TOWARDS A NEW DELIVERY APPROACH TO IMPROVE THE PERFORMANCE OF NON-STRUCTURAL ELEMENTS IN NEW ZEALAND

How design, coordination and construction of non-structural elements has a significant effect on the resilience of buildings and the wider New Zealand Economy

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Abstract

Observations made in past earthquakes, in New Zealand and around the world, have highlighted the vulnerability of non-structural elements such as facades, ceilings, partitions and services. Damage to these elements can be life-threatening or jeopardise egress routes but typically, the main concern is the cost and time associated with repair works. The Insurance Council of New Zealand highlighted the substantial economic losses in recent earthquakes due to poor performance of non-structural elements.

Previous inspections and research have attributed the damage to non-structural elements principally to poor coordination, inadequate or lack of seismic restraints and insufficient clearances to cater for seismic actions. Secondary issues of design responsibility, procurement and the need for better alignment of the various Standards have been identified. In addition to the compliance issues, researchers have also demonstrated that current code provisions for non-structural elements, both in New Zealand and abroad, may be inadequate.

This paper first reviews the damage observed against the requirements of relevant Standards and the New Zealand Building Code, and it appears that, had the installations been compliant, the cost of repair and business interruption would have been substantially less. The second part of the paper highlights some of the apparent shortcomings with the current design process for non-structural elements, points towards possible alternative strategies and identifies areas where more research is deemed necessary.

The challenge of improving the seismic performance of non-structural elements is a complex one across a diverse construction industry. Indications are that the New Zealand construction industry needs to completely rethink the delivery approach to ensure an integrated design, construction and certification process. The industry, QuakeCentre, QuakeCoRE and the University of Canterbury are presently working together to progress solutions. Indications are that if new processes can be initiated, better performance during earthquakes will be achieved while delivering enhanced building and business resilience.

Introduction

Non-structural elements within a building are generally classified into three broad categories:

- Architectural elements, such as exterior cladding and glazing, ornamentations, ceilings, interior partitions and stairs,
- Mechanical and Electrical components and equipment, including air conditioning equipment, ducts, lifts, escalators, pumps and emergency generators, and
- Building contents, such as movable furniture, bookshelves, computers and entertainment equipment.

Non-structural elements suffered extensive damage in the Canterbury (Dhakal 2010), Cook Strait and Kaikoura earthquakes (Stanway & Curtain 2017). Figure 1 illustrates a sample of some of the damage observed. The cost of repair work for damage and business interruption due to poor performance of non-structural elements in the Christchurch, Cook Strait and Kaikoura earthquakes has been substantial, although difficult to quantify as the economic losses are not recorded separately by insurers, or the wider industry. The damage also highlighted the potential for large consequential damage (such as sprinkler failure), and the complexity and duration of repairs which significantly impact the business interruption (Stanway & Curtain 2017).

Figure 1: Illustrating damage to non-structural elements observed in the Canterbury earthquakes (left, from Dhakal, 2010) and Kaikoura earthquake (right, from Radio NZ/Susie Ferguson).

Observations following the Canterbury, Cook Strait and Kaikoura earthquakes indicated (Stanway & Curtain, 2017) that new buildings that had code compliance certificates did not necessarily meet New Zealand Building Code requirements relating to non-structural elements. This resulted in considerably more damage to non-structural elements than would be expected for compliant installations with the corresponding impacts on repair cost and operational disruption. Nevertheless, in this paper it will also be argued that improvements will be required to building code requirements if reliable performance of non-structural elements is expected in future earthquakes.

Performance Requirements for Non-Structural Elements

When reviewing the performance requirements of non-structural elements, it is necessary to not only consider the relevant Standards but to also consider the overarching performance requirements of the New Zealand Building Code (NZBC).

The New Zealand loadings code (NZS 1170.0) includes two serviceability limit state (SLS) loading checks: (i) SLS 1 for which “the structure and the non-structural components do not require repair” for earthquake loading with 1/25 year return period and (ii) SLS2 for buildings with special post disaster facilities that should maintain operational continuity for 1/500 year earthquake loading. A comparison of the various Standards used for the design of building services (NZS 4219), suspended ceilings (NZS 2785) and sprinkler systems (NZS 4541) highlights, however, varying performance requirements between the standards and the NZBC (Stanway & Curtain, 2017). It has also been highlighted that there are inconsistencies in the interpretation of the New Zealand earthquake loadings Standard NZS1170.5, and those inconsistencies are then being applied in the design of non-structural elements through the use of NZS 4219 and NZS 4541, which are dependent on NZS 1170.5 for seismic actions (Ferner et al, 2016). The current fragmented nature of the requirements and interaction between ceilings, sprinkler systems and engineered systems does not support the coordination of these non-structural elements.

