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Rocking response of non-structural free-standing components

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Abstract

The vulnerability of non-structural free-standing components in buildings is well documented from the occurrence of numerous historic earthquakes worldwide. In most commercial buildings, numerous free-standing components are commonly found unrestrained and these components often pose severe risk of overturning failure with life threatening consequences and acute economic losses in the event of an earthquake. Most studies conducted to date on non-structural components have been based on the classical model for overturning. The static and dynamic analyses of free-standing objects using a finite element modelling approach is presented in this paper. The study outlines the development and validation of the finite element model comprising of rigid elements requiring large deformation to simulate the rocking response associated with free-standing slender objects. Dynamic testing of representative free-standing components on a shaking table subjected to base excitation provides the basis for validating the finite element models. The displacement time histories of both experiment and FE models show matching consistency in both time and frequency domains while replicating the peak displacement of the rocking objects. Such modelling approach reported in this study provides a cost-effective approach for understanding the rocking behaviour of non-structural free-standing components.

Keywords: Non-structural, free-standing, rigid body, rocking, finite element model.

1. INTRODUCTION

Non-structural components of a building comprise of elements and components that are not part of the structural system of a building. These components that includes architectural elements including cladding, mechanical and electrical equipment and building contents can be responsive when subjected to dynamic motion. Such components often consist of assemblies of unbonded elements that are regarded as rigid body objects (RBO). Under strong ground excitation, rigid body objects within a building may slide or rock. Other generic examples of rigid objects include a rigid prismatic block resting on a rigid foundation, tombstones, electrical transformers and free-standing water tanks. If friction is high enough to prevent sliding and the earthquake acceleration exceeds a certain limit, these components would undergo rocking motion over their edges as illustrated in Figure 1. Rocking motion is an oscillation characterised by an instantaneous shift between centres of rotation. Initiation of rocking of rigid objects occur when the overturning moment caused by the inertia force exceeds the gravitational restoring moment. During the recent earthquake events of 2011 in New Zealand (Mw = 6.3) and 2012 in Northern Italy (Mw = 5.0), it was reported that numerous historical statues overturned and resulted in severe damage (Cubrinovski et al., 2010; Rossetto et al., 2012; Wittich and Hutchinson, 2015).

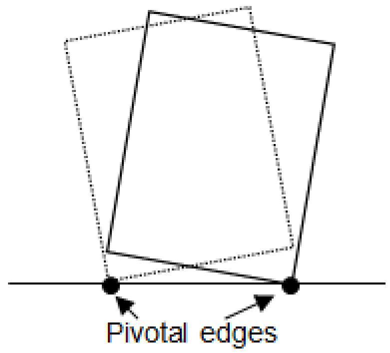


Figure 1: Rigid body rocking

Numerous unrestrained free-standing objects can be found within residential and commercial buildings; either in the form of household furniture or appliances within habitable spaces in residential homes or filing cabinets, storage racks, computer units or similar office and laboratory equipment in commercials spaces. Economic assessment of structural elements, non-structural components and building contents for various classes of buildings have shown that investment cost in non-structural components exceed the cost of structural elements (Whittaker and Soong, 2003) as illustrated in Figure 2. Post-earthquake assessments have revealed that non-structural components and building contents likely to exhibits rigid body behaviour during earthquake events pose severe risk of overturning failure.

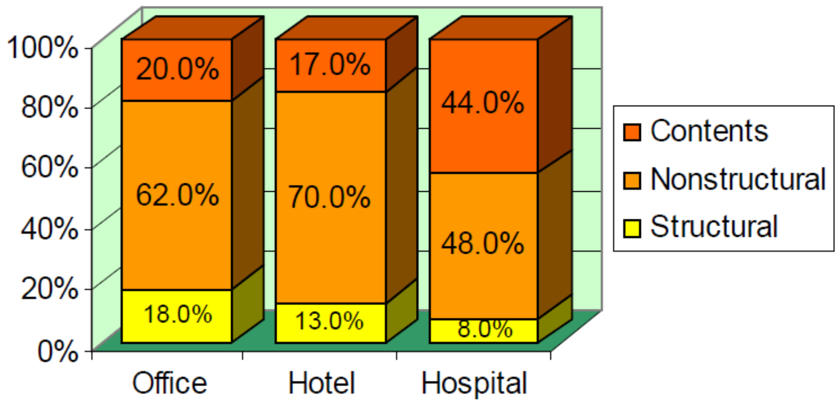


Figure 2: Investment cost in typical buildings (after E. Miranda)

