Modern Multi-storey Buildings and Moderate Earthquakes

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ABSTRACT: Recent moderate earthquakes overseas have highlighted that the combined cost of direct damage and indirect effects of such events can be significant. In the case of multi-storey buildings, the non-structural damage is likely to be considerable, and will involve extensive occupancy disruptions.
This paper summarises a recently completed EQC research project which examined the following aspects:

- The characterisation of moderate earthquakes in terms of engineering design parameters
- Quantifying the level of lateral drifts anticipated for modern multi-storey buildings under this level of ground shaking
- Highlighting the major process issues and likely durations associated with the damage assessment and repair phase

Analysis of a 13 storey moment resisting concrete frame building designed to NZS 4203:1984 under the corresponding response spectrum indicated that structural damage is likely, in addition to extensive non-structural damage. From the displacements determined from this analysis, it is suggested that the damage ratios that are commonly applied to modern multi-storey buildings for MM8 intensity shaking represent lower bound damage estimates only.

1 INTRODUCTION

1.1 *Project Origins*

Recent moderate earthquakes overseas (Loma Prieta, Newcastle, Northridge) have highlighted that the combined cost of direct damage and indirect costs resulting from the disruption which follows such events can be much greater than generally anticipated. Furthermore, the methodology for obtaining estimates of indirect losses from either moderate or major earthquakes is much less well-established than for loss estimates relating to physical damage. It is the contention of the authors that damage levels to building and other structures is likely to be greater than predicted by traditional damage ratio approaches.

Over the past decade, designers and planners have been provided with "tools" to address the issue of moderate earthquakes by way of serviceability limit state criteria and hazard scenarios with shorter return periods. However the advent of serviceability limit state design of buildings for earthquake is relatively recent, and the criteria are still only in their formative stages. Also, the reality is that most of the multistorey buildings constructed in the "boom" period of the

1980's were designed with only passing regard to the physical consequences of a moderate earthquake. The majority of buildings in this category are flexible moment-resisting frame structures, and can be expected to experience considerable drift in even moderate earthquake shaking.

In recovery terms, the considerable non-structural damage from a moderate earthquake is likely to take longer and be more disruptive than generally anticipated, with associated cost implications.

This paper is a summary of an EQC-funded research project (Brunsdon & Clark, 2000).

1.2 *Aim and Objectives*

The aim of this study was to explore the issues associated with the likely impacts of moderate earthquakes on modern multi-storey frame buildings, and to highlight areas where further consideration should be given.

The broader purpose of this project has been to promote a change in emphasis for earthquake preparedness from *major* to *moderate* earthquakes. It is hoped that this shift in emphasis will instill a greater sense of urgency in the business community with regard to business continuance planning.

The key aspects that this project focused on were:

1. Characterising moderate earthquakes in terms of parameters used in the engineering design of new buildings
2. Quantifying the level of lateral drifts anticipated for modern multi-storey buildings
3. Identifying the non-structural damage that could potentially be caused by such movement
4. Highlighting the major issues and likely durations associated with the damage assessment and repair process

1.3 *Project Methodology*

This research project involved the following steps:

1. Characterisation of a moderate earthquake in terms of intensity and acceleration parameters
2. Physical inspection of two modern ductile multi-storey concrete frame buildings designed in accordance with NZS 4203: 1984
3. Analysis of one of these buildings using the parameters obtained from Step 1 to identify the likely order of drift in a moderate earthquake Consideration of the level of damage resulting, and comparing this against conventional damage ratios
4. Consideration of the recovery scenario, including the time implications associated with the assessment and repair process

2 CHARACTERISTICS OF A MODERATE EARTHQUAKE

2.1 *General*

It is acknowledged that the term "moderate earthquake" is to an extent conceptual, and lacks formal definition. This project sought to characterise a moderate earthquake in both general terms (ie. Modified Mercalli scale) and specific terms (ie. engineering design parameters).

