Seismic Assessment of Building Contents Combining Force and Displacement Principles

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ABSTRACT: Existing procedures for assessing the seismic performance of building contents are mainly founded on force-based principles wherein the maximum seismic force is estimated in accordance with the predicted peak floor acceleration. Such force-based procedures tend to be over-conservative when adapted to determine the minimum base width requirement to prevent overturning instability of unrestrained (free-standing) objects, as the capacity of the object to displace without overturning has not been accounted for. The displacement capacity of a free-standing object can be checked against the peak floor displacement in situations where it is safe to rock. This paper introduces a new procedure which combines both the force and displacement principles to check overturning stability. Results obtained from this approach indicate that objects with a base width exceeding 300mm will not overturn for most seismic regions of Australia based on a 500 year return period.

1 INTRODUCTION

Seismically induced damage to building contents or non-structural components can prevent the continuous functioning of important facilities including critical medical and communication facilities which can be vital for the protection of lives. In addition, the overturning of hazardous material containers and the falling of debris from building facades or ceilings can cause severe injuries and deaths.

This paper addresses in particular the overturning stability of objects such as : internal unreinforced masonry partition walls, building services plant (e.g. generators, pumps, air-conditioning units), furniture items (e.g. shelving units, storage racks) and other items (e.g. medical and surgical equipment, gas containers, museum exhibits). Such objects which can be non-rectangular or irregular, are represented generically by a rectangular block with matching mass, base dimensions, center-of-gravity (c.g.) location and radius of gyration for overturning (r).

In high seismicity regions, critical equipment or potentially hazardous containers are generally restrained by ties, straps or anchors. The seismic safety of such items can be evaluated using a force based (FB) procedure in which the maximum inertia force is determined at the c.g. to determine the required strength capacity of the restraining devices. Several FB procedures which have been used, or proposed, for the analysis of fully restrained objects are reviewed in Section Two.

Items such as furniture and mobile equipment are normally un-restrained, particularly in low and moderate seismicity regions. Although the terminology "unrestrained" has been used, it is understood that the object is actually prevented from overturning by its own weight and base widths. Traditionally, the FB procedure has been used to evaluate the overturning stability of free-standing objects. However, it can be shown that such analyses poorly represent the actual seismic response, as the capacity of the object to wobble, rock and displace without overturning cannot be realistically represented using the principles of statics.

A new procedure to evaluate the overturning stability of free-standing objects combining force and displacement principles is introduced in Section Three. This new procedure recommends a Displacement Based (DB) analysis for situations where the floor accelerations are large but the displacements are small. Conversely, a conventional Force Based (FB) analysis is recommended for situations where the floor displacements are significant (and objects may overturn if not adequately restrained).

Base-isolated or very flexible components require special considerations and are beyond the scope of this paper.

2 FULLY RESTRAINED OBJECTS

The design seismic inertia force calculated using the FB procedure is equal to the product of the object self-weight (W) and the object peak acceleration (a_p). The a_p is normally specified as the product of a number of factors as shown in Eqn.1a & 1b.

$$a_p = A_p \, . \, PFA \qquad (1a)$$

and $$PFA = HF.M_\mu .I_p.PGA \qquad (1b)$$

where,

A_p = Attachment Factor,
PFA = Peak Floor Acceleration,
HF = Height Factor,
M_μ = Structural Ductility Factor,
I_p = Importance Factor,
PGA =Design Peak Ground Acceleration.

Each of these factors are described in this section with reference to the International Building Code (abbreviated as "IBC" [1]) and the Draft Australian/ New Zealand Standard for Earthquake Actions (abbreviated as "SANZ" [2]). In addition, a simplification of the SANZ procedure for applications in Australia is summarised in Appendix A.

The PGA (denoted as "C_g" in SANZ and "C_a" in IBC) is normally consistent with the response spectral acceleration or seismic coefficient specified for the design of rigid buildings possessing a "zero" natural period.

The HF (or Structural Amplification Multiplier) typically varies linearly between 1.0 at ground level to a maximum value of between 3.5 and 4 at roof level. These figures are based on the estimated maximum acceleration amplification of low-rise buildings, and are therefore overly conservative for tall buildings. There are special provisions in SANZ to reduce this factor substantially for structures classified as "intermediate" based on their estimated natural period, the number of storeys and the estimated ductility capacity of the building.

The "First Mode Modal Analysis" [3] procedure and the "Equivalent Static Force" [3,4] procedure are alternative analytical methods which can be used to determine the Height Factor based on the period dependent response spectral acceleration of the building. These procedures provided the basis for the SANZ provisions for structures classified as "simple" and "intermediate".

