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A DETAILED INVENTORY OF MEDIUM- TO HIGH-RISE BUILDINGS IN WELLINGTON'S CENTRAL BUSINESS DISTRICT

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ABSTRACT

Recent earthquakes in New Zealand not only highlighted the vulnerabilities of the existing building stock but also the need for: (i) a better understanding of the building inventory, and (ii) easy access to information for quicker response after an event. In the case of Wellington, efforts over the years by the City Council and other stakeholders have produced a number of useful datasets about the building inventory. These available datasets when put together are critical in understanding the composition and characteristics of the building inventory in Wellington. This paper describes the available information, and the process to combine the different strands of data possessed by multiple stakeholders into an effective and usable multi-disciplinary building inventory database for Wellington's CBD. The uses and future directions for this collated database are also discussed.

INTRODUCTION

Earthquakes pose a serious risk to Wellington, New Zealand's capital city. The most recent major earthquake that affected Wellington occurred on November 14, 2016 at 12:02am local time and had a moment-magnitude (M_w) of 7.8. Although the epicentre was in Kaikoura more than 200 kilometres away, the closest extent of fault rupture was 50 km South of Wellington [1] and caused widespread damage to buildings across Wellington. In the immediate aftermath of the earthquake, about 10% (~167,000 m^2) of the city's office space was closed for assessment, forcing relocation of thousands of workers from their offices [2]. At the time of publication, 20 buildings had been demolished or remain vacant, approximately 10 additional buildings were initially closed but then re-opened upon the completion of detailed inspections [3] – see Figure 1.

Most of the damaged buildings were located in the central business district (CBD) of the city (as shown in Figure 1). A large number of them were located around the port, on reclaimed land or land along a shoreline that was uplifted by a strong earthquake in the 19^{th} century. Ground motions were amplified by basin-edge effects in the Thorndon and Te Aro basins [1]. Most of the affected structures in the CBD were moment-resisting reinforced concrete frame buildings with 6 to 15 floor levels constructed after 1980 [4]. The spectral content of the ground motion (with peaks in demand for periods around 1-2s) was identified as one plausible cause for this concentration of damage. The damage observed in these buildings also highlighted key structural vulnerabilities of medium- to high-rise RC buildings that were not fully recognized before the Kaikoura Earthquake.

Prior to the Kaikoura Earthquake, the attention of researchers and policymakers was primarily directed towards older unreinforced masonry (URM) buildings and reinforced concrete (RC) buildings built before 1976, which were acknowledged to have high inherent seismic vulnerability. But evidence from the recent events shows that some newer RC buildings (constructed post-1980's) also have structural vulnerabilities that pose risk to human life and require further investigation.

One such example is the Statistics House building located in the port area in Wellington's CBD. Statistics House experienced localised structural failure when two precast floor units collapsed during the Kaikoura Earthquake [5]. In this instance, injury and loss of life was avoided because the earthquake occurred at night, when the office building was not occupied. The collapse of one concrete building (the CTV building constructed in 1986) in the 22 February 2011 Christchurch Earthquake accounted for about 60% of the 185 fatalities in the catastrophe [6]. The failure of precast floors in Statistics House could have also caused multiple deaths had the earthquake occurred during the working day.

Beyond the life-safety risk associated with medium- to high-rise RC buildings, the recent earthquakes damaged numerous concrete buildings resulting in wide-ranging costs imposed on property owners (e.g. loss of rental income), building occupiers (e.g. business interruption), and insurers. Tenants of office space in the Wellington CBD (private firms, government and other public and non-profit entities) have responded to this by demanding spaces that have an earthquake rating of at least two thirds of the New Building Standard (NBS) threshold which is well above the 34% NBS legal threshold for buildings classified as 'earthquake-prone.' Seismic assessments are likely to classify many of the newer buildings below this new market-imposed threshold, putting pressure on owners to strengthen their buildings or consider redevelopment options.

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Densification of the Wellington CBD, which is expected to nearly double in population in the next 25-30 years with over 15,000 new residents, will prompt conversion of many lower quality/grade, ageing commercial buildings to apartments, and is likely to change the risk profile of the city [7]. Seismic retrofitting of these vulnerable buildings to above the acceptable seismic risk level can have other benefits (e.g. increased rent, longer lease duration) beyond the benefits of surpassing the legally-defined threshold for 'earthquake-prone' buildings [8]. Comprehensive multi-disciplinary databases can aid researchers and policymakers to streamline the process of identifying vulnerabilities and provide a key step towards developing resilient communities.

In the case of Wellington, efforts over the years by the City Council and other stakeholders have produced a number of useful databases about the building inventory. These data, however, are not readily available and accessible by local emergency managers, city planners, and the engineering community. Different stakeholders possess different strands of data related to the building inventory, with some of it remaining isolated to specific audiences with little means for cross-disciplinary sharing of resources and information. Yet, the available data, when collated, are critical in understanding the composition and characteristics of the building inventory and guiding policy development to address existing and newly identified vulnerabilities.

This paper describes the available information contained in existing databases and presents an overview of a project targeted to combine these different strands of data into a single, effective and usable multi-disciplinary building inventory database for the Wellington CBD. Future directions for this database and its uses are also discussed. The ultimate aim of this database is to assist the next generation of research in evaluating the risks, impacts, and viable solutions for reducing the seismic risk of existing medium-to high-rise buildings in the Wellington CBD. The database would also provide the opportunity to integrate this building inventory with other geo-spatial hazard datasets (e.g. site condition, ground motion, faults location) to optimise investment into risk-reducing measures and identify appropriate risk management strategies for Wellington. Unfortunately, because of commercial interests and privacy sensitivities, the database dicussed in this paper is only available, at this point, to the research and policy communities.

It should be noted that there are a number of international databases which consist of data collected during post-earthquake reconnaissance efforts [9-12]. Most of these databases have been compiled for specific uses such as quantifying and documenting structural performance, social and economic loss estimation for a given region, emergency response planning, etc. The scope of the database presented in this paper goes beyond one single aspect of the inventory as we are connecting the structural aspects with occupancy, use category, and potentially geo-spatial hazards.

HISTORY OF CONSTRUCTION IN THE CBD

The Wellington building inventory consists of a mixture of construction types including unreinforced masonry, reinforced concrete, precast concrete, and structural steel buildings. Figure 2 shows a timeline from 1900 to present day for the different construction types and major earthquakes and building codes that may have influenced them. Distribution of age for approximately 500 buildings in Wellington's CBD with a total height of more than 12m is shown in Figure 3.

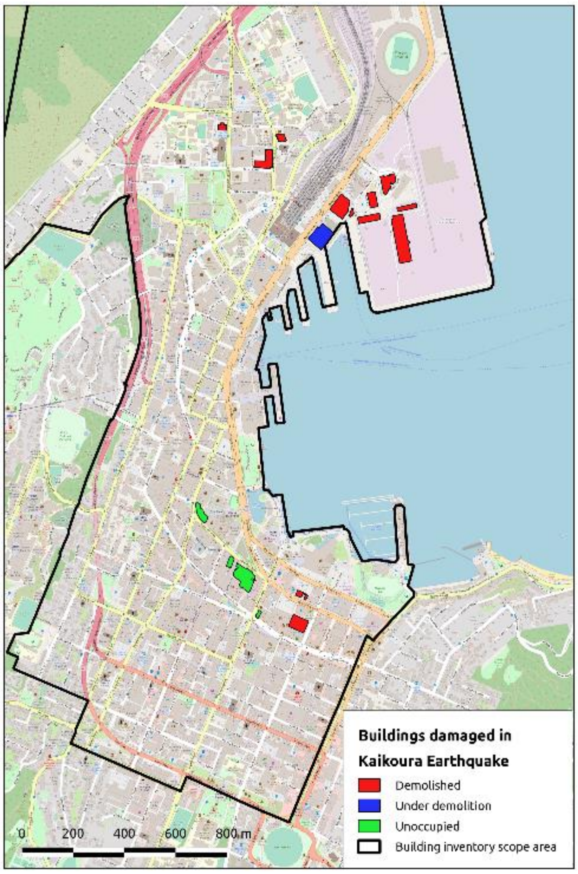

Figure 1: Demolished and unoccupied buildings in Wellington's CBD (area of interest for this paper) following the 2016 Kaikoura Earthquake [as of February 2019].

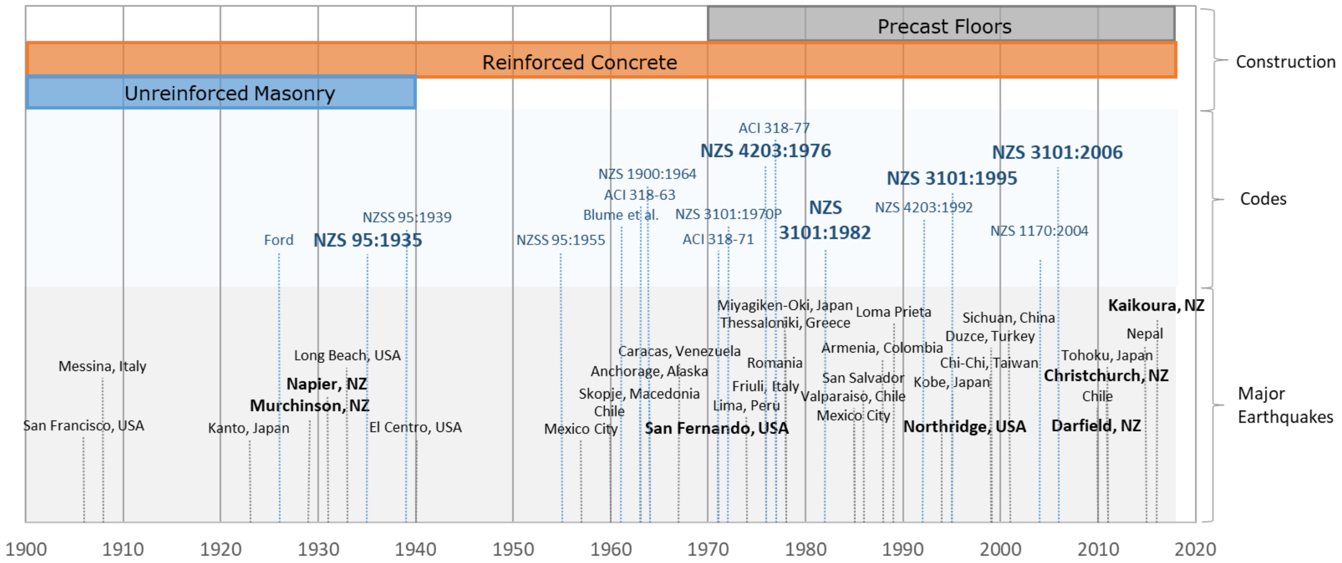

Figure 2: Timeline of construction in New Zealand.

Figure 3: Distribution of age for buildings with 5 storeys or more in Wellington CBD (Source: CityScope).

Of the building stock that exists in Wellington today, unreinforced masonry (URM) buildings are perhaps the oldest/ earliest buildings constructed. URM construction in New Zealand started to grow in the early 1900s and peaked between 1920 and 1930. Most existing URM stock was constructed before 1940 [13]. It declined because of the Great Depression in the 1930s as well as changes to building codes after the 1929 Murchison- and 1931 Napier Earthquakes. The use of URM for main structural elements has not been permitted since the 1935 building standard.

