The Poor Performance Of Non-Structural Components In Seismic Events In Context

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ABSTRACT

Damage to non-structural components (NSCs) in seismic events has been identified as a recurring problem in New Zealand for decades. It is also a problem in comparable seismic risk countries. Whilst improvements have been made and lessons learned, the complexity of suspended ceilings has also grown.

The purpose of this article is to review the situation for suspended NSCs and to discuss recommendations. Whilst NSCs have not received the attention that structural components have, they are a significant source of costs and consequences should they fail in seismic events. Several articles have emerged surrounding NSC failure but owing to the inherent complexity of the subject, there is no one document that covers all aspects.

The poor performance of NSCs in seismic events has been known and written about for several decades. The USA and Japan provide comparable and useful information around what has proven to be effective and system-changing.

Keywords

Seismology, earthquake, retrofitting.

INTRODUCTION

The performance of non-structural components (NSCs) in New Zealand and overseas seismic events has been covered extensively in technical literature. Components of a building can be categorised as structural (that is, slabs, beams, columns, and foundations) and non-structural (everything that is not structural, including services and contents). Structural failures affect non-structural components, while the reverse does not necessarily follow. Following each recent earthquake, a more detailed picture has emerged of the poor performance of NSCs here. In California, NSCs can typically reach about 80 percent of building costs in commercial buildings (Taghavi, 2003). In New Zealand the proportion can reach up to 70 percent (Ferner H.; Lander, 2016; Stanway, 2017). Suspended ceilings and permanently installed in-ceiling systems to provide building services are the largest source within NSC costs. Examples of building services are: water reticulation; electricity supply; communications; Heating, Ventilation and Air Conditioning (HVAC); and fire sprinklers. Services, and their interaction with suspended ceilings, are the particular focus of this article.

Several guidance documents and practice notes have been released for NSCs in recent times but not all aspects are comprehensively covered by a single document. It is the intention here to give an overview of: 1) lessons learnt in recent earthquakes; 2) details of restraints that had performed satisfactorily; and 3) challenges and recommendations identified to implementing improvements.

Failures in NSCs can lead to significant numbers of injuries, repair costs, and lost time. Injuries are generally minor, compared with injuries from structural failures. However, they are still a cause for concern to those, for example, who work underneath inadequately-restrained suspended systems. Failures of NSCs also occur in other earthquake-prone well-developed places such as the USA and Japan (Ferner H., Wemyss, 2014; Murty, 2012).

Design, installation and sign-off of NSCs are part of the legal framework in New Zealand. Depending on a building's type, location, occupancy, etc. there are different pathways that can be taken to show compliance to the performance requirements in the legislation (Ministry of Business, Innovation and Employment, 2015).

BACKGROUND

International Classifications

Building parts and portions can be generally classified into their structural and non-structural components. Non-structural components (such as contents, cladding, services, ceilings, etc.) are supported by, or attached to, or inside the structure (NZS1170.5, 2004). There are cases of structural elements being mistaken for non-structural elements, such as unreinforced masonry, and rooftop water tanks (Murty, 2012). Comparisons in data between countries are not always absolutely valid and so care in interpretation is required.

Recent Earthquake Events

Several international earthquakes are referred to in this review. Summary data are in brackets (magnitude, year). In New Zealand, major recent events are: Darfield (7.1, 2010), Christchurch (6.3, 2011), Seddon (6.5, 2013) and Kaikōura (7.8, 2016) (Baird, 2017; Dhakal, 2010; Dhakal, 2011). In California, two major recent earthquakes of note are Loma Prieta (6.9, 1989) and Northridge (6.7, 1994) (Smolka, 1996). In Japan, there were the Kobe (6.9, 1995) and offshore Tōhoku (9.1, 2011) earthquakes (Baird, 2016). Reporting on structural failures is almost always the focus after earthquakes in less developed countries. However, some injury data from non-structural elements are mentioned regarding Turkey (7.6, 1999) and in India (Baird, 2016).

Overview of Literature

A large body of literature regarding seismic requirements of NSCs has been developed in the last 10-20 years within the New Zealand context. These can be broadly categorised, although there are often multiple subjects covered. Subjects include: site visit observations; technical information and guidance; international comparisons; effects on people (injuries and fatalities); samples/surveys; recommendations; and earthquake insurance. Parties commonly involved in writing or commissioning literature include: academics, engineering consultants; professional bodies, the Building Research Association of New Zealand (BRANZ), the Ministry of Business, Innovation, and Employment (MBIE); and industry groups.

There are several articles available reviewing or mentioning the poor performance of NSCs in recent New Zealand earthquakes. These include site visits by engineers concerning damages observed in the 2010, 2011 and 2016 earthquakes in commercial buildings (Baird, 2017; Dhakal, 2010; Dhakal, 2011; Stanway, 2017). Being observations, they have a part in informing typical performances and recommendations. However, one limitation is that they are not population (census) or randomly-selected studies. Due to things like site safety, urgency of repairs, and availability of engineers, this is necessarily the case for observations following earthquakes. The following are the key observed failure modes for the interaction of services with suspended ceilings:

1. Inadequate seismic gaps between services and suspended ceilings or hanger wires.

2. Hanger wires for suspended ceilings connected to services when not physically able to be connected to the floor above.

3. Inadequate or non-existent seismic bracing of services weighing more than 10 kg, such as HVAC.

4. Services, such as lights, braced to suspended ceilings without specific seismic design.

The Building Research Association of NZ (BRANZ) has published fact sheets providing guidance on design and installation of seismic restraints for NSCs (BRANZ, 2015). These fact sheets are short documents intended to help with interpretation of legislation and identification of where flexibility exists. A comprehensive guidance document published by the Association of Wall and Ceiling Industries is also available (AWCI, 2015). Other technical articles cover the implementation of legislative changes for industry, to more detailed technical analyses of seismic performance of ceilings (Badillo-Almaraz, 2007; Dhakal, 2016; Elkink, 2015; MacRae, 2012; Oosterhoff, 2017). In general, engineering design to avoid earthquake damage to these suspended systems requires restraining lateral/vertical movements of individual fixtures, maintaining adequate clearances, and incorporation of flexible connections.

