Structural seismic attributes of Auckland's commercial building stock

2014 NZSEE Conference

K.Q. Walsh

University of Auckland & Auckland Council, Property

P.A. Cummuskey

Auckland Council, Building Control

D.Y. Dizhur & J.M. Ingham

University of Auckland

ABSTRACT: As part of past hazard modelling projects in New Zealand, pilot studies have been performed to determine building typological information relevant to structural engineers and seismological hazard researchers. Relevant typological information includes construction material, structural configuration, age of the structure, number of stories, as well as the presence of structural vulnerabilities including parapets, geometric irregularities, pounding potential, and short column effects. The procurement of such typological information permits risk modellers to compose more accurate simulations, structural engineers to develop assessment and retrofit techniques for prototypical buildings, and for large asset owners to more precisely evaluate their risk profiles in comparison to the total building population. However, these studies have often been limited by the availability of structural plans and specifications and, in particular, efficient database storage of such relevant information on a large scale. Hence, many of these pilot studies have consisted mostly of visual inspections from street walks in a few specific cities within the country, with the data then being extrapolated to other cities in proportion to census data and commercial real estate figures.

As territorial authorities, government agencies, and other large asset owners are responding to regulatory and market forces in the wake of the 2010-2011 Canterbury earthquakes to assess and retrofit buildings determined to be particularly vulnerable to earthquakes, an opportunity exists to expand upon the knowledge of structural typologies within New Zealand's commercial building stock. Two departments at Auckland Council – Building Control and Property – are currently engaging in proactive efforts to assess thousands of commercial and industrial buildings across the Auckland region. Auckland is expected to have the most varied building stock containing representative examples of nearly all types of buildings throughout New Zealand given that it houses one-third of the country's population and has been isolated from major, infrastructure-destroying earthquakes such as other major New Zealand population centres have experienced in the past 150 years that have subsequently resulted in those areas having more homogenous building stocks today.

1 INTRODUCTION

While the apparent seismic hazard in Auckland is relatively low, especially in central Auckland where a plurality of population and URM buildings reside, the vulnerability of Auckland's built infrastructure is high. As of 2012, Auckland's economy accounts for an estimated 37% of New Zealand's GDP, and the region's economic growth has outpaced New Zealand's national economic growth 7 of the past 11 years (Monitor Auckland 2012). Auckland's regional population of about 1.3 million in 2006 (Statistics New Zealand 2006) accounted for 32.4% of the nation's population. Hence, a major natural disaster in Auckland would directly or indirectly affect most people throughout New

Zealand.

Auckland Council released its updated *Earthquake-Prone, Dangerous & Insanitary Buildings Policy* (Auckland Council 2011) in response to the Building Act (New Zealand Parliament 2004) requirements that territorial authorities adopt such policies (Section 131) to identify if buildings are considered earthquake-prone (Section 122), dangerous, or otherwise unsuitable for human occupation. The 2011 policy was an update to the 2006 policies of the former Auckland territorial authorities. Under the current policy, a process has been outlined for identifying earthquake-prone buildings and, where applicable, working with building owners to establish a scope and timetable for any building improvements. Auckland Council regulatory policy mandates that most normal buildings deemed by Building Control to be earthquake-prone be retrofitted within 20 years, and additional allowances are provided for buildings with heritage value.

Separate from the local policy, the Canterbury Earthquakes Royal Commission (CERC, Cooper et al. 2012) reported on the causes of building failure as a result of the 2010-2011 Christchurch earthquakes as well as the legal and best-practice requirements for buildings in New Zealand Central Business Districts (CBDs). Auckland's CBD is one of these districts. The inquiry began in May 2011 and recommendations from the Royal Commission are likely to be implemented into building regulations by the Ministry of Business, Innovation and Employment (MBIE) and into a new version of the Building Act (New Zealand Parliament 2004) expected in 2014. New regulations from MBIE (2013) detailing such proposed regulations recommended that consideration be given to accelerating average seismic assessment timeframes across the country such that all "earthquake-prone" buildings be inspected within 5 years and seismically retrofitted within 20 years from the passing of the next Building Act. Regulations related to seismic risk notification and mitigation will also be addressed in a pending update to the Health and Safety in Employment Act (New Zealand Parliament 1992) expected in 2014.

In addition to regulatory policy and technical guidelines, the Auckland Plan (Auckland Council 2012) was developed as the master plan for all activities within Auckland Council, with the primary goal of "creating the world's most liveable city." The Auckland Plan addresses the built environment and lists "build resilience to natural hazards" as one if its priorities and to "increase the proportion of residents who understand their risk from natural hazards and are undertaking measures to mitigate or reduce their risk from 2011 levels to 80% by 2040" as one of its targets. The Auckland Plan directly references "ground shaking hazards" as one of these natural hazards.

In response to these regulations, policies, and plans, Auckland Council has worked with contracted professional engineers and with researchers from the University of Auckland to assist the Auckland Council departments of Property and Building Control to inspect and document buildings in the region that are most likely to be vulnerable to earthquakes. All affiliates follow inspection guidelines to procure data, records, and photographs to aid the council in prioritising buildings for further assessment and, potentially, seismic retrofitting. The inspectors have been utilising a programme based largely on the Initial Evaluation Procedure (IEP) per NZSEE (2006), but they have also been applying more advanced metrics in order to improve both the accuracy and the bandwidth of building assessment scores so as to facilitate efficient retrofit prioritisation.

2 BUILDING TAXONOMIES AND DATA CONSIDERED

With the intention of leveraging the data being procured through the aforementioned inspection processes for application to hazard models, the authors considered two specific building taxonomical classification schemes – the Global Earthquake Model (GEM 2013) and Riskscape (King and Bell 2006; Riskscape 2010). Charleson (2011) provides a review of other existing structural taxonomies and explains the suitability of GEM on a global scale. Riskscape is the preferred hazard modelling system of the Institute of Geological and Nuclear Sciences (GNS) in New Zealand, so classifying building data to its taxonomy provides the most regional relevance and correlates with previous work in this area (Uma et al. 2008). Table 1 lists the general attribute groups considered by each taxonomy and marks with "X" the attribute groups considered in this paper. Note that the biggest difference between the two classification schemes is that Riskscape considers more attributes related to occupancy and costs, whereas GEM considers structural attributes more strictly and more thoroughly.

Table 1. Summary of building taxonomies and attributes

GEM (2013)		Riskscape (2010)	
Attribute group	Data availability	Attribute group	Data availability
Direction	*		
Material of the lateral load-resisting system	X	Construction type	X
Lateral load-resisting system	X		
Height (Incl. # of storeys above ground)	X	Floor height	*
		Storeys	X
Date of construction or retrofit	X	Year of construction	X
Occupancy (Usage type)	X	Use category	X
Building position within a block	*		
Shape of the building plan	*		
Structural irregularity	*		
Exterior walls	*	Wall cladding class	*
Roof	*	Roof cladding class	*
		Roof pitch	*
Floor	*	Floor type	*
Foundation system	*		
		Condition	*
		Contents value	
		Deprivation Index	
		Employee daily income	
		Floor area	**
		Footprint area	**
		Occupancy (# people)	**
		Parapet	*
		Replacement-cost	**
		Vehicle value	
		Vehicles	

Notes:
X = attribute information currently considered within existing inspection programmes;
* = attribute information that will be considered within planned, future inspection programmes;
** = attribute information available through other data sources such as Quotable Value NZ

For purposes of this study, the term "commercial" buildings is defined as including industrial buildings and multi-unit, rent-tenanted residential buildings in addition to those traditionally considered commercial. However, low-unit residential (e.g., single-family houses and condominiums) are excluded. This definition is consistent with the regulatory authority of Auckland Council Building Control.