2.2 *Modified Mercalli Scale*

The Modified Mercalli scale (MM) is a subjective measure of the intensity of earthquake ground shaking based on personal observations. As such, it has limited application in quantifying ground shaking measurements, with increasing emphasis being placed on parameters such as displacement, velocity and acceleration (eg. peak ground acceleration). The historical emphasis on early construction also causes difficulties in applying the MM scale to modern construction. Paulay and Priestley (1992) observe that the expected performance of well-designed modern buildings cannot be directly related to Modified Mercalli intensity. The usefulness of the MM scale with regard to modern reinforced concrete buildings has also been questioned in the field of post-earthquake reconnaissance (Brunsdon, 1993). A linkage with the MM scale is however necessary as it continues to provide important linkages to historical data which use damage ratios to form the basis for loss estimates.

For the purposes of this study, a moderate earthquake is taken as one that produces a peak intensity on intermediate soils (as defined in NZS 4203:1992) of level 8 on the Modified Mercalli scale.

A revision of the MM scale to take greater account of modern construction (Smith et al, 1992) indicated the following likely damage for MM 8:

- *Buildings Type III* (designed to resist earthquakes but without special damage limiting measures ie. mid 1930's to mid 1970's) *damaged in some cases*
- *Some pre-1965 infill masonry panels damaged*
- *A few post-1980 brick veneers damaged*
- *Houses not secured to foundations may move*

While no mention of the likely performance of post-1980 multi-storey buildings is made under MM 8, "damage or permanent distortion to some buildings" is indicated for these buildings under MM 9.

Dowrick (1996) has proposed a development of the descriptions for higher MM intensities which builds upon the earlier work by Smith et al. This work includes the addition of a set of performance indications for buildings from the capacity design era (ie. the same set as the subject of this study). In this proposal, no performance indication is given for MM8 intensity. For MM9 the following damage description is given:

"Damaged in some cases, some flexible frames moderately".

Given the extensive use of this scale in the analysis and description of historical earthquakes, an improved set of damage descriptors for modern buildings under MM8 and MM9 shaking in terms of both non-structural and structural performance is clearly warranted.

2.3 *Moderate Earthquake Scenario for Wellington*

As part of this project, the Institute of Geological and Nuclear Sciences was commissioned to prepare a moderate earthquake scenario for Wellington. This scenario is outlined in detail by McVerry (1996), with a summary of the key findings presented in this section.

This study identified that an earthquake of magnitude 6.0-6.5 at a depth of 10-30 km at some unspecified location up to 40 km from central Wellington is representative of a scenario for a “moderate” earthquake in Wellington. Such an earthquake is estimated as likely to cause peak ground accelerations over a large part of the region of about 0.2g on rock, which may be amplified to about twice this value at some soil sites. The probability of a shallow earthquake of magnitude 6.0-6.5 within a horizontal distance of 40 km of Wellington city is estimated as 30% in 50 years, corresponding to an average recurrence interval of 140 years. No such event is known to have occurred in this region since 1840, but several precedents in regions with analogous tectonic regimes have occurred in recent years, such as the 1990 Weber and 1993 Ormond earthquakes. The June and August 1942 Wairarapa earthquakes both generated felt intensities of MM6 and 7 in Wellington City and the Hutt Valley respectively (Dowrick, pers. comm.).

This scenario is consistent with the regional event scenario used in a recent study of lifelines in Wellington (WELG, 1993). It represents a larger event than the Scenario 1 earthquake developed by the Wellington Regional Council (Kingsbury and Hastie, 1992).

Elastic response spectra for 5% damping were estimated for rock, stiff (intermediate) soils and deep soils for the scenario events (refer Figure 1). Depending on site conditions, the amplitudes of the peaks of the estimated spectra reach between 50% and 94% of the peaks of the NZS4203:1992 code spectra, falling to lower ratios at longer spectral periods. The spectra exceed the serviceability levels of the code, for which no structural damage and minimal non-structural damage is expected.