The desired performance requirements for non-structural elements during earthquake are defined in NZS 1170.5 and we understand that further clarity around interpretation, especially with regard to the performance requirements for various non-structural elements, are to be included in future updates to NZS 1170.5 (Ferner et al, 2016).

Based on observations from recent earthquakes (Stanway & Curtain 2017, Baird & Ferner 2017), the main reasons that non-structural elements are not performing as desired appear to stem from:

- Issues with the existing procurement process and current practices on installation and compliance check for non-structural elements.
- Issues with current code provisions for non-structural elements.
- Limitations of our understanding of the seismic behavior of non-structural elements.

These three points are elaborated on in the sections that follow.

Issues with the existing procurement process and current practices on installation and compliance check for non-structural elements

The current procurement process for the design of seismic restraints of non-structural elements in New Zealand is summarised below based on the traditional procurement method where the design team prepares tender and building consent documentation, followed by tender award and construction:

- Architect provides performance specification requirements in relation to suspended ceiling bracing, bracing of internal partition walls and seismic performance of glazing and façade systems. This is usually provided without details.
- Building Services (mechanical, electrical and fire engineers) provide performance specifications for the design and installation of seismic restraints of building services plant, pipework, ducting and equipment.
- The current industry practice is for the design team to provide performance specifications that reference NZS 4219, NZS 4541 and AS/NZS 2785 with minimal seismic design, detailing or coordination between the various elements.
- The base build work is procured through the Main Contractor during tender and sub-contracted out to individual sub-contractors working in the various sub-trades.
- Main contractor is responsible for the coordination of all seismic restraints of non-structural elements for the base build.
- Fit-out works are often procured separately (ceilings, partitions, HVAC and lighting) by the tenant.

The current procurement process puts all risk of the design, coordination and installation of non-structural elements to meet current New Zealand Building Code requirements onto the main contractor. Because the current process does not include a fully coordinated design prior to the procurement process, the main contractor carries significant risk that they may have not have fully understood the complexity of the installation, including the challenge of finding sufficient room to adequately install, restrain and provide clearances to all non-structural elements within the context of the design which has been issued for tender. Following the installation, it can be difficult for building consent authorities to confirm compliance with the Building Code when the seismic restraint of non-structural elements was consented by reference to performance specifications and the design team is not contractually responsible for undertaking inspections to confirm the installations have been installed in accordance with the relevant standards.

Issues with current code provisions for non-structural elements

In addition to the compliance issues identified in the previous section, a growing body of research has also demonstrated that current code provisions for non-structural elements, both in New Zealand and abroad, may be inadequate. Examples where the code provisions appear to require revision include:

1. The estimation of acceleration demands on non-structural elements: These are usually computed using a code procedure that effectively defines floor acceleration response spectra at different levels of a building. However, Sullivan et al. (2013) and others have demonstrated that international standards all provide poor predictions of floor spectra demands, particularly for non-structural elements characterized by low levels of damping. The left side of Figure 2 shows that the acceleration demands on non-structural elements characterized by 2% damping atop an 8-storey RC wall building are likely to be underestimated by a factor of around three when the period of the component corresponds to the 2nd mode period of the building (0.5s for the case shown). The right side of Figure 2 reminds us that the amplification of acceleration demands felt by components is not new, with Biggs (1971) reporting high amplification of demands on equipment (with 0.5% damping) almost 50 years ago. More recently, shake table tests on ceilings (Pourali, 2018) and numerical investigations (Welch and Sullivan 2017) have confirmed that the ratio between the maximum acceleration of the component to that of the floor can be much larger than the ratio prescribed in codes. The factors affecting the acceleration imposed on a component are known to include the intensity of the ground motion, the component's period of vibration and damping, and the dynamic characteristics of the supporting structure (noting that the dynamic response of a building will lead to different floor acceleration demands at different locations up the height of the building). These points are also relevant to acceleration demands in the vertical direction. No international standards, including NZS1170.5, currently appear to account for all these factors.

