

# Overturning of Non-Structural Components in Low-Moderate Seismicity Regions

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**ABSTRACT:** The objective of this paper is to review key issues concerned with the proper engineering of non-structural components in buildings for their safe and satisfactory performances in projected seismic conditions in regions of low and moderate seismicity. Initially, the paper provides an overview of the conventional force-based provisions for the calculation of the required strengths for full restraints of non-structural components. Given the relatively small displacement demand of the ground in conditions of low and moderate seismicity, provisions for protection of non-structural components should only target at items which have been identified to be vulnerable to overturning and their failure can have serious consequences. In this context, the displacement-based (DB) model for overturning and its linearisation is presented. The DB model can potentially become very useful as technical reference when it comes to identifying potentially hazardous items which risk overturning if unrestrained. The paper concludes with a discussion on engineering for earthquake safety in buildings in a broader context than merely regulating the structural design of the building.

**KEYWORDS:** seismic, earthquakes, building contents

## 1 INTRODUCTION

Non-structural components in the context of this paper refer to architectural features, mechanical/electrical equipment providing services to the building and building contents (refer Table 1). Widespread damage to non-structural components in buildings continues to be observed in recent earthquakes. Whilst statistical cost data for non-structural damage are scarce, it is widely agreed and reported that the economic effects of all non-structural damage combined generally exceed those of structural damage in an earthquake (Brunsdon & Clark, 2001). For example, in a survey of 355 high-rise buildings after the 1971 San Fernando earthquake, it was shown that in dollar value terms, 79% of the damage was non-structural (Arnold et al, 1987). Despite this, earthquake engineering research worldwide has been directed mainly to performance issues associated directly with the structural elements or the building structure as a whole.

The argument for explicit considerations of non-structural damage is even stronger in low to moderate seismicity regions which are characterized by the infrequent occurrences of earthquakes of low-medium magnitude ( $<M7$ ). When struck by relatively shorter duration, and higher frequency, ground shaking generated by those events, the majority of buildings including those that have not been designed to resist earthquake loading would not risk collapsing in earthquake scenarios consistent with a

notional peak ground acceleration in the order of 0.1g. This phenomenon can be explained by the limited drift demand of the earthquake given that the drift demand increases with increasing moment magnitude when the peak ground acceleration is kept constant. It is noted, however, that certain buildings including those with a soft-storey feature are considered to be at risks due to their very limited displacement capacity.

Slender objects that are free-standing within the building are particularly vulnerable to overturning given that the amount of displacement to overturn a slender object can be very small, and furthermore, the displacement of the floor at the upper level of the building can be many times higher than that of the displacement of the ground. Containers of hazardous items that are not secured to the wall, or floor, of the building can also be at risk of overturning.

The same can be said of items which are initially attached to the building but become unrestrained when the attachment fails. This phenomenon is well exemplified in the M5.6 earthquake which struck the city of Newcastle, New South Wales, Australia in 1989 at an epicentral distance of about 15 km (Melchers Ed., 1990). All but one building survived the earthquake without suffering collapses but the entire city was devastated by the widespread collapse of brick façade walls (and parapet walls) which had not been adequately secured to the structural frame of the building. The outer-leaf layer of brickwork were both slender and unrestrained when without the

adequate support by effective brick ties. Another class of potentially vulnerable items which has become a feature of the urban streetscape in cities like Hong Kong is advertisement signs that proliferate above the road pavement. Gantries supporting the signs from the building facade can become vulnerable in an earthquake because of their sensitivity to force (acceleration) demand at ultimate conditions. Furthermore, the seismically induced inertia forces applied to the sign gantry can superpose on the gravitational forces (whilst wind forces would not necessarily superpose in the same way). When the force capacity of the attachment has been overcome, the amount of displacement required to dislodge the gantry can be merely the embedment depth of the anchor bolts.

The objective of this paper is to review our current state of knowledge on the key issues that have been outlined. Section 2 contains a review of the conventional force-based approach in contemporary codes of practices for designing the full restraints of non-structural components. Section 3 introduces the alternative displacement-based (DB) methodology which can be used for assessing the overturning vulnerability of items that are unrestrained, or inadequately restrained. Non-structural components that are the subject matter of interests in this paper are floor motion sensitive components. Another class of NS components includes facades and vertical piping. The performance of this latter class of components in an earthquake depends on the amount of interstorey drift which is directly translated into the deformation of the component. The performance assessment of drift-sensitive components are outside the scope of this paper.

Table 1. Non-structural components.

Categories	Examples
Architectural Features	Partitions, false ceilings, facades, parapets, chimneys, canopies.
Mechanical/Electrical Equipment	Boilers, transformers, pumps, motors, piping.
Building Contents	Furniture, shelving, heavy items on racks and other free-standing items.

## 2 FORCE-BASED ASSESSMENT OF FULLY RESTRAINED COMPONENTS

Current Standard provisions for protecting floor mounted objects in buildings as outlined above are mainly about estimating the peak acceleration of the floor in order that the required strength of the restraints can be estimated (FEMA302, NZ4203 & AS

1170.4). Design calculations are always aimed at estimating the transmission and amplification of the peak horizontal acceleration from the ground to the individual floor, and eventually to the centre of inertia of the component (Clark, 1993; Hall, 1995; Arnold et al, 1987 and Arnold, 1991; Lam et al, 1998; Beattie, 2000 & 2001). In designing the restraints of an acceleration sensitive component, the seismic design force (F) is basically the product of the self-weight of the component ( $W_c$ ) and the peak ground acceleration ( $a_{ground}$ ). Meanwhile, the importance factor ( $I_c$ ) is introduced as a scaling factor. Amplification by the component mounting is taken into account by the factor  $a_c$ , whilst amplification by the building floor is taken into account by the factor  $a_f$ . The overall principle is illustrated in Figure 1.

