OPINION PAPER

Building Structural Systems in Christchurch's Post-Earthquake Reconstruction

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After the 2010–2011 Canterbury earthquakes, much of the Christchurch Central Business District was demolished, and a new city is in the process of emerging in its place. A series of interviews conducted with key professionals involved with the reconstruction, together with data collected from various sources (including Christchurch's City Council database), has made it possible to (1) quantify variations in the selection of a structural system as a function of various parameters and (2) identify some of the drivers that have influenced decisions about the selection of structural material and specific structural systems used. Key points on factors that may affect post-earthquake structural engineering practice are drawn from the data collected. As such, the Christchurch rebuilding experience provides insights into some of the mechanisms that can dictate structural engineering decisions during the post-earthquake reconstruction of a modern city. [DOI: 10.1193/052818EQS126O]

INTRODUCTION

In the years following the 2010–2011 Christchurch earthquake sequence, and most significantly the February 22nd 2011 most damaging event (New Zealand Society for Earthquake Engineering (NZSEE) 2011), a substantial percentage of the buildings in Christchurch's Central Business District (CBD) that were damaged by the earthquake have been demolished and for the most part have been replaced or are in the process of being replaced. The space created by the demolition has allowed the reconstruction to start. Although reconstruction is taking place throughout the broader Christchurch metropolitan area, much of the rebuilding with multistory buildings is taking place at the heart of the city (Christchurch City Council 2011). At the time of the study, more than six years after the February 22, 2011 earthquake, the Christchurch reconstruction was far from complete. This rate of recovery is consistent with what is reported in the existing literature on post-earthquake reconstruction around the world, acknowledging the different socioeconomic and political constraints in various locations (e.g., Amaratunga and Haigh 2011, Comerio 2015, Lu and Xu 2015, Platt and So 2017, Tierney and Oliver-Smith 2012). Nevertheless, significant reconstruction has occurred, and it is interesting to take stock of what has been accomplished to date, recognizing that this is an early picture and not necessarily an accurate predictor of future directions.

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The new "heart" of Christchurch is emerging into a city with a variety of structural forms. These include a number of innovative and emerging structural systems that are quite different from what existed prior to the earthquakes. The authors have attempted to (1) describe the background context for the reconstruction, (2) quantify the extent to which each structural system has been used in the new buildings as part of the Christchurch reconstruction effort, (3) understand the structural system decision-making process and how it changed with the earthquakes, (4) document the major factors affecting decisions about the selection of these systems, and (5) describe the implications of the findings. This paper synthesizes findings from a report describing this study (Bruneau and MacRae 2017).

RECONSTRUCTION CONTEXT

In any postdisaster situation, decisions affecting rebuilding activities are made in the context of the local culture/environment and the perceptions and biases of the key actors and stakeholders. Many of these factors have been studied and are further described in the existing literature (e.g., Loosemore 2003, Earthquake Engineering Research Institute (EERI) 1998, Alesch and Petak 1986). It is beyond the scope of this work to investigate all such matters. However, a few must be briefly mentioned, because they are significant in the New Zealand (NZ) context and may have had an impact on the overall decision process in the years following the Christchurch earthquake.

1. Insurance: NZ has a wide insurance penetration/coverage for both commercial and residential structures. Approximately 80% of the losses in the Christchurch earthquake sequence were covered by insurance (Marquis et al. 2017). Such widespread insurance coverage in NZ has made reconstruction possible. According to the NZ Insurance Council (Lucas 2016), the NZ insurance sector is controlled by the global reinsurance market. As NZ is less than 0.1% of that market, it does not influence it significantly. There are therefore no drivers from the NZ insurance market to encourage the use of specific types of construction that would have seismic performance beyond code requirements. Other international drivers control the conditions in NZ. Lucas (2016) indicated that while insurance costs initially went up after the Canterbury events (as was also shown by Marquis et al. 2017), the lack of worldwide disasters over the past few years has led to a surplus of reinsurance funds, and this has resulted in a subsequent insurance cost decrease.
2. Legislative context: In NZ building regulations, all structures are required to comply with the Building Code (NZ Legislation 1992). Section B1, which deals with the building structure, states that there should be a low probability of damage to people and property from damage, or lack of amenity, within the building life. Specific compliance documents (i.e., design standards and some guidance documents) have been approved as acceptable means of satisfying the Code for many conventional structural systems (see MacRae et al. 2011) under the NZ Building Act (New Zealand Legislation 2004). However, there are currently no such documents for many newer structural systems, such as base isolation, buckling restrained braced frames, rocking walls, and other "low-damage" structural systems. The NZ legislative framework is "performance based," allowing new systems to be implemented in actual structures without

large disincentive as long as they meet the intent of the NZ Building Regulations (1992), and the onus is on engineers and peer reviewers to ensure that this is the case.

3. Changes in the market and research: Almost all of the multistory buildings in Christchurch at the time of the earthquakes had been constructed using reinforced concrete construction, following the work of Park, Paulay, and others. Over the years immediately preceding the earthquakes, a significant amount of research was carried out in NZ and overseas on different types of low damage (or resilient construction). Some key research results had been turned into design guidance. In addition, the industry had developed alternative construction technologies to change past practices. For example, the use of traditional detailing for hollowcore floor units, which had been used for flooring systems in many buildings, had been discredited after experiments that showed floor collapse (Structural Engineering Society of NZ et al. 2009) and concrete columns moving apart from each other because of reinforced concrete beam plastic hinge elongations during lateral loading (Matthews 2004, Bull 2004). Also, cold formed steel decking profiles supporting composite floors had been developed. It is worth noting that the last two multistory buildings built before the Canterbury earthquakes used structural steel framing (Clifton et al. 2011).
4. Cost of steel: In mid-2008, the price of steel peaked to a record high value of $1,265 USD/metric-ton and quickly decreased by mid-2009, with prices always less than 50% of the peak 2008 value (Trading Economics 2017).

METHODOLOGY

The work conducted as part of this project was undertaken in the four stages outlined below, as summarized from the report (Bruneau and MacRae 2017) and following the approach of Baxter and Jack (2008).

1. Informal reconnaissance: Informal reconnaissance of the CBD occurred in 2014 and 2015. The variety of new forms being constructed provided the authors with the impetus to document what was occurring and seek financial support for the exercise. A tentative plan was made and discussed with the Quake Centre, who agreed to sponsor this project.
2. Scoping exercise: Exploratory scoping interviews were conducted in early 2016 with leading engineers from ten different engineering firms. Participation in all interviews was on a voluntary basis, and no compensation of any kind was provided for this purpose. Interview goals were to (1) establish with the engineers the best methodology to collect data towards the final project objectives; (2) obtain an initial indication of the likely drivers for the rebuild decisions; (3) determine how engineers could contribute to this project and make it relevant; and (4) consider methods to improve project quality and impact. Engineers made many valuable suggestions that were followed throughout the project because it was intended that the information collected and findings from this study were to be used primarily by engineers and other stakeholders in the construction industry. The engineers that participated all considered face-to-face interviews with designers of the majority of buildings to be the most effective way to obtain good quality information about the drivers for decisions and something both

interesting and usable. They advised against sending out surveys, which were not considered to be effective, and indicated that it would be better to collect data and information through in-person meeting and direct conversations.

3. Data collection: The data were assembled in several ways:

   a. *Building information sidewalk survey and web search*: A survey of individual buildings during construction was conducted by the authors as they walked around the city to obtain this publicly accessible information. Furthermore, Web searches were sometimes conducted, providing additional information on specific buildings.
   b. *Building information database search*: Several different sources were used, including spreadsheet lists from Christchurch City Council and Steel Construction NZ (SCNZ), providing floor areas and other information. In some cases, consultants also provided a sheet highlighting a specific building for publication in the report appendix.
   c. *Interviews*: In early 2017, a second round of in-person interviews was conducted with structural engineers and others, providing detailed information on specific buildings and descriptions of the factors affecting the decision for any particular structural form (i.e., the decision drivers). Generally, the information came from the structural engineering consultant associated with each specific building. To consider a large number of buildings, while keeping the project manageable, interviews were limited to firms that had designed the largest number of buildings under construction or that had been constructed. The ten consultants selected were responsible for over 65% of the new multistory buildings constructed in the Christchurch CBD and Addington areas since 2012. Interviews were also held with a Christchurch architect, project manager, and developer. Follow-up interviews were conducted with engineers in Wellington and Auckland to determine how the Christchurch earthquakes changed practice in those other NZ cities. No interviews were held specifically with tenants who were not in the other categories mentioned above. However, those interviewed gave their opinions as to when tenants desired certain considerations to be met.

