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DAMAGE TO NON-STRUCTURAL ELEMENTS IN THE 2016 KAIKŌURA EARTHQUAKE

Andrew Baird[1] and Helen Ferner[2]

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ABSTRACT

This paper describes the damage to non-structural elements in buildings following the 14th November 2016 Kaikōura earthquake. As has been observed in recent earthquakes in New Zealand and around the world, damage to non-structural elements is a major contributor to overall building damage. This paper focusses on damage to non-structural elements in multi-storey commercial buildings, in particular damage to the following: suspended ceilings, suspended services, glazing, precast panels, internal linings, seismic gaps and contents. The nature and extent of damage to each of these components is discussed in this paper with the help of typical damage photos taken after the earthquake. The paper also presents observations on the seismic performance of non-structural elements where seismic bracing was present. These observations suggest that seismic bracing is an effective means to improve seismic performance of non-structural elements.

INTRODUCTION

Damage to non- structural elements has been a recurring observation from recent New Zealand earthquakes [1, 2]. The 14 November 2016 Kaikōura earthquake provides extensive examples of the vulnerability of non-structural elements (e.g. ceilings, cladding, partitions, building services, plant equipment and piping etc.).

This paper focusses on non-structural damage to commercial multi-storey buildings in Wellington observed in the immediate aftermath of the Kaikōura earthquake. The buildings inspected were mostly of modern construction, built in the 1980s or more recently and were typically concrete moment frames with precast concrete floors and in-situ topping slabs.

The observations in this paper are based on a high level assessment completed in the days immediately after the earthquake before the damage was cleaned up and buildings reopened for operation.

Although noticeable structural damage occurred in a small proportion of the building stock, damage to non-structural components and contents appeared to be significantly more widespread. Of the buildings inspected, the extent of damage to non-structural elements (such as ceilings, services, facades, partition walls) was more than that observed to the primary structural components. This is in agreement with outcomes of previous seismic loss which have concluded that non-structural and content damage contribute a major share of the total losses in an earthquake [3].

Commonly observed types of damage to non-structural elements and contents are described in this paper with some typical damage photos taken after the earthquake. Based on the level of inspection undertaken, it is not possible to provide statistics on the percentage of damage, or detailed typology of

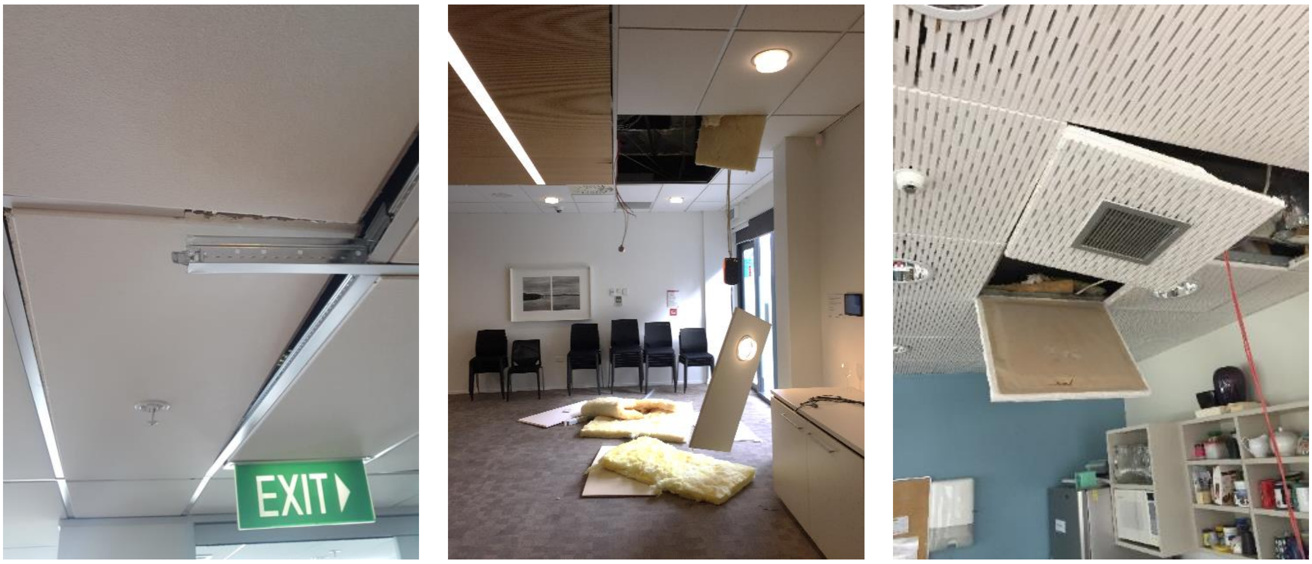

Figure 1: Damage to suspended ceilings: failed ceiling t-rail (left), fallen lightweight ceiling tiles (centre), fallen heavy plaster tiles (right).