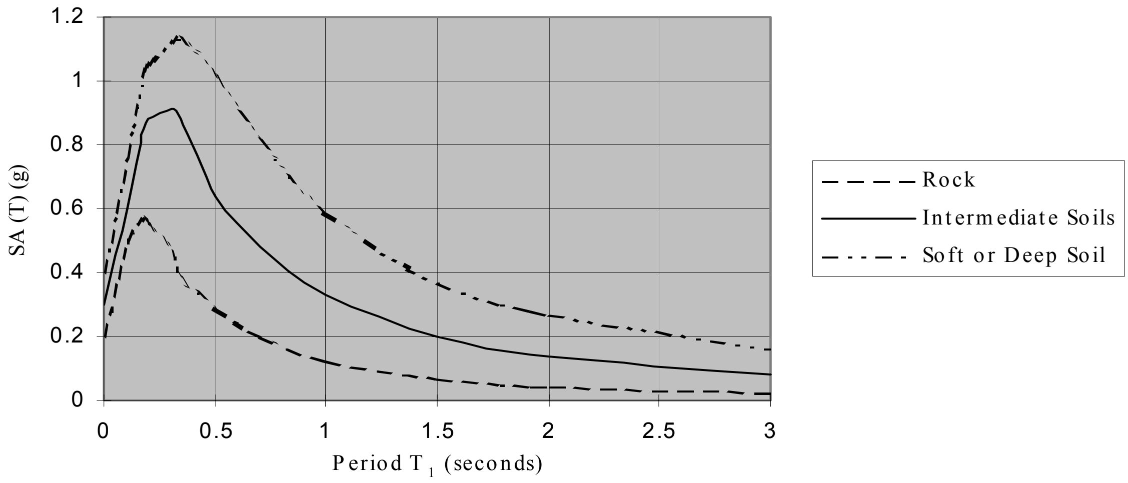

Figure 1: "Moderate" Elastic Spectra for Wellington (McVerry 1996)

3 STRUCTURAL RESPONSE OF A MULTI-STOREY BUILDING TO A MODERATE EARTHQUAKE: A CASE STUDY

A thirteen storey moment-resisting concrete frame building constructed in Wellington in 1988 was chosen as a case study example for this project. It is both vertically and horizontally regular, and constructed in a predominantly precast form that was common to this era.

The building was designed in 1987 using ETABS version 4 as the principal analysis tool. As with the majority of concrete frame structures designed in New Zealand, the design was governed by interstorey drift considerations. In this case, the critical interstorey drift was between ground and first floor; the limit of 0.01H from NZS 4203:1984 required a 48mm maximum drift for this level, and 36mm for upper floors.

A modal response spectrum analysis was carried out on the building structure in accordance with NZS 4203: 1992, modified by the use of a "Moderate" earthquake response spectra as developed for this study by McVerry (1996). The objective was to determine interstorey displacements and implied ductility demand, hence potential for non-structural damage due to a moderate earthquake.

This analysis indicated a maximum interstorey displacement between ground and level 1 under moderate earthquake shaking of 20mm, and a drift ratio for both levels of 0.0042. The corresponding peak displacement for the NZS 4203 ultimate limit state earthquake is 35mm. As this is associated with a ductility demand of 6, the ductility demand for the "Moderate" earthquake scenario is therefore suggested to be of the order of 3.

These values however need to be rationalised in view of the differences between moderate and large earthquakes that are not taken account of in this spectral analysis. In the absence of more comprehensive time history analyses, the above values are likely to overestimate the actual response, as moderate earthquakes are typically weaker in long-period components. They nevertheless indicate that a degree of inelastic action can be anticipated in critical building locations, with larger responses applying to buildings on soft sites where considerable amplification is likely under lesser shaking.

For the purposes of the discussions and qualitative analyses in subsequent sections, representative performance parameters for the critical lower storeys of modern buildings on intermediate soil sites of peak interstorey displacement of 10 to 15mm (drift ratio of 0.002 to 0.003) and local displacement ductility demand of 1.5 to 2 have been assumed.

These values are greater than the peak displacement and ductility demands for a serviceability limit state earthquake of 6mm and 1.25 respectively.

