Pragmatic approaches to improving the seismic resilience of Non-Structural Elements in existing buildings

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ABSTRACT: Following the recent earthquakes in New Zealand, there is a growing awareness of the seismic vulnerability of non-structural elements as well as the costly consequences of their failure. The next big challenge facing engineers and building owners is finding cost-effective and pragmatic solutions to improve the seismic resilience of non-structural elements in both new and existing buildings.

This paper presents an approach which brings together code requirements and learnings from the recent Christchurch and Lower North Island earthquakes to upgrade non-structural elements in existing buildings. A “best bang for the buck” approach is advocated by identifying and focussing on non-structural elements that could cause injury or items where significant improvements in resilience can be achieved relatively easily. This approach is presented through illustrated examples of issues and the solutions which have been adopted. It also discusses the challenges with trying to upgrade non-structural elements within existing operational buildings, including for example, congestion issues and practicalities of access.

The paper concludes by postulating on approaches, tools and regulatory options which could be developed to lift the seismic resilience of non-structural elements in existing buildings.

1 INTRODUCTION

The 2010/2011 Christchurch earthquakes and the more recent 2013 Lower North Island earthquakes at Cook Strait, Lake Grassmere and Castlepoint illustrated the vulnerability of a building’s non-structural elements (e.g. ceilings, claddings, partitions, building services equipment and piping etc.). Widespread damage and loss of business continuity from the performance of non-structural elements was widely observed and noted (Schouten 2013; Thomson and Bradley 2014; Helm 2014).

The Canterbury Earthquakes Royal Commission (CERC, 2012) identified the need to improve the performance of non-structural elements in earthquakes, with Recommendation 70 noting:

“To prevent or limit the amount of secondary damage, engineers and architects should collaborate to minimise the potential distortion applied to non-structural elements. Particular attention must be paid to prevent the failure of non-structural elements blocking egress routes.”

We consider that a pragmatic approach is required to improve the performance of non-structural elements in earthquakes in line with the recommendation of CERC, using sound risk-based social and economic criteria. This paper presents such an approach, focusing on addressing non-structural elements that could cause injury or where significant improvements in resilience can be achieved relatively easily.

2 BACKGROUND

Following the Loma Prieta and Northridge Californian earthquakes in the late 1980's and mid 1990's where significant damage occurred to non-structural elements, the United States government responded with legislative reforms, industry-wide education, research and development, documentation and procurement reforms, plus the growth of a non-structural element seismic design, product supply and inspection industry (CUREE 2009). These improvements have contributed to significant advances over time. This process continues in the USA two decades on as they continue to seek improvements in the delivery and cost effectiveness of non-structural element seismic performance.

The recent Christchurch and Lower North Island earthquakes have echoed the situation in California. While past practices relating to the seismic design of non-structural elements may have been widespread and considered "reasonable" at the time, we now know, based on evidence from the performance of non-structural elements in recent earthquakes, that they may fail the fundamental performance objectives of the Code, or that the performance objectives are not reflective of societies expectations. Improvements in New Zealand will also require reforms similar to those carried out in the USA, and in particular, significant effort towards industry-wide education of building owners, project managers, quantity surveyors, architects, engineers, main contractors, sub-contractors, product/system suppliers, and building consent authorities.

We consider that in order to improve the seismic performance of non-structural elements in existing buildings, the greatest value for the money (or 'best bang for the buck') will be achieved by focussing on:

- Actual risks (for both life safety and business continuity).
- Current knowledge of non-structural element seismic bracing requirements, rather than considering historic requirements based on seismic knowledge and practice when the non-structural elements were originally designed and installed.
- What is reasonably practicable given the specific circumstances (e.g. the practically of potentially significant construction works within operating facilities, hospitals and the like), and
- The post-earthquake operational requirements for the facility.

3 APPROACH

The three key considerations for improving the seismic resilience of non-structural elements are:

- Restraint – to resist the seismic loads.
- Clearance – to avoid damage/failure due to interactions between components.
- Flexibility – to avoid damage/failure to components due to displacements within or between the primary building structure.

The amount of work involved in addressing each of these considerations for every non-structural element in a building is enormous. This too often leads to either nothing being done, or the effort is not focussed in a sensible and efficient way. Therefore, we propose that to improve the seismic resilience of non-structural elements, an approach is necessary that takes into account further considerations to identify where effort is best focussed. This pragmatic approach is based on considering the following:

- Life Safety considerations
  - Will the elements, if they fall, cause a direct life safety risk to those below?
  - If elements fall, will they block egress routes?