Major earthquake loading standards around the world are based on similar principles, but different notations have been used and expressions used for the calculation of the individual factors can vary a great deal between the standards for similar conditions and component type. Whilst the notations adopted in equation 1 and Table 2 are based on provisions in AS 1770.4 (2007) developed for Australia, this section is intended to provide a generic overview on the framework adopted by major design codes of practices around the globe.

$$F = W_c \cdot Z \cdot I_c \cdot a_f \cdot a_c / R_c \quad (1)$$

The seismic hazard zone factor (Z) can be described as the notional peak ground acceleration on an average rock site for the area under considerations (and can be taken as the value of  $a_{ground}$  in Figure 1). In regions of low and moderate seismicity such as Australia, the value of Z typically varies in the range: 0.05g – 0.15g and may increase up to 0.4g in regions of high seismicity such as California.

The importance factor ( $I_c$ ) typically varies between 1.0 and 1.5 depending on the consequence of failure of the component in regard to life-safety and to the continuous functioning of the affected facilities. In the New Zealand Standard, the importance of the building and the importance of the component are represented by separate factors.

The height amplification factor of the floor ( $a_f$ ) in simplified code models typically varies linearly from the ground level to the roof level. In Australia, the value of  $a_f$  at the roof level can be taken as 3 but much lower values are stipulated for low-rise buildings (refer Figure 2a). NEHRP recommendations adopt the more rational approach of defining  $a_f$  at roof level as the product of (i) the normalised elastic response spectral acceleration at the fundamental natural period of the building (which is dependent on the site class) and (ii) a participation factor of 2.

Provisions in the New Zealand Standard is more elaborate as ductility and over-strength in the building are both taken into account in the calculation of the floor responses. Alternatively, the floor acceleration may be obtained by dividing the seismic design force of the floor by the mass of the floor in which case the calculated floor accelerations might not necessarily vary linearly between the ground and the roof of the building (refer Figure 2b). Whilst rigorous analysis of the building structure can be employed to provide accurate estimates of the floor response, they do not offer a convenient way of estimating the behaviour of existing buildings when their design calculations are not readily available.

The component amplification factor ( $a_c$ ) typically varies between 1 for components which are generally regarded as rigid and 2.5 for flexibly mounted components, or spring isolated components. In the NEHRP recommendations, values of  $a_c$  are clearly stated for different component types. In the New Zealand Standard, the response behaviour of the component and its mounting is modeled in a manner similar to that for the aseismic design of a building. Thus, the inelastic response spectra stipulated in the Standard for the calculation of the seismic forces applied to the side of a building are also used for the calculation of the seismic forces applied to a non-structural component. With this calculation approach, the amplification response behaviour and the energy dissipation characteristics of the component mounting are covered by similar factors.

The Reduction Factor ( $R_c$ ) varies a great deal between the Standards, and very different values are specified by the same standard for different components. The Australian Standard is relatively conservative given that  $R_c = 1.0$  is specified for components made of ceramic materials (ie. no reduction) and a default value of 2.5 for other components. Provisions developed for high seismicity countries such as NEHRP allow  $R_c = 6$  to be taken for certain ductile components. For the majority of components, the recommended values of  $R_c$  does not exceed 3.

Inconsistencies between the Standards are evident from the brief review presented above. A comprehensive comparison of the force-based provisions in major codes of practices for the restraining of NS components in buildings was given by Phan & Taylor (1996) which revealed up to five-fold discrepancies in the recommended amplification factors.

The review publication by Rodriguez et al (2002) made recommendations for the peak floor accelerations based on rigorous non-linear dynamic analysis of building structures ranging between three and twelve stories. An independent study by Yao & Chiu (2001) developed floor spectra from floor accelerograms recorded in 19 buildings during the 1999 Chi-

Chi earthquake (Taiwan). These studies revealed very high amplification factors as well as considerable uncertainties in the prediction of the peak floor accelerations. It should be noted that none of these studies directly addresses motions and shocks experienced by components which have not been adequately restrained to the floor.

To illustrate this knowledge gap, a floor mounted liquid container is used herein as an example. If the strength of the restraining device is exceeded during moderate floor shaking, damage is initiated by yielding of the bolts and yielding/tearing of the brackets. Repair work would then be required. However, the continuous functioning of the container is not necessarily interrupted, provided the connector pipes remain intact. It should be noted that high acceleration may only cause rattling or limited rotation of the container in the vertical plane without necessarily causing overturning (which is dependent on the displacement at the centre of gravity of the container). The vulnerability to damage initiation of the restraining device must be distinguished from the vulnerability to loss of function or overturning of the container which can result in extensive collateral damage.

A recent field survey undertaken by the author and his collaborators in Melbourne, Australia revealed a total lack of restraints to a whole range of building components including boilers, cabinets and storage racks (Al Abadi et al, 2003 & 2004). Implementing a blanket policy to restrain all existing components is a major undertaking. The costs involved in this undertaking would be difficult to justify particularly in regions of low and moderate seismicity where risks of damage and destruction by an earthquake are widely perceived to be "remote". Furthermore, building contents such as furniture items are beyond the scope of control of building design regulators and yet the performance of these items has important life safety implications in the event of an earthquake. For example, the overturning of free-standing tall furniture items (eg. shelving racks) with heavy storage items are potentially fatal and could hinder the safe egress of occupants following an earthquake whilst fires are often triggered by earthquake induced shaking of the building. With objects which are unrestrained, or inadequately restrained, it is important to know precisely how vulnerable are these objects to overturning in the event of an earthquake (noting that the failure of the restraining device is not necessarily translated into overturning). Resolving these unknowns would result in the correct ranking of relative vulnerability of components in a building.

