Using holistic design to improve the seismic performance of non-structural elements and building resilience

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ABSTRACT

Non-structural elements typically contribute around 80% of the total cost of a building. Damage to these components as well as works to repair and replace earthquake damaged non-structural elements can mean buildings are unable to be used and occupied for significant periods of time following earthquakes. This occurred in many buildings following the Canterbury, Cook Strait and Kaikoura earthquakes where buildings only suffered minor structural damage but the impact on the non-structural elements and the ability to continue to use and occupy buildings was significantly affected.

Improving the seismic performance of non-structural elements will minimise the need to close buildings for repair after smaller earthquakes which will lead to improved resilience of the organisations and entities that occupy the buildings. Reduced damage and need for repair and replacement of non-structural elements will reduce the amount of waste generated to restore buildings and consequently reduce the Whole-of-Life embodied carbon emissions from our buildings.

This paper provides an overview of the key design, coordination, and installation issues that impact the seismic performance of non-structural elements and discusses how to incorporate holistic design to improve the overall seismic performance and resilience. The paper highlights the importance of structural response on the seismic performance of non-structural elements and discusses improvements to the design process, detailing, coordination and construction to improve the future seismic performance of buildings. The impacts of structural earthquake damage are discussed in the context of impact of the structural damage on the future performance of non-structural elements.

1 INTRODUCTION

Following the major Canterbury earthquakes in 2010 and 2011, there was a Mw 6.5 earthquake in 2013 (Cook Strait) that generated shaking in Wellington close to, or slightly exceeding a 1 in 25-year earthquake event. Whilst there had been extensive damage and learnings regarding the seismic performance of non-structural elements in Christchurch there was a focus on the structural damage sustained by buildings in Canterbury. The Cook Strait earthquake put significant focus on the impacts of damage to non-structural elements in smaller, more frequent earthquake events where minimal structural damage occurred. One notable modern building sustained significant damage to the non-structural elements throughout the building including damage to a sprinkler head that led to significant flooding throughout the building requiring the tenant to immediately vacate the building for months until the repairs were completed.

It became evident that the seismic performance of non-structural elements (which account for 70 – 80% of the building's capital cost) can have a bigger impact on <u>operational disruption</u> for businesses and tenants than failure of structural elements. Consequently, following the 2013 Cook Strait earthquake the insurance industry called for there to be a shift in the debate from the baseline structural minimum 'preservation of life' to building and business resilience (Stanway and Curtain, 2017).

There appears to be increasing awareness in the earthquake engineering community that improved seismic performance of non-structural elements is key to limiting the damage and disruption caused by earthquakes (Filiatrault and Sullivan, 2014). We learnt that consideration of the seismic performance of non-structural elements is not only important for buildings that need to continue operation post major earthquake (such as hospitals), but also important for our school buildings, supermarkets, office buildings, apartment buildings, industrial buildings, and transportation links that need to be functional following moderate earthquake events, as these are essential for the economy and wellbeing of our communities. This observation is supported by the recently published white paper 'Societal expectations for seismic performance of buildings' (Horsfall et al., 2022), which documented, from a **community perspective**, nationwide societal expectations for the seismic performance of buildings. This report acknowledged the importance of life safety in building performance expectations but also highlighted the importance of resilience for schools, aged care facilities, community meeting places, residential apartments and houses, supermarkets, and the like.

We are starting to see more resilience conversations occurring in New Zealand with some clients requesting higher than New Zealand Building Code minimum performance requirements for new buildings. However, the code minimum requirements to achieve no damage that requires repair following a 1 in 25-year event, remains the dominant serviceability limit state performance requirement for most buildings. Following a 1 in 100-year seismic event this code minimum design practice can lead to significant damage and repair/replacement of the non-structural elements, which can result in business interruption, significant generation of waste and costs of repair.