1 *Corresponding Author, Structural Engineer, Beca Ltd, Auckland, andrew.baird@beca.com (Member)*
2 *Technical Director, Beca Ltd, Auckland, helen.ferner@beca.com (Member)*

buildings where damage was observed, however it was evident that more damage was observed to buildings located on reclaimed land adjacent to the Wellington port, in the Thorndon area close to parliament and the Te Aro area.

This earthquake also provides some examples of the performance of non-structural elements that had been braced either as part of repairs and seismic retrofit following previous recent earthquakes or new building design where considerations of the performance of non-structural elements were specifically taken into account in an effort to minimise damage.

OBSERVED DAMAGE

This section reports on typical observed damage by non-structural element typology.

Suspended Ceilings

Widespread damage to suspended ceilings in multiple buildings was observed. Refer to Figure 1 for examples of typical damage to suspended ceiling systems.

The observed damage included examples of failure due to overloading of the ceiling components, and damage which appeared to be the result of displacement incompatibilities between the ceiling and other components. Failure of several t-rails was observed which suggests that the inertial forces imposed on the component by the overall ceiling system exceeded the capacity of the t-rail leading to failures similar to that shown in Figure 1 (left). Such failures of the ceiling grid were predominantly observed for large, uninterrupted areas of suspended ceiling. This indicates that the seismic restraint of the ceiling was reliant on perimeter fixing of the grid to the structure, and the ceiling rails were inadequate for the area of ceiling they were being required to provide restraint to.

Numerous examples of damage appeared to have resulted from interaction between the suspended ceiling and other components, such as suspended services, partitions, and the primary structure. Earthquake induced deformations of the ceiling system (or adjacent components) result in damage to the ceiling tiles and grid when these components interact, as shown in Figure 1 (centre). This type of damage was observed to often occur at the perimeter of ceilings, adjacent to walls and partitions. It appears the ceiling was either not adequately braced to prevent movement of the suspended ceiling relative to the other adjacent building components or potentially the other building components were reliant on the ceiling for seismic restraint, which the ceiling may not have been designed for.

A noticeable feature of the ceiling damage observed was the extent that damage occurred where various services components such as lights, were supported by the suspended ceilings. It appeared that the ceiling grid system was not strong enough to support these additional loads leading to failure of the ceiling system at these locations. In other instances the lights and other services elements fell from the ceiling grid or out of the ceiling tiles.

Both lightweight and heavy tiles were observed to have fallen in a number of instances. Although lightweight ceiling tiles, such as the mineral fibre tiles shown in in Figure 1 (centre), only weigh a couple of kilograms, some heavy tiles, such as the plaster tiles shown in Figure 1 (right), may weigh upwards of 10kg. The life safety risk of heavy tiles falling was clearly apparent to building occupants.

The observed damage points to the vulnerability of suspended ceiling systems in earthquakes. In particular where they are not braced against movement relative to other building elements and where the suspended ceiling grid members and connections have not been adequately designed for seismic loads. The extent, prevalence and type of damage observed indicated a widespread lack of consideration of seismic effects on suspended ceilings in commercial multi-storey office buildings. These observations align with a recently completed, but yet to be published, survey of Wellington and Auckland commercial offices which identified that ceiling seismic bracing is often absent from existing fit outs.