Historically, earthquakes have demonstrated that failure of these free-standing objects could result in severe life safety and economic consequences that is caused by overturning of these objects. During the 1994 Northridge earthquake, it was reported that the estimated cost of building damage was about $18.5 billion with 50% of this cost accounted for non-structural damage (Kircher, 2003). There has also been several reports of overturning damage of electrical transformers, computer systems and laboratory equipment following earthquake events (Aslam et al., 1980; Konstantinidis and Makris, 2009).

Numerous studies have established the vulnerability of non-structural components, which has contributed to improve the seismic performance of these components, particularly the response behaviour of free-standing building content. Most studies undertaken to date has focused on the rocking behaviour of objects with uniform geometry (Aslam et al., 1980; Al Abadi et al., 2006; Lam and Gad, 2008) and assumed to have a regular mass distribution. Few researchers have also conducted studies to investigate the rocking behaviour of asymmetrical objects (Agbabian et al., 1988; Podany, 2008; Di Egidio and Contento, 2010; Al Abadi et al., 2019). Majority of these research are also based on the classical model for overturning focusing on the free rocking response of symmetrical objects (Housner, 1963) and by using the principles of conservation of angular momentum. Experimental investigations of rigid objects have also been undertaken in an attempt to establish the dynamic response of various scaled specimens (Aslam et al., 1980; Tso and Wong, 1989; Wong and Tso, 1989) including dynamic shaking table tests (Kafle et al., 2009; Wittich and Hutchinson, 2015). While majority of building contents do not have regular mass distribution, it is evident that assuming a geometrically symmetric idealisation and using the classical model for overturning would not be representative of the true rocking response of objects with non-uniform mass distribution and asymmetric idealised objects. Conducting experimental tests to evaluate the response behaviour of different geometrically shaped object could also be costly and time consuming. Thus, simple evaluation methods could provide cost-effective solution for evaluating the dynamic response of any rigid object geometry.

The static and dynamic analyses of free-standing objects using a finite element (FE) modelling approach is presented in this paper. The study outlines the development and validation of the finite element model comprising of rigid elements requiring large deformation to simulate the rocking response associated with free-standing objects. Dynamic testing of representative free-standing components on a shaking table subjected to base excitation provides the basis for validating the finite element models. A summary on the behaviour of rigid body objects is described in the next section, followed by the finite element model development and its benchmarking against the experimental shaking table test results.

2. RESPONSE OF RIGID BODY OBJECTS

The dynamic behaviour of rigid body rocking has been of interest to researchers for many years (Housner, 1963; Ishiyama, 1982; Augusti and Sinopoli, 1992; Spanos and Koh, 1984; Tso and Wong, 1989; Wong and Tso, 1989; Yim et al., 1980). Over the last two decades, few analytical models have been proposed to understand the rocking phenomenon of rigid objects. Based on the displacement based (DB) approach, Doherty et al. (2002) developed a simple analytical model for predicting the overturning behaviour of rigid body masonry walls. The force-displacement (F-Δ) relationship of these objects has been proposed using the idealisation of a single-degree-of-freedom (SDOF) system as depicted in Figure 3. More recently, a linearized model for rigid body object was proposed by Al Abadi et Al. (2008) to ascertain the risk of overturning. The fundamental dynamics of rigid body motion is not covered in this paper and could be found elsewhere (Housner, 1963; Makris and Roussos, 1998; Doherty, 2000; Prieto and Lourenço, 2005; Al Abadi, 2008; Gesualdo et al., 2018).