At the above levels of displacement and ductility demand under moderate earthquake shaking, structural damage to primary beam and column members can be anticipated. Appreciable cracking with some spalling of concrete is likely to occur in critical locations such as potential plastic hinge regions. There would clearly be considerable damage to non-structural elements and contents under such movement.

4 REVIEW OF LIKELY REPAIR COSTS

Table 1 presents a breakdown of the construction costs for a typical multi-storey office building into the principal elements. These figures are extracted from the section on elemental costs of buildings in the New Zealand Construction Handbook by Rawlinson (1997) for a categorisation of 'Office building with air conditioning in the range 6 to 15 storeys'. The category of 'structural components includes the structural frame, floors (including roof), structural walls and stairs.

Also shown in the table are subjective estimates from the authors of the level of damage in costs terms that such a building may incur in a moderate earthquake, expressed as a percentage of total replacement cost.

The category of *Preliminaries* includes the following items of relevance to post-earthquake reconstruction:

- Removal and cleaning up of damaged material
- Temporary screens and protection of property
- Authority charges (building consent fees)
- Contractor supervision
- Contingency

Consultants' costs for initially establishing the level of damage, along with subsequent contract administration and verification, are also not included in the above. It is understood that these are typically aggregated separately under the category of the cost of the claims process.

Table 1: Breakdown of Construction Costs and Likely Repair Costs for Multi-storey Buildings Damaged in a Moderate Earthquake

Element	% Breakdown of Construction Cost	Likely Repair Cost Breakdown
Preliminaries	8%	*1% - 4%*
Foundations	6%	-
Structural components	18%	-
Non - structural components	30%	*5% - 18%*
External walls and glazing	*12%*	*1% - 5%*
Internal walls, partitions and doors	*6%*	*1% - 4%*
Ceilings	*4%*	*1% - 3%*
Other finishes, fittings and fixtures	*8%*	*2% - 6%*
Building services	38%	*1% - 8%*
	100%	***7%-30%***

While the analysis of the case study building in Section 3 identified that some structural damage is likely under moderate earthquake shaking, no repair cost estimate is made alongside structural elements in the table above. This is principally because the level of structural damage and its distribution throughout the building has a high level of uncertainty associated with it, pending further quantitative analysis. Moreover, a major cost contributor to this category can be the extensive opening up of linings and other finishes to ascertain whether or not there is a structural problem.

The exclusion of structural elements from these figures is intended to highlight the potentially significant additional impact on the overall likely repair costs ratio if structural repairs are found to be necessary.

Other assumptions inherent in compiling the right-hand column of Table 1 include that the exterior glazing system is largely unaffected. Damage to services as a result of water saturation from sprinklers is a significant unknown, and has also largely been ignored in these figures.

It should be remembered that the percentages in the right-hand column of Table 1 are effectively taken over all levels of a building, whereas a greater variation of non-structural damage with height can be anticipated from moderate earthquake shaking. However offsetting this is the reality that the cost of repairing partially damaged elements in situ within a functioning building can exceed the original installation (or full element replacement) cost.

These indicative estimate figures can be compared against established damage ratio parameters. Mean damage ratios from ATC 13 (ATC, 1985) for modern medium and high rise frame buildings under MM VIII shaking are 6.2% and 7.5% respectively. The figures from Table 1 suggest that these values represent only the lower bound of direct damage that can be anticipated.

5 SUMMARY OF THE DAMAGE ASSESSMENT AND REPAIR PROCESS TO BE FOLLOWED

It is instructive to set down the likely damage assessment and repair process on a step-by-step basis, as follows:

Owner ***(structural and non-structural damage)***	**Tenant** ***(contents damage)***
Loss adjuster to assess damage to structural, non-structural elements (incl. partitions, ceilings, plant & equipment and any water damage)	Loss adjuster to assess damage to contents including water damage
Insurer's engineer to assess above damage and compile repair specification (building consent may be required)	Insurer gives approval for the repair of minor damaged items and the replacement of written-off equipment
Agreement with owner (and owner's engineer) required	Tenant organises repairs, places order for replacement equipment
Contractor prices the repairs	Replacement equipment obtained and installed
Repair work underway	
Repair work completed	
Verification that repair work is to the satisfaction of all parties	

The key difference between owner and tenant processes is that in the majority of cases, the replacement or repair of tenants' contents will not involve construction contracts. The complications relating to tenant designed and owned fit-outs should however be noted.

