EXPERIMENTAL INVESTIGATION INTO RESIDUAL DISPLACEMENTS DUE TO INELASTIC TORSIONAL RESPONSE

Didier Pettinga[1], Stefano Pampanin[2], Constantin Christopoulos[3], Athol Carr[2] and Rolando Castillo[4]

1. Glotman Simpson Consulting Engineers, 1661 West 5th Avenue, Vancouver, (BC) V6J 1N5, Canada.
2. Department of Civil Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
3. Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, (ON) M5S 1A4, Canada
4. Department of Civil Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand (formerly)

Recent numerical studies into the residual deformation response of structures with in-plan asymmetry have shown that in some cases, such irregularities can lead to significantly different behaviour from equivalent symmetric, or 2-dimensional in-plane structures. In order to verify these findings, a series of dynamic shake-table tests using a simple 3-dimensional frame model capable of exhibiting stiffness, strength or mass eccentricity have been carried out.

A summary of the test setup and procedure is provided here, along with some selected results that highlight important aspects of the observed behaviour. The experimental findings demonstrate that residual deformations can be larger on one side of a structure due to the effects of torsional response. However it is seen that the side exhibiting the larger maximum transient displacement, may not necessarily have a correspondingly larger permanent displacement. Finally, as a reference to mitigating permanent deformations through explicit design measures, results are presented for tests using materials with different amounts of strain-hardening and therefore exhibiting different system post-yield stiffness. The experimental results demonstrate that increasing the post-yield stiffness ratio reduces residual drifts in the model structure.

KEYWORDS: Shake-table experiment, inelastic torsion, residual displacements, residual mitigation, performance-based design

1. INTRODUCTION

Experimental studies are an integral part of earthquake engineering research, yet there is a noticeable lack of experimental investigation into the response of in-plan asymmetric structures subject to earthquake-type ground motion. While the reasons for this apparent knowledge gap vary, it can largely be attributed to the difficulty of developing satisfactory scale models for shake-table use, especially given that such tests would ideally be repeatable, or the models reconfigurable, to allow a range of asymmetric conditions to be tested.

A model capable of meeting the above testing criteria was developed by Castillo [2004] for use on the uni-directional shake-table in the Structures Laboratory at the University of Canterbury. This model was designed and constructed based on a symmetrical four-storey model first developed by Kao [1998]. The model structure designed by Castillo is a simple one-storey 3D dis-mountable model that allows for the repetition of tests, and in doing so, gives the flexibility to introduce stiffness, strength or mass eccentric in-plan conditions. The model structure is also reconfigurable such that both torsionally unrestrained and restrained setups, according to the definitions of Paulay [1998] can be tested.

This paper addresses the residual drift response of the shake-table model structure with symmetric and asymmetric in-plan conditions. The investigation draws on the numerical investigations of single-degree-of-freedom and simple in-plane structures [MacRae and Kawashima, 1997; Borzi et al., 2001; Christopoulos and

Pampanin, 2004; Ruiz-Garcia and Miranda, 2006], and of single-mass three-dimensional systems [Pettinga et al., 2007a]. These investigations highlighted the influences on permanent deformation behaviour, and proposed design and assessment frameworks within which this additional level of performance could be explicitly considered. Of the various influences, it has been demonstrated that the post-yield stiffness ratio (i.e. post-yield stiffness to initial stiffness ratio) plays a very significant role in controlling the magnitude of the residual deformation in a structure. Christopoulos and Pampanin [2004] proposed an approach to explicitly consider permanent deformations in a performance-based design. Following the findings of Pettinga et al. [2007], an example result demonstrating the reduction of permanent drifts by increasing the material strain-hardening is included within this contribution.

2. SHAKE-TABLE MODEL STRUCTURE SUMMARY

The model structure is a single-mass system that does not represent any particular prototype structure due to the shake-table capacity limitations [Ang, 1985]. The primary ductile lateral-resisting elements in the direction of ground motion were pin-based moment-resisting frames. In the transverse direction either an elastic fixed-base column (located at the centre of the structure) or ductile transverse pair of pin-based frames could be used, thus providing the torsionally unrestrained or restrained configurations respectively. Figure 1 and Figure 2 shows the model in the torsionally restrained configuration. Further details can be found in Castillo [2004] and Pettinga et al. [2007a].