International comparisons often refer to seismic effects seen in buildings in Japan and the USA (usually in California) (Ferner H., Wemyss, 2014; Ferner, 2016; Murty, 2012; Smolka, 1996). These are pertinent comparisons for New Zealand, because many of the technical standards here are based on American standards.

These places are also developed, less corrupt, nations, and will likely face more similar challenges to New Zealand than developing nations. Some major differences between New Zealand and these places are to do with the take-up of insurance (for Japan) and compliance costs (for the USA).

Analyses for injuries and fatalities from the failure of non-structural components in seismic events tend to include numerous caveats. In New Zealand, a more comprehensive database was begun in 2010, called "Researching the Health Implications of Seismic Events". The study from Beca Ltd using this database analysed injuries from NSCs and made some international comparisons (Baird, 2016). One Japan study following the 1995 Kobe earthquake had several rather descriptive categories, including injuries from "fence and objects" (Yamazaki, 1996).

A (non-random) sample and analysis was done for 20 commercial buildings in Auckland and Wellington (Geldenhuys, 2016). It was found that almost nine out of 10 ceilings were non-compliant. This restates a point from earlier: observations (especially when not random) are not a census, but observations can legitimately provide information about what typically seems to be happening.

Financial analyses include mentions of insurance costs and repair costs (Grafton, 2014; Stanway, 2017). Prevention of failures in the first place are also part of the analyses.

OBSERVATIONS OF NSC FAILURE

Complexity in systems arises from non-independent and non-linear behaviours. Assessing NSC failure is not simply about the consideration of individual parts in the ceiling, but how they interact with each other. Nor is the suspended ceiling itself the only facet of this complex system. The system extends also to the legislative framework, the different parties involved, the materials, nature of seismic events, and so on.

The sequence of failure is not always clear (Baird, 2017). The interaction of services with suspended ceilings can be due to one or more failures in the NSC system. The failure of one ceiling tile can lead to a cascading failure in other tiles and services.

Two important background points are that:

1. A high ratio of non-structural (compared with structural) failures will, of course, be entailed by improvements in (i.e. reduction of) poor performance of structural components. Because failure of structural components definitely leads to failure of non-structural components, it is understandable to focus primarily on structural components.

2. Injuries from non-structural failure tend to be much less severe than injuries from structural failures (covered more in Injuries below). It is right to focus first on structural performance before non-structural performance. This does not mean non-structural performance is ignorable or unimportant. It is the concern from deaths in structural failures in many countries that means NSCs do not receive due attention (Murty, 2012).

New Zealand

Site visits in the 2011 Christchurch earthquake noted several NSC failures. Hanger wires for suspended ceilings were in some cases connected to services such as HVAC, rather than the floor slab above. This means the ceiling is reliant on services for seismic restraint, which they are not designed to withstand. The movement of services interfered with hanger wires for the suspended ceilings. Damage from a rigid fire sprinkler system with inadequate seismic gaps was found. Some AC ducts were unbraced and went through the suspended ceiling. It was concluded that poor installation led to several of these problems. The tendency to quickly replace ceilings after an earthquake may also exacerbate a re-occurrence of failure (Dhakal, 2011).

Again in 2016, seismic bracing was a major cause of ceiling failure. Where seismic bracing was installed, even if imperfectly, it was observed to typically reduce failure significantly. Many examples were also found of failure due to inadequate seismic gaps. Various service components, such as lights, were reliant on the suspended ceiling for seismic restraint, which is not what the suspended grid system was designed to carry. Damage to suspended services almost always causes damage to the suspended ceiling. They cannot be separated from one another. That is, failure in one typically leads to failure in the other. Sometimes, no bracing of HVAC and AC ducts was in evidence leading to services falling out of the ceiling (Baird, 2017).

Japan and the USA

Comparisons in this article (and several referenced articles) mainly take into account New Zealand, Japan, and the USA. New Zealand, Japan, and West USA are located along the Pacific "Ring of Fire", a well-known zone with a prevalence of major earthquakes and volcanoes. They are also well-developed countries and members of the Organisation for Economic Cooperation and Development (OECD). Past responses to earthquakes in these countries provide apt case studies. The USA is also similar to New Zealand in the facts of being English-speaking and having a similarity of engineering standards in the legislation.

Mention is made of NSC damage in the 1994 earthquake being mainly from sprinkler systems. Cases of non-structural damage in California were far more prevalent than cases of structural damage (12-40 times, and probably higher in other areas). This ratio would have been lower in Japan, due to many older buildings at higher risk of collapse (Smolka, 1996). Muza Hall in Japan is a concert venue whose ceiling collapsed, despite being 300km from the epicentre (which was about 70 kilometres from Japan's coast). The ceiling had a seismic rating of 5 (the highest is 7), yet services in the ceiling collapsed (Iuchi, 2011).

Characteristics of NSC fragility

The main characteristics of inadequate and fragile NSC systems are inadequate design and/or incorrect installation. Failures in the plenum (the space between the ceiling and floor overhead) were numerous in New Zealand earthquakes. Reasons for failure included incorrect installation, inadequate gaps for movement of services, and unsuitable designs. Noted American problems were: lack of awareness; lack of legal framework; lack of those championing NSC improvement; and inadequate literature (Murty, 2012).

CONSEQUENCES OF NSC FAILURE

Injuries and Deaths

The 2016 Kaikōura earthquake fortunately occurred at night, leading to less severe consequences for people (Baird, 2017). The 2010 Darfield earthquake also occurred outside normal office hours, at 4:35 a.m (Dhakal, 2010). A report was prepared by Beca in October 2016 (prior to the November Kaikōura earthquake) for MBIE that covered injury data back to the 4 September 2010 Darfield earthquake. Data related to 1048 injuries in commercial buildings, using a new database from the "Researching the Health Implications of Seismic Events" Group, based in Christchurch. It was found that 61% injuries were from NSC failures (see Figure 1). However, all deaths were from structural failures (including masonry). The nature of injuries from NSC failure was mostly of the lowest-severity category (90 percent).

