QUANTITATIVE ANALYSIS OF FACTORS INFLUENCING POST-EARTHQUAKE DECISIONS ON CONCRETE BUILDINGS IN CHRISTCHURCH, NEW ZEALAND

by

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Abstract

The 2010-2011 Canterbury Earthquake Sequence resulted in unprecedented losses including 185 casualties, an estimated $NZ 40 billion cost of rebuild, and the demolition of 60% of reinforced concrete buildings in the Christchurch Central Business District (CBD). Intriguingly, demolition rate is unexpectedly high compared to the reported damages. This study thus sought to explore factors influencing the post-earthquake decisions on buildings (demolition or repair).

Focusing the study on multi-storey reinforced concrete buildings in the Christchurch CBD, information on building characteristics, assessