Review of recently constructed buildings that combine steel frames and concrete walls

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ABSTRACT

Recent building construction in New Zealand has exhibited an increase in the use of structural steel due to its availability and perception of good seismic performance. Despite the renewed popularity of structural steel framing, concrete walls remain a common choice of lateral force resisting system, leading to a trend of 'hybrid' buildings that combine steel frames and concrete walls. This study aims to understand and characterise this building type, focusing on buildings constructed in Auckland and Christchurch from 2014 onwards. Through sidewalk surveys and desktop research, an initial list of buildings of interest was developed, and structural drawings were obtained from council property files or from structural engineers. The drawings were examined and relevant typological information identified, including building use, importance level, ductility, building height, wall configuration, wall construction method, steel framing system, connection details, and suspended floor system. Buildings were classified according to their lateral load-resisting system in two directions, resulting in the categorisation of five distinct building types that represent these new 'hybrid' buildings. Further investigation of the building types and connection detailing will identify critical aspects of this hybrid system that need verification by testing and modelling.

1 INTRODUCTION

Structural steel has become a popular choice of construction material due to its availability and perception of good seismic performance, as well as its good weight-to-strength ratio that makes it suitable for certain soil conditions. Despite the increase in structural steel use, concrete walls remain a common choice of lateral load resisting system. The stiffness of concrete walls provides excellent drift control and protection against storey-sway mechanisms. Moreover, concrete walls have the added advantage of built-in fire rating and insulation, and readily serve functional use for stairs, lifts, and property boundaries. When combined, steel frames and concrete walls allow for reduced member sizes, resulting in larger floor areas and economical building solutions (Garcia et al. 2010). As such, there has been a growing trend of 'hybrid structures' in New Zealand, where steel frames and concrete walls are combined.

A study conducted in Christchurch by Bruneau and MacRae (2017) showed that almost half of the buildings constructed post-2010/11 Canterbury earthquakes used concrete walls as the primary lateral load resisting system, 75% of which were combined with steel frames. In Auckland, similar trends are apparent, as a significant number of new buildings use precast concrete walls with steel gravity beams and frames. Despite the number of such hybrid buildings constructed in New Zealand in the recent years, the structural performance of this building type has not been fully investigated. Current structural standards are compartmentalised into materials and do not explicitly address the design of buildings with mixed-material structural system (NZS 3404:1997; NZS 3101:2006). Existing research on steel frame-concrete wall buildings in other high-seismicity areas focus on high-rise or super high-rise buildings, whereas New Zealand does not have many high-rise buildings (Aimin & Deyuan 2005; Hou et al. 2006; Li et al. 2011). The widespread use of precast floors in New Zealand poses even more questions regarding the seismic performance of diaphragms in such hybrid structures. There is also little research on steel frame-concrete wall connections, and existing tests focused on in-plane connections (Hawkins et al. 1980; Roeder & Hawkins 1981; Shahrooz, Tunc et al. 2004; Shahrooz, Deason et al. 2004; Tunc et al. 2000).

It is therefore important to investigate how this emerging form of hybrid building in New Zealand will perform. To understand the current state of practice, a review of recently constructed buildings in New Zealand combining structural steel frames and concrete walls was conducted, and typologies were developed to categorise the structural systems used.

2 SURVEY OF STEEL FRAME-CONCRETE WALL BUILDINGS IN CHRISTCHURCH AND AUCKLAND

A review of structural features of recently constructed buildings in Auckland and Christchurch was undertaken to identify the common typologies of steel frame-concrete wall buildings in New Zealand. An initial list of buildings was developed through desktop research, sidewalk surveys, and discussions with engineers. Structural drawings were obtained from structural engineers and council property files. The following criteria was used to select buildings for the database:

- The building was constructed in or after 2014.
- The building is located in Christchurch or Auckland.
- Structural concrete walls are part of the lateral load resisting system.
- Structural steel frames or beams are part of either lateral or gravity load resisting systems.