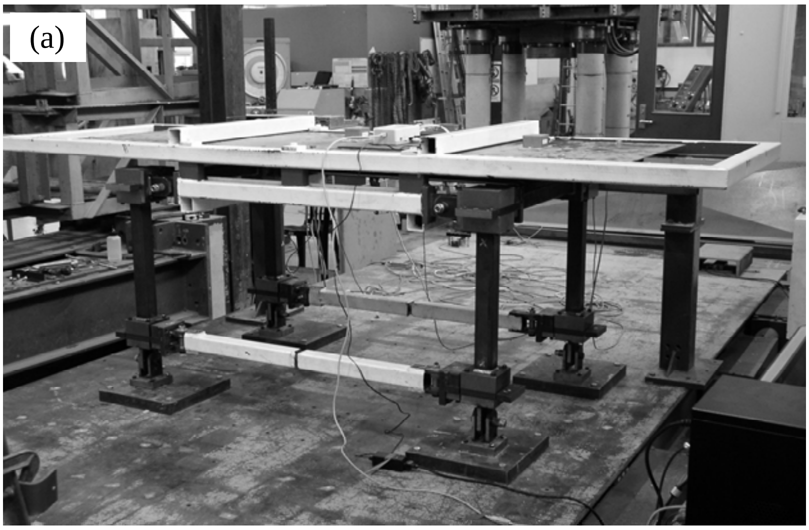

Figure 1. Photo of the mounted shake-table model structure in the torsionally restrained configuration.

The principal innovative feature developed by Kao [1998], and employed for this single storey model, is the use of replaceable beam-column connections that provide a defined plastic-hinge region at the end of the beams, also referred to as a fuse. The replaceable plastic-hinges were made of 20mm thick mild-steel plates (fuse-plates) that could be milled to a specified section size over a 5mm deformable length. This provided a set length within which the lateral deformations, both elastic and inelastic, were effectively concentrated thus providing a nearly perfect plastic-hinge.

The beams, columns and diaphragm frame consisted of 50x50x3 mm square hollow sections (SHS). Within the depth of the diaphragm frame five lead ingots could be installed. These ingots were connected together by a topping plate, thus creating a rigid-diaphragm condition. These individual masses could be shifted along the diaphragm X-axis to introduce mass eccentricity from the geometric-centre. The total weight of the five ingots was 1.73 kN, while the weight of the structural frame was 2.05 kN.

For brevity, only the torsionally restrained model structure is discussed here. Transverse (to the uni-directional shake-table excitation) moment-resisting frames are included along gridlines A and B (Figure 2) to provide the torsional restraint. These beams acted in the same fashion as those along gridlines 1 and 2, using replaceable plastic-hinge plates. The low position of the beams did not alter the behaviour of the transverse mechanism, and was simply used for ease of construction and fabrication of the fuse-plates.