The current amalgamated database of commercial buildings in Auckland includes 17,414 buildings. The authors expect that this list represents a large majority of commercial buildings in Auckland. Estimates of the total number or percentage of buildings within a particular typology are considered as if 17,414 is the total number of commercial buildings in Auckland. However, not all of the 17,414 buildings have been inspected. Where appropriate, a distinction has been made between whether quantitative values represent "documented" or "estimated" buildings as well as whether percentages represent proportions including or excluding unknown building attribute data. Furthermore, a bias exists in the documented data. Investigators have prioritised older buildings most likely to be vulnerable to earthquakes, producing a partiality in the data pool to older, taller buildings close to the city centre with a particular emphasis on unreinforced masonry buildings. These biases have been accounted for and corrected as much as possible, as noted in the following sections. Finally, non-occupied monuments, kilns, chimneys, and ruins are not considered in this study.

3 PRIMARY LATERAL LOAD-RESISTING MATERIAL AND SYSTEM

In the amalgamated database, 2570 buildings have been documented with a particular primary lateral load-resisting system (LLRS). Auckland Council Building Control has provided the vast majority of this information, so the structure type nomenclature used in the Auckland Council / University of Auckland (AC / UoA) study has been matched to the precedent set by Building Control. These categories are listed in Table 2 along with their presumed equivalents in the Riskscape (2010) taxonomy. The GEM (2013) taxonomy has been left out of Table 2 for simplicity but is included in Table A.1. The number of documented buildings within each AC / UoA structure type category, as well as the estimated total number and percentage of buildings within each Riskscape construction type category, are also listed in Table 2.

Table 2. Summary of primary lateral load-resisting material and structural system attributes

Auckland Council / University of Auckland (AC / UoA)		Riskscape (2010)		
Structure type category	**Documented # bldgs**	**Construction type category**	**Estimated total # bldgs**	**Estimated % of total**
Concrete shear wall*	38	Reinforced concrete shear wall or tilt up panel	611	4%
RCF*	482	Reinforced concrete moment resisting frame (to include hybrid wall/frame)	11925	68%
RCF with block infill*	119			
RCF with brick Infill	139			
RCF with masonry shear wall*	2			
Steel frame*	77	Steel braced frame or steel moment resisting frame	549	3%
Steel frame with brick	1			
Steel frame with concrete block*	2			
Steel frame with RCF*	1			
Timber*,**	764	Light timber	2612	15%
Timber with blockwall perimeter*	1			
Timber with brick	3			
Timber with brick cladding*,**	2			
Timber with concrete block*	1			
Timber with steel frame*	1			
Other with steel tanks	4	-	-	-
URBM	812	Brick masonry (to include stone masonry)	1026	6%
Stone masonry (URSM)	19			
Masonry shear wall	102	Concrete masonry	691	4%
Unknown	14843	Unknown commercial	-	-
Unknown with brick cladding	1		-	-
Total	**17414**	**-**	**17414**	**100%**

Notes:
* = building groups where estimated % of total is adjusted for construction date bias as explained in Section 5
** = "Timber with brick cladding" appears to have been a largely overlooked classification option during the inspection process as it is assumed that many buildings documented as consisting merely of "timber" likely also have brick cladding; however, this is a trivial point for the results discussed here.
RCF = reinforced concrete frame
URBM = unreinforced brick masonry
URM = unreinforced masonry, which includes both brick and stone construction
URSM = unreinforced stone masonry

The bias in the documented data for structural system likely over-represents unreinforced masonry and timber buildings because these are the two building types associated with older, heritage-designated buildings. While light timber-framed buildings are not usually considered especially vulnerable to earthquakes, they have been inspected in greater numbers in the attempt to document all unreinforced masonry buildings in Auckland per the recommendations of the CERC (Cooper et al. 2012) recognising that these two building types often appear similar at street view. Hence, for estimations of the total building stock (assumed to be 17,414 buildings as noted previously), the estimated total number of unreinforced masonry buildings was capped at 1026 per Russell (2010) and Russell and Ingham (2010), and the estimated percentage consisting of timber buildings was capped at 15% per Cousins (2005), who extrapolated building data from Wellington to Auckland. Note also that Cousins (2005) assumed that Auckland's URM buildings represented 5% of its total commercial building stock, which is consistent with the estimated numbers listed in Table 2. Proportions of the building stock consisting of steel and concrete masonry construction were assumed to be accurately represented in the documented data, and the remainder of the total building stock was assumed to consist of reinforced concrete (RC) construction with the proportion of frames (RCF, including hybrid wall/frame systems) to shear walls (19.5:1) assumed to be consistent with documented data. A comparison of documented and estimated structure type proportions is included in Figure 1 using Riskscape (2010) construction type categories.

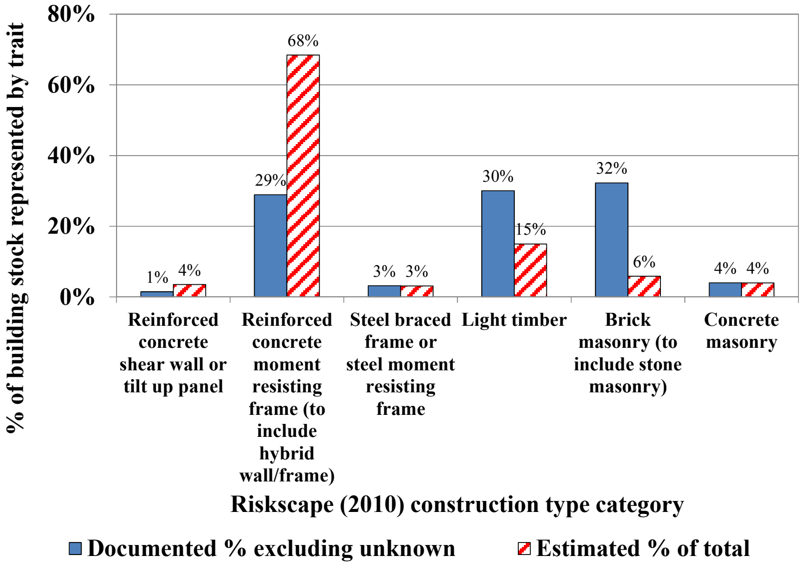


Figure 1. Proportions of documented and estimated, respectively, commercial buildings in Auckland by construction type

4 NUMBER OF STOREYS

In the amalgamated database, 5480 buildings (of various structure types) have been documented with a particular number of storeys above grade, although Auckland Council Building Control has simplified the data entry by capping the recording of number of storeys at eight or more, as shown in Figure 2. Furthermore, for typological groupings to include multiple attributes (e.g., structure type, number of storeys, and age of construction), buildings with a number of storeys below eight have been grouped into categories of 1-3 storeys and 4-7 storeys, consistent with previous typological groupings used in New Zealand (Uma et al. 2008). The proportions associated with these simplified storey groupings are listed in Table A.2.