4. Data analysis: Data collected during the scoping and data collection exercises were compiled. They were used to generate the information about the types of buildings and the decision drivers given in the following sections. Interviews often provided interesting overarching comments that went beyond what could be captured in a graph or table, so these perspectives and interpretations were collected and summarized.
5. Verification and report style: All interviewees were given a copy of this report prior to publication and asked whether they agreed to be identified or preferred to remain anonymous. None chose anonymity. However, except for the information collected from the sidewalk survey and that readily available on public websites, all findings have been purposely presented in a manner that does not explicitly identify the buildings for which specific decisions were made by those interviewed or their clients. This was done to ensure candid discussions as part of the interviews.

Note that this study did not investigate how the spatial distribution of reconstruction over time aligns with the city plans proposed after the earthquake and the original size of the CBD or other urban planning or social issues. However, readers seeking that kind of information may find the following interesting—an animated map presented by Gates (2015) that tracks from February 2011 to December 2014 all buildings partially or completely demolished, vacant lots, and reconstruction projects underway or completed.

BUILDING FORMS CONSTRUCTED IN CENTRAL CHRISTCHURCH

Findings on materials and types of structural systems used in Christchurch's CBD reconstruction are first presented here, as a function of year of consent (equivalent to the year of building permit in a North American context). For 2017, only the first three months of the year are considered in the collected data, because the last interviews were conducted in March 2017. Overall, data have been obtained for a total of 74 buildings, collectively adding to a total of 482,317 square meters of floor space. While this may seem small compared to the number of demolitions reported in the literature, it is important to recognize that many of the new projects are taking the place of multiple older buildings. For example, Gates (2015) stated that "The new bus exchange, for example, is being built on the site of about 24 demolished buildings, while The Terrace development is being built on the site of 17 demolished buildings."

The dynamics of the construction industry are influenced by a number of trade associations that advocate for the use of specific materials in buildings. It is therefore of interest from the collected data to determine which materials have been used as part of Christchurch's reconstruction effort. First, given that buildings are designed one at a time (i.e., one decision on choice of structural material and lateral load–resisting structural system per building), Figure 1 presents the number of new buildings with steel, concrete, or timber lateral load–resisting structural systems. For those buildings that had different types of structural systems in orthogonal directions, each direction was counted as one-half of a building when tallying the numbers. Note that one building had masonry walls in one direction (counted as 0.5 building), but this small number was lumped together with the concrete walls. Results in Figure 1 show that there was almost an equal number of buildings with steel and concrete lateral load–resisting systems consented (i.e., NZ terminology for "having received a building permit") in each of the years following the earthquake, except for 2016, which saw nine steel buildings versus four reinforced concrete buildings. In total, over the 6-year reconstruction period covered by this study, for the 74 buildings considered, 35.5, 35, and 3.5 had steel, reinforced concrete, and timber lateral load–resisting systems, respectively.

Figure 1a shows the same information in terms of percentages. Totals are not shown, but the 100% breaks down into a sum (for all the years considered) of 48%, 47%, and 5% for steel, concrete, and timber, respectively. Figure 1b shows the cumulative number of buildings with lateral force–resisting systems of each material, progressively populating the parts of Christchurch considered in this study. Again, this shows steel and concrete almost on par in terms of number of buildings.

Data gathered and presented here primarily focus on the type of lateral force–resisting systems. However, it was noted that gravity-resisting frame systems made of steel beams and columns were not only used in structures with steel lateral load–resisting systems but were also used in approximately three-quarters of the buildings with a lateral force–resisting system that consisted of reinforced concrete walls. As a consequence, if expanding the focus

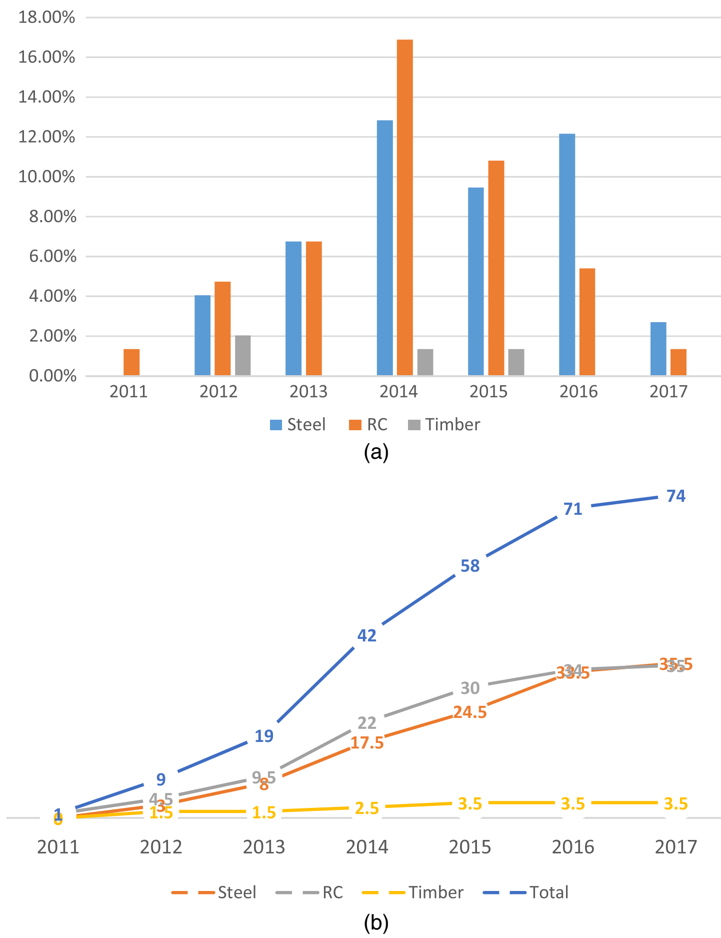


Figure 1. Number of new buildings with lateral load–resisting systems of each material type: (a) percentages; (b) cumulative.

beyond the sole issue of lateral load–resisting systems, it turns out that structural steel was used in approximately 62 (or 88%) of the buildings considered.

While the data in Figure 1 are informative, not all buildings rebuilt in Christchurch are of the same size. Figures 2 and 3 are therefore provided to provide additional needed perspective.

Figure 2 presents the total floor area (in square meters) of new buildings with steel, concrete, or timber, lateral load–resisting structural systems. In essence, for the same 74 buildings used in Figure 1, Figure 2 shows that steel, reinforced concrete, and timber lateral load–resisting systems have been used in buildings respectively totaling 378,000 square meters, 99,000 square meters, and 5,800 square meters, for a total of 483,000 square meters 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 to about 94%.