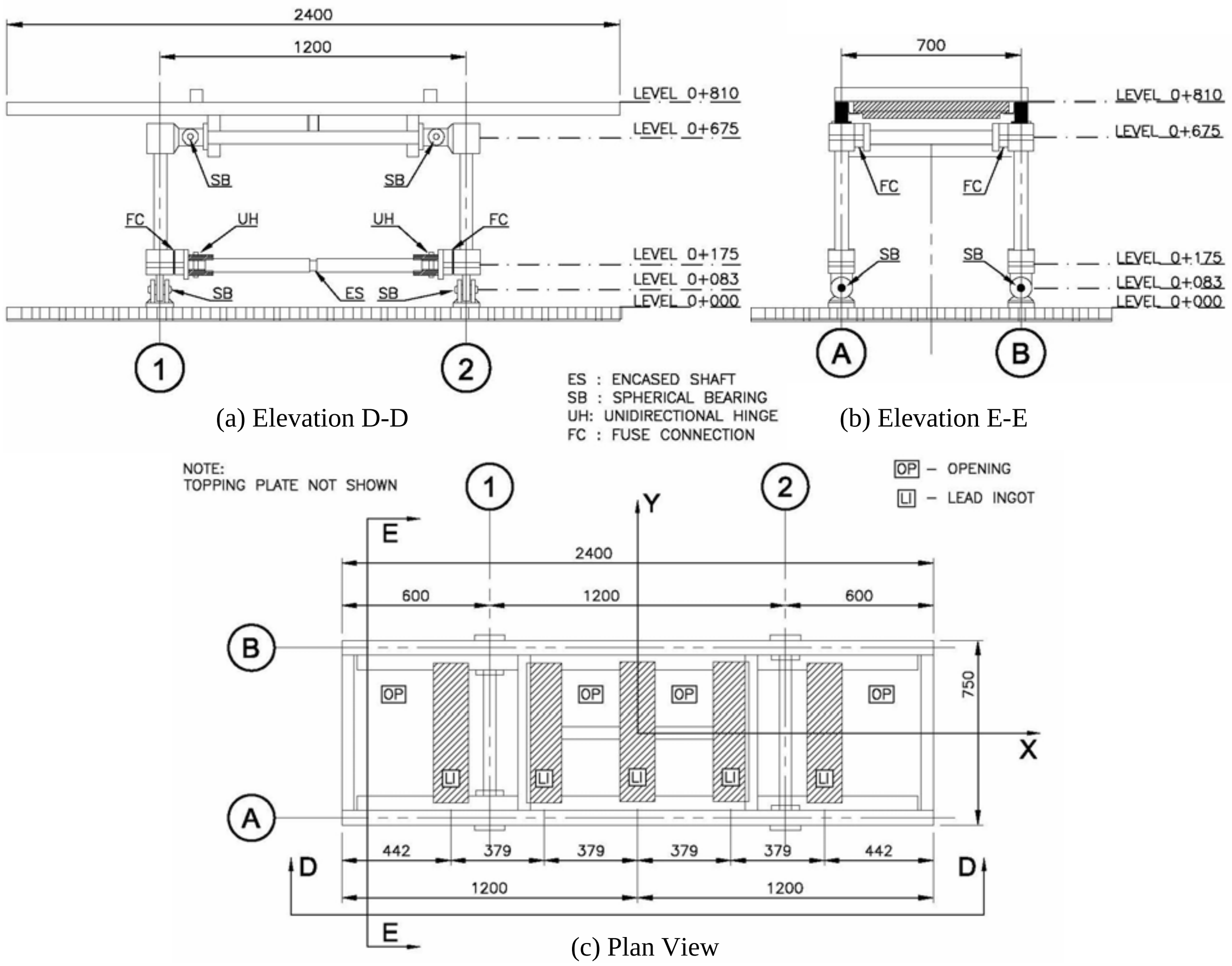

Figure 2. Torsionally restrained model (from Castillo [2004])

The steel connection blocks (Figure 3) limited rigid-block type movement of the replaceable fuse-plates. However there still exists a certain level of strain-penetration that develops within the plates beyond the milled fuse length. Castillo [2004] gives a comprehensive review of the moment-rotation relations of the fuses required for determining the appropriate modelling parameters both at a fuse-section and structural system level.

2.1 Model Design and Test Setup

A modified Direct Displacement-Based Design procedure [Priestley et al., 2007] was used for the test design. Full details of the designs used for the test series are given by Castillo [2004] and Pettinga et al. [2007a]. Stiffness and strength, or stiffness irregular configurations were tested, with eccentricities ranging from five to ten percent of the diaphragm width, following the experimental program of Castillo [2004]. Diagrams of the test models and a summary of the model structure asymmetric conditions are provided in Figure 4(a to c). The accelerogram used for the shake-table input was the 010 component recorded at Llolleo from the 3rd March 1985 Valparaiso earthquake in Chile. The record was compressed to half the time length in order to meet the shake-table stroke capacity. This resulted in a peak table acceleration of 0.66g and associated maximum displacement of 26 mm.