The broader point though is that the ability of tenants to resume normal business operations will be significantly impacted by owner-related activity to investigate and repair structural and non-structural elements. These activity strands are highly interactive.

There are likely to be appreciable difficulties in reaching agreement on the scope of repair specifications for minor/moderate damage. There is a significant cost difference between "patch repair" and "comprehensive or total repair". This can also have considerable time implications.

This project included the development of a repair timeline, which indicated that some multi-storey buildings could take between 5 and 7 weeks before full re-occupancy can be assured for this supposedly minor level of damage. The main question in terms of putting a time-frame to these steps is the availability of suitably experienced adjusters, architects, engineers and contractors following even a moderate earthquake.

This first-principles assessment is consistent with the mean value of 9 weeks given in ATC 13 for full usability for buildings in the social function class of *professional, technical and business services* for a moderate damage state.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 *Summary of Findings*

- A moderate earthquake can be characterised as one that generates MM8 intensity on intermediate soils. In Wellington, such an event is considered to be represented by a magnitude 6.0 to 6.5 earthquake which has a return period of approximately 140 years (probability of occurrence 30% in 50 years).
- The maximum likely interstorey drift of a 13 storey moment resisting frame building designed to NZS 4203:1984 in such an event was found to be 10 to 15mm, and the corresponding local displacement ductility demand between 1.5 and 2. This indicates that a moderate earthquake is likely to cause structural damage to a number of buildings of this type, in addition to extensive non-structural damage.
- The likelihood of structural damage occurring under MM8 shaking contrasts with the qualitative damage descriptions for the lower values of the MM scale, whereby damage is not implied to modern construction until higher levels of shaking.
- Damage ratios that are commonly applied to modern multi-storey buildings for MM8 intensity shaking are around the 6 to 8% level. First principles qualitative assessments based on the above drift levels are used to suggest that ratios of 7 to 30% may be more appropriate. This indicates that typical damage ratios for moderate earthquake intensities represent lower bound damage estimates only.
- Consideration of the insurance and engineering processes for damage assessment and repairs following earthquakes has highlighted that even for buildings sustaining non-structural damage, there are a number of interactive steps involved. These steps can involve owners and tenants with separate but inter-related building, contents and business interruption policies. Analysis of the impact of the likely interaction plus the disruptive effect of repairing non-structural damage has indicated that some multi-storey buildings could take between 5 and 7 weeks before full re-occupancy can be assured.

6.2 *Recommendations*

6.2.1 *General*

- There needs to be a better awareness of the level of damage and disruptive impact of earthquakes that are smaller than “design” events but correspondingly more likely to occur
- The limited protection to non-structural and contents elements in moderate earthquake events afforded by modern ductile frame structures needs to be more clearly conveyed by designers to owners and prospective tenants. This category of construction is essentially untested in terms of actual earthquake exposure in New Zealand.

6.2.2 *Specific*

- A working party comprising insurance adjusters and earthquake engineers should be established to map the claims process for commercial premises following earthquakes, and to identify prior training needs and post-event guidance requirements for the engineering profession and the insurance industry
- Given the extensive use of the MM scale in the analysis and description of historical earthquakes, an improved set of damage descriptors for modern buildings under MM8 and

MM9 shaking in terms of both non-structural and structural performance should be developed.

- The findings from this study in terms of structural performance parameters should be further examined with regard to the frequency and duration of shaking from the scenario spectra. This aspect could involve the application of appropriately scaled time history earthquake traces to sample buildings.

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7 **RETURN TO INDEX**