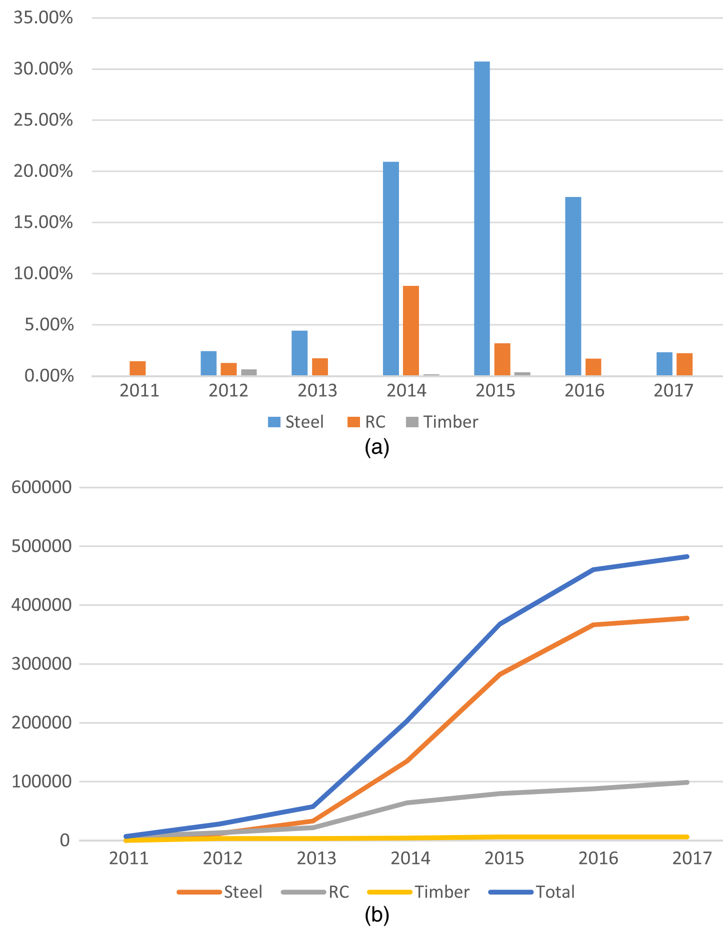


Figure 2. Floor area of new buildings with lateral load–resisting systems of each material type: (a) percentages; (b) cumulative.

"Drilling" through the spreadsheet data indicates that most buildings relying on reinforced concrete walls indeed tended to be smaller buildings and the larger buildings have steel framing systems of one kind or another. This confirms the impression one gets walking the streets of the CBD that Christchurch has "seismically shifted to steel."

Figure 3 presents the percentage of new buildings with steel, concrete, or timber, lateral load–resisting structural systems as a function of building height expressed in the number of stories, for the same 74 buildings considered in Figure 1. This complementary information shows that 80% (12.5 out 16) of the 2-story buildings had reinforced concrete lateral load–resisting systems and the number of such reinforced concrete buildings rapidly decreased with the number of stories. Buildings with steel lateral load–resisting systems became dominant in buildings taller than three stories. Also, 87% of the new multistory buildings in Christchurch to date have ranged from 2 to 5 stories in height.

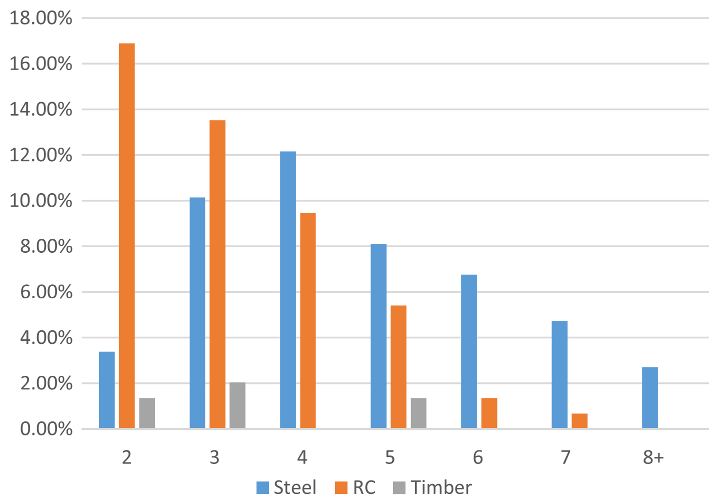


Figure 3. Percentages of new buildings with lateral load–resisting systems of each material type as a function of building height expressed in number of stories.

Further breaking down the data in terms of number of stories (or in terms of story height) for each structural system was not done, because there were insufficient data to draw conclusions in this regard on each structural system, except for buildings with reinforced concrete walls (i.e., in Figure 3, all the reinforced concrete structures are effectively wall structures). However, with respect to steel buildings, to the extent permitted by the limited data, the authors have seen no discernable relationship between the building height and types of steel lateral force–resisting system used. For example, both buckling restrained braces (BRBs) and moment-resisting frames have been used in buildings ranging from two to nine stories. The tallest buildings with eccentrically braced frames (EBFs) had six stories.

Figures 2 and 3 together confirm that buildings relying on reinforced concrete lateral force–resisting systems have typically been smaller that the steel ones.

Beyond material issues, recognizing that structural engineers first and foremost design specific structural systems, it is important to determine how extensively each lateral force–resisting structural system has been used as part of Christchurch's reconstruction. In fact, from the perspective of the authors (who are structural engineers), this was a primary goal of this study. Consistently with the rationale used for Figures 1 and 2, this is investigated in terms of both the number of buildings and floor areas.

The number of new buildings with different types of lateral load–resisting structural systems, systems have been broken down into the following categories: BRBs (11 total); CBF = Concentrically Braced Frames (3 total); EBFs = Eccentrically Braced Frames (2 total); EBR = EBFs with replaceable links (4 total); MRF = Steel Moment-Resisting Frames (9.5 total); MFF = MRFs with friction connections (1 total); MFD = MRFs with Reduced Beam Sections (4.5 total); RCW = reinforced concrete walls (32.5 total); RCF = Reinforced Concrete Moment-Resisting Frames (0.5 total); RFS = Rocking Frame Steel (1.5 total);

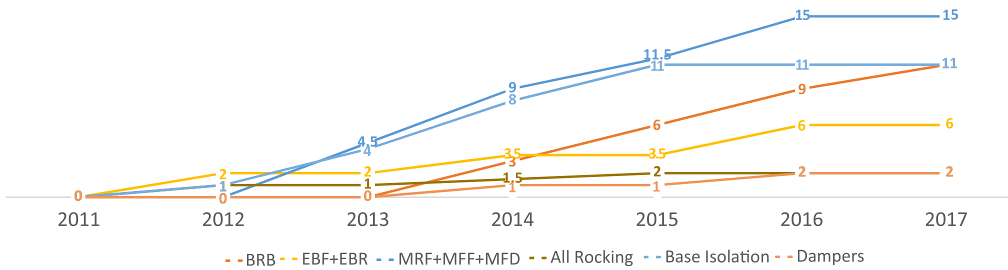


Figure 4. Cumulative number of new buildings with various types of lateral load–resisting systems for a subset of structural systems.

RFC = Rocking Frame Concrete Precast Walls (0.5 total); LVL = Laminated Veneer Lumber (2.5 total); B = Base Isolation (11 total); D = Dampers (2 total); and H = Hybrid (7 total), where hybrid structures are here defined as those that have a combination of different structural systems in a given direction or even different structural systems over their height. Figure 4 shows data on a subset of these structural systems.

Data have been obtained on the same 74 buildings, but, for clarity, the building with masonry walls in one direction (0.5 masonry building) and a building with braced plywood walls (1.0 building) are not added to the figures, reducing the sum to 72.5 buildings. Also, for the results presented, a structural system on top of base isolators is counted twice (once as the structural system type and once as a base isolated structure). Likewise, buildings with MRFs with dampers are counted twice (once for frames and once for dampers), as are hybrid buildings. This explains the higher total of 92.5 buildings obtained (= 72.5 systems + 11 base isolated buildings + 2 dampers + 7 hybrids).

As an outcome of this approach, reinforced concrete walls are found as having the largest number of implementations simply because this category (contrary to the others) has not been broken down into subcategories. Cumulative results are shown for the most popular structural systems grouped together and without the reinforced concrete results to better distinguish the other trends. In other words, in these figures, both types of EBF have been added together, and all three types of steel MRF have been also combined. On that basis, within the steel frame systems, the most commonly used are BRBs (in 11 buildings), steel MRFs (in 15 buildings), and EBF (in 6 buildings).

Figure 4 shows a rapid implementation of base isolation and rocking systems in the early years after the earthquake, with fewer numbers in the past few years. Base isolated buildings were first consented in 2012, rapidly growing and plateauing at a total of 11 by 2015 (i.e., 15% of the 74 buildings considered). BRBs were first consented in 2014 and have since grown in numbers at a steady pace, reaching a total of 11 by 2017.

To better understand the significance of these results in terms of building size (by analogy to Figure 2), information on the same structural systems shown in Figure 4 is presented in Figure 5 in terms of the floor areas (in square meters) of the structural systems.