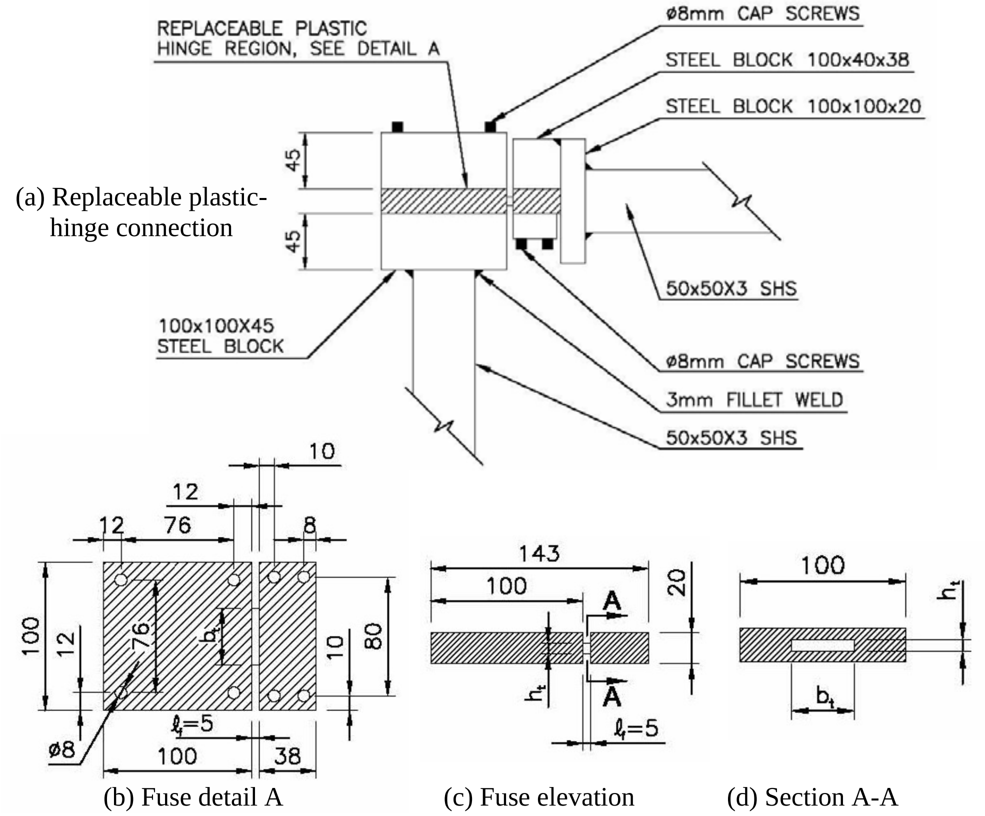

Figure 3. Beam-column connection details (from Castillo [2004])

Displacements, accelerations and rotations were measured during the dynamic shake-table tests. A plan-view of the instrumentation layout is given in Figure 4(d). This shows the location of the three potentiometers, three accelerometers and fibre-optic gyroscope relative to the model frame and diaphragm.

3. ASYMMETRIC MODEL RESULTS AND MITIGATION OF RESIDUAL DRIFTS

Recent research (Kiggins and Uang, 2006; Pettinga et al., 2007b) has demonstrated that significant reductions in residual storey drifts can be achieved through the use of simple allowances and changes to typically used construction, both for reinforced concrete and structural steel.

The principal aim of these simple approaches was to increase the post-yield stiffness ratio (i.e. post-yield stiffness to initial stiffness) which has been shown to be the most significant parameter affecting permanent deformations when not using self-centring systems. One such approach to achieving a higher post-yield stiffness ratio looked at using materials with a higher level of strain-hardening which implies a higher post-yield stiffness. This option was tested experimentally using the shake-table model structure.