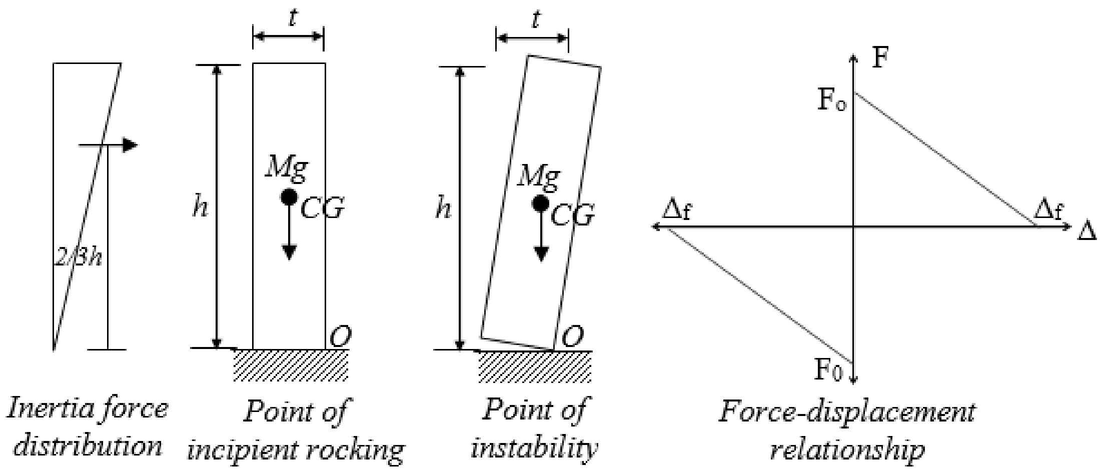


Figure 3: Force-displacement behaviour of rigid objects

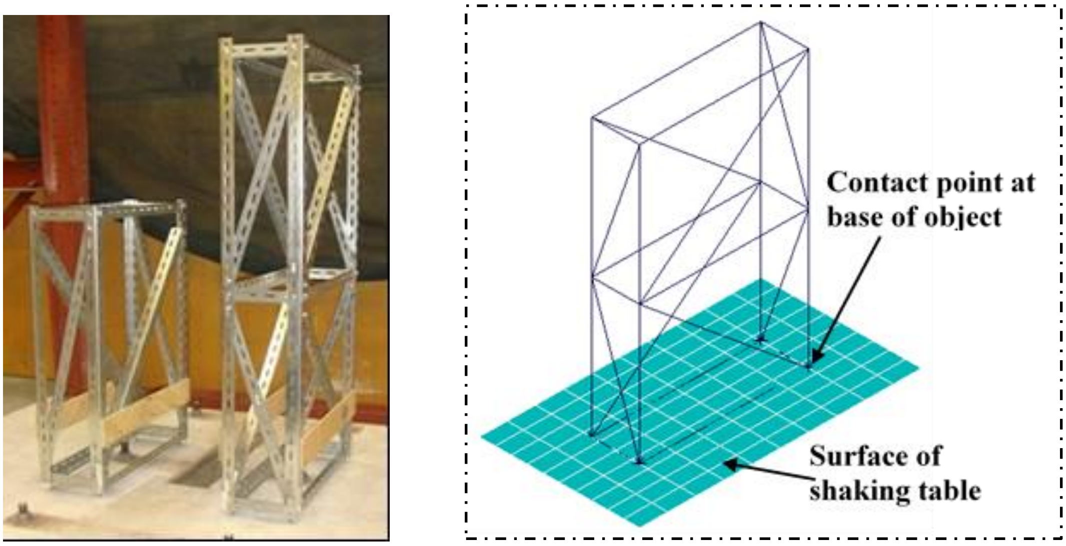
Comprehensive details of the experimental study undertaken on rigid body objects and which provides the basis for validation of this study has already been reported (Kafle et al., 2009). The main objective of the experimental study was to establish the influence of the aspect ratio on the dynamic response of rigid body objects. The finite element analyses presented in this paper utilises the same geometry and configuration of the specimens (refer Table 1) that were fabricated using slotted steel angle sections and experimentally tested. Spectral properties of the earthquake ground motions used in the shaking table tests as previously reported (Kafle et al., 2009) were also intentionally selected for analysing the finite element models described in this paper as given in Table 1. In the experimental test setup, displacement transducers were used to capture various displacements (absolute and relative) of the rocking objects. Accelerometers and displacement transducers were also used to respectively measure accelerations and displacements of the shaking table and all data generated from the dynamic tests were logged on to a high-speed data acquisition system. Processed experimental results then provide the basis for validation of the finite element models presented herein.