The bias in the documented data for number of storeys above grade likely over-represents taller buildings given the initial emphasis on inspecting buildings near the city centre as well as the inherent higher profile of taller buildings and the higher risk consequence associated with them. Hence, the total number of estimated buildings with 8+ storeys (287) was capped at the current number of buildings documented with 8+ storeys, and proportional extrapolations were made only for buildings with fewer than 8 storeys.

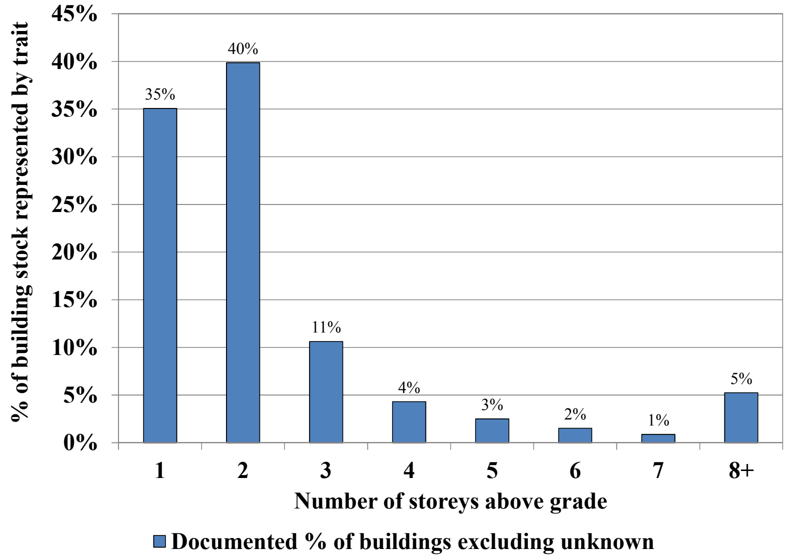


Figure 2. Proportions of documented commercial buildings in Auckland by number of storeys above grade

5 YEAR OF CONSTRUCTION OR RETROFIT

In the amalgamated database, 12,541 buildings have been documented with a particular or approximate year of construction, reconstruction, or seismic retrofit to the primary lateral load-resisting system. For typological groupings to include multiple attributes (e.g., structure type, number of storeys, and age of construction), buildings have been grouped into ranges of years consistent with major updates to the loading standard and with previous typological groupings used in New Zealand (NZSEE 2006; Uma et al. 2008; Fenwick and MacRae 2009). The proportions associated with these simplified year groupings are illustrated in Figure 3 and listed in Table A.3.

As noted previously, the bias in the documented data for year of construction likely over-represents older buildings. Hence, for groups of buildings likely to be affected by this bias in accordance with their structure type category (as noted in Table 2), the estimated number of buildings within those categories has been re-proportioned in accordance with the values shown in Figure 3. Uma et al. (2008), by comparison, estimated approximate proportions of 44% for pre-1977, 28% for 1977-1992, and 28% for 1993+ construction for all of New Zealand, which would indicate that Auckland's building stock is slightly older relative to the rest of the country.

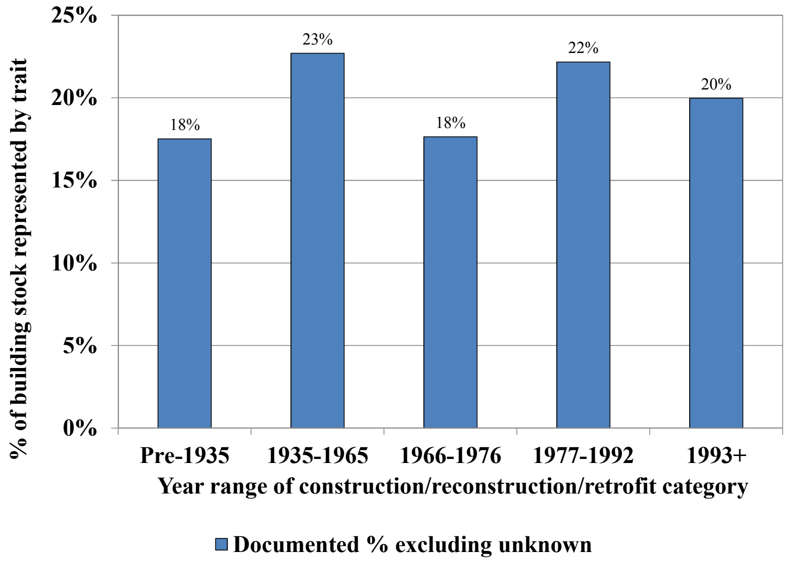


Figure 3. Proportions of documented commercial buildings in Auckland by year of construction, reconstruction, or seismic retrofit

6 TYPOLOGICAL GROUPINGS BY STRUCTURE TYPE, NUMBER OF STOREYS, AND YEAR OF CONSTRUCTION

To facilitate typological groupings conducive to assigning accurate building fragility functions within seismic hazard models, the three primary structural attribute categories of structure type, number of storeys, and year of construction were combined in a hierarchical fashion (consistently for all structure type categories) as exemplified for one structure type category in Table 3 and Figure 4. Note that while such hierarchies within building taxonomies are common and perhaps most useful regionally, they can be restrictive within more encompassing taxonomies and are not favoured in GEM (Charleson 2011). However, the information is presented here in such a fashion for simplicity.

Table 3. Example of typological breakdown by structure type, number of storeys, and year of construction for RCF (without infill) buildings

AC / UoA structure type category	Documented # bldgs within structure type category	Storeys category	Documented # within # storeys category	Year of constr. category	Documented # within year category	Estimated total # of bldgs
RCF*	482	1-3	227	Pre-1935	39	750
				1935-1965	93	973
				1966-1976	57	756
				1977-1992	28	950
				1993+	10	856
				Unknown	0	-
		4-7	138	Pre-1935	47	456
				1935-1965	44	591
				1966-1976	25	460
				1977-1992	11	577
				1993+	11	520
				Unknown	0	-
		8+	96	Pre-1935	16	44
				1935-1965	16	57
				1966-1976	33	44
				1977-1992	18	56
				1993+	13	50
				Unknown	0	-
		Unknown	21	-	-	-
Subtotal	**482**		**482**		**461**	**7139**
Notes: * = building group where estimated % of total is adjusted for date of construction bias as explained in Section 5						

The fifty most prominent building typological groupings by estimated percentage of the total commercial building stock are listed in Table A.4, representing 97% of all of Auckland's commercial buildings. Note the dominance of low to mid-rise reinforced concrete frames in this list.

