

# THE SEISMIC ASSESSMENT OF SOFT-STOREY BUILDINGS IN MELBOURNE

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## ABSTRACT:

Buildings with soft-storeys are well known to be particularly vulnerable to collapse and severe damage under earthquake excitation. Despite this, buildings possessing soft-storey features are commonly found in low to moderate seismic countries such as Australia. Cost effective retrofitting of soft-storey buildings to improve seismic performance is possible if the seismic demand and building capacity can be realistically estimated. Conventional seismic design procedures involve the determination of the building's seismic base shear demand using a structural response factor to account for inelastic action and overstrength. Such methods are approximate and do not provide guidance on likely seismic performance under an extreme event.

This paper presents a simple and effective non-linear static procedure to compare the seismic demand and capacity of a soft-storey structure. The seismic demand is represented by a recently developed response spectrum model that realistically estimates the maximum acceleration, velocity and displacement response in ADRS format. The capacity of the soft-storey is ascertained using a deformation model that accounts for the effects of axial compression, flexure, shear, column-end rotation and foundation flexibility. The uneven sharing of shear forces between the columns and the significant additional shear demand associated with strut actions in masonry infill are amongst the numerous important issues that are raised for special attention. A proposed experimental program to evaluate the accuracy of the analytical procedure is described.

## 1. INTRODUCTION

A soft-storey possesses horizontal stiffness and/or strength properties that are much less than that of adjacent storeys and are typically the weak link in the resistance of the building to horizontal loading. The concentration of damage in the soft-storey often results in building collapse under severe seismic excitations. Soft-storey construction is commonly associated with poor seismic performance and is prohibited by regulatory controls in most high seismic regions. However, buildings featuring soft-storeys are still commonly found in regions of low or moderate seismicity including Australia. A recent survey by the authors of high-rise apartment buildings around the metropolitan area of Melbourne revealed the widespread use of reinforced concrete portal frames, which are designed to transfer vertical and horizontal loads from the first floor level to the ground floor level. The flexible portal frames which constitute a soft-storey are designed to support the "rigid-block" like upper floors consisting typically of reinforced concrete walls and slabs. This paper presents the findings from an analytical investigation into the seismic response behaviour of typical soft-storey buildings using a case study building.

The traditional force-based approach in current codes of practices uses a "structural response factor" ( $R_f$ ) to account for both overstrength and inelastic response behaviour of a building structure. The complex non-linear behaviour of a soft-storey is influenced significantly by factors such as axial compression and shear span-depth ratio of the columns and cannot possibly be modeled accurately and reliably by a single  $R_f$  parameter. Furthermore, there are no specific provisions in current codes of practices (e.g. AS1170.4, 1993) to address soft-storey structures.

Non-linear static procedures (NSP) seem to be the most suitable method for assessing the seismic performance of buildings possessing soft-storey features. In this paper, results from analyses using NSP are presented in the acceleration-displacement response spectrum (ADRS) format [ATC-40, 1996] to illustrate the performance of a soft-storey building.

## 2. CAPACITY PREDICTION OF SOFT-STOREY BUILDINGS

The force-displacement behaviour of a typical soft-storey building is illustrated in this section using a case study example. The lateral displacement of the soft-storey primarily results from the deformation of the columns consisting of flexural deformation, shear deformation, yield penetration and end joint rotation.

Flexural deformation can be relatively accurately estimated by integrating curvatures that have been calculated in accordance with representative stress-strain relationships of both the concrete and steel [Watson et al., 1994] assuming plane section remaining plane. Shear deformation is particularly significant with short columns possessing low shear-span to depth ratios. In this study, a truss analogy method developed for cracked concrete [Park and Paulay, 1975] was used to predict shear deformation assuming linear elastic behaviour of the concrete "struts" and the steel "ties". An alternative method would be to use compression field theory [Vecchio and Collin, 1986].

