LESSONS ON ATTAINING RESILIENCE BASED ON THE CHRISTCHURCH REBUILD STRUCTURAL FORM DRIVERS STUDY

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Abstract

After the 2010–2011 Canterbury earthquakes, much of the Christchurch Central Business District (CBD) was demolished, and a new city has emerged in its place. A study was conducted to (a) quantify the extent to which various types of structural system have been used in the new buildings constructed by early 2017, and (b) identify some of the drivers that have influenced decisions about the selection of structural material and specific structural systems used. Input was obtained from key engineers, as well as an architect, a developer and a project manager.

The work culminated in a 2017 report written by the Bruneau and MacRae published by the QuakeCentre entitled "Reconstructing Christchurch: A Seismic Shift in Building Structural Systems".

This paper briefly discusses the report and draws lessons for the development of resilient building systems. It is shown that many stakeholders had a knowledge of resilient construction, and made decisions to avoid the forms of construction which required the most repair after the earthquakes. It was also demonstrated that the goodwill of stakeholders alone is insufficient to make all construction in Christchurch resilient. Means of ensuring resilient construction are discussed.

Introduction

On February 22, 2011, an earthquake of Magnitude 6.3 having its hypocentre at a depth of 5 km and a horizontal distance of less than 10 km from the city's Central Business District (CBD). It was the strongest of a string of earthquakes that struck the Canterbury area starting in 2010. The effect of these earthquakes have been extensively documented (NZSEE 2011). Access to Christchurch's Central Business District (CBD) was a severely restricted for months (years in some parts); since then, many of the buildings in the CBD have been demolished, and reconstruction has started. Much of the rebuilding with multistorey buildings is taking place at the heart of the city (Christchurch City Council 2011). Where new buildings were predominantly built of reinforced concrete structures prior to the earthquakes, the "new Christchurch" that is emerging is a city with a variety of structural forms. The structural systems used are diverse, ranging from traditional systems to innovative systems. This is a dramatic departure from past practice.

To quantify the extent of the shift in construction practice taking place there, and, more importantly, to identify some of the drivers that have influenced the decisions about the choice of structural material and specific structural systems, the authors have conducted a series of interviews with the structural designers of more than 60% of the post-earthquake buildings constructed to date in Christchurch's CBD, as well as with other stakeholders. Results presented in Bruneau and MacRae (2017) show that the drivers are diverse and include costs, construction speed, perceptions of damage and of structural performance, tenants' requirements, engineering culture, and other factors. These are explained through the narratives obtained from the interviews.

A summary of some aspects of this work and key quantitative findings of this study are presented here. The complete findings from this study are presented in the 170-page report "Reconstructing Christchurch:

A Seismic Shift in Building Structural System", that can be downloaded for free from: http://resources.quakecentre.co.nz/reconstructing-christchurch/.

Quantitative Findings

The complete methodology used to collect the data is presented in Bruneau and MacRae (2017). In essence, the most important step of the methodology was interviews conducted with the structural engineering consultants. The consultants interviewed were selected based on the number of buildings their firm had designed that were constructed or being constructed as part of the Christchurch recovery. The final ten consultants selected for interviews were responsible for over 65% of the multistorey buildings, and a slightly greater percentage of the total floor area, of the new buildings being constructed in the Christchurch CBD and Addington areas.