The M_μ factor accounts for the ductile behaviour of the building structure. However, this factor is often assumed equal to 1 in view of the uncertainties associated with the over-strength of the building.

The A_p factor is normally expressed as the product of a component amplification factor (which accounts for resonance effects in flexibly mounted components) and a component ductility factor (which accounts for the energy absorption capabilities of the attachments). The component amplification factor varies between 1.0 and 2.5 in IBC, and between 1.0 and 2.75 in SANZ. In contrast, the ductility factor varies between 0.67 and 0.25 (reciprocal of 1.5 and 4 respectively) in IBC, and between 0.5 and 1.0 in SANZ. IBC adopts an empirical approach of identifying each type of component with the respective factors, whereas SANZ expresses the same factors as functions of the natural period ratio (component/building) and the component ductility capacity ratio.

The I_p factor varies between 1.0 and 1.5 in IBC, and between 1.0 and 1.35 in SANZ depending on the relative importance of the component.

The design object peak accelerations determined in accordance with the factors described above can be used to check or design the seismic restraining devices.

3 UNRESTRAINED OBJECTS

The FB procedure described in Section 2 has traditionally been used to check the overturning stability of unrestrained components (or free-standing objects). It can be simply shown that the limiting aspect ratio (*t/h*) for overturning stability of a uniform rectangular object is given by Eqn.2.

$t/h = PFA$ (2)
where h = object height,
t = object based dimension
PFA = peak floor acceleration

Eqn.2 is based on the principles of statics and hence only realistically models the effects of sustained loads (e.g. wind) as opposed to the reversible excitations generated by an earthquake.

Experimental and analytical research undertaken to examine the out-of-plane behaviour of unreinforced masonry parapet walls in Australia in recent years has contributed significantly to the understanding of the overturning behaviour of rigid and deformable objects [5-8]. Shaking table tests carried out on wall specimens using periodic excitations [5] showed a good correlation between the applied peak floor displacement (*PFD*) and the wall rocking displacement (Δ). The correlation was particularly good when the observed natural period of free-rocking (i.e. rocking period) significantly exceeded the period of the applied excitation as shown in Fig. 1. In theory, the rocking period (T) is non-unique and is directly dependent on the displacement amplitude. However, a notional estimate of T based on the concept of linearisation as described in Fig. 2 can be defined by Eqn. 3.

$T = 2\pi \sqrt{(2h/3g)}$ (3)

This linearisation enables a rocking response to be predicted from an elastic displacement response (RSD) spectrum. The RSD (Fig. 1b) shows that the amplified rocking displacement (Δ) is $1/2\zeta$ times the PFD when the object is in resonance with the approximate harmonic motion of the building floor (i.e. Δ=10*PFD* when ζ=0.05). Importantly, Δ is reduced to 2*PFD* when T equals 1.4 times the building period (T_b). Δ converges gradually to *PFD* when T is further increased. Δ can be predicted conservatively using Eqn. 4a if the condition of Eqn. 4b is satisfied.

$$\Delta = 1.5 \text{ x} 1.4\, PFD \sim 2PFD \qquad (4a)$$
$$T \geq \sqrt{2} T_b \qquad (4b)$$

The factor of 1.5 in Eqn. 4a is to allow for the 50% error margin associated with linearisation [6].

The required base width (t) to prevent the overturning of a rectangular object can be expressed by Eqn.5 as shown in Fig. 1a.

$$t > 1.5\,\Delta \qquad (5)$$

Substituting Eqn. 4a into Eqn. 5 leads to Eqn. 6 which expresses the minimum required base width to prevent overturning in terms of *PFD*.

$$t > 1.5 \text{ x } 2\, PFD = 3PFD \qquad (6)$$

The Displacement Based (DB) assessment is demonstrated in the following for the seismicity level defined by RZ=0.1g and Site Subsoil Class D (soft or deep soil sites) as defined in SANZ. This RZ (or PGA) value is generally representative of most Australian capital cities for a 500 year return period [2]. The maximum displacement demand of 30mm implied by the response spectra of SANZ for Australia is translated to a PFD of about 60mm in most low and medium-rise buildings (assuming a structural amplification factor of 2). From Eqn.6, the minimum base width (t) to safeguard overturning is 180mm (3 x 60mm) at the upper levels of a building. This assumes that the object rocking period (T) exceeds 1.4 times the building natural period (T_b). Clearly, most utility and furniture items have sufficient displacement capacity to prevent overturning provided that the rocking period criterion as defined by Eqn.4b is satisfied. (It has been assumed that the objects have sufficient frictional resistance to prevent sliding. This could be checked using a FB procedure).

