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Shaking Table Tests on Strength Degradation Behaviour

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Structures such as unreinforced masonry walls, soft-storey buildings, gravity structures and components which include free-standing objects are well known to be non-ductile and yet they are commonly found in regions of low-moderate seismicity. Potential significant degradation in strength in these structural systems in projected earthquake scenarios has been a cause for concern. Shaking table experiments undertaken recently by the authors revealed very interesting phenomena with the behaviour of the ("non-ductile") free-standing objects in an earthquake. Vulnerability to overturning is shown not to be sensitive to the height of the object nor its aspect ratio. The trends revealed earlier by the authors based on analytical modeling have been confirmed experimentally. Importantly, the displacement time histories predicted by program Rowmanry and Romain are shown to be very consistent with recordings from the shaking table experiments.

Keywords: Shaking table, strength degradation, rocking, displacement time history.

1. INTRODUCTION

Structures such as unreinforced masonry walls, soft-storey buildings, gravity structures and components which include free-standing objects are well known to be non-ductile and yet they are commonly found in regions of low-moderate seismicity. Many historical earthquakes namely 1989 Loma Prieta, 1994 Northridge and 2001 Nisqually have demonstrated that damage to non-structural components and building contents generally exceeds those due to the structural components (Shephard et al, 1990; Hall, 1995; Filiatrault et al, 2001). Such failures often result in fatalities, severe building impairment and major economic losses even when damage due to the structural components would not be significant (Filiatrault et al, 2001). While current regulatory standards and codes of practice provide recommendations for securing building contents and restraining devices (NZS 4203, 1992; Eurocode 8, 1996; FEMA 273/274, 1997; IBC, 2006; AS1170.4, 2007), there are no provisions for seismic assessment and performance of the building contents. It is therefore important to assess the response behaviour of such contents and identify their vulnerability to overturning under earthquake induced motion.

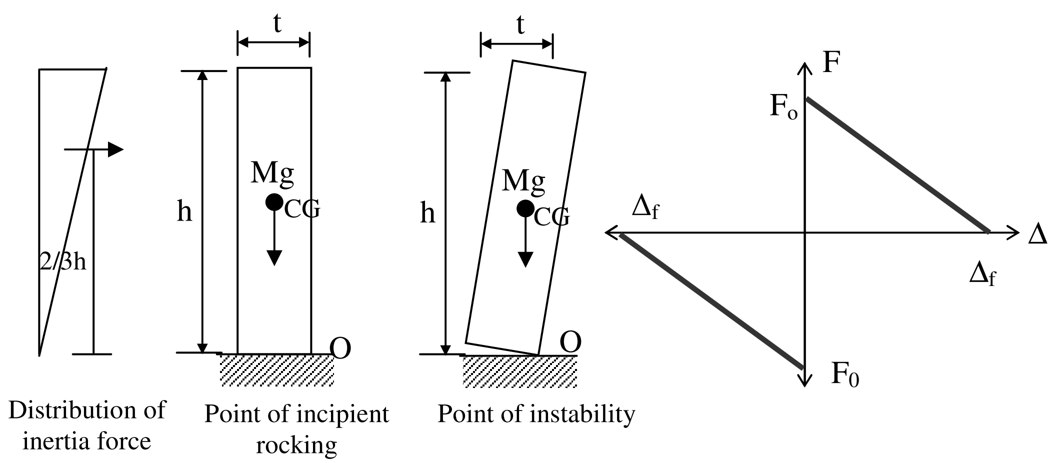
The dynamic rocking response of rigid bodies was pioneered by the work of Milne, 1885. A classical model has been developed by Housner, 1963 which considers the dynamic equations of equilibrium of an object experiencing rocking displacement. Many numerical studies on rigid body object (RBO) have been undertaken by different researchers (Yim et al, 1980; Ishiyama, 1982; Wong and Tso, 1989a and 1989b; Al Abadi et al, 2006; Tobita et al, 2006; Purvance et al, 2008) but with few complemented by experimental verifications. A simple analytical model based on displacement based (DB) approach for predicting the overturning of rigid objects has been developed (Doherty et al, 2002; Al Abadi et al, 2006). The force-displacement (F-Δ) relationship of rigid objects has been proposed using idealization of the objects as single- degree-of-freedom (SDOF) systems.