Table 2. Factors controlling the seismic force applied to a non-structural component.

Factor	Description
$W_c$	Weight of the component.
$Z$	Seismic hazard zone factor.
$I_c$	Importance factor.
$a_f$	Height amplification factor of the floor which takes into account the dynamic response behaviour of the building up its height.
$a_c$	Amplification factor of the component which takes into account the dynamic amplification behaviour of the component mounting.
$R_c$	Reduction factor which takes into account the effects of energy dissipation of the component mounting.

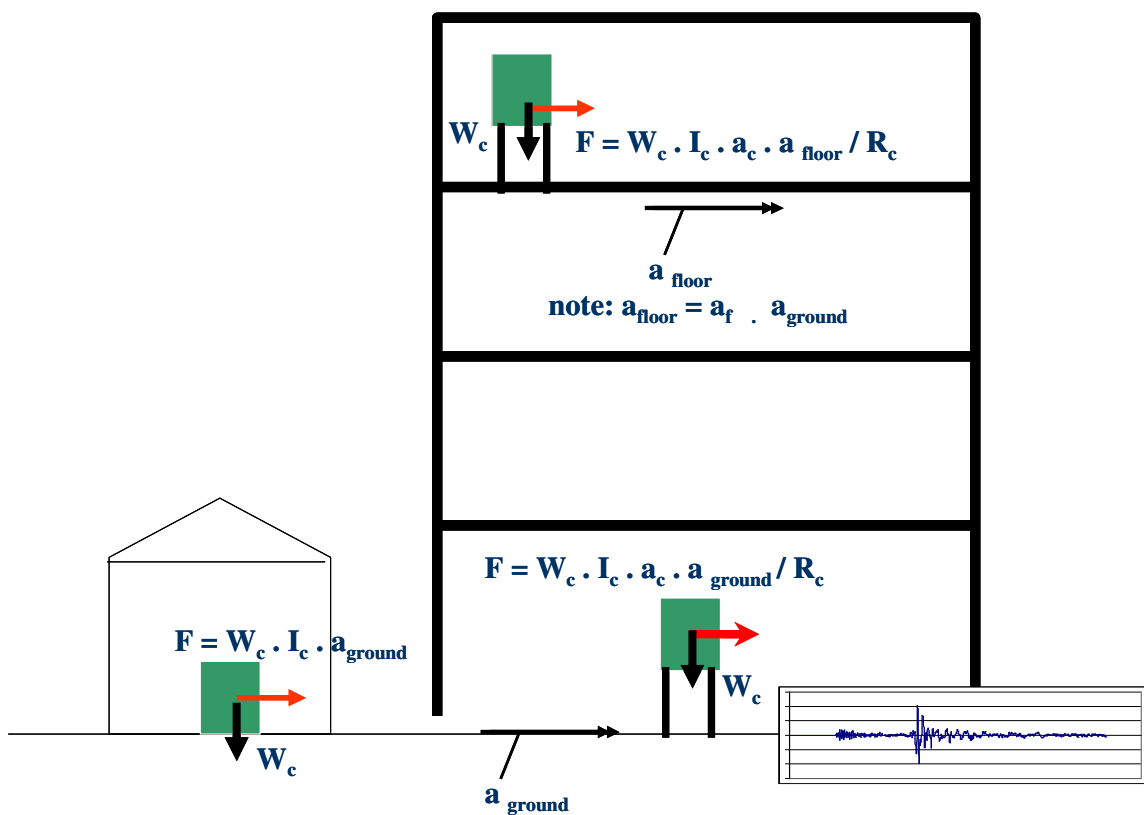
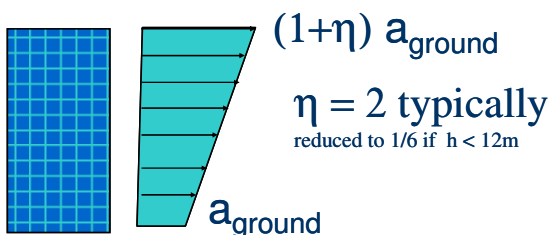


Figure 1. Schematic illustration of code model for seismic force on component.

Typical provisions :

Simplified approach :

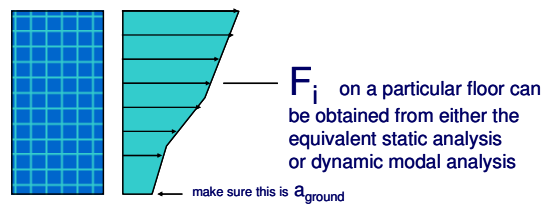
$$a_{\text{floor}} = a_{\text{ground}} \times \text{height amplification factor}$$



(a) Simplified Model

The alternative analytical approach :

$$a_{\text{floor}} = \text{Design inertia force of floor / floor mass, or } F_i / M_i$$



(b) Rigorous Model

Figure 2. Height amplification of floor acceleration.

Clearly, the current approach of calculating peak acceleration and seismic inertia force is too restrictive to distinguish between tolerable and intolerable damage for the purpose of retrofit planning. This lack of knowledge in the component vulnerability is conceded in code commentaries (e.g. FEMA303) and is reflected in the very conservative response factors specified for components mounted on common anchoring devices (FEMA273, FEMA303 & NZ4203).