2 HOLISITIC DESIGN FROM PROJECT INCEPTION THROUGH TO PROJECT COMPLETION

The single biggest change to improve the seismic performance of non-structural elements in New Zealand is expected to occur when the holistic consideration of non-structural elements from the project inception to completion of construction is embedded in our design and construction process. The following sections describe the key considerations.

2.1 Procurement

The most common procurement practice is to use 'Design-Build' (often lowest price conforming) to procure the design and construction of non-structural elements. This procurement method attempts to transfer the risk of design, coordination, and construction of non-structural elements to the contracting teams even though the consultants now have exception tools available to them, such as BIM, to undertake this coordination. Typically, the consultants complete the building design without coordination of the final layout and sizing of the building services equipment, ducting and piping or the seismic restraints for the building services, ceilings and partitions which are documented for the contracting teams using Performance Specifications. The final design usually has significant changes to the layout and seismic bracing details once the building services design is completed and equipment chosen, compared to the basic details and layouts provided at consent and tender stage.

Using a holistic design process, the design consultants and contracting teams would be procured such that risk is distributed to the various parties in an equitable way. The scope of work for each design consultant needs to clearly set out the expectations for the overall building performance and requirements for holistic coordination between all parties to achieve the required building performance. Clear definition of scope will enable appropriate fee estimates and design timeframes to be allocated.

It is noted that traditional timeframes to complete detailed design may need to be extended to allow sufficient time for coordination between disciplines with the potential for the seismic restraint design and coordination of non-structural elements to lag a phase behind the main design disciplines.

2.2 Structural form

The structural system must not only achieve the architectural intent but should be chosen such that the drift and floor accelerations of the building for either damage limitation or continued functionality, results in cost-effective choice of non-structural elements. The structural team should provide a structural form during concept design based on consideration of the following:

- What cladding system is to be used? What is the drift limit for initiation of damage to the proposed cladding system?
- What is the extent of partitions in the building?
- Are there fire wall partitions in the building?
- Should the partitions be fixed floor to floor or have a seismic slip joint just above the ceiling level?
- What detailing is going to be required to achieve the performance objectives for the non-structural elements? For example, damage to partitions initiates around 0.3% drift (Davies et al., 2011; Mulligan et al., 2020), and standard ccommercial curtain wall glazing systems can lose water tightness at 0.35% drift (Arifin et al., 2020).
- Are there multiple wet areas (e.g., membrane showers as is provided in multi-residential units are vulnerable to the membrane being torn in the corners due to building drift)?
- A lightweight metal roof may appear to be cost effective with thin-walled purlins supported on optimized steel rafters/portal frames, but how are the gravity and seismic loads from the mechanical and electrical plant and equipment going to be resisted? If the equipment isn't specified, the building services team need to provide design details of plant and equipment and layout sufficient for the structural engineer to appropriately assess and choose the structural roof system to mitigate the need for costly secondary steel being needed to restrain the demands.
- Where are heavy non-structural elements going to be located and how are they going to be restrained for seismic demands? Beware that large, filled pipes have considerable weight.
- Does the proposed floor system have sufficient capacity to resist localized hold down demands from overturning of the mechanical and electrical plant?
- Only use ductility greater than 1.0 for non-structural elements where non-linear response in the proposed configuration has been confirmed through testing or research. There is little evidence from research or in-situ observations that the ductility reduction factors included in some codes (including NZS 1170.5) to allow reduction of elastic acceleration demands (allowing for some non-linear response of components) are appropriate (Stanway et al., 2018).
- Note that gussets, fly braces, collars and baseplates should be included in 3D coordination models as these components often have significant coordination impacts for the non-structural elements.

- How are fire wall partitions going to achieve a fire seal to the soffit of structural floor slabs? Trapezoidal metal deck concrete floors are challenging, time consuming and expensive to create a fire seal. Instead consider the use of flat metal deck concrete floor slabs, refer Figure 1.