Analytical investigations based on non-linear time-history analysis (THA) by time-step integration techniques have been undertaken to evaluate the potential performance of these “less than ideal” structural systems to estimate their risk of collapse in an earthquake. Based on recent analytical researches (Doherty et al, 2002; Al Abadi et al, 2006), these structural systems have shown satisfactory performance. Whilst time-history analysis techniques have been well established, accuracies with computations in the post linear range are still uncertain and more so when the response is characterized by non-ductile behaviour. This has prompted the authors to conduct shaking table experiments on RBO (generic single-degree-of-freedom models) that are representative of systems possessing non-ductile (strength degradation) behaviour. This paper presents result from shaking table experiments and validation using analytical techniques. Results from the experiments were used to validate those obtained analytically by non-linear THA.

Theoretical background for the non linear behaviour of the rigid body object is briefly described in Section 2. The experimental set up; testing protocols are described in Section 3. Experimental results are described in Section 4. Non-linear time history analyses has been undertaken and validation of results with experiments are presented in Section 5. Conclusions from this research are presented in Section 6.

2. FORCE DISPLACEMENT RELATIONSHIP OF RIGID BODY OBJECTS

A simple analytical model based on DB approach for prediction of overturning of rigid body objects has been developed (Doherty et al., 2002; Al Abadi *et al.*, 2006). The force-displacement (F-Δ) relationship of such objects has been proposed using idealization of the objects as SDOF systems as presented in Figure 1. The resistance force F is the equivalent point force applied at two-thirds of its height representing the triangularly distributed inertia force and Δ is the effective displacement which is defined as 2/3 of the maximum displacement of the height. The force-displacement relationship is characterised by: i) vertical line at zero displacement, indicating infinite stiffness prior to rocking and ii) a straight line with negative stiffness representing the linear decrease of resistance force with the increase of displacement amplitude. This significant strength degradation of RBO has been incorporated in non-linear THA.



(a) Idealisation of rigid objects *(b) F-Δ relationship*

Figure 1: Force-displacement behaviour of rigid objects

The force-displacement relationship indicates that rigid objects possess infinite initial stiffness and hence infinitely small initial natural period. This non-linear behaviour of the system has been incorporated by using average secant stiffness which corresponds to a line going through the centroid of the area under the non-linear force-displacement curve.

This non-linear behaviour with similar loading, unloading and reloading indicates that the objects possess excellent self-centering capabilities due to gravitational load. As a result, the dynamic behaviour of rigid objects exhibits no energy dissipation characteristic. The energy dissipated during impacts of the pivotal edges and the ground which has been observed in the earlier studies (Housner, 1963; Lipscombe, 1990; Doherty et al., 2002; Al Abadi *et al,* 2006) has been modeled by Rayleigh damping with mass and stiffness proportional damping coefficients in non-linear THA.

3. SHAKING TABLE EXPERIMENT

Experimental shaking table test was conducted in the structural laboratory of the Department of Civil & Environmental Engineering, University of Melbourne to study the rocking behaviour of Rigid Body Objects. This section briefly describes the overview of the test program.