Velocity, as opposed to acceleration, has been used as the alternative parameter to characterize the risk of damage to free-standing objects. For example, isolated studies by (Ishiyama, 1984) have identified the direct link between floor velocity and the overturning vulnerability of uniform objects based on idealized representation of the floor motion. However, the developed model based on the considerations of velocity could not be generalized to the realistic excitations of a small-medium sized earthquake which is characterized by displacement controlled behaviour (wherein the highest displacement demand of the earthquake can be accommodated by the component). Risk assessment for overturning based on displacement controlled principles will be described in detail in Section 3.

### 3 DISPLACEMENT-BASED ASSESSMENT OF VULNERABILITY TO OVERTURNING OF FREE-STANDING OBJECTS

Studies reported in this section were based purely on free-standing conditions, and without any restraints. The authors believe that the condition of “free-standing” is a conservative assumption when applied to components that are with some, but inadequate, restraints in which case the component is only free of restraints in the later part of the excitations following failure of the holding-down connections. The accurate modelling of the behaviour of partially restraint components is outside the scope of this study.

The classical model for overturning, which was initiated by Housner (1963) and refined by Lipscombe (1990) and Makris & Roussos (1998), is based on the dynamic equations of equilibrium of an object (of homogenous distribution of mass) experiencing rotational, or “rocking”, displacement. This “rocking model” which satisfies the principles of the conservation of momentum has incorporated the abrupt change in the angular velocity of the object immediately following the impact of its base with the ground. Parametric studies have since been undertaken to study the response of free-standing objects to periodic motions, pulse-type motions and seismic-

cally induced motions (Yim et al, 1980; Spanos & Koh, 1984; Hogan, 1989; Tso & Wong, 1989a; Makris & Roussos, 2000). Experimental investigations involving the calibration of the modelling parameters have also been undertaken (Aslam et al, 1980; Priestley et al, 1978; Ishiyama, 1982; Tso & Wong, 1989b).

The dynamic equations of motion for a rectangular rigid object undergoing rocking motion can be derived from the principles of statical equilibrium. This involves summing moments about the edge of the object that is in contact with the ground (the “pivotal edge”). The equations of moment equilibrium of a slender object experiencing positive and negative rotation are represented by equations 2a & 2b are respectively.

$$\Delta \ddot{\theta}(t) - \left( \frac{3g}{4R} \right) \Delta \theta(t) = -\frac{3}{4} \frac{\ddot{U}_g(t)}{R} \quad [\Delta \theta < 0] \quad (2a)$$

$$\Delta \ddot{\theta}(t) + \left( \frac{3g}{4R} \right) \Delta \theta(t) = -\frac{3}{4} \frac{\ddot{U}_g(t)}{R} \quad [\Delta \theta > 0] \quad (2b)$$

where  $\Delta \theta(t)$  and  $\Delta \ddot{\theta}(t)$  is the change in rotation and rotational acceleration of the rocking object respectively,  $\ddot{U}_g(t)$  is the time-history of the acceleration of the base support and R is the diagonal distance between the centre of mass of the object and the pivotal edge.

The dynamic equilibrium conditions cannot be represented by a single equation due to a discontinuity at zero displacement (when the object is vertical). Thus, a dual expression is required for the formulations of the non-linear “F -  $\Delta$ ” relationship associated with the rocking motion (as represented by the dotted lines in Figure 3a). Whilst individual terms in the equations are linear, the signs associated with individual terms of the expressions are not representative of linear behaviour.

In the substitute-structure method of analysis, the effective displacement ( $\Delta_{\text{eff}}$ ) of a single-degree-of-freedom (SDOF) system is the displacement of the object at the effective height which is two-thirds up the height of the object as shown in Figure 3b. Overturning is defined at the instance when the centre-of-gravity is displaced to a point which is directly above the pivotal edge of rocking. Thus, the effective displacement at the threshold of overturning ( $\Delta_{\text{OT}}$ ) is equal to two-thirds of the object thickness (ie.  $\Delta_{\text{OT}} = 2/3 t$ ).

According to the basic principles of statics, the force required to initiate overturning is equal to  $\frac{3}{4}$  times  $Mgt/h$  (see Figure 3b). In summary, the  $F - \Delta$  relationship of Figure 3a has two key features : (i) a vertical line at zero displacement and (ii) a straight-line representing the linear decrease in resistance to overturning with increasing displacement.

The slope of the linearised force-displacement line (solid line in Figure 3a) is defined by equation 3 and is denoted herein as the effective stiffness ( $K_{eff}$ ) of the system. The linearization is based on the excursion of the object to the limit of overturning.

$$K_{eff} = \frac{\frac{3}{4}Mgt}{\frac{2}{3}t} = \frac{9}{8} \frac{Mg}{h} \quad (3)$$

The effective mass (or generalised mass)  $M_{eff}$  is defined by equation 4 assuming rigid body behaviour.

$$M_{eff} = \frac{3}{4}M \quad (4)$$

Equation 5 which provides an estimate for the effective natural period ( $T_{eff}$ ) is obtained by combining equations 3 and 4.

$$T_{eff} = 2\pi \sqrt{\frac{2h}{3g}} \quad (5)$$

The correlation of the object height,  $h$ , with the effective natural period  $T_{eff}$  as defined by equation 5 is shown in Figure 4 for object heights varying between 0.5 m and 4.0 m. By the ‘‘pendulum analogy’’, a pendulum with length equals to two-thirds the height of the rectangular object will have a natural period equal to the effective natural period of rocking (see Figure 3c). By linearisation, the object effective displacement demand ( $\Delta_{eff}$ ) can be estimated from an elastic displacement response spectrum of the ground, or the displacement response spectrum of the floor (ie. the floor spectrum) for any given effective natural period of rocking (refer Figure 3d). If the maximum displacement of the object is restricted to 50% of its displacement capacity, the (modified) effective stiffness is then defined by equation 6 and the modified effective natural period ( $T_{m-eff}$ ) by equation 7.

