# Seismic performance of non-structural elements within buildings

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**ABSTRACT:** The recent earthquakes have illustrated the vulnerability of non-structural elements of buildings (e.g. ceilings, cladding, building services equipment and piping etc.). With architectural and building services components comprising up to 70% of a building's value, significant damage to these elements resulted in some buildings being declared economic losses, even when the structure itself was not badly damaged. The recent earthquakes also illustrated the significant damage that can occur to building contents due to failure of the non-structural elements. Impacts on business continuity due to the damage of non-structural elements have been identified as a major issue in recent earthquakes in New Zealand, as well as worldwide. It appears a step change is required in the seismic performance of non-structural elements in New Zealand.

This paper explores whether the current approach being used in New Zealand, for non-structural contractor designed elements, is appropriate in meeting society's expectations. It contrasts the approach that has historically been taken in New Zealand, with that followed overseas, and discusses some of the work being undertaken at present across the New Zealand construction industry. The paper goes on to explore the issues associated with the restraint of non-structural elements, and identifies possible future approaches to improve their seismic performance.

## 1 INTRODUCTION

The recent Canterbury earthquake sequence and the more recent Seddon, Lake Grassmere and Castlepoint earthquakes have raised awareness of the risk earthquakes pose to the New Zealand community from a life safety perspective, as well as a cost viewpoint, in both monetary and societal terms. An analysis of the losses due to the 1994 Northridge earthquake indicated that of the approximate $6.3 billion of direct economic losses to non-residential buildings only about $1.1 billion was due to structural damage (Kircher, 2003). A similar study completed in 2004 suggested that losses associated with damage to non-structural elements and building contents represents 50% of total costs of an earthquake in a developed country (Bachman, 2004).

The costs associated with non-structural damage are intrinsically linked to the vulnerability of non-structural elements. A study of the 66,000 buildings damaged by the 1994 Northridge earthquake showed that while some buildings suffered significant structural damage, approximately three quarters of the buildings suffered damage to non-structural components alone (Charleson, 2008). The recent Lake Grassmere earthquake serves as an example of an earthquake that resulted in limited structural damage, but the non-structural damage was quite extensive.

As buildings become more complex with increasingly sophisticated and extensive building services systems and architectural finishes, an increasing proportion of the building value is dedicated to the non-structural elements and building contents. The earthquake engineering community, as well as society in general, are becoming increasingly aware of the potential losses associated with non-structural damage. This increasing awareness provides an opportunity, while the impacts of the recent earthquakes are high on society's mind, to effect change across the construction industry to improve the performance of non-structural elements in the New Zealand environment. It is evident that allowing the current level of poor performance is not an acceptable outcome.

In order to help improve the seismic performance of non-structural elements, this paper outlines current design and construction practice both in New Zealand and overseas, and the key issues identified with these practices that affect seismic performance. Finally, methods to improve seismic performance are suggested, along with recommendations to address the key problems identified.

## 2 RECENT PRACTICE

### 2.1 New Zealand

The structural codes used in New Zealand have a primary focus on designing buildings for life safety in the event of an earthquake. Much progress has been made over the past 50 years in the design of structural systems with ductile features able to dissipate energy and resist repeated cycles of seismic loads without excessive strength degradation. Buildings designed with these features provide a higher level of life safety performance in severe earthquakes compared with buildings without these features.

The structural engineer for a building project has traditionally focussed on the design of the building structure but not the non-structural elements, which are often proprietary items attached to the building. Examples include: cladding, partitions, ceiling systems, lights, mechanical equipment, piping and specialist equipment. Damage limitation and prevention has not traditionally had the same level of focus by building owners, developers, tenants and insurance companies, and hence structural engineers; although this view may now be changing.

Architects generally specify ceiling systems, cladding systems, partitions and architectural finishes. The building services and fire engineers specify mechanical services, electrical systems, piping and fire protection systems. The building services and often architectural elements are most often specified on a performance basis, with the requirements rather than the specific products being specified in the design documents. The specifications for the non-structural elements generally include a requirement for the non-structural elements to be seismically braced according to the requirements of NZS 4219:2009 in the case of mechanical systems and such like, or AS/NZS 2785:2000 for ceilings. The design and installation of the seismic bracing system for the non-structural proprietary elements is thus typically the responsibility of the contractor and his subcontractors.