Suspended Services

Damage to suspended services, such as HVAC, electrical and pipework was observed in multiple buildings. If a suspended ceiling was present, damage to suspended services almost always caused damage to the suspended ceiling also, since the ceiling was not strong enough to support the service component falling from above. Often it was difficult to determine the cause of the failure; the ceiling system or the services or a combination of both. Examples of damage to suspended services included damage to pendulum lighting fixed to ceiling tiles, as shown in Figure 2 (left). The damage observed indicates that the interaction of suspended lights

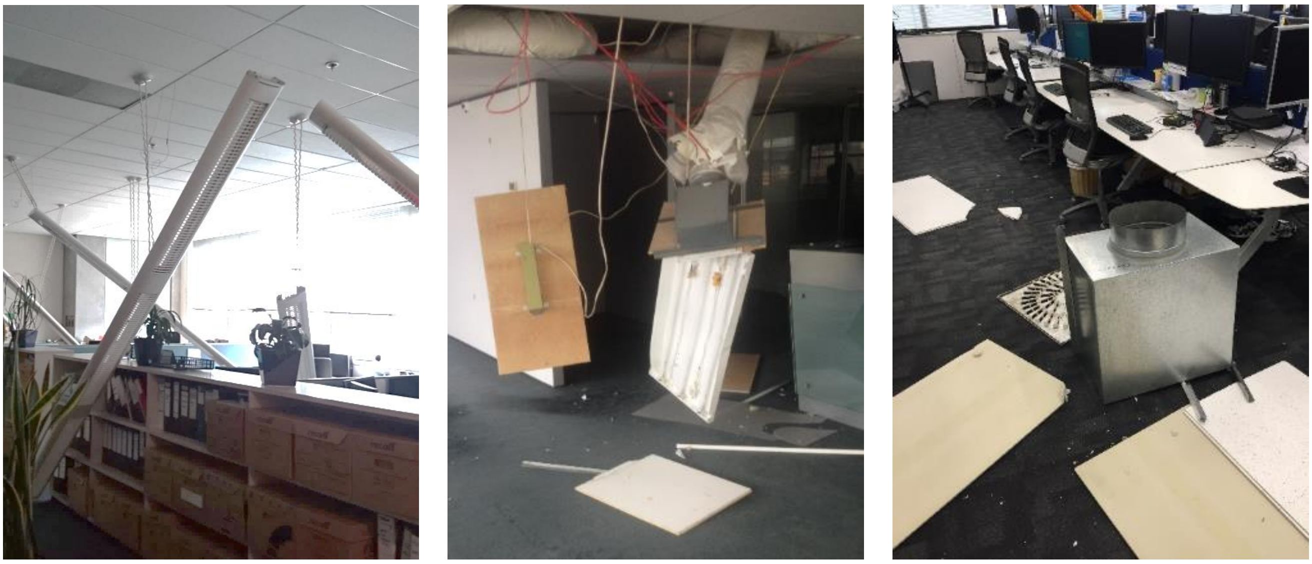

Figure 2: Damage to suspended services: fallen suspended pendulum lighting (left), fallen diffuser fixed to ceiling grid (centre), fallen HVAC diffuser (right).

Figure 3: Damage to precast concrete panels: ejected seals (left), top connection of precast panel with oversized hole for bolt (centre), sheared off bolts of precast panel connection with oversized washers (right).

hung from suspended ceiling system requires specific consideration when designing the seismic bracing of the ceiling system.

Other examples include HVAC equipment and ducting located above ceilings where it was observed neither the ceilings and/or the HVAC equipment was braced, as shown in Figure 2 (centre and right). Damage appeared to have resulted from the relative displacement of the various services elements relative to the ceiling system leading to multiple instances of services components falling out of the ceiling. The life safety risk associated with the falling of services components including lights, diffusers, ducting, etc. was noted.

Precast Panels

Damage to several precast concrete panels was visible from outside buildings on street level, however such damage was minor, consisting of hairline cracks in panels, panels being out-of-plumb, or torn or ejected sealant, such as that shown in Figure 3 (left).

Previous earthquake reconnaissance has found that more critical damage is often concentrated in the connections between the precast panels to the primary structure [4]. Such damage is a result of the connections being required to accommodate relative deformation between panels and the primary structure. If precast panel connections are not properly detailed it is possible for the connections to be severely damaged even when the panel itself shows little signs of distress. A thorough damage assessment of precast panels is generally difficult due to the connections normally being concealed from view. It is only once internal linings have been removed that the full extent of damage can be understood. The minor damage visible from street level can be a strong indicator that more significant damage may exist, since this is normally indicative of movement of the panels.