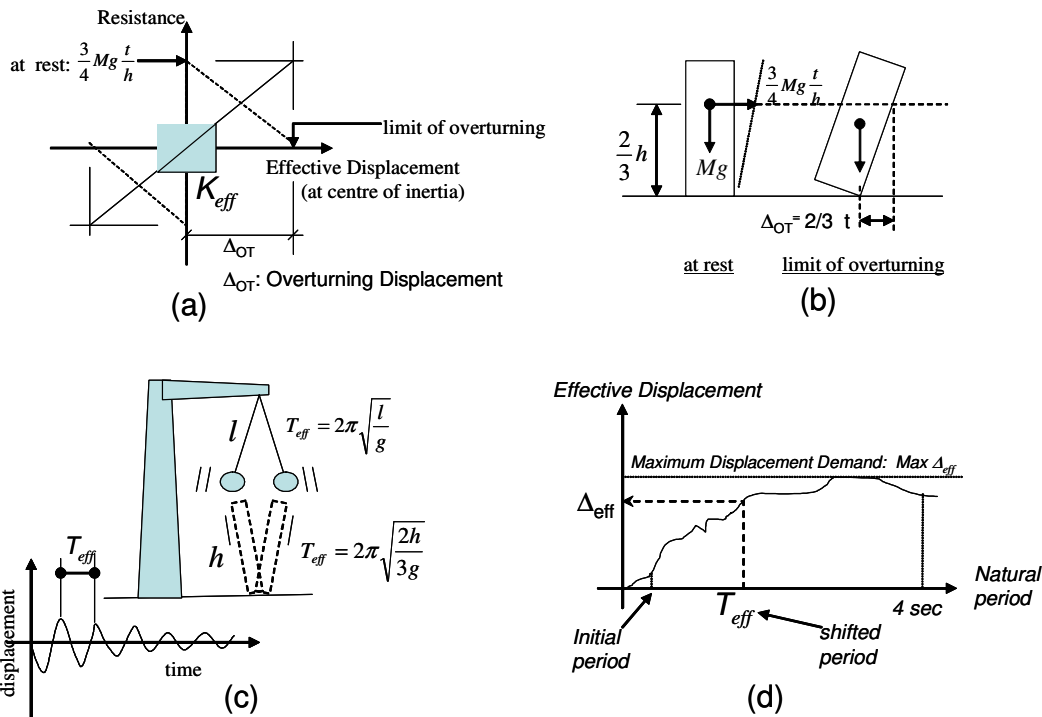


Figure 3. Linearised model for rocking

The effective natural period which is calculated in accordance with equations 6 & 7 based on the new limit is approximately 0.6 times (i.e.  $1/\sqrt{3}$ ) of that defined by equation 5. The value of  $T_{m-eff}$  calculated for a range of object heights is also shown in Figure 4. The concept of linearisation as described in this section was based purely on free rocking responses. It is shown that the value of  $T_{m-eff}$  for building contents would not be expected to exceed 2 seconds. In other words, buildings with fundamental natural period exceeding 2 seconds (ie. buildings taller than 30 storeys) are unlikely to develop resonance with their building contents based on equation 7 (which assumes that all objects are displaced by no more than 50% of its capacity for overturning).

$$K_{m-eff} = \frac{9 Mg}{4 h} \quad (6)$$

$$T_{m-eff} = 2\pi \sqrt{\frac{h}{3g}} \quad (7)$$

In the foregoing developments, the rocking response behaviour has been simplified to linear elastic response behaviour through the linearization of the effective stiffness. The amount of equivalent viscous damping which represents energy dissipation during rocking has yet to be quantified in order to provide a complete definition of the linearised model. The ratio of decrement in velocity ( $r$ ) associated with energy loss on impact (of the base of the object with the ground) during rocking may be estimated using equation 8 (Al Abadi et al, 2006).

$$r = 1 - 1.5 / (1 + (h/t)^2) \quad (8)$$

where  $h/t$  is the aspect ratio of the object

The rate of velocity decrement that are resulted from viscous damping ratio is given by equation 9.

$$\zeta = -\log_e r / \pi \quad (9)$$

Combining equations 8 and 9 enables the equivalent damping ratio ( $\zeta$ ) to be determined for emulating the loss of energy through rocking. This is illustrated in Figures 5a & 5b which shows that the usually assumed (notional) damping ratio of 5% in elastic response spectra is consistent with a rate of decrement ( $r$ ) of 0.85 which is predicted for objects with an aspect ratio of 3. It is shown that the value of  $r$  becomes insensitive to the aspect ratio (AR) when AR is greater than 3.