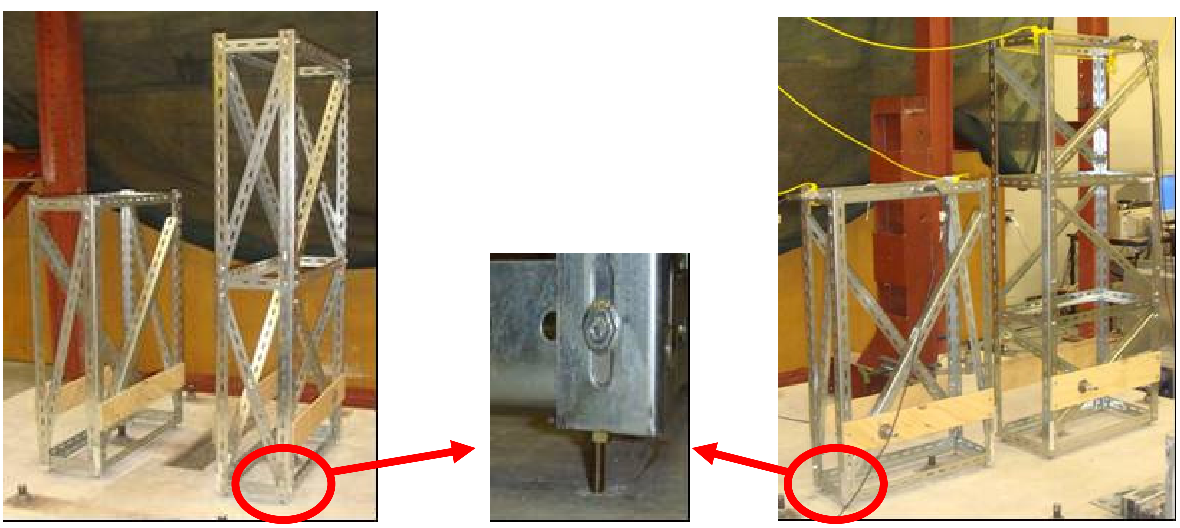
3.1 Description of specimens

Specimens that are representative of rigid body objects were fabricated using slotted angle sections. The geometrical configurations of the specimens are given in Table 1 and represent a range of RBO to fulfill the objective of the experimental program. Typical fabricated specimens are shown in Figure 2. The base of the specimens was provided with pin-points to ensure free rocking about the pivotal points (refer Figure 2).

To study the dynamic behaviour of RBO, two phases of experiments have been conducted. The first phase includes objects with equal thickness but of different heights while the second incorporate objects with the same aspect ratio but of different thickness. The objective of the shaking table experiments with same thickness was to study the effect of the object height on their response behaviour. Testing objects with same aspect ratio was to observe the effect of thickness on the object's response. The specimens were tested in pairs on the shaking table.

Table 1: Test specimen dimensions

Specimen	Thickness, t (mm)	Height, h (mm)	Width, b (mm)	Aspect ratio	Remarks
1	170	1000	600	5.88	Specimens 1 & 2 have same thickness and specimens 1 & 3 have same aspect ratio.
2	170	1500	600	8.82	
3	255	1500	600	5.88	



a) Objects with same thickness (170 mm) *b) Objects with same aspect ratio (5.88)*

Figure 2: RBO specimens for Phase I and II of the experimental program

3.2 Test set up

A typical test set up for the experimental program is shown in Figure 3. Linear voltage displacement transducers (LVDTs) were used to measure the absolute displacements of the table and relative displacements of rocking objects. Due to the limited capacity of the LVDTs, they were fixed at a lower level on the rocking object (approximately 250 mm above the base). The responses at the top of the objects were then obtained by extrapolation. Uniaxial accelerometers were also used to measure the horizontal acceleration of the table. These accelerometers were also placed at the top of the rocking objects and alongside the LVDTs to enable validation of the direct displacement measured. In total, twelve (12) accelerometers and four (4) LVDTs were used for each test. All instrumentation was logged on to a high speed data acquisition system. Output data were recorded to a Personal Computer running custom data acquisition software written in LabView.