Other countries are also included in the Beca report. In two California earthquakes (1987 and 1994), 50-55 percent of non-fatal injuries were attributable to NSC failure. In the 1999 Turkey earthquake, around 75 percent of non-fatal injuries were attributable to NSC failure. Definitions of what NSC includes or excludes can sometimes differ, therefore care should be taken in comparing these data. A 1996 Japan study reported at least 37 fatalities prior to the 1995 Kobe earthquake from "fences and fallen objects". Structural failures (such as "collapse of wooden houses") caused the most fatalities. In that study it was noted that as the structural components have improved, injuries in recent earthquakes from building contents has become a major category (Yamazaki, 1996).

The focus of this article is services within suspended ceilings, but as a side note, contents were found to cause the most injuries in NZ, with 69 percent of NSC injuries coming from these (see Figure 2).

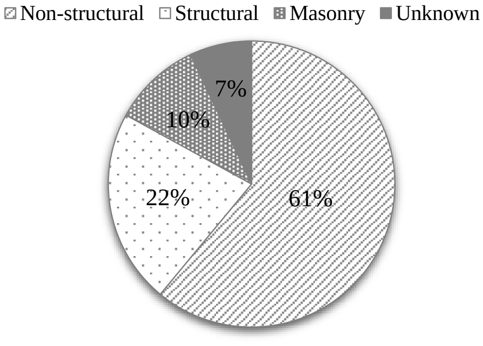

Figure 1. Earthquake-related injuries by structural type (source: Beca Ltd)

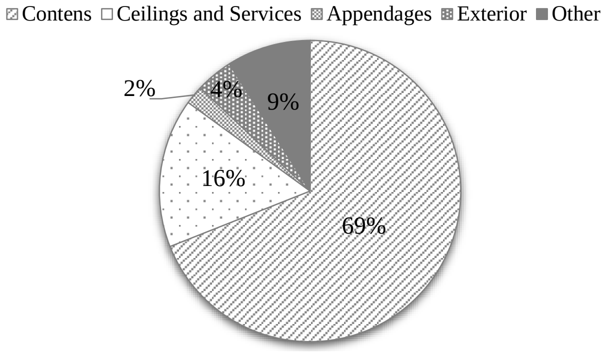

Figure 2. Earthquake-related injuries within NSCs (source: Beca Ltd)

Pre-earthquake and Post-earthquake Costs

The building cost of NSCs in commercial buildings is likely to take a large share of the total cost. In a study of 23 buildings, structural costs were 18 percent for office buildings, leaving 82 percent for non-structural and contents costs (Taghavi, 2003). In New Zealand, the NSC share can comprise up to 70 percent (Ferner H., Wemyss, 2014). In California, where compliance costs are higher, the NSC share can be as high as 90 percent for hospitals. In India, the share used to be about 5 percent in the 1970s and is now up around 60-70 percent (Murty, 2012).

The primary factor reducing NSC costs was an early design process. Design costs were estimated to be adequately accounted for at 0.25-1.0 percent. Focusing on the most relevant building types requiring NSC seismic restraints, there were total construction costs of 8.7 billion dollars in 2016. To install adequate seismic restraints for these, 0.4 billion dollars was the estimated cost, or around 4.9 percent. However, the variability around this figure is uncertain. One specific case study for a four-storey office refurbishment estimated a 25.4 percent share of NSC seismic restraint costs to total building costs (Stanway, 2017).

NZ’s contribution to the global insurance pool is 0.01 percent. Insurance take-up rates are significantly higher in New Zealand (around 90-95 percent) compared with Japan and California. Due to excessively high (or unobtainable) insurance rates in Japan, making buildings stronger is in effect the insurance against seismic events. This has the potential to become the case for New Zealand as well (Stanway, 2017).

Failures in NSCs were known to be responsible for a significant portion of losses in the 2011 Christchurch earthquake (Dhakal, 2011). Precisely how much is unclear, but the total estimated loss is approximately 40 billion dollars. Of this, around half is borne by taxpayers (Stanway, 2017).

Evidence tends to be anecdotal in nature, along with the available physical evidence. These indicate substantial costs. The insurance industry is unable to provide costs from repair work and business interruption regarding NSCs however. Scenario modelling produced estimates ranging from approximately 1 million to 30 million dollars (Stanway, 2017). Business interruption from NSC failure in New Zealand and overseas has been identified as a major issue (Ferner, 2016). Failures to NSCs in New Zealand have also led to buildings being demolished that were otherwise structurally sound (AWCI, 2015). In California, around five-sixths of the estimated 6.3 billion dollars of costs after the 1994 earthquake were because of NSCs (Kircher, 2003).

LEGISLATIVE FRAMEWORK

Standards

The most relevant standards for NSCs in seismic events are (with approximate numbers of pages in brackets):

AS/NZS1170.5 for Earthquake Actions in NZ (90 pages) (NZS1170.5, 2004). It covers determination of earthquake action effects on structures in NZ. It includes verification methods and seismic design of parts of structures. See especially Section 8: Requirements for Parts and Components. Following a seismic event, parts required to be operational for occupancy (P5 classification) must be returned to an operational state within an acceptably short timeframe.

AS/NZS 2785 Suspended Ceilings – Design and Installation (50 pages) (AS/NZS2785, 2000). For use in commercial, industrial and residential applications. This includes discussion of installation as it relates to services (such as air/electrical services).

AS/NZS 4541 Automatic Fire Sprinkler Systems (500 pages) (NZS4541, 2013). This covers design, installation, and maintenance to achieve adequate fire protection in a building.