RC construction was used in New Zealand starting from the early 1900s [14], but became more prevalent following the decline of URM construction in the 1930s. Buildings made of reinforced concrete could be taller and were also considered to be "better" for resisting seismic demands. A study funded by Earthquake Commission (EQC) collected data for RC buildings built in Wellington between 1935 and 1975 [15] and suggested that prior to 1950 'perforated walls' was the dominant type of structural system used to resist seismic demands in RC buildings. The study also suggested that frame and frame-wall construction gained importance in the 1950s and frames became dominant in the 1970s. It is important to note that early building codes (standards) starting from 1935 did not prescribe stringent requirements for seismic detailing. The focus of the design provisions was mostly on the strength of the structure to resist "equivalent" lateral forces, and not on the reinforcement detailing required to resist drift demands. Research studies, and lessons learnt from events, such as the San Fernando Earthquake in 1971, contributed to major improvements to building design standards in the 1970s, and this process of improving the standards continues to this day. The 1970s was also a period of shift to 'ductile' design philosophy in New Zealand where structural components were detailed to accommodate inelastic displacement demands. Nevertheless, loopholes for detailing in gravity columns (i.e., columns not part of the seismic force resisting system) remained in the standards until 1995, as discussed later in this paper.

Construction of buildings using precast floors began in the early 1970s, around the same time ductile framing was gaining momentum, and became the dominant floor system in New Zealand from the 1980s onward [16]. The use of precast floors became popular because fabricating floor elements off-site in a plant was more efficient, reduced on-site work including preparation of formwork, and had higher quality control. The fabrication/construction process using precast floors was simple: floor units were cast in long beds in precasting plants, transported to the work site, craned in place and seated on beams, and finally tied into the structural system by casting a thin topping slab. The development of precast concrete floor systems was also supported by the construction boom of the 1980s, leading to the majority of large commercial buildings in Wellington CBD using precast floors.

A large amount of research on precast systems was conducted in the 1990s and 2000s both at the component- and system-levels [17-21]. These studies led to vast improvements in the design of precast flooring systems (NZS 3101: 2006 [22]); provisions were added to limit the possibility of: (i) floors falling down by increasing seating depth, and (ii) brittle failure by requiring low-friction bearing strips, linking slab, etc.. Both the industry and research community are actively involved in retrofit and repair options for these systems after the Christchurch (2011) and Kaikoura (2016) Earthquakes highlighted vulnerabilities.

Although New Zealand has vast resources of iron ores only a handful of steel-frame buildings were constructed until the later part of the 20th century. It has been reported that large-scale use of structural steel was disrupted for many years starting in the late 1970s during the construction of a landmark 30-storey building in Wellington because of a labour demarcation dispute with the boilermakers trade union which claimed exclusive rights to weld steel [23]. Steel framing construction started to pick up again following the Christchurch Earthquake in 2011 [24]. Because of this reason, steel-framed buildings only form a small percentage of the existing building inventory in Wellington's CBD.

Table 1: Source Datasets.

#	Name of Dataset	Acronym	Source	Description
1	WCC Building Footprints	WCC-BFP	WCC	Footprints of buildings in Wellington CBD
2	Colliers	COLL	Colliers International	Biannual survey of commercial building stock to establish the amount of vacant space in Wellington CBD
3	Building Seismic Assessment (IEP, DEE)	BSA	WCC	Compiled using WCC IEP and DEE datasets. Buildings built to Pre-1976 code standards and assessed by licensed engineers
4	1935-1975 RC Buildings		Earthquake Commission	RC buildings in Wellington CBD constructed between 1935 and 1975. Includes year of construction, # storeys, floor areas, use, etc.
5	Drawings	DWG	WCC	Structural and architectural drawings of buildings in Wellington CBD extracted from property files held by WCC
6	Hollow-core Floors	HOLL	MBIE, WCC	Buildings with precast hollow-core floors. Contains detailed information about flooring system including spans, reinforcement details and seating length.
7	Targeted Damage Evaluation	TDE	WCC	5 to 15 storey concrete moment frame buildings with precast concrete floors assessed by licensed engineers. Includes detailed information about flooring system.
8	Concrete Columns	CONCOL	MBIE	Buildings with non-ductile columns built between 1982 and 1995. Consists of general building information as well as detailed data about columns.
9	CityScope	CITYSCP	WCC	Database of commercial property information containing details about building attributes, tenancy, and sales history
10	WCC District Valuation Roll	WCC_DVR	WCC	Contains information about rating of each unit within the district (or territory authority) prepared in accordance with Rating Valuation Act of 2008 to provide a fair basis for determining rates
11	Mesh Model, Google Maps	3D MODEL	WCC	Resembles a 3-D view of the city. Allows the identification of façade types, as well as existence and type of vertical and horizontal irregularities. Google maps street view was concomitantly used with the Mesh-Model.

SOURCE DATASETS

Multiple stakeholders, including government and private sectors, have created datasets related to different aspects of the building inventory in Wellington. These datasets were created to suit different contexts/purposes, and therefore vary in the types of buildings included, variables collected and geographic scope. Several of these datasets made available for use in this project (herein referred to as 'source datasets') are listed in Table 1. These datasets contain information about occupancy, structural characteristics, heritage status, and potential vulnerabilities. They represent a sample of what exists today in Wellington and provide rich information that can be used to inform not only engineering practice, but also emergency management and national and local policies.

In general, datasets which do not focus on specific engineering characteristics—such as the Colliers Vacancy Survey, and Wellington City Council (WCC) Building Footprints—tend to contain a larger number of buildings than datasets focussed on specific structural characteristics collected for specific purposes. For example, the Building Seismic Assessment dataset (BSA) was compiled using WCC's Initial Evaluation Procedure (IEP) and Detailed Engineering Evaluation (DEE) data, and consists of buildings that were built prior to 1976 and assessed by licensed engineers. Similarly, the Targeted Damage

Evaluation (TDE) dataset consists of detailed information for only 64 buildings with precast floors identified as potentially vulnerable to damage following the Kaikoura Earthquake. Irrespective of the number of buildings in each dataset, the availability of a wide range of data presents a unique opportunity to understand the existing inventory, and can help determine the best use of resources to strengthen the buildings and improve seismic resiliency.

In the following sections these datasets are used in combination with available literature to describe two aspects of the existing building inventory in Wellington's CBD: 1) structural vulnerabilities, and 2) building use and occupancy classifications. The longer-term objective is to connect these two aspects of the building inventory with other spatial data such as shaking intensity for scenario earthquakes, ground conditions, population distribution, etc. to help better quantify the earthquake risks and impacts in Wellington.

STRUCTURAL VULNERABILITIES

This section highlights some of the structural vulnerabilities of the building inventory in the Wellington CBD. The City Council has made efforts to promote strengthening of many of the remaining URM Buildings starting in the 1960s [13] and to identify and assess RC buildings built before 1976. Nevertheless, research has shown that buildings built even after the mid-1970s are vulnerable to damage during earthquakes [25]. The recent experiences of the Christchurch and Kaikoura Earthquakes highlighted key structural vulnerabilities of gravity columns and precast floors in modern medium-rise RC buildings built after 1976 which were not addressed or appreciated sufficiently before the events. The aftermath of these earthquakes presented an opportunity to consolidate observations and increase efforts towards identifying potentially vulnerable buildings and assessing options for repair and retrofit. The available datasets, in addition to existing literature, are used here to present a snapshot of the building inventory and the associated structural vulnerabilities. The focus here is on RC buildings as these are currently the buildings with the most available data. Ultimately, our goal is to have data for all buildings within the Wellington CBD.

Reinforced Concrete Buildings

It is well-known that RC buildings with non-ductile elements designed according to building standards prior to the 1970s have high inherent seismic vulnerability [25]. Most vulnerabilities associated with RC buildings can be attributed to poor design and reinforcement detailing practices, and sometimes low-quality construction. A comprehensive overview of vulnerabilities, major revisions to standards and key changes made in relation to the design of concrete structures since 1957 is provided in the 'Guidelines for Detailed Seismic Assessment of Buildings not identified as potentially Earthquake Prone (EPB)' [25]. Figure 4 summarizes some of these changes.

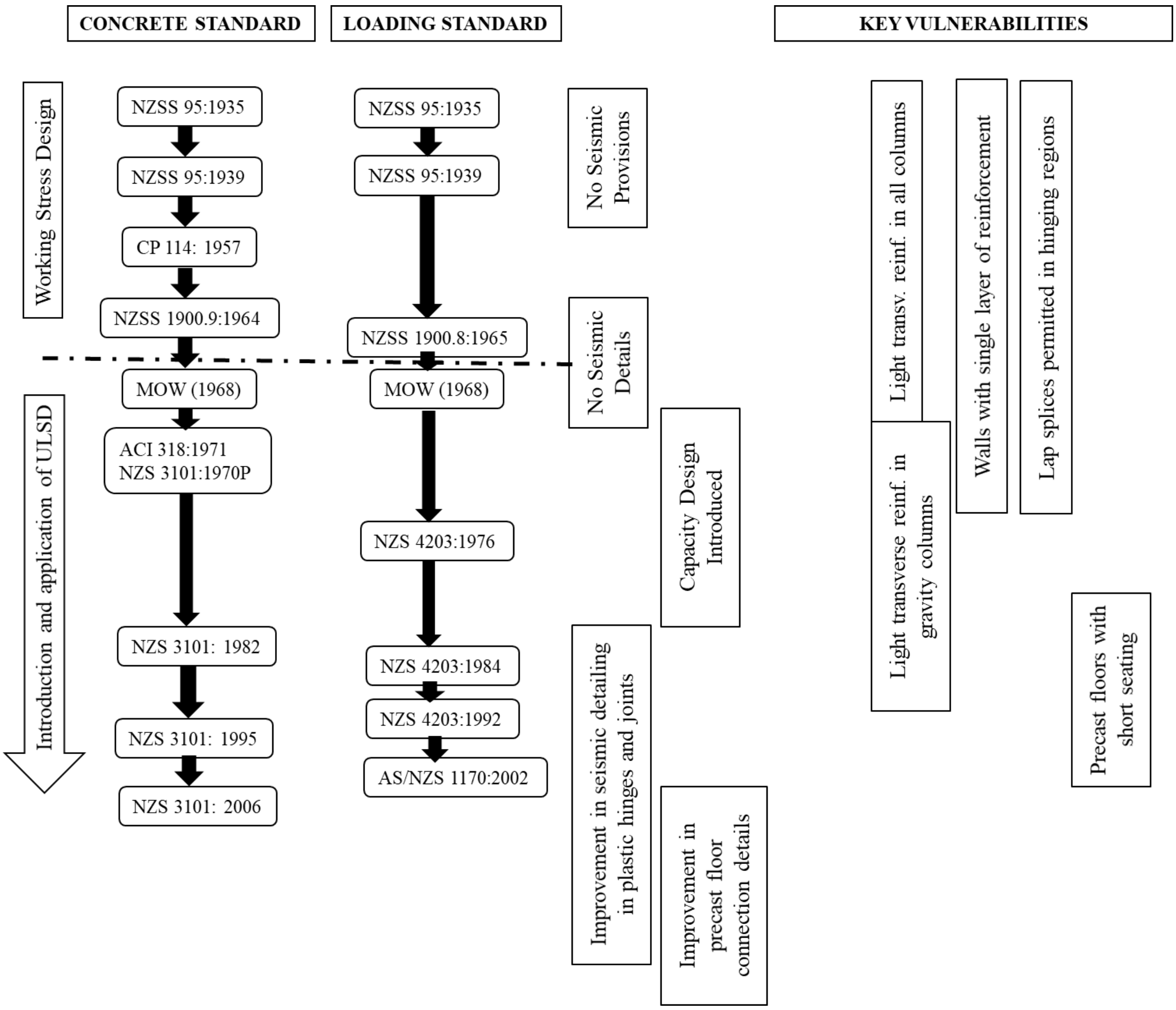

Figure 4: Overview of major revisions to Concrete and Loading Standards in New Zealand.