Minor visible exterior damage was visible for the one known case of precast panel connection failure that occurred. The failure involved full-height panels on a six storey building. The panels were fixed to the structure with a rigid weld plate connection at the base. This plate was welded to an angle bracket that was cast into the floor slab. The top connection consisted of an angle cast into the soffit of the floor beam with an oversized hole in it. A bolt was fixed through the angle into a cast in TIM in the panel. A 6mm oversized washer on the bolt then allowed the bolt to (theoretically) move within the oversized hole, as shown in Figure 3 (centre).

Although it appeared the design had considered the requirement for relative deformation between the structure and panel with the oversized hole, it was apparent on inspection that no sliding of the bolts had occurred. The 6mm washers appeared to have been bent into the oversized hole, causing the connection to lock up. It is likely that the bolts were unable to slide due to being over-tightened. Experimental testing of slotted connections has also found that the connections are at risk of locking up if a thin washer is used [5].

With no ability to accommodate the inter-storey drift of the building, the washer sheared straight through the top connection bolts, as shown in Figure 3 (right). Of the 6 storeys of panels, only 3 bolts remained out of a total of 24. The panels did not fall from the building, due to the nominal

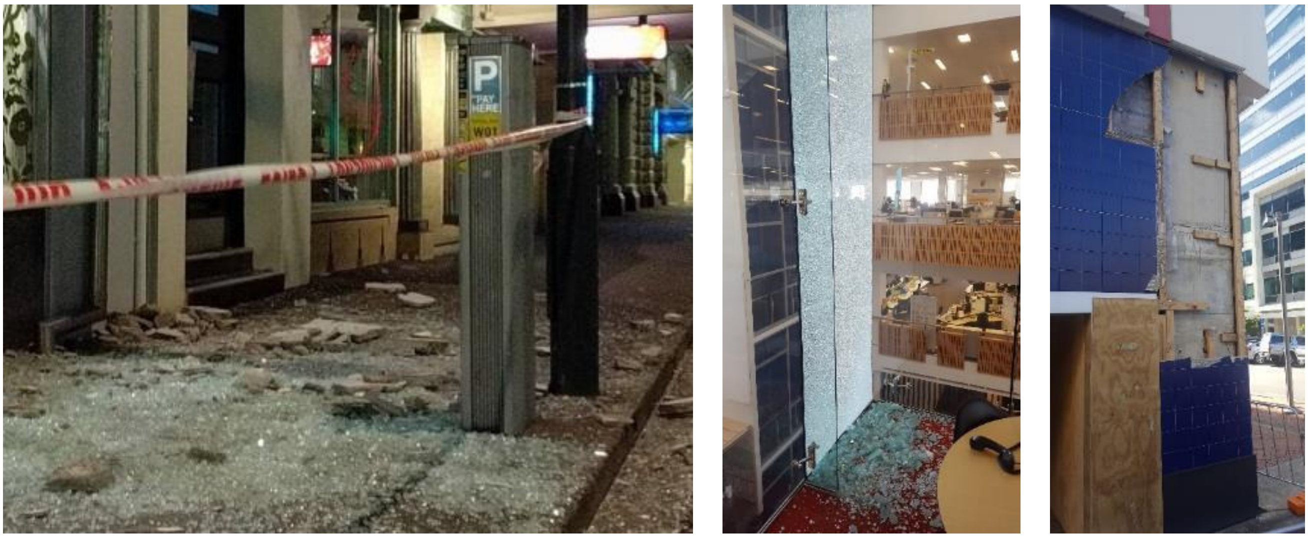

Figure 4: Damage to exterior cladding and glazing: glass and debris on footpaths in Wellington CBD [7] (left), spider glazing failure (centre), tiled cladding failure (far right).

moment capacity provided by the base detail. Once discovered, the street below was cordoned off until a new connection was fitted.

Due to the aforementioned difficulty in identifying high risk damage of precast panels, the Kaikōura Earthquake Technical Clearinghouse provided a session for the Wellington City Council 'Targeted Assessment Programme' that specifically included additional guidance for damage evaluation of precast concrete floor systems and cladding panels [6].