- Operational considerations for IL4 buildings
  - Is the service, e.g. electrical supply, required in the immediate post-earthquake environment?
  - Will the elements, if they fall, result in a direct loss of a critically required service in the immediate post-earthquake environment, e.g. services located above critically required transformers etc.
- Functional requirements for the operational spaces below the in-ceiling services.
  - Are the clients' operational requirements such that loss of function in the operational space below the in-ceiling services in the immediate post-earthquake environment would be unacceptable, e.g. the trading area of a bank.

4 EXAMPLES

The following examples present issues, solutions, benefits and pitfalls for improving the seismic resilience of non-structural elements in existing buildings. These examples are presented for building services, suspended ceilings, partitions and the fixing of restraints. The examples also identify how the pragmatic approach introduced previously is applied in order to get the "best bang for the buck".

4.1 Building Services

Building services can encompass a wide variety of items such as; pipes, ducts, cable trays, heavy plant, and electrical and communication equipment. These services are typically suspended from the floor/roof above, fixed to the floor or supported off a wall. The gravity supports for suspended services are typically slender, flexible elements, e.g. rod hangers, and consequently, additional bracing of these elements is required to transfer horizontal seismic loads back to the primary structure. The brace itself is critical in determining the seismic performance of services, so is discussed further here.

4.1.1 *Brace Types*

There are a number of different brace types commonly used to restrain services, each with their own pros and cons. The main types are detailed below in Table 1.

Table 1. Comparison of different brace types.

Brace Type	Brief Description	Pros	Cons
Rigid Bracing	Can carry both tension and compression loads, e.g. equal angle	• Only one brace required at each restraint location (in each 90^{o} direction)	• Addition of a rigid brace to an existing non-structural rod hung element adds additional tension loads to the existing hangers in earthquakes. This can significantly increase the potential for gravity support failure in a seismic event if the existing gravity support anchors have not been designed for the additional seismic induced loads. • Rigid bracing can be relatively heavy and difficult to lift into place for manual installation overhead.
Cable Bracing	Can carry tension loads only, e.g. wire cable or steel strap bracing	• Lightweight and easy to install overhead. • Cable can easily be cut to installed lengths. • Allows for more thermal movement and so less likely to compromise existing pipework thermal expansion provisions.	• Two braces required either side of restrained elements. This may be difficult to fit in, particularly in congested areas. • Addition of cable bracing may require existing gravity tension rod hangers to resist compression loads requiring alteration of the existing gravity support system.

Brace Type	Brief Description	Pros	Cons
Proprietary Brace Systems	Can be rigid or cable bracing, e.g. ISAT, unistrut or Mason Industries	• Reasonably straight forward to specify from technical tables as standardised design and drawings already completed.	• Braces often cover large load ranges leading to conservative designs. • Proprietary products typically have a price premium over specific designed bracing. • Technical literature is often expressed based on American or European loading requirements and standards, so not easily comparable to NZ standards and code requirements.

4.1.2 *Bracing to Floor Underside*

Provision of seismic restraints through bracing to the underside of the floor above is the most common situation in multi-storey buildings. The non-structural elements in the ceiling space are typically hung-mounted from overhead. Floors in multi-storey buildings in New Zealand generally comprise precast or cast in-situ concrete floors, e.g. hollowcore or double-tee units, necessitating connection of the brace to the underside of these floor systems.

Two bracing solutions to the underside of the floor above are shown in Figure 1. The left photograph shows the restraint of pipework on a single trapeze. Rigid Sikla bracing was used to brace the services to the existing in-situ concrete floor slab. Note the transverse brace was installed within the cable run to avoid clashes with existing services. The right photograph shows rigid bracing that was used to brace the ducts and pipes to the existing precast floor slab. Note the congestion and coordination required to avoid clashes between the different braced services in both directions. It has been observed that fixings to precast concrete floors in particular can be problematic; this is discussed later in Section 4.4.

Figure 1. Restraint of new pipework in an existing building on a single trapeze to reduce the number of braces required (left) and restraint of existing pipework in a modern building (right).

A.V. and other electronic equipment which hang below a ceiling also require bracing. A common method is to brace the vertical dropper with diagonal wire cable in three directions, as shown in Figure 2. Care must be taken to ensure that displacement incompatibilities do not arise between the movement of the dropper and the ceiling which it passes through.