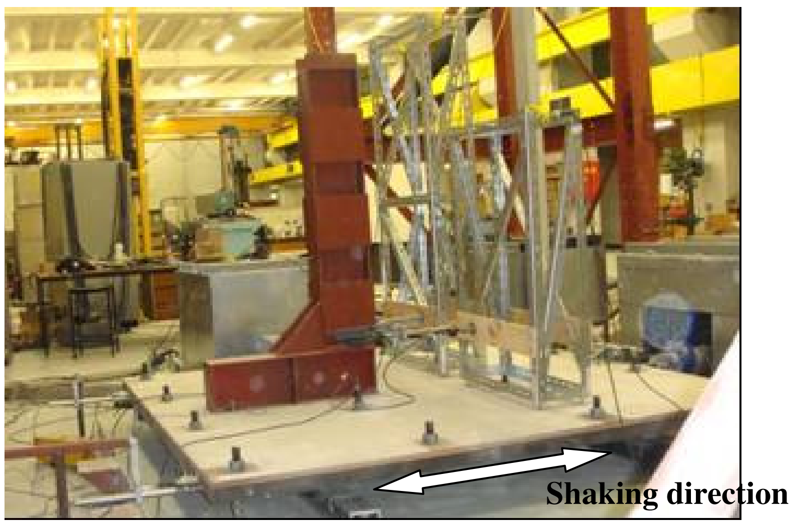


Figure 3: Typical Test set up for the experiment

3.3 Types of base motion

In order to study the dynamic (rocking) behaviour of RBO, three different tests were conducted for each phase: a) Free rocking motion, b) Harmonic motion using single pulse with different frequency and amplitude, and c) Random motion i.e. earthquake excitation. The free rocking motion helps to identify the parameters used in the theoretical analysis and at the same time to calibrate the analytical simulations. Harmonic tests and random earthquake tests allow studying the behaviour of RBO undergoing rocking motion ranging from simple displacement pulse to earthquake excitations.

Tests on specimens were conducted with displacement pulses of frequency ranging from 0.5 Hz to 3 Hz and with displacement amplitude of 20 - 30 mm on the surface of the table. Earthquake motions used in the experiments were based on events with magnitude 5.5 to 7.5 and at epicentral distance of within 50 km. Some of the earthquake motions were generated by stochastic simulations of the seismological model using program GENQKE (Lam, 2002). Table 2 presents the summary of earthquake motions used for this experiment. These earthquake motions have also been employed in the analytical study by Lumantarna et al.

(2009). The acceleration time history of the selected excitations were double-integrated to obtain their corresponding displacement time history and used as input into the shaking table.

Earthquake motions record nos. 1-5 are generally representative of projected earthquake scenarios in regions of low to moderate seismicity; whereas record nos. 6 & 7 were from major events in high seismic regions. The selected earthquakes are classified based on the Peak Displacement Demand (PDD), which is defined herein as the highest point on the elastic displacement response spectrum for 5% critical damping and natural period of up to 5 seconds. Record nos. 1-5 (and with exception of record no. 3) has PDD in the displacement range 50 mm-100 mm whilst record nos. 6 & 7 have PDD in the range 250 mm-500 mm. The spectral properties of the earthquake scenarios are classified based on the position of the 2nd corner period T_2. For records nos. 1- 3, T_2 is below 1 second and for record nos. 4 & 5, the value of T_2 is in between 1 and 2 seconds, and greater than 2 seconds for record nos. 6 & 7. Another property of the ground shaking which influences the displacement demand behaviour is the duration of strong shaking. The earthquake scenarios chosen for this experiment can also be categorized based on its duration properties. The duration of record nos. 1-3 is 10 seconds, record nos. 4 & 5 is 10 – 20 seconds and of 6 & 7 is 20 – 30 seconds.

Table 2: Accelerograms used for this study

Record No.	Spectral properties category	Name of place	Moment Magnitude	Epicentral Distance (km)	Name of input	Remarks
1	A	Generated	6.5	40	A1	Site Classification D*
2	A	Friuli	5.5	19	A2	Date: 11/09/1976 16:35:01, Site Classification D*
3	A	Generated	5.5	17	A3	Site Classification D*
4	B	Generated	7	40	B1	Site Classification D*
5	B	San Fernando	6.6	25	B2	Date: 09/02/1971, Site Classification C*
6	C	Northridge	6.7	3.4	C1	Date: 17/01/1994, Site Classification D*
7	C	El Centro	7	13	C2	Date: 19/05/1940, Site Classification D*

** Site classification is according to IBC (2006)*

4. EXPERIMENTAL RESULTS

4.1 Validation of shaking table excitation

In order to examine the reliability of shaking table during the experiment, acceleration and displacement of the table were measured. The earthquake input record and the measured displacements produced by the shaking table were compared. Generally, the maximum response of the peak ground accelerations and displacements of the shaking table corresponds to that of the specified earthquake input excitations. Comparison of the input displacements with that of the shaking table output for a typical earthquake excitation is given in Figure 4. The corresponding acceleration response spectra is presented in Figure 5 and were generated based on 5% damping.

