Re-Shaping Hysteresis: Seismic Semi-Active Control Experiments for a 1/5th Scale Structure

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ABSTRACT:

Semi-active resetable devices can improve seismic response. Novel 2-4 devices independently control each device chamber to customise structural hysteresis loops to reduce both displacement and base shear demands. Here, 2-4 devices are experimentally validated on a one-fifth scale test structure weighing 35kN with a natural period of 0.6 seconds. Four seismic inputs over a wide range of intensity levels are use in 27 tests. Results for resetable semi-active devices that modify hysteretic behaviour using different control laws are compared to spectral response analyses that predict ~30-50% peak displacement reductions. Fully uncontrolled tests were also done for lower intensity ground motions, along with fail-safe valves-open tests. Results show 25-50% peak displacement reductions compared to the valves open case, depending on the semi-active control law used and matching spectral analysis results. Additionally, a semi-active control law designed to simultaneously reduce base shear reduces it 10-20%. In contrast, 10-20% increases are seen for other approaches, as predicted. Overall, these are the first large-scale tests of this type of novel resetable devices. The results validate prior simulation and spectral analyses, and clearly show the potential. Finally, semi-active methods that re-shape hysteresis to control response and simultaneously limit base shear demand, are experimentally demonstrated for the first time.

1 INTRODUCTION

Reducing structural damage during seismic events is necessary to reduce adverse social and economic impacts on communities (Horwich, 2000, Myrtle *et al.* 2005, Mulligan, 2007**)**. Traditionally, structural energy resulting from large seismic events is dissipated via sacrificial damage to all or specific structural members. This method of energy dissipation can result in costly repair or demolition and rebuilding following particularly large seismic events. Structural control offers an alternative method, which has the potential to reduce or possibly eliminate structural damage.

The purpose of this research is to examine the response of a realistic one-fifth scale structure utilising semi-active resetable devices as the structural control system. In addition, this research was conducted to validate prior proposals and research in this field and to contribute to the understanding of semi-active devices in structural control applications. These experiments utilising semi-active resetable devices in structural application are the first large-scale tests to be conducted using novel devices that are able to sculpt hysteretic response and base shear forces (Mulligan, 2007, Rodgers *et al*. 2007, Chase *et al*. 2006). Hence, these tests are a first look at resetable device performance in more realistic environments, and provide a reliable baseline experimental set up for similar testing and devices.

The resetable devices utilised in this research use a novel disconnected chamber design allowing a variety of control laws to be implement. These control laws result in different force-displacement hysteresis loops that are cannot be achieved with conventional resetable devices or semi-active control techniques (Chase *et al*. 2006, Mulligan *et al*. 2007). Thus, the resetable device response is able to be manipulated to obtain the desired or best result for each structural application (Mulligan, 2007).

2 METHODS

2.1 Experimental Layout and Instrumentation

The test structure is a 1/5th scale steel moment resisting frame structure constructed to respond in a similar manner to a full-scale building. The test structure has three floors and a roof level with the elevation comprised of one long and one short bay. The structure has a similar natural frequency of a full-scale building, of approximately 0.6 seconds, rather than a natural frequency defined by laws of similitude (Kao, 1998). To achieve the same natural period, a large amount of added mass on each floor level is required. Structural connections are designed with yielding fuses to accurately represent this full-scale structural behaviour as well as providing the capacity to re-use the structure after yielding has occurred by replacing these fuses (Kao, 1998). Figure 1 shows a schematic of the structure indicating the devices and instrumentation, and Figure 2 shows a photograph of the structure with the resetable devices attached.

Two resetable devices are installed on the structure, one on each long side, as depicted in Figures 1 and 2. The devices are attached from the ground to the third floor via a rigid tendon. Thus, the devices and tendon span the entire length of the long side of the structure. This control architecture was chosen after extensive non-linear finite element simulation in Ruamoko (Franco Anaya *et al*. 2007). The relative displacement across each device is measured by a potentiometer and a load cell measures the force reacted by each device.