3.1 Change in Steel Properties of the Plastic-hinge

It was found that the mild-steel used for the fuse-plates in the tests presented by Pettinga et al. [2007a] had significantly greater strain-hardening compared to the mild-steel used by Castillo [2004]. It is also noted that yield stress differed by 26%, however the residual deformation behaviour is assessed here using the ratio of residual drift/maximum drift, implying that the results using the different steel types can be satisfactorily compared in a qualitative manner. The bilinear idealisation of each mild-steel stress-strain curve is shown in Figure 5.

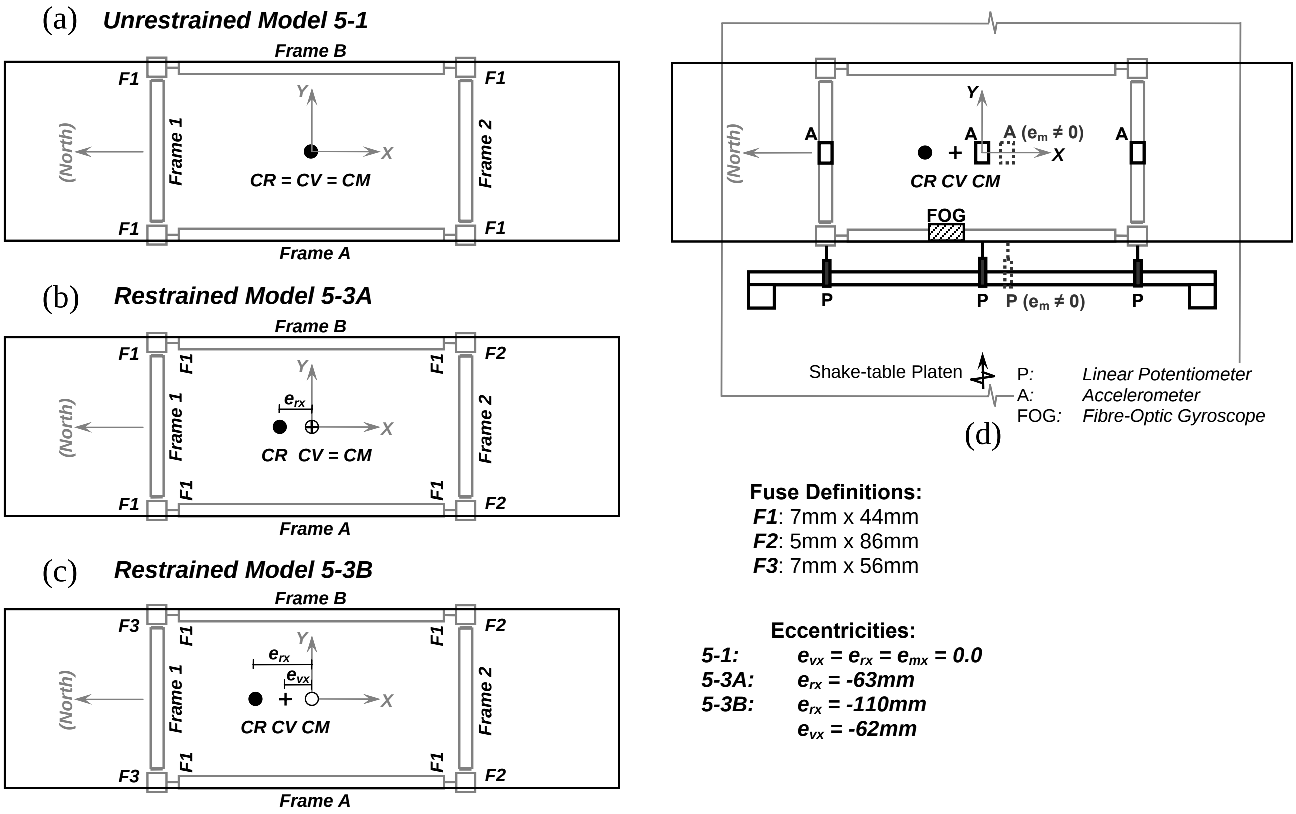

Figure 4. Schematic plan representation of test models (a) to (c) and (d) plan view of instrumentation placement used for shake-table models