Concrete and loading standards prior to 1976 permitted the construction of buildings with soft storeys, columns with poorly detailed lap splices, walls with a single layer of longitudinal reinforcement, insufficient confinement, and widely-spaced transverse reinforcement. The collapse of the Pyne Gould Corporation (PGC) Building during the 2011 Christchurch Earthquake is an example of a catastrophic failure of a building with pre-1976 details. The PGC building was constructed in 1963 and an investigation conducted after the catastrophe suggested that the collapse occurred because of insufficient capacity of lightly, centrally-reinforced shear walls: a detailing requirement not addressed until the late 1970s in NZS 4203: 1976 [26]. In the 1970's, the Loading Standard NZS 4203:1976 [27] and Concrete Standard NZS 3101:1970P [28] required the use of ultimate strength design, and also introduced provisions for detailing of plastic hinge regions including: 1) requirement for shear reinforcement to resist both gravity shear and shear induced by formation of flexural hinges, 2) not permitting lapping of bars in plastic hinge regions, and 3) requiring column confinement when axial load ratio exceeded 40% of the load at balanced condition [25]. In addition, the 'capacity-design' methodology for elements resisting seismic demands was introduced in the 1970s and commonly adopted in the late 70s and 80s.

NZS 3101: 1982 [29] introduced stringent requirements for shear design, confinement of column plastic hinges and lapping of reinforcing bars [25]. Nevertheless, these provisions did not require 'gravity' columns to have sufficient transverse steel to resist large drift demands. Such columns, commonly referred to as 'non-ductile', are susceptible to brittle modes of failure potentially leading to loss of axial-load carrying capacity at small to moderate drift demands [9, 25, 30-33]. For design purposes, these non-ductile gravity columns, which are components of the global building system, were not considered to be a part of the lateral system designed to resist earthquake demands. However, during seismic events, the entire structure, including the gravity columns, is subjected to the same lateral drift demands. Requirements to ensure gravity columns are able to achieve expected drift demands were introduced in NZS 3101:1995 [34].

The global seismic behaviour of structures with these columns is dependent on the availability of alternative load paths for the gravity load supported by the vulnerable column, and structures without sufficient redundancy are likely to suffer partial or total collapse. The non-ductile columns in question are considered to be a contributing factor to the collapse of the CTV building (built in 1986) during the Christchurch Earthquake on 22 February 2011 [6].

Another category of modern (post-1980) RC buildings with vulnerabilities are those with precast floors. Some of these vulnerbilities were highlighted during the 2016 Kaikoura Earthquake after which varying levels of damage, from light cracking to collapse of multiple units (Statistics House), were observed in buildings across Wellington [35]. Buildings with precast floors comprise a large percentage of the commercial building stock in many cities in New Zealand, and the number of residential buildings with older precast floor details is also increasing as buildings are being converted from commercial to residential use. If measures are not taken to address known deficiencies, multiple floor collapses may occur during future earthquakes. The New Zealand research community and engineers conducted substantial research on precast floor systems (summarized in [21]) and many of their findings were incorporated in NZS 3101:2006 [22] and researchers are still actively pursuing retrofit options [35]. Since 2010, several buildings in Wellington have been retrofitted with supplemental support for precast floors, however the number of retrofitted buildings is unknown at this time.

The importance of the aforementioned vulnerabilities on the global response of buildings has been observed in past earthquakes. Recognising this, efforts were made by various government entities to identify buildings with the key vulnerabilities noted above. These efforts have resulted in accumulation of a large volume of meaningful data, and three sets of these data are used here to understand the vulnerabilities associated with RC buildings in Wellington. The first dataset consists of RC buildings built between 1935 and 1975, the second consists of buildings built between 1982 and 1995, and the third consists of buildings with precast floor systems generally constructed after 1980.

1937-1975

A study for the Earthquake Commission in 1990 investigated RC buildings in Wellington built between 1935 and 1975 (Blaikie and Spurr, 1990) in the area shown in Figure 5. The report contains a comprehensive description of the findings and a snapshot of the building data is reproduced here in Figures 6 through 9. Data for this EQC study were obtained from a collection of datasets including Valuation New Zealand, Earthquake Risk Buildings List, Wellington City Scope, Design Feature Reports and Building Survey Data for Public Buildings [15].

Blaikie and Spurr [15] indicated that the survey area consisted of mostly buildings meant for commercial use (Figure 6a). Buildings with fewer than 3 storeys constituted approximately 50% of the total number of RC buildings constructed between 1935 and 1975 but made up for only 22% of the total floor area (Figure 6b and Figure 7). Most of the floor area in this subset concentrated in buildings with four or more storeys. For this reason, and because of paucity of information, buildings with 2-3 storeys were excluded from further study by Blaikie and Spurr [15].

Buildings with four or more storeys made up nearly 80% of the floor area in the subset of 1935-75 RC buildings. Most of these buildings (~86%) were constructed in the 1960's and early 70's (Figure 6b and Figure 8). Hence, to achieve the greatest seismic risk reduction in the overall building inventory, Blaikie and Spurr [15] suggested that efforts to evaluate and address seismic risks of 1935-75 buildings should focus on the buildings constructed between 1960s and 70s. Floor area in each 'structural type' category is shown in Figure 9, indicating the majority of floor area in wall structures in 1960s followed by an increase in frame structures in early 1970s.

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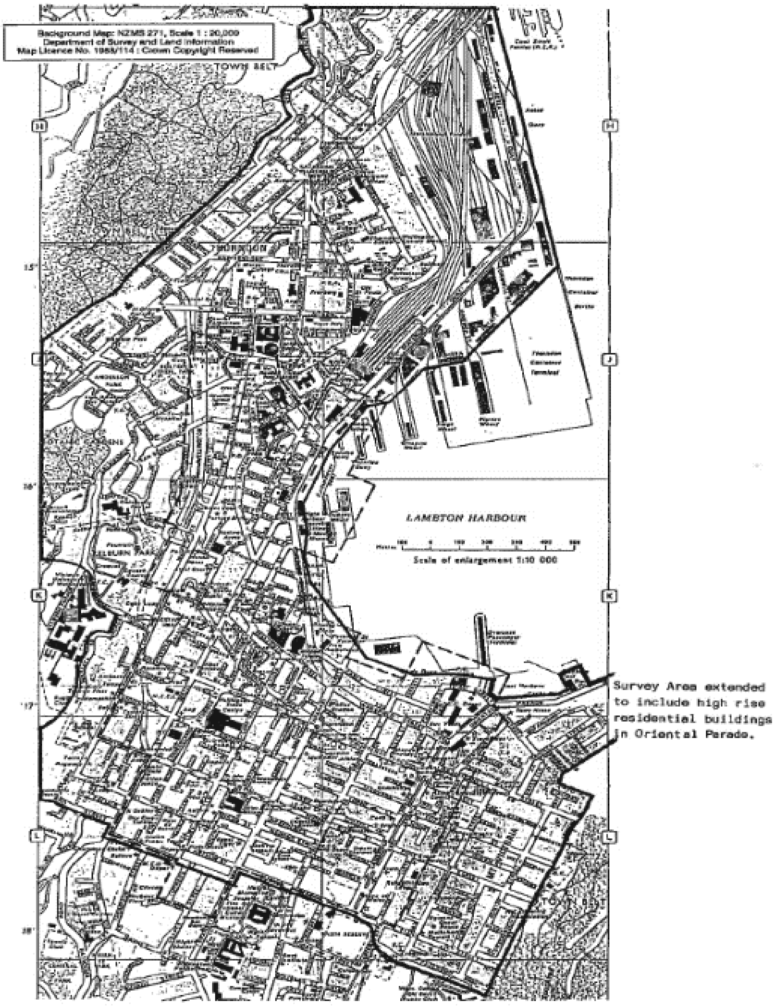
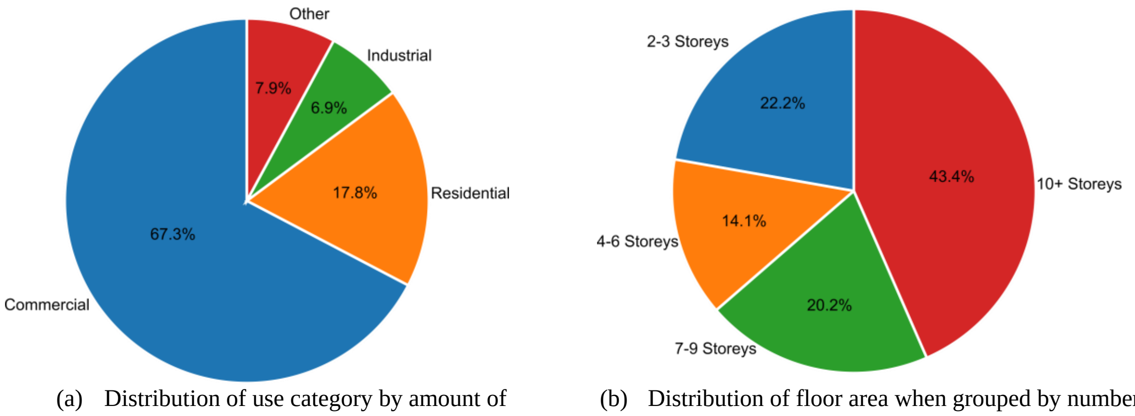


Figure 5: Boundary of Survey Area (Fig. 1.1 [15]).



(a) Distribution of use category by amount of surveyed floor area

(b) Distribution of floor area when grouped by number of stories. Values are % of total floor area = 1,015,980 sq. m

Figure 6: Distribution of floor area of RC buildings built between 1935 and 1975. Values are % of total floor area = 1,015,980 sq. m (data from [15]).

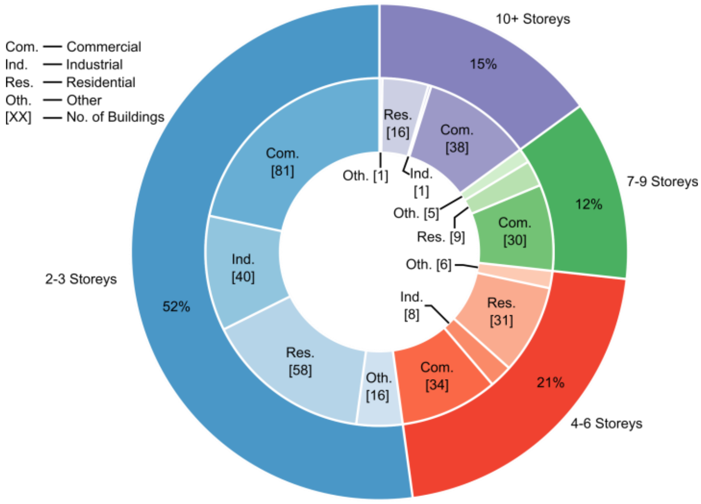


Figure 7: Distribution of number of RC buildings built between 1935 and 1975 subdivided by use category. Values are % total number of buildings = 374 (Data from Blaikie and Spurr [15]).