Drawings were examined and significant structural features were identified. Data was aggregated by city to determine if there were regional differences in steel frame-concrete wall building trends between Christchurch and Auckland.

Overall, 38 sets of building drawings were included in the study, 28 in Christchurch and 10 in Auckland. There are other Auckland buildings known to fit the selection criteria but researchers are yet to obtain structural drawings for these buildings, therefore they are not included in the preliminary database. The buildings were designed by 14 different structural engineering firms, indicating that combining steel frames with concrete walls is indeed becoming a trend, rather than just a practice limited to a few engineering firms.

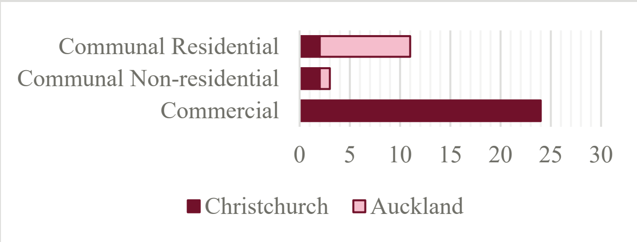

Figure 1: Building use by city

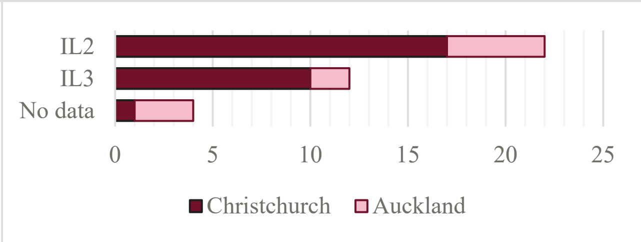

Figure 2: Importance level by city

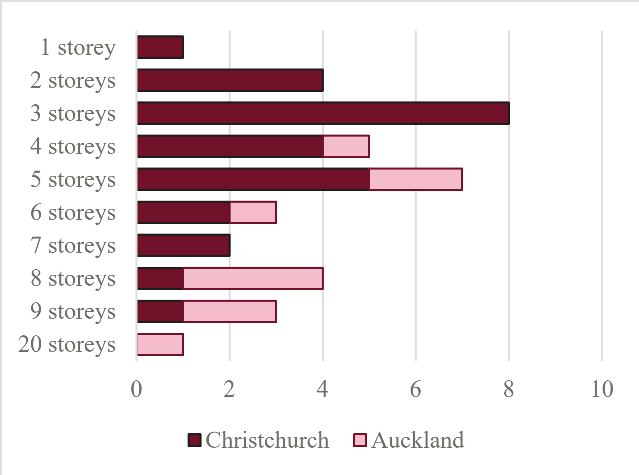

Figure 3: Building height (number of stories) by city

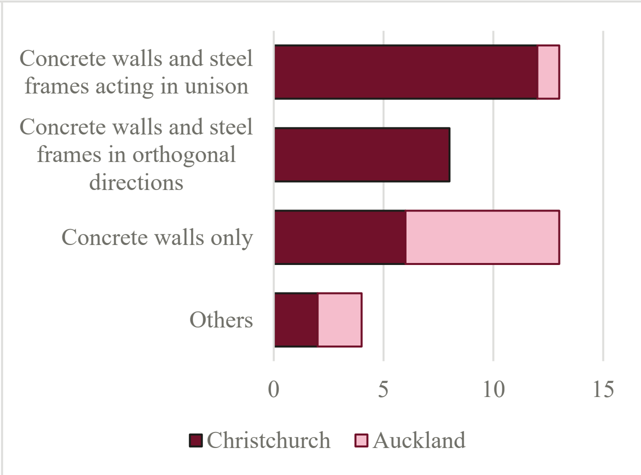

Figure 4: Lateral load resisting system by city

2.1 Building use

The building use for the surveyed buildings is summarised in Figure 1. The Auckland buildings were mostly comprised of communal residential use (e.g. apartments, retirement homes), whereas the Christchurch buildings were mostly commercial use (e.g. offices, retail). A few buildings also served communal non-residential use (e.g. schools, universities). This is likely not just the case for steel frame-concrete wall buildings, but rather the general trend in building construction in the respective cities.

