

AN INNOVATIVE APPROACH TO THE SEISMIC ASSESSMENT OF NON-STRUCTURAL COMPONENTS IN BUILDINGS

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ABSTRACT:

The analysis and design of structural systems to comply with life safety requirements have been the main thrust of earthquake engineering research. As community expectations increase, there has been increasing attention to address potential economic losses resulted from earthquakes. The economical impact associated with damage to non-structural building components in recent earthquake events has been found to exceed those associated with structural damage. In this paper, the economic significance of earthquake induced non-structural damage and the limitations of current design methodology is discussed. An alternative assessment approach based on considering acceleration, velocity and displacement is introduced and explained by relating to fundamental principles. The merit of this approach in making simple and realistic assessments for regions of low and moderate seismic activity is demonstrated. Whilst the new methodology is yet to be fully developed, the innovative concept presented is original and has never been published previously.

1. INTRODUCTION

Research into the seismic performance of non-structural (NS) components is guided by two principal objectives. The first objective is to reduce potential casualties and injuries resulted directly from the failure of NS components. The second objective is to mitigate the ensuing economic costs associated with (i) loss of function both during and after the event, (ii) repair and replacement work and (iii) collateral damage.

NS components is a generic term which encompasses a diversity of building items which can be grouped into the following categories: (a) interior components including partitions and ceilings; (b) exterior components such as building facades; and (c) building services components. Refer Figure 1.

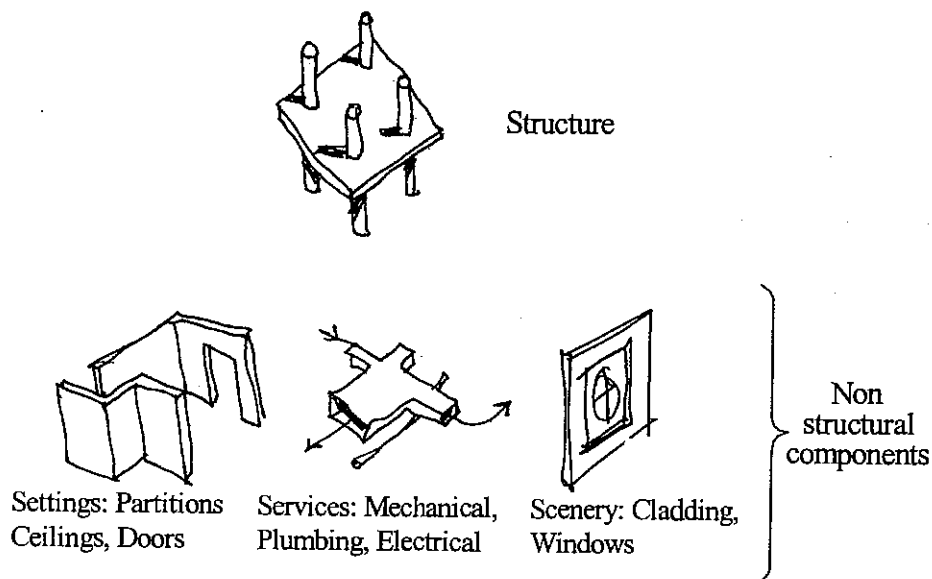


Figure 1 - Structural and non-structural building components (Hira *et al*, 2002)

The percentage breakdown of individual NS items in a typical Australian office building is listed in Table 1 to demonstrate the significance of NS components in economic terms (Rawlinson, 2000).

Table 1. Percentage breakdown of cost items for office buildings in Australia.

Element	storey nos:	7-20	21-35	36-50
Builder's preliminaries (plant, scaffolding, insurance, etc.)		17.5	20.0	22.1
Substructure (excavation, foundations, service tunnels, etc.)		1.4	1.1	0.9
Superstructure				
- Columns, upper floors, staircases & roof		12.7	11.0	10.2
- External walls and windows (facades)		14.1	18.1	17.7
- Internal walls and doors		4.1	4.7	4.4
Finishes (wall, floor and ceiling)		7.9	6.9	6.7
Fitting (fitments and special equipment)		0.8	0.6	0.6
Services (plumbing, mechanical, fire, electrical, transportation)		39.0	35.1	34.9
Contingency		2.5	2.5	2.5

The combined value for facades and services is shown in Table 1 to account for over 50% of the total construction cost. The demonstrated significance of NS components is consistent with the result of a post-disaster survey for the 1971 San Fernando earthquake in California involving 355 high-rise buildings. The survey showed that 79% of the damage costs in dollar terms was non-structural (Arnold, 1987). Direct replacement costs of NS components can be only a small part of the total costs which account for the loss of function and lost of inventory. Such indirect costs can be two to three times the cost of replacing the damaged structure (Phan and Taylor, 1996). NS components in low-moderate seismic regions deserves engineering attention even in situations where the risk of structural damage seem very low. For example, buildings responding elastically can produce highly periodic floor motions which can be very damaging to certain NS components even at very low intensity.