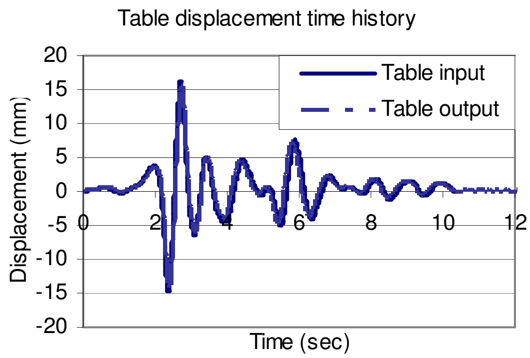


Figure 4: Displacement time history of table input and measured output for A2

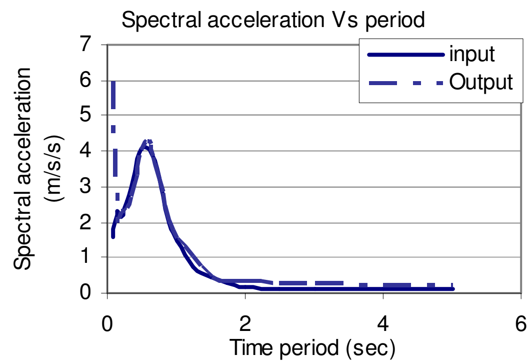


Figure 5: Acceleration response spectra for input and measured output for A2

These plots show that the shaking table reproduced the required displacements accurately and responded well within acceptable accuracy. Table 3 also shows the maximum input and measured output table displacements for all earthquake scenarios.

4.2 Response of rigid body objects

The test was conducted using the input earthquakes given in Table 2. Tests were repeated by gradually amplifying the amplitude of each input motion until either of the specimens (or both) overturns. During the experiment, it was observed that there was no sliding of the objects during shaking. This is because the minimum aspect ratio of test specimen is in order of 6 (reciprocal of 0.17), while the coefficient of friction between the table surface and the base of the object is generally in the range of 0.6-0.9 (Ferdinand et al, 2004). The behaviour of the RBOs was observed to be perfectly rocking motion. Typical displacement time histories of objects' responses for different input excitations are presented in Figure 6 for each specimen.

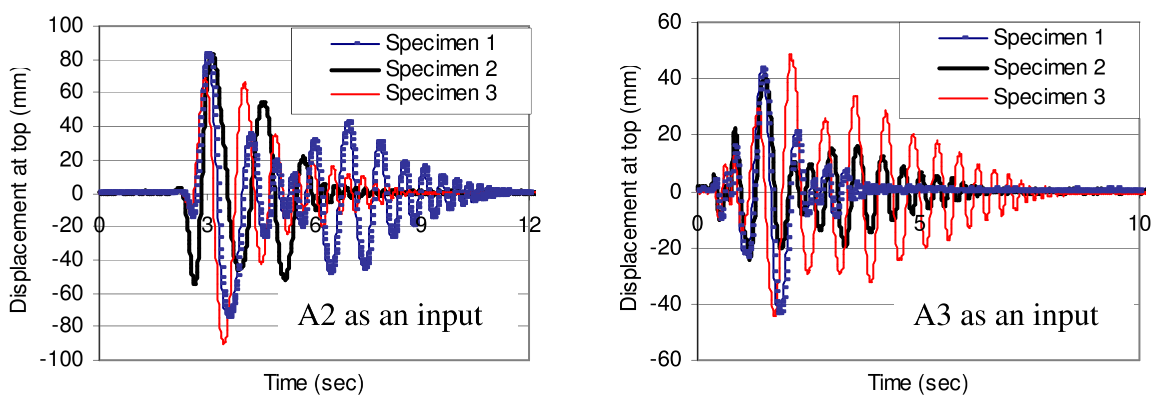


Figure 6: Displacement time history of all three specimens

It was generally observed that the response and its peak value of the objects were similar despite having different geometrical configurations irrespective of the type of input motion. It was observed from the experiment that the maximum response of the taller object was not much more than that of the shorter one. Thus, it implies that the responses of the objects were not dependent on their heights. The maximum response displacements of each of the specimens are tabulated in Table 3 along with the properties of the input motions and input & measured output table displacement.