For situations where the object rocking period is less than 1.4 times the building natural period (i.e. resonance effects could be of significance as shown in Figure 1b), a complimentary FB assessment is required to ensure that the occurrence of rocking is prevented using Eqn.2. This is best illustrated by a case study of a 1.4m high object :

An object height of 1.4m corresponds to a rocking period (T) of 1.9 secs (Eqn.3) and a limiting building period (T_b) of 1.4 secs (Eqn.4b) as shown in Fig. 3. Objects which are located in a building with T_b exceeding 1.4secs must be prevented from rocking to avoid any occurrences of resonance and overturning instability (Fig. 1). To prevent any occurrence of rocking, the FB procedure must be used and the aspect ratio checked using Eqn.2 and Appendix A. This procedure predicts a PFA of 0.21g at T_b=1.4 and RZS_p=0.1 in the Class D subsoil conditions (Fig. 4). The required minimum base width to prevent rocking for the 1.4m high object is 0.3m approximately (from Eqn.2).

Similar FB calculations have been repeated for objects of variable heights to determine the dependable minimum required base widths (t). Results shown in Fig. 5 indicate that t is bounded by an upper limit of 300mm to prevent rocking in a potential resonance condition. This limit also satisfies the DB requirement of 180mm to prevent overturning of a rocking object in a non-resonance condition. Thus, objects with base widths exceeding 300mm are considered safe from an overturning stability perspective, irrespective of the height of the object or the natural period of the building. It should be recognized further that this evaluation covers non-rectangular or irregular objects although rectangular objects were assumed in the analyses. Significantly, a pure FB procedure which neglects the capacity of the object to rock would have required a much larger minimum base width to ensure stability. This is shown by the broken line in Fig. 5. The implied *t/h* ratio of approximately 0.5 is based on Eqn.2 with *PFA* calculated from Appendix A for the most onerous case of an object located on the roof of a building with T_b= 0.1-0.3secs (for site subsoil class D and *RZ*=0.1g).

4 CONCLUSIONS

Numerous FB procedures used to determine the strength capacity of restraining devices have been reviewed in this paper. Whilst this method is appropriate for the design of restrained objects, it tends to be over-conversative when adapted to determine the minimum base width requirement to prevent overturning instability of unrestrained objects.

A new procedure combining FB and DB principles has been developed to overcome the shortcomings of the FB method. The recommended procedure permits rocking (DB analysis) in non-resonance conditions ($T>1.4T_b$) whilst prohibiting the occurrence of rocking (FB analysis) in potential resonance conditions ($T<1.4T_b$). It has been demonstrated by the combined procedure that objects with a base width exceeding 300mm should be generally safe from overturning in most parts of Australia on both rock and soft soils for a 500 years return period. In contrast, the use of the FB procedure only would misleadingly imply that objects located on the roof of a low rise building and with a *t/h* ratio of less than 0.5 to be "unstable" from an overturning perspective.

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5 APPENDIX A

SIMPLIFIED PROCEDURE (COMPLYING WITH SANZ) TO DETERMINE THE PEAK FLOOR ACCELERATION FOR APPLICATIONS IN AUSTRALIA

$$PFA = HF.\ M_\mu\ .\ I_p\ .\ PGA \qquad \text{(A1)}$$

where I_p = Importance Factor (provided by Ref[2]), $M_\mu = 1$

$PGA = RZ\ C_h(0)$ (RZ provided by hazard map of Ref[2] and $C_h(0)$ by Table A1)

$HF = 1.5 + [1.5M_d\ \{C_h(T_b)/C_h(0)\} - 1.5]\ (H_x/H_n)$ (A2)

$M_d = (3.0+n^2/70)/3.5 \quad \leq 2.0$ (A3)

H_x = Floor Height; H_n= Height of roof of building

$C_h(T)$ is the seismic hazard acceleration coefficient as defined in Table A1

T_b = notional natural period of building $= 0.05H_n^{\ 0.75}$ secs (H_n in metres) (A4)

Table A1 Seismic hazard acceleration coefficients for sites in Australia (extracted from Ref [2])