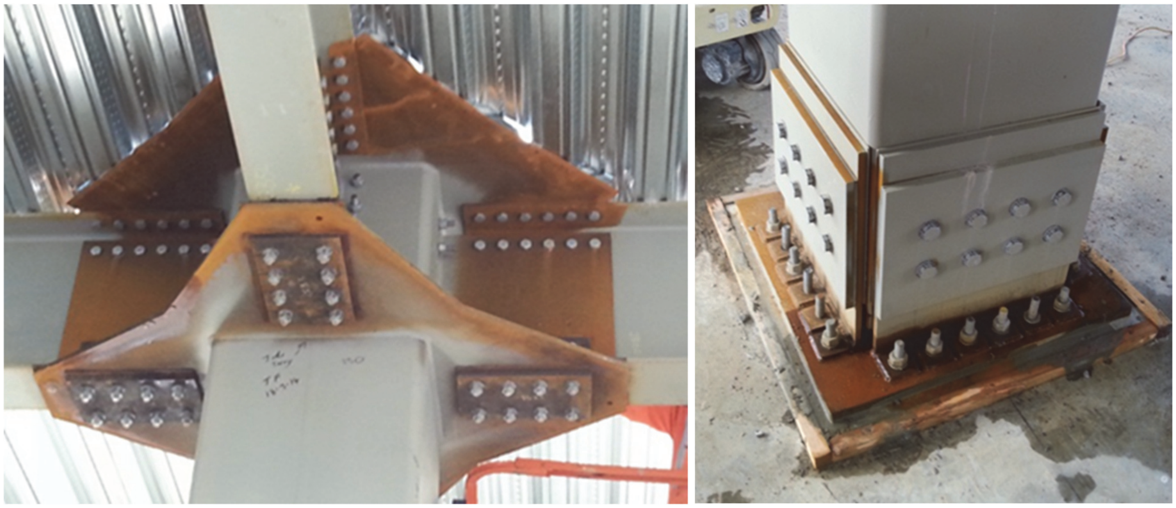
Quantitative results obtained following the methodology are presented in this section. Note that where information is presented as a function of year of consent, it must be recognized that results for 2017 are only for the first three months of the year (as data was collected, and last interviews were conducted, in March 2017). Overall, data has been obtained on a total of 74 buildings, collectively adding to a total of 482,317 square metres of floor space.

The types of lateral load resisting systems that were included as part of this sample include: Buckling Restrained Braces (BRB), Concentrically Braced Frames (CBF), Eccentrically Braced Frames (EBF), Eccentrically Braced Frames with replaceable links (EBR), Steel Moment Resisting Frames (MRF), Steel Moment Resisting Frames with friction connections (MFF), Steel Moment Resisting Frames with Reduced Beam Sections/"Dogbone" (MRD), Reinforced Concrete Walls (RCW), Reinforced Concrete Moment Resisting Frames (RCF), Rocking Frame Steel (RFS), Rocking Frame Concrete Precast Walls (RFC), Laminated Veneer Lumber (LVL), Base Isolated buildings (B), buildings with Viscous Dampers (D), and building with multiple structural systems along height or in a given horizontal direction, called Hybrid (H).

Representative steel moment resisting frame examples are presented in Figures 1 (MRF) and 2 (MFF). Figure 3 shows example eccentrically braced frames, with replaceable links (EBR) or without (EBF). Figure 4 shows an example building with buckling restrained braces, and Figure 5 illustrates an example rocking frame.

(a) Global view of space moment frame *(b) Close-up of RBS- bolted end-plate RCFT connection*

Figure 1: MRF at the Crossings, 71 Lichfield Street



(a) Completed bi-directional moment connection; *(b) Base connection detail*

Figure 2: Details of the friction connections on the Terrace Project at Oxford Terrace