Results show that the following lateral force–resisting systems have been used for buildings totaling the following floor areas: BRB: 111,000 square meters (23%); CBF: 38,500

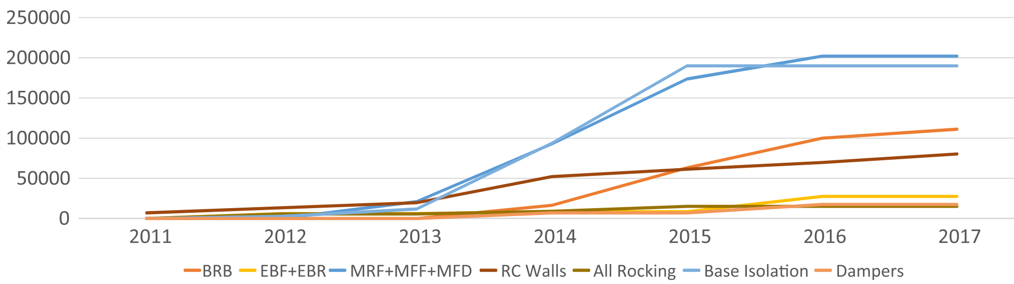


Figure 5. Cumulative floor area of new buildings with various types of lateral load–resisting systems.

square meters (8%); EBF+EBR: 27,500 square meters (6%); MRF+MFF+MDF: 202,000 square meters (43%); RCW: 80,400 square meters (17%); and RFS+RFC: 15,000 square meters (3%).

Interestingly, the 11 base isolated buildings (15% of the total number of buildings) alone provide a total 190,000 square meters, 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 than 102,000 square meters (21% of the total floor area of the buildings considered here). Considering the three largest instead, their floor area adds up to 129,000 square meters (and 27% of the total floor area). Also, there is a strong correlation between floor areas for base isolated buildings and MRFs.

Figures 6 and 7 are similar to Figures 4 and 5, but only consider structures that have not been base isolated. This is worthwhile information because (1) interviews indicated that base isolation was more readily desired by owners in the years immediately following the earthquake than in more recent years, so data on non-isolated buildings could be indicative of trends in a continued reconstruction scenario further away from the initial damaging event, all other things being equal; (2) engineering firms comfortable designing types of structural systems that fall outside of the design standards (such as those specifying base isolation) might have been overrepresented among the ten engineering firms interviewed, which were selected because they were the most active in the Christchurch reconstruction; and (3) for its own sake, it is interesting to identify which structural systems have been more dominantly used when buildings have not been base isolated.

Figures 6 shows the results in terms of number of buildings, and Figure 7 provides the same break-down in terms of floor area. Given that steel structures have been used in base isolated structures in all cases except for one reinforced concrete structure (half walls and half moment frame), a timber one, and one with reinforced concrete walls in one direction and CBF in the other direction, the number of buildings with reinforced concrete walls is not significantly different than before and is therefore not included in Figures 6 and 7. Figure 6 shows that for all steel frame systems, the most commonly used are BRBs (in 11 buildings), MRFs (in 9.5 buildings), and EBF (in 6 buildings). This also indirectly shows that most base isolated buildings had MRFs or CBFs.

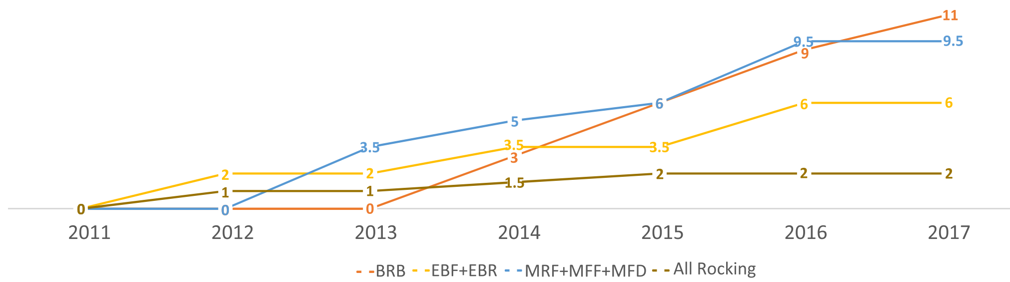


Figure 6. Cumulative number of new non–base isolated buildings with various types of lateral load–resisting systems for a subset of structural systems.

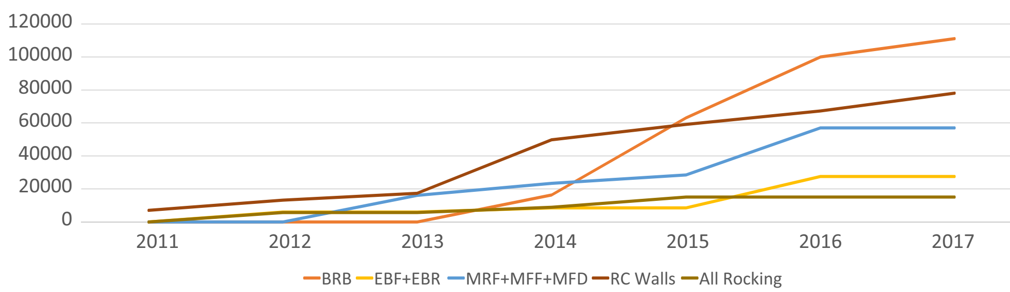


Figure 7. Cumulative floor area of new non–base isolated buildings with various types of lateral load–resisting systems.

Similarly, in terms of floor area, Figure 7 shows that the contribution of lateral force–resisting systems to total non–base isolated reconstruction floor area is BRB: 111,000 square meters (38%); CBF: 0 square meters (0%); EBF+EBR: 27,500 square meters (9.5%); MRF+MFF+MDF: 57,000 square meters (20%); and RCW: 78,000 square meters (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.

DECISION-MAKING PROCESS

CONSTRUCTION INDUSTRY MOMENTUM DISRUPTION FRAMEWORK

Many factors have affected the decision-making process for the selection of structural systems as part of the Christchurch reconstruction. On the basis of discussions with the engineers, it became clear that, after the earthquakes, decisions about structural form were different than before, in part because the earthquakes had disrupted the momentum associated with the construction industry, bringing in a new era. This provides an interpretive framework for post-earthquake decisions that is described below.

It is recognized that over periods of stability, the building construction market develops practices that are driven by the priorities and expectations of its various stakeholders.

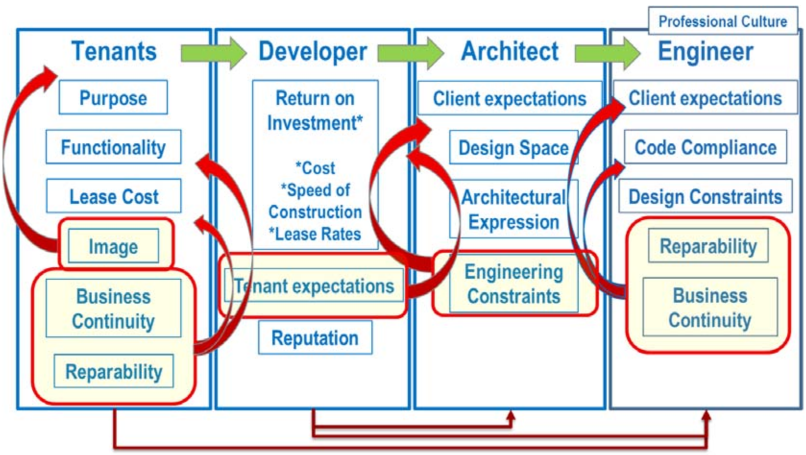


Figure 8. Conventional pre-earthquake revised hierarchy of priorities.

Figure 8 schematically lists the hierarchy of priorities typically followed in the process for each stakeholder, ranked from highest (top) to lowest (bottom) priorities. Note that prior to the earthquake, business continuity and reparability were typically not priorities for the stakeholders (or only low priorities implicitly deemed covered through insurance). Prior to the earthquake, the relationship between tenants, developers, architect, and engineer was typically linear, as represented by the arrows linking these stakeholders at the top of Figure 8. For context, a brief description of these established pre-earthquake relationships (that effectively create the momentum) is first provided.

From the interviews, it became clear that at the root of the process, the type of tenant (secured or speculated) defines the purpose of a building, be it an office, residential, commercial, or medical building (to name a few). The type of tenant then defines many of the functionality needs. For example, office buildings for government agencies and law firms differ in their layout and space requirements, as they serve different clienteles. These priorities then impact lease cost and the image to be projected by the building. For example, a high-profile law firm that targets corporate clients has different expectations than a restaurateur in a highly competitive market. Tenant needs may also directly or indirectly drive choice of structural systems. For example, a trade organization whose purpose is to promote a certain construction material often demands first and foremost a building that showcases its technology, whereas residential construction requires higher levels of sound isolation requirements between units (that some construction material can inherently provide).

The top priority of developers is typically return on investment, as money-losing propositions usually find no takers. This return depends on the cost and speed of construction, as well as lease rates that the market can bear. Many decisions are then driven by tenant expectations, either explicitly when a tenant has been secured prior to development or implicitly for speculative projects targeting a specific type of tenant. Note that here, the term "developer" is used broadly, either referring to developers working on behalf of an owner, developers planning to sell to an owner, or developers who are investors with a long-term perspective.

In most markets, the developer hires an architect whose primary focus is to meet the developer's (client) expectations while satisfying the architectural priorities of organizing the design space to meet functionality, achieving a satisfying architectural expression, and dealing with constraints imposed by engineering and regulatory requirements (bringing a structural engineer into the project team in the process). The structural engineer seeks to meet the architect's (client) expectations (and those of other stakeholders) while achieving code compliance and meeting other design constraints.

Obviously, the process is not as linear as implied by Figure 8, as significant input to the process is also provided by contractors, cost estimators (known as Quantity Surveyors in NZ), and project managers sometimes hired by the developer/clients to represent them in dealing with the architect, engineer, quantity surveyor, contractor, and other professionals. While the construction industry is competitive (with different players looking for new and better ways of getting and delivering work) and there are seasonal and yearly fluctuations in work available, a healthy construction sector also seeks stability and efficiency for repeatable processes and procedures to minimize risk, maximize profit, and avoid insolvency. As such, the industry becomes set up to deliver a familiar "product," with well-understood practices, costs, risks, relationships, procurements, etc., leading to a predictable return on investment (Gottlieb and Haugbølle 2010). It leads to a natural tendency do things as they were done before, and new ideas and procedures generally modify this slowly and incrementally. This tendency creates a substantial and hard-to-reverse "momentum."

The extensive and widespread damage suffered during the Christchurch earthquakes disrupted this momentum. The industry as a whole had to adjust to deliver various new "products," with new practices, costs, risks, relationships, and procurements, leading to a less predictable return on investment. This occurred because of changes in relationships between the stakeholders, and changes in their respective priorities, as described below.

First, the traditional "chain-of-command" was disturbed, as many tenants and owners in urgent need of post-earthquake evaluations and repairs established direct relationships with structural engineers, by-passing the architect (these new relationships are illustrated by the horizontal arrows at the bottom of Figure 8). This is because the engineer, rather than the architect, answered the many questions asked about building performance after the events. Contrary to practice prior to the earthquake, structural and geotechnical engineers are now often brought into the project at the same time as the architect, sometimes sooner. This reversal of roles occurred because the earthquake raised the awareness of the clients to the fact that not all code-compliant structural systems will provide the same level of seismic performance.

Second, all stakeholders reassessed their hierarchy of priorities. Figure 8 highlights new priorities that arose (such as business continuity and reparability) or existing ones that moved up in the list, as schematically indicated by the curved vertical arrows. For example, for the government (as one major tenant category), a top priority became "anchor projects" intended to accelerate recovery and herald the news that Christchurch was re-opening for business. Also, from the tenant's perspective, issues of business continuity and reparability became part of the conversation, whereas they were previously either taken for granted or relied upon through insurance coverage; for some types of tenants where employees cannot temporarily work from home, this became a prime consideration. This brought forth discussions on types of structural systems. There had been heavy media coverage that reinforced concrete buildings had not behaved well, reporting that they had collapsed, suffered severe damage, leaned over, and trapped occupants with stair collapses. This included many buildings that remained standing but were damaged and then later demolished as a result of their deemed "irreparability" due to concerns about the beam plastic hinge residual capacity, movement apart of columns, and integrity of floors (MacRae and Clifton 2013). The many damaged buildings that did not collapse or kill anyone met the life safety performance objective and thus behaved as, or better than, expected under the very severe shaking. However, the lack of easy repair and reoccupation caused significant problems. The fact that the two tallest steel structures in Christchurch were able to be repaired, and that the one outside the cordon (HSBC tower) was the first multistory building to be reoccupied three months after the earthquake, provided an indication that steel structures may be preferable.

For owners/developers, return on investment obviously remained the top priority. However, in light of the disrupted momentum, developers tried to anticipate the post-earthquake expectations of tenants with respect to the seismic performance of buildings and guess the possible impact that this might have on lease rates that could be charged to ensure a return on investment. Those interviewed reported that most projects in the early stages of Christchurch's reconstruction targeted government, banks, lawyers, accountants, and big firms, as these were seen to be sophisticated tenants with high expectations and less sensitive to cost, but as the market progressively shifted from office projects to other clients (including apartment buildings, health care and education facilities, and hotels), developers constantly needed to adjust their understanding of tenant expectations to remain competitive.

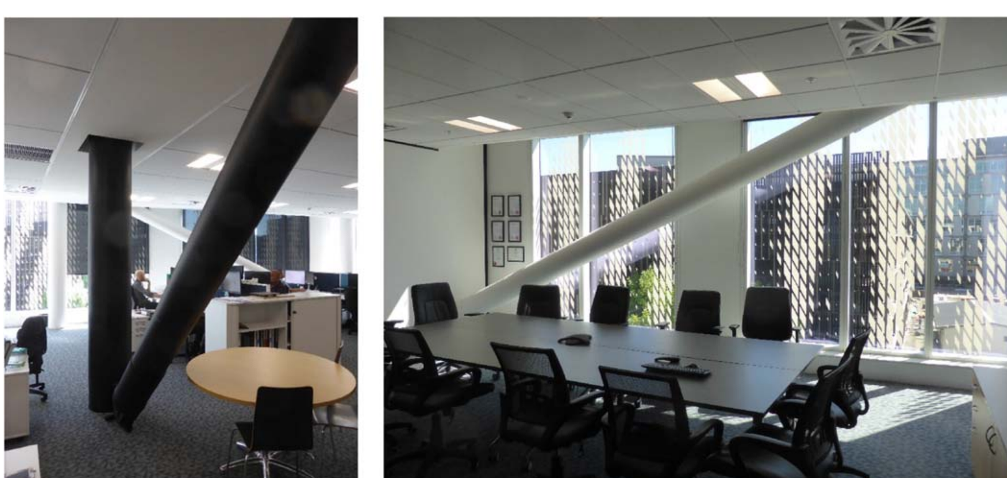
For architects, as a consequence of developers and tenant expectations, engineering constraints became a foremost consideration as part of the reconstruction. However, consistently with Christchurch's architectural tradition, engineering elements (such as BRBs) were integrated and showcased into the architectural expression of many buildings. For engineers, beyond the fact that issues of reparability and business continuity suddenly became important considerations, a major impact of the Christchurch earthquake was that it changed the professional culture and thus a large part of the previous momentum. While professional culture has always driven decisions of engineering firms, the interviews conducted as part of this project revealed the significant role this can play as part of post-earthquake reconstruction. The following section expands on this significance.

STRUCTURAL ENGINEERING CULTURE AND DECISION PROCESSES

Seasoned structural engineers (similarly to other professionals) typically have developed a philosophy of practice from their years of experience. This philosophy of practice is influenced by the type of work conducted for clients, experience and professional opinion on the respective benefits of various structural systems (which depends, to some degree, on opportunities provided by past projects), and business relationships. Some engineers satisfied with past experiences with a particular seismic system may also have a tendency to repeatedly use that system—and likewise work with the same people.

Consciously or not, decisions made are affected by the factors above, as well as multiple other factors that include formal professional development activities, informal individual education by interpretation/synthesis of skills and information from various scientific and non-scientific fields, and professional ethical and moral obligations. The end result, not surprisingly, is that rather than one structural engineering culture, there are in fact many distinctive "cultures" from one engineering firm to the next—cultures that embody the engineering judgment, experience, and philosophy of their founders and/or subsequent leaders. Not surprisingly, these various professional cultures often drive the engineering process towards solutions that may differ from firm to firm.

The resulting breadth of valid engineering solutions as part of the reconstruction (Bruneau and MacRae 2017) can be regarded as the expression of differences in this culture. This, together with different professional opinions regarding (1) the expected seismic performance of various structural systems, (2) a hierarchy of priorities in rebuilding Christchurch, and (3) how these various priorities can be best met for specific buildings, has affected structural engineering decisions made. In other words, while some structural systems have been used more extensively than others during Christchurch's reconstruction, there exists no "one-size-fits-all" solution in structural engineering. This is illustrated when considering the fact that structural engineering firms are also tenants in buildings. Of the ten firms interviewed, three companies either had their office in a base isolated building or were about to move into one; two companies were in a building with BRBs, with the BRBs typically visible from inside their office, as shown in Figure 9; and one was in a building with viscous dampers. Nearly all of them designed the building in which their office was (will be) located. This professional culture evidently transpired in the discussion engineers had with their client, but many firms indicated they had walked their clients through the pros and cons of various options. While this has facilitated the implementation of innovative systems, it has often been stated that more resilient structural systems (rocking frames, base isolation, etc.) generally entail a cost premium and many clients still prefer to rely on insurance to protect their asset rather than



(a) (b)

Figure 9. BRBs prominently featured in an engineering firm's office: (a) inside working space (painted black); (b) along the facade (painted white).

investing more into the structural system. Or, as one engineer said, some owners want low damage, but with established procedures—"leading edge, not bleeding edge."

Note that in some cases, the client has practically been the tenant, as the owner is a contractor/developer tailoring the project to a specific high-profile tenant whose voice is important. Since the Christchurch earthquakes, from which many "campfire stories" resulted regarding the behavior of structures, some of these tenants have gone as far as wanting to know the engineer for the project. Some have even been wanting to meet the engineer to have their specific questions answered directly. One engineer reported having made presentations to as much as five tenant groups in recent years. Knowledge that direct tenant interaction may occur affects the engineer's decision-making process, as they have to defend their decisions to the end users.

However, a number of engineering firms have stated that client awareness is slowly fading as the years push the earthquakes, as well as the 2013 Seddon and 2016 Kaikoura earthquakes (NZSEE 2016), further in the historical past. Some clients have reverted to the pre-earthquake practice of bringing the engineer into the project late—particularly for projects involving foreign developers.

STRUCTURAL SYSTEM DECISION DRIVERS

PERCEPTIONS: REINFORCED CONCRETE VERSUS STEEL BUILDINGS

For reasons mentioned previously, engineers indicated that many of their clients have the perception that reinforced concrete buildings have not performed well during the earthquake. This reflects the general view of many people in Christchurch, even though most of the damaged reinforced concrete buildings were 1980s vintage moment-resisting frames. Coupled with the heavily promoted fact that the two tallest steel structures in Christchurch (the Club Tower and Pacific Tower buildings) exhibited satisfactory seismic performance and were reopened relatively fast (Clifton et al. 2011), the perception of many tenants and owners following the Christchurch earthquake has been that steel structures are preferable. The safe solution for engineers was therefore to move to structural steel, which also has the advantage of being lighter (also leading to lesser seismic forces and less weight on the foundation) and a fast construction speed.

This perception has been a major driver as part of the Christchurch reconstruction. As a momentum shift, the Christchurch earthquake gave the engineering community an opportunity to "brush-up" and "get-up to speed" on steel design, to the point that while reinforced concrete was the default option before the Christchurch earthquake, there is nowadays "no objection" or "no resistance" to using steel. In other words, to paraphrase one engineer, the industry in Christchurch is now "geared" to do steel on a large scale.

However, there have been significant issues with the quality of steel imported from certain parts of Asia (e.g., Tovey 2015). As a result, some engineers and contractors have been proactive to independently control the quality of steel imported from countries where mills have mixed reputations to address these issues (e.g., SCNZ 2016).

It is interesting to note that the global market price of structural steel, with price fluctuations from 2011 to 2017, does not seem to have had an impact on the Christchurch reconstruction, as none of the engineers interviewed mentioned that changes in the price of steel since 2011 have an impact on their decisions.

BUILDING COST-VALUE CONSIDERATIONS

A few engineering firms highlighted the fact that the early reconstruction market consisted predominantly of office buildings for "premium" tenants that typically sign long-term (10+ year) leases. These include government departments or large law firms that compete to attract the best employees. These tenants are prepared to pay a higher cost for a better building, and one of the factors that can influence this is better perceived seismic resilience (Bruneau et al. 2003). In contrast, for multistory residential buildings with developers planning to sell at project completion (or soon thereafter), engineers reported it difficult to convey the benefit of higher cost buildings designed above minimum code level.

In a number of projects, while minimum construction cost might not have initially been a factor, it became a driving factor as the project unfolded. Specific to the Christchurch context, it was mentioned that some owners received limited insurance payments and had to reconstruct within a tight budget. Another engineer stated that a lot of projects in Christchurch have stalled, or not started, because developers cannot make the expected return on investment work.

Some firms indicated that while the Christchurch earthquake had a significant impact in raising the developers' awareness of the earthquake risk, this awareness is fading and that practice is returning to its pre-earthquake ways, with the minimum cost being the major driver in most instances, the exception being critical infrastructure projects in which the protection of both buildings and content is paramount.

LOW DAMAGE/REPARABLE BUILDING CONSIDERATIONS

A number of clients, without asking for any specific type of structural system, requested an IL3, IL4, low-damage building, or reparable structural system, where IL3 and IL4 refer to Importance Level 3 and Importance Level 4 in New Zealand design codes. IL3 and IL4 buildings are moderate importance and high importance buildings, respectively, designed for higher levels of seismic force than normal commercial (IL2, for Importance Level 2) structures. The term "low damage" is understood by some clients to be equivalent to some sort of "extra protection" against future earthquakes but seems to be loosely defined, sometimes considering nonstructural elements and other times not. This typically prompts the engineer to ask clients to better define their expectations when asking for low damage and allows engineers to describe the respective pros and cons of various types of structural systems.

In some instances, the motivation for developers to seek IL3 buildings has been to attract a tenant. Examples of this marketing practice can be seen on some "For Lease" signs in Christchurch advertising "'A' Grade Seismic Systems" on a list of desirable features to attract tenants. Owners typically asking for an IL3 structure, which is designed for 130% of the lateral force value required for normal buildings, generally plan to own their property for a long time. However, they do not necessarily wish for an IL4 building designed for 180% of the normal building lateral force value.

In some projects, IL3 or IL4 seismic performance was achieved using base isolation, rocking frames, MFFs or viscous dampers, and other innovative systems. Broader implementations have typically been impeded by costs. For example, one engineer volunteered that, although he preferred viscous dampers to braces, "adding a $30k damper in a structure is a 'hard-sell' when a comparable brace is $4k." Others are owners who originally considered base isolation but backed away from that decision to other systems when cost estimates exceeded the desired "price-point."

More commonly, Buckling Restrained Braced Frames, EBFs, or reinforced concrete walls were used to control drift limits and rely on the fact that such structures can be rapidly returned to service. Some of these issues are explored in the sections below.

In addition to low-damage issues, which were discussed, it is interesting that a number of things were not discussed. For example, most engineers did not talk explicitly about nonstructural element design considerations, even though there was a lot of costly damage both in the major shakes and strong aftershocks and as part of the inspection of hidden structural elements. It seems that the engineers did not consider nonstructural elements to be their responsibility. One reason for this may be that many nonstructural elements are part of post-construction tenant fit-out. However, there was one case in which inspection windows were placed in the nonstructural interior plasterboard beside the structural joints, so that inspection may be conducted without incurring plasterboard damage. There was also little explicit discussion about rapid return to service as a result of damage, residual capacity, or building system reparability. However, such overall building performance considerations were implicitly mentioned in the desire for stiff/strong buildings and the loose term "low damage," which can be applied to the building as a whole or its components. A low-damage structure should have low damage, rapid return to service, and high residual capacity and require little/no repairs.