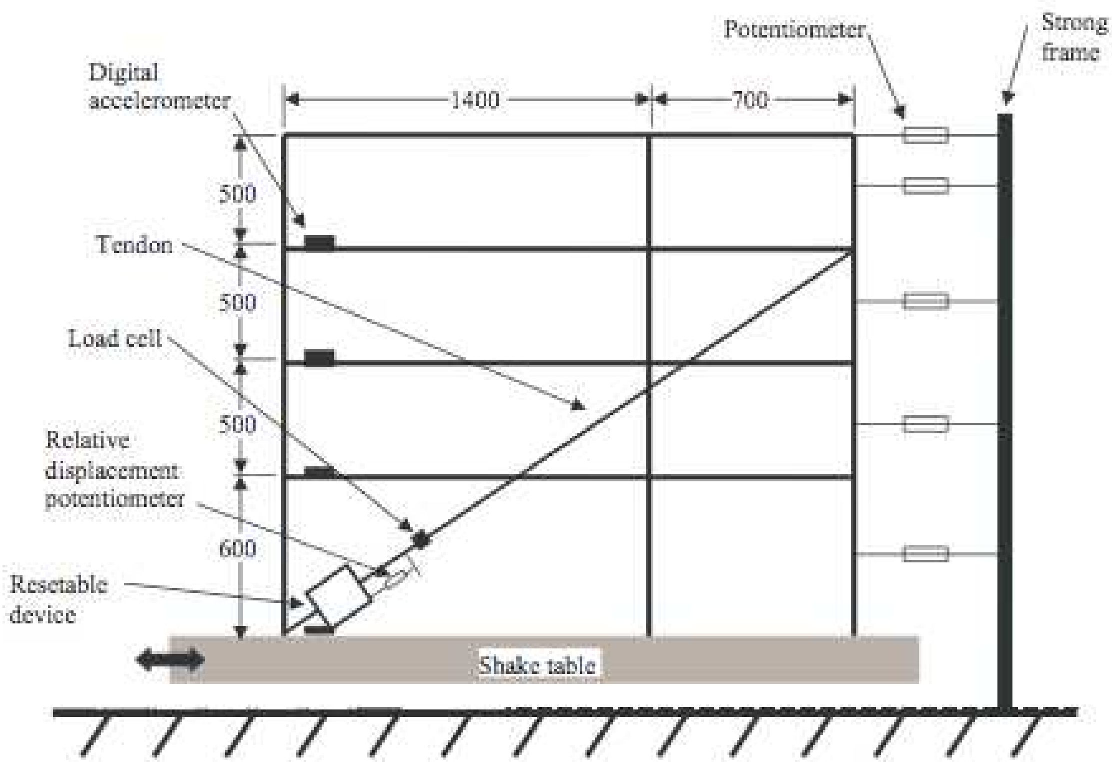

Figure 1. Schematic of test structure illustrating instrumentation and resetable devices.

Figure 2. Photograph of test structure on the shake table with the devices installed.

A digital accelerometer placed on each floor of the structure record floor level acceleration data at 2kHz. A digital accelerometer is attached to the shake table to obtain data of the actual ground motion acceleration input to the test structure. Five linear potentiometers up the height of the structure, sampled at 1kHz, measure the absolute horizontal displacement of the midpoint of each storey and the roof. The shaking table absolute displacement is measured with a linear potentiometer sampled at 1kHz. Floor displacements are calculated by linearly interpolating the displacement measured by the potentiometer directly above and below the corresponding floor level. These derived displacements were verified to be accurate representations of the floor displacements by comparison with the double integration of the digital accelerometer data for each floor, and results of other studies (Kao, 1998).

The input to the device control laws is the relative displacement across the devices. This displacement data is filtered in real time to ensure the devices operate at an optimal level and to mitigate extraneous device actuation and resetting (Mulligan, 2007). All recorded data was bandpass filtered in the 0.2 to 15.0Hz range after collection. The filter was designed in Matlab R® to have 0dB gain in the pass region and -80dB in the stop regions. A post processing zero-phase forward and reverse filtering method was used to avoid introducing any phase lag in the data.