**Figure 1. Widespread damage to a ceiling system (left), failure of a lightweight cladding system (right)**

The design and installation process for non-structural elements typically occurs after the building consent documentation has been processed by the appropriate building consent authority. It is a "just in time" design approach. The design of the seismic bracing is generally completed by the non-structural element subcontractor's staff or an engineer employed by the subcontractor. While the selection of the specific units and systems are reviewed by the services design engineer or architect employed by the building owner to ensure compliance with the design objectives, often this has not included a design review or installation check on the seismic bracing for the non-structural element or system. The building consent authorities typically have not required any specific design or construction review producer statements for the seismic bracing of the non-structural systems, and hence generally none have traditionally been provided.

The recent earthquakes have highlighted that while New Zealand has a requirement to brace non-structural elements for seismic loads, this may not be happening consistently resulting in damage. Anecdotal evidence suggests recent construction includes buildings built without effective restraint systems or in some cases without restraint systems installed at all.

## 2.2 **USA**

The experience in the USA has been similar to that in New Zealand. The 1989 Loma Prieta and 1994 Northridge earthquake exposed the lack of effective bracing for a wide range of non-structural systems. The Olive View Hospital, demolished following the 1971 San Fernando Earthquake due to extensive structural damage, and then rebuilt to a much higher structural design standard, never-the-less had to be evacuated following the 1994 Northridge Earthquake due to non-structural damage. Maximum accelerations of 0.82g at the base and 1.7g at the roof were recorded in the earthquake. The structural system performed without significant damage, yet damage to the ceilings, sprinkler piping and chilled water piping, and the resultant water damage throughout, closed the facility and necessitated extensive repairs (SSC, 2000)..

Historically in the US, while there have been code provisions for many years, (over 70 years in the Uniform Building Code (UBC)), regulating the seismic design of non-structural elements, the design and installation of architectural, mechanical, electrical and plumbing (MEP) systems has traditionally been done largely without consideration of seismic forces or checks for compatibility of deformations.

Like New Zealand, design of seismic bracing for non-structural elements in the USA was traditionally the responsibility of the non-structural proprietary item manufacturers, rather than the structural design engineers retained as part of the consultant design team for the design of the building. Bracing requirements were typically included in the MEP specifications prepared by the services engineers. The contractors arranged for the design and installation of the bracing for non-structural elements. Inspections to ensure the bracing was installed correctly were traditionally limited, or non-existent.

In 1972, the Office of Statewide Health, Planning and Development, (OSHPD), became responsible for hospital building safety in California following passing of the Hospital Seismic Safety Act 1972 (SB 519) (SSC, 2000). Recognising that bracing of non-structural elements significantly improves the performance of these buildings in earthquakes, OSHPD started to check that the bracing systems were designed and installed correctly. The present arrangement for bracing of non-structural systems in hospitals in California is the following:

- The MEP contractors are required to hire a licenced structural engineer for the design of the bracing systems. The design and documentation of the bracing system must be signed and stamped by this structural engineer who takes responsibility for the design of the bracing system.
- The structural engineer for the building reviews the non-structural bracing design both to check it has been designed correctly, and that the loads the non-structural elements and systems impose on the structure do not overload the building structure. The structural engineer for the building signs off the design drawings for the bracing system as reviewed.
- OSHPD also complete a detailed plan check process of the bracing system using their in-house structural engineers and sign it off prior to construction of the bracing starting.
- The special inspector for non-structural elements, a role which is required for all hospital jobs in California, checks that what is installed matches the bracing design drawings and signs off that the installation is as-designed.
- Any changes from the approved drawings to the bracing of non-structural elements during the

installation process is required to go through the entire process again and be stamped and signed by each of the parties.

This process has been identified as being both very costly and slow, but has resulted in the seismic performance of non-structural systems in hospitals in California being significantly improved. An analysis of temporary closures due to non-structural damage following significant earthquake events shows a reduction of 50% when comparing data from before and after when the Act was passed into law (Holmes & Burkett, 2006).