The actual dissipation of energy experienced by the rocking object can be much higher than the modelled

values due to energy losses in both the flooring material and the rocking object itself. This is in contrasts with the damping relationships outlined above which were based on a hard floor surface with zero coefficient of restitution on impact. Other sources of energy dissipation in the system can add to the differences. Shaking table experimentations on unreinforced masonry (URM) parapet walls for out-of-plane rocking behaviour reported an average damping ratio of 0.03 (3%) for a wall aspect ratio of 9 (Lam *et al*, 1995a & b). Similar experimentations with URM walls with effective aspect ratios varying between 4 - 8 reported damping ratios varying between 4% and 10%, and with large scatters (Griffith *et al*, 2004). These results suggest that the actual level of equivalent damping could be 2-3% higher than what is predicted using equations 8-9. On the other hand, the damping level could well be lighter than is predicted because of the “asperity” on the underside of the object (Lipscombe, 1990). Thus, the estimated amount of dissipated energy could err either way. A rigorous procedure which incorporates a variable damping parameter (ie. variable  $r$  and  $\zeta$ ) does not seem to be justified in view of the uncertainties with real behaviour. Recognising this, it seems reasonable to adopt a constant value of  $\zeta$  for reasons of simplicity. The common (default)

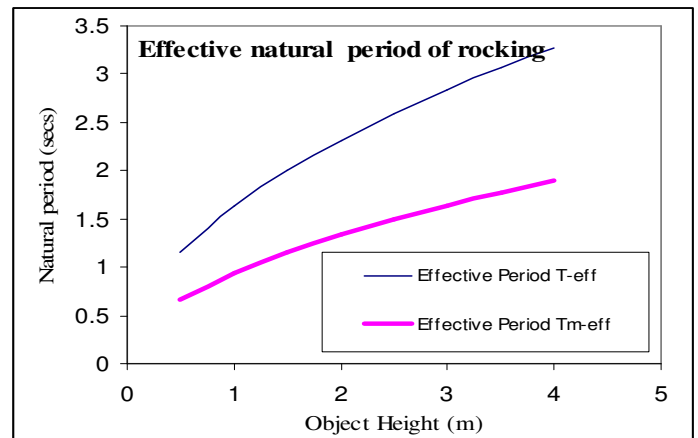


Figure 4. The effective natural period for rocking

damping value of  $\zeta = 5\%$  seems to be most consistent with the behaviour of objects with aspect ratio of 3 or higher.

In essence, the proposed linearised model for overturning is about predicting the effective displacement demand on the object ( $\Delta_{eff}$ ) based on the displacement response spectrum of the base excitations and the comparison of  $\Delta_{eff}$  with the thickness ( $t$ ) of the object.

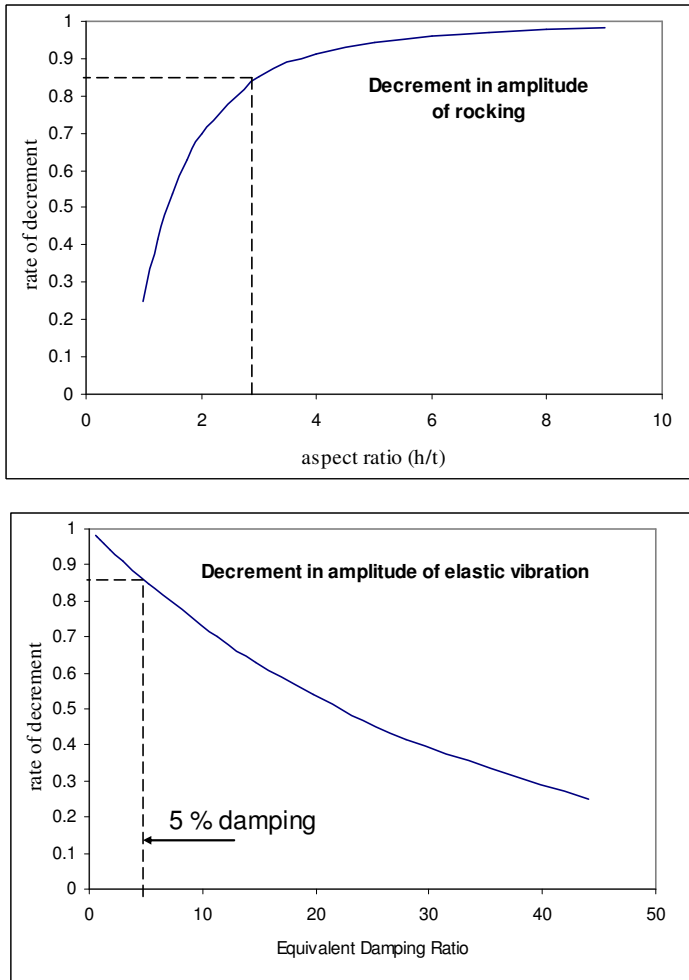


Figure 5. Rate of velocity decrement and equivalent damping ratio for rooting

A free-standing object is considered to be unlikely to overturn if  $\Delta_{eff}$  is less than or equal to  $t/3$  (risk level is “low”). This limit is based on a 50% margin for safety. In contrast, the object is expected to overturn if  $\Delta_{eff}$  is greater than  $2/3 t$  (risk level is “high”). There are uncertainties in the behaviour of objects in between the two limits due to errors arising from non-linear behaviour (risk level is “moderate”). Table 3 and Figure 6 provides a summary of the stated risk criteria. In the estimation of  $\Delta_{eff}$  there are uncertainties as to what natural period should be assumed when taking readings from the response spectrum. The period-shift behaviour of rocking means that the object actually experiences a range of natural periods as the rocking displacement is increased. It is proposed by the author that the highest displacement demand (Max  $\Delta_{eff}$ ) over the period range of 0 – 4.0 seconds be taken as the estimated amount of rocking displacement for the purpose of Table 3 and Figure 6.