Exterior Cladding and Glazing

Damage to exterior cladding and glazing was widely reported in the media immediately following the Kaikōura earthquake [7]. Such damage typically consists of glass and debris on footpaths below buildings, as shown in Figure 4 (left). Depending on the size of the glass shards, and the type of glass, (e.g. tempered glass vs non-tempered glass), such falling objects can present a life-safety risk to pedestrians outside buildings.

Damage to exterior cladding and glazing is typically attributed to a lack of movement allowance within the glazing system. Once the movement allowance of the cladding system is exceeded the stiff, brittle glass cracks and potentially falls out of the framing. It was observed that older glazing systems were more likely to exhibit glazing damage, likely due to the fact that they have very little ability to accommodate building movement. The one exception to this was the relatively modern frameless glazing system, of which a number of cases of significant damage were observed. Frameless glazing, often referred to as spider glazing, typically utilises tempered glass so when the movement allowance of the system is exceeded, the stress concentrations in the glass result in the entire glass panels shattering, as shown in Figure 4 (centre). The amount of deformation a spider glazing system can accommodate is not large (1% drift is the limit of a typical system) and since the system does not have any redundancy like framed systems, large failures can occur. Similar damage was previously observed to frameless glazing systems in the 2010-11 Canterbury earthquakes, highlighting their vulnerability to earthquake induced deformations [5].

Several other instances of damage were observed to various cladding systems that appeared to be due to the system being unable to accommodate structural deformations, such as the tiled cladding shown in Figure 4 (right).

Internal Linings

Damage to internal linings, in particular plasterboard lined interior partition walls, was widely observed throughout a number of buildings. Refer to Figure 5 for examples of typical damage to internal linings.

In most cases the damage comprised of cracks to the plasterboard lining due to the lining being unable to accommodate the earthquake induced movement of the structure. Partitions are relatively stiff but also weak in their in-plane direction, therefore they require some method of seismic separation when spanning between levels to avoid damage. In all instances observed it appeared the damage was due to relative displacement between building elements, and a lack of seismic separation, rather than damage due loss of connection capacity holding the wall linings to the supporting structure.

Figure 5: Damage in internal linings: plasterboard debonding from structural beam (top left), cracked and delaminated plasterboard (top centre), cracked plasterboard lining of stairwell (top right), broken glass lining adjacent to stair (bottom left), typical movement induced cracking in plasterboard (bottom right).

Where large partitions had no seismic separation, damage was typically located at the joints between individual panels of plasterboard, as shown in Figure 5 (top right and bottom right). In other locations earthquake induced movement had caused cracks through the panels, and these were typically observed to have been initiated at corners or other discontinuities, such as that shown in Figure 5 (top centre). A small number of instances were observed where the plasterboard had been glued directly to the structure, and the structural movements had caused the lining to de-bond and break away, or otherwise become dislodged, as shown in Figure 5 (top left).

While none of the observed damage to internal wall linings was considered to have presented a life safety risk to occupants, the potential impact on fire ratings was noted, in particular the linings in egress ways such as stairs. Considering how this damage may compromise fire separations may need to be included as part of a building assessment in future before a building is reoccupied following a significant earthquake.

The damage of many internal linings also demonstrated that structural movements are not always adequately understood by architects and there is a need for such movements to be better communicated. One example of this was damage to a glass lining adjacent to a stair, as shown in Figure 5 (bottom left). The stair appeared to have been detailed to slide to accommodate inter-storey drift, as movement was evident at the base of the stair. However a large glass panel had been fixed to both the stair and the adjacent structure and consequently, as the stair moved relative to the structure during the earthquake the glass had been heavily damaged.

Although not seen to be a life safety risk from a structural engineering perspective, damage to internal linings can be very concerning to the public due to the highly visible nature of such damage. Discussions with tenants during inspections found that organisations were uncomfortable about staff working in buildings with obvious damage to interior wall linings. This indicates that considerations of non-structural damage extend beyond life safety to include public perception issues as well as costs and time to undertake repairs.

Seismic Gaps

Although not a non-structural element, the performance of seismic gaps has been included in this paper due to the observed damage to architectural finishes. This damage highlights one of the main issues facing the seismic performance of non-structural elements; the need to understand and communicate seismic movements to architects, building owners and tenants.