2.2 **Control Laws**

Resetable device control laws are described by the quadrants on a force-displacement hysteresis loop in which the devices provide a resistive force (Chase *et al*. 2006). The one through four or 1-4 control law provides resistive forces in all four quadrants of a force-displacement plot, while the 2-4 law provides a resistive force in only the 2^{nd} and 4^{th} quadrants, when the structure is moving away from the centre or neutral position. Both the 1-4 and 2-4 control laws were utilised during the experiments with the specific law applied to both devices in a given test. In addition, the structural system was tested with all the device valves open to give friction damping results (Chase *et al*. 2006, Mulligan, 2007). The uncontrolled structure response with the entire tendon arrangement removed was obtained for comparison. These uncontrolled test results are limited to a selected fewer ground motions where structural yielding was not expected to occur based on preliminary finite element analysis (Franco Anaya *et al*. 2007). Therefore, the valves open case is used as a surrogate uncontrolled case for comparison of all results even though the tendon arrangement provides some additional stiffness to the system.

Finally, the fail-safe mode, where all valves are closed to give air spring results was also tested. The fail-safe mode is so termed because it is the state that occurs if power is lost to the structural control system with this particular device design. The fail-safe mode is chosen to be all valves closed rather than all valves open because reasonable supplemental reaction forces are provided with the valves closed. More specifically, the response forces resulting from valves closed are large enough to resist the structural motion, whereas the valves open case is analogous to a very low stiffness tendon, where response forces consist of static friction and viscous air damping (Mulligan, 2007).

2.3 Ground Motion Inputs

Four earthquake records at various intensity levels were used during the experiments, for a total of 27 input ground motions, as summarised in Table 1. The input motions were selected such that the minimum and maximum percentages for each different record utilised had similar peak ground accelerations and intensity measures. In between, either 5%, 10% or 20% increments of peak ground acceleration were used for each record. The intensity measure is the spectral displacement of a structure with a fundamental frequency of 2.5Hz. Note, the recorded peak ground acceleration (PGA) for the Sylmar 5% record is significantly greater than the 10% and 15% values for the same record. This large value is due to a very short pulse that was not present in the original acceleration record and was determined to be caused by a spurious motion of the shake table. Therefore, an approximated and more representational value derived from the original input acceleration record is shown in brackets. PGA values are presented as recorded values as opposed to original acceleration record values because these recorded values best represent what the test structure experienced during testing.

Some minor modification was used to ensure the ground motion records could be accurately tracked by the shake table. Specifically, the limiting factor for accurately tracking the displacement input motion is the maximum table velocity, before servo-valve saturation occurs, of 0.24m/s. Therefore, the earthquake records are modified such that the velocity does not exceed this saturation level, while retaining as much of the acceleration record as possible. The modification method is similar to that detailed in Chase et al. (2004). This modification should thus ensure no unexpected acceleration spikes occur while also ensuring optimal (<0.1mm) tracking of the table reference input.

2.4 Performance Metrics

The response metrics of interest are the 3rd floor maximum acceleration, the 3rd floor maximum relative displacement and the maximum total base shear measured on the test structure. These metrics indicate the damage done to the occupants and non-structural elements of the structure, the structure itself, and the foundations of the structure, respectively. A reduction in one of these metrics can result in an increase in another metric in some cases (Rodgers *et al*. 2007). For example, the added non-linear stiffness contribution by resetable devices often reduces displacements of all types, but at a cost of increased accelerations (Hunt, 2002, Barroso et al. 2003b). However, using customised control methods, such as those developed in this research (Chase *et al*. 2006, Mulligan, 2007), reductions in all metrics, or large reductions coupled with only small increases in these metrics, can be achieved (Rodgers *et al*. 2007).

Results are normalised by the intensity measure of the earthquake record allowing comparison across the different earthquake records used in the analysis. In addition, this normalisation allows comparison to previous spectral examinations of the semi-active devices. The results are reported as cumulative distribution functions as they are then more readily incorporated into a standard hazard analysis and performance based design (Barroso *et al*. 2003a, Rodgers *et al*. 2007).