Table 1: Geometry of specimen and earthquake properties (Kafle et al., 2009)

Properties of specimens for FE simulations					Earthquake input properties	
Specimen	Thickness, t (mm)	Height, h (mm)	Width, b (mm)	Object's Aspect ratio	Earthquake input	Moment magnitude (Mw)
1	170	1000	600	5.88	A2, A3	5.5
2	170	1500	600	8.82	A2, A3	5.5
3	255	1500	600	5.88	A2, A3	5.5

3. FINITE ELEMENT (FE) MODELLING

The methodology employed for developing and validating the FE model is presented in the following subsequent sections. The objective of this section is to develop a simple numerical model for simulating the behaviour of rigid body objects when subjected to earthquake excitation. The FE model representing the rigid body object was developed using the ANSYS FE package. Three-dimensional (3D) beam elements were used to model the geometry of the rocking objects. The equivalent cross-sectional area of the steel sotted sections and density of steel were used as real constants into the FE model. This makes it possible to check the weights of the physical objects against those of the FE models. The four corners at the base of the object were fitted with contact elements to represent the pin points that were in contact with the shaking table surface during the experiment. Comprehensive details of the properties of the finite element model and the systematic numerical procedure implemented in ANSYS is reported elsewhere (Paton-Cole, 2014). The shaking table was represented with a 3D rigid platform and modelled with a target element on the surface. A schematic of the finite element representation of the rigid body object is shown in Figure 4. In the FE analyses, the three representative configurations tabulated in Table 1 were modelled, evaluated and validated as described below.



(a) (b)

Figure 4: Representative rigid body object: (a) Fabricated specimen (Kafle et al., 2009); (b) FE model

4. EXPERIMENTAL AND FE EVALUATION

To reliably verify the dynamic rocking behaviour of the rocking objects presented in this paper, two sets of analyses were conducted in ANSYS namely: (a) Static analysis; and (b) Transient analysis. Details of these analyses are described in the following sections.

4.1 STATIC ANALYSIS

Prior to conducting the dynamic analysis, the models were verified using static analysis. This was achieved using the displacement-based concept of a uniform rectangular object when displaced to the point of incipient instability (Lam and Gad, 2008). In this analysis, an increasing displacement was applied at the top of a representative FE model (200 mm wide) and the force (F_0) which represents the point of incipient rocking (when Δ=0) of the model evaluated. The displacement was applied until the point of incipient instability at which point when the object is about to overturn. At the point of incipient instability, the displacement at the top equals the thickness of the object. The force displacement relationship for the static analysis of the specimen is shown in Figure 5. The FE model exactly matched the calculated threshold force, F_0 of 10.8 N at incipient rocking.