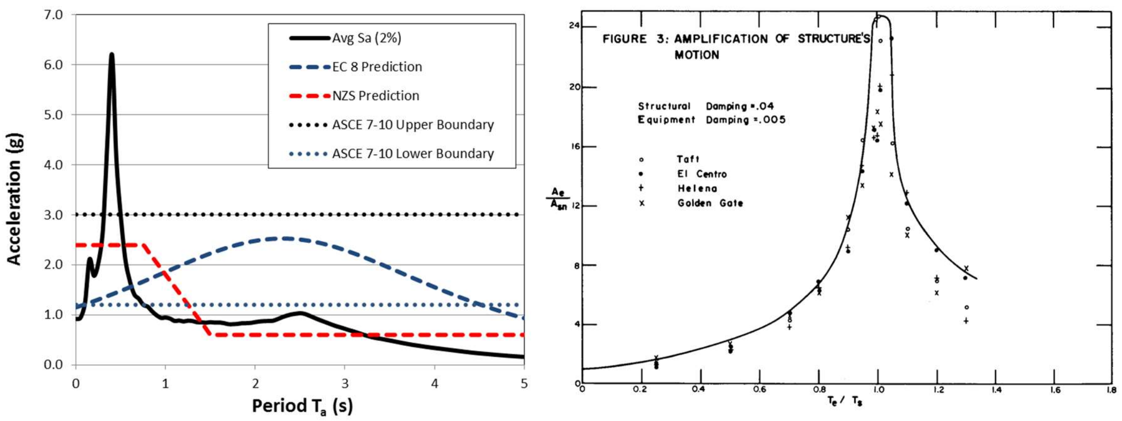

Figure 2: Comparison (left) of predicted floor acceleration response spectra at top level of an 8-storey RC wall building (from Sullivan et al. 2013) and (right) dynamic amplification factors (ratio of acceleration demand on a component to peak floor acceleration demand) from Biggs (1971).

2. Design provisions to account for non-linear deformation capacity of non-structural elements. Currently, ductility reduction factors are included in codes to allow reduction of elastic acceleration demands to design levels that allow for some non-linear response of the component. However, it would appear that there is little evidence from research or in-situ observations that the ductility reduction factors included in codes are appropriate.
3. The NZ standard provides guidelines to calculate the seismic demands for acceleration sensitive non-structural components, but further guidance should be provided for the verification of drift sensitive non-structural components. Currently, the standard requires the structural engineer to evaluate drift demands which are then included in a design features report with the expectation that the various non-structural components are detailed to ensure that the drift demands can be

achieved for the different limit states (see earlier discussion about performance objectives). However, there is only limited guidance for contractors on how to demonstrate compliance.

4. Proprietary guidelines for the design of different non-structural elements. Most of these prescribe the maximum spacing of the seismic bracings for different components. The specifications, however, do not distinguish between (i) different component mass (e.g., larger pipes vs smaller pipes), (ii) size and inclination of the braces, and (iii) type of connections between the brace and the components or the supporting component of the structure (e.g. floor). Obviously, the component mass governs the seismic demand on the component, and the brace or connection type/size/inclination governs the capacity of the braces, so these variables should be explicitly accounted for in design.

Limitations of our understanding of the seismic behavior of non-structural elements

While it is recognized that improvements can be made to our current code provisions, it should also be recognized that there are limitations to our understanding of the seismic behavior of non-structural elements. This refers to both our understanding of the strength and deformation capacity of elements as well as the dynamic response and interactions that can occur between elements.

For example, fragility of non-structural elements is key to assess their seismic performance but fragility functions for all non-structural elements are not known. Although significant efforts have been invested on researching NSEs in New Zealand (Dhakal et al 2016a) and fragility functions have been developed for some components (for example; Dhakal et al 2016b and 2016c), there are still many non-structural elements without reliable fragility functions. To compound this problem, for many NSEs the fragility functions depend heavily on the details of their connections with the supporting structure and any fragility function developed based on tests in one country with one detail is not applicable in other countries where the commonly practiced details differ.