3 RESULTS AND DISCUSSION

Figure 3 shows the base shear response versus the ground motion intensity measure for all the control methods. Figure 4 similarly shows the maximum 3rd floor displacement response. In each case, the results presented are a summary obtained by a non-linear least squares fit from each ground motion response (Mulligan, 2007). In some cases, all 27 records were not utilised for each control case as the test structure was expected to yield at higher intensity, particularly for the valves open and uncontrolled cases. Hence, these specific cases were not tested as part of the overall experimental protocol. However, response trends are able to be accurately deduced from the available data.

Table 1. Summary of scaled ground motion records used for shake table analysis. The ground motion magnitude is determined by the percentage of the original record, the measured peak ground acceleration (PGA), and the spectral displacement intensity measure for a single-degree-of-freedom structure with 2.5Hz natural frequency.

	% of record	PGA (recorded)	Spectral Displacement (2.5Hz)
El Centro	10	0.845	0.0024
	20	1.06	0.0048
	30	1.29	0.0073
	40	1.45	0.0097
	50	1.68	0.0121
	60	2.14	0.0145
	70	2.64	0.0170
	80	2.96	0.0194
	90	3.04	0.0218
	100	3.51	0.0242
Kobe	5	0.88	0.0045
	10	1.15	0.0090
	15	1.51	0.0135
	20	1.82	0.0180
	25	2.17	0.0225
	30	2.54	0.0269
	35	2.85	0.0314
Taft	20	1.50	0.0028
	40	2.74	0.0056
	60	3.77	0.0083
	80	5.01	0.0111
Sylmar	5	1.35 (0.44)	0.0040
	10	0.95	0.0081
	15	1.22	0.0121
	20	1.44	0.0162
	25	1.88	0.0202
	30	2.26	0.0242

Figure 3 indicates a distinct capacity limit where the base shear reaches increases at a slower rate per unit of intensity measure. This test structure base shear capacity was designed to be 3kN. However, a pushover analysis by Kao (1998) using the structure modelled in Ruamoko indicated a base shear capacity of 6kN. This apparent discrepancy was caused by over-strength actions of the yielding fuses (Kao, 1998). The base shear of the structure including the resetable devices and tendons is approximated as 16kN from Figure 3. This value is far higher than prior analysis values and the discrepancy is most likely due to the altered structure, slightly different fuse designs in the test structure and increased strength of these fuses.

Figure 3 shows that the 2-4 control law provides the largest buffer between the demand and capacity base shear for a given intensity measure as expected by design of this control law (Mulligan, 2007). The 1-4 case has the smallest buffer with the fail-safe having similar results. The valves open case is approximately between the 2-4 and fail-safe result.

Reduction in the base shear demand for a given intensity measure means the structural system can withstand larger ground motions without damage to the foundation and the base of the columns. This result is significant for buildings where large foundations are expensive or prohibited by site conditions. It is equally or more significant for retrofit of existing structures, where reducing the demand is preferable over expensive and potentially difficult foundation strengthening.

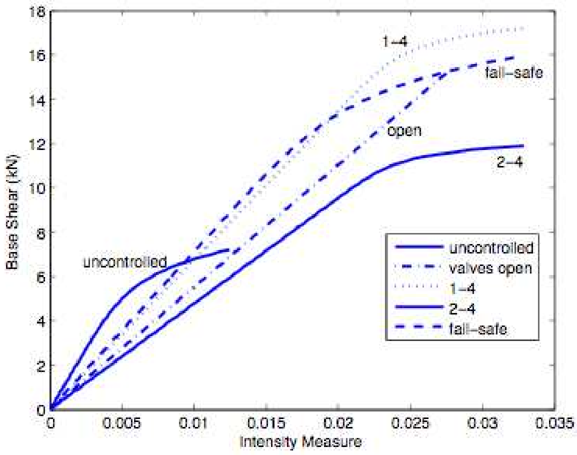

Figure 3. Least squares fit of base shear comparing all control types and the uncontrolled case relative to the spectral displacement intensity measure.