An extensive parametric study by Al Abadi *et al* (2006) involving some 2800 non-linear time-history analyses for rocking responses was undertaken to

validate this model. About 1800 of these cases were classified as having “low” overturning risks according to the classification criterion defined by Table 3. Non-linear time-history analyses undertaken on these “low risk” cases indicated that only 2 cases (out of a total of 1800 cases) actually experienced overturning. In contrast, cases that were classified as having “high” risks had an overturning rate of about 80%.

The simple displacement model described above can be used for the “quick-scan” assessment of the overturning vulnerability of free-standing objects in a building. The calculations involved are very simple. For example, take an area where the level of seismicity is characterized by the design peak ground velocity of about 60 mm/sec on rock (which is generally representative of the average level of seismic hazard in Australia for 10% exceedance in a design life of 50 years, or a return period of 500 years). The highest displacement demand on an elastic displacement response spectrum for 5% damping is accordingly 20 – 30 mm on rock sites and be amplified to around 80 – 100 mm on soft soil sites.

First, consider free-standing objects which are located at the ground level of the building where the effects of height amplification can be neglected. The response spectrum of the site and that of the floor are therefore identical. Thus, the maximum value of  $\Delta_{eff}$  (ie. Max  $\Delta_{eff}$  as illustrated in Figure 3c) for the purpose of assessing overturning of objects is in the order of 80 - 100 mm. In such conditions, free-standing objects (components) with base dimension exceeding 300 mm (ie. 3 x 100mm) may be considered safe from overturning if homogeneous distribution of mass is assumed (refer Figure 6a). Detailed (follow-up) assessment of the stability of components in the building would only be required if the base dimension of the object is less than 300 mm and if their overturning could result in serious consequences. The risks model of Figure 6 enable vulnerable items to be identified for any given value of Max  $\Delta_{eff}$ . However, a realistic estimate of Max  $\Delta_{eff}$  requires an accurate modelling of the potential site response and building floor responses to earthquake excitations. Developing these response spectra require the dynamic properties of the site (ie. site natural period) and the building to be ascertained with good accuracies. The current approach of broad-based site classification would not serve this purpose. The current building regulations do not require designers to produce floor spectra which accurately incorporates the dynamic properties of the site.

It can be shown that similar recommendations can be made of components contained within low-rise buildings of up to around 5-storeys irrespective of the positioning of the component within the building.

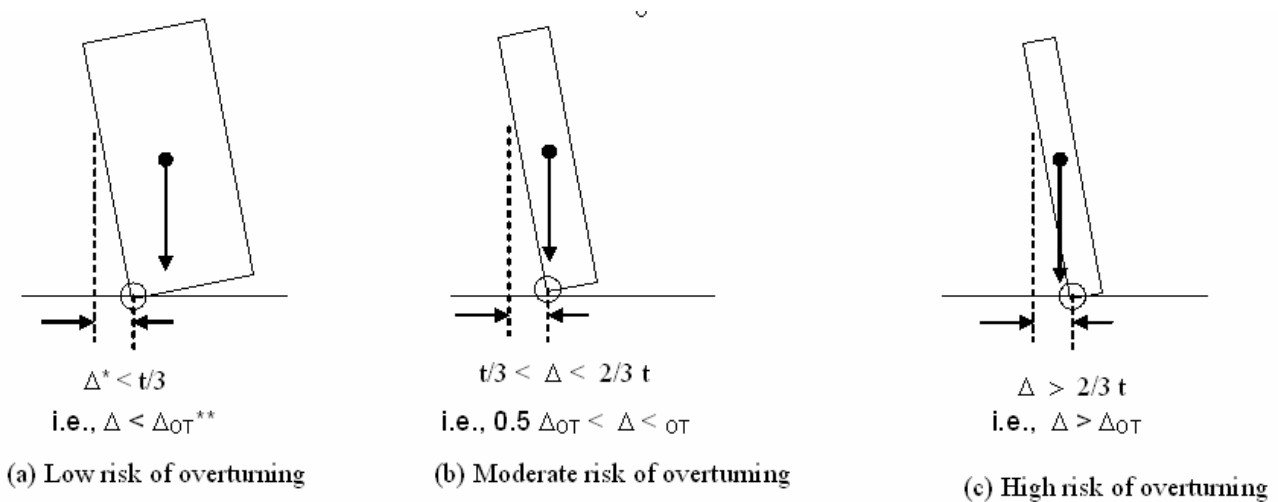
Table 3. Criteria for risk levels for overturning (after Al Abadi *et al*, 2006)  
(notation  $\max \Delta_{eff}$  is abbreviated herein as  $\Delta$ )

Inequality statements	Risk Level
$\Delta \leq \frac{t}{3}$	Low
$\frac{t}{3} < \Delta < \frac{2}{3} t$	Moderate
$\Delta \geq \frac{2}{3} t$	High

It is shown in Franke *et al* (2005) that conditions do not necessarily become more onerous as the building becomes so tall that the natural period of the building is considerably higher than that of the site. This is the case with buildings possessing a fundamental natural period of 2 seconds or higher. It has been demonstrated by analyses that when this happens the building effectively behaves as an isolation medium. The potential damaging effects of the ground shaking can be tempered, rather than accentuated, by the “filtering” of the motion up the height of the building. Research into the behaviour of the displacement floor spectra in tall buildings is on-going.

Clearly, the overturning model developed in this section was based on the behaviour of uniform rectangular objects. A similar model (details not presented herein) that are generalised to all geometrical shapes with a vertical axis of symmetry could also be developed. The generic model is parameterised by (i) the mass radius of gyration and (ii) diagonal distance R which is measured from the centre of mass of the object to its pivotal edge. For an object of any arbitrary shape and non-uniform distribution of mass, an equivalent rectangular object with identical values of the rocking parameters could be identified. Consequently, the presented overturning model could be extended for the stability assessment of a much wider class of (non-uniform and non-rectangular) objects.