The results of the experiment shown in Table 3 are for 100 % of the input motion given in Table 2 (except for input C1, which was only 50 % due to the capacity of the instrumentation). From the test of objects with same thickness and different aspect ratio (phase I), the maximum response of taller object was not much more than that of the shorter one. On the contrary for objects with same aspect ratio (phase II), shorter object was observed to be vulnerable for input motion greater than 100 %. These interesting observations from the shaking table experiments are consistent with the analytical study carried out by the authors and collaborators (Bhamare et al, 2008).

Table 3: Summary of test results

Name of input	Input			Response			
	PGA (m/s/s)	RSD_{max} (mm)	Maximum target table displacement (mm)	Maximum measured table displacement (mm)	Maximum response displacement (mm)		
					Specimen 1	Specimen 2	Specimen 3
A1	2.42	56.1	13.0	12.8	68.2	43.6	64.7
A2	2.31	69.8	24.4	23.7	83.7	83.8	90.5
A3	4.01	34	7.9	7.2	48.2	41.2	48.6
B1	1.19	102.9	22.8	22.7	0#	122.5	0#
B2	1.42	98.9	28.0	27.3	0#	89.5	0#
C1*	4.63	542.7	47.2	46.4	overturned	overturned	overturned
C2	3.06	239.4	46.5	46.0	140.9	overturned	201.9
A2+	2.31	69.8	54.9	52.4	overturned	overturned	168

** Applied earthquake in test is only 50 % of C1, while PGA and RSD_{max} shown in table are for 100%.*
 # Rocking did not commence
+ Applied earthquake in test was 225 % of A2, while PGA and RSD_{max} shown in table are for 100%.

It was also observed that the response of objects is dependent on the properties of earthquake inputs. As shown in Table 3, there is no response of specimen 1 & 3 for inputs B1 & B2, while specimen 2 responded. This is due to the fact that rocking of object could be initiated if peak ground acceleration (PGA) of input motion is greater than that of reciprocal of object's aspect ratio.

5. EXPERIMENTAL VERIFICATION

The computer program ROWMANRY (Doherty, 1999) which was developed from the original program ROMAIN (Lam, 1995) was used for the non-linear THA to obtain displacement time history at the top of the RBO. Prior to using the ROWMANRY, it was necessary to calibrate for damping of the specimens for analytical program. There is no constant frequency for the rocking object as it increases with decrease in amplitude of vibration. Hence, the damping of the objects depends on the frequency of vibration and no constant value of frequency and damping could be deduced. The free vibration test conducted for each specimen was used to determine the equivalent viscous damping to be used for the

THA. The damping of the system was modeled with Rayleigh damping with mass and stiffness proportional damping coefficients. Result from the THA is compared with those obtained from the shaking table experiments for the different input excitations. For this purpose, the displacement at the top of RBO was obtained during the experiments and the responses in terms of displacement calculated from non- linear THA. Table 4 summarizes the comparison of maximum response displacement from THA for each RBO with those from the experiments. Clearly, the maximum response displacements obtained from analysis are consistent with those from the experiments.

To validate the result of the non- linear THA from program ROWMNARY and ROMAIN, the displacement time history response obtained from the experiment for a particular input excitation was compared with those from the analysis as shown in Figure 7.