NZS 4219 Seismic Performance of Engineering Systems in Buildings (110 pages) (NZS4219, 2009). This includes requirements for minimum clearances of components (Table 15: Clearances). This standard excludes suspended ceilings (covered in AS/NZS 2785) and fire sprinkler system pipework (covered in NZS 4541).

In *Section 5.8 Piping Systems* of NZS 4219, requirements for seismic restraints are given. *Section 5.8.1* states the circumstances where seismic restraints are not required. This applies to pipes less than 50 mm in diameter and able to be suspended with clearances of 150 mm (vertically and to adjacent suspended components). Although, there may still be situations where even these must be seismically restrained. An important point to note from this is that certain designs can reduce the need for seismic restraints.

NZS 4104 Seismic Restraint of Building Contents (60 pages) (NZS4104, 1994). This mainly refers to such contents as bookcases, cabinets, desks and the like. It relates to contents under 300kg (NZS4219 or the 1170 suite covers contents above this weight).

Other Legislation

Building Act 2004 (340 pages). The main purposes of the Act are to ensure people's safety in buildings, and to ensure building work is compliant with the building code (contained in Schedule 1 of the Building Regulations 1992). It specifies the performance required, but allows for flexibility in meeting these requirements.

The Building Code (100 pages). The code sets out general requirements of buildings and elements of buildings. Safeguarding people and other property is one of the main purposes of the code. The people in (or users of) a building will in some cases have different requirements. For example, resthome residents (principal users) have different requirements to staff (secondary users). Other users include maintenance staff, services or other personnel.

In terms of serviceability after a seismic event, the building code sets out performance-based requirements for the safety and health of a building's users. Thus, air must be clean, water facilities must be hygienic, etc. Operational services in suspended ceilings (such as HVAC, heating, water, and lighting) are thus a major determinant of a building's non-structural serviceability.

Figure 3 shows how the New Zealand legislative environment has been set up.

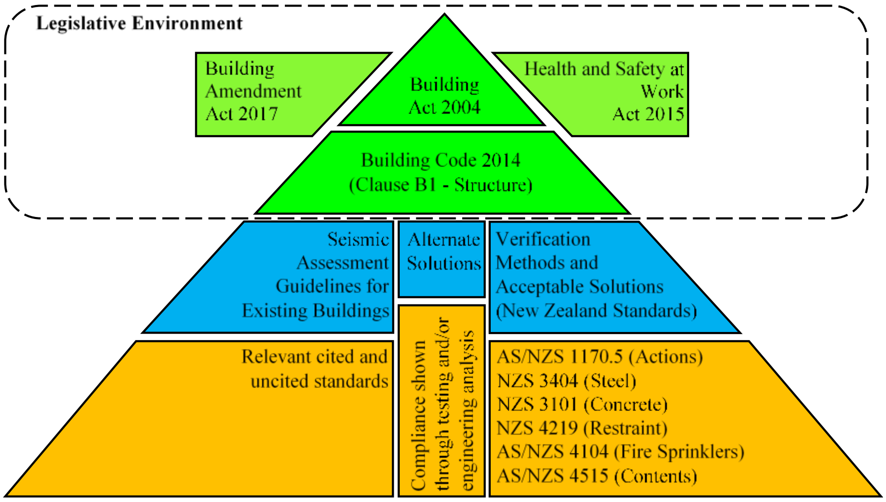

Figure 3. How different legislation relates together

The standards and other legislation mentioned above total over 1000 pages, although far fewer pages than that number relate to the seismic performance of NSCs. There is mention of how NSCs interact in some of these standards. It should be noted that MBIE publishes acceptable solutions or verification methods for demonstrating compliance, though these are not actually mandatory to be used (MBIE, 2015).

Producer Statements

There are four types of Producer Statements (PSs) used in New Zealand. They can aid councils in issuing building consents and building code compliance certificates. However, they have no legal status under the Building Act 2004. A PS is a professional expert opinion using sound engineering knowledge, but does not guarantee compliance or product quality 2013). The four PSs refer to: 1) design; 2) design review; 3) construction; and 4) construction review.

In the case of NSCs, building consent authorities traditionally have not required specific design or construction review PSs, which means they are not provided (Ferner H., Wemyss, 2014). A guidance document was issued by the Association of Wall & Ceilings Industries (AWCI). It includes advice on when PSs are likely to be required by councils. Seismic ceiling grades range from SG1-4 (with SG4 being the most complex ceiling). Advice is that SG1 would not require a PS2 or a PS4 (and only a PS1 and a PS3 if specified), while SG4 would require a PS1, PS3 and a PS4.

REASONS FOR NON-COMPLIANCE OF CEILINGS

Owners, designers, and contractors must use limited labour and money to produce a fit-for-purpose structure. Because of this, there is no such thing as a building 100 percent resistant to earthquakes. However, being fit-for-purpose implies minimum standards have been met, which is not often the case for NSCs. There are several reasons for non-compliance (Ferner, 2016).

Potential damages and costs from NSC failure, for varying reasons already discussed, can often be unexpected; as a consequence, expense on prevention in the form of correct bracing may not be being prioritised. Generally, the earlier NSCs are designed and integrated, the better; currently, there is allowance made for ‘tagging out’ NSC design in the tendering process until later (Ferner H., Wemyss, 2014). Related to late design, services that are installed early have more leeway; later-installed services may not have adequate room to be fitted as initially intended. As previously noted, injuries from structural failures are much more severe than injuries from non-structural failures; site visits are understandably prioritised for structural checks rather than non-structural bracing checks later in the process. Also, post-construction changes made to services can result in non-compliance if not consented and monitored.

EMPIRICAL IMPROVEMENTS

Learning lessons from what has worked (or not) elsewhere can be a valuable source of ideas for improving NSC performance. Even if everything were known about how to prevent consequential seismic damage to non-structural elements, it is of no use without the implementation of this knowledge. It is worth noting that several problems occurring recently are also problems from more than four decades ago (Glogau, 1976).