Figure 2. Wire cables added to brace A.V. equipment above ceiling level.

4.1.3 *Bracing to Roof*

Even in multi-storey buildings, it is common for the roof structure to comprise of a lightweight steel frame. Further considerations must be made with respect to supporting and bracing non-structural secondary elements to these lightweight structures, including:

- Relative stiffness, periods and relative differential movements in an earthquake of the lightweight roof structure compared with the supporting (often stiffer) structure below;
- Challenges associated with the additional point loads from the braces being applied to structural elements, e.g. the existing steel purlins, may not have been designed for loads in their weak axis;
- Extent and location of primary steelwork and purlins. Additional steelwork may be required for support of the non-structural elements;
- If the ceiling void is large enough, consideration could be given to adding a secondary steel grid above ceiling level – refer to Figure 3 below. A secondary steel grid can support the ceiling and services without the need for diagonal bracing, resulting in reduced congestion and improved clearances.

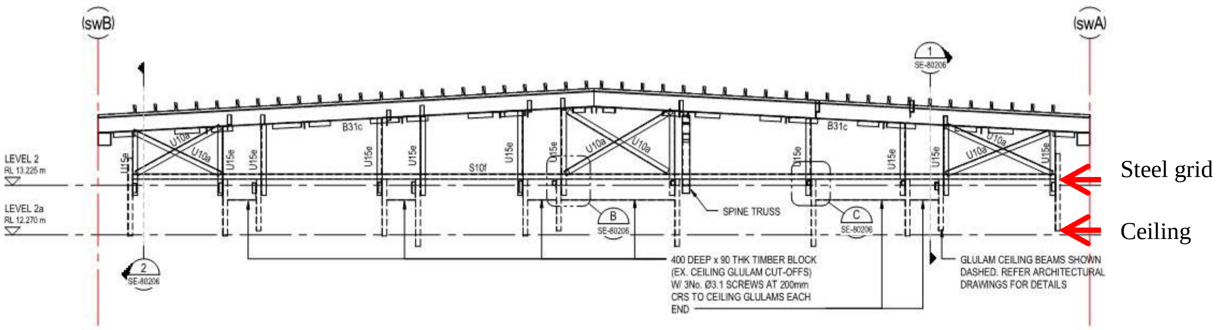

Figure 3. Specifically-designed secondary steel grid between roof and ceiling to support all services and ceiling.

Two bracing solutions to roof steelwork are shown in Figure 4. The left photograph shows services braced with cables to secondary steelwork and roof purlins. Note the vertical rod hanger has been bent to suit purlin location and the hanger has not been stiffened to resist upward compression loads. The right photograph shows proprietary (ISAT) rigid bracing in the transverse and longitudinal directions fixed to steel roof purlins. Note the longitudinal bracing has been installed at a flat angle so it can be connected to the adjacent purlin.

Figure 4. Cable bracing fixed to secondary steelwork and roof purlins (left) and proprietary rigid bracing in the transverse and longitudinal directions fixed to roof purlins (right).

4.1.4 *Other Considerations*

Adequate clearance must be provided between services and other elements, e.g. where a service passes through a wall. Often an oversized hole is provided that may require fire-rated material to be added if required, as shown in Figure 5 (left). Alternatively, a flexible length of service can be substituted for the rigid service, as shown in Figure 5 (right).

Figure 5. Rigid services passing through a wall utilising an oversized hole (left), or flexible duct (right).

Where services protrude through ceilings, flexible droppers or oversized holes with escutcheon plates can be used, as shown in Figure 6. Oversized holes are typically drilled into ceiling tiles to allow 25mm clearance to the service. These details allow the ceiling and services to move independently with reduced likelihood of damage.