BASE ISOLATED BUILDINGS

NZ engineers have been pioneers in the development of base isolation technologies, and a number of buildings throughout the country have been base isolated. The NZ public is somewhat familiar with the concept because of news reports and a visitor gallery showcasing the isolators at Wellington's base isolated Te Papa Museum of NZ. Whereas clients typically did not express any preference for specific structural systems when approaching engineers, base isolation is the exception to that rule. Some projects in the Christchurch reconstruction required base isolation at the initial request of the client. Some of these projects developed as intended; others switched to a different structural system as part of the development and cost-assessment process.

Some projects as part of the Christchurch reconstruction effort have heavily promoted the fact that their building was base isolated. For example, the Christchurch Justice and Emergency Services Precinct, which is a major public "anchor project" intended to revitalize the city, has both a dedicated webpage (NZ Government 2017) and Facebook page (Christchurch Justice and Emergency Services Precinct 2017) to inform "people interested in the construction and development" of the project.

One engineering firm underscored that, in some cases, owners insisted on having a base isolated building even when the building was not well suited for base isolation or provided no benefits over other structural systems. To the contrary, in another case, the owner specifically did not want base isolation because he had been advised by a professor that it was a bad idea to use base isolation in Christchurch.

In spite of the strong desire of some owners for base isolation, in many instances, clients objected to it on the basis that the resulting design reduced the amount of leasable floor space within a fixed lot boundary. Examples were also provided of cases in which the owner initially wanted a base isolated building but decided otherwise when project costs were considered.

Interestingly, while some engineering firms were active promotors of base isolation, others had significant reservations. While all understood the principles and potential benefits of base isolation, there was not unanimity among the engineering firms that base isolation was an appropriate structural system for application in Christchurch, which had been subject to near-fault shaking and where there are many soft-soil sites. A number of engineering firms mentioned that designing base isolation can be "off-putting" because there is no design standard for that structural system in NZ. Therefore, base isolated projects must be peer-reviewed, which can create challenges and delays, particularly when the respective advocates of lead rubber bearing isolators and sliding friction bearings are at odds in their recommendations. An engineer mentioned that comments from peer reviewers with affiliations to competing bearing systems have bordered on unethical and have delayed projects. This, from a distance, would seem detrimental to the base isolation industry as a whole.

Beyond the above concerns, on a project-by-project basis, when the base isolation option was declined by the client, it was either due to cost or a desire to maximize use of the site. One engineer underscored that while the cost premium for a base isolated building could be 5%–7% of the total cost for a large building like a hospital, it is actually a much higher percentage for an office building, because the base cost of an office building is significantly less than the base cost of a hospital. He also suggested that some private sector clients are more cost-conscious and less likely to favor a base isolation solution.

Engineering firms also expressed different preferences when it came to the type of base isolators used (i.e., lead rubber bearing versus friction isolators). Some emphasized that "not all bearings are similar," as some will induce greater accelerations than others. Some expressed concerns about the reliability of the performance of specific devices, the fact that some are tuned to a particular earthquake level, or the behavior of the isolated structure under vertical ground accelerations. This related to the device initial strength, durability, and behavior under cyclic loading. Sometimes these concerns came from the peer reviewer. However, in some projects, a specific type of bearing was used only because competitors arrived to the Christchurch market too late, or because some concerns remained unanswered with respect to the competing isolation systems at the time of implementation.

BUCKLING RESTRAINED BRACED FRAMES

As indicated by the data presented above, a proportionally large number of buildings have been designed with BRBs as part of the Christchurch reconstruction activities.

An engineer even ventured that most of the new office buildings still on the drawing board in Christchurch were being designed with BRBs. Most of the engineers interviewed have used BRBs in at least one project and were positive in their assessments. Many reasons were provided to explain the emerging popularity of BRBs in Christchurch. First, there has been substantial promotion from BRB manufacturers following the Christchurch earthquake. This was certainly an opportune enterprise at a time when engineers were looking for alternative "low damage" designs (particularly by limiting drifts) and solutions that would allow rapid return to service (by being rapid to repair) while being at lower cost than base isolation. Some firms expressed being more convinced of the ability to achieve those goals when using steel frames with BRB rather than more conventional EBF. Second, engineers who favored BRB frames indicated using them because they are stiffer than EBF, and their strengths can be specifically defined to be close to the design force demands over the building height, thus limiting system overstrength and making it cost-effective to limit drifts to low values (targets of 1% to 1.5% drift were frequently specified on some projects). Third, although engineers stated that BRBs are more expensive than a regular brace, they emphasized the benefit that their fabrication is quick and they are considered to be a well-tested and robust system. Fourth, many engineers stated that architects in Christchurch desire modern architecture and have showcased BRBs in many projects, considering the system to be suitable for the architectural requirements of a modern office space, calling for lots of glass facades. In some projects, the architect selected BRBs over EBF purely for aesthetic reasons. One engineer went as far as saying, "BRB is the vernacular of Christchurch." However, others were aware of current discussions/concerns in the profession about BRB performance seen in some experimental tests (e.g., Sitler et al. 2017) and issues in design procedures for the BRB system, such as those described by MacRae and Clifton (2015), as well as the lack of an NZ industry design guide to deal with these issues.

EBFS

EBFs have been used in a number of reconstruction projects. In some cases, "conventional EBFs" were used, detailed as in decades prior. In other cases, EBFs with especially detailed replaceable links were used.

Some engineering firms stated that they considered EBFs to be the most cost-effective structural system to use. One engineer from that firm mentioned telling his clients that EBFs are what should be used nowadays (i.e., post-Christchurch) when cost effectiveness is the driver. Another firm indicated that they used EBFs or CBFs on projects before they became familiar with BRBs.

Opinions were almost evenly split as to whether EBRs are better than conventional ones. Some firms expressed a strong preference to using bolted replaceable links and appreciated that doing so also facilitated the design of EBFs by decoupling the size of the link from that of the link-beam. Other firms held that replacing the link in a conventional EBF is not necessarily more difficult and is relatively easy, given that yielded steel links can be cut and replaced by new segments welded in place, as performed in a number of post-Christchurch repairs.

MOMENT-RESISTING FRAMES

Steel moment-resisting frames are more expensive, since they are not as light as braced frames. However, even in the post-Christchurch context, some clients insisted on having open facades and more flexibility internally (i.e., without braces in one or more directions), even though they understand that using braced frames would be more economical. Other than when built as base isolated frames, in three instances it was mentioned that MRFs were used because the building was triangular. To ensure reliable energy dissipation, either friction connections or reduced beam sections were provided.

REINFORCED CONCRETE WALLS

It was mentioned multiple times as part of the interviews that prior to the Christchurch earthquake, many buildings had reinforced concrete frame structural systems, both for gravity and lateral force resistance. These were only used on one base isolated building in the rebuild (in a case where more mass was needed). None of the engineers indicated a desire to design such systems in the future. However, many engineers commented that reinforced concrete wall buildings can provide excellent seismic performance in many instances. They are designing such buildings, often with steel gravity systems with rolled-shape columns and composite decks (i.e., concrete poured on top of a corrugated steel decking sheet) connected to steel beams. In particular, in many instances, large concrete walls, which have a 3-hour fire rating, are used to provide the required fire protection between buildings sharing a property boundary line. In such instances, these walls are used for lateral force resistance in that direction. Sometimes they are used with steel moment frames parallel to the street front. Given the typical length of the property line and relatively low building heights in Christchurch, these walls tended to be designed to remain elastic or have very low ductility demands.

With respect to type of implementation, a large number of engineering firms suggested that, unless dictated otherwise by special requirements, it is possible that future multistory residential construction in Christchurch will likely be of concrete walls with steel gravity frames, because once the walls are up, one automatically gets fireproofing and sound transmission class rating (i.e., acoustic isolation), and, in some cases, dividing walls between apartments. Achieving equivalent acoustics ratings with cold formed steel and drywalls was said to require a double system with an airgap. However, as pointed out by one engineer, fireproofing has become more economical in recent years, so things could change.