In the last 5-10 years, there has been increasing recognition across California that the traditional approach for seismic bracing non-structural elements generally used for all buildings, except hospitals, has resulted in significant damage, economic losses and disruption to buildings following earthquakes due to non-structural damage. This recognition prompted changes in the latest International and California building codes (IBC, 2012; CBSC, 2013). The code now requires periodic inspections of seismic bracing by an approved "special inspector" for electrical emergency power systems, pipes and equipment handling hazardous materials, along with exterior cladding and non-bearing walls over 9m above grade for buildings in high seismic zones. It also requires seismic bracing for high (over 2.4m) equipment racking systems and computer floors in high seismic zones. The code includes more extensive requirements for high importance buildings in high seismic zones.

The structural engineer responsible for designing the building is required to include the seismic criteria and basis of design as notes directly on the "for construction" drawings, so this information is easily accessible to the other designers and contractors involved in the design and construction of the building or associated non-structural elements. The code also requires that special inspection requirements are to be identified in a "statement of special inspections" filed with the building consent application, so the building officials are aware and have a record of the required inspections. These are carried out by a building official approved "special inspector" who is not necessarily the building structural engineer.

In addition, some building owners in California, particularly long term owners of large buildings, (e.g. universities), have started to require a non-structural seismic coordinator be hired as an additional member of the design team to:

- Improve the implementation of code intent for seismic protection of non-structural elements compared to current standards of practice in design and construction.
- Investigate the efficacy of design alternatives in terms of seismic performance of non-structural elements and systems.
- Provide guidance for the longer term use of the facility by preparing a seismic installation manual for building contents e.g. furniture, lab equipment and speciality items.

This role is intended to supplement the current responsibilities of the design team with respect to design, coordination and construction administration, but not transfer, modify, or eliminate any existing contract obligations. This approach was used for the recently completed Stanley Hall, a bioengineering research facility at University of California, Berkeley.

## 2.3 **Chile**

The Chilean standard (Earthquake Resistant Design of Buildings) is based primarily upon the UBC and includes provisions for enforcing the anchorage and tying of non-structural elements to the primary structure (NCh433, 1996). Lateral resistance criteria are specified in a similar way to that in NZS 1170.5:2004. Whether these criteria are enforced for non-structural elements is entirely at the discretion of the building owner.

The Chilean code includes stringent drift criteria (more stringent than U.S. and NZ codes). This has resulted in an almost exclusive use of shear wall systems in buildings. As a result, drift-related non-structural damage in the 2010 $M_w$8.8 Maule earthquake was reportedly significantly reduced compared to that observed in earthquakes in other developed countries (FEMA E-74, 2011). Even so, about 60% of the 130 hospitals were damaged by non-structural failures, which caused substantial economic losses, as well as a failure to meet the code requirement that these facilities remained operational following a large earthquake (EERI, 2010).

# 3 ISSUES WITH CURRENT PRACTICE

## 3.1 Cost

Market cost intelligence used by project managers and estimators in the New Zealand environment to advise clients has not traditionally allowed for significant design or construction costs for bracing of non-structural elements. The New Zealand construction industry is very cost conscious regarding both design and construction costs. Anecdotal evidence suggests the cost of bracing of non-structural elements is minimised as far as possible as people are not used to including significant costs for bracing when planning projects.

As non-structural systems become more complex and interconnected it is likely the costs of bracing will rise, exacerbating the issue.

## 3.2 "Just in Time" Design Timing

The selection of the proprietary non-structural elements is often made late in the design and construction process, often during the construction phase itself. This "just-in-time" design provides many advantages to clients and others commissioning new buildings. In an environment of rapidly changing technology this approach ensures that the most up to date technology is actually installed into the building. It minimises redesign when previously identified units or components are no longer available or as a consequence of detailed coordination between different proprietary elements. Crucially, it encourages competitive tendering amongst the subcontractors by allowing each tenderer to propose a solution based on the performance specification, generally using proprietary products they have exclusive access to.

This approach is generally seen as providing the best value possible to the owner. However it does result in any design for these elements, such as bracing, being completed after the regulatory building consent approvals process has been completed and once the contactor, along with subcontractors, has been selected.