Multiple Checks and Enforcement

There are several hurdles to clear in the Californian legislative system for earthquake bracing, which goes back to 1972 for hospitals. Specialist design and review (and incorporation of changes) makes for a costly and slow process in the USA. An adaptation for New Zealand could be to require a PS1 and PS4 specifically for non-structural elements (Ferner H., Lander, 2016). Fire sprinkler system reviews are done by Fire Marshalls in the USA. Because of specialist installers and specialist reviewers, installations are of good quality and well enforced (Stanway, 2017).

There was a key difference between buildings built prior to and after the 1972 Seismic Safety Act. It was not that code requirements for NSC seismic restraints were different, but that the code requirements were implemented correctly after the State took control of oversight (Ferner, 2016).

Use Experiments to be Prescriptive

Authors of the American Standards found shake-table tests to provide very effective data. By undertaking tests for various construction details, they could determine their capacity and performance. This then meant they could issue prescriptive details for industry that would be optimal. Details such as types of screws in ceiling systems can be tested and made prescriptive. In the context of California, it was found that these details were ignored if not made prescriptive though (Stanway, 2017). Drawings are included in the appendix of this article detailing suitable seismic restraints for services within suspended ceilings.

Non-Structural Seismic Coordinators

This is not a required position in California, though some construction projects (e.g. courthouses) require them (Ferner, 2016). A specialist focused only on non-structural elements would potentially mean: one person or team takes responsibility for a building’s non-structural design, compliance, cost-effectiveness, etc.; it is easier to stay up-to-date with latest products and learnings from around the world; a specialist being available for long-term maintenance and/or retrofits; installation instructions and processes would be up-to-date with best practice, making processes simpler for subcontractors installing services. For example, in the USA, the use of cast-in anchors has meant locations of various elements are co-ordinated well in advance of installation (Stanway, 2017). Not having a structural engineer significantly involved in non-structural elements has previously been identified as an issue with current practice here (Ferner H., Lander, 2016).

Maintaining Alignment of Standards

An update was made to ASCE-7 *Minimum Design Loads for Buildings and Other Structures*. However, it was not until other national industry standards were updated that practices improved (Stanway, 2017). A possible problem in New Zealand is the sheer number of standards and pages to keep track of. Likewise, NZS1170.5 has been substantially revised in response to recent experiences, whereas these changes have not been reflected in the seismic actions section of NZS 4230.

Optimal Technical Improvements

Flexible fire sprinklers are becoming more common in New Zealand. These have been proven to perform better than their rigid counterparts in shake-table testing (Soroushian, Maragakis et. al, 2012). In the testing, no damage was observed to the ceiling from flexible sprinkler systems, while damage was observed even with code-compliant gaps between the ceiling and rigid fire sprinkler systems.

Even imperfect seismic bracings have been observed to perform adequately in earthquakes (Baird, 2017). While that observation does not make it a recommendation to install below-standard restraints, it nevertheless displays the sense behind always installing restraints.

Coordinated Documentation

Building Information Modelling (BIM) is 3D software that allows for clashes to be identified and remedied before installation (among other benefits). BIM is widely used in Australia and the UK (Stanway, 2017). One historical example of engineering improvement is the Boeing 777 jetliner. Boeing was the first company to develop a jetliner fully with 3D software during the early 1990s. This was a successful project that coordinated 10,000 engineers around the world. The software alone, however, was not the reason for the success of the project, with a focus on good coordination between teams also significantly contributing (Glende, 1997). A Non-Structural Seismic Coordinator could help in this regard.

EXPERT RECOMMENDATIONS

Back in a 1976 paper by the chief structural engineer at the Ministry of Works and Development, O. A. Glogau, it was established that non-structural damage caused the bulk of monetary losses in an earthquake. It was also noted that standards provided for minimum control measures for quality. In response to this, it was deemed more likely that incentives through insurance rates would lead to higher quality control measures. The added costs to insurers from classification could then be recovered through greatly reduced losses, rather than higher premiums (Glogau, 1976).

Insurance Premiums that Reflect Non-Structural Strength

Financial incentives are not always associated with better design that limits damage to NSCs. This can be the case with lending institutions and insurance companies (Ferner H., Lander, 2016). Californian insurance premiums rose as a result of the 1994 Northridge Earthquake for residential homeowners. The residential take-up of insurance dropped from 34 percent in 1994 to just 10 percent. Because insurance is a product people can choose, some people decide to *"…just take our chances."* (Goldstein, 2016).

One substitute product people can purchase is to 'insure' the non-structural elements themselves by building to a higher quality that reduces consequences in a seismic event. In New Zealand, the take-up rate for insuring buildings is 90-95 percent. This could be in part due to cheaper insurance here, compared with Japan and California. If insurance became much more expensive, one recourse would be to spend money that would have gone to insurance on strengthening NSCs.

More Transparency

Suspended ceilings tend to be rather inaccessible (physically and/or visually). This makes inspection more difficult and time-intensive. It would also likely be disturbing to workers to see what is above them. However, if there were ways to improve transparency of ceilings (in aesthetically pleasing ways) this would help speed up inspection and certification.

St Louis County in Missouri adopted a new approach to NSCs in 2011. They require a Seismic Block with every set of drawings submitted for building consent. A Seismic Block outlines the required seismic protection for the NSC system, and those responsible for its design (Ferner, 2016).

One idea that has been suggested by the Insurance Council to help transparency is to ensure compliance of non-structural elements within the existing annual Building 'Warrant of Fitness' (ICNZ, 2014). Industry ratings systems are also in use in NZ. These include: Green Star (nzgbc.org.nz) and Quake Star (quakestar.org.nz).

Legislation that is Easier to Follow

As mentioned in the Overview of Literature section, there are several guidance documents available online. Through expert advisors, guidance documents, good software, etc. this can make legislation easier to follow. However, as the volume of information increases, knowledge of it all becomes more difficult. In the example of the Boeing 777, software that detected clashes in the jetliner design became an industry norm after the successful completion of that project. New technology to make compliance easier may provide the most promising avenue for improvement.