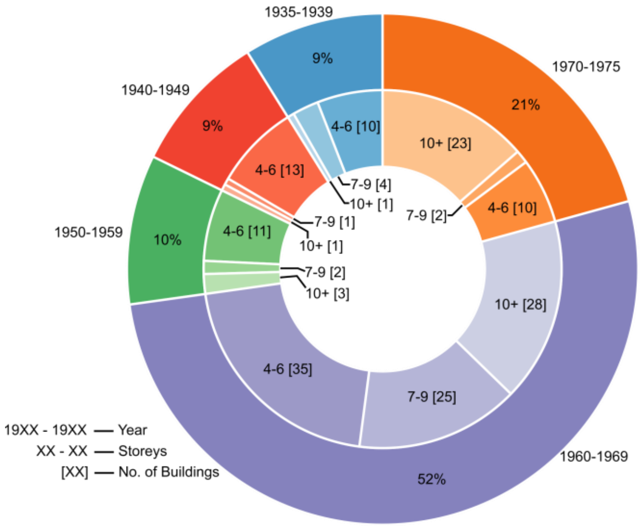


Figure 8: Distribution of buildings with four or more storeys constructed in each decade subdivided by number of storeys. Values are % total number of buildings = 169 (Data from Blaikie and Spurr [15]).

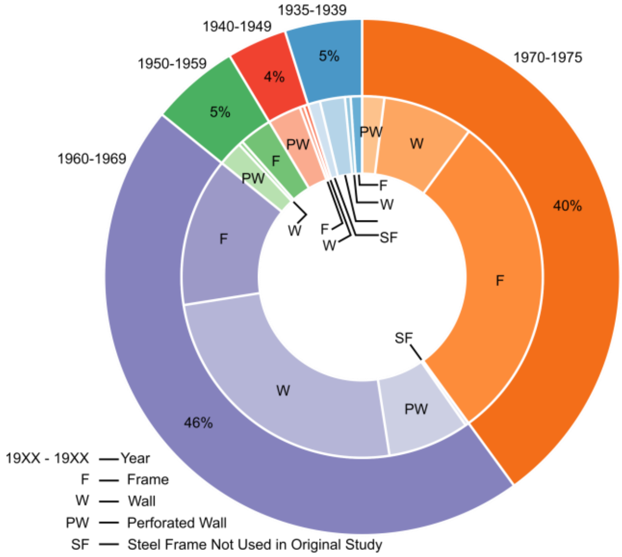


Figure 9: Distribution of floor area of buildings with four or more storeys constructed in each decade subdivided by the structural type. Values are % of total floor area = 785,972 sq. m (data from Blaikie and Spurr [15]).

1982-1995

As mentioned earlier, most of the vulnerabilities associated with concrete buildings were addressed in the 1976 and 1982 versions of the standards, except for a loophole associated with confinement in gravity columns. NZS 3101:1982 [29] permitted some columns in the structural system which were not relied on for lateral resistance to be treated as 'secondary elements' [15]. These were typically 'gravity' columns supporting large floor areas and NZS 3101:1982 allowed those designed with a strength reduction factor of 0.7 to use widely-spaced transverse reinforcement. Such columns have limited deformation capacity and are susceptible to brittle failures under seismic demands. This loophole meant that a certain crop of buildings designed in the 1980s had non-ductile gravity columns which are susceptible to brittle failures under seismic demands [9, 30-33].

In response to findings from the Canterbury Earthquake Royal Commission, in 2012, the MBIE commissioned structural engineers in NZ to identify buildings with non-ductile columns across New Zealand to aid in future assessment and retrofit options. From the MBIE database, a subset of 80 multi-storey buildings designed in Wellington between 1982 and 1995 was reviewed. Figure 10 shows the distribution of building properties as well as the ranges of column details for these buildings. It should be noted that this information pertains to when the database was compiled and that a number of these buildings may have been retrofitted since then.

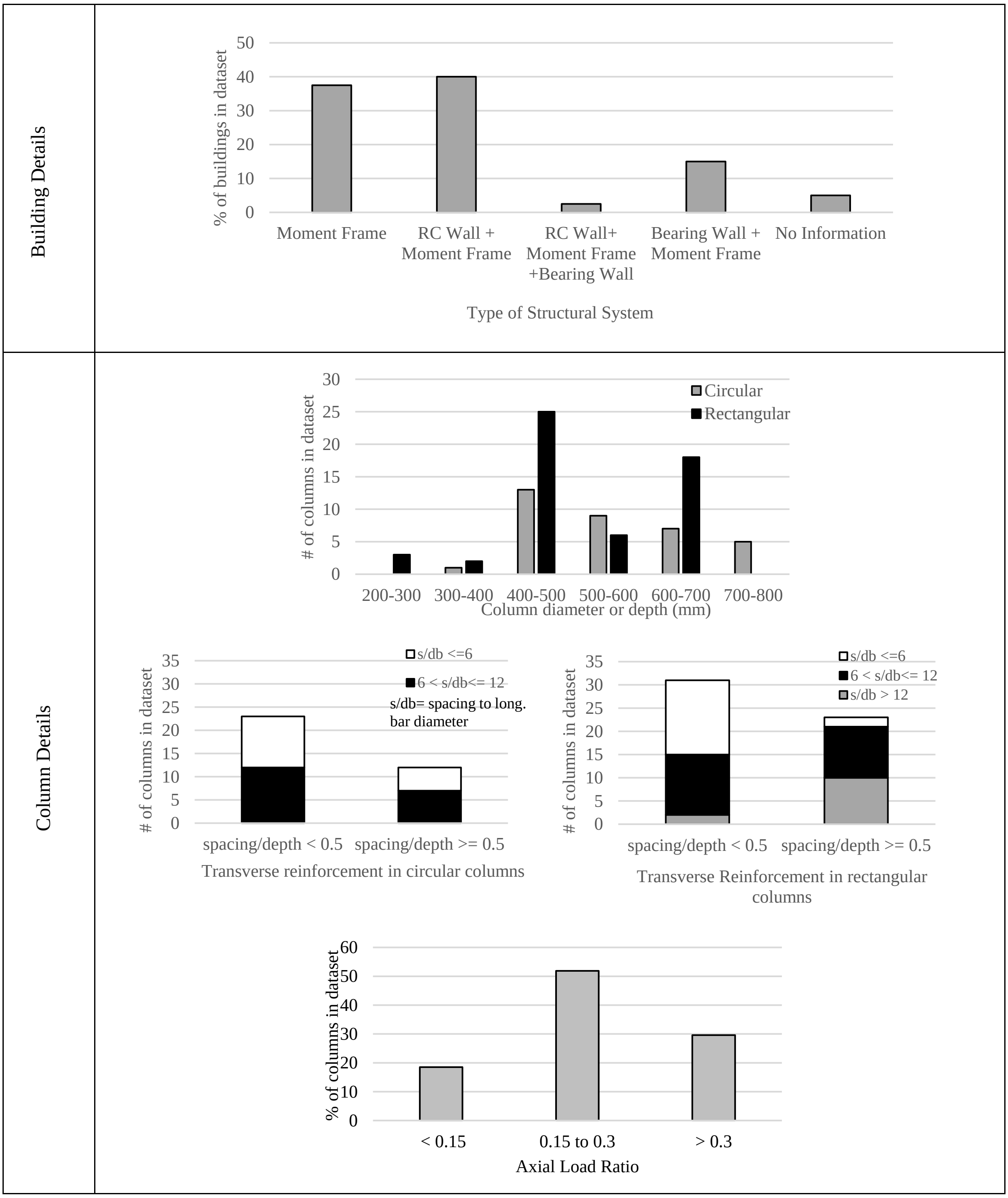
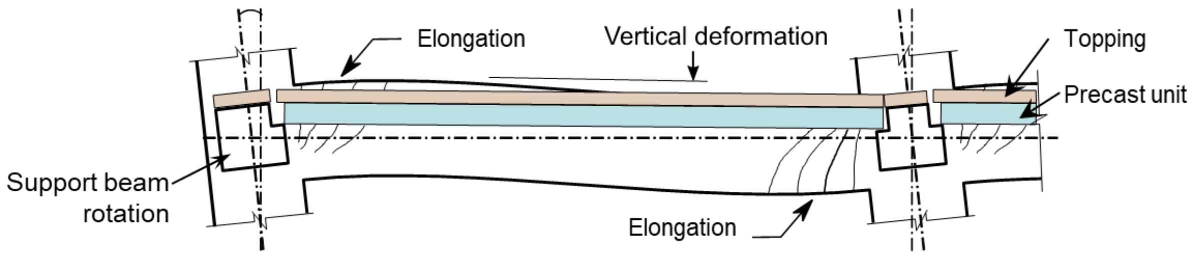


Figure 10: Summary of Properties of 1982-1995 Non-Ductile Columns Dataset (CONCOL).

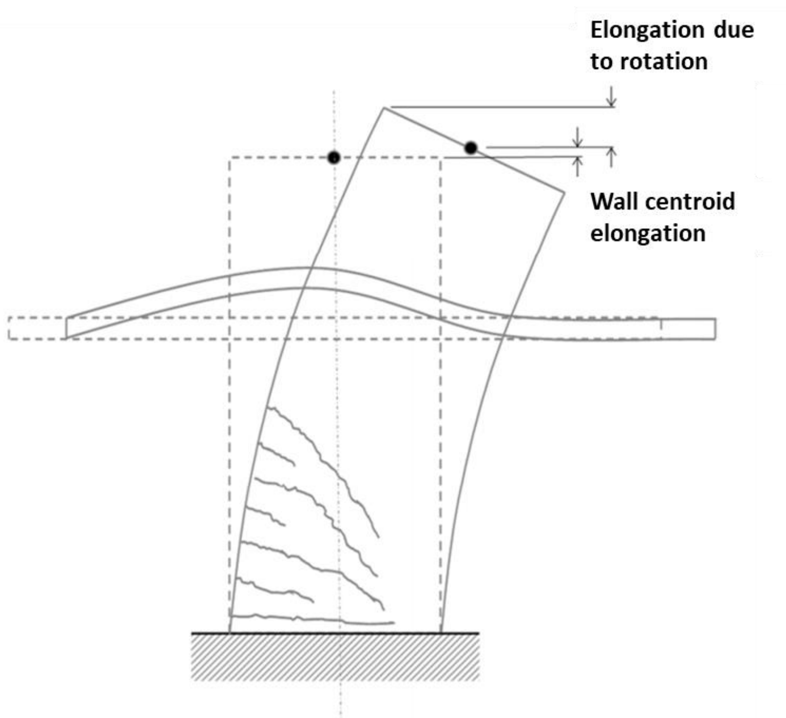
All buildings considered consist of either moment resisting frames or a combination of moment resisting frames with other types of structural systems (in one or both floor-plan directions). Geometric properties and structural detailing of columns within the first three floors of each building were considered. For buildings with only rectangular or circular columns, one column with the smallest dimensions and/or smallest longitudinal reinforcement ratio and/or largest ratio of stirrup spacing to effective depth and under largest tributary area, was chosen. For buildings with both rectangular and circular columns, the column with the smallest size and/or worst detailing, for each shape, was selected. Out of the 76 buildings with available drawings, 14 had both circular and rectangular columns. The final dataset consisted of 89 columns– 35 circular, 37 square and 17 rectangular in shape. Most of these columns had a diameter or depth between 400- and 500-mm. Transverse reinforcement spacing was larger than one-half the column depth in approximately 40% of the cases. For all columns in the dataset, axial load ratio was estimated by approximating the tributary area and calculating gravity loads in accordance with NZS 1170.0:2002 [37]. In cases where information on nominal concrete compressive strengths was available, expected compressive strength was assumed to be 1.5 times the specified strength [25]. In cases where information on concrete compressive strength was not available, a probable value of 40MPa was assumed [25]. Approximately 70% of the columns in the dataset had calculated axial load ratios smaller than 30%. Nevertheless, in the remaining 30% of the cases, axial load ratio exceeded 30% suggesting that they could be potentially compression-controlled and highly vulnerable to seismic demands.