In regions of low and moderate seismic activities such as Australia, most of these NS items have not been fully engineered for satisfactory seismic performance. When seismic actions are calculated, adequate structural engineering input is not always provided to check the installations for compliance, particularly for items installed during the service life of the building (Beattie, 2001). The complex interactions between certain NS components with the structural system which might have high performance implications are often not considered. For example, heavyweight cladding systems have been shown to contribute to additional lateral stiffness and might also alter the dynamic properties of the structure (Henry & Roll, 1986). Partitions made of plasterboard-clad steel-framed walls have also been found to contribute to 10-20% of the lateral stiffness of the structure (Freeman, 1977). In addition, such partitions add significantly to damping, particularly for low intensity responses. Overall, there is generally little control over the seismic protection of NS components and building contents in Australia.

The limitations of existing methodologies developed for assessing NS components are discussed in Section 2 and the alternative innovative methodology introduced in Section 3. Due to space limitations, the rest of the paper only addresses components that can be considered as an isolated component excited by the floor motions. Thus, the effect of structural deformation is not considered.

2. REVIEW OF EXISTING ASSESSMENT METHODS

The modelling methodology adopted in contemporary seismic loading codes (e.g. AS1170.4, 1993) is based on 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, in order that the seismic inertia force can be calculated (Lam, 1998). Interestingly, a comparative study by Phan and Taylor (1996) revealed up to five-fold discrepancies in the recommended amplification factors from several major code of practice, suggesting significant uncertainties in the estimated amplification factors. A recent study by Rodriguez (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 (2001) developed floor spectra from floor accelerograms recorded in 19 buildings

during the 1999 Chi-Chi earthquake (Taiwan). These recent studies also revealed considerable uncertainties in the prediction of peak accelerations. Importantly, none of the studies addresses the mechanism of damage leading to failure of a component.

Isolated studies have identified the direct link between floor velocity (and displacement) and the overturning vulnerability of uniform objects (Ishiyama, 1984; Clark, 1993). However, the absence of reliable information on these floor motion parameters has limited further development of such a model. Full-scale dynamic testing of physical models of suspended ceiling modules (Yao, 2001), fire sprinklers and air-conditioning ducts (Beattie, 2001) have also been reported. Observations from these tests provide valuable insights into the vulnerability of the tested components, but further research efforts are required to generalize these test results for practical applications. A generic probabilistic procedure for quantifying damage cost has been proposed recently by Porter (2000). Whilst the philosophy is sound, its implementation is only possible when reliable vulnerability models are available.

3. PROPOSED ASSESSMENT METHOD

The assessment method proposed in this paper is to be developed from results obtained by a combination of dynamic testing and finite element analysis of calibrated computer models. The observed non-linear behaviour is approximated by a linearised system possessing 2-5% critical damping (these limits are currently reviewed based on calibration with experimental observations). The recent review by Miranda (2002) shows that displacement estimated by the linearisation methodology applied to simple building models has been found to be in reasonable agreement with non-linear analysis results in terms of ensemble average, provided the effective period and damping of the linearised system has been suitably selected. A recent achievement in modelling the out-of-plane overturning behaviour of masonry walls based on linearisation is described in Doherty (2002). The linearisation of NS component behaviour which is characterized by abrupt change in the "dynamic stiffness" represents a new challenge.

Linearisation enables the seismic response of the component to be approximated by an elastic floor spectrum. The velocity floor spectrum in the tri-partite logarithmic form is bounded by 3 straight lines representing the peak response acceleration (A_0), velocity (V_0) and displacement (D_0) responses, respectively, as shown in Figure 2.

Taking the suspended ceiling as an example (refer 2nd row of Table 2), the initiation of damage to the ceiling is evidently represented by the force required to separate the edge of the ceiling from the wall supports, and this force is bounded by the peak response acceleration (A_0). As the ceiling becomes disengaged from the initial restraints and pounds against the wall and neighbouring objects, the damage associated with the pounding is best represented by the peak response spectral velocity (V_0). As the ceiling is subject to significant drift, the deformation of the fire-sprinklers and air ducts, etc, (which are in contact with the ceiling) is related directly to the peak response spectral displacement (D_0). This modelling approach allows the progressive deterioration of the component to be tracked.