2.2 Building height

Figure 3 shows that surveyed buildings were typically mid-rise, with more than half having three to five storeys. It is also notable that Auckland buildings tend to be taller than Christchurch buildings, although this may simply be a result of general construction trends in the respective cities.

2.3 Importance level

As summarised in Figure 2, the surveyed buildings were approximately two-thirds IL2 and one-third IL3.

2.4 Lateral load resisting system

Based on Figure 4, many of the surveyed buildings in Christchurch were designed as "dual systems", where frames and walls act together to resist lateral loads in one or two directions. In other cases, steel frames and concrete walls worked in orthogonal directions. There were also cases where the steel frames were only designed for gravity, and the concrete walls resisted all the lateral loads. In many Auckland buildings, concrete walls also act as columns, while steel beams served to carry gravity loads only. This appears to be a trend for apartment buildings, as concrete walls are effective for separating and insulating apartment units, whereas office and retail buildings require open spaces. It is also possible that soil conditions in Auckland allow for heavier structures and therefore more concrete walls.

There are a few instances where the lateral load resisting system was more complex, varying in different areas and / or different storeys of the building. For example, one building in Christchurch combined concrete walls and concentrically braced frames (CBFs) acting orthogonally in the first storey, and eccentrically braced frames (EBFs) and moment-resisting frames (MRFs) acting orthogonally in upper storeys. Such complex buildings were lumped together in the "Other" category.

2.5 Ductility

In Christchurch, 50% of the surveyed buildings were designed as limited ductile (μ = 2.0 to 3.0), while 20% were nominally ductile. In some cases where steel frames and concrete walls act as lateral load resisting systems in orthogonal directions, the walls were designed as nominally ductile (μ = 1.25) and frames were designed as limited ductile. In many instances, the reinforcement of concrete walls are detailed for higher ductility (up to μ = 6.0). In Auckland, nominally ductile buildings are dominant.

2.6 Steel framing system

Figure 5 shows that EBFs and MRFs were the common choice of frames in Christchurch, with a few CBFs as well. Even though buckling-restrained brace (BRB) frames are the most popular type of steel frames in recent Christchurch buildings (Bruneau & MacRae 2017), they were not commonly used in combination with concrete walls. Nevertheless, two instances of BRB frames used with concrete walls were observed in this survey. In one case, BRB frames resisted 100% of the base shear and the pinned base concrete walls merely served to protect against storey-sway mechanism. In the other case, BRB frames were used with "rocking" walls that act in orthogonal directions. In Auckland, on the other hand, steel gravity beams used together with gravity load-bearing concrete walls were dominant.

2.7 Wall construction, configuration, and design

In both cities, precast walls were most common, with only a few instances of in-situ construction, as shown in Figure 6. Some buildings were also found to use both precast and in-situ. One building in particular had thick in-situ walls in lower storeys and thinner precast walls in upper storeys. Wall configurations were a mix of core walls, internal walls, perimeter walls, and combinations thereof. Most buildings use cantilevered reinforced concrete (RC) walls. Exceptions include one building that had coupled RC walls with steel beam couplers, two buildings with "rocking" walls, and one building with pinned-base RC walls.

2.8 Suspended floor system

Rib & timber and composite steel tray (e.g. ComFlor) were the most common suspended floor systems in Christchurch buildings, as shown in Figure 7. Rib & timber was also common in Auckland, as well as double tees. Few instances of hollow-core floors and flat slabs were also found. Such variation may indicate that suspended floor systems do not influence the decision to use steel frames with concrete walls.