(a) With replaceable *(b) Without replaceable links*

Figure 3: Example EBFs

(a) Global view *(b) Connection to column*

Figure 4: BRB frame in building at 254 Montreal St

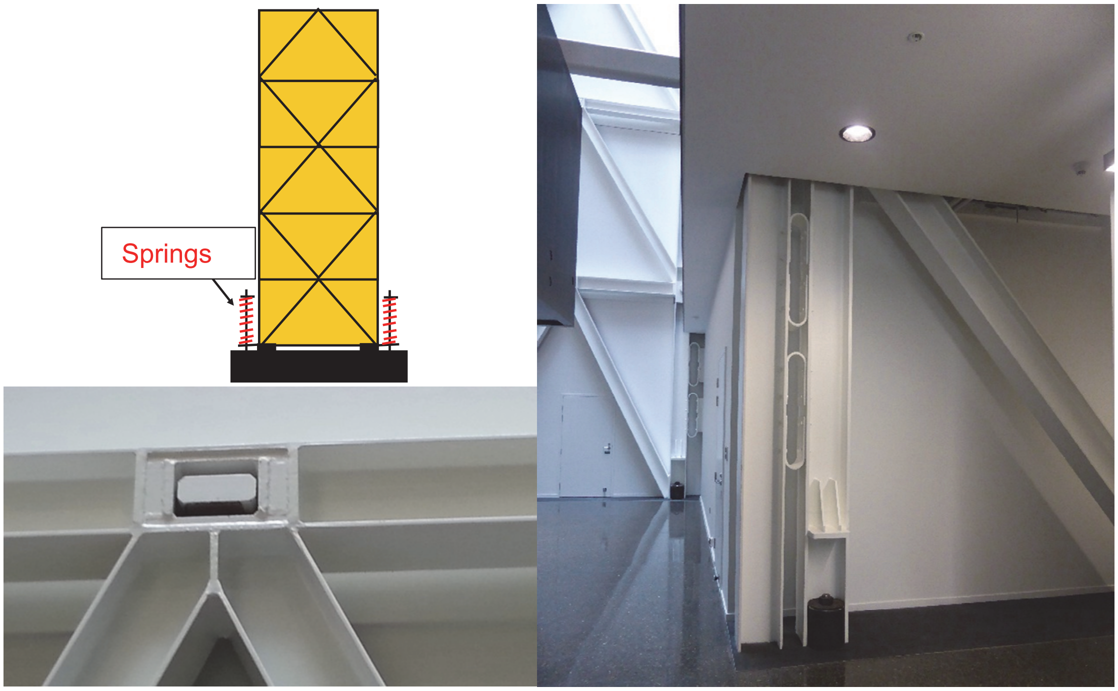


Figure 5: Rocking frame system implemented in building at 141 Cambridge Terrace.

Figure 6 presents the total floor area (in square metres) of new buildings having steel, concrete, or timber, lateral-load resisting structural systems. The results in Figure 6 show that steel, reinforced concrete, and timber lateral-load resisting systems have been used in buildings respectively totalling 377,929 sq. m., 98,572 sq. m., and 5,816 sq. m., for a total of 482,317 square metres of floor space. This corresponds to 78.4%, 20.4%, and 1.2% of the total floor area for the three materials respectively. If the gravity systems were to be included in the above numbers, the total floor area supported by structural steel would be further increased. This is because steel gravity framing (columns, beams, floors) has been used in about 75% of the buildings having reinforced concrete walls as their lateral load resisting system. This results in approximately 95% of the total supported floor areas in new buildings relying on steel framing.

In particular, as shown in Figure 6b, in 2015 and 2016, approximately 10 times more square metres of floor area were consented for buildings with steel than concrete lateral force resisting systems. "Drilling" through the spreadsheet data indicates that most buildings relying on reinforced concrete walls indeed tend to be smaller buildings, and that the larger buildings have steel framing systems of one kind or another.

Figure 6c shows that, in terms of floor area, the rate at which reinforced concrete was built peaked in 2014 and decreased by more than half afterward (from floor areas of 42,500 m^2 in 2014 to 15,500 m^2 in 2015); for steel, rates peaked in 2015, with a decrease in the subsequent year (from floor areas of 148,000 m^2 in 2015, to 84,500 m^2 in 2016).

Note that data presented in Figure 6 differentiates in term of the material used for the lateral force resisting systems of each building. As such, the number do not reflect the fact (mentioned earlier) that steel gravity-resisting frame systems were not only used in structures having steel lateral-load resisting systems, but also in approximately 75% of the buildings with reinforced concrete walls.

