Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 49, No. 1, March 2016

PRAGMATIC IMPROVEMENTS TO SEISMIC RESILIENCE OF NON-STRUCTURAL ELEMENTS – PRACTITIONERS PERSPECTIVE

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(Submitted *April 2015*; Reviewed *June 2015*; Accepted *November 2015*)

ABSTRACT

The recent Canterbury earthquake sequence and the more recent Seddon, Lake Grassmere and Castlepoint earthquakes have raised awareness of 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. Impacts on business continuity due to the damage of non-structural elements have also 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.

The paper goes on to explore a pragmatic "best bang for the buck" approach to upgrading non-structural elements in existing buildings. The approach is presented through illustrated examples of issues and solutions that 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 with ideas on possible ways to improve the seismic performance of non-structural elements within the New Zealand environment and regulatory regimen from both design and construction perspectives.

INTRODUCTION

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 [1]. 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 [2].

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 [3]. The recent Lake Grassmere earthquake serves as an example of an earthquake that resulted in limited structural damage, whereas 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.

The Canterbury Earthquakes Royal Commission [4] confirmed 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."*

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.

The authors consider that a pragmatic approach is required to improve the performance of non-structural elements in

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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. Methods to improve seismic performance are suggested, along with recommendations to address the key identified problems.

BACKGROUND

Following the Loma Prieta and Northridge Californian earthquakes in the late 1980s and mid 1990s 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 [5]. 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 society's 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.

The authors 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.

RECENT PRACTICE

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 [6] in the case of mechanical systems and such like, or AS/NZS 2785:2000 [7] 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 (top), failure of a lightweight cladding system (bottom).

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.

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 was demolished following the 1971 San Fernando Earthquake due to extensive structural damage. It was then rebuilt to a much higher structural design standard. Never-the-less it 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 [8].

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 including 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.

Similar to New Zealand practice, the 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 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) [8]. Recognising that bracing of non-structural elements significantly improves the performance of these buildings in earthquakes, checking of the design and installation of the bracing systems was started.

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 (SE), 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. Sometimes the MEP contractors hire the building structural engineer for this role.
- The structural engineer for the building reviews the non-structural bracing design (if they haven't designed it) 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 then complete a detailed plan check of the bracing system using their in-house structural engineers and sign it off prior to construction of the bracing starting.
- The "special inspector", 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 [9].

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 [10, 11]. 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 9 m above grade for buildings in high seismic zones. It also requires seismic bracing for high (over 2.4 m) 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 [10, 11] 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.

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 [12]. Lateral resistance criteria are specified in a similar way to that in NZS 1170.5:2004 [13]. 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_w8.8 Maule earthquake was reportedly significantly reduced compared to that observed in earthquakes in other developed countries [14]. 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 [15]. As a result extensive new requirements for the bracing of non-structural elements have been added to the Chilean code.

ISSUES WITH CURRENT NZ PRACTICE

This section summarises key issues with current New Zealand practice that can have a negative impact on the seismic performance of non-structural elements.

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 budget allowances in the project cost estimates for 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.

"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.

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.

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.

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.

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. If, for example, piping added post original construction is installed across seismic joints without flexible connections, the result is 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.

Code Compliance

NZ society has traditionally 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 provided financial incentives to recognise the considerably reduced risk associated with damage limitation designs, (e.g., reduced insurance premiums or lower lending costs).

Industry Survey of Issues

EERI conducted a survey of US industry members in 2009 to try and understand people's opinions of changes required to improve the situation surrounding the poor performance of non-structural elements [16]. 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 issues around the seismic restraint of non-structural elements and systems are not unique to New Zealand.

With the background and key issues associated with the seismic performance of non-structural elements identified, the paper now focusses on ways to improve the resilience of non-structural elements. This includes pragmatic solutions, along with recommendations and future considerations.

PRACTICAL CONSIDERATIONS TO IMPROVING RESILIENCE OF NON-STRUCTURAL ELEMENTS IN EXISTING BUILDINGS

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. Too often this 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 directed. 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 within a building below non-structural elements e.g. in-ceiling services:

- Are the clients' operational requirements such that loss of function in the space in the immediate post-earthquake environment would be unacceptable, e.g. the trading area of a bank?