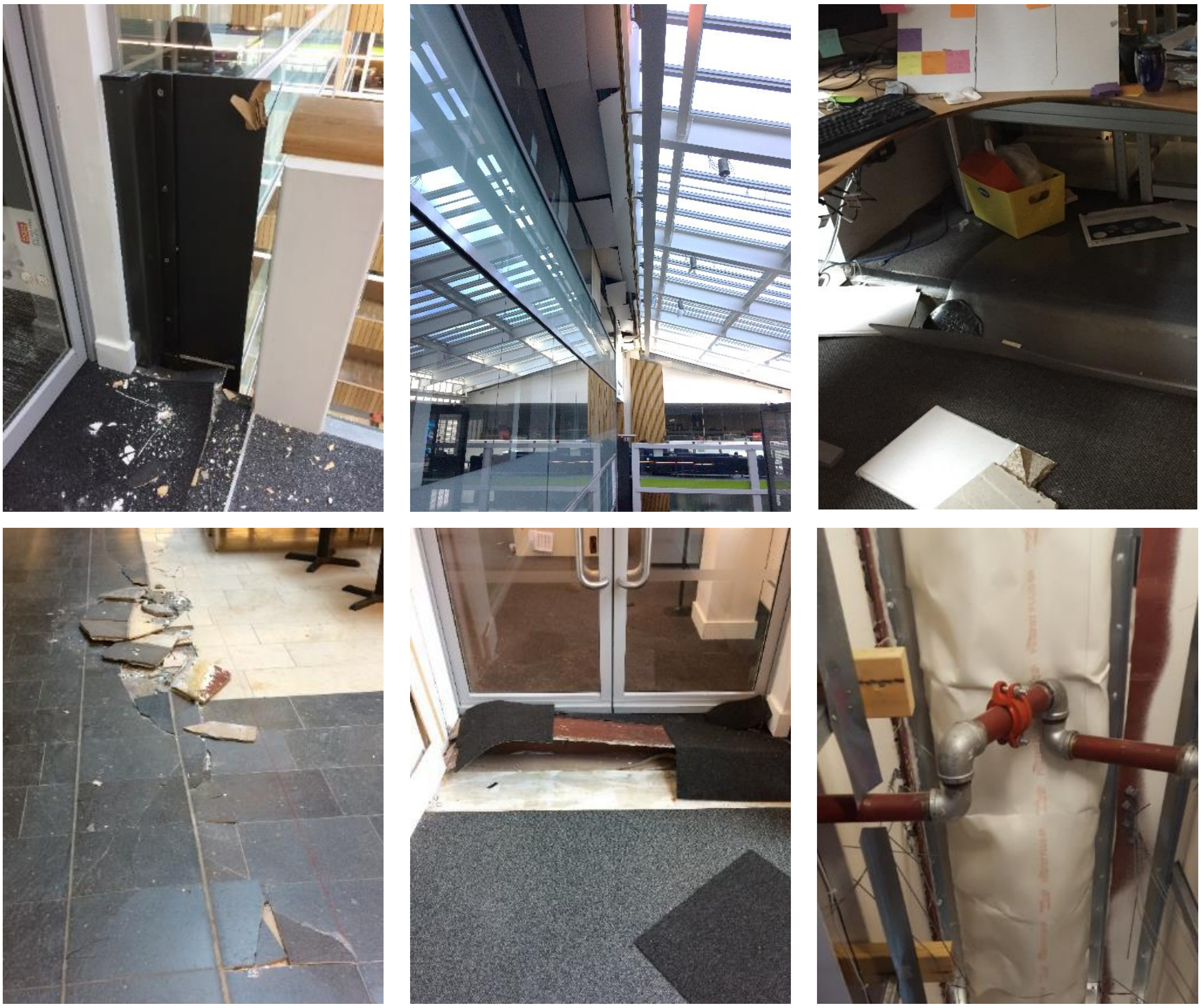

Figure 6: Damage at seismic gaps: timber boards enclosing atrium bridge at seismic gap (top left), dislodged ceiling tiles at seismic gap (top centre), seismic gap underneath desk (top right), tile damage at seismic gap (bottom left), bent seismic gap cover plate (bottom centre), undamaged sprinkler pipe and fire seal at seismic gap (bottom right).