Figure 5: Steel framing system by city

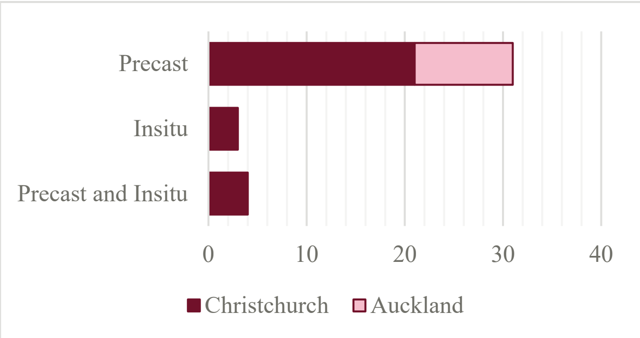

Figure 6: Wall construction method by city

2.9 Connections

2.9.1 Floor to beam connections

Because rib & timber and composite steel trays were the common floor systems, shear studs were most widely used in floor to beam connections. A few rib & timber floors were found to have bent starter bars welded towards the beam flanges, and others had the steel beams embedded in the concrete topping with floor reinforcements passing through drilled holes in the beam.

Figure 7: Suspended floor system by city

2.9.2 Floor to wall connections

Floor to wall connections comprise two parts: (1) a seating angle that supports the precast floor, and (2) floor starters for the concrete topping. As shown in Figure 8, seating angles were typically attached to the wall using post-installed anchors. For floor starters, bent starter bars were dominant. A few other buildings used threaded inserts to connect the concrete topping to the walls.

2.9.3 Beam to wall connections

In many instances, steel beams were connected orthogonally to the wall plane. In such cases, cast-in plates were typically attached to walls using headed studs or anchor bars. Steel beams were bolted to flat plates or cleats (also called "shear tab"), which were welded onto the cast-in plates, as shown in Figure 9. In a few cases, moment-resisting connections had steel beams directly welded onto endplates attached to the wall with post-installed anchors. On the other hand, beams connected to the wall along the wall plane were less common. In one case, a set of coupled walls were connected by steel coupling beam embedded into the walls. Another building used cast-in plates that were deeply embedded into the wall with reinforcing bars.

2.10 Low-damage solutions

Two cases of rocking walls were observed in Christchurch buildings. No low-damage structural systems were found among Auckland buildings.

3 DEVELOPING A TYPOLOGY FOR STEEL FRAME-CONCRETE WALL BUILDINGS IN NEW ZEALAND

To develop a typology for steel frame-concrete wall buildings in New Zealand, the lateral load resisting system was initially considered. However, buildings that use concrete walls to resist all lateral loads were

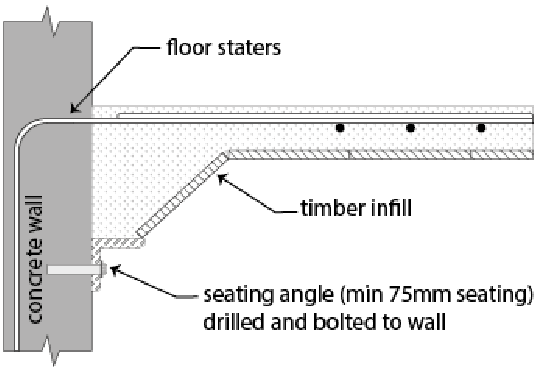

Figure 8: Section view of a typical floor to wall connection

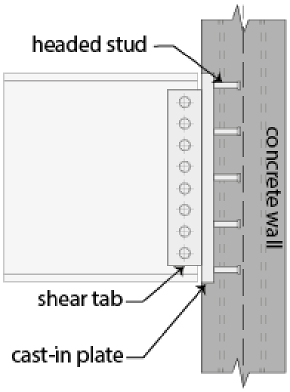

Figure 9: Section view of a typical beam to wall connection

further categorised as to whether they use steel gravity frames or steel beams only (i.e. there are no steel columns and concrete walls also carry gravity loads). As a result, the proposed typology shown in Table 1.

