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Post-Earthquake Reparability of Buildings: The Role of Non-Structural Elements

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Abstract

Recent earthquake events in New Zealand have highlighted the need to improve the post-earthquake reparability of buildings. This paper describes a number of avenues for improving the post-earthquake reparability of buildings and reviews a number of recent and ongoing efforts to improve post-earthquake reparability in New Zealand. Attention is given to the role that non-structural elements play in the reparability of buildings. The work explains how the design and detailing of non-structural elements can be enhanced to achieve improved reparability. To reduce the vulnerability of drift-sensitive non-structural elements, such as plasterboard partition walls, a number of alternative detailing strategies are under development. For acceleration-sensitive components such as ceilings and suspended piping, issues with the industry design, installation and inspection provisions are highlighted and ongoing research aimed at understanding system interaction effects is discussed. The last part of the paper proposes different ways of improving reparability during the conceptual design of a building. Various possibilities are identified, such as the definition of inspection and repair criteria and the relocation of non-structural elements away from structural locations to improve access to non-structural elements. It is concluded that by considering potential inspection and repair needs during concept design, considerable time and repair cost could be saved following intense earthquake shaking, with considerable socio-economic benefits for the community.

Keywords: residual capacity; reparability; non-structural elements; concept design; Canterbury earthquakes

Introduction

Seismic design codes have traditionally focused on ensuring life safety in rare earthquakes, typically associated with 475 year return period shaking intensity, and a serviceability limit state in more frequent earthquakes. Examination of the performance of buildings following the 1994 Northridge earthquake (Los Angeles, USA) and the 2010–2011 Canterbury earthquakes (New Zealand) would suggest that the codes are achieving the life-safety design objective. However, there is increasing recognition that engineers should be aiming to provide more than just life-safety seismic performance, even in rare earthquakes. The costs and disruption due to building damage in the Canterbury earthquakes were extensive and upsetting, with widespread psychological impacts across the community.[1] An important challenge that emerged following the Canterbury earthquakes was the uncertainty as to whether a building could be repaired and what residual capacity it possessed.[2]

Figure 1 provides an overview of demolition/repair decisions for 223 reinforced concrete (RC) buildings [88% of RC buildings three storeys or greater in the central business district (CBD) of Christchurch] following the Canterbury earthquakes. The figure, developed from previously published data,[3] identifies demolition decisions as a function of estimated repair costs. The repair costs were estimated based on visual estimates of building damage and are presented as a ratio of repair cost to replacement cost. It can be seen that a large proportion of buildings with only low repair cost estimates was demolished. This highlights the fact that assessing the reparability of a building is a complex task. Given that the Canterbury earthquakes caused damage that resulted in only a limited number of fatalities (185 people in the most intense event) but resulted in over NZ $40 billion losses,[4] further work is required to improve building reparability and mitigate the negative socio-economic impacts of future earthquakes on our communities.

Overview of a Multifaceted Strategy for Improving Reparability

Improved reparability of a building can be achieved in a variety of ways. Ref. [5] proposes a framework for resilient seismic design provisions that includes consideration of prescriptive and non-prescriptive approaches to resilient design. It was pointed out[5] that both approaches could use procedures such as Federal Emergency Management Agency (FEMA) P-58[6] to assess building performance metrics relevant to resilience, such as those proposed in the Resilience-Based Earthquake Design Initiative (REDi) rating system.[7] More recently, the Earthquake Engineering Research Institute (EERI)[8] has considered a conceptual framework for functional recovery, raising questions about what functional recovery would mean and proposing that an eventual code focused on functional recovery would set acceptable functional recovery times for different building use types. These contributions all point towards building design approaches that improve post-earthquake reparability. However, they do not explore a number of the avenues for improved reparability that have become apparent in New Zealand following the 2010–2016 Canterbury earthquake sequence and the 2016 Kaikoura earthquake.