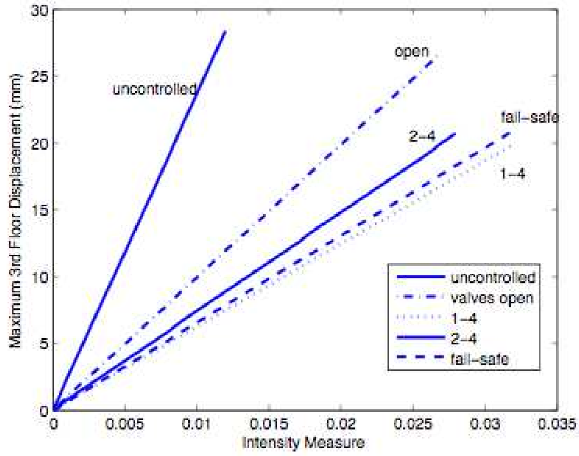

Figure 4. Lease squares fit of maximum 3rd floor displacement comparing all control types and the uncontrolled case relative to the spectral displacement intensity measure.

All control laws show reduced peak 3rd floor displacements compared to uncontrolled cases for a given intensity measure. The 1-4 and fail-safe cases have similar results with the best reductions. The 2-4 law shows significant reductions, which are very close to but not as great as the 1-4 and fail-safe cases. This hierarchy of displacement performance matches the spectral analysis by Rodgers *et al*. (2007).

The cumulative distribution functions of the 3rd floor maximum acceleration and displacements, and the base shear, relative to units of ground motion input intensity, show a lognormal distribution. The performance metrics are normalised to the ground motion intensity measure recorded during the experiment. Ordinarily, the normalisation results from using ground motion records scaled for probability of exceedence for the region of interest. However, these shake table experiments utilised four ground motion records with varying levels of intensity, which were chosen to provide a range of inputs and so that the test structure did not yield. Thus, to create the cumulative probability results, the normalisation appears in the performance metrics rather than the ground motion records. This is in contrast to other studies (Hunt, 2002, Hunt *et al*. 2002, Rodgers *et al*. 2007).

Fitted lognormals for the cumulative distributions for the base shear, maximum 3rd floor displacement, and maximum 3rd floor acceleration, are shown for each control law and the uncontrolled case in Figures 5 to 7. Each distribution contains the data for all records utilised for the specific control method examined. In addition, Table 2 summarises the data shown in Figures 5 to 7, and presents the lognormal mean ($\hat{x}$) and multiplicative variance (σ).

The cumulative probability plots indicate the probability of exceeding a given metric (per ground motion intensity) for each control method. Thus, the demand on the structural system is reduced as the cumulative probability function moves to the top left corner of Figures 5 to 7. An ideal curve is a vertical line at the left most limit of each plot that plateaus at a cumulative probability of 1.0. This ideal curve represents an assurance of not exceeding the performance metric for all ground motions or intensity measures examined. Table 2 presents the mean and multiplicative variance, or uncertainty of the results in Figures 5 to 7. A low multiplicative variance indicates low uncertainty in the result or small deviations away from the mean. Hence, a control case with a low mean and low multiplicative variance is the best case scenario and closest to the ideal curve.

All the semi-active control method results are to the left of the uncontrolled case (lower mean values) in the cumulative probability plots, indicating improved performance from adding the semi-active resetable devices. This difference is particularly pronounced for the maximum 3rd floor displacement metric, where the mean probability for the 1-4 or 2-4 control methods gives a value of < 550 to 600mm/I.M which is at least three times less than that for the uncontrolled case (> 2000 mm/I.M).

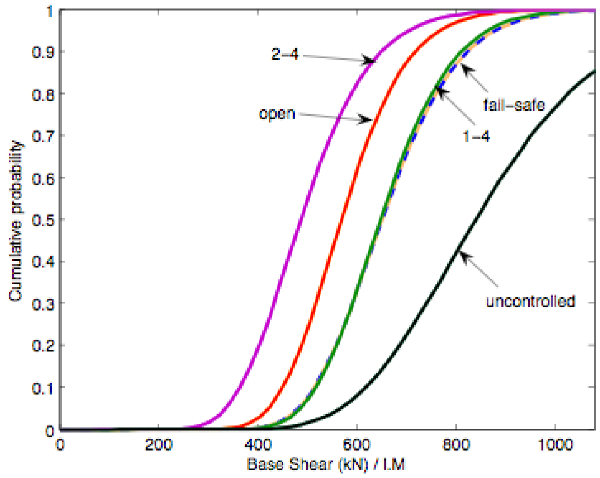

Figure 5. Fitted log-normal cumulative distribution of the base shear normalised to the ground motion intensity measure for all the control cases. The 2-4 control law results in the best response.