TRENDS IN STRUCTURAL SYSTEM DECISION DRIVERS

In the interviews, engineers were asked to identify which of 14 different factors drove decisions on the choice of structural systems for each of their reconstruction projects. By grouping together all the factors that relate to cost (such as construction time and lowest cost), client requests (base isolation, IL4, IL3, low damage, no damage, or no concrete), and constraints (site layout and soil conditions), Figure 10 below can be constructed. Note that on that figure, decisions driven by the engineer's choice of structural system and decisions made by the architect wanting to showcase the structure remained individual categories on their own, as in the original interviews. What is observed in Figure 10 is that from 2012 to 2017, the yearly percentages of buildings for which structural engineers considered themselves to be the driving factor for the choice of structural system

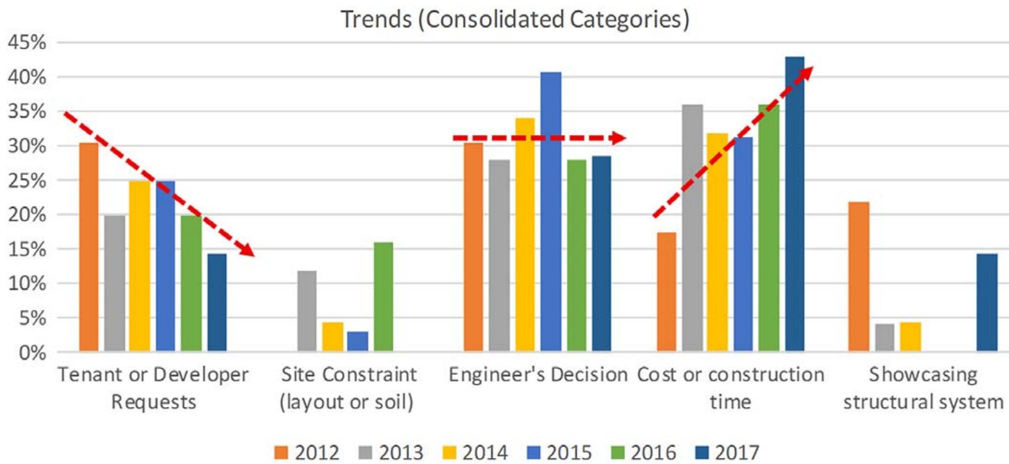


Figure 10. Factors driving decisions on choice of structural system over time.

remained the same, whereas tenant or developer requests decreased over time, while cost considerations progressively became more significant (and, in fact, returned to be the most dominant factor in recent years). The impact of cost on such decisions is further discussed in the next section.

INFERRED BENEFITS OF FINDINGS

The work conducted in this study and presented here provides broad perspectives from the points of view of those interviewed. First and foremost, the results summarized here are expected to provide valuable insights to those who can identify themselves as likely to play a similar role after future earthquakes elsewhere, particularly when it comes to the selection of structural systems. To that end, it provides a reference documenting the use of a wide variety of structural systems implemented over a few short years in a well-defined downtown area being reconstructed post-earthquake, capturing what has already been done and some of the factors and considerations that have driven that process. Other engineers may gauge how this information may impact their decisions after future similarly damaging earthquakes elsewhere.

The information presented may also be useful to other stakeholders. In particular, it provides decision makers in other cities and countries one example of how the construction sector responded with post-earthquake reconstruction in a developed country that has state-of-art design codes and specifications, how a particular scenario unfolded given the background context (which includes the legal system, relative costs, insurance, lessons from previous earthquakes, marketing, research progress, industry culture/momentum, etc.), damage incurred, and decision drivers that are unique to this city.

As a result, the work may facilitate a change towards better performing structures in other regions before a significant earthquake occurs there. It was made clear during this work that all reconstruction work is done on a building-by-building basis, meeting the needs of different clients with different values and priorities. Out of that process, some buildings will be more resilient than others. Therefore, in light of this uncoordinated process, if there is a desire to achieve regional resilience (rather than some resilience for individual structures), government regulations would be required for this purpose. In this study, this transpires when taking stock of the number of diverging drivers/incentives observed for the relatively small range of building owners. In other words, in any given region, a few major structures designed to code minimums may detrimentally affect access to many parts of an otherwise "low-damage" city and impede recovery/resilience.

CONCLUSIONS

A study was carried out to determine the structural forms used in the new buildings constructed as part of the Christchurch rebuild after the 2010–2011 Canterbury earthquakes, understand the process of decision making for structural form in the construction industry, and quantify the decision drivers for different structural forms. This was done mainly using information from databases and via interviews with involved engineers and other stakeholders in their workplaces, as it was suggested by the structural engineering practitioners in Christchurch to be the best approach to collect this information. It was found that:

1. Prior to the earthquakes, NZ law permitted the use of new structural systems, a number of novel structural systems and new inexpensive construction techniques had been developed, and the price of structural steel had dropped considerably from its 2008 high.
2. For the 74 multistory buildings constructed in central Christchurch since 2011 and considered in this study, the number of buildings with steel, concrete, and timber lateral force–resisting systems have been in the ratio of approximately 10:10:1, while the respective floor area ratio was 79:20:1. Furthermore, most concrete buildings had structural steel gravity frames. Concrete structures in the rebuild were nearly all structural wall systems. Steel buildings have been constructed using a variety of lateral load–resisting systems, some of them novel. Most new base isolated buildings used either MRFs or CBFs. When considering only non–base isolated buildings, BRBs have been used in buildings, adding up to nearly 40% of the total new constructed floor area.
3. From interviews with the ten firms having designed the largest number of new buildings as part of the Christchurch reconstruction, tenant expectations were shown to strongly impact the choice of structural systems for individual buildings either directly or indirectly. Tenant expectations led developers to construct buildings to meet their post-earthquake expectations, with input from architects and engineers. The stakeholder industry practices which had evolved over many years prior to the earthquakes had a momentum and tended to ensure predictable return on investment and profitability for all involved by maintaining similar practices over time. This momentum/culture of building design/delivery was significantly disrupted by the earthquakes. New practices had to emerge in response to this disruption. While these increased uncertainty and risk, many used these opportunities to construct building systems that were not common in the past, including new/novel solutions.
4. Decisions about structural form were influenced by many factors, including public perceptions, economy, ease of design, and architectural issues. The most

important ones can be summarized as follows: (a) There were widespread perceptions among the Christchurch public (which constitute many of the future building occupants/tenants) that reinforced concrete buildings suffer damage that is hard to repair, in contrast to steel structures that could behave well and be reparable if repair was needed. The stakeholders responded accordingly, and got "up to speed" on steel design and construction, developing both expertise and appreciation in the process. (b) There was a widely held post-earthquake sentiment that the performance objective of simply designing and constructing structures to prevent loss-of-life is not sufficient anymore for a good modern structure. The industry (without governmental intervention) therefore generally moved away from traditional code-compliant systems with high expected ductility demand and displacement/drift, which can significantly damage the frames, floor system, and nonstructural elements. This is because many of these structures were difficult to inspect, repair, and reinstate, leading many to be demolished. There was therefore a major move towards structural systems for which lower damage and higher seismic performance is anticipated compared to those used in the past. Some of this was achieved at a cost premium using novel low-damage systems, while other ways mentioned to control building damage simply involved using some of the traditional systems while limiting drift and ductility demands. It was noted that with the passage of time, fewer owners/developers are requesting or being prepared to pay for the novel low-damage systems. (c) Even when considering resilient/low-damage construction, return on investment was indicated to be a most important consideration for structural system selection by owners. (d) In a large number of cases, advice from the structural engineer (with their own experiences, industrial relationships, and biases) generally drove the selection of the structural system, generally reacting to the developers' more general requirements for performance and cost.

5. While specific selections of structural system were made in Christchurch, the same systems are not likely to be used in the same way in other parts of the world simply because the context is likely to be different. However, many aspects of the decision-making process are likely to be similar. Likewise, the longer term Christchurch tendency of moving towards the traditional economical construction forms that have more resilient characteristics than others provides a pathway for immediate implementation in other locations. However, if the goal is to achieve global regional resilience, rather than some resilience for individual structures, regional coordination is required because of the broadly diverging drivers/incentives for the range of building owners in a given region.

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