Table 1: Proposed typology for steel frame-concrete wall buildings in New Zealand

Label	Typology	Description
A	Concrete walls with steel gravity frames	This building type relies on concrete walls to resist lateral loads. The steel frames are designed for gravity only. A core wall configuration is typically used, sometimes with additional perimeter walls.
B	Concrete walls and steel frames acting as a dual system	This building type primarily relies on a combination of steel frames (e.g. MRF, CBF, EBF) and concrete walls to resist lateral loads in one or both directions. A core wall is typically used, sometimes with additional perimeter walls.
C	Concrete walls and steel frames in orthogonal directions	This building type has internal walls or perimeter walls as the lateral load resisting system in one direction. In the other direction, lateral loads are resisted by steel frames.
D	Concrete walls with steel beams	This building type uses concrete walls that resist both lateral and gravity loads. Steel beams are used to connect the walls. This type may include buildings that use a few RC or composite beams or columns.
E	Other	This includes buildings with complex designs that do not fit into any other type. It may include buildings that use combined steel frames and concrete walls in certain storeys / areas, but different lateral force resisting systems in others.

3.1 Mapping structural features against the proposed typology system

To illustrate trends among steel frame-concrete wall buildings, the structural features reviewed in the survey are mapped against the proposed typology. Notable findings are summarised below.

3.1.1 Building location

Figure 10 shows that Types A, B, and C were mostly found in Christchurch, whereas Type D was only found in Auckland.

3.1.2 Ductility

Type A buildings were an equal mix of nominally ductile and limited ductile. Type B were mostly designed as limited ductile. Type C were either designed as limited ductile, or had nominally ductile walls and limited ductile frames. Type D, which were mostly found in Auckland, were designed as nominally ductile.

3.1.3 Steel framing system

Types A and D were classified according to their steel framing system (i.e. gravity frames and gravity beams respectively) and therefore the trends for these two building types are apparent in Figure 11. In Type B buildings, EBFs, CBFs and MRFs were all utilised often. Type C also showed a variety of steel framing systems, including portal frames observed in warehouse-like structures.

3.1.4 Wall configuration

Figure 12 illustrates that Type A buildings typically had core walls. Type B were a mix of core, perimeter and internal walls. Type C generally had perimeter walls. Finally, Type D combined perimeter, core and internal walls. This is expected as the concrete walls in Type D buildings also served as columns.