## 3.3 Procurement

The competitive tendering model generally used in New Zealand for the selection of contractors for building projects focusses on initial capital costs. Life cycle costs, including the cost of non-structural elements is inevitably under pressure in such an environment.

In our observation the subcontract tendering and selection process for non-structural systems can result in subcontractors tagging out the seismic bracing in order to provide a more cost competitive tender compared with other subcontractors competing for the work. Sometimes this tag is not made clear or recognised by those involved in tender selection resulting in the seismic bracing, noted in the specifications as being required, not in fact being installed.

Without an owner focussed on ensuring that bracing is installed to limit damage and downtime due to an earthquake, or some sort of regulatory requirement contractors are obliged to meet, market forces will continue to apply pressure to reduce or remove seismic bracing from the construction contract.

## 3.4 Construction Process and Programme

Non-structural elements are typically installed late in the construction process. The structure has been erected and is generally in the process of being made weather tight before any of the non-structural elements and proprietary items are introduced to the site for installation.

Generally this means that the structural engineer is no longer visiting the site to inspect key aspects of the construction of the structure at the time the non-structural elements are being installed. If inspections of bracing for non-structural elements are required then these will entail specific site visits.

## 3.5 Engagement of Consultants

The structural engineer's scope of work is traditionally confined to the building structure only, and excludes design of bracing for non-structural proprietary elements. This is because the focus has traditionally been the design of the primary structure, and often there has not been a request or expectation on the part of the owner, lead design consultant, MEP design engineer, or the proprietary item manufacturer, for structural engineer involvement in the design of these elements. Also, structural engineering consultants are often looking for ways to keep their fees within the traditionally expected boundaries in order to be competitive and secure the engagement, and so are not seeking to expand the structural scope of work to include non-structural bracing.

Expectations and tradition have meant that structural engineers designing buildings have historically not had significant involvement in the design and construction monitoring associated with non-structural elements attached to the structure.

## 3.6 Existing Buildings

A challenge associated with existing buildings is that new non-structural elements are regularly installed or altered over the life of the building. Sometimes these modifications are completed without the benefit of a building consent and generally without any oversight to ensure adequate seismic bracing is installed. Sometimes seismic bracing, installed as part of the original construction, is modified or removed as part of later alterations affecting the seismic performance of the non-structural elements. As an example, piping added post original construction and installed across seismic joints without flexible connections results in a piping network highly vulnerable in an earthquake.

The installation of seismic bracing for non-structural elements requires continued focus and oversight over the course of the life of the building.

## 3.7 Code Compliance

NZ society traditionally has had an expectation that the building code requirements will fully meet their needs. Building owners rarely, in our observation, seek to construct buildings that exceed the minimum code requirements. With the New Zealand building codes primarily focused on life safety, damage prevention and limitation has not had the level of focus that it might have. The lending institutions and insurance companies associated with building projects have not typically recognised the considerably reduced risk associated with damage limitation designs with financial incentives, (e.g., reduced insurance premiums or lower lending costs).

## 3.8 Industry Survey of Issues

EERI conducted a survey of US industry members in 2009 (EERI, 2009) to try and understand people's opinions of changes required to improve the situation surround the poor performance of non-structural elements. This study identified the following key issues:

- Speed of design and construction,
- A requirement to coordinate with many people, across many different disciplines, and between designers, manufacturers and contractors,
- A diffused responsibility matrix,
- The normative effects of individual behaviour where individuals behave as they think others are behaving, and
- Costs involved with provision of non-structural bracing, both design and construction.

These key issues closely align with our observations of the issues associated with current New Zealand practice, confirming the issue around the seismic restraint of non-structural elements and systems are not unique to New Zealand.

## 4 RECOMMENDATIONS

Based on the key issues identified with current practice surrounding the design and installation of non-structural elements, we suggest the following actions to improve the seismic performance within the New Zealand environment and regulatory regime:

1. **Include the structural design criteria directly on the drawings.**

   The structural design criteria for the building should include both seismic load and drift expectations. This will allow contractors, manufacturers, designers of non-structural elements and building officials to be appraised of the design requirements for non-structural elements.

2. **Provide a list of design and inspection requirements for non-structural elements as part of the building consent documentation.**

   These may only cover critical services, e.g. fire, emergency power, and hazardous materials, or they may be a more comprehensive list based on specific client requirements.