7 UNREINFORCED MASONRY BUILDINGS (URM)

Cousins (2005) suggests that unreinforced masonry (URM) buildings are 5.4 times more fragile (e.g., empirically-based mean ratio of repair cost to replacement cost is 5.4 times higher) than are post-1980 reinforced concrete (RC) buildings. By comparison, the second-most fragile building type is pre-1980 RC at 2.3 times the fragility of post-1980 RC. Hence, as building performance in the Canterbury earthquakes has proven (Ingham and Griffith 2011a, 2011b; Cooper et al. 2012), URM buildings deserve special attention in a discussion on building typologies in Auckland for purposes of seismic hazard modelling.

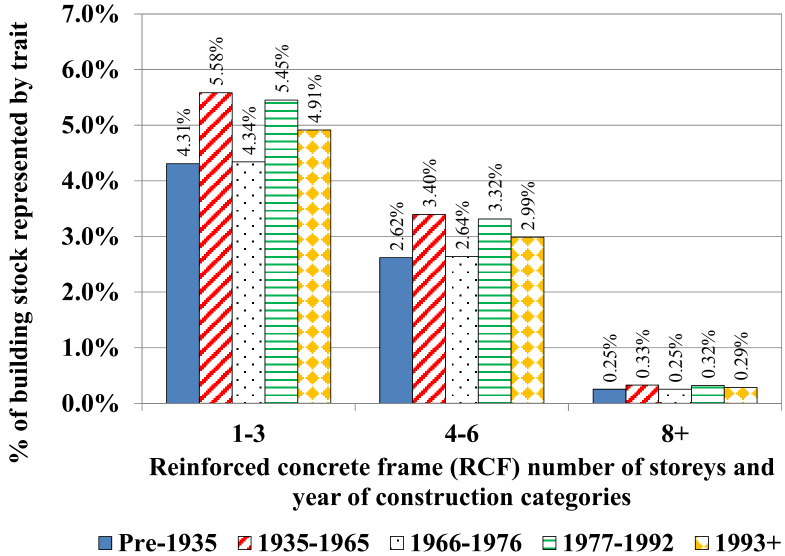
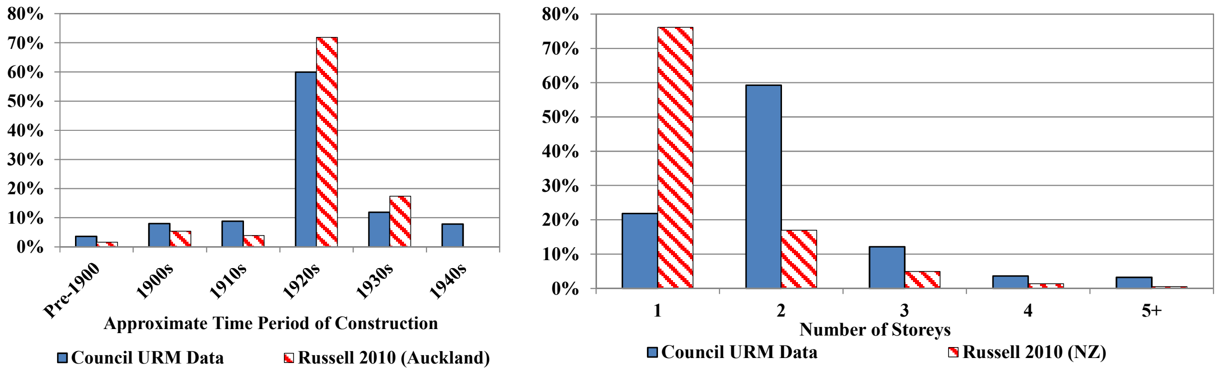


Figure 4. Example of estimated typological breakdown by structure type, number of storeys, and year of construction for RCF (without infill) buildings

Russell (2010) performed an encompassing review of URM buildings across New Zealand and began by cataloguing URM buildings into different sub-typologies based on number of storeys and footprint geometry (e.g., isolated versus row building and rectangular geometry versus non-rectangular). Regarding construction and materials, Russell determined that most URM buildings in New Zealand were constructed of clay brick masonry (approximately 230x110x76 mm bricks) with solid walls being 3 leafs thick. Wall thickness in the base storey will typically increase by one leaf per every 2 storeys in height, such that the lower wall of a 6-storey URM building may be 6 leaves thick. Ground mortar (used between foundations and the walls) in Auckland URM buildings is likely to include red scoria ash, sand, and hydraulic lime that was ground in a mortar mill (O'Connor 1919), and mortar between bricks is likely to include either lime or cement as the adhesive agent, with a wide variety of sand particles depending on how close any given building was to ocean beaches and river banks, as the sand was usually taken from nearby the construction site. Lime-based mortars do not perform as well over time compared to cement-based mortars, especially in buildings near the ocean and exposed to higher concentrations of sea salt spray (Russell 2010).

Russell (2010) estimated construction time periods for the URM buildings in Auckland and number of storeys for URM buildings across the country, and in Figure 5 these estimates are compared to documented data from Auckland. Note that the time periods of construction are fairly consistent between the two data sets. That Auckland would have taller URM buildings than most other New Zealand cities should be expected given its size and density relative to other New Zealand cities. Few URM buildings in Auckland thus far have been found to include seismic retrofits. Most URM buildings in New Zealand were originally constructed before 1940, although a few were constructed in Auckland as late as the 1950s. In the 1965 standard building by-law (NZSS 1900:1965), URM buildings with more than two storeys were prohibited as new construction in Auckland, and no URM buildings of any height have been identified as having been constructed after 1965. Hence, any URM buildings documented as being constructed post-1965 denote major reconstruction or retrofit to an existing URM building. Unfortunately, the specific type of reconstruction or seismic retrofit has not yet been documented for most buildings.



a) Auckland URM building construction time periods, documented AC / UoA amalgamated data for Auckland versus Russell (2010) estimations for Auckland

b) Auckland URM building storeys, documented amalgamated AC / UoA data for Auckland versus Russell (2010) estimations for all of New Zealand

Figure 5. URM data comparisons

University of Auckland researchers identified 19 occupiable buildings in Auckland with above-grade, load-bearing unreinforced stone masonry (URSM) walls. While stone masonry buildings represents such a small portion of the Auckland building stock that they could likely be neglected in high-level hazard models, these buildings tend to be associated with significant heritage, community, and religious value. Furthermore, the GEM (2013) taxonomy accommodates such specific material characteristics as formation of stone (e.g., rubble, semi-dressed, or dressed), type of stone (e.g., limestone, basalt, etc.) and type of mortar (cement, lime or lime-cement). Basalt is the prominent stone-type amongst these buildings.

8 OCCUPANCY / USAGE TYPE AND IMPORTANCE LEVEL

The third component of risk that must be quantified in models, along with hazard and vulnerability, is consequence. Both GEM (2013) and Riskscape (2010) consider attributes related to the functional use or occupancy of the buildings being considered. As noted in Table 1, GEM and Riskscape have different applications for the word "occupancy," but both consider building usage type somewhere within their taxonomies.