To demonstrate how the change in steel affects the design parameters of the shake-table models, a summary of frame properties is provided in Table 1 for the three different fuse dimensions used for *Frames 1* and *2* in the testing program. It is seen that the higher strength steel leads to larger yield displacements and base-shear capacities. These increase proportionally, therefore the stiffness values remain constant. The increase in yield displacements leads to lower system ductility values. There is evidence to suggest that residual displacements are intensity dependent, implying that lower ductility demands will reduce the permanent drifts, however studies have shown that increased post-yield stiffness is the more dominant influence.

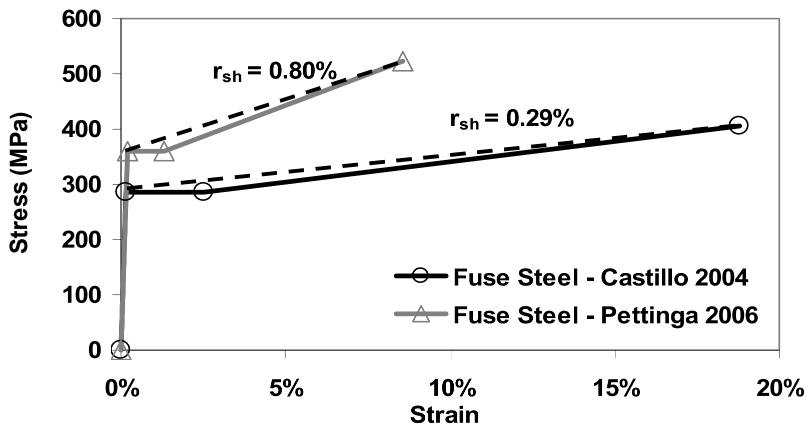

Figure 5. Bi-linear fuse-steel stress-strain curves showing strain-hardening ratio comparison

Table 1. Summary of frame properties for fuse-steel types as used by Castillo [2004] and Pettinga et al. [2007]

		Fuse 7x44		Fuse 5x86		Fuse 7x54	
		Castillo	**Pettinga**	**Castillo**	**Pettinga**	**Castillo**	**Pettinga**
Δ'_{ye1}	**(mm)**	2.21	2.95	3.10	4.14	2.21	2.95
$(\Delta_{ye1})_e$	**(mm)**	5.35	7.14	6.60	8.82	5.60	7.48
V_{she1}	**(N)**	879	1145	877	1172	1079	1443
V_{ne1}	**(N)**	610	750	609	750	749	942
$(k_{e1})_e$	**(N/mm)**	164	160	133	133	193	193
μ_Δ	-	3.86	2.54	3.12	2.06	3.68	2.42