Figure 2 identifies avenues for improving reparability, building on previous contributions in the literature. An obvious starting point for improved reparability is to develop building components and systems that are less likely to be damaged. This needs to include consideration of both structural and non-structural building

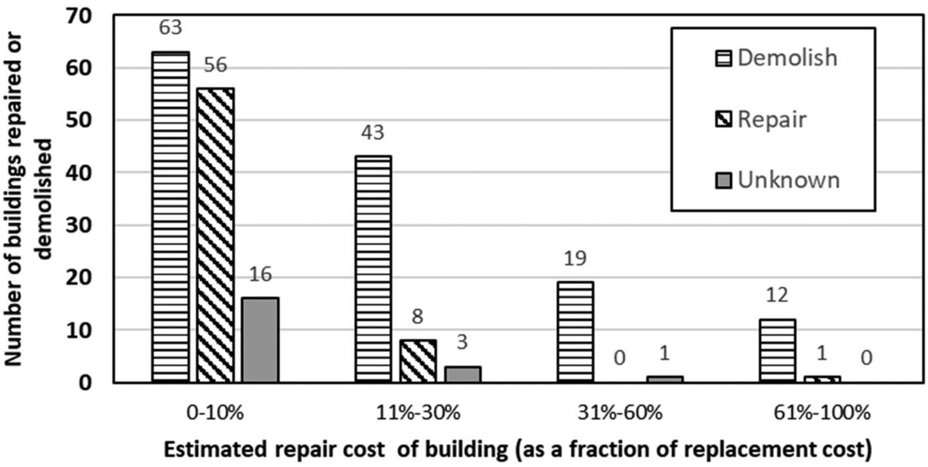


Fig. 1: Overview of repair decisions for reinforced concrete buildings in the Christchurch central business district following the 2010–2011 Canterbury earthquakes (After Elwood et al.[3])

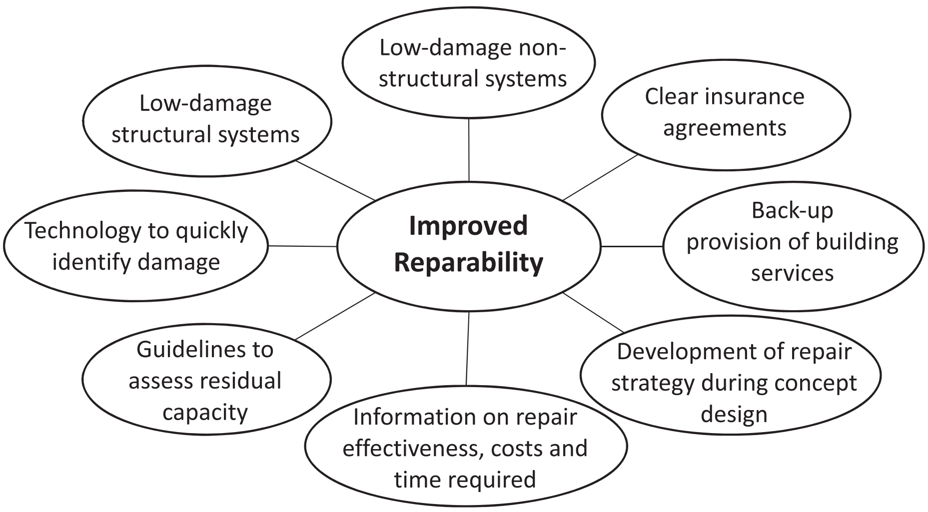


Fig. 2: Avenues for improving building reparability

components and systems, as emphasised in previous proposals[7] and elaborated on further in this paper. In addition, provision of back-up services such as power, telecommunications and water should be encouraged, as emphasised in Ref. [7], among others. *Figure 2* also shows that reparability needs to address the questions that will be raised in the aftermath of an earthquake. Questions will be raised about the extent of damage that has occurred. Thus, there is a role for instrumentation[7] and new technologies that help to quickly identify damage locations.[9] In addition, a predefined inspection and repair strategy should be developed during concept design. Such inspection works will be costly if there is a requirement to remove and later reinstate a large number of non-structural elements, as will be explained further in this paper, and so the impact of design decisions in relation to the positioning of non-structural elements made during design will affect reparability.