In the amalgamated database, 17,377 buildings (nearly all) have been documented with a particular use category. Auckland Council Building Control has provided the vast majority of this information, so the use category nomenclature used in the Auckland Council / University of Auckland (AC / UoA) study has been matched to the precedent set by Building Control. The ten most prominent use categories by estimated percentage of the total commercial building stock are listed in Table 4, representing 86% of all of Auckland's commercial buildings. The presumed counterparts to the AC / UoA use categories in the GEM and Riskscape taxonomies are included Tables A.5 with re-rankings based on the different nomenclature (and by extension, groupings of buildings) listed in Table A.6.

Table 4 also includes a listing of the ten most prominent use categories by average importance level (NZS 1170.0:2002). The importance level can be indicative of the number of people within a building as well as its post-disaster pertinence. Table 5 summarises information from building standards and seismic hazard assessments most relevant to Auckland's buildings. Most buildings in Auckland will likely be considered to have 50-year design working lives for assessment and retrofit design purposes, but some buildings of particular significance to the community could be considered for 100-year design working lives. For design and assessment purposes, most buildings will be assigned importance levels 2 or 3. Importance level 2 applies to normal structures, and importance level 3 applies to buildings containing larger crowds, valuable assets, or serving important functions as defined in the loadings standard (NZS 1170.0:2002). Buildings in Auckland that would most regularly be considered for importance level 3 criteria would likely include schools, libraries, and town halls. Hence, while most buildings would be considered for a design basis earthquake (DBE) to occur every 500 years on average, higher-profile buildings will need to be considered for less frequent events. The recurrence intervals listed in Table 5 correspond with ultimate limit state (ULS) design parameters to include strength, ductility, serviceability, and durability.

Table 4. Ranking of top 10 building occupancy / usage type attributes by percentage of estimated total for Auckland Council / University of Auckland use categories and importance level, respectively

Rank	Auckland Council / University of Auckland		Importance level (NZS 1170.0:2002)	
	Use category	% of total incl. unknown	Use category	Avg. importance level
1	Commercial	54.8%	Excluding special structures with importance level = 5	
2	Retail	7.9%		
3	Office	5.0%	Petrol holding tanks	4.0
4	Education	4.9%	Utility station	3.8
5	Residential	3.8%	Mass transit station	3.7
6	Preschool	3.4%	Emergency services facility	3.7
7	Medical centre	1.6%	Recreation	3.5
8	Utility station	1.5%	Hospital	3.2
9	Church	1.3%	Government	3.2
10	Restaurant	1.2%	Prison	3.1
Total	**-**	**86%**	**-**	**-**

The Modified Mercalli (MM) scale is used to describe the damage and intensity experienced by people at a particular location. MM7 and MM8 intensities approximate the range of hazards relevant to the Auckland region, as shown in Table 5. MM7 intensity is associated with slight to moderate structural damage in well-built ordinary buildings, while MM8 intensity implies considerable structural damage with partial collapse of well-built ordinary buildings (Lindeburg and McMullin 2008).

Table 5. Building design criteria and recurrence hazards for Auckland (NZS 1170.0:2002; Cousins 2005)

Design life	Importance level	Importance level comment	Annual prob. of exceedance for EQ ULS	Approx. MM intensity
50 years	2	Normal structures	1/500	MM6.8
	3	Crowds or valuable assets	1/1000	MM7.2
100 years	2	Normal structures	1/1000	MM7.2
	3	Crowds or valuable assets	1/2500	MM7.6

9 SUMMARY AND FUTURE WORK

As noted in Table 1, commercial buildings in Auckland have been grouped by attributes of structure type, number of storeys above grade, year of construction, and by a combination of these three attributes in order to facilitate the implementation of structural vulnerability functions in seismic hazard models that are more representative of Auckland's actual building stock. Furthermore, the component of consequence has been accounted for provisionally by quantifying buildings by usage type. All of these estimated quantities of building attributes have been tied to their original nomenclature in addition to having been correlated to the taxonomical classification systems of the Global Earthquake Model (GEM, 2013) and the New Zealand GNS Riskscape (2010).

Other data relevant to one or both of these taxonomies is also being accrued currently. Referencing findings from Ingham and Giffith (2011a, 2011b), the CERC (Cooper et al. 2012) emphasised the risk to people nearby buildings from the collapse of parapets, especially parapets consisting of unreinforced masonry and poorly connected concrete. Hence, information on parapets and their relative geometry is planned for future inspections. Information pertaining to building position within a block, shape of the building plan, structural irregularities, and foundation system are also being accrued through structural inspections, and this information is relevant to the GEM taxonomy. Information pertaining to exterior wall cladding material, roof material and geometry, and floor system is being accrued, and this information is relevant to both the GEM and Riskscape taxonomies. Consequence-related information relevant to Riskscape, such as such as condition, floor area, footprint area, number of occupants, and replacement costs, is available through other sources.

10 ACKNOWLEDGEMENTS

The authors acknowledge members of the Departments of Property, Building Control, and Civil Defence at the Auckland Council whose efforts provided much of the cause, background, and current data referenced in this paper. The work done by former students at the University of Auckland, including Alistair Russell, Charlotte Knox, and Ronald Lumantarna, by Marta Giaretton at the University of Padova, and by Lisa Moon, Hossein Derakhshan, and Professor Michael Griffith at the University of Adelaide, is heavily referenced in Section 7.

REFERENCES

Auckland Council 2011. Earthquake-Prone, dangerous & insanitary buildings policy (2011-2016). Adopted by Auckland Council, 24 November, Auckland, New Zealand.

Auckland Council 2012. The Auckland plan, March, Auckland Council, Auckland, New Zealand. http://theplan.theaucklandplan.govt.nz

Charleson, A. 2011. Review of existing structural taxonomies, Global earthquake model. Retrieved 25 December 2013. http://www.nexus.globalquakemodel.org/gem-building-taxonomy/posts/review-of-existing-structural-taxonomies

Cooper, M., Carter, R., and Fenwick, R 2012. Canterbury Earthquakes Royal Commission (CERC) Final report, Vol 1-7. Christchurch, New Zealand. http://canterbury.royalcommission.govt.nz

Cousins, J. 2005. Estimated damage and casualties from earthquakes affecting Auckland City: a report prepared for the Auckland City Council. Institute of Geological & Nuclear Sciences (GNS), Lower Hutt, New Zealand.

Fenwick, R. and and MacRae G. 2009. Comparison of New Zealand standards used for seismic design of concrete buildings, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 42, No. 3, Sept.

GEM 2013. GEM building taxonomy v2.0: an overview, Retrieved 25 December 2013, Global Earthquake Model. http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/

Ingham, J. and Griffith, M. 2011a. The performance of unreinforced masonry buildings in the 2010/2011 Canterbury earthquake swarm, Report to the Royal Commission of Inquiry. ENG.ACA.0001F.2. http://canterbury.royalcommission.govt.nz/documents-by-key/20110920.46.