The overturning model reviewed in this section was first applied by the author and his collaborators to the vulnerability assessment of unreinforced masonry parapet walls and gable walls subject to seismic loading in the out-of-plane direction (Doherty *et al*, 2002; Lam *et al*, 2003). The presented model considers rocking responses only. Therefore, conditions under which the response is of rocking nature only are examined. For example, vertical accelerations of the building floor is neglected and jumping of the object is assumed not to occur.



\* Maximum  $\Delta_{eff}$  as defined in the text is abbreviated here as  $\Delta$ .

\*\* $\Delta_{OT}$  is the Overturning Displacement.

Figure 6. Risk of overturning based on displacement

Also, sliding is assumed not to occur implying that the base horizontal acceleration has not surpassed the coefficient of friction between the base of the object and the flooring surface. The aspect ratio of a typical computer cabinet is in the order of 3 (reciprocal of 0.33), while the coefficient of friction is in the range 0.60-0.90 (Ferdinand et al, 2004) when rubber attached to the base of the cabinet is in contact with a concrete floor. The assumption of no-sliding appears to be generally valid for this type of installations.

#### 4 DISCUSSION

A range of models have been reviewed in this paper. The force-based model presented in Section 2 is about estimating the force demand on restrained items (and the associated literature underpinning the provisions) and provides little indication of how vulnerable items that are without adequate restraints. The model for overturning as presented in Section 3 can potentially become very useful as technical reference when it comes to identifying potentially hazardous items which risk overturning if unrestrained. Objects which have been classified having moderate, or high, overturning risks by the overturning model could be retrofitted with holding down devices in accordance with conventional force-based principles to ensure that large (rocking) displacement would not take place.

An accurate prediction for  $\text{Max } \Delta_{\text{eff}}$  which forms part of the evaluation framework requires the potential motion behaviour of the building floors to be modelled. Uncertainties in the demand predictions can be translated into difficulties in modelling the behaviour of our building infrastructure and its contents in the projected seismic conditions in order that their safe and satisfactory performances can be guaranteed. These design challenges are compounded with additional challenges with effectively implementing the intentions of the building designer into actual practices. Clearly, the designer of the building has little control over installations of components and the management of the utilization of the building whilst in service.

Engineering for earthquake safety in a building is clearly much broader than merely regulating its architectural and structural design. What is essential is proper control of all major installations and regular inspection of the utilization of building during its entire service life. Tight legislative controls and inspection procedures are already well established in most established community to ensure responsible behaviour of the building owners and operators for countering the risks of fire. However, there are hard-

ly any parallel provisions for countering potential earthquake hazards. The author proposes that inspection procedures for countering the risks of fire be broadened to address a diversity of potential hazards including earthquake hazards given that they are all to do with the safe and proper utilization of space and the storage of hazardous items.

Effective control of seismic risks in buildings is only possible if the items of concern have been correctly targeted. Building operators and authorities responsible for the monitoring must be well informed of the behaviour of both restrained and unrestrained items in the building in the projected earthquake scenarios. For example, realistic modelling for overturning requires the dynamic behaviour of both the building and the site sub-soil to be ascertained. The same can be said of deformation modelling of the building facades and vertical piping. Both types of modelling requires much more information than is readily available in a form that can be practically implemented and monitored. In the opinion of the author, this is exactly where future research and development efforts should be directed at.

#### 5 CONCLUSION

- a) The full restraints of non-structural components, the overturning of slender objects, the vulnerability of sign gantries and the brittle failure of building facades and vertical piping have been identified as issues to be addressed.
- b) Typical provisions in contemporary standards for calculating the seismic design forces for the full restraints of non-structural components have been reviewed (refer Table 2 and Figures 1 and 2). The overall modelling framework adopted in the different standards are generally consistent but the stipulated factors can be at large discrepancies. The shortcomings of the force-based approach in assessing the potential seismic performance of non-structural components has been illustrated using the case-study of a floor mounted liquid container.
- c) The mechanics of rocking and the linearised version of the rocking model has been briefly introduced (refer Figure 3). The risk of overturning of a free-standing object can be assessed by comparing the thickness of the object against the maximum effective displacement demand ( $\text{Max } \Delta_{\text{eff}}$ ) as read off from the elastic displacement response floor spectrum (refer Table 3 and Figure 6). A free-standing object is considered unlikely to overturn

if  $\Delta_{\text{eff}}$  is less than or equal to  $t/3$  (risk level is “low”).

- d) The overturning behaviour of objects in tall buildings depends on the dynamic properties of the building and the natural period of the site. For example, if the natural period of the building is considerably higher than that of the site the building effectively behaves as an isolation medium. The potential damaging effects of the ground shaking can be tempered, rather than accentuated, by the filtering of the motion up the height of the building.
- e) Design regulations alone would not necessarily improve the level of preparedness significantly (because regulations for controlling the design of a new building would not cover for installations and disposition of storage items during its service life). The engineering of non-structural components and building contents for countering potential earthquake hazards should not be restricted to merely designing restraints, and particularly so for regions of low and moderate seismicity. The author proposes that inspection procedures for countering the risks of fire be broadened to address a diversity of potential hazards including earthquake hazards given that they are all to do with the safe and proper utilization of space and the storage of hazardous items.
- f) Modelling the potential seismic performance for the whole range of NS components in a building requires much more information than is readily available in a form that can be practically implemented and monitored. In the opinion of the author, this is exactly where future research and development efforts should be directed at.

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