Once the damage has been located, the challenge will be to assess the residual capacity of the structural system and the effectiveness of proposed repair techniques. There has only been limited research into the effectiveness of repair techniques and research on this topic is ongoing.[10,11] Furthermore, questions will be raised about the implications of damage on the non-seismic performance aspects of the building. For instance, many non-structural elements, such as partition walls and glazing, play important roles in ensuring acceptable fire performance, and thus doubts will arise as to whether earthquake-induced damage to these elements affects their fire rating. Building occupants were unable to re-enter buildings in the Canterbury and Kaikoura earthquakes due to damage to plasterboard partitions compromising the fire rating of stairwells and other egress routes.

Guidelines to assess the residual capacity and assist in defining the repair works required should be developed by industry ahead of time. There will be little time or resources available to develop such guidance in a post-earthquake environment. Having insurance in place will also assist in covering the economic impact of earthquake-induced damage. Indeed, the economic impact of the Canterbury and Kaikoura earthquakes was significantly mitigated by the high level of insurance coverage in place at the time. However, experience from recent earthquakes in New Zealand also shows that the insurance claims process can be drawn out and may require legal proceedings to resolve disputes. As such, the development of insurance agreements that are clear to both parties, possibly aligned with predefined repair strategies, would assist in improving reparability.

There are risk factors external to the building, not indicated in *Fig. 2*, which could also impact on a building's reparability. This could include the risk or hazard posed by adjacent buildings that would hamper or complicate repair works. Alternatively, access to a building may be hampered due to damage to a transport network or enforcement of a cordon, recognising that parts of the CBD of Christchurch were cordoned off for a number of years following the Canterbury earthquakes.

This paper reviews recent and ongoing efforts to improve post-earthquake reparability by improved consideration of non-structural elements in seismic design. Two areas will be discussed: (a) improving the design and detailing of non-structural elements, and (b) conceptual design decisions on the relative positioning of structural and non-structural elements.

Improving the Design and Detailing of Non-Structural Elements

As explained in Ref. [12], the majority of non-structural elements can be classified as being either drift sensitive or acceleration sensitive. Some components might be classified as velocity sensitive or possibly both drift and acceleration sensitive (such as masonry infill walls), but the former are not common and the latter are not common for new design in New Zealand. This section reviews a number of developments that are currently being made in New Zealand to improve the seismic performance of non-structural elements and hence lead to improved reparability.

Drift-Sensitive Components

Drift-sensitive elements are those that are damaged as a result of the drift imposed on the elements. For example, cladding panels, glazing, partition walls and any elements that are attached to two floors of a building will be damaged when the lateral displacement of one floor relative to the other (i.e. the drift) becomes excessive. Plasterboard partition walls are one of the most vulnerable non-structural components in a building, typically exhibiting the first signs of damage when storey drifts reach around 0.3%.[13] Considering that a typical RC frame building will begin to yield at a storey drift of 1.0%, it is apparent that partition walls may require repair after only moderate earthquake shaking. In fact, during the Canterbury earthquake sequence it was observed that some buildings required repairs to plasterboard partition walls six times, with aftershocks damaging the freshly repaired walls.

To reduce the vulnerability of plasterboard partition walls, a number of alternative proposals have been made in the literature.[13–15] Recent experimental testing of partition walls at the University of Canterbury was conducted in collaboration with industry partners and it was quickly recognised that revised detailing needed to be developed considering vertical service movements, fire and acoustic performance requirements. In light of this, two partition wall systems were tested: (a) gapped wall systems[16] inspired by previous work,[13] and (b) partly sliding partition wall systems,[17] which were similar to sliding-track systems developed and tested in the USA.[13] *Figure 3* illustrates the testing of a partly sliding partition wall system with an acoustic and fire-rated joint, where it can be noted that significant lateral deformations were developed locally prior to damaging the joints. Such efforts show that changes in detailing can be effective in reducing the likelihood of damage to non-structural elements and hence improving the reparability of building systems.

Acceleration-Sensitive Components

Acceleration-sensitive components are those that are damaged as a result of the acceleration imposed on the elements. For example, ceilings, piping systems, heating, ventilation and air conditioning (HVAC), lighting and contents all tend to be classified as acceleration sensitive. Improved performance of acceleration-sensitive components can be achieved through adequate bracing or through innovative design.

Issues currently being addressed in New Zealand in relation to the seismic performance of acceleration-sensitive components relate to the following:

- inadequate industry procurement processes and controls on the installation of non-structural elements and their restraints
- inaccurate estimation of acceleration demands on non-structural components
- lack of understanding of the behaviour and interactions of non-structural elements.