Ingham, J. and Griffith, M. 2011b. The performance of earthquake strengthened URM buildings in the Christchuch CBD in the 22 February 2011 earthquake, Report to the Royal Commission of Inquiry. http://canterbury.royalcommission.govt.nz/documents-by-key/20111026.569

King, A. and Bell, R 2006. RiskScape New Zealand: A multihazard loss modelling tool. Proc. of the New Zealand Society for Earthquake Engineering Conference, Napier, New Zealand, 2006. Paper 34, 9p.

Lindeburg, M. and McMullin, K. 2008. Seismic design of building structures, 9th ed. Professional Publications, Inc. (PPI), Belmont, California, United States, 2008.

MBIE 2013. Managing earthquake-prone buildings: Policy decisions, Retrieved 25 December 2013, Ministry of Business, Innovation and Employment, Wellington, New Zealand. http://www.dbh.govt.nz/epb-policy-review

Monitor Auckland 2012. Gross domestic product (GDP) and average annual change, Auckland Council. Last updated: 20 January 2012. Retrieved: 12 December 2012. http://monitorauckland.arc.govt.nz/MonitorAuckland/index.cfm?242A576B-1279-D5EC-EDD1-A4B81624B46D.

New Zealand Parliament 1992. Health and safety in employment act, Date of assent 27 October 1992, Department of Labour, New Zealand Government, Wellington, New Zealand.

New Zealand Parliament 2004. Building act, Date of assent 24 August 2004, Department of Building and Housing – Te Tari Kaupapa Whare, Ministry of Economic Development, New Zealand Government, Wellington, New Zealand.

NZSS 1900:1965. Model building by-law, Chapter 8: Basic design loads, New Zealand Standards Institute, Wellington, New Zealand.

NZS 1170.0:2002. Structural design actions, Part 0: General principles, Incorp. Amends. 1-5. Australian Standards (AS) and Standards New Zealand (NZS) Joint Technical Committee BD-006, Wellington, New Zealand.

NZS 1170.5:2004. Structural design actions, Part 5: Earthquake actions – New Zealand, Standards New Zealand (NZS) Technical Committee BD-006-04-11, Wellington, New Zealand.

NZSEE 2006. Assessment and improvement of the structural performance of buildings in earthquakes, recommendations of a NZSEE study group on earthquake risk of buildings, Incorp. corrigenda nos. 1 & 2. New Zealand Society for Earthquake Engineering (NZSEE), Wellington, New Zealand.

O'Connor, J. 1919. Courtville Apartments Architectural Specifications. Auckland, New Zealand.

RiskScape 2010. RiskScape user manual, Ver. 0.2.30, 10 May, Institute of Geological & Nuclear Sciences (GNS), Lower Hutt, New Zealand.

Russell, A.P. 2010. Characterisation and seismic assessment of unreinforced masonry buildings, Doctoral thesis, University of Auckland, Dept. of Civil and Environmental Engineering, Auckland, New Zealand. https://researchspace.auckland.ac.nz/handle/2292/6038

Russell, A. and Ingham, J. 2010. Prelavance of New Zealand's unreinforced masonry buildings, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 43, No. 3, Sept.

Statistics New Zealand 2012. 2006 census, QuickStats about Auckland region. Retrieved 12 December 2012. http://www.stats.govt.nz/Census/2006CensusHomePage/QuickStats/AboutAPlace/SnapShot.aspx?id=1000002&type=region&ParentID=1000002.

Uma, S., Bothara, J., Jury, R., and King, A. 2008. Performance assessment of existing buildings in New Zealand. Proc. of the New Zealand Society for Earthquake Engineering Conference, Wairakei, New Zealand, 11 p.

APPENDIX

Table A.1. Summary of primary lateral load-resisting material and structural system attributes

Auckland Council / University of Auckland (AC / UoA)		**GEM (2013)**					**Riskscape (2010)**		
Structure type category	**Documented # bldgs**	**Material of the LLRS system level 1**	**Material of the LLRS system level 2**	**LLRS Level 1**	**Est. #**	**Est. % of all commercial bldgs**	**Constr. type category**	**Est. #**	**Est. % of all commercial bldgs**
Concrete shear wall*	38	CR (Concrete, reinforced) or SRC (Concrete, composite with steel section)	CIP (Cast-in-place concrete) or PC (Precast concrete) or CIPPS (Cast-in-place prestressed concrete) or PCPS (Precast prestressed concrete)	LWAL (Wall)	611	3.5%	Reinforced concrete shear wall or tilt up panel	611	4%
RCF*	482			LFM (Moment frame)**	7139	41.0%	Reinforced concrete moment resisting frame (to include hybrid wall/frame)	11925	68%
RCF with block infill*	119			LFINF (Infilled frame) [1/2]	2176	12.5%			
RCF with brick Infill	139			LFINF (Infilled frame) [2/2]	2588	14.9%			
RCF with masonry shear wall*	2			LDUAL (Dual frame-wall system)**	21	0.1%			
Steel frame*	77	S (Steel)	SR (Hot-rolled steel members)	LFM (Moment frame)	524	3.0%	Steel braced frame or steel moment resisting frame	549	3%
Steel frame with brick	1			LFINF (Infilled frame) [1/2]	8	0.0%			
Steel frame with concrete block*	2			LFINF (Infilled frame) [2/2]	8	0.0%			
Steel frame with RCF*	1			LH (Hybrid lateral load-resisting system)	8	0.0%			
Timber*	764	W (Wood)	WLI (Light wood members)	LWAL (Wall) [1/2]	2585	14.8%	Light timber	2612	15%
Timber with blockwall perimeter*	1			LFINF (Infilled frame) [1/2]	4	0.0%			
Timber with brick	3			LFINF (Infilled frame) [2/2]	8	0.0%			
Timber with brick cladding*	2			LWAL (Wall) [2/2]	8	0.0%			

APPENDIX

Table A.1. Summary of primary lateral load-resisting material and structural system attributes

Auckland Council / University of Auckland (AC / UoA)		**GEM (2013)**					**Riskscape (2010)**		
Structure type category	**Documented # bldgs**	**Material of the LLRS system level 1**	**Material of the LLRS system level 2**	**LLRS Level 1**	**Est. #**	**Est. % of all commercial bldgs**	**Constr. type category**	**Est. #**	**Est. % of all commercial bldgs**
Timber with concrete block*	1			LDUAL (Dual frame-wall system)	4	0.0%			
Timber with steel frame*	1			LH (Hybrid lateral load-resisting system)	4	0.0%			
Other with steel tanks	4	MATO (Other material)	-	LO (Other lateral load-resisting system)	0	0.0%	-	-	-
URBM	812	MUR (Masonry, unreinforced)	CLBRS (Fired clay solid bricks) or CLBRH (Fired clay hollow bricks) and/or RCB (Reinforced concrete bands)	LWAL (Wall)	1006	5.8%	Brick masonry (to include stone masonry)	1026	6%
Stone masonry (URSM)	19		STRUB (Rubble (field stone) or semi-dressed stone) or STDRE (Dressed stone)	LWAL (Wall)	20	0.1%			
Masonry shear wall	102	MR (Masonry, reinforced)	CBH (Concrete blocks, hollow) and RS (Steel-reinforced)	LWAL (Wall)	691	4.0%	Concrete masonry	691	4%
Unknown	14843	MAT99 (Unknown material)	-	-	-	-	Unknown commercial	-	-
Unknown with brick cladding	1				-	-		-	-
Total	**17414**	**-**	**-**	**-**	**17414**	**100%**	**-**	**17414**	**100%**