To quantify the number of new buildings having different types of lateral-load resisting structural systems, the data has been broken down into the following categories for the lateral load resisting systems mentioned previously:

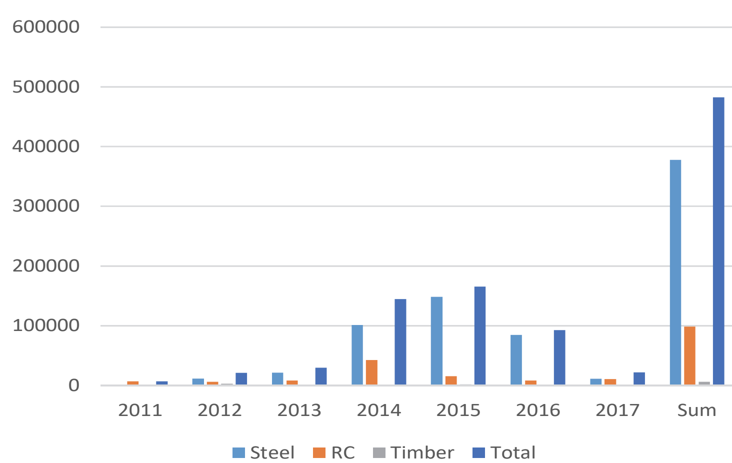
- BRB: 11
- CBF: 3
- EBF: 2
- EBR: 4
- MRF: 9.5
- MFF: 1
- MRD: 4.5
- RCW: 32.5
- RCF: 0.5
- RFS: 1.5
- RFC: 0.5
- LVL: 2.5
- B: 11
- D: 2
- H: 7

Details of how buildings are counted are presented in Bruneau and MacRae (2017). By analogy to Figure 6, information is presented in Figure 7 in terms of floor areas (in square metres) per structural systems. Note that cumulative results are shown for the most popular structural systems grouped together.

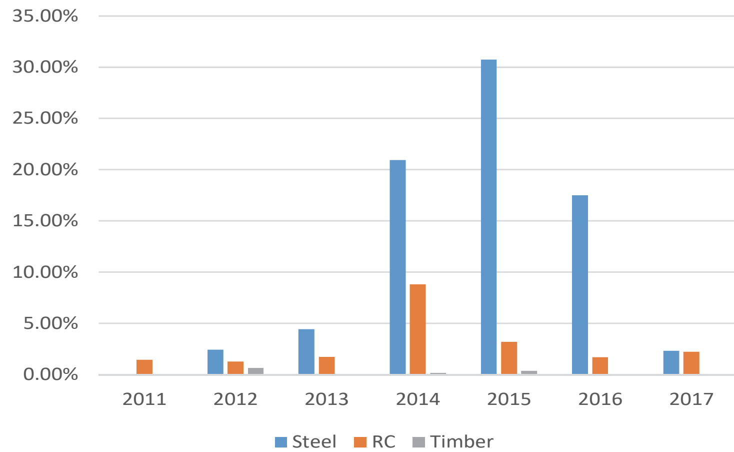
Results show that the following lateral load resistance systems have been used for buildings totalling the following floor areas:

- BRB: 111,000 m^2 (23%)
- CBF: 38,500 m^2 (8%)
- EBF+EBR: 27,500 m^2 (6%)
- MRF+MFF+MFD: 202,000 m^2 (42%)
- RCW: 80,400 m^2 (17%)
- RFS+RFC: 15,000 m^2 (3%)