Table 4: Summary of analysis results with experimental comparison

Name of input	Maximum displacement response at top of RBO (mm)					
	Specimen 1		Specimen 2		Specimen 3	
	Analysis	Experiment	Analysis	Experiment	Analysis	Experiment
A1	65.2	68.2	59.8	43.6	65.8	64.7
A2	61.7	83.7	86.1	83.8	87.8	90.5
A3	48.7	48.2	35.5	41.2	50.2	48.6
B1	0#	0#	155.8	122.5	0#	0#
B2	0#	0#	115.6	89.5	0#	0#
C1*	Overturned	Overturned	Overturned	Overturned	Overturned	Overturned
C2	138.5	140.9	Overturned	Overturned	172.9	201.9

** Applied earthquake in test is only 50 % of C1*

 # Rocking did not commence

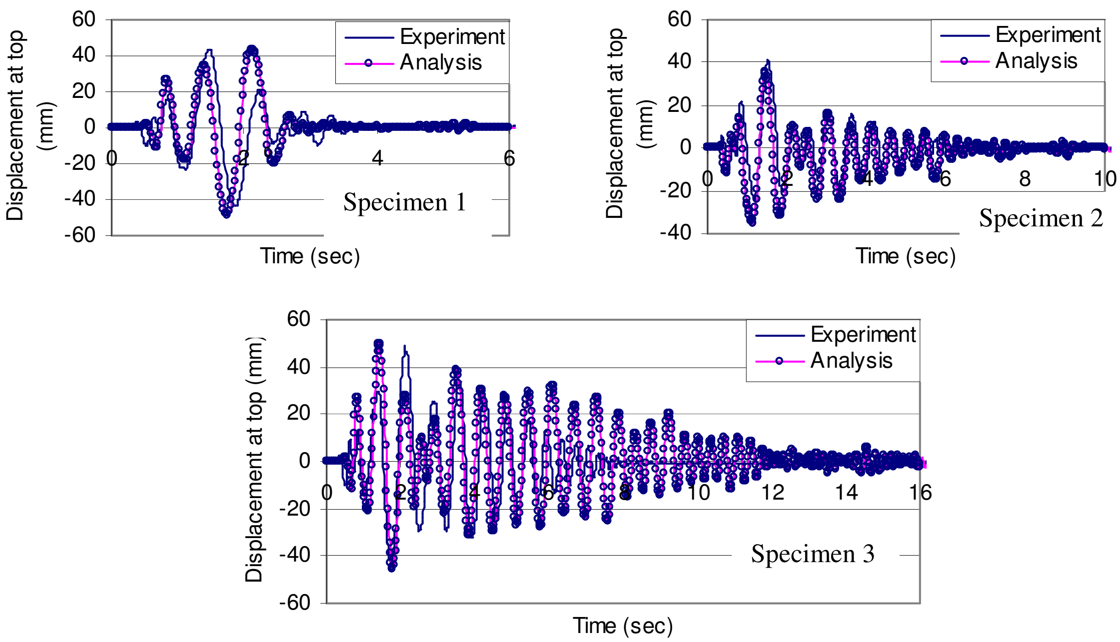


Figure 7: Comparison of displacement time history of different objects for input A3

Overall, the analyses predictions are shown to be consistent with those obtained from the experiments. The responses were in phase for all specimens and were quite matching in the frequency domain. The peaks of the analytical prediction also matched with those from the experiment.

6. CLOSING REMARKS

This paper describes the experimental shaking table test of generic single-degree-of-freedom models that are characterized by non-ductile (strength degradation) behaviour (rigid body objects (RBO) in this case). Extensive shaking table experiment was conducted to observe the rocking behaviour of the RBOs with different thickness and heights. The experimental results are accompanied with the analytical prediction using the well known non-linear time history analysis. Results from the experiments were compared with the analytical results. The analytical predictions are consistent with those obtained from the experiment in terms of peak response, frequency content and phase. It was observed from the experiment that shorter object overturned while the taller one was still rocking during different input excitations. Therefore, it could be concluded that the height of object is not the only factor affecting its response while the thickness is an important parameter that defines the vulnerability of the object in an earthquake. This observation is aligned with the outcomes of recent studies by Al Abadi et al, 2006 and Bhamare et al, 2008.

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