Buildings with Precast Floors

Precast concrete floor systems consist of precast slab units (hollow-core, double-tee, rib and infill, or flat slab) seated on ledges on supporting beams and a lightly reinforced concrete topping cast in-situ as illustrated in Figure 11a. These precast elements are typically connected to the structure using ‘starter’ bars which extend into the supporting beams. When subjected to strong ground shaking, the building, depending on its flexibility, may experience drift demands that cause damage to precast floor units. As shown in Figure 11a, inter-storey drift demand in frames is accommodated by rotation of the support beams and elongation of the beam parallel to the span of the slabs. In this scenario, plausible vulnerabilities resulting from poor detailing include unseating of the unit or failure of precast unit at the slab-beam connection. Damage to precast floors is directly related to the drift demands and deformation incomtibility (Figure 11), and hence, buildings located on soft soils or have flexible lateral systems are most vulnerable to precast floor damage.



(i) Frames



(ii) Walls

Figure 11: Deformation incompatibility in precast floor systems adjacent to (i)frames and (ii)walls (from [21] and [25]).

Of all precast floor systems, hollow-core floors comprise largest total floor area of precast construction in New Zealand. Considering their widespread use and the urgent need for assessment and retrofit methods, much of the focus of research in the last two decades has been on vulnerabilities associated with hollow-core floors. Previous research (summarized by Fenwick et al, [21]) has identified three primary plausible failure modes in hollow-core floor systems: 1) loss of seating (LOS), 2) positive moment failure (PMF), and 3) negative moment failure (NMF). A summary of past detailing practices and their consequences in relation to these failure modes is presented in Table 5.1 of the CNRE Assessment of Hollow-Core Floors for Seismic Performance [21]. Typical support details prescribed in pre-2006 standards included short seating lengths, which could result in LOS. The placement of units on mortar beds or cover concrete or prestressing being less effective at the ends of the unit (particularly in cases where units are stressed too early) increases the likelihood of PMF. Vulnerabilities also exist because of the discontinuity caused at the termination of 'starter' bars which could lead to NMF. Research studies so far have pointed out that stronger or shorter starter bars may be more critical (Fenwick et al., 2010). In addition, hollow-core units are inherently prone to brittle shear failure as the extrusion process used to manufacture them in New Zealand prevents the use of shear reinforcement in the units. Many of the mentioned vulnerabilities were addressed in the 2006 version of the Concrete Standard (NZS 3101:2006 [22]) and these are discussed in detail by Fenwick et al. [21].

The use of precast double-tees in building construction in New Zealand is believed to be less widespread than the use of hollow-core units, but datasets containing information about buildings with double-tee units are currently unavailable. Prior to 2010, double-tee units were typically installed as flange-hung with so-called 'pig-tail' reinforcement details which cannot be demonstrated to provide a reliable load path according to engineering mechanics [38]. Web seated double-tees may also be vulnerable to seating failure induced by spalling because of large contact stresses developed at the supports.

Efforts undertaken by MBIE and WCC have produced datasets of buildings with precast floor systems in Wellington CBD. Two different datasets are available at this time: One consists of 112 buildings with hollow-core floors (HOLL) and the other (TDE) consists of sixty-four buildings with different precast floor systems.

The HOLL dataset was compiled by the Department of Building and Housing [39] to determine the extent and usage of hollow-core floor systems in NZ and their vulnerabilities. This dataset consists of 112 buildings with hollow-core floors in Wellington and a summary of properties is presented in Figure 12.

Key points to note are that: 1) over 50% of the buildings have fewer than 6 storeys, 2) approximately 50% of the buildings have flexible structural systems (i.e., the buildings are expected to have lateral displacements larger than 1.0% of storey height [39]), 3) over 70% of the buildings have units with seating length not exceeding 50 mm (small seating lengths may result in LOS), 4) 80% of the buildings have 200-mm deep hollow-core units, 4) over 80% of the buildings have floor spans smaller than 10 m, 5) in approximately 75% of the cases, there is only one beam parallel to the floors (single span) and in about 20% there is more than one beam parallel to the floors (intermediate columns), 6) over 60% of the cases have starter bar lengths not exceeding 600 mm (the most vulnerable cases are the ones with larger strength and shorter length), and 7) over 80% of the cases have a 65 mm topping slab with Gr.665 (cold drawn) welded wire mesh reinforcement. It should be noted that this dataset was compiled using drawings and hence as-built details may differ. The dataset does not cover the entire building stock in the target area, but helps identify vulnerabilities in buildings of certain types described earlier in this section. It is important to note that the database does not identify which buildings have been retrofitted, an important future step in understanding the vulnerability of buildings in Wellington. One potential use of a dataset of this type is described by Puranam et al. [40] where guidelines for assessment of precast floor systems [25] are applied to the dataset to obtain an overview of the vulnerabilities.

Following the 2016 Kaikoura Earthquake and the collapse of precast flooring in Statistics House, the WCC launched the Targeted Assessment Programme [4] to address public safety and conduct engineering investigations of buildings most affected by the earthquake. This program produced a list of 64 buildings (TDE dataset) with characteristics similar to Statistics House for targeted damage evaluation (TDE). These buildings were evaluated following the Targeted Damage Evaluation Guidelines prepared by New Zealand Society of Earthquake Engineering (NZSEE) and Structural Engineering Society of New Zealand (SESOC) [41]. Figure 13 presents a summary of the buildings in the TDE dataset. Approximately 95% of these buildings had more than 5 storeys and approximately 70% had ductile concrete moment-frames for lateral resistance. Over 80% of the total floor was occupied by commercial and public entities. Approximately 65% of the cases had hollow-core floor units, approximately 20% had rib and timber infill units, and about 10% had double-tee units. Further details about this dataset were presented in the Kestrel Group Report [4].

BUILDING USE AND OCCUPANT CLASSIFICATIONS IN THE STUDY AREA

Wellington is the fourth most densely-populated city in Australasia. Recent employment growth has been heavily concentrated in the CBD, which also explains the strong trend toward inner-city apartment living [42]. Therefore, understanding exposure of businesses and residents to seismically vulnerable buildings will help with minimising economic disruption and population loss following seismic events. The aim is to integrate structural vulnerabilities with building use and occupancy details to eventually identify the occupancies most likely to be disrupted by future earthquakes.

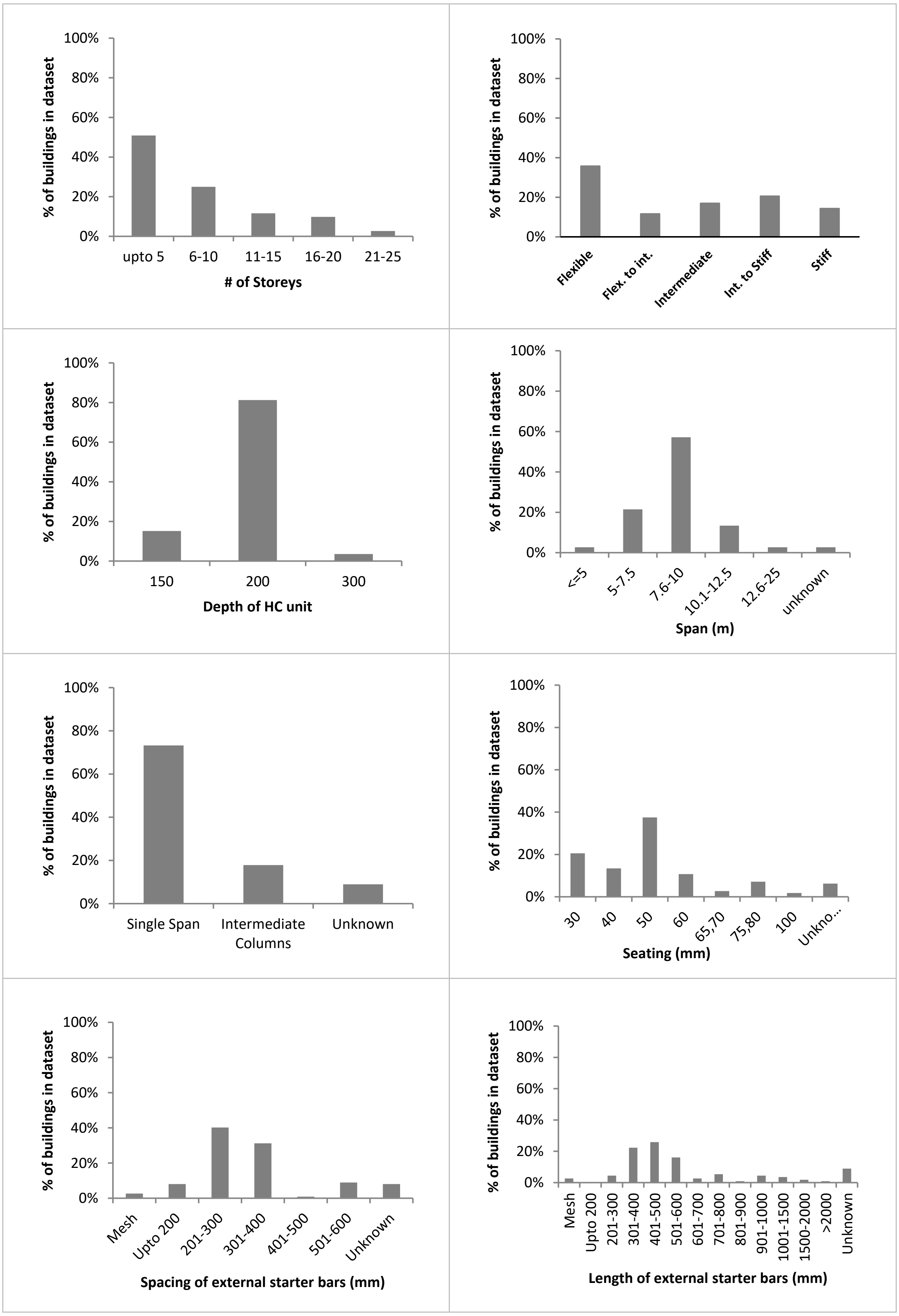


Figure 12: Summary of HOLL Dataset.