3. **Require a PS1 (design) to be submitted by the appropriate design engineer, contractor or an engineer employed by the contractor for the identified non-structural elements.**

   This PS1 will be linked to the list of design and inspection requirements provided as part of the building consent documentation. It will provide clarity of design responsibility for these elements with regulatory overview provided by building officials.

4. **Require a PS4 (construction review) for specified non-structural elements.**

   The requirement of a separate PS4 will address concerns surrounding construction review and verification of most non-structural elements.

5. **Review the codes relating to non-structural bracing.**

   A review of New Zealand Building Code and standards for design loadings, building services and suspended ceilings currently in use in New Zealand indicates various ambiguities and possible interpretational issues which would benefit from being clarified or revised.

6. **Encourage bracing for non-structural elements and systems to be listed separately from the equipment in tenders.**

   This will assist in providing visibility to main contractors and those assessing tenders for owners that costs for non-structural bracing has been included in the tender prices.

7. **Encourage education of all involved in the construction industry, (designers, contactors as well as building owners) about damage limitation and prevention, the benefits, and how this can be better achieved.**

   Education across the industry is vital to improve the performance of non-structural elements in earthquakes.

## 5 THE FUTURE

The above listed actions will improve the seismic performance of buildings within the New Zealand environment as owners and others with an interest in buildings become educated in the value of reducing damage and disruption as a result of earthquakes. Increased recognition of the benefits of reducing non-structural damage will also lead to an increased appreciation that this is an additional cost and service worth paying for.

A range of tools are being developed industry-wide in New Zealand and internationally along with possible future technology developments and ideas on ways to engage industry participants. These point the way to the future in the effort to improve the performance of non-structural elements in earthquakes. These include:

1. **Damage Control Limit State (DCLS)**

   The damage control limit state has been defined by Priestley et al, (2007) as the limit state whereby a certain amount of repairable damage is acceptable, but the cost of repair should be significantly less than the cost of replacement. This is not a limit state defined by NZS1170.5. However it is generally comparable with the SLS2 requirement for critical post disaster designated buildings in NZS1170.5, which requires that the structure be designed so that it can be returned to a fully operational state in a short timeframe (usually minutes to hours, rather than days).

   The use of such a limit state would provide a mechanism to discuss with building owners their objectives for the performance of the building in an earthquake.

2. **Performance Assessment Calculation Tool (PACT)**

   The Applied Technology Council (ATC) of the USA is currently developing a software tool, the Performance Assessment Calculation Tool (PACT) that identifies the seismic vulnerability, or fragility, of each structural and non-structural component along with the component value breakdown of a building. It provides a simple method to calculate probable loss so one can compare the expected damage and costs associated with different non-structural components (FEMA P-58-1, 2012). It is anticipated this tool will provide avenues for financial incentives to improve the bracing of non-structural elements e.g. through insurance premium reductions.

3. **Building Information Modelling (BIM)**

   Future use of Building Information Modelling (BIM) will help to improve the identification of clashes between non-structural elements, as well as allow design of non-structural elements to progress at an earlier stage. Sub-contractors can input information into the model before beginning construction, with opportunities to pre-fabricate or pre-assemble some systems off-site.

4. **Non-structural Seismic Coordinator**

   The introduction of the role of non-structural seismic coordinator, such as that used by UC Berkeley for Stanley Hall, would provide a designated person within the team responsible for considering seismic protection of non-structural elements. This role may be something building owners, particularly long term owners of large complex buildings, may consider is appropriate on future projects.

## 6 CONCLUSIONS

A combination of a lack of focus on the seismic performance of non-structural elements by structural engineers and other designers, and a history of low expectations, has resulted in generally poor performance of non-structural elements of buildings in New Zealand historically. It is becoming clear that seismic design in the future will be driven at least in part by the need to improve the seismic performance of non-structural systems. Performance-Based Earthquake Engineering (PBEE), and future developments in structural engineering seismic design, will be fuelled in part by the need to improve the seismic performance of non-structural systems. Post-earthquake functionality and operability will not be delivered until effective strategies are devised to minimize non-structural damage.

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