Focusing on Consequences rather than Predictions

Predictions are not necessarily helpful, or even 'better than nothing'. One major downside to any prediction is people can assume they are safe if they follow them. In fact, risky behaviour may be being encouraged. Standards specify minimum requirements to be followed for, say, a once-in-50-year event.

N. N. Taleb, a professor of risk engineering at New York University suggests focusing on consequences, not probability, of unexpected events (The Economist, 2007). This is particularly relevant to earthquake damage of non-structural elements. In an article previously referred to, some people have opted not to buy expensive residential earthquake insurance or seismically strengthen and instead chosen to simply hope no damage occurs (Goldstein, 2016). By not buying insurance or seismically strengthening, consequences could be severe.

CONCLUSIONS

The consequences of NSC failure are known to be fairly large. This is despite there being no precise answer as to 'how large?'. There are significant downsides to NSC failure, such as harm to people, repair costs, and lost time. Lack of knowledge around NSC failure (which is continually reducing) does not appear to be a primary factor. Bracing systems have been observed to perform satisfactorily even if not perfectly correctly installed.

Legislation in New Zealand often borrows from the USA. California in particular has had to deal with severe earthquakes over the years and provides a suitable case study. Enforcing legislation in the USA has demonstrated the importance of suitable inspections and sign-off.

Several analyses have been carried out and recommendations made regarding consequences of NSC failure. These recommendations can refer to different aspects, such as products themselves, legislative changes, and installation practices. Particular reasons for non-compliance have also been studied and reported on, and do not appear to be mysterious. The complexity of NSC failure is apparent. However, this does not rule out there being effective, innovative, and affordable solutions for improving the performance of NSCs here.

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APPENDIX A: POSSIBLE SEISMIC RESTRAINT DETAILS

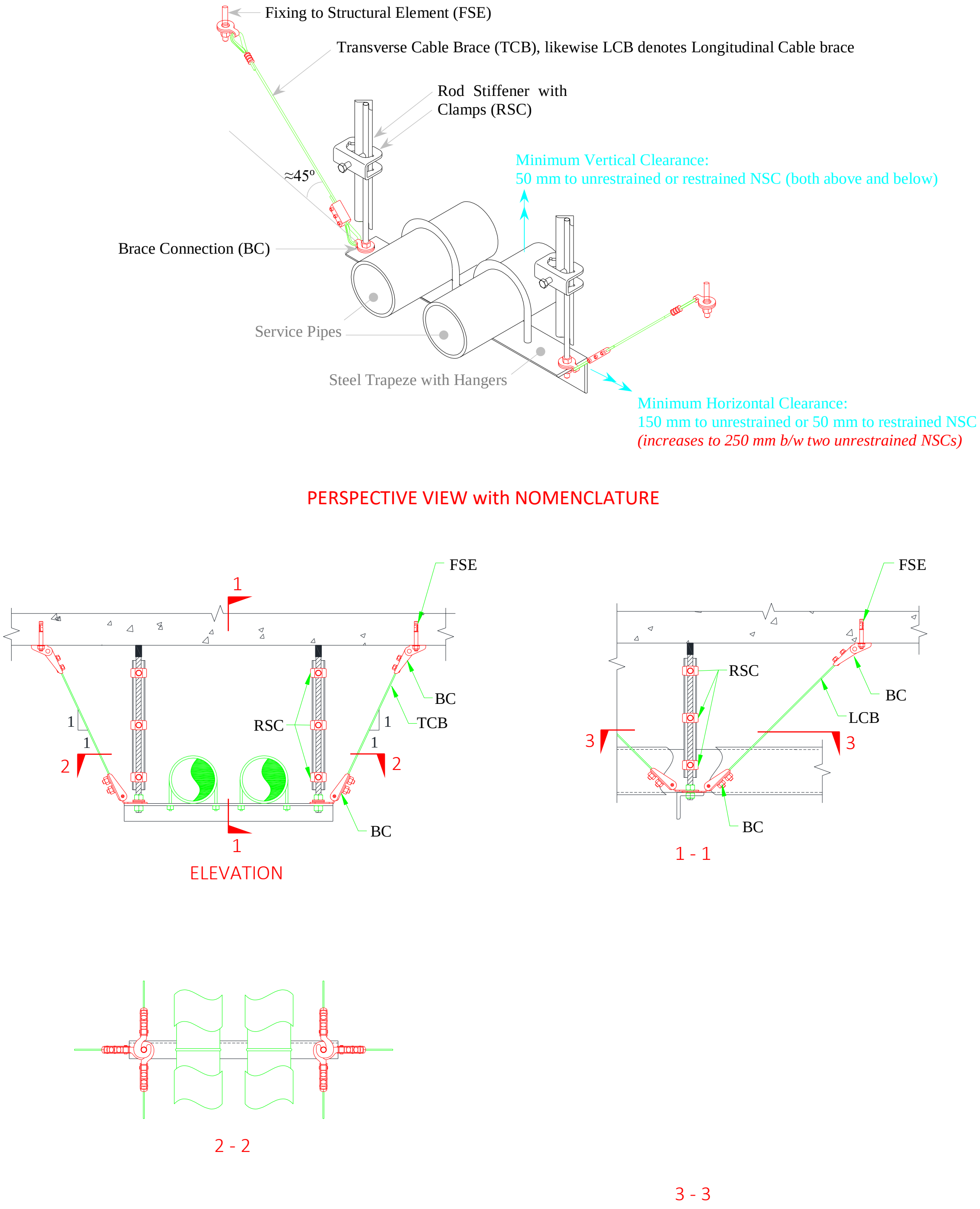

Figure 4. Seismic Cable Bracing for Trapeze supported pipes

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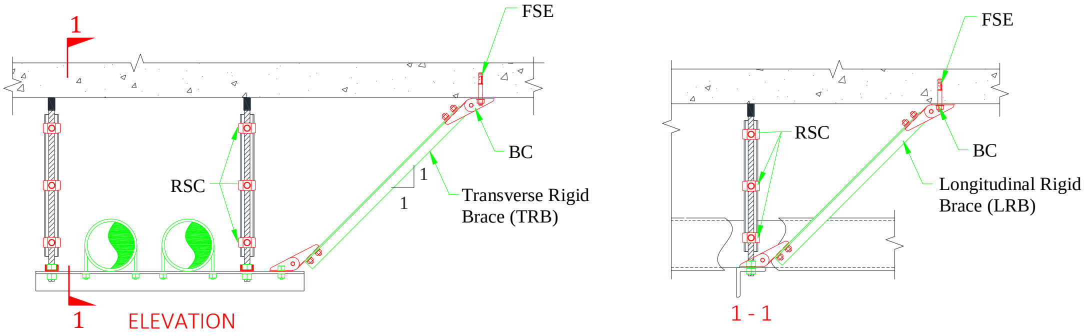