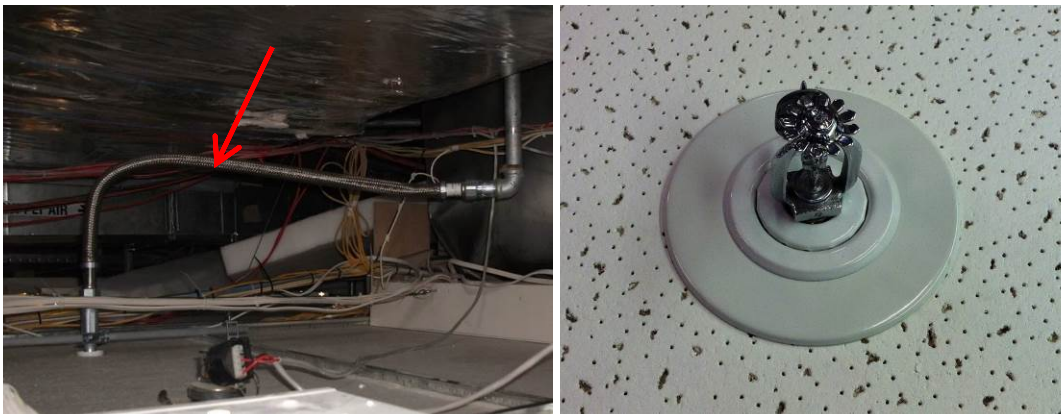

Figure 6. Compliant flexible sprinkle pipe fixed to ceiling tiles (left), escutcheon cover plate (right)

Splice joints at cable trays can be strengthened with the addition of proprietary splices as shown in Figure 7 (left). In the case of the example shown, the splices were added so that the calculated seismic loads could be transferred to adjacent braces. It is a requirement under NZS4219:2009 that services supported by the suspended ceiling that weigh ≤10kg should be positively fixed to the ceiling grid. Items weighing >10kg require independent support, as shown in Figure 7 (right) plus 25mm clearance to the ceiling. This support also includes a wire tether which acts as a back-up support should the primary support fail. This added redundancy is a cost-efficient way of improving life-safety performance when heavy plant is involved.

Figure 7. Proprietary seismic clip added to cable tray to strengthen splice (left), wire tether on HVAC kit (right).

Communication and data room floors, which often contain heavy plant, generally incorporate false floors to allow cabling to run beneath them. These floors are often supplied with no diagonal sub-floor bracing and can displace and distort during an earthquake. Diagonal braces can be added to the sub-floor as shown in Figure 8.

Figure 8. Sub-floor bracing added to proprietary false flooring.

4.2 Suspended Ceilings

Suspended ceilings typically transfer their inertial seismic load to the primary structure either through perimeter fixings or by bracing to the floor above.

4.2.1 *Ceiling System Options*

The following options can be considered when determining the seismic restraint requirements for ceilings:

- Restrain ceilings on all 4 sides (‘small’ rooms only)
- Restrain ceiling on 2 adjacent sides and release the 2 other sides
- Release ceiling on all 4 sides and brace to the floor/roof above

In heavily congested areas, vertical inverted portals, rather than diagonal bracing, can be installed as shown in Figure 9 (left). Like all ceiling bracing, these portals need to designed to be stiff enough to limit ceiling movement and distortion. These also help to minimise chances of clashing with services.

Failure in a ceiling grid often occurs at junctions splice points. These can be strengthened with the addition of proprietary seismic clips as shown in Figure 9 (centre). Ceiling hangers should be relocated where clearance to services is insufficient, as shown in Figure 9 (right).

Figure 9. Vertical inverted portals designed to brace ceiling (left), seismic clips retrofitted to ceiling grid (centre), and ceiling hangers relocated to provide adequate clearance to services (right).

4.3 **Partitions**

Historically, the heads of partitions have been connected to the underside of ceilings.

Options for partition restraints include:

- Isolating the partitions from the floor above. Horizontal bracing is installed above the ceiling level which braces adjacent walls together as a ‘box’ as shown in Figure 10 (left). Note the steel lintels and posts to frame out the glazing.
- Diagonal bracing from the top plate to the floor/roof above with a sliding top plate as shown in Figure 10 (right).
- Full-height steel posts at regular centres within the partition walls, providing restraint on three sides to the walls.

Figure 10. Horizontal bracing above ceiling level (left), restraint of timber partition wall at ceiling level to primary steelwork using tension/compression brace (right)

4.4 Fixings

The fixings are commonly the weakest link in restraint systems. Many of New Zealand's buildings contain precast floors which have limited ability for post-installation of fixings into the underside and typically have prestressed tendons which require 30mm clearance from any fixings or penetrations. Furthermore, hollowcore floors generally require the use of toggle clamps which require large holes to be drilled, creating dust and noise while also being time consuming to install.