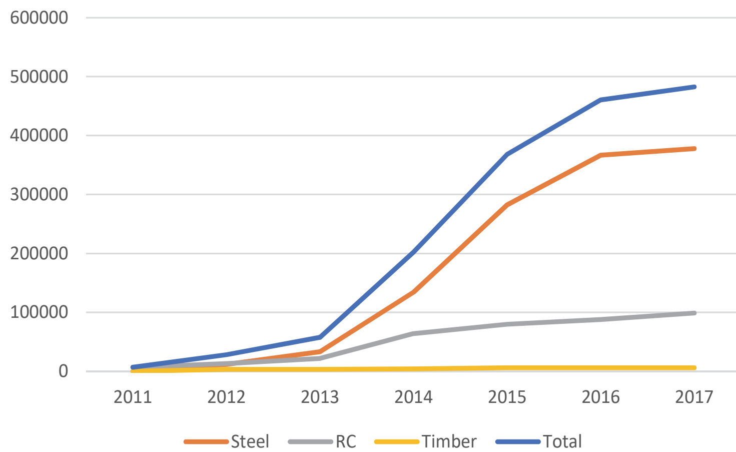
Interestingly, the 11 base isolated buildings (15% of the total number of buildings) alone provide a total 190,000 square metres, equivalent to 40% of the total floor area of the buildings considered in this study. This indicates that the base isolated buildings have generally been large buildings. Indeed, the two largest base isolated buildings alone, built specifically for public sector tenants, together add-up to more 102,000 square metres (21% of the total floor area of the buildings considered here). Considering the three largest instead add-up to 129,000 square metres (and 27% of the total floor area). Also note the strong correlation between floor areas for base isolated buildings and steel moment resisting frames.



(a) Absolute numbers (m^2)



(b) Percentages



(c) Cumulative numbers (m^2)

Figure 6: New building floor areas with lateral-force resisting systems material type

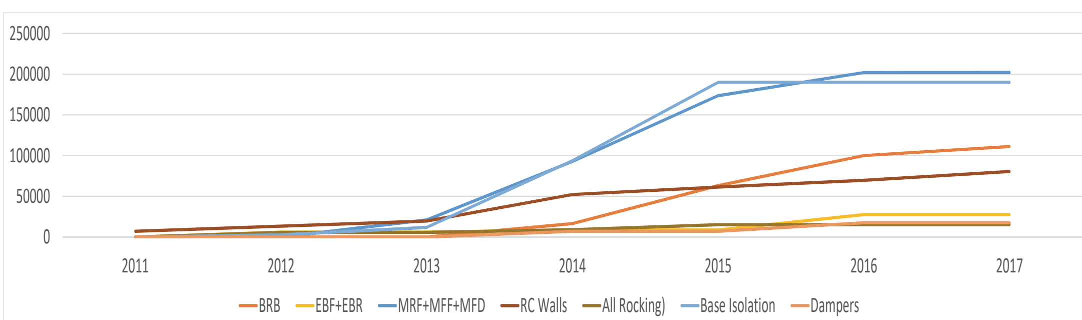


Figure 7: Growth over time in total floor area of new buildings (m^2) having various types of lateral-load resisting systems (regrouped as shown)

To better understand trends in design, Figure 8 shows the same results as Figures 7, but for all structures that have not been base isolated, as it is interesting to identify which structural systems have been more dominantly used when buildings have not been base isolated. Figure 8 shows that contribution of lateral load resistance systems to total non-base-isolated reconstruction floor area is:

- BRB: 111,000 m^2 (38%)
- CBF: 0 m^2 (0%)
- EBF+EBR: 27,500 m^2 (9.5%)
- MRF+MFF+MDF: 57,000 m^2 (20%)
- RCW: 78,000 m^2 (27%)

As such, with respect to new non-base-isolated buildings, concrete lateral-load resisting systems have been used for 27% of the floor area, and steel for 68% of the floor area, with all the other systems (i.e., hybrid structures, timber structures, rocking frames, etc.) accounting for 5%.