One building complex inspected comprised several individual structures interconnected on various levels at a central multilevel atrium with bridges and seismic gaps between each structure. From a structural point of view, all of the seismic gaps were observed to have performed as intended as it was evident that significant amounts of relative movement between buildings had occurred. No ledge failures were observed or loss of structural support at any of the seismic gaps. Inspection indicated that while the structure had been designed to allow relative movement of the different structures at the seismic gaps this consideration had not extended to the architectural finishes. Damage to the architectural elements, such as balustrades, floor coverings, and architectural panel was extensive, as shown in Figure 6.

In some instances the architectural finishes covered the seismic gap and were damaged as a result of the earthquake induced movements, for example the floor finishes. In other instances an insufficient movement gap had been allowed at the seismic gap for the architectural finishes causing balustrades and various architectural panels to be damaged. In one instance the balustrades were glass and hence the damage meant that the bridge was no longer safe for use. Some pieces of the glass balustrade fell a short distance onto landings and walkways while other pieces fell multiple storeys to the ground level of the atrium below.

The arrangement of this building meant that some of the seismic gaps were at elevated positions multiple storeys above the ground floor atrium area. Architectural panels and other finishes were damaged and became dislodged, some falling several floors to the ground floor level. The life safety risk of these architectural elements falling to building occupants was clearly apparent.

A notable feature of this complex was that the seismic joints appeared to be located at main egress paths meaning these walkways would likely be used in the immediate post-earthquake environment. The implications of movement at a seismic joint appear to have been poorly understood when the finishes were being considered or the possible health and safety implications if damage occurred.

Fire sprinkler pipes were observed to cross one of the seismic gaps as shown in Figure 6 (bottom right). The pipe arrangement indicates the installer had some idea that a movement joint was required for the sprinkler main. It is however noted that the installed joint does not meet the requirements for a groove mechanical joint in NZS4541:2013 or the alternative flexible V loop type system [8]. Even so, no failure of the pipe at this junction was observed.

Observations from this building suggest that perhaps more attention is needed when considering architectural finishes at seismic joints. This is particularly relevant to finishes which if damaged could cause a life safety risk to building occupants below or as they exited a building immediately following an earthquake.

The extent of the damage at the seismic joint areas was striking both from a repair cost perspective and the implications on building operability in the immediate post-earthquake environment.

It is evident that the risks associated with seismic gaps need to be better communicated and understood by the end users of buildings. This is exemplified by the desk located on top of a seismic gap shown in Figure 6 (top right). The chair at this desk had fallen into the seismic gap during the earthquake, and it is likely that if someone was working at the desk at the time, that serious injury could have occurred.

Contents

Widespread damage to contents was noted in the commercial buildings included in the post-earthquake reconnaissance. Figure 7 illustrates typical examples of contents damage, such as overturned book cases and storage. Contents spilling from drawers and cupboards or falling from desk tops and other surfaces within the offices was widely observed. Damage to contents in retail shops and supermarkets was also reported [9]. This indicates the retail industry may not have learnt the lessons from the experience in the Canterbury earthquakes, e.g. protecting contents using catches, wires, etc.

While relatively easily repaired and cleaned up post-earthquake, the extent and types of furniture which fell suggests a potential for injury to people within the building during an earthquake. The significant contribution building contents made to injury numbers has been noted in recent New Zealand earthquakes [9]. This suggests that building tenants should consider the restraint of building contents as part of fit out works. For example fixing cupboards and bookcases to floors and / or walls and including positive catches on cupboard doors or drawers to restrain the contents from falling out.

Seismic Bracing of Non-Structural Elements

The adequacy of non-structural seismic restraint was evident during the post-earthquake reconnaissance of Wellington