Notes:
* = building groups where estimated % of total adjusted for date of construction bias as explained in Section 5
**= it is anticipated that many dual RC wall/frame systems have likely been documented as simply RC frames
RCF = reinforced concrete frame; URBM = unreinforced brick masonry; URM = unreinforced masonry, which includes both brick and stone construction; URSM = unreinforced stone masonry

Table A.2. Summary of documented building storeys above grade

Storeys above grade category	Documented # bldgs	% excl. unknown	Storeys above grade	Documented # bldgs with # storeys	% of total excl. unknown
1-3	4688	86%	1	1922	35%
			2	2184	40%
			3	582	11%
4-7	505	9%	4	236	4%
			5	137	3%
			6	84	2%
			7	48	1%
8+	287	5%	8+	287	5%
Unknown	11934	-	-	-	
Total	**17414**	**100%**	**-**	**5480**	**100%**

Table A.3. Summary of documented building construction year ranges

Year of construction/reconstruction/retrofit category	Documented # bldgs	% of total excl. unknown
Pre-1935	2196	18%
1935-1965	2847	23%
1966-1976	2213	18%
1977-1992	2780	22%
1993+	2505	20%
Unknown	4873	-
Total	**17414**	**100%**

Table A.4. Ranking of top 50 building typological categories by number of estimated buildings

Rank	AC / UoA structure type category	Storeys category	Year of construction/reconstruction/retrofit category	Estimated # bldgs	Estimated % of total
1	RCF with brick infill	1-3	1935-1965	1095	6.3%
2	RCF	1-3	1935-1965	973	5.6%
3	RCF	1-3	1977-1992	950	5.5%
4	RCF	1-3	1993+	856	4.9%
5	RCF with brick infill	1-3	Pre-1935	812	4.7%
6	RCF	1-3	1966-1976	756	4.3%
7	RCF	1-3	Pre-1935	750	4.3%
8	URBM	1-3	Pre-1935	750	4.3%
9	RCF	4-7	1935-1965	591	3.4%
10	Timber	1-3	1935-1965	582	3.3%
11	RCF	4-7	1977-1992	577	3.3%
12	Timber	1-3	1977-1992	568	3.3%
13	RCF	4-7	1993+	520	3.0%
14	Timber	1-3	1993+	512	2.9%
15	RCF	4-7	1966-1976	460	2.6%
16	RCF	4-7	Pre-1935	456	2.6%
17	Timber	1-3	1966-1976	452	2.6%
18	RCF with block infill	1-3	1935-1965	450	2.6%
19	Timber	1-3	Pre-1935	449	2.6%
20	RCF with block infill	1-3	1977-1992	439	2.5%
21	RCF with brick Infill	4-7	Pre-1935	415	2.4%
22	RCF with block infill	1-3	1993+	396	2.3%
23	RCF with block infill	1-3	1966-1976	350	2.0%
24	RCF with block infill	1-3	Pre-1935	347	2.0%
25	Masonry shear wall	1-3	1935-1965	322	1.9%
26	Masonry shear wall	1-3	1966-1976	200	1.1%
27	Concrete shear wall	1-3	1935-1965	139	0.8%

Table A.4. Ranking of top 50 building typological categories by number of estimated buildings

Rank	AC / UoA structure type category	Storeys category	Year of construction/reconstruction/retrofit category	Estimated # bldgs	Estimated % of total
28	Concrete shear wall	1-3	1977-1992	135	0.8%
29	URBM	1-3	1935-1965	126	0.7%
30	Concrete shear wall	1-3	1993+	122	0.7%
31	Concrete shear wall	1-3	1966-1976	108	0.6%
32	Concrete shear wall	1-3	Pre-1935	107	0.6%
33	Steel frame	1-3	1935-1965	99	0.6%
34	Steel frame	1-3	1977-1992	96	0.6%
35	RCF with brick infill	1-3	1966-1976	94	0.5%
36	Steel frame	1-3	1993+	87	0.5%
37	Steel frame	1-3	1966-1976	77	0.4%
38	Steel frame	1-3	Pre-1935	76	0.4%
39	RCF with brick infill	4-7	1935-1965	75	0.4%
40	Masonry shear wall	1-3	1977-1992	69	0.4%
41	RCF	8+	1935-1965	57	0.3%
42	RCF	8+	1977-1992	56	0.3%
43	Masonry shear wall	1-3	1993+	54	0.3%
44	URBM	4-7	Pre-1935	52	0.3%
45	RCF	8+	1993+	50	0.3%
46	RCF	8+	1966-1976	44	0.3%
47	RCF	8+	Pre-1935	44	0.3%
48	RCF with block infill	4-7	1935-1965	43	0.2%
49	RCF with block infill	4-7	1977-1992	42	0.2%
50	RCF with brick infill	1-3	1993+	38	0.2%
Total	**-**	**-**	**-**	**16920**	**97%**

Table A.5. Summary of building occupancy / usage type attributes

Auckland Council / University of Auckland			Avg. imp. level (NZS 1170.0:2002)	GEM (2013)			Riskscape (2010)	
Use category	Documented # bldgs	% of total incl. unknown		Occupancy category level 1	Occupancy category level 2	% of total incl. unknown	Use category	% of total incl. unknown
Hostel	29	0.2%	2.0	RES (Residential)	RES3 (Temporary lodging)	0.4%	Commercial - Accommodation	0.7%
Hotel	37	0.2%	2.5					
Motel	2	0.0%	2.0					
Office/residential	8	0.0%	2.0	MIX (Mixed use)	MIX2 (Mostly commercial and residential)	0.3%		
Retail/residential	43	0.2%	2.0					
Church	231	1.3%	2.4	ASS (Assembly)	ASS1 (Religious gathering)	1.3%	Religious	1.3%
Cinema	8	0.0%	2.9		ASS3 (Cinema or concert hall)	0.1%	Commercial - Business	71.2%
Theatre	10	0.1%	2.4					
Gambling	1	0.0%	2.0	COM (Commercial and public)	COM5 (Entertainment)	0.0%		
Commercial	9545	54.8%	2.0		COM3 (Offices, professional/tehcnical services)	60.0%		
Funeral parlour	3	0.0%	2.0					
Office	878	5.0%	2.0					
Office/retail	25	0.1%	2.0					
Offices	2	0.0%	2.0					
Restaurant	217	1.2%	2.0		COM1 (Retail trade)	11.1%		
Retail	1376	7.9%	2.0					
Retail/café	20	0.1%	2.0					
Retail/office	94	0.5%	2.0					
Bank	79	0.5%	2.1					
Café	99	0.6%	2.0					
Hazchem store	1	0.0%	2.0					
Shopping centre	21	0.1%	2.5				Fast Moving Consumer Goods	0.3%
Supermarket	24	0.1%	2.3					
Club	42	0.2%	2.0		COM6 (Public building)	1.5%	Community	1.5%
Community facility	165	0.9%	2.5					
Events centre	12	0.1%	2.8					
Hall	6	0.0%	2.2					