There are issues with the procurement process that encourage tendering for non-structural elements prior to the seismic design being undertaken.[18] Issues are also present with the correct installation of non-structural supports (hangers and braces). *Figure 4* shows a case in which a ceiling grid has been supported off a sprinkler pipe as there was insufficient room to fix the ceiling grid to the floor above. In light of such issues, Ref. [18] emphasises the need for (a) full design and coordination of non-structural elements and their seismic restraint in the main design documentation, and (b) independent inspections and certification/sign-off that the installation of non-structural elements is consistent with the agreed documentation [or building information modelling (BIM) model] which, in turn, should ensure that the installation meets the requirements of relevant standards.

Work has been proceeding to quantify better the seismic demands on non-structural elements. This has mainly focused on the definition of floor response spectra, with literature[19] showing that international codes all differ and are unable to provide reliable predictions of acceleration demands. *Figure 5* compares the roof-level response spectra recorded in an instrumented five-storey building in Wellington during the 2016 Kaikoura earthquake with code predictions using the same input ground accelerations. It can be seen that the international guidelines are not able to accurately predict the recorded acceleration demands. New guidelines are now emerging to provide more accurate floor response spectra. One of the important characteristics affecting the demands on non-structural

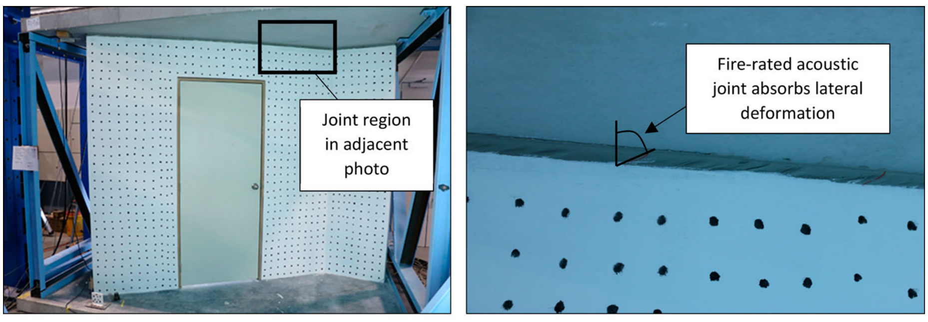


Fig. 3: (a) Testing of a partly sliding partition wall system; (b) acoustic and fire-rated joint (adapated from Ref. [17])

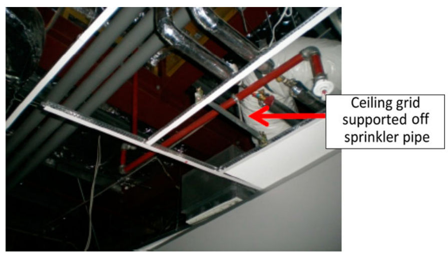


Fig. 4: Ceiling grid system being inappropriately supported off a sprinkler pipe (Courtesy of Jan Stanway)