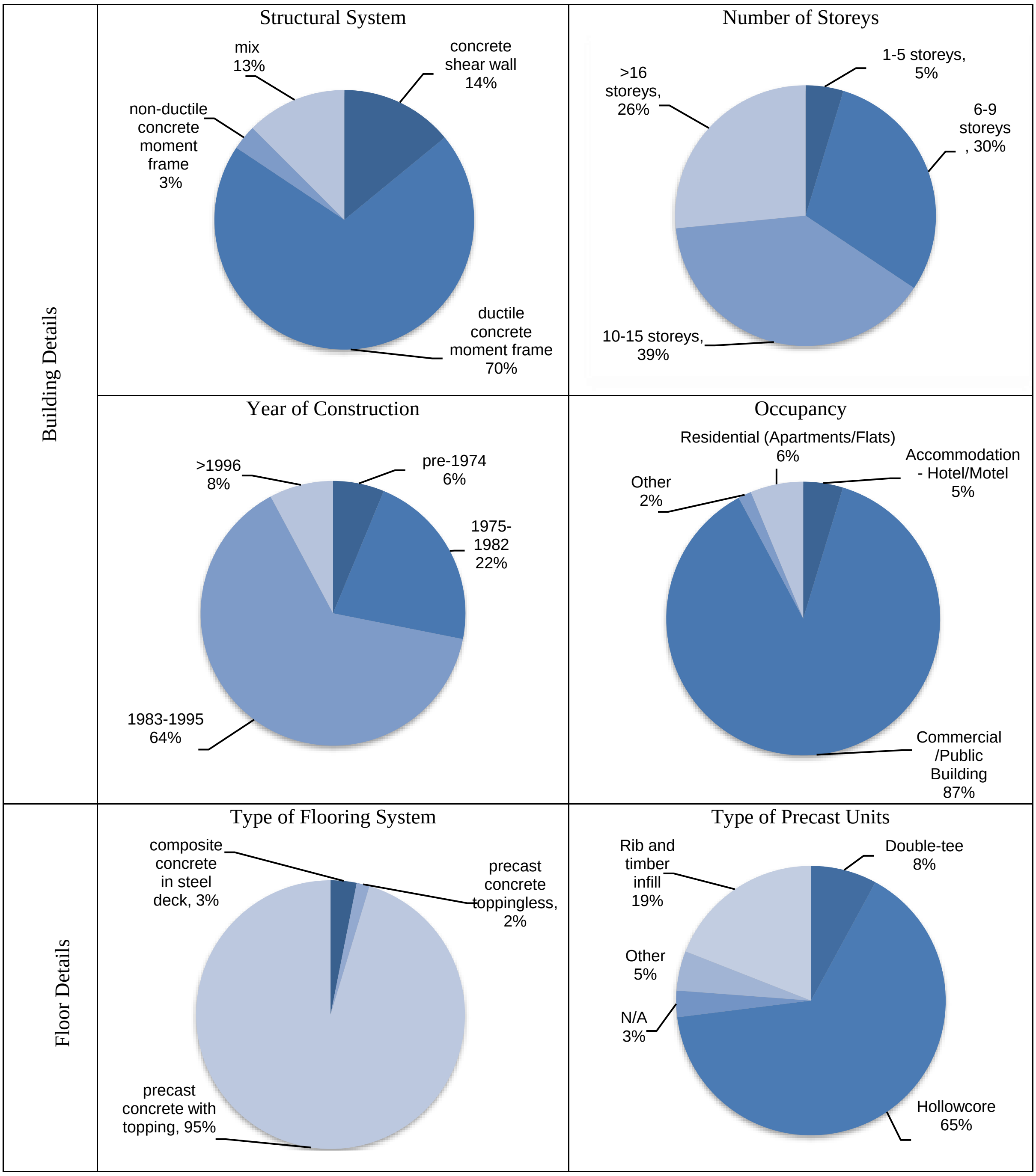


Figure 13: Summary of TDE Dataset.

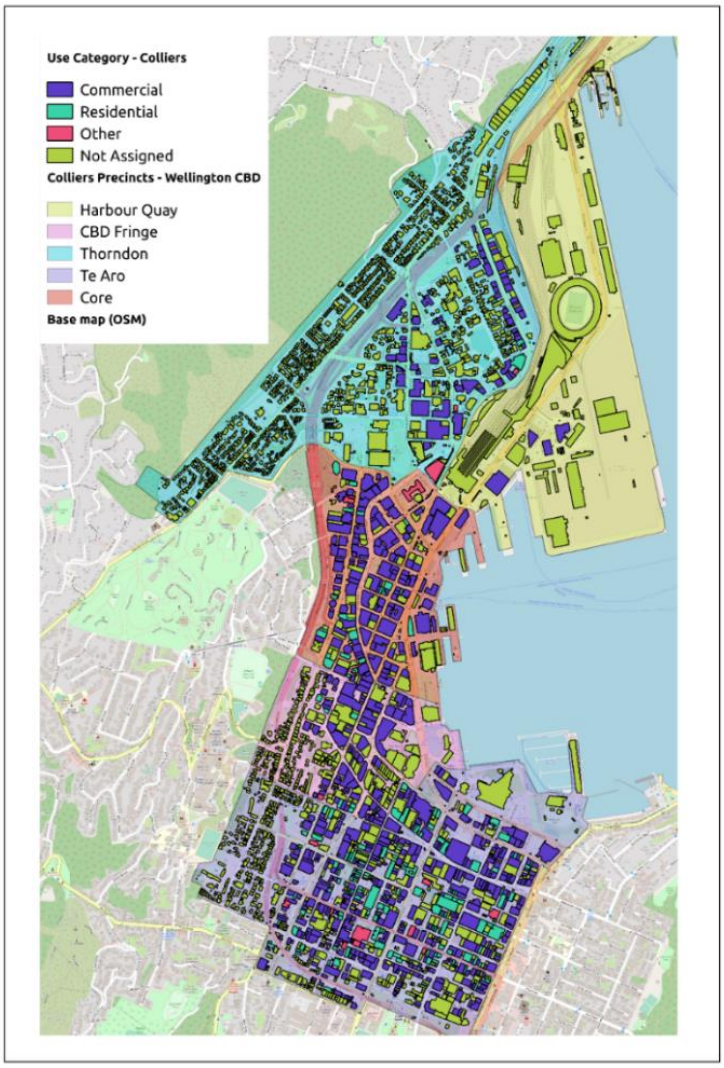


Figure 14: Boundaries of precincts and representation of buildings within the Colliers survey

Several private firms conduct regular surveys of commercial space availability within the Wellington CBD. The primary purpose of these surveys is to update the supply of commercial office space and identify space available for rent. Colliers International supplied their June 2016 (pre-Kaikoura) and June 2017 (post-Kaikoura) vacancy surveys for the current study. The Colliers dataset contains 974 buildings covering various building uses such as commercial (office, retail, accommodation), residential and other (e.g. utilities, transport, religious etc). The primary purpose of the survey is to quantify the amount of office space available to rent. Detailed information on occupants (tenants) is only collected for office buildings and contains information such as building address and name, tenant/occupant company name by floor level, amount of space occupied by floor level, vacant spaces and an indicator of the building's quality in relation to the market (assigned using the standard Property Council of New Zealand office quality grading - A, B, C). The area covered by the survey is divided into five precincts: Core, Fringe, Thorndon, Harbour Quays and Te Aro (Figures 14 and 15). Consistent with Blaikie and Spurr [15], commercial office buildings continue to constitute a majority of the building stock in the CBD, followed by retail and multi-unit residential buildings. Inventory of office space in Wellington's CBD indicates there is approximately 1.4 million m^2 of lettable area (Table 2). It should be noted that commercial properties in Harbour Quays precinct were removed from the June 2017 Colliers survey because of damage following the Kaikoura Earthquake[1]. The highest concentration of office space is in the Core precinct constituting nearly half of all available space in the CBD as well as providing the majority of the higher-grade facilities. In contrast, Te Aro's older office stock offers mostly C-grade premises for occupants (Figure 16). As a result of new builds in the CBD and the central government's Wellington Accommodation Project (aimed to reduce government office footprint), vacancy rates of lower grade office space (B and C) are expected to continue to increase. For example, while the overall vacancy rate in the CBD is around 7%, Te Aro's vacancy sits at 17%. As office buildings become obsolete and unmarketable, they are becoming increasingly popular targets for residential conversions [43, 44].

1 Colliers survey monitors space availability in six commercial buildings within the precinct. All of the space was unavailable in June 2017 due to seismic damage.

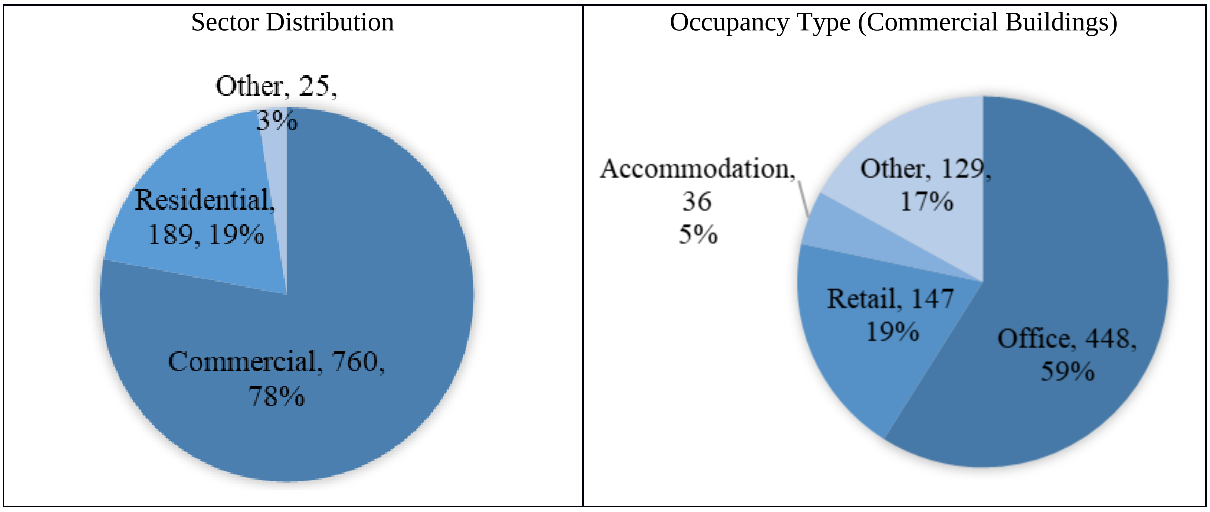


Figure 15: Sector and occupancy type distribution of buildings within the Colliers survey.

Table 2: Inventory of occupied office space in Wellington CBD (includes user-owned and letted areas).

Precinct	Core	Thorndon	Fringe	Te Aro	Harbour Quays*
Lettable area (m^2)	700,979	164,435	286,228	261,972	38,633
No of buildings	111	28	56	125	4

* Harbour Quays office buildings suffered damage in the Kaikoura Earthquake and were removed from the survey

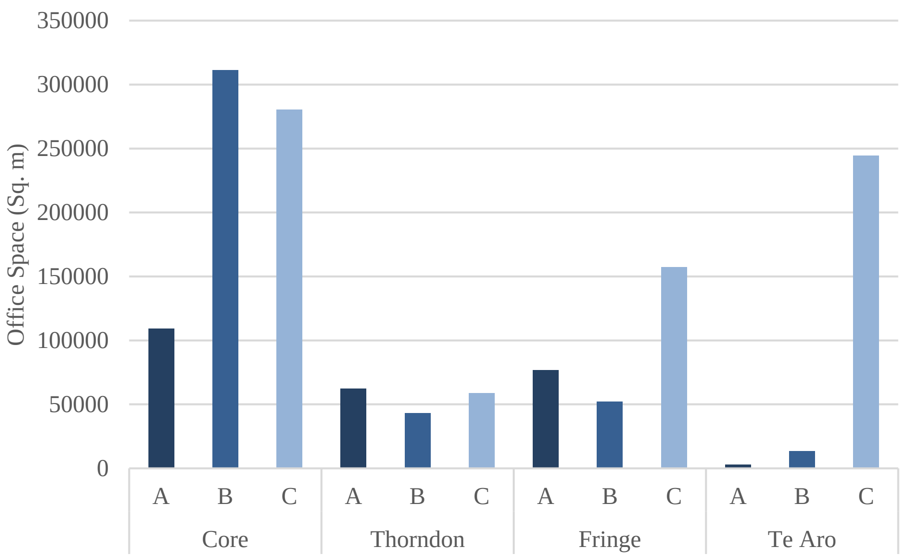


Figure 16: Space inventory by quality grade and precinct.