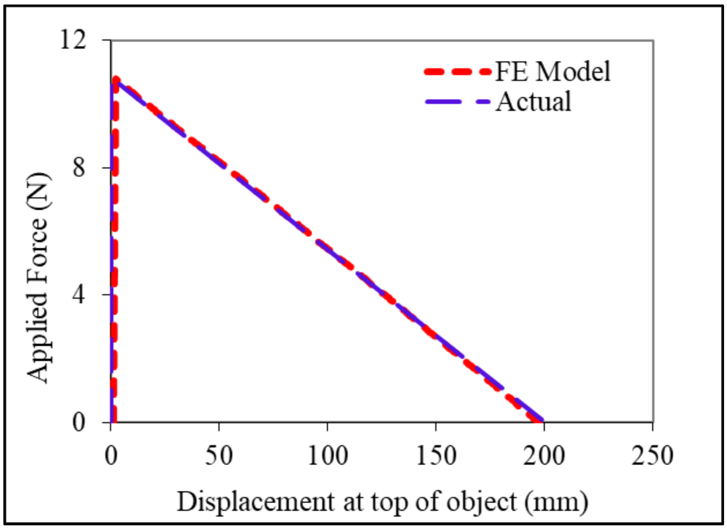


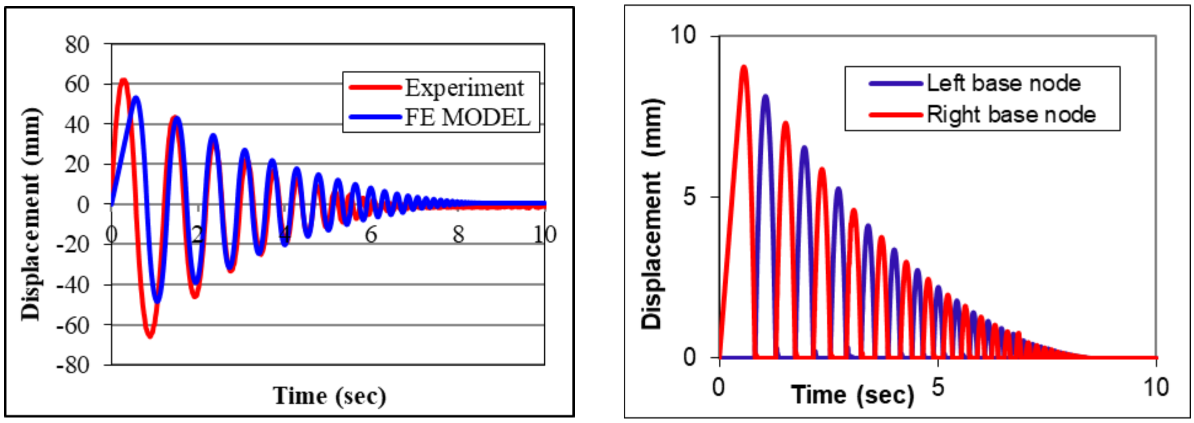
Figure 5: Force-displacement relationship of rigid body object from static analysis

As expected, as the external displacement is applied, the object exhibited an infinitely stiff resistance (overturning resistance) characterised by a vertical line at zero displacement until the threshold force (F_0) is reached as shown in Figure 5. As the object is further displaced, a negative stiffness is obtained until the centre-of-gravity is above the pivotal edge (point O), reaching the point of incipient instability.

4.2 FREE VIBRATION TEST

Experimental validation of the FE model was undertaken by conducting free rocking test on one of the specimens. The test was performed by displacing the object within the limits of incipient instability and then released to rock freely between the pivotal contact points at the base. Comparison of the response between the free vibration test result obtained experimentally and the FE model for specimen 1 (170 mm x 1000 mm) is shown in Figure 6a. The responses show a very close correlation as the FE model adequately represents the dynamic response of the test specimen. The disparity between the first cycles of vibration resulted in the different positions from which the object was released to rock in the experiment and FE analysis respectively. However, as the object rocks between its pivotal points, the responses matched satisfactorily in terms of the displacement amplitude and time domain for subsequent cycles. The results from the free vibration tests provided the basis to determine the equivalent viscous damping used in the finite element model developed for the shaking table test simulations.

The vertical displacement of the base nodes of the rocking object was evaluated and compared as shown in Figure 6b. As characterised, it is evident that the base nodes were rocking successively as energy loses from damping gradually returns the object to rest. No observed penetration through the node contact or surface target elements at the base to shaking table interface. Upon verification of the free vibration test, it was concluded that the properties chosen for representing the rigid body objects and the contact and target elements were appropriate. Thus, it was concluded that the rocking response of rigid body objects under earthquake base excitation could be satisfactorily modelled using numerical simulations and yielding results within acceptable level of accuracy.



(a) (b)

Figure 6: Specimen 1: (a) Comparison of free vibration results; (b) Vertical displacement of base nodes

4.3 SIMULATION OF DYNAMIC TESTS

To further verify the accuracy of the responses obtained from the numerical study, the FE model was subjected to the same earthquake intensities used for conducting the experimental shaking table tests as given in Table 1. For validation purposes of the representative FE models reported in this study, only earthquakes A2 and A3 were used to analyse specimens 1, 2 and 3 whose geometries are summarised in Table 1. For reliability of the results, the displacement-time histories recorded at the shaking table during the laboratory investigation were used as base input for exciting the FE models. Comparison of the displacement time histories of the input excitation and the shaking table output showed matching responses (Kafle et al., 2009). Using the displacement output time-histories of the shaking table ensures that the FE rocking models were subjected to the same level of excitation as the physical specimens that were experimentally tested. To validate the FE model results, the peak displacements measured at the top of the object during the shaking table test were correspondingly compared with those obtained for the FE model. Figures 7 (a-d) shows comparison of the displacement-time history results for the specimens analysed. As indicated by the responses, the FE simulations and experimental results show an acceptable level of correlation with negligible discrepancies.