The effects of yield penetration in the column longitudinal reinforcement at the anchorage to the foundation was calculated in accordance with the recommendations by Alsiwat and Saatcioglu [1992]. Finally, end rotations of the column contributed mainly by the flexibility of the piled foundation and the connecting ground beams have been incorporated into the analysis according to the recommendation in ATC-40 [1996]. The relative contributions from each of the deformation mechanisms to the total deformation of the column have been studied by push-over analysis using the example column shown in Figure 1.

The displacement behaviour of the portal frame as a whole was also studied. Analysis results show that compressive stresses in the columns arising from the "push-pull" actions associated with the application of the horizontal load could be very significant (refer Figure 2). The initial axial load ratio of 0.15 under gravity loading could be increased to 0.3 as the horizontal force is applied to the frame. Importantly, the stiffness properties of the column are very sensitive to the induced axial compression. Consequently, columns within the same portal frame possess very different stiffness properties. The force-displacement relationships (defining the effective stiffness) of the individual columns along with that representing the portal frame as a whole are presented in Figure 3 (points 1 to 3). The analytical deformation model described previously (refer Figure 1) was augmented by the empirical model of Panagiotakos and Fardis [2001] to extrapolate the response to failure. (i.e. beyond the point annotated with a "3" in Figure 3)

The differential stiffness in the columns resulted in a very uneven sharing of the horizontal shear forces between the columns within the portal frame. In the presented case study of a 13-storey building (Figure 2), the more heavily loaded column (i.e. column subjected to a higher compressive stress) attracted twice the shear force of a lightly loaded column. Such differential load-sharing between the columns is typically not modeled by the commonly used structural analysis packages. Thus, the seismically induced shear forces in soft-storey columns are often understated by conventional analyses.

Finally, the calculated displacements of the superstructure (associated with tilting of the foundation) and P-delta effects have been included in the analysis to obtain the force-displacement relationship of the whole building (refer Figure 3).