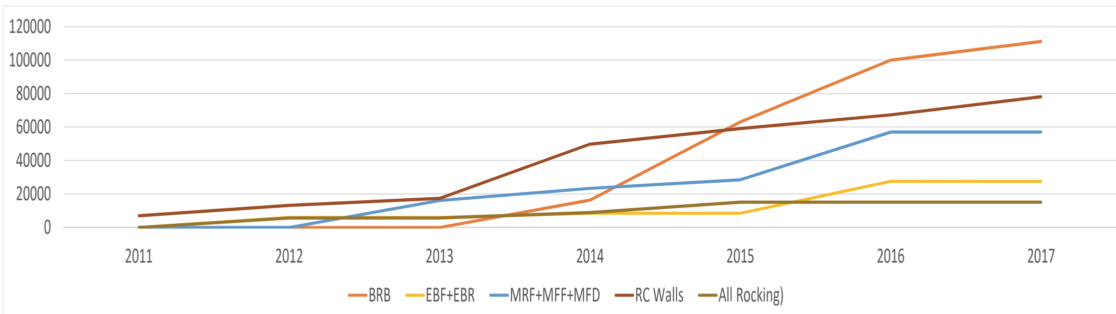


Figure 8: Growth over time in total floor area (m^2) of new non-base-isolated buildings having various types of lateral-load resisting systems (regrouped as shown)

Qualitative Findings

The interviews conducted also provided a valuable overarching narrative on the reconstruction process that goes beyond the quantification process. Bruneau and MacRae (2017) have compiled and presented the opinions expressed by those met. Using the words of those interviewed (but ordering the modified sentences to improve readability), the document highlights the various factors identified as having a significant impact on the decision process of owners/tenants and structural engineers (from the perspective of those interviewed), and the conditions that have been necessary for those factors to drive (or not), in some instances, the choice of specific structural systems. The narrative shows that some of the opinions presented are contradictory to other opinions expressed, illustrating the diversity of opinions amongst those interviewed.

This critical part of the report (i.e., 75 of the total 170 pages) cannot be summarized without losing critical perspective of this breath of opinions, the reasons that sustain it, and important nuances that impact decisions from case to case. However, it can be drawn from this narrative that:

- Preventing loss of life is less frequently an acceptable seismic performance objective for modern buildings;
- The professional opinions of structural engineers drive the adoption of low-damage systems, but tenant expectations have a significant direct or indirect impact on the choice of structural systems for individual buildings;
- Context directly affects these decisions, and;
- While the reconstruction experience has paralleled an increase in stakeholders' knowledge, government regulations would still be required if the objective was to achieve an across-the-board increase in seismic performance for all buildings in a community (something unforeseen to occur at this time).

Conclusions

Major findings from the quantitative part of this study can be summarized as follows:

- While before the earthquakes almost all new building being built in the Christchurch CBD and Addington areas had reinforced concrete frames or walls as their structural systems, in the rebuilding of Christchurch that has taken place since 2011, the number of buildings with steel, concrete, and timber lateral force resisting systems have been in the ratio of approximately 10:10:1. However, the floor area ratios of the same buildings with steel, concrete and timber lateral force resisting systems is about 79:20:1, because the steel systems tend to have been used in larger structures. Furthermore, for the above concrete buildings, the internal gravity frames have been found to be of structural steel three-quarters of the time.
- Concrete structures in the rebuild were nearly all structural wall systems.
- Steel buildings have been constructed using a variety of lateral-load resisting systems. The most frequently used systems, by decreasing numbers of buildings in which they have been implemented, are: buckling restrained brace frames; traditional moment resisting frames (MRFs); MRFs with reduced beam sections; eccentrically braced frames (EBFs) with replaceable links; concentrically braced frames, traditional EBFs, and rocking steel frame systems and MRF friction frames. Most new base isolated buildings are supporting either steel moment resisting frames or concentrically braced frames. When considering only non-base-isolated buildings, buckling restrained braces have been used in buildings adding up to nearly 40% of the total new constructed floor area.
- Of the 74 buildings considered, 9% buildings were hybrid systems, 14% were base isolated and 3% used viscous dampers.

Acknowledgments

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