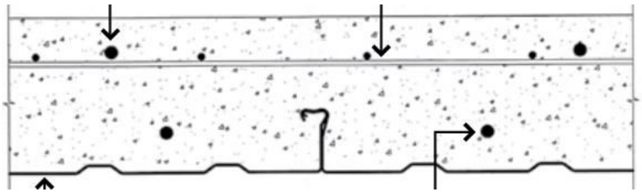

Figure 1: Flat soffit metal deck concrete slab to simplify fire wall connection and fire sealants

2.3 Potential for increased vulnerability of non-structural elements due to damage of the primary structure

Another important learning from the recent earthquakes is that structural damage can reduce the stiffness of structures, in particular concrete moment resisting frames. Research (Marder et al., 2020), found that epoxy-repaired plastic hinges can exhibit different behaviour from identical undamaged components in terms of reduced stiffness, increased strength and increased axial elongation but achieve comparable energy dissipation and deformation capacities. Decreased stiffness will result in increased drift. The research (Marder et al. 2020) provides recommendations for stiffness reduction that enables structural engineers to undertake analysis to understand the implications of the drift on the future performance of non-structural elements to ensure non-structural elements are not more vulnerable to damage.

Residual drift of a building following an earthquake presents unique challenges for building restoration that need to be appreciated as part of post-earthquake assessment and repair strategy but is just as important to be considered as part of the original holistic design of the structure. As an example, an apartment building suffered earthquake damage that included a 0.5% residual drift. Unsurprisingly the windows were damaged and require full replacement, the solid plaster cladding was damaged and leaking and requires full replacement. If the new windows and cladding system are installed vertically, a future earthquake that causes the building to displace to 0.25% drift in the opposite direction would result in all original building components experiencing 0.25% drift, whereas the new windows and cladding system will experience 0.75% drift and almost certainly be damaged including the weathertightness. If the new windows were installed to align with the existing drift the install will likely damage the windows during the install and would leave gaps at the edges of the opening windows as exists presently, refer Figure 2.

Figure 2: Air gap in corner of window due to residual drift of building

The impact of potential residual drift of buildings should be considered by the structural team as part of the holistic design of new buildings and retrofit of existing buildings, such that the building is repairable and can continue to meet the building performance objectives following future earthquakes.

2.4 Design coordination

It is still common that not all non-structural elements and their seismic restraints are documented and coordinated in the design stages e.g. ICT, electrical for mechanical, small pipework, details of all tenancy walls etc. are often excluded from design documentation and BIM models. The design of these items are commonly procured as design-build and coordinated with the remainder of the building components during the construction phase. It is not uncommon to find that there is insufficient room to install code compliant non-structural elements and their seismic restraints within the space provided within the building envelope. Changes of this magnitude are often too difficult to make during the construction phase and this often leads to compromises in compliance with the potential to lower the expected seismic performance of the overall building. The issues around non-compliance were highlighted in the research by Geldenhuys et al. (2016) who found that most of the non-structural elements inspected in recently constructed buildings did not have adequate restraint in accordance with the relevant standards and 80 to 90 % of the inspected partition walls, fire systems, HVAC systems and ceilings needed upgrade to comply with the relevant standard. In addition, it was found that many seismic restraints were compromised by poor fixing at the restraint, structure, or both.

Holistic design aims to eliminate the need to compromise building performance requirements and compliance through coordination based on knowledge and understanding of the seismic performance and response of the various structural and non-structural elements that make up the building.

Holistic design does not need all components of the building to be fully designed and documented by the design. Where architectural and building services components are to be procured as design-build elements, the design disciplines need to provide sufficient information to the wider design team to ensure the structural team understand the drift sensitive components and their drift limits as well as the expected weight and layout of plant and equipment so that the seismic demands and restraints can be determined. This will increase the likelihood that sufficient 'real estate' and capacity of structural components are allocated for not only the potential size of the components but also the required seismic restraints.

Design of buildings undertaken this way should significantly reduce the risk that when the contractor does the final design and coordination of these design-build components that there is insufficient room within the context of the building to enable full coordination and achieve the building performance requirements (which may be set higher than minimum code compliance).