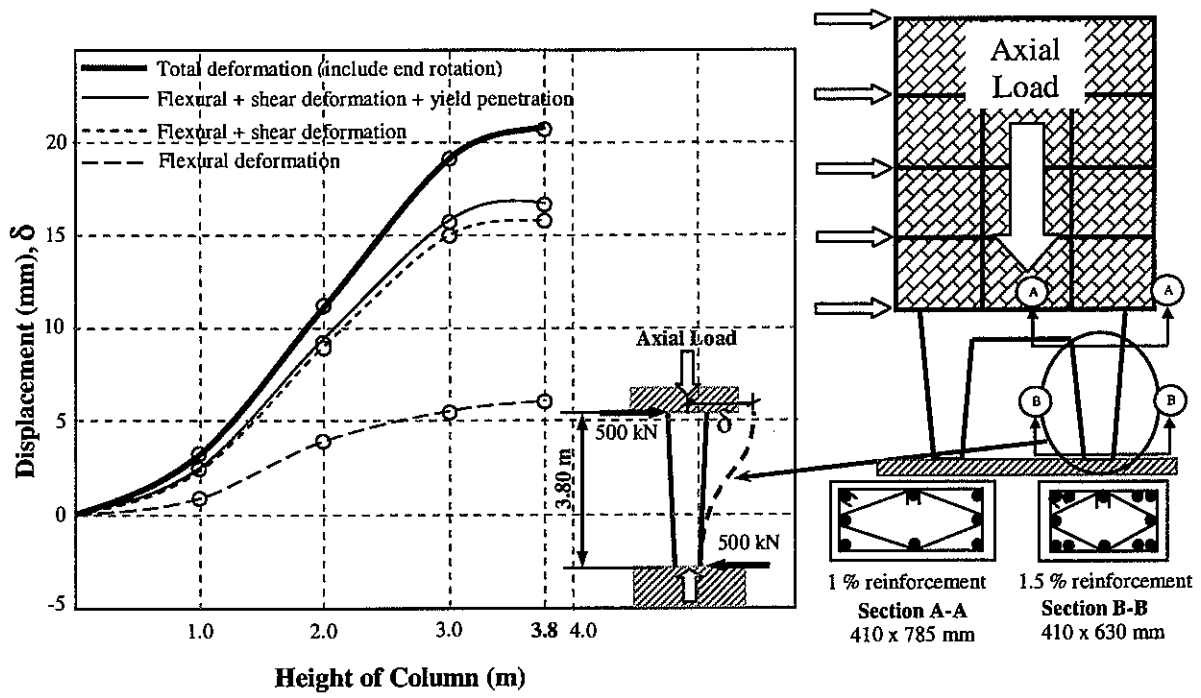


Figure 1. Deformation along the height of column subjected to horizontal shear

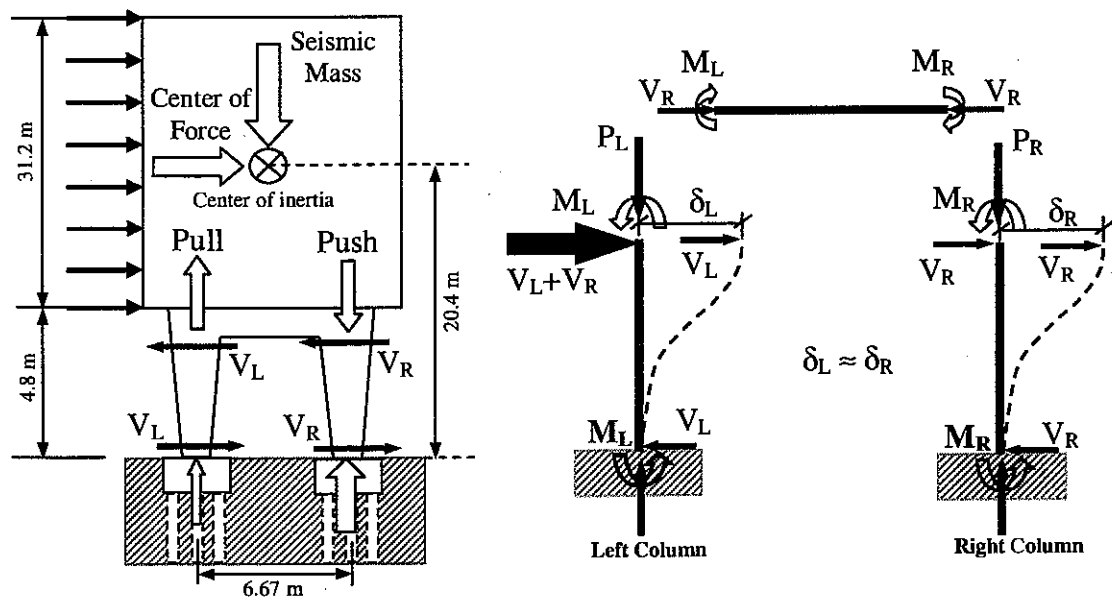


Figure 2. Portal frame under axial load variations

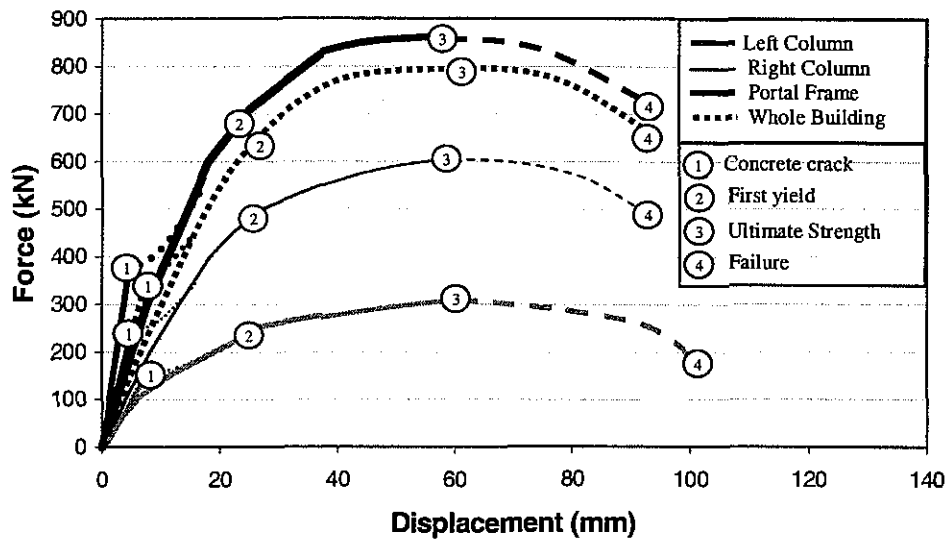


Figure 3. Shear – displacement behavior of columns, portal frame and whole building

### 3. PERFORMANCE EVALUATION OF SOFT-STOUREY BUILDINGS

The potential seismic performance of the soft-storey building was assessed by the capacity spectrum method (CSM) [ATC-40, 1996] based on the force-displacement relationships developed in Section 2. An introduction to CSM can be found in Wilson and Lam [2003]. The assumed seismic demand was based on provisions incorporated in the draft Joint Australian/New Zealand Standard for Earthquake Actions [AS/NZS 1170.4 Draft No.8: 