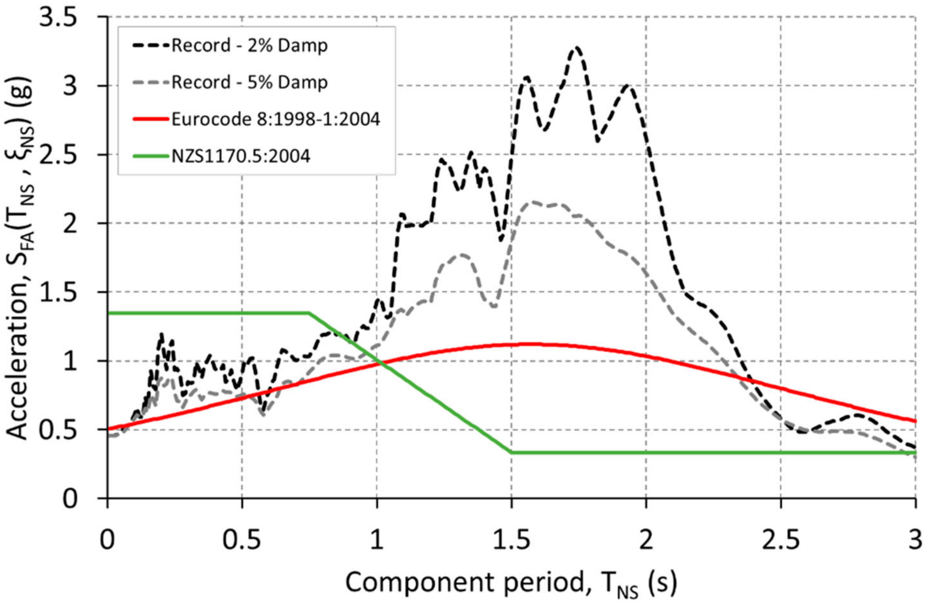


Fig. 5: Floor acceleration spectra recorded at roof level of an instrumented five-storey building during the 2016 Kaikoura earthquake compared with those predicted using standard code procedures

elements is the inherent damping. As such, experimental testing of acceleration-sensitive components includes this as one of its objectives.

Even with better predictions of acceleration demands, it is also appreciated that the engineering community does not yet have the tools and knowledge to accurately predict the behaviour of non-structural systems. This is partly due to limitations in knowledge of the components, but also due to the complex interactions that can occur between non-structural elements and between non-structural and structural components. An experimental testing project is currently underway to undertake testing of a three-storey building in China in which non-structural systems are included. In particular, the test will examine the performance of precast concrete cladding, glazing, plasterboard partition walls, ceilings and sprinkler systems. See Ref. [20] for further details.

Inclusion of Repair Strategy at Conceptual Design Stage

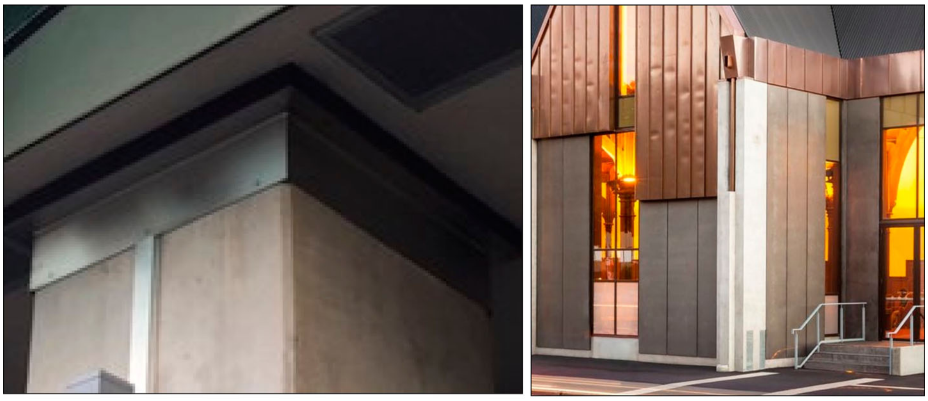
At the conceptual design stage of a project, key recommendations will be made about the structural system and the strategy for providing services within a building. To improve the post-earthquake reparability, it is recommended that a repair strategy be formulated as part of the concept design phase and that efforts be made to provide access for inspection and repair post-earthquake. A suitable repair strategy could be as simple as identifying where damage should be expected to occur in the structural system (i.e. identification of likely plastic hinge zones), recognising that these zones will require inspection post-earthquake. This process will increase recognition of the need to provide easy access to structural elements and highlight the need to consider the location of services relative to structural elements. *Figure 6* shows damage to the links of steel eccentrically braced frame (EBF) structures observed in a 22-storey building during the Canterbury earthquakes.[21] The links of a traditional EBF structure are intended to be damaged in rare intense earthquakes as part of the seismic design philosophy. However, it is apparent from *Fig. 6* that the positioning of non-structural elements (and, in particular, telecommunications and piping) in the vicinity of the links could significantly hamper repair works. In fact, the industry reported that to repair one link of the type shown in *Fig. 6*, approximately NZ $20 000 was required just to remove and later reinstate the non-structural elements in the vicinity. Such expense could be avoided at the concept design stage if access for inspection and repair were considered as part of the concept design.