EXAMPLES OF IMPROVEMENTS TO NON-STRUCTURAL ELEMENTS IN EXISTING BUILDINGS

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".

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.

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.

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 2. The top 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 bottom 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.

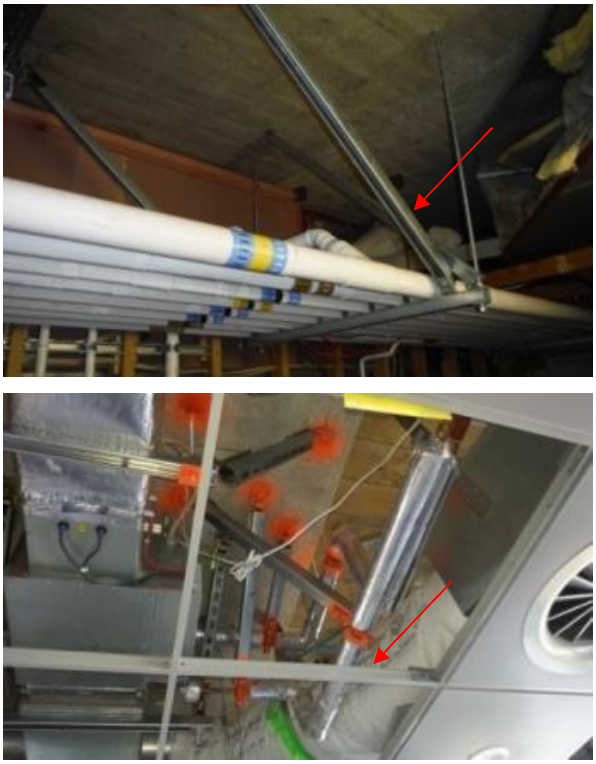

Figure 2: Restraint of new pipework in an existing building on a single trapeze to reduce the number of braces required (top) and new restraint (painted orange) of existing pipework in a modern building (bottom).

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 3. 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 3: Wire cables added to brace A.V. equipment above ceiling level.

Bracing to Roof

Even in multi-storey buildings, it is common for the roof structure to comprise 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

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.
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.

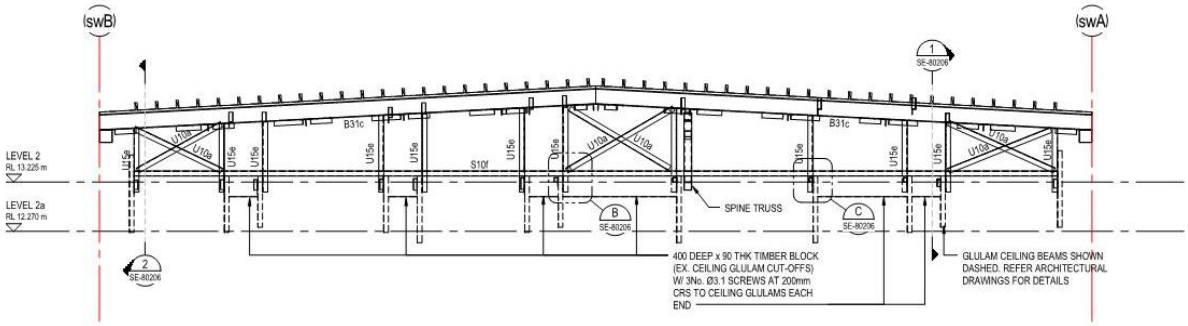

Figure 5: Specifically-designed secondary steel grid between roof and ceiling to support all services and ceiling.

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 4. A secondary steel grid can support the ceiling and services without the need for diagonal bracing, resulting in reduced congestion and improved clearances.

Figure 4: Cable bracing fixed to secondary steelwork and roof purlins (top); and proprietary rigid bracing in the transverse and longitudinal directions fixed to roof purlins (bottom).