From the three models considered in the numerical simulations, a total of six analyses were conducted using earthquakes A2 and A3. The maximum displacement responses obtained for all FE analyses are compared with those obtained from the experimental test and summarised in Table 2. The tabulated rocking displacements show that the FE model adequately simulated the peak responses of the physical objects with acceptable accuracy. The FE analyses revealed that the responses of the rocking models exhibited pure rocking motion and no sliding of objects occurred when the earthquake excitation was applied. Upon evaluation of the results, it was concluded that the FE model will thus provide an accurate basis for simulating the response of rigid body objects and can be used to investigate a range of rigid rocking scenarios.

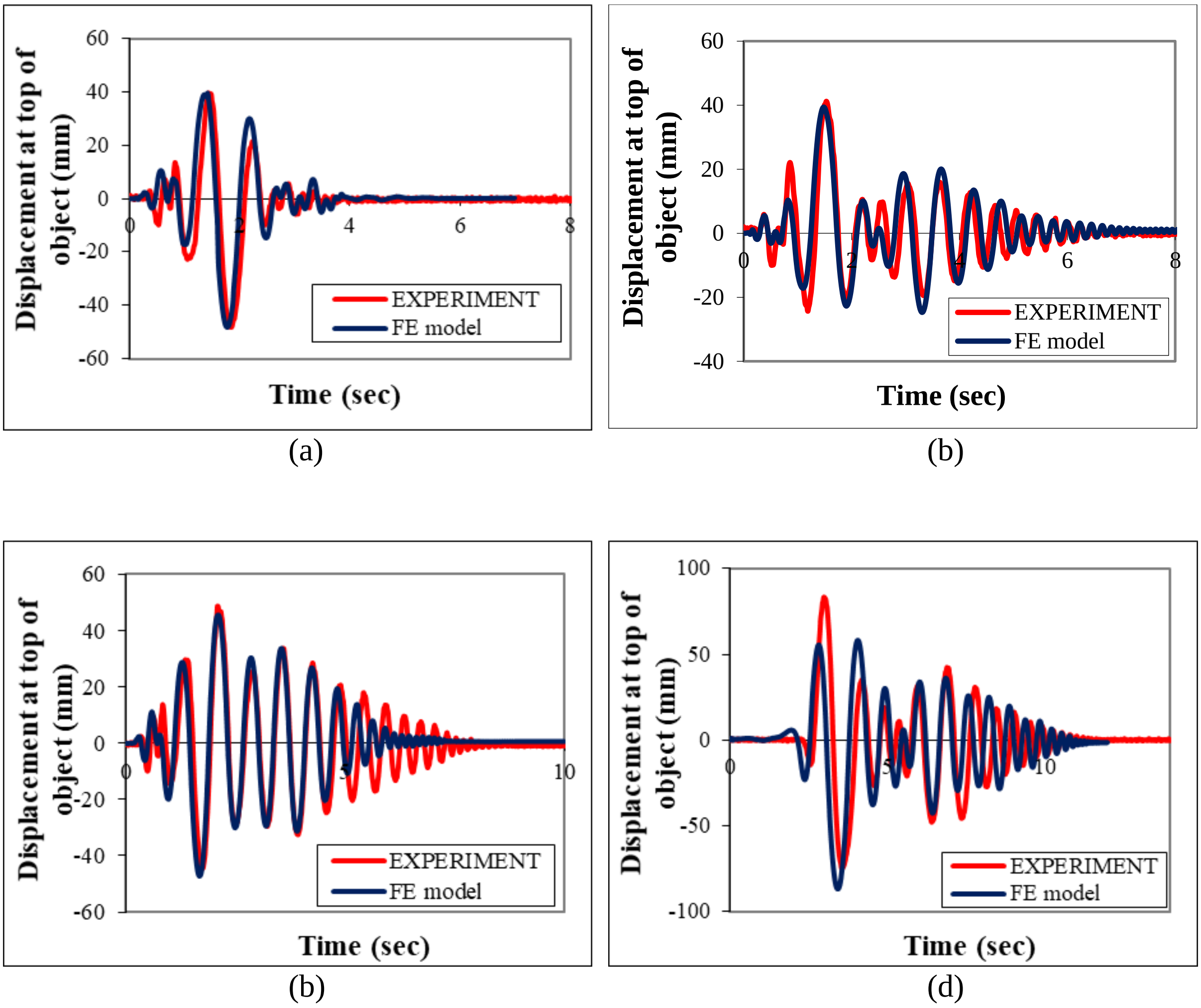


Figure 7: Comparison between experiment and FE simulation displacement time-histories: (a) specimen 1 for earthquake input A3; (b) specimen 2 for earthquake input A3; (c) specimen 3 for earthquake input A3; (d) specimen 1 for earthquake input A2

Table 2: Summary of results compared between Experiment and FE analyses

Earthquake Input	Maximum rocking displacement response at top of specimen (mm)					
	Specimen 1		Specimen 2		Specimen 3	
	FE Model	Experiment	FE Model	Experiment	FE Model	Experiment
A2	86.4	83.7	84.6	83.8	88.5	90.5
A3	48.1	48.2	39.4	41.2	45.5	48.6

5. CONCLUSION

Non-structural components and building contents represent a significant portion of the investment cost in various classes of buildings and their overall value generally exceeds that of their structural counterpart. During earthquake events, damage to non-structural components and building contents often constitute a substantial part of the estimated cost of the overall damage. Post-earthquake reconnaissance assessments have reported the vulnerability of these building elements while numerous researches have experimentally and analytically demonstrated the rocking ability of these components with the risk of overturning failure.