2.4.1 Multi-storey apartment buildings

Multi-storey apartment buildings are a particularly challenging building type because they are heavily compartmentalised with walls that must perform to required fire and acoustic performance levels. In some cases, developer clients don't like to see movement joints in ceilings (or access hatches to inspect walls) and so request these to be omitted (Stanway et al., 2021). Apartment bathrooms incorporate tiled walls and floors with waterproof membranes that may be easily torn in a seismic event. Proper isolation of the tops of walls from the floor slab above can be challenging especially at an intertenancy wall.

2.4.2 Seismic restraint of building services

The seismic restraint of non-structural elements is commonly subcontracted to specialist seismic designers who are structural engineers by trade but have limited knowledge of the systems that they are restraining e.g. heating pipes, steam pipes, chilled water pipes, fire dampers. Functionality of these components is often not well understood by the specialist seismic restraint designers, and restraint details are often provided that do not enable heating and chilled water pipes to expand or fire dampers to break away.

The seismic restraint designer should coordinate fire dampers with the fire engineer and appreciate the relative movement between the fire wall partition (through which the fire damper is installed and possibly fixed to the slab below with a sliding joint at the top) and the movement of the duct either side of the fire damper which is hung from the slab above. Whilst considering the response of the 'system' the seismic restraint designer must ensure that any seismic restraint provided does not prevent the breakaway joint from working in the event of a fire.

It can be very challenging, if not impossible, to appropriately provide a detail that requires acoustic, fire and seismic performance as they inherently have competing requirements, e.g. separation verses connection.

2.4.3 Passive fire considerations

There are a limited range of tested passive fire systems. This can make it challenging to detail an unusual non-standard situation and with the additional requirement to accommodate seismic movement, an architect may require the input of a specialist passive fire engineer. Without the experience and knowledge, these issues can result in non-code compliant outcomes (Stanway et al., 2021).

Knowledge and experience in the industry on how to appropriately incorporate seismic design into passive fire design has largely been driven by Importance Level 4 projects (facilities that need to continue function following a disaster, such as hospitals) which require that the passive fire components achieve operational continuity following a 1 in 500-year seismic event.

It is most often by good luck rather than good management that seismic performance is appropriately incorporated into the passive fire design. The good luck component is that some firestop systems inherently have good firestop performance in a seismic event because they are already seismically isolated or restrained as part of normal design (Stanway et al., 2021). Further research is required to support the seismic performance of various passive fire systems and detailing to enable appropriate detailing for various structural forms and to support post-earthquake damage and repair assessments.

2.4.4 Façade system considerations

Different façade systems have different pros and cons. Curtain wall or unitised window systems tend to perform well with the preferred approach to have a rainscreen over a drained cavity. The issue with this is that damage to components of the waterproof line in the cavity may not be noticed for some time after an event. Also, a number of these products lack specific test information, or are suitable only for low-rise situations (Stanway et al., 2021).

2.5 Responsibility for coordination during construction

For design-build procurement with performance specifications it becomes the contracting team's responsibility to adequately design, coordinate and install the non-structural elements. Contractor's (and often Principal's) take on the risk that if appropriate coordination for all non-structural elements has not been undertaken from project inception, that significant additional costs and work arounds may be required to achieve compliance with the New Zealand Building Code.

New Zealand contractors reported (BIP 2020) that contracting teams want to construct and install fully resolved designs, but they are currently taking on design risk for the coordination of non-structural elements and their seismic restraints that is difficult to accurately assess and price at tender. They noted it is common for items to need to be reconfigured three or more times to get the installation right.

Following the holistic design principles, one entity will have ownership of the installation and coordination of non-structural elements and their seismic restraints during construction.

When alternative equipment substitutions are offered that indicate cost savings may be made, the true cost, including knock-on implications of installing the alternative equipment into the holistic building design can only be understood through interrogating a fully coordinated design/construction model.