Table A.5. Summary of building occupancy / usage type attributes

Auckland Council / University of Auckland			Avg. imp. level (NZS 1170.0:2002)	GEM (2013)			Riskscape (2010)	
Use category	**Documented # bldgs**	**% of total incl. unknown**		**Occupancy category level 1**	**Occupancy category level 2**	**% of total incl. unknown**	**Use category**	**% of total incl. unknown**
Library	30	0.2%	2.5					
Education	852	4.9%	2.3	EDU (Education)	EDU99 (Education, unknown type)	4.9%	Education	8.3%
Institutional	2	0.0%	2.0					
Preschool	595	3.4%	2.0		EDU1 (Pre-school facility)	3.4%		
Emergency services facility	198	1.1%	3.7	GOV (Government)	GOV2 (Government, emergency response)	1.1%	Fire Station or Police	1.1%
Courts and judicial services	11	0.1%	3.1		GOV1 (Government, general services)	0.3%	Government	0.3%
Government	16	0.1%	3.2					
Prison	19	0.1%	3.1					
Hospital	208	1.2%	3.2	COM (Commercial and public)	COM4 (Hospital/medical clinic)	2.8%	Hospital, Clinic	2.8%
Medical centre	284	1.6%	2.0					
Laboratory	1	0.0%	3.0					
Garage / shed	6	0.0%	2.2		COM2 (Wholesale trade and storage (warehouse))	1.2%	Industrial - Manufacturing, Storage	2.3%
Warehouse	173	1.0%	2.1					
Warehouse (retail)	31	0.2%	2.0					
Factory	11	0.1%	2.3	IND (Industrial)	IND99 (Industrial, unknown type)	0.1%		
Workshop	186	1.1%	2.0		IND2 (Light industrial)	1.1%		
Funpark	2	0.0%	3.0	COM (Commercial and public)	COM11 (Recreation and leisure)	0.8%	Lifestyle	0.8%
Gallery	17	0.1%	2.1					
Museum	12	0.1%	2.3					
Recreation	11	0.1%	3.5					
Recreation centre	18	0.1%	2.3					
Tavern	72	0.4%	2.0					
Petrol holding tanks	4	0.0%	4.0	OCO (Other occupancy	OCO (Other occupancy type)	2.8%	Lifeline Utilities	1.9%
Petrol station	57	0.3%	2.0					

Table A.5. Summary of building occupancy / usage type attributes

Auckland Council / University of Auckland			**Avg. imp. level (NZS 1170.0:2002)**	**GEM (2013)**			**Riskscape (2010)**	
Use category	**Documented # bldgs**	**% of total incl. unknown**		**Occupancy category level 1**	**Occupancy category level 2**	**% of total incl. unknown**	**Use category**	**% of total incl. unknown**
Post office	5	0.0%	2.0	type)				
Telecommunications	3	0.0%	3.0					
Toilet block	6	0.0%	1.2					
Tower	1	0.0%	5.0					
Utility station	262	1.5%	3.8					
Demolished	1	0.0%	2.0				Clear Site	0.5%
Derelict	43	0.2%	2.0					
Vacant site	45	0.3%	2.0					
Dam	10	0.1%	5.0				Other	0.5%
Graveyard	1	0.0%	1.0					
Greenhouse	1	0.0%	2.0					
Heritage	40	0.2%	2.0					
Unknown	37	0.2%	2.0	OC99 (Unknown occupancy type)	OC99 (Unknown occupancy type)	0.7%		
Car yard	53	0.3%	1.4				Parking	0.6%
Office/car yard	27	0.2%	2.0					
Carparking building	25	0.1%	2.0	COM (Commercial and public)	COM7 (Covered parking garage)	0.1%		
Resthome	6	0.0%	2.0	RES (Residential)	RES2 (Multi-unit, unknown type)	4.5%	Resthome	0.0%
Heritage residential	97	0.6%	2.0				Residential Dwellings	4.5%
Residential	663	3.8%	2.0					
Residential (Large)	25	0.1%	2.0		RES2F (50+ Units)	0.1%		
Airfield	13	0.1%	3.1	COM (Commercial and public)	COM10 (Airport)	0.9%	Territorial Authority/Civil Defence	1.5%
Airport	149	0.9%	2.4					
Mass transit station	6	0.0%	3.7		COM8 (Bus station) or COM9 (Railway station)	0.0%		
Military facility	101	0.6%	2.1	GOV (Government)	GOV99 (Government, unknown type)	0.6%		
Total	**17414**	**100%**	**-**	**-**	**-**	**100%**	**-**	**100%**

Table A.6. Ranking of top 10 building occupancy / usage type attributes for each taxonomy scheme by percentage of estimated total

Rank	Auckland Council / University of Auckland		Importance level (NZS 1170.0:2002)		GEM (2013)		Riskscape (2010)	
	Use category	% incl. un-known	Use category	Avg. importance level	Occupancy category	% of total incl. unknown	Use category	% of total incl. unknown
1	Commercial	54.8%	Excluding special, non-building structures with importance level = 5		COM3 (Offices, professional/tehcnical services)	60.0%	Commercial - Business	71.2%
2	Retail	7.9%			COM1 (Retail trade)	11.1%	Education	8.3%
3	Office	5.0%	Petrol holding tanks	4.0	EDU99 (Education, unknown type)	4.9%	Residential Dwellings	4.5%
4	Education	4.9%	Utility station	3.8	RES2 (Multi-unit, unknown type)	4.5%	Hospital, Clinic	2.8%
5	Residential	3.8%	Mass transit station	3.7	EDU1 (Pre-school facility)	3.4%	Industrial - Manufacturing, Storage	2.3%
6	Preschool	3.4%	Emergency services facility	3.7	COM4 (Hospital/medical clinic)	2.8%	Lifeline Utilities	1.9%
7	Medical centre	1.6%	Recreation	3.5	OCO (Other occupancy type)	2.8%	Territorial Authority/Civil Defence	1.5%
8	Utility station	1.5%	Hospital	3.2	COM6 (Public building)	1.5%	Community	1.5%
9	Church	1.3%	Government	3.2	ASS1 (Religious gathering)	1.3%	Religious	1.3%
10	Restaurant	1.2%	Prison	3.1	COM2 (Wholesale trade and storage (warehouse))	1.2%	Fire Station or Police	1.1%
Total	**-**	**86%**	**-**	**-**	**-**	**94%**	**-**	**97%**