This paper presents a comprehensive numerical study that can be used for simulating the rocking response of non-structural free-standing objects. The approach presented in this paper provides a basis to simulate the rocking response of non-structural components representative of any form and provide a cost-effective solution for evaluating the dynamic response of rigid body objects regardless of geometry or mass distribution. Results from extensive shaking table experiments were used to validate the accuracy of the numerical models presented in this study and considering various modes from static and dynamic tests. Comparative analysis between the experimental results and FE simulations showed matching responses in the time/frequency domain with corresponding peak displacements.

6. REFERENCES

Agbabian, M., Masri, S., Nigbor, R. & Ginell, W. (1988). Seismic damage mitigation concepts for art objects in museums. *Proceeding of ninth world conference on earthquake engineering*, August 2–9, 1988, Tokyo-Kyoto, Japan. pp. 235–240.

Al Abadi, H. (2008). *Unrestrained Building Contents in Regions of Low-Moderate Seismicity.* Ph.D Thesis, The University of Melbourne.

Al Abadi, H., Lam, N. & Gad, E. (2006). A simple displacement-based model for predicting seismically induced overturning. *Journal of Earthquake Engineering*, 10**,** 775-814.

Al Abadi, H., Paton-Cole, V., Gad, E., Lam, N. & Patel, V. (2019). Rocking Behavior of Irregular Free-Standing Objects Subjected to Earthquake Motion. *Journal of Earthquake Engineering*, 23**,** 793-809.

Aslam, M., Scalise, D.T. & Godden, W.G. (1980). Earthquake rocking response of rigid bodies. *Journal of the Structural Division*, 106**,** 377-392.

Augusti, G. & Sinopoli, A. (1992). Modelling the dynamics of large block structures. *Masonry Construction***,** 195-211.

Cubrinovski, M., Green, R., Allen, J., Ashford, S., Bowman, E., Bradley, B.A., Cox, B., Hutchinson, T., Kavazanjian, E., Orense, R., Pender, M. & Wotherspoon, L. (2010). Geotechnical Reconnaissance of the 2010 Darfield (New Zealand) earthquake. *University of Canterbury*, New, Zealand.