2.6 Independent QA

Whilst it is starting to change, up until around 2020 it was typical that the design, coordination and installation of non-structural elements and their seismic restraints relied on self-regulation of the industry. Observations suggest that self-regulation is not working (BIP 2020; Geldenhuys et al., 2016).

Independent QA during construction is important to confirm that the installation of the non-structural elements meets the design intent and ultimately achieves the performance objectives for the building.

3 FUTURE WORK TO SUPPORT IMPROVED BUILDING PERFORMANCE

3.1 Research and testing

While research into the seismic performance of non-structural elements has been on-going for decades (e.g. Yancey and Camacho, 1978; Villaverde 1997), recent research (BIP 2020) has demonstrated significant gaps in technical knowledge both nationally and internationally, especially with regard to how various non-structural elements respond to seismic accelerations and building drifts and the interaction, impact and damage of various building components during seismic events.

Since the 2010-11 Canterbury earthquake sequence, multiple research projects have progressed that seek to improve the wider understanding and to provide new and improved details for use in the construction industry (Sullivan et al., 2013; Dhakal et al., 2016, 2016a, 2016b, 2019; Pourali et al., 2014, 2017; Yeow et al., 2018; Khakurel et al., 2019; Bhatta et al., 2020; Mulligan et al., 2020; Arifin et al., 2020a, 2020b).

There are a number of areas where further research would support the industry, these include:

- The post-earthquake performance of passive fire protection systems,
- Testing to provide assurance and information on the expected post-earthquake performance of non-structural elements in various configurations and seismic restraint. In particular, the industry needs clearer understanding on the way forward to achieve low-damage and continued operational/performance objectives in relation to water/weathertightness and thermal/acoustic performance of cladding and glazing systems, partition and ceiling systems, mechanical and electrical equipment,
- Details that require acoustic, fire and seismic performance,
- Estimations of repair costs, repair time, environmental impact and embodied carbon emissions for building components.

3.2 Seismic classification framework

A seismic classification framework is proposed (Sullivan et. Al 2020) that will provide a database and rating for each non-structural element system according to the drift and acceleration capacity of each system. It is proposed that the framework is developed as part of the Building Innovation Partnership programme of works where both researchers and industry will input into the framework. The framework promises to:

- Help engineers to appropriately specify and detail non-structural elements for buildings of different importance levels in line with their expected performance in earthquakes,
- Help the design team choose the most cost-effective combination of various structural systems at concept design alongside the expected costs for the detailing for the non-structural elements to achieve the

associated non-structural element Drift and Acceleration Element Class for each structural system considered,

- Assist in communicating the performance expectations for all categories of non-structural elements and restraints,
- Help facilitate inspection and compliance checks for sign-off of non-structural elements,
- Help facilitate inspection and assessment post-earthquake.

4 CONCLUSIONS

We need to look at building resilience differently. Building resilience is not only for buildings that have a post disaster function. Improving the seismic performance of our community meeting places, grocery stores, residential apartments and housing, as well as our schools, government, council offices and food production facilities is key to achieve the post-earthquake social and economic resilience expectations of our communities.

Improving the seismic performance of non-structural elements will reduce, to acceptable levels, the need to close buildings following earthquakes or to close them to enable the repairs to be completed, and hence improve the seismic resilience of our buildings. Reduced damage and resulting repair works will also reduce the amount of waste generated to restore the buildings and consequently reduce the Whole-of-Life embodied carbon emissions for our buildings.

Holistic design will address many of the industry challenges that caused poor performance outcomes in previous earthquakes. Holistic design requires coordination of the full design team and integration of the coordination to the contracting team. The structural engineers need to consider the impact of the structural response on the seismic performance of non-structural elements as well as the seismic demands on the structure to restrain components and provide appropriate structure to resist those actions. It requires the design team to provide sufficient real estate to enable the contracting team to appropriately design (as necessary) and install the non-structural elements, such that the thermal, acoustic and passive fire requirements are not compromised to achieve the seismic performance expectations for buildings as a whole.

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