelastic strains in the compression toe of a PT concrete member will cause the response to deviate from a non-linear elastic hysteresis behaviour and increase the residual drifts that are observed from the cyclic hysteresis response.

Time-history showed that that a PT concrete wall system with significant residual drift observed in the cyclic hysteresis response can still self-center with negligible residual drift following an earthquake due to dynamic shake-down.

To ensure a seismic resilient structure is achieved, design procedures need to be revised to account for the realistic behaviour of the self-centering structure and check that the maximum residual drifts following an earthquake are below acceptable limits.

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