Di Egidio, A. & Contento, A. (2010). Seismic response of a non-symmetric rigid block on a constrained oscillating base. *J Engineering Structures*, 32**,** 3028-3039.

Doherty, K. (2000). *An investigation if the weak links in the seismic load path of unreinforced masonry buildings.* Ph.D Thesis, The University of Adelaide.

Gesualdo, A., Iannuzzo, A. & Monaco, M. (2018). Rocking behaviour of freestanding objects. *Journal of Physics: Conference Series (Vol. 1141, No. 1)*, 2018. pp. 012091.

Housner, G.W. (1963). The behavior of inverted pendulum structures during earthquakes. *Bulletin of the seismological society of America*, 53**,** 403-417.

Ishiyama, Y. (1982). Motions of rigid bodies and criteria for overturning by earthquake excitations. *Earthquake Engineering & Structural Dynamics*, 10**,** 635-650.

Kafle, B., Paton-Cole, V.P., Lam, N.T., Gad, E.F. & Wilson, J.L. (2009). Shaking Table Tests on Strength Degradation Behaviour. *Proceeding of annual technical conference of the Australian Earthquake Engineering Society*, Dec. 11- 13, 2009, 2009, Newcastle, NSW, Australia. pp. paper No. 37.

Kircher, C.A. (2003). It makes dollars and sense to improve nonstructural system performance. *Proc. ATC 29-2. Seminar on seismic design, performance and retrofit of nonstructural components in critical facilities*, October 23-24, 2003, 2003, Newport Beach, CA. pp.

Konstantinidis, D. & Makris, N. (2009). Experimental and analytical studies on the response of freestanding laboratory equipment to earthquake shaking. *Earthquake Engineering & Structural Dynamics*, 38**,** 827-848.

Lam, N. & Gad, E. (2008). Overturning of Nonstructural Components in Low-Moderate Seismicity Regions. *Electronic Journal of Structural Engineering***,** 121-132.

Makris, N. & Roussos, Y. (1998). Rocking response and overturning of equipment under horizontal pulse-type motions. *Pacific Earthquake Engineering Research Center*.

Paton-Cole, V.P. (2014). *Out-of-plane dynamic response behaviour of brick veneer steel-framed walls.* Ph.D Thesis, The University of Melbourne.

Podany, J. 2008. *Advances in the Protection of Museum Collections from Earthquake Damage: Papers from a Symposium Held at the J. Paul Getty Museum at the Villa on May 3-4, 2006*, Getty Publications.

Prieto, F. & Lourenço, P.B. (2005). On the rocking behavior of rigid objects. *Meccanica*, 40**,** 121-133.

Rossetto, T., Alexander, D., Verrucci, E., Ioannou, I., Borg, R., Melo, J., Cahill, B. & Kongar, I. (2012). The 20th May 2012 Emilia Romagna Earthquake. *UCL EPICentre, University College London,* United Kingdom.

Spanos, P.D. & Koh, A.S. (1984). Rocking of rigid blocks due to harmonic shaking. *Journal of Engineering Mechanics*, 110**,** 1627-1642.

Tso, W.K. & Wong, C.M. (1989). Steady state rocking response of rigid blocks part 1: Analysis. *Earthquake Engineering & Structural Dynamics*, 18**,** 89-106.

Whittaker, A. & Soong, T. (2003). An overview of nonstructural components research at three US Earthquake Engineering Research Centers. *Proc., ATC Seminar on Seismic Design, Performance, and Retrofit of Nonstructural Components in Critical Facilities*, 2003, Redwood City, CA. pp. 271-280.

Wittich, C.E. & Hutchinson, T.C. (2015). Shake table tests of stiff, unattached, asymmetric structures. *Earthquake Engineering & Structural Dynamics,* 44**,** 2425-2443.

Wong, C.M. & Tso, W.K. (1989). Steady state rocking response of rigid blocks part 2: Experiment. *Earthquake Engineering & Structural Dynamics,* 18**,** 107-120.

Yim, C.S., Chopra, A.K. & Penzien, J. (1980). Rocking response of rigid blocks to earthquakes. *Earthquake Engineering & Structural Dynamics*, 8**,** 565-587.