Classification - ANZSIC06 New Zealand Standard Industrial Output Categories (NZSIOC)

Level 1	Level 2	Level 3	Level 4	
MN	**Professional, Scientific, Technical, Administrative and Support Services**			
	MN1	Professional, Scientific and Technical Services		
		MN11	Professional, Scientific and Technical Services	
			MN111	Scientific, Architectural and Engineering Services
			MN112	Legal and Accounting Services
			MN113	Advertising, Market Research and Management Services
			MN114	Veterinary and Other Professional Services
			MN115	Computer System Design and Related Services
	MN2	Administrative and Support Services		
		MN21	Administrative and Support Services	
			MN211	Travel Agency and Tour Arrangement Services
			MN212	Employment and Other Administrative Services
			MN213	Building Cleaning, Pest Control and Other Support Services

Figure 17: Extract from the NZIOC industry classification system.

Using the listed company names within the Colliers dataset, each occupant was further categorised under standardised industry classification (e.g. accounting services, early childhood education, central government administration, etc.). Industry assignment was completed with the NZSIOC [New Zealand Standard Industrial Output Categories] classification system which consists of four levels (**see** Figure 17). Businesses (occupants) were assigned the most detailed industry category, which is contained in Level 4. Using company name and address, we conducted online searches to assign appropriate classifications. For example, 'Travel Harbour City' is a travel agency and was assigned classification 'MN211' (Travel agency and tour arrangement services). Through this process, the industry composition within the CBD and their spatial concentration/dispersion were analyzed. Unsurprisingly, the single largest occupant in the CBD is the Central Government, mostly taking up space in the adjacent precincts of Core and Thorndon. This is followed by supporting industries within the Professional, Scientific, Technical, Administrative and Support Services category. Combined, these two industries constitute over 50% of occupied space in the CBD (Figure 18).

Assigning industry classification helps with identifying, for example, the approximate number of occupants, and their demographic profile, at different hours of the day (e.g. childcare centres). This information is useful both for post-disaster recovery and for answering the questions posed in the research pursued with the data (e.g., retrofitting prioritization). Combining knowledge of location-based hazards (e.g. soil class, ground shaking intensity), structural vulnerabilities of the building stock, and characteristics of building occupants can also help reduce risk and inform seismic policy. In the next section, we describe the creation of the database of buildings in some detail.

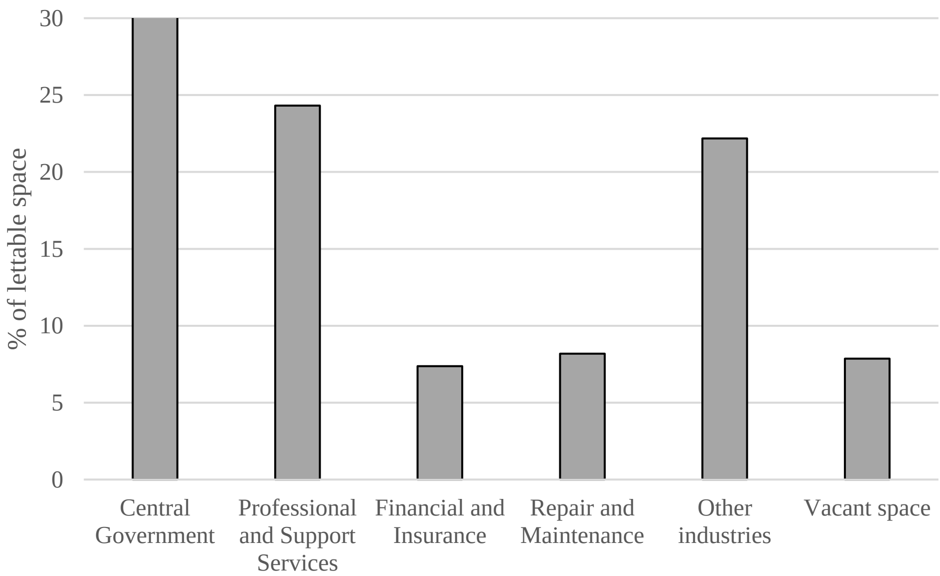


Figure 18: Percentage of lettable space occupied by industry (based on June 2017 survey).

BUILDING INVENTORY DATABASE

A database of buildings in Wellington's CBD was compiled to aid a multi-disciplinary project with the following aims: 1) provide best scientific knowledge about the expected seismic performance of concrete buildings; 2) assess the impact of multiple building failures including the downstream consequences of associated cordoning; 3) provide a path for seismic retrofitting that includes prioritization of retrofits and; 4) inform the design of a regulatory structure that can facilitate the reduction of risk associated with concrete buildings vulnerable to earthquakes as described in (1)-(3).

The inventory contains critical geo-referenced structural and occupancy-related information that is building-specific and therefore presents a useful description of the existing building stock in the Wellington CBD. All data were extracted from the source datasets described in Table 1 and vetted through a street-level survey, and can also be readily updated in the future. In addition, the database is mounted on a map viewer that allows users to access building information based on different access-level profiles. Some of the basic operations that users are able to perform with the map viewer include visualization and filtering. Higher-level operations allow users to access the data (or source datasets) through simple downloads in standard file formats i.e. csv, shp or through standard geospatial services such as WBS and WFS.

Figure 19 provides an overview of the components involved in the creation of the database. A dataset of building footprints collected by the WCC was used as the base layer. Building characteristics including occupancy, use, structural system, flooring system, age of building (obtained from multiple datasets listed and described in Table 1) were linked to the building footprints using their coordinates. The source datasets without information about coordinates (latitude, longitude) but with street addresses were geocoded and then linked to the building footprints. Each footprint was assigned a unique ID which serves as the common link between all datasets. The database is mounted on a map viewer (Figure 20) where the different attributes of the building (see Table 3) can be visualized, queried and accessed.

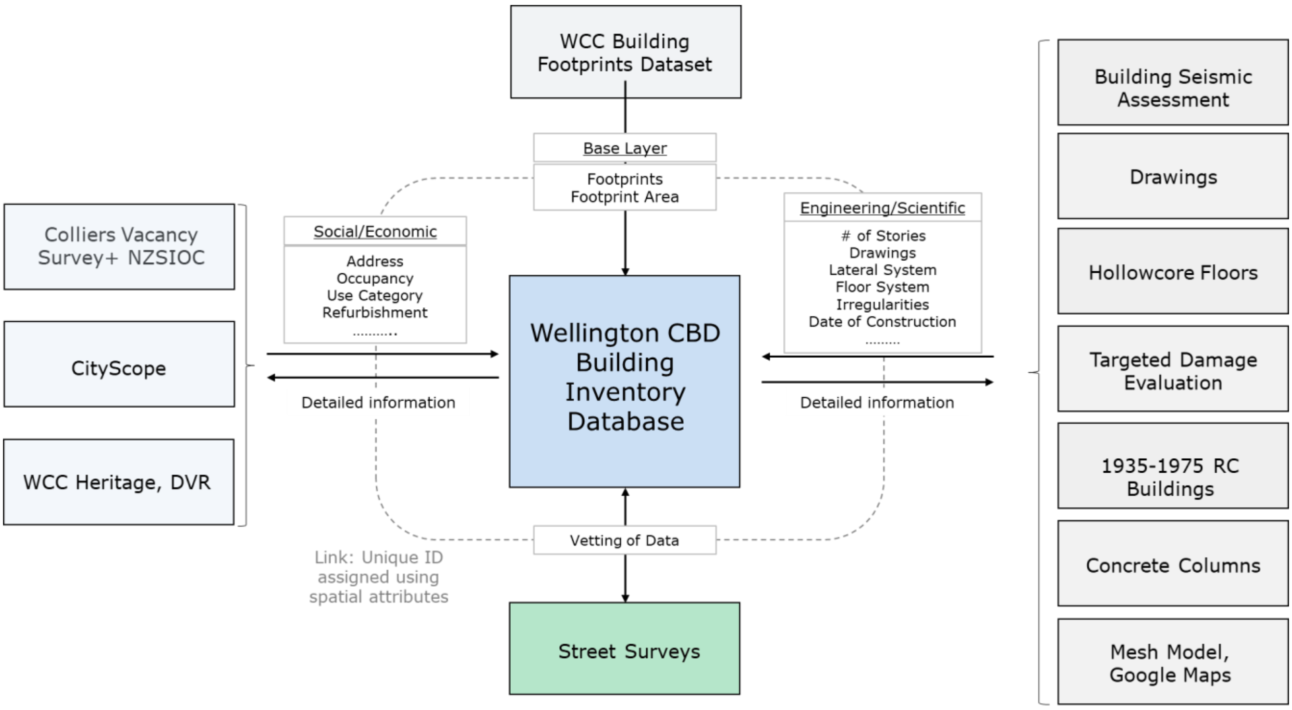


Figure 19: Overview of components of collated building inventory dataset.

This first layer of attributes is meant to provide an overview of spatial distribution of socio-economic, and engineering characteristics. For each variable in the first layer, information was obtained from specific datasets listed in Table 3 and following the hierarchy in which they are listed so that data are extracted from the most reliable sources available. For example, structural systems were identified using vetted databases including BSA, TDE, HOLL, DWG and CONCOL. For buildings with different structural systems in each plan direction, the database identifies the lateral system in each floor-plan direction. The presence of vertical and horizontal structural irregularities was obtained from a mesh model which is a 3-D view of the city, and entered in the database as 'yes' or 'no'. More detailed information is available for different groups of buildings through the source datasets and may be accessed by users with required permissions. The underpinning design of the map viewer is a relational, geospatial database that enables access to the source datasets to investigate specific and detailed aspects of each building with regard to its occupants, age, structural characteristics, ground conditions, etc.

The ultimate goal is to have a database of the building inventory in Wellington's CBD which provides researchers and practitioners with information that is vetted and has high level of confidence/accuracy. To assist with this effort, a street survey co-funded by WCC was also conducted. The purpose of the survey was to vet information within the inventory dataset and to collect missing information. The surveyors (engineering students guided by an engineer) were supplied with tablets pre-loaded with: (i) the building inventory in the map viewer for field data collection, and (ii) a set of detailed guidelines for vetting. The viewer consisted of fields that were editable such as building location, number of storeys, presence of vertical or horizontal irregularities, facade types, and use of ground, basement and upper floors. A critical aspect of the field survey consisted of the determination of the number of unique building structures within the building footprint. In addition, surveyors took photos of the exterior and the occupancy board (for office buildings). Whenever it was possible, surveyors took pictures of any signs of strengthening, visible structural damage, and the warrant of fitness certificate. This information has been added as complementary information to the building inventory and is available through the map viewer. The surveyors also made a note of any inconsistencies between the information in the inventory dataset and visual inspection from the street (e.g. records indicated that the building has a URM system when from the street it appeared to be RC). This is flagged for further checking by an experienced engineer.