T_b	Site Subsoil Class A	Site Subsoil Class B	Site Subsoil Class C	Site Subsoil Class D
0.0	1.00	1.00	1.27	1.52
0.1	1.28	1.92	2.88	3.84
0.2	1.28	1.92	2.88	3.84
0.3	1.28	1.90	2.88	3.84
0.5	0.78	1.14	1.80	2.40
0.7	0.55	0.81	1.29	1.71
1.0	0.27	0.40	0.90	1.20
1.5	0.12	0.18	0.40	0.53

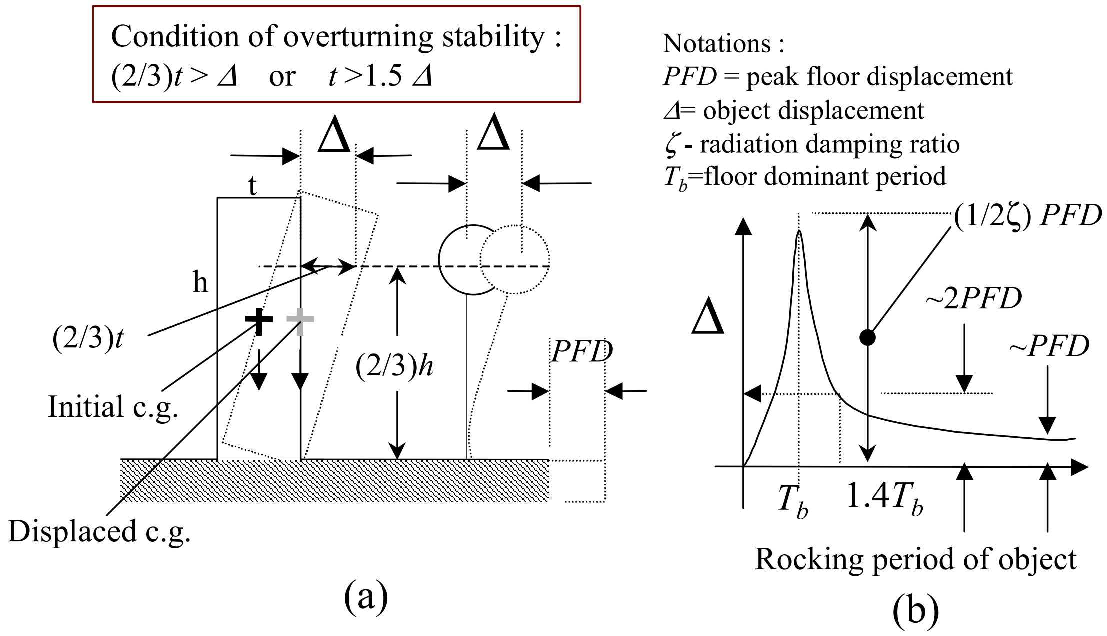

Figure 1 DB Assessment for Overturning

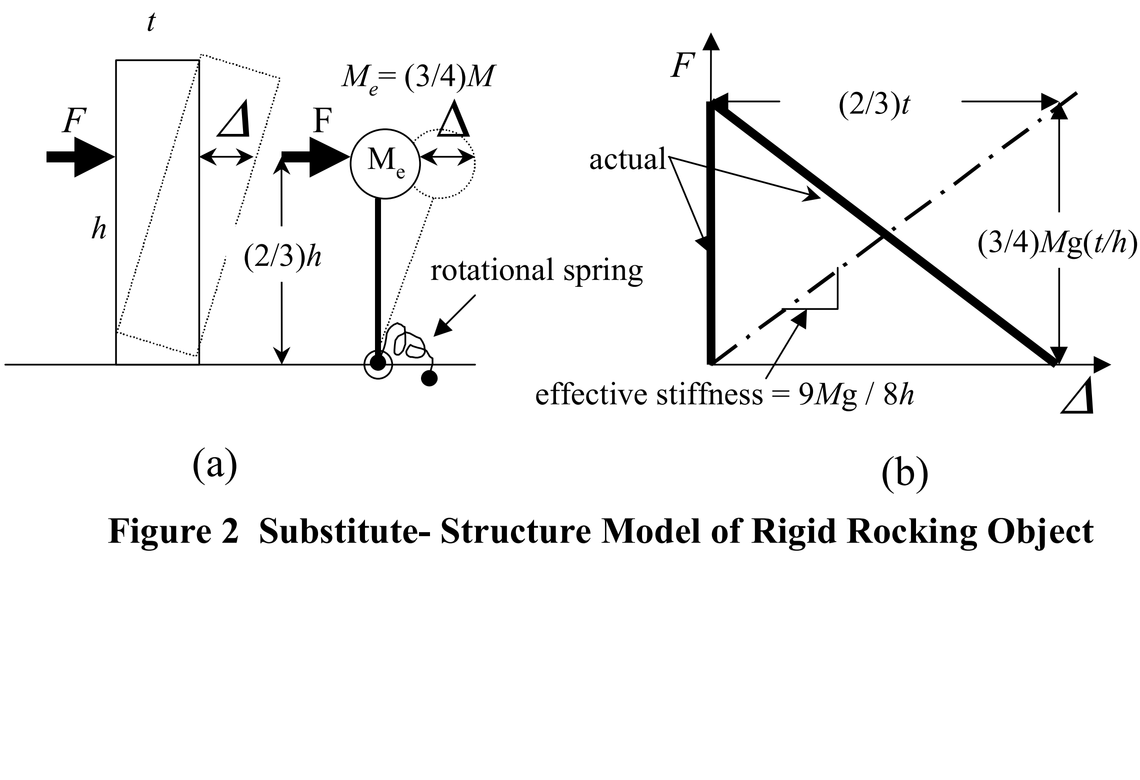