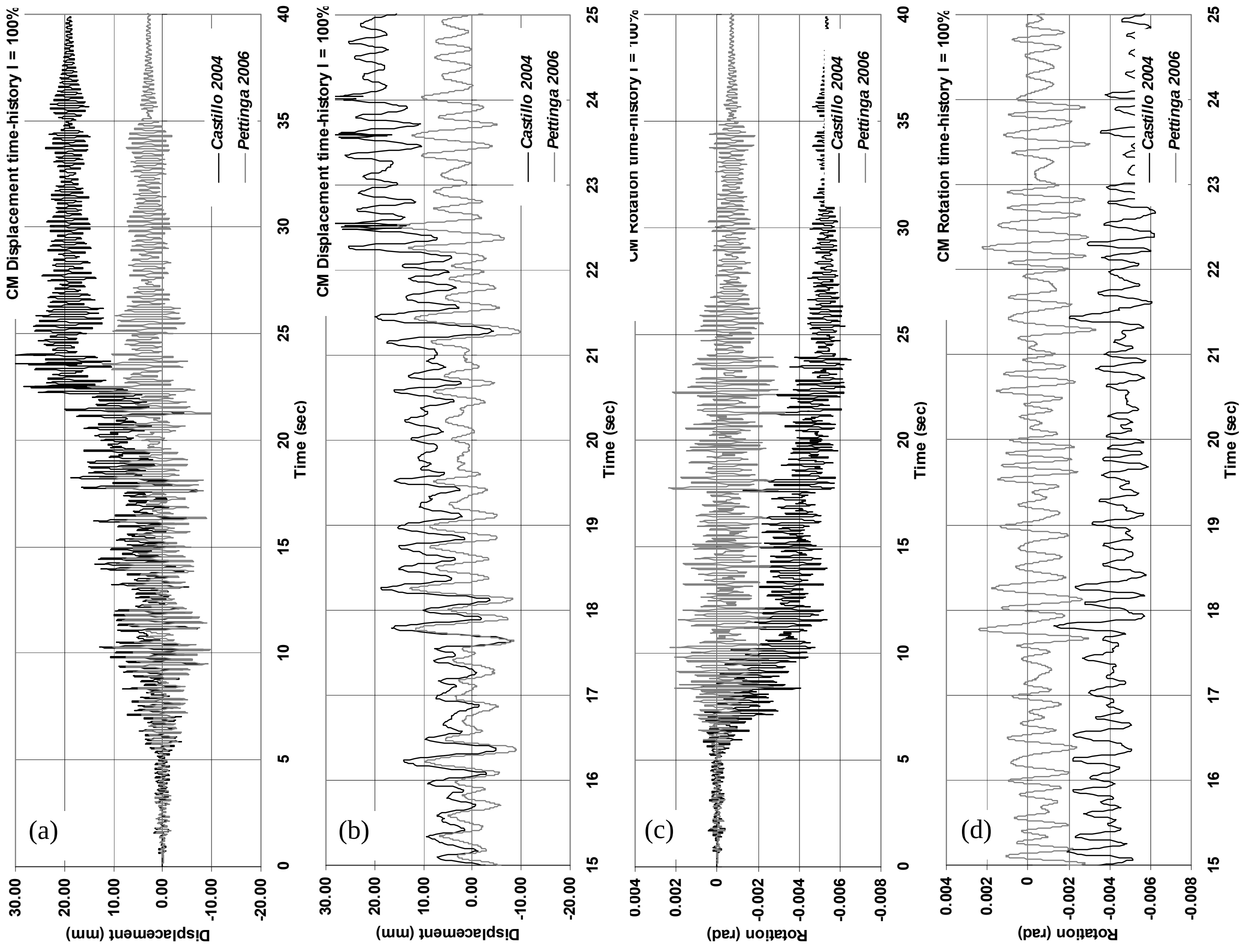

Figure 6. Model 5-3B (e_{rx} = -0.092 e_{vx} = -0.052) CM (a, b) displacement and (c, d) rotation response comparison as tested by Castillo [2004] and Pettinga et al. [2007].

Of the asymmetric configurations considered by Castillo [2004], three were re-tested using the higher strength and strain-hardening steel. These three configurations were torsionally unrestrained symmetric, torsionally restrained stiffness eccentric and torsionally restrained strength and stiffness eccentric. The comparison of displacement and diaphragm rotation responses in Figure 6 for the stiffness and strength eccentric model demonstrates the effect of using steel with different levels of strain hardening and yield strength. From the experimental response history plots, it is seen that significant changes in centre-of-mass translation response only occur from 18 seconds onwards, from which point the higher post-yield stiffness of the plastic-hinges limits the crawl of the structure in one direction. Note that the individual cycle amplitudes remain similar throughout the response, and indicate that the reduced permanent displacement is due to the post-yield stiffness (Pettinga et al., 2007b), rather than higher yield stress.

The reduction in residual diaphragm rotation is also significant. The original record from Castillo [2004] shows a very significant permanent rotation at the end of the response, however this is reduced when the higher grade steel is used by approximately 75%. This reduction occurs, even though the individual rotation cycle amplitudes are much greater in the test by Pettinga et al. [2007a].