Damping of NSEs is known to affect their design demand, but damping is not well documented. While elastic force demand on NSEs can be estimated using standards and/or principles of mechanics, their nonlinear behavior is not well understood, which makes it difficult to estimate inelastic force and deformation/displacement demands, which govern the clear spacing required around the NSEs and their bracings.

Similarly, interaction between different non-structural elements and between a non-structural element and the supporting/surrounding structure is another very important phenomenon which is not well understood. After an earthquake, often damage is reported to multiple NSEs (typically ceilings, partitions, HVACs and services in the plenum space), and it is not at all clear which element failed first and triggered the failure of others due to the inevitable interaction.

Towards a New Design and Delivery Approach

Reviewing the causes of damage to non-structural elements, it is clear that the current delivery approach is a significant contributor to the poor performance of non-structural elements in past earthquakes. The damage and insurance losses sustained during recent earthquakes clearly shows that there is a value proposition for both business and wider macro-economic resilience for improvement in the seismic performance of non-structural elements. Interestingly, whilst the cost to design and install seismic bracing to non-structural elements is relatively small compared to the overall cost of building projects, the actual performance of the building will be dependent on whether appropriate clearances are provided and restraints and services are installed as per the design documentation.

All these point towards the need of a new delivery approach. Indications are that implementing the following delivery model will significantly improve the seismic performance of non-structural elements in New Zealand and consequently reduce the economic costs and downtime arising from damage to non-structural elements in future seismic events:

1. Full design and coordination of non-structural elements and their seismic restraint in the main design documentation.
   - Coordination of ceilings, partitions, structure, mechanical plant and ductwork, electrical cable runs, hydraulic and sprinkler pipework routes using a 3D BIM model would enable designers to consider clashes and clearance issues well before the design is completed. Whilst this will increase the time and cost to prepare the detailed design documentation, this cost is currently included by the contractor noting that there are often clashes during construction that require significant rework and cost.
   - Discussions with contractors indicate that significant savings in physical works costs and construction build times will be realized when contractors are provided with fully coordinated design documentation which includes non-structural elements and their seismic restraints (Stanway & Curtain 2017).
   - A significant barrier to harnessing the value of BIM is the lack of a cohesive and fit-for-purpose data scheme that meets the needs of designers, constructors, the supply chain and ultimately building owners and facility managers. What the industry ultimately needs is a set of common standards and deliverables that can be easily understood and readily implemented.

2. Independent inspections and certification/sign off that the installation of non-structural elements is consistent with the agreed final BIM model which in turn should ensure that the installation meets the requirements of the New Zealand Building Code and relevant Standards.
   - Inspections following recent major earthquakes in New Zealand found that fire safety systems in recently constructed buildings were typically found to be code compliant. It is likely that this is due to the requirements for as-built drawings of the system and an independent visual assessment to be completed by an approved inspectorate (FPIS or AON) prior to the code compliance certificate being issued.
   - The requirement to undertake these inspections are mandated in NZS 4541 (Automatic fire sprinkler systems). Enforcement regimes for other non-structural elements would be expected to significantly improve the rate of code compliance for new buildings.

Conclusions

Further research into the response of various non-structural elements in buildings is expected to inform updates to New Zealand Standards which will not only provide more robust estimation of seismic design actions but will also provide better understanding of how various non-structural elements perform during seismic events. Together these will result in improved seismic design, detailing and determination of appropriate clearances enabling the system as a whole to be considered and appropriately designed and coordinated.

Review of the observations into the performance of non-structural elements in past earthquakes has highlighted a recurring issue that the majority of the damage to non-structural elements was caused through lack of appropriate seismic restraints and clearances for seismic actions. In most cases the damage sustained to non-structural elements in recent earthquakes could have been significantly reduced if they had been seismically restrained, appropriate clearances provided and the effects of the entire system considered. The result would have been reduced business interruption costs, reduced repair costs, less replacement of building materials and therefore reduced environmental impacts. While not easily quantifiable, it is also understood that there are less social and health-related effects when people can quickly return to their place of work and continue their employment following major seismic events.

Feedback from consultants and the construction industry indicates that the New Zealand construction industry, as a whole, needs to introduce design and coordination of non-structural elements including the seismic bracing, during the design phase which is followed up with independent inspections to confirm that the final installation meets the requirements of the relevant Standards. Indications are that if this occurs not only will the installations have considerably better performance during earthquakes, but the installation efficiencies will lead to reductions in both time and cost.

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