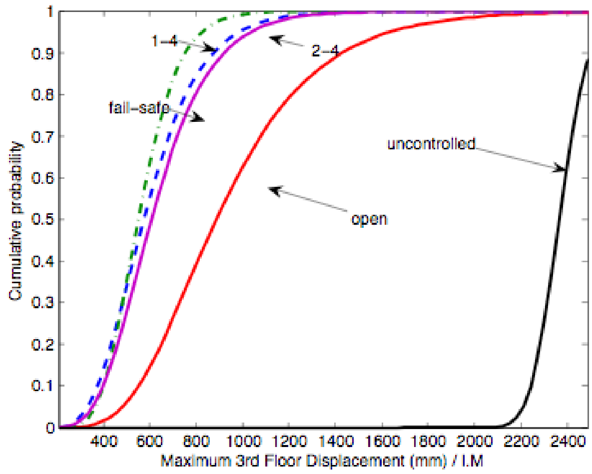

Figure 6. Fitted log-normal cumulative distribution of the maximum 3rd floor displacement normalised to the ground motion intensity measure for all the control cases. The 1-4 control law gives the best response with the fail-safe and 2-4 cases having similar results.

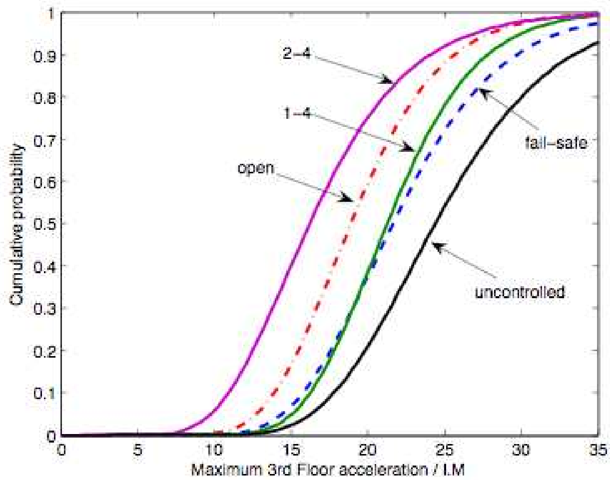

Figure 7. Fitted log-normal cumulative distribution of the maximum 3rd floor acceleration normalised to the ground motion intensity measure for all the control cases. The 2-4 control law once again provides the best structural response.

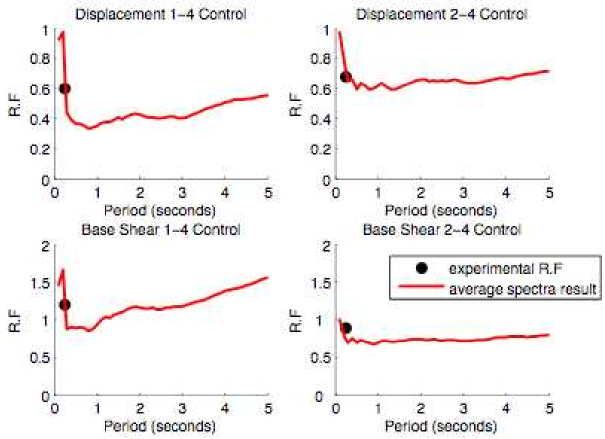

Figure 8. Response spectra of structure displacement and base shear with the experimental reduction factor superimposed. Close correlations between the spectral analysis and experimental data is evident.

Of particular note is the ability of the devices under 2-4 control to limit both the 3rd floor displacements and to significantly reduce the base shear and 3rd floor accelerations compared to the other control and fail safe cases, which typically increases the base shear demand. Thus, devices controlled with the 2-4 control law are able to improve the structural performance for all metrics. In contrast, 1-4 control and the fail safe mode provide large reductions in one metric, usually displacement, with a concomitant increase or no change to other base shear or acceleration metrics. These results also quantitatively match the spectral analysis by Rodgers *et al*. (2007). Additionally, the trends match analytical studies using the SAC suites scaled for probability of occurrence (Hunt, 2002, Chase *et al*. 2004, Chase *et al*. 2006).