Two bracing solutions to roof steelwork are shown in Figure 5. The top 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 bottom 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.

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 6 (top for the rigid service, as shown in Figure 6 (bottom).

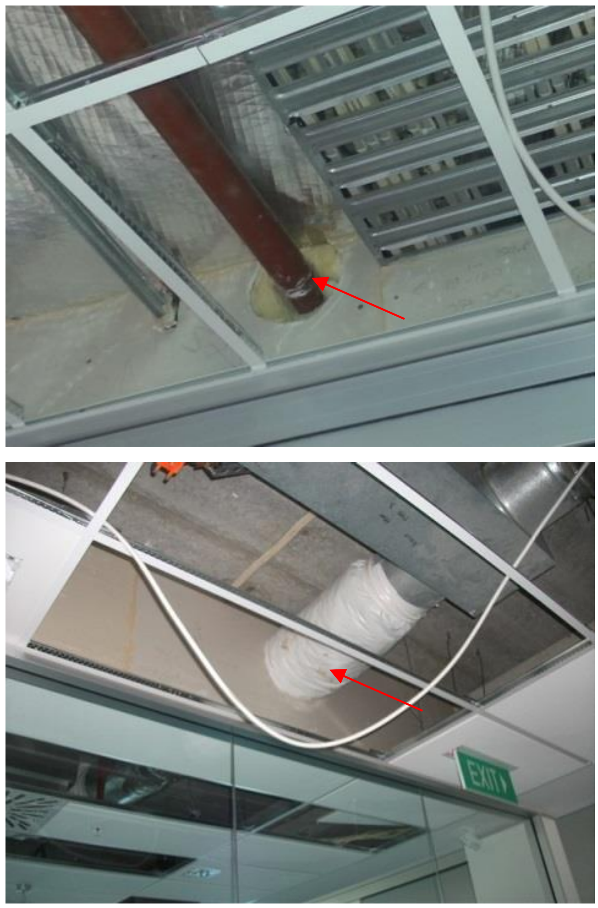

Figure 6: Rigid services passing through a wall utilising an oversized hole (top), or flexible duct (bottom).

Where services protrude through ceilings, flexible droppers or oversized holes with escutcheon plates can be used, as shown in Figure 7. 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.

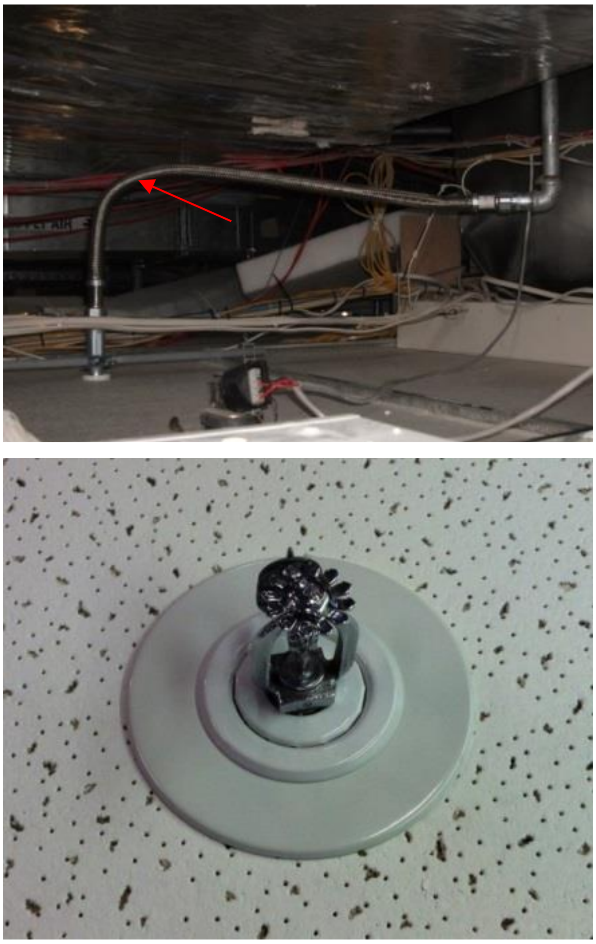

Figure 7: Compliant flexible sprinkle pipe fixed to ceiling tiles (top), escutcheon cover plate (bottom).