This database may be considered 'work-in-progress' as additional datasets are being sourced and combined to fill gaps. For example, after the Kaikoura Earthquake it was widely recognised that non-structural components of buildings are also vulnerable and pose high seismic risk, but little effort had been made earlier to collect data related to these components. Through the street survey, some information was collected about non-structural components (e.g. type of cladding). Street surveyors did not have access to collect more detailed information about the interior non-structural components. The goal is to also collect this information in the near future.

So far, structural and architectural drawings from property files held by the City Council have been obtained for over 250 buildings and those for the remaining buildings in the dataset are currently being collected. The availability of drawings is helping understand a number of other parameters (for example, presence of vulnerabilities associated with non-ductile concrete columns or precast floors, type of structural irregularities). This information is also of importance for the second objective of the project related to scenario testing and consequences of building failure. Within the map viewer, researchers are able to identify vulnerable buildings by specific characteristics (e.g., non-ductile concrete columns, hollow-core floor units with short seating lengths, etc.) and access links to other resources such as drawings or photos taken by the street-level surveyors.

As mentioned previously, the focus of this project is on the Wellington CBD. There are over 3400 building footprints in project scope area (Figure 1) in the Wellington Footprints Dataset. From this, a subset of 709 footprints in the CBD consisting of buildings with total height more than 12 m was selected to represent buildings with 5 or more storeys. Only 709 buildings with 5 or more storeys are currently included in the inventory database. The ultimate objective is to include buildings with fewer than 5 storeys and also expand beyond the CBD area, as additional resources become available.

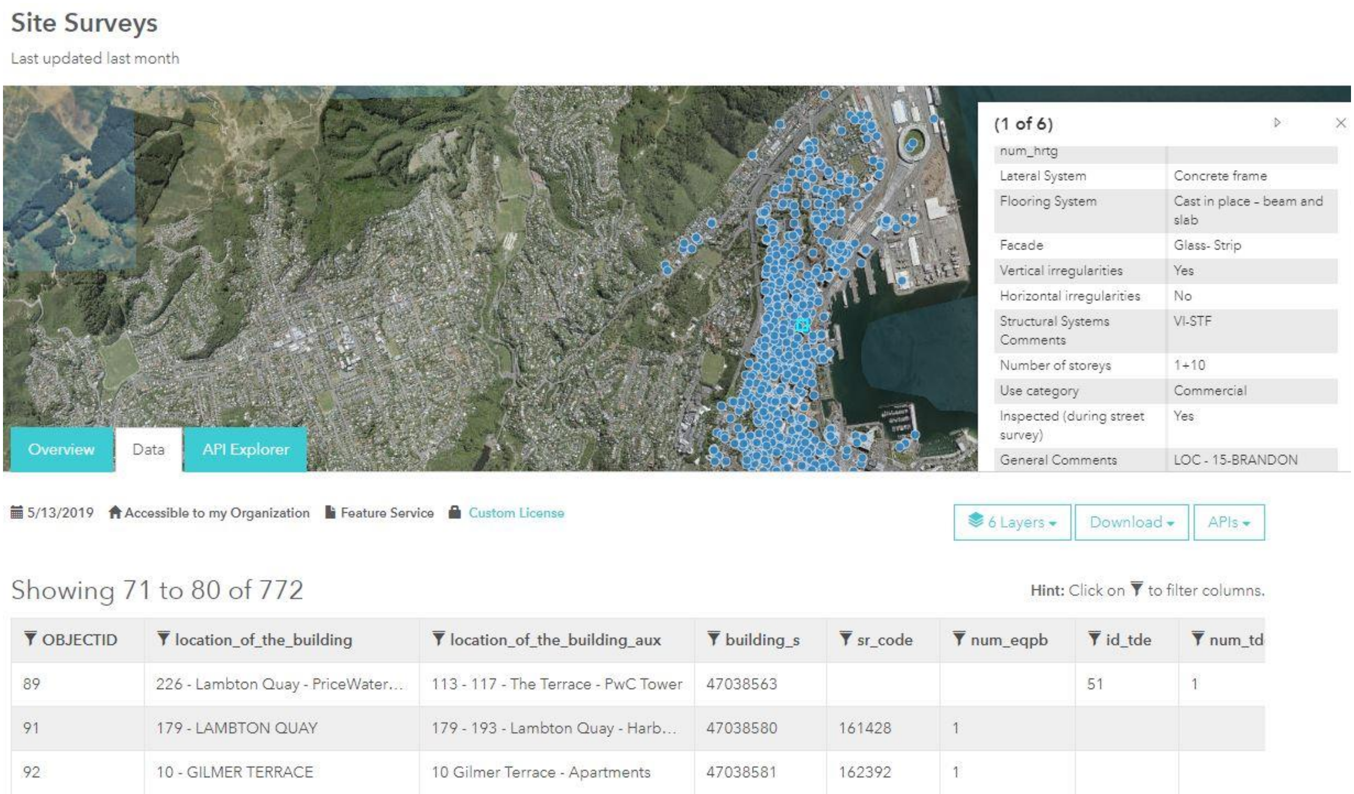


Figure 20: Screen capture of the online building inventory viewer.

Table 3: Summary of properties of base layer.

No	Variable	Source Datasets (Table 1)
1	Inspected (during street survey)	STREET SURVEY
2	Exterior building photos	STREET SURVEY
3	Scanned drawings	DWG
4	Lateral system	BSA, TDE, HOLL, DWG, CONCOL
5	Flooring system	HOLL, TDE, DWG
6	Facade	3D MODEL - STREET SURVEY
7	Presence of Vertical irregularities (yes/no)	3D MODEL- STREET SURVEY
8	Presence of Horizontal irregularities (yes/no)	3D MODEL - STREET SURVEY
9	Comments – structural systems	STREET SURVEY
10	Number of storeys	TDE, HOLL, DWG, 3D MODEL, STREET SURVEY
11	Year of construction	BSA, HOLL, TDE, WCC (parcels), CONCOL, DRAWINGS
12	Address	BSA, TDE, DWG, HOLL, STREET SURVEY
13	Heritage	WCC
14	Use category	COLLIERS – CITYSCOPE – STREET SURVEY
15	Comments – general	STREET SURVEY
16	Spatial Building ID	WCC-BFP
17	Meshblock ID	STATS NZ – Meshblocks 2013
18	Floor area	TDE, HOLL, DWG, 3D MODEL * WCC or CITYSCOPE
19	Footprint area	WCC- BFP
20	Approximate Height	WCC- BFP
21	Last year of Refurbishment	CITYSCOPE
22	Building name	BSA, TDE, HOLL, DWG, COLLIERS, CITY SCOPE, STREET SURVEY
23	Number and Street address	BSA, TDE, HOLL, DWG, COLLIERS, CITYSCOPE, STREET SURVEY
24	Earthquake-prone status	BSA

A problem encountered early on in creating the database was the disconnect between the different strands of data (i.e. source datasets): most datasets do not cover - in detail - the entire building stock in the target area. For example, the Colliers dataset includes information about 60% of the 709 buildings. Datasets of structural characteristics created for specific purposes offer the highest reliability but least coverage. For example, the TDE dataset covers only 8% of the selected cases in the target area, but includes information vetted by engineers (Figure 21). In future work, we aim to develop processes that will allow a user to identify buildings that are similar to a building whose data are missing, so that it can be assessed as a 'proxy' building.

The available datasets serve as valuable resources to understand the building inventory in Wellington and present the opportunity to identify effective means for future data collection. Examples of lessons learnt and solutions to challenges encountered thus far include the creation of a unique building ID to merge information from different source datasets and using a hierarchy to extract information from the most reliable source for cases where one parameter is listed in multiple datasets. An example of one of the uses of the integrated dataset is shown in Figure 22. The observed damage to a number of modern commercial buildings during the November 2016 Kaikoura Earthquake was attributed to ground conditions. Merging ground conditions with the comprehensive building inventory dataset, will help prioritise buildings for retrofitting in vulnerable locations.

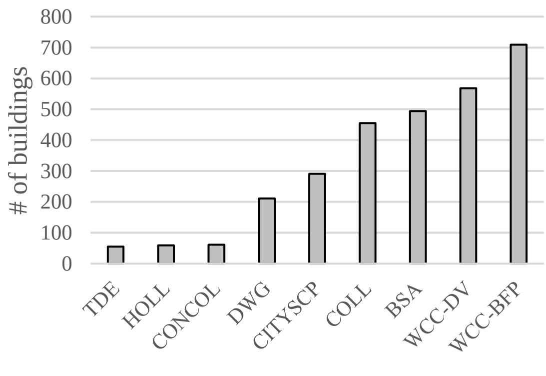


Figure 21: Distribution of source dataset coverage for buildings with total height larger than 12 m in Wellington CBD.

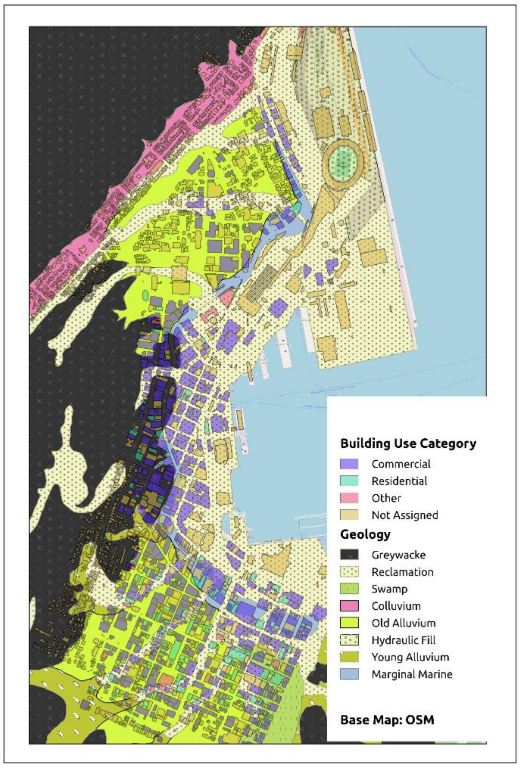


Figure 22: Geologic characteristics of Wellington CBD (Semmens et al., [45]) overlaid with building use category information (Colliers International).

SUMMARY

Efforts made by the WCC and other public and private stakeholders have produced a number of useful databases that contribute to the construction of an integrated building inventory database for Wellington CBD. This paper presented a summary of existing building inventory in Wellington using the available datasets with the view that an integration/ combination of these datasets and easy access to information can lead to better understanding of seismic risks, informed mitigation actions, and quicker response after an earthquake.

Two aspects of the building inventory (structural vulnerabilities, use category and occupancy) were discussed in detail. Structural vulnerabilities of the existing reinforced concrete buildings were explained using information from four different datasets, while use and occupancy were described using biannual surveys conducted by Colliers International.

The paper also described an on-going effort to integrate the different strands of data possessed by multiple stakeholders into an effective and usable multi-disciplinary building inventory spatial database for Wellington CBD as well as future directions for this database and its uses. The ultimate objective of this multi-disciplinary project is to develop a tool which combines information in disparate building databases to improve seismic resiliency by informing strategic retrofit prioritization through the identification of critical structural deficiencies which can lead to building failures, and quantifying the downstream economic and social impacts of these failures.

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