Figure 5. Seismic Rigid Bracing for Trapeze supported pipes

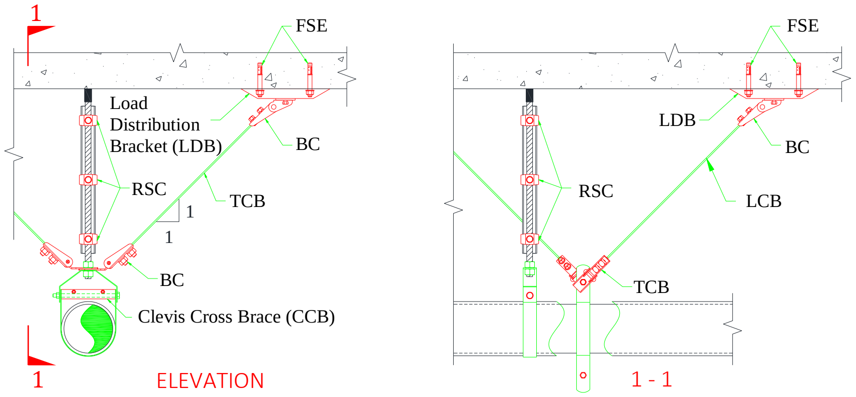

Figure 6. Seismic Cable Bracing for clevis supported pipes with diameter larger than 200 mm

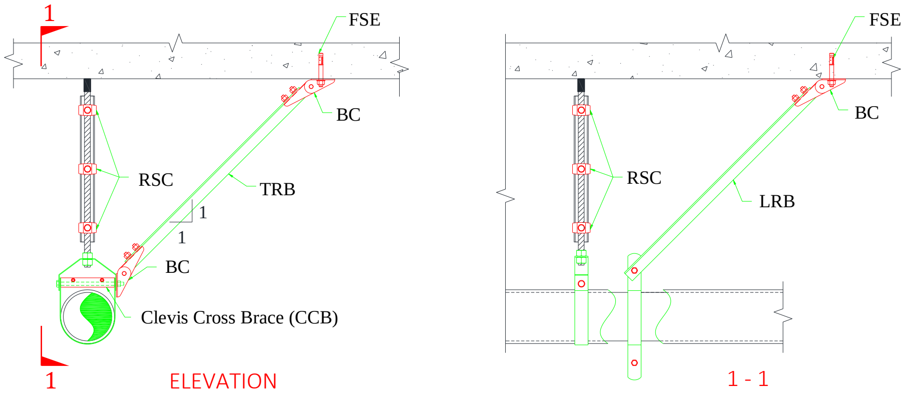

Figure 7. Seismic Rigid Bracing for clevis supported pipes with diameter larger than 200 mm