In the wake of such experiences, there are signs that the industry in New Zealand is indeed beginning to consider accessibility/reparability within new building design. Two examples of this from buildings in Christchurch, New Zealand, are shown in *Fig. 7*; in *Fig. 7a* one can see a removable stainless steel cover at the top of a column, encapsulating a base-isolation device, while in *Fig. 7b* a removable stainless steel cover, screwed on four sides, permits easy inspection of a rocking column base connection detail in Knox Church. In such structures, the post-earthquake inspection can be carried out without costly damage to non-structural elements and, therefore, these are examples of buildings with enhanced reparability.

To clarify further how the consideration of reparability could affect the development of a building's design, *Fig. 8* compares the concept design solution for a hypothetical four-storey building with and without consideration of reparability. At first glance, the two buildings appear very similar and it should be noted that both would be code compliant. However,

(a) (b)

Fig. 6: (a) Fracture of an eccentrically braced frame (EBF) link at level 6 after the February 2011 event; (b) non-structural elements in the vicinity of a less damaged EBF link (From Clifton et al.[21])



(a) (b)

Fig. 7: (a) Removable stainless steel cover at the top of a column, encapsulating a base-isolation device; (b) removable stainless steel cover, screwed on four sides, to permit easy inspection of a rocking column base connection detail (Courtesy of Aurecon)

the concept design solution that considers reparability is indicating a raft foundation instead of pad footings. This is because raft foundations are more likely to be able to accommodate differential settlements of the ground and would be more readily relevelled if required post-earthquake. The steel structure in the two systems looks equivalent, but in the reparable system one would advocate a low-damage system, possibly using replaceable link elements or friction connections that dissipate energy through sliding rather than yielding of elements.[22] The other five concept design ideas called out for the new scenario in *Fig. 8* relate to non-structural elements. These include instrumentation that can quickly indicate where both structural and non-structural damage is likely to have occurred, as well as view panels so that non-structural elements do not need to be damaged and later repaired in order to inspect the structural system. Low-damage non-structural elements are also present, shown in the form of deformable partition systems (such as those in Ref. [14]) and low-damage ceilings (such as those advocated by Ref. [23]). BIM is used to ensure that data relevant to seismic assessment are available, and the design features report for the building describes the expected damage in rare earthquake events and includes a recommended inspection and repair strategy. Finally, an insurance agreement is in place that has clear criteria regarding assessment and repair procedures and the claims process.

Quantifying the benefits of enhancing reparability is difficult at present, principally because a number of the avenues proposed in *Fig. 2* have not yet been tested in practice. The impact of utilising low-damage structural and non-structural components can be quantified using procedures such as FEMA P-58,[6] as suggested previously.[5,24] However, recall that the use of low-damage systems is only one avenue for enhanced reparability. Another means of improving reparability described earlier was to strive, during the concept design phase, to