Typically greater capacities and hence fewer or smaller fixings are required when chemical fixings are used as opposed to mechanical fixings. Issues that need to be considered when choosing the type of anchors include:

- **Substrate thickness:** With the adoption of lighter precast concrete floors, post-installing anchors can be an issue. The limited floor thickness may limit the size of anchors that can be used to M10 or M12, potentially leading to an increase in numbers of anchors required.
- **Floor type:** Hollowcore floors allow limited opportunity for fixings and often require the cores to be broken out and filled to allow fixing. Other precast floor types with prestressed strands limit the locations where fixings can be installed.
- **Fixing location:** Overhead or wall installation of services often lends itself to the use of mechanical anchors. Tighter control of installation is required for overhead installation of chemical anchors, i.e. to ensure the correct depth of hole is drilled and to allow full coverage and mixing of the chemical epoxy. Chemical anchors have a period of time before the epoxy can set and the anchor can be loaded, whereas mechanical fixings can typically be loaded immediately.
- **Fire-rating:** Chemical anchors often have insufficient fire rating to carry gravity loads so they are often not suitable for support of gravity hung elements.

Cast in fixings are sometimes used when large and/or heavy non-structural elements require restraint. These fixings require considerable coordination during the design stage. At that stage the exact type and location of vendor supplied information is generally not available causing difficulties as the non-structural elements have not yet been selected.

5 FUTURE

Improving the performance of non-structural elements in existing buildings will also require a range of responses and reforms to historic and current New Zealand practice. A range of tools and possible actions point the way in the effort to improve the performance of non-structural elements in earthquakes, these include:

5.1 Inclusion of Non-Structural Elements in Building Assessments

At present, initial seismic assessments using the IEP procedure do not include explicit consideration of the impact that non-structural elements will have on building performance in the event of an earthquake. A possible action would be the addition of qualitative risk grades (high, medium and low) for non-structural elements that potentially present life safety risks. This idea was presented in the SESOC 2012 conference paper 'Building Seismic Risk Assessment - Enhancing the IEP: 'IEP Plus' (Spencer, 2012). This points a possible way to include non-structural elements in initial building performance assessments.

5.2 Changes to Code Requirements

The recent earthquakes have drawn attention to a general level of non-compliance of the seismic restraint of non-structural elements in existing buildings due to systemic and industry wide problems with the regulation, design, procurement, installation and certification of non-structural bracing within the NZ construction industry. A historic difference in performance objective expectations, application and interpretation of NZS1170.5:2004 for non-structural elements between building services engineers and structural engineers has been identified. This includes, for example, possible consideration of vertical seismic loads in non-structural element bracing design.

Possible changes to NZS1170.5:2004 to make the objectives clearer for designers and regulators include clarifying what elements need to be included in meeting the stated objectives for the limit states is suggested. This may lead in turn to changes to standards dependent upon NZS1170.5:2004, such as NZS4219:2009 (Seismic Performance of Engineering Systems in Buildings) and NZS 4541:2013 (Fire Sprinkler Systems), NZS 4104:1999 (Seismic Restraint of Building Contents) and AS/NZS 2785:2000 (Suspended Ceilings, Design and Installation).

5.3 Building Information Modelling (BIM)

Future use of Building Information Modelling (BIM) to identify possible brace locations and orientations within existing buildings will assist with the retrofit design of non-structural element bracing. We note this level of detail is already used in California, particularly for hospitals. We anticipate this level of detail will likely only be financially viable in heavily serviced, high importance level buildings such as hospitals, police stations, research laboratories and the like.

We anticipate this will be assisted in the future by point cloud technology where the location of existing non-structural elements can be accurately located within the ceiling space and within the structure by 3-dimensional photographic means assisting the seismic brace designer and constructor.

6 CONCLUSIONS

A combination of a lack of focus on the seismic performance of non-structural elements by engineers, architects, contractors and subcontractors, and a history of low expectations, has resulted in generally poor performance of non-structural elements of buildings in earthquakes in New Zealand.

Our experience is that very significant expenditure is involved if one attempts to address all the historic compliance issues associated with non-structural element bracing and we question whether this represents best value in terms of seismic risk reduction compared with cost.

We recognise a major challenge is to decide what non-structural elements to focus effort towards. A pragmatic approach is to base the selection of what elements to brace on:

- life safety considerations,
- requirements for maintaining the operation of key services required for post-earthquake operations in buildings classified as IL4, and
- client’s functional requirements for the operational spaces below the hung services.

By focussing on non-structural elements that could cause injury or building disruption we consider the greatest cost effective improvement of the resilience of non-structural elements in existing buildings can be achieved.

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