Figure 2 Substitute- Structure Model of Rigid Rocking Object

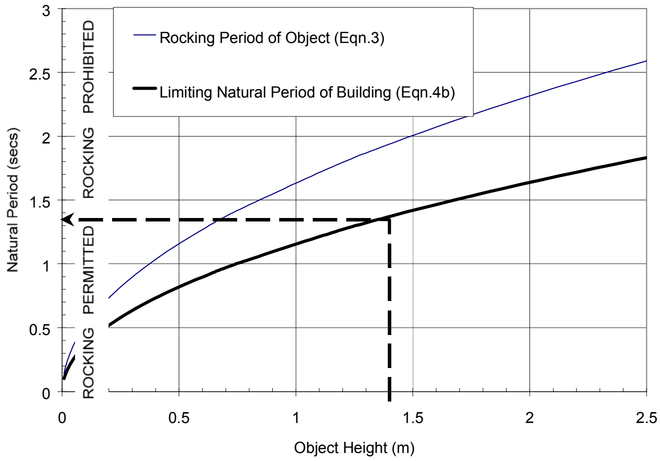

Figure 3 Object-Height Dependent Natural Period Behaviour

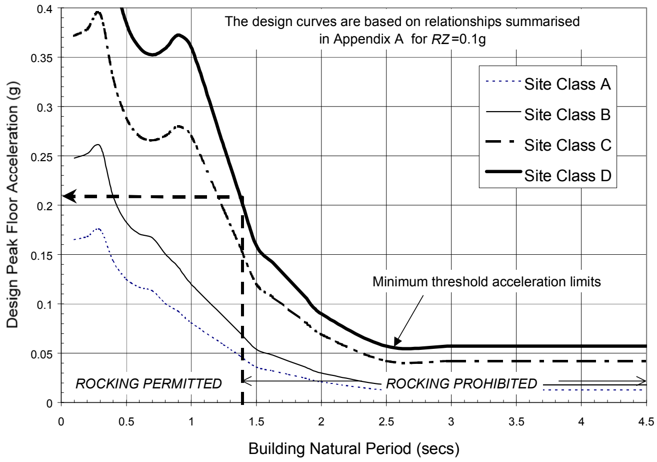

Figure 4 Design Peak Floor Acceleration at Roof Level (*RZ*=0.1g)

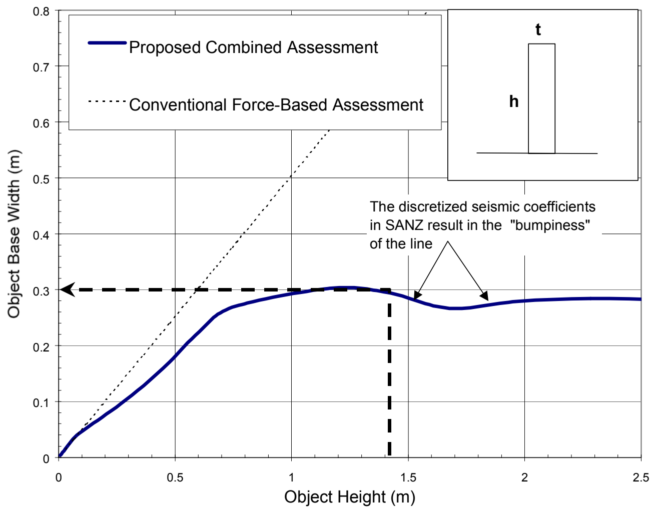

Figure 5 Object Height and Required Base Width (RZ=0.1g)

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