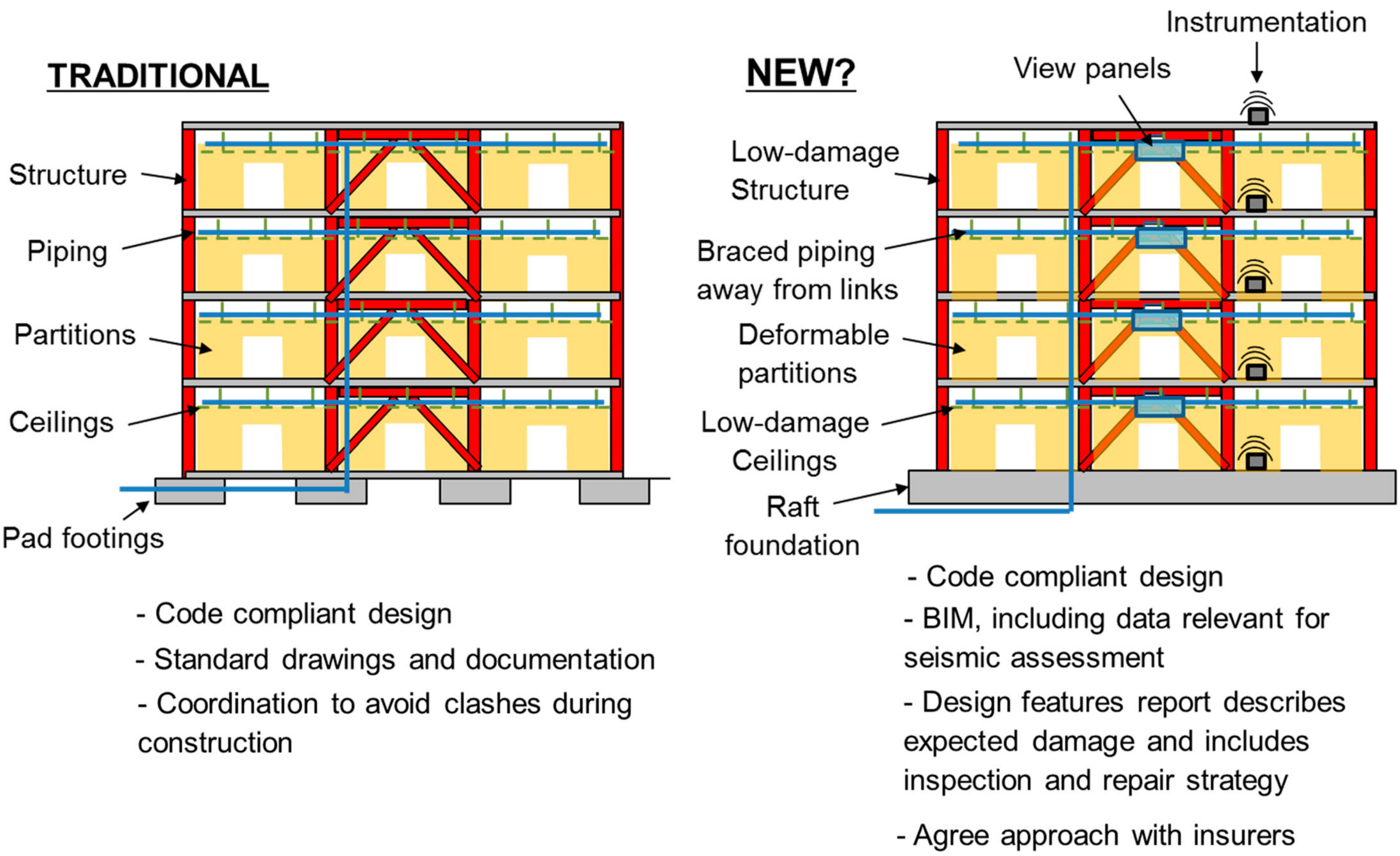


Fig. 8: Comparison of a concept design solution developed with and without consideration of reparability for a hypothetical four-storey building. BIM: building information modelling

locate non-structural elements away from locations in which structural repairs are likely. To gauge the potential impact of this approach, the loss assessment process for the 22-storey building conducted in Ref. [24] is repeated for the 22 February 2011 earthquake with a revised link-repair cost function that presumes that non-structural elements do not need to be removed and then reinstated. From this process, it is found that the total repair costs would have been reduced by approximately US $1.26 million (which equates to 4.7% of the estimated replacement cost for the building) simply by ensuring that access for repairs to the steel EBF links (shown in *Fig. 6*) would not have been hindered by the presence of non-structural elements. This point emphasises the important role that non-structural elements have to play in the post-earthquake reparability of buildings.

Conclusions

Recent earthquake events in New Zealand have highlighted the need to develop buildings that are more reparable after an earthquake. This paper has proposed a variety of means of improving the post-earthquake reparability of buildings and has reviewed a number of recent and ongoing efforts to improve post-earthquake reparability in New Zealand. Attention is given to the role that non-structural elements play in the reparability of buildings. The work has explained how the design and detailing of non-structural elements can be improved to achieve improved reparability. To reduce the vulnerability of drift-sensitive non-structural elements, such as plasterboard partition walls, several alternative detailing strategies are under development. For acceleration-sensitive components such as ceilings and suspended piping, issues with the industry design, installation and inspection provisions have been highlighted and ongoing research aimed at understanding system interaction effects has been identified. The last part of the paper has proposed the need to consider reparability during the conceptual design of a building. It is concluded that by considering potential inspection and repair needs during concept design, considerable time and repair cost could be saved following intense earthquake shaking, with considerable socio-economic benefits for the community.

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