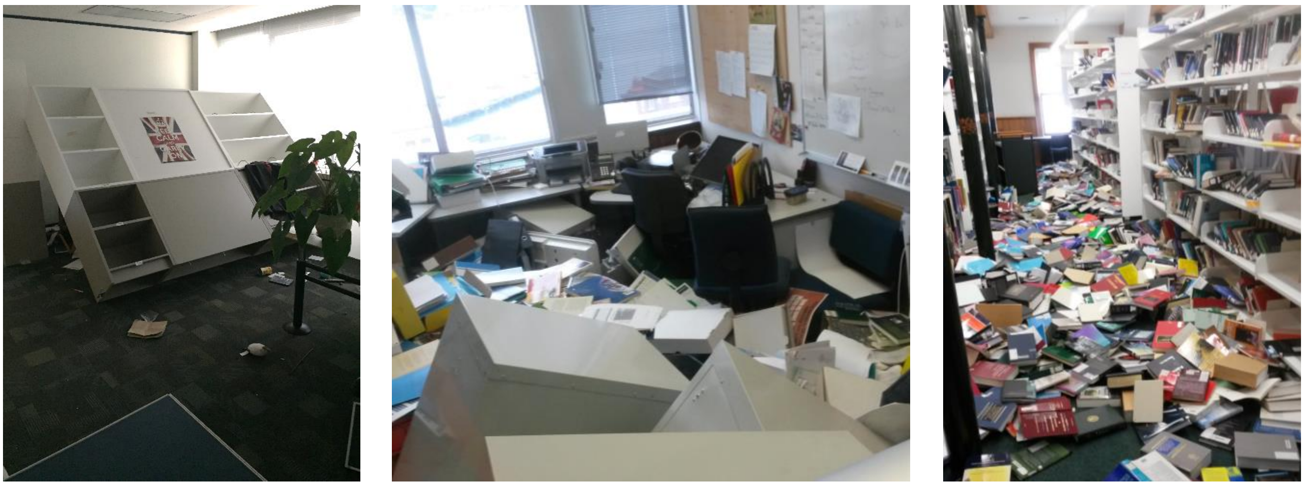

Figure 7: Damage of building contents: toppled bookcase (left), toppled office furniture (centre), books spilt from bookcases (right).

commercial buildings. It was observed that where seismic bracing, or seismic restraint of overhead services was present, there was often no visible damage to the non-structural elements.

The inspection was not detailed at a sufficient level that the seismic bracing could be assessed for compliance with NZS4219:2009 [10]. However, it was possible to inspect whether the bracing appeared to be appropriate for the elements being restrained. Several instances were observed where the seismic bracing appeared to have been lacking, e.g. no vertical stiffener present at a diagonal bracing member. Even so, it was apparent that when seismic bracing was installed, it had performed well, often with no visible damage. This result suggests that typical seismic bracing solutions do work (and may often be conservative in nature), and that even when a perfect bracing solution may not be achievable the adage 'something is better than nothing' seems to hold true for seismic bracing of non-structural elements [11].

DISCUSSION

When considering the vulnerability to earthquake damage, non-structural elements can be categorised as being sensitive to deformations, accelerations or both [12]. It was evident that the damage to non-structural elements following the 2016 Kaikōura earthquake was predominantly due to an inability to accommodate deformations of the primary structure, or other interconnected non-structural elements. Based on this observation, it is the author's opinion that communicating seismic movements to architects, building services engineers, building owners and building tenants needs to improve in order to reduce such damage in future earthquake events. The multitude of examples of damage around seismic gaps served as powerful examples of how poorly such movements are currently being communicated.

The risks associated with seismic gaps also serves as a good example of the need to better communicate risks from a health and safety perspective. Engineers have a responsibility to draw the attention of those affected by the life safety risk associated with their work. Although often architects may wish to conceal the location of seismic gaps, it is the author's opinion that the opposite approach is needed. More attention needs to be drawn to the location of seismic gaps to ensure adequate strategies around protecting building occupants are taken.

Damage of non-structural elements can present a significant cost due to repair time and costs [13]. However, the observations made in this paper confirm that damage to non-structural elements can also pose a significant life-safety risk. It was fortunate that the 2016 Kaikōura earthquake occurred at night when many buildings were not occupied.

The latest revisions to NZS1170.5:2004 [14] include updates to the 'Part Categories' used for determining the seismic loads that non-structural elements need to be designed for [15]. One such change is the introduction of the Serviceability Limit State 2 (SLS2) for all 'parts required to be operational / functional for the building to be occupied'. Previously this requirement only existed for Importance Level 4 (IL4) buildings but now includes IL2 and IL3 buildings. The standard also notes that for normal structures, elements should return to an operational state within hours or days following an earthquake. In the case of the Kaikōura earthquake, the majority of buildings were reoccupied in the days following. Subsequently, the level of damage observed in this earthquake may serve as an example of what would be considered acceptable for this SLS2 state in future design.

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