A summary of the maximum and residual response for each of the three tests using each mild-steel type is provided in Figure 7. Overall the higher strain hardening ratio is seen to significantly improve the residual displacement and residual diaphragm rotation response of the three systems, as evidenced by the reduced Res/Max ratios for each case.

The ability to mitigate residual drifts through explicit design to increase the element or system post-yield stiffness ratio has been demonstrated to be effective, particularly for structural steel buildings [Pettinga et al., 2007b]. The experimental application of increasing the post-yield ratio through greater strain-hardening, confirms these findings. Comparing the results of Castillo [2004] with those presented by Pettinga et al. [2007a], it is noticeable that even though maximum drifts were reduced due to the stronger steel used in the latter tests, the residual drifts were decreased by a greater proportion. It is this reduction in residual/maximum ratio that is attributed to the increasing in system post-yield stiffness ratio, and is seen developing in the response history plots of displacement in Figure 6.

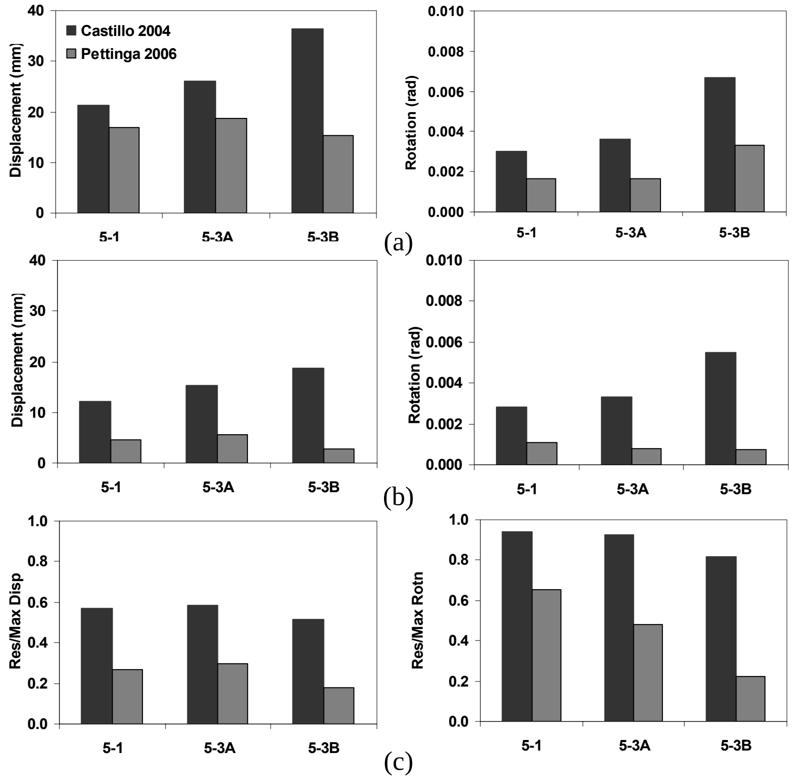

Figure 7. Comparison of CM displacement and rotation results comparing the effect of using steel with different properties for fuse-plates (a) maximum (b) residual (c) residual/maximum

4.CONCLUSIONS

A simple shake-table model structure has been developed using a system that allows a wide range of in-plan asymmetric conditions to be investigated. Using a single component earthquake excitation the maximum and residual response behaviour of the model structure has been obtained. Results presented here focus on the residual displacements of an asymmetric structure, and demonstrate that the permanent deformations can be different on each side of a building, implying that asymmetric torsional response of structures should be considered when assessing residual deformation performance of structures.

An example of a simple residual displacement mitigation approach has been presented. Comparative tests were carried out using the same eccentric conditions, however the steel properties differed such that one model structure had a higher level of strain-hardening in the plastic-hinges, which gave a greater post-yield stiffness ratio. This has been numerically shown to reduce permanent drifts. The experimental results confirm this approach does lead to lower residual drifts for three different test configurations.

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