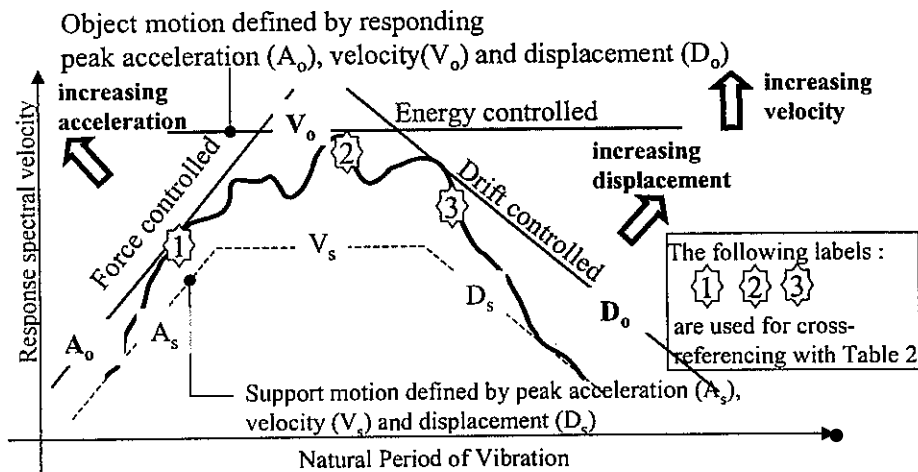


Fig.2 Proposed Generalised Floor Spectrum Model

Table 2: Floor motion parameters and component vulnerability

Basic floor motion parameters	A_o	V_o	D_o
Ceiling suspended components	<p>pull-out of angle-section</p> <p>Acceleration (force) initiates "pendulum" action</p>	<p>ceiling panels dislodged by shocks during pounding</p> <p>Velocity controls damage caused by pounding</p>	<p>straining of HVAC ducts and sprinkler heads</p> <p>Displacement controls damage to drift-sensitive items (e.g. fire sprinklers)</p>
Floor mounted components	<p>Acceleration (force) initiates yielding of base restraints</p>	<p>Velocity controls damage to restraints</p>	<p>Displacement of centre of gravity controls overturning (when freed from restraints)</p>
Components susceptible to sliding	<p>Acceleration (force) initiates sliding</p>	<p>Velocity controls damage to colliding objects</p>	<p>Displacement controls objects sliding off their support</p>

The damage mechanisms of floor mounted components and unrestrained components are similarly linked to the A_o - V_o - D_o parameters that can be articulated to operate a fast-track "scanning" procedure to determine the component vulnerability. As shown in Table 2 (3rd row), floor mounted components are deemed safe from overturning if either D_o is insufficient to move its centre of gravity (c.g.) far enough to its edge or if A_o is insufficient to result in static instability. For components located at a lower level of a

building, or on a rock site where the shaking is characterised by high frequency and low displacement (low D_0), the displacement approach is clearly preferred. For components located at the upper levels of a tall building where the shaking is characterised by low frequency and low acceleration (low A_0) the force approach is preferred instead. In the latter situation, overturning is deemed unlikely since damage to the restraints cannot be initiated.

The A_0 - V_0 - D_0 parameters can also be combined to obtain refined estimates in situations where initial scanning shows non-compliance. For example, direct displacement based (DB) assessment is particularly convenient in checking drift related damage, as drift is upper bounded by D_0 irrespective of the component mass, natural period and the complex interaction with other components possessing incompatible stiffness properties. Should the initial DB assessment based on D_0 show non-compliance, drift may be re-calculated based on V_0 using energy principles. Should the first two assessments show non-compliance, drift may be re-calculated again based on A_0 using conventional principles of force and stiffness. Interestingly, the component is deemed satisfactory should any one of the three assessments show compliance. This is justified by the fact that each of the A_0 - V_0 - D_0 lines making up the tri-linear envelope represents an upper bound estimate of the seismic demand (see Figure 2).

Refined estimates for the peak response velocity and acceleration could be obtained similarly using the "3-steps" approach described above. The new modelling framework is in significant contrast with the contemporary acceleration based approach which often requires the natural period of both the component and the building to be determined, or else the " A_0 envelope" would be overly conservative. Flexibility and versatility is clearly lacking in such an approach.

4. CONCLUSIONS

This paper highlights the significance of non-structural components under seismic actions. Traditionally, the vulnerability of non-structural components has been higher than that associated with the structural elements. In order to minimise the damage to non-structural components and reduce the potential cost of earthquakes, an integrated system approach should be adopted to ensure compatibility between the non-structural and structural components in the building.

The presented methodology employing a three-step scanning procedure is based on representing seismic demand in terms of acceleration, velocity and displacement. The concept of combining acceleration, velocity and displacement demand to predict the seismic response behaviour of structures possessing different natural periods of vibration has been employed for a long time. The use of response spectra in the tri-partite format is also standard in engineering seismology. However, the articulation of these basic principles for rapid assessment and for tracking the deterioration of non-structural components is new and innovative, and has distinct advantages over conventional methods. Whilst the new methodology is yet to be fully developed, the presented innovation in the context of modelling NS component behaviour is original and has never been published previously.

5. ACKNOWLEDGEMENTS

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