Table 2. Summary of cumulative probability data presented in Figures 5 to 7.

	Base Shear		Maximum 3rd Floor Displacement		Maximum 3rd Floor Acceleration	
	$\hat{x}$	σ	$\hat{x}$	σ	$\hat{x}$	σ
uncontrolled	839	1.27	2368	1.04	24	1.28
open	568	1.20	887	1.45	19	1.27
1-4	647	1.19	549	1.28	21	1.23
2-4	468	1.25	605	1.39	16	1.36
fail-safe	650	1.20	573	1.39	22	1.28

Reporting results as cumulative probability functions readily allows the findings to be incorporated into probabilistic performance based design methods (Barroso, 1999, Barroso *et al*. 2003a, Rodgers *et al*. 2007). For example, if a building code states that a hospital requires a 90% certainty the base shear demand cannot safely exceed 700kN per unit of ground motion intensity due to a foundation design constraint. Using Figure 5 the valves open and 2-4 control law configurations meet this criteria. However, the 2-4 case has a much larger buffer between the allowance and response. In addition, the reduction in displacement response for the 2-4 control law far exceeds the reduction for valves open, as shown in Figure 6. Therefore, the 2-4 control law is the best option for this scenario.

Performance based design using these cumulative probability functions allows tradeoffs in design to be rapidly assessed. The broad view of a series of potentially contradictory performance metrics used here discourages narrow focus on one particular metric, avoiding potential errors or failures in the design procedure. In addition, probabilities of exceedence are a useful design tool where varying levels of assurance of damage limits are dependent on different building uses. In combination, the overall method presented offers a generalisable and complete foundation for taking these resetable devices into regular design practice with confidence.

Comparison of experimental test structure reduction factor results with the spectral analysis by Rodgers *et al*. (2007) shows good correlation. Figure 8 shows displacement and base shear experimental reduction factors on the spectra for the 1-4 and 2-4 valve control cases. The experimental reduction factor is normalised to the valves open case, or surrogate uncontrolled condition, and averaged over all ground motions. The spectra results are presented as averages over the three suites of ground motions. This close correlation indicates the efficacy of the spectral analysis and the resetable device models used in the analysis in predicting the actual response of a test structure using the resetable device structural control system (Mulligan, 2007). In addition, these close correlations between analytical and experimental data validate the links between each development step and the tools and models used in analysis prior to the full-scale testing (Mulligan, 2007).

4 CONCLUSIONS

The addition of two semi-active resetable devices including a tendon arrangement in a structural control system greatly improves the structural performance of a 1/5th scale moment resisting steel frame building under simulated earthquake loading. The different control laws implemented generally result in an improvement in some performance metrics with a corresponding increase in other metrics. However, the most significant results are using the 2-4 control law. This control case presents favorable results that show improvements in all performance metrics, base shear, displacement, and acceleration, as expected from prior spectral and other analysis. This result is particularly important for retrofit applications where reductions in the structure displacement is necessary to reduce structural damage but the foundations may have insufficient strength to meet increased demand.

The fail-safe case presents the worst case scenario with a control system utilising resetable devices.

This case occurs when the power to the devices fails or the control system malfunctions. The structure dynamics with the fail-safe mode are still favorable over the uncontrolled or surrogate uncontrolled (valves open) cases, indicating the robust nature of resetable device control systems. Overall, these shake table experiments have shown the efficacy of semi-active resetable devices as structural control components. Results are presented in a format that can be readily and directly incorporated into performance based design methods that indicate the relative performance of each control method for the performance metrics. In addition, these experiments are the first large-scale structural application of this type of semi-active resetable devices. They are also the first experiments to utilise and validate the customised hysteresis loops this novel design enables. Thus, the findings are an important step to realising full-scale structural control with customised semi-active hysteretic behaviour using these novel semi-active resetable devices, or any other device capable of providing these unique capabilities.

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