Splice joints at cable trays can be strengthened with the addition of proprietary splices as shown in Figure 8 (top). 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 [6]. Items weighing >10kg require independent support, as shown in Figure 8 (bottom) 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.

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 9.

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.

Ceiling System Options

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

Figure 8: Proprietary seismic clip added to cable tray to strengthen splice (top), wire tether on HVAC kit (bottom).

Figure 9: Sub-floor bracing added to proprietary false flooring.

- 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 10 (top). Like all ceiling bracing, these portals need to be 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 10 (centre). Ceiling hangers should be relocated where clearance to services is insufficient, as shown in Figure 10 (bottom).

Figure 10: Vertical inverted portals designed to brace ceiling (top), seismic clips retrofitted to ceiling grid (centre), and ceiling hangers relocated to provide adequate clearance to services (bottom).

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 11 (top). 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 11 (bottom).
- Full-height steel posts at regular centres within the partition walls, providing restraint on three sides to the walls.

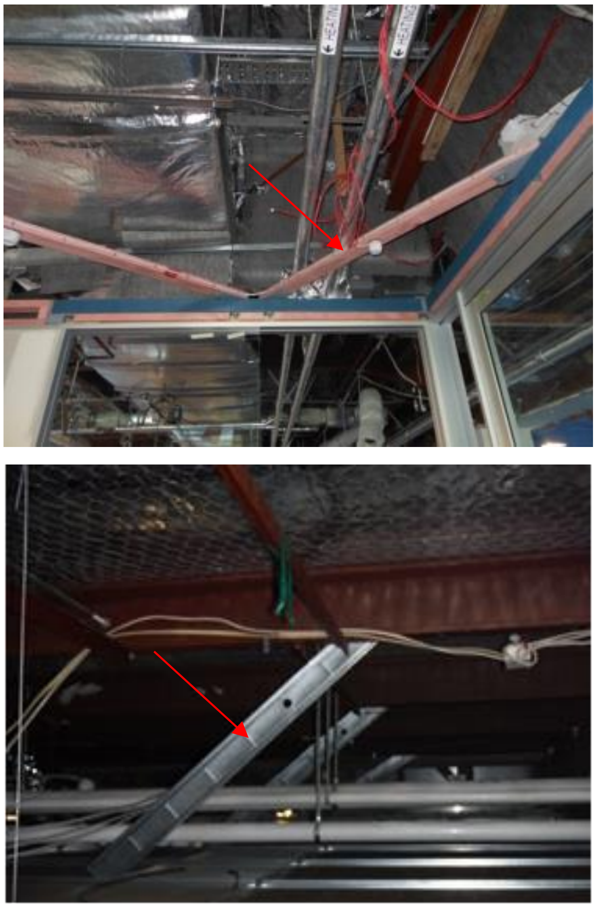

Figure 11: Horizontal bracing above ceiling level (top), restraint of timber partition wall at ceiling level to primary steelwork using tension/compression brace (bottom).

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 30 mm 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.

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. **Apply a pragmatic approach to the selection of what elements to focus bracing effort towards.**

   The approach should be based upon: 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.

8. **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.

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:

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 [17]. 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) [13].

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.

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 is intended to be developed into a simple method to calculate probable loss so one can compare the expected damage and costs associated with different non-structural components [18]. 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.

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.

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.

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'' [19]. This points a possible way to include non-structural elements in initial building performance assessments.

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. This topic is discussed in greater detail in a companion paper within this Special Edition of the *Bulletin of the New Zealand Society for Earthquake Engineering*. 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 [13]. 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 [13]. 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), AS/NZS 2785:2000 (Suspended Ceilings, Design and Installation), NZS 4541:2013 (Fire Sprinkler Systems), and NZS 4104:1999 (Seismic Restraint of Building Contents) [6, 7, 20, 21].

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.

The authors' 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. 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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