2003]. Information from borehole records taken from the area indicates a Class C site. The performance point obtained by intercepting the demand curves with the force-displacement (capacity) curves has displacement in the order of 20mm and the corresponding acceleration is 0.14g approximately (refer Figure 4). This may conclude that under the earthquake, this building will perform satisfactorily under the elastic limit.

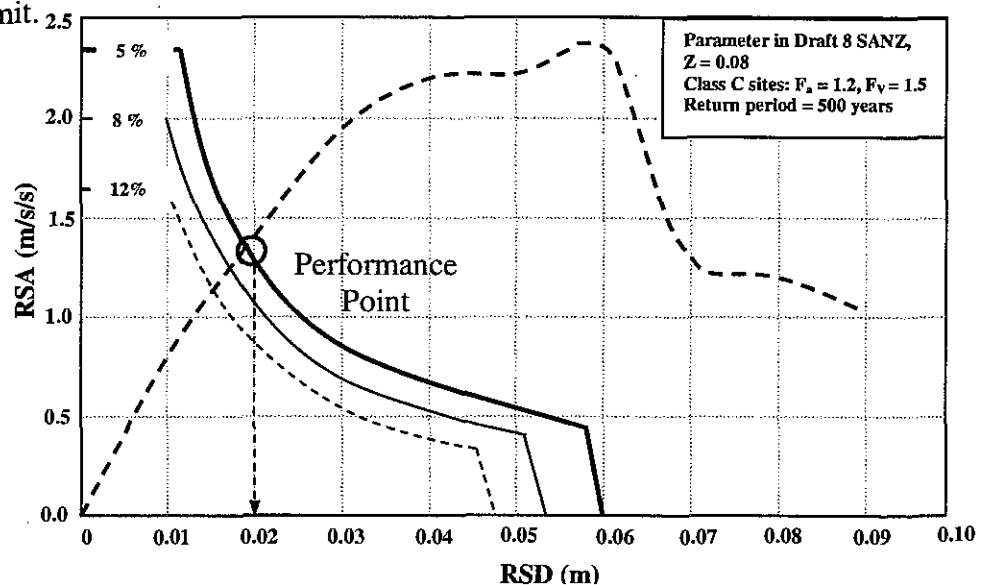


Figure 4. Capacity spectrum diagram of the case study building

#### 4. ASSESSMENT OF ELEMENT PERFORMANCE

The shear capacities of the columns and possible "weak links" including beam-column joint failure have also been checked against the shear demand. In calculating the shear demand, the effects of the masonry infill have also been taken into account.