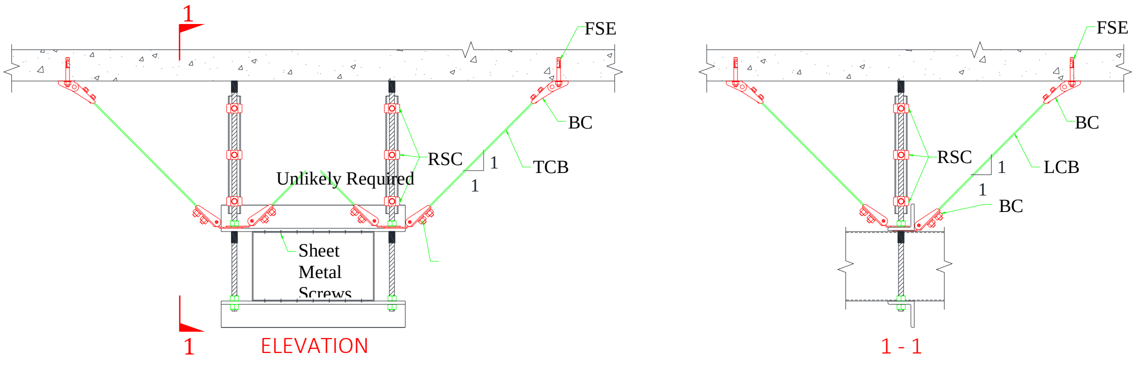

Figure 8. Seismic Cable Bracing for rectangular/oval duct

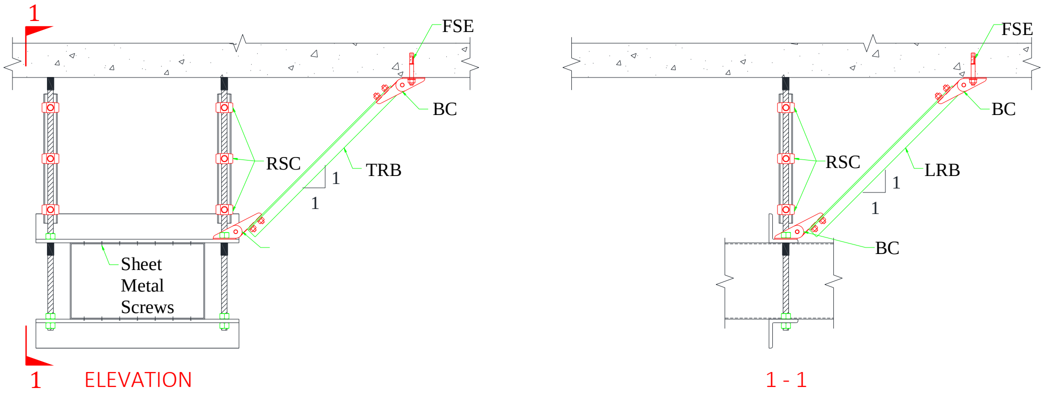

Figure 9. Seismic Rigid Bracing for rectangular/oval duct

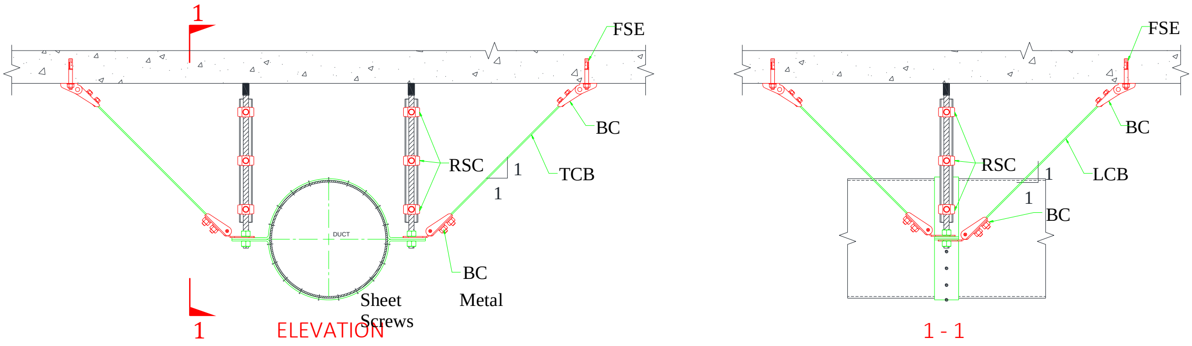

Figure 10. Seismic Cable Bracing for round duct

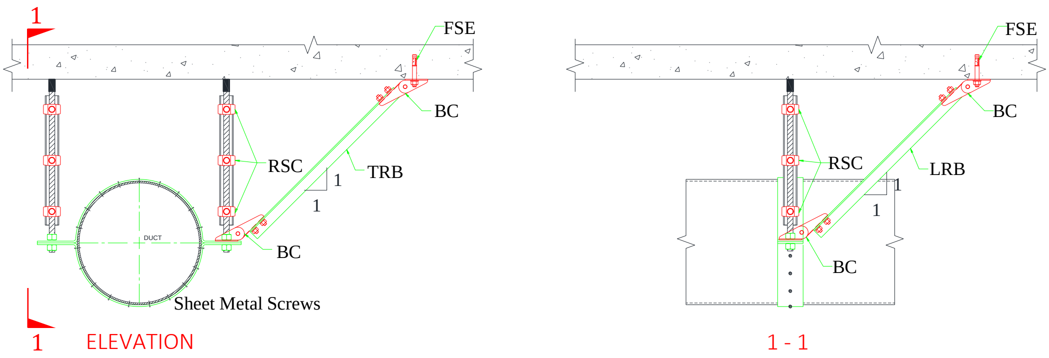

Figure 11. Seismic Rigid Bracing for round duct

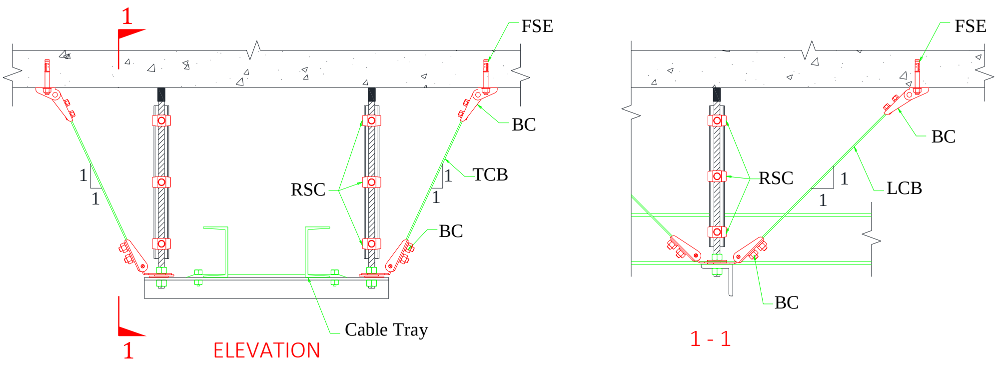

Figure 12. Seismic Cable Bracing for Trapeze supported electric cable trays duct

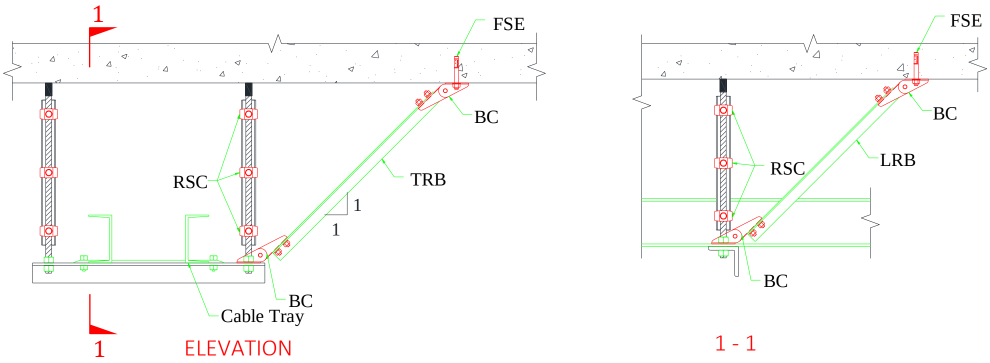

Figure 13. Seismic Rigid Bracing for Trapeze supported electric cable trays duct