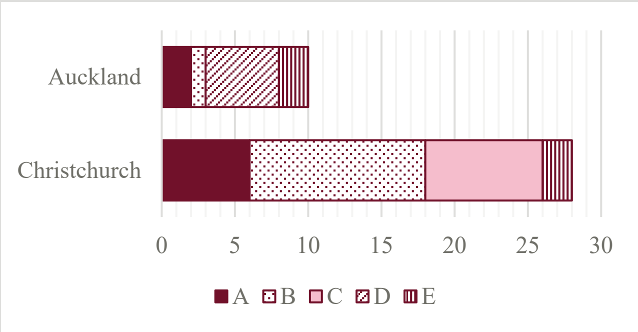

Figure 10: Building location by typology

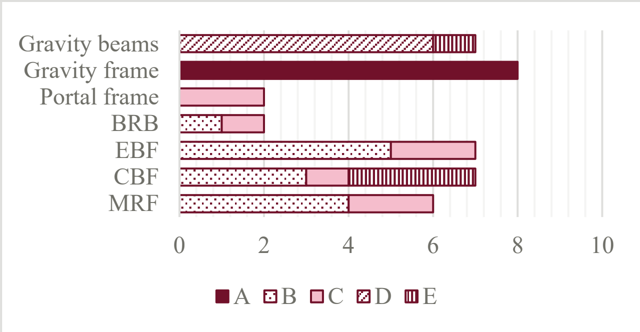

Figure 11: Steel framing system by typology

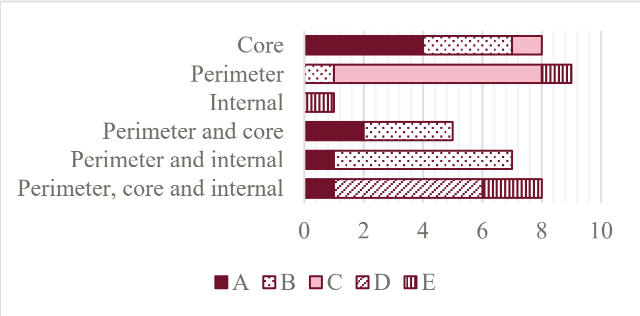

Figure 12: Wall configuration by typology

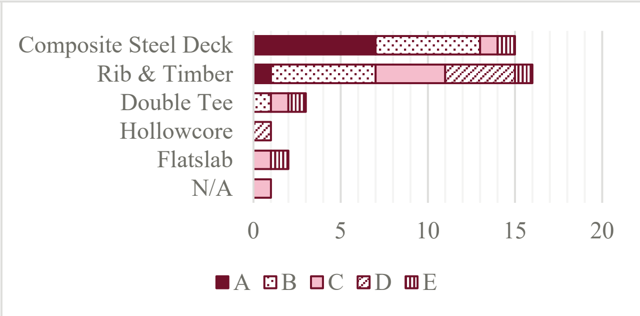

Figure 13: Suspended floor system by typology

3.1.5 Suspended floor system

In Figure 13, Type A buildings predominantly had composite steel tray floors. Type B was an equal mix of composite steel tray and rib & timber. Type C, on the other hand had more variety although half the buildings use rib & timber. Finally, Type D buildings were 80% rib & timber.

3.2 Summary of typical steel frame-concrete wall buildings in New Zealand

3.2.1 Auckland

Although more building drawings in Auckland are being sought, current survey results indicate that Auckland buildings tend to be residential apartments five to nine stories high. Precast concrete walls that resist lateral and gravity loads are connected with steel gravity beams, which typically supported rib & timber or double tee floors. The buildings were usually designed for a nominally ductile response.

3.2.2 Christchurch

Christchurch buildings were usually office or retail buildings two to five storeys high, with rib & timber or composite steel tray floors. There was, however, more variety in structural systems than Auckland. 40% of surveyed buildings had dual systems comprising precast concrete walls with EBFs, MRFs or CBFs, and are usually designed for limited ductile response. Almost 30% used steel frames and precast concrete walls as lateral load resisting systems in orthogonal directions. In such cases, the buildings are either designed for limited ductile response, or the steel frames are designed as limited ductile and the walls nominally ductile. This included three warehouse-like structures that had portal frames or MRFs with concrete walls running along its sides. 20% used steel gravity frames with core walls.

4 CONCLUSION AND FUTURE WORK DIRECTION

A review of structural features of recently constructed buildings in Christchurch and Auckland that combine steel frames and concrete walls was conducted. A total of 38 buildings were reviewed, 28 from Christchurch and 10 from Auckland. Overall, a typology consisting of five building types was developed based on the lateral load resisting systems in both directions. Key findings are summarised as follows:

- In both Auckland and Christchurch, 20% of surveyed buildings used concrete walls with steel gravity frames, designed for either nominally ductile or limited ductile response.
- Majority of Christchurch buildings were two to five storey commercial buildings with rib & timber or composite steel tray floors. 40% used dual systems typically designed for limited ductile response.
- Almost 30% of Christchurch buildings had concrete walls resisting the lateral loads in one direction and steel frames in the other. In such cases, either the buildings were designed as limited ductile, or had limited ductile steel frames with nominally ductile concrete walls.
- In Auckland, nominally ductile precast concrete wall buildings with steel beams were dominant. These are usually apartments five to nine stories high, with rib & timber or double tee floors.

The next step for this study is to conduct interviews with structural engineers to validate the proposed typology and to understand design philosophies for steel frame-concrete wall buildings. Ultimately, the typology developed in this study will serve as basis for creating archetypes of steel frame-concrete wall buildings. Connection tests will be undertaken based on these archetypes to investigate further the interactions between steel frames and concrete walls. Consequently, the outputs of connection tests will serve as inputs to numerical building models, which will provide insight on the expected seismic performance.

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