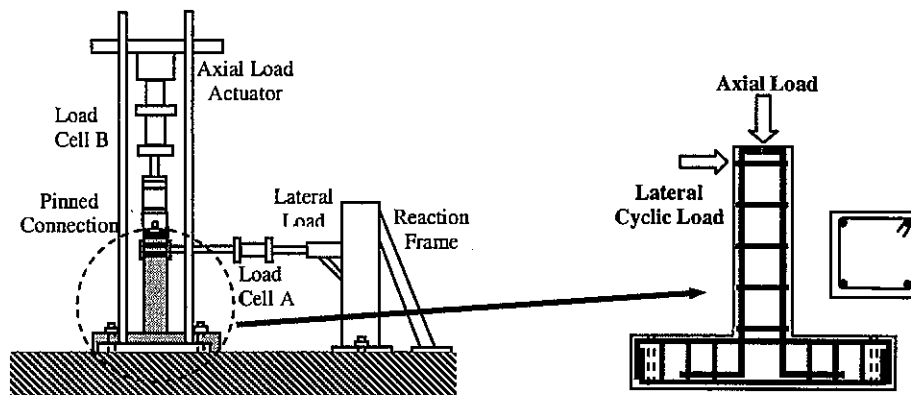
The shear capacity of the columns was estimated with reference to a multitude of code provisions including that of AS3600 [2001] and ACI-318 [2002] along with the well-known recommendations by Priestley et al. [1994] and Moehle et al. [2002]. The 500-year return period shear demands on the columns without masonry infill were found to be significantly less than the shear capacity.

The introduction of concrete cavity masonry infill wall panels between RC columns at ground level was found at a limited number of locations. The stiffening effect of the infill wall can be idealized as a diagonal strut that braces the portal frame until the wall strength is reached. This strut action could induce excessive local shear forces in the adjacent RC columns and result in the shear resistance of a few of the ground floor columns being exceeded. This was not considered critical to the overall stability of the building since alternative load paths exist in adjacent portal frames and the global response of the structure is displacement and not force controlled. In view of the limited displacement demand of the earthquake (20mm), the failure of a column in shear would not lead to the collapse of the building provided that the column is effectively braced by adjacent lateral load resisting elements, which perform satisfactorily.

The shear capacity of the beam-column joints has also been assessed in accordance with the estimates of the forces that could be transmitted from the adjoining beams and columns. The resulting stress conditions associated with "joint opening" and "joint closing" actions have been analysed using the Mohr's circle approach based on recommendations by Priestley [1995]. This approach is preferred over the simplified method suggested by FEMA273 [1997], which does not explicitly account for the effects of axial pre-compression in the joint. The critical principal tensile and compressive stresses developed at the beam-column joints were found to be within the permissible limits in both tension and compression.

#### 5. EXPERIMENTAL PROGRAM ON SOFT-STOREY COLUMNS

In this study, an experimental program on typical soft-storey columns will be undertaken to develop and verify the analytical column-deformation model. Cantilever column specimens representative of current constructional practices will be tested to study the force-displacement behaviour under both monotonic and cyclic loading. The typical experimental set-up is shown in Figure 5. The newly established *Digital Close-range Photogrammetry Technique* [Fraser, 1997] will be used for measuring deformation and surface strains. One of the key objectives of the experiments is to evaluate the accuracy of the analytical procedure in resolving deformation into the respective components including the contributions from flexure, shear and yield penetration.



**Figure 5.** Experimental equipment for cyclic load test

## 6. CLOSING REMARKS

This paper presents the application of a simple and effective non-linear static procedure to evaluate the seismic performance of a soft-storey building by comparing the seismic demand with the capacity. The seismic demand is represented realistically by a recently developed response spectrum model plotted in ADRS format. The capacity of the soft-storey is ascertained using a deformation model that has accounted for the effects of axial compression, flexure, shear, column-end rotation and foundation flexibility. The uneven sharing of shear forces between the columns and the significant additional shear demand associated with the strut actions in the masonry infill are amongst the numerous important issues that have been raised for special attention. An experimental program is being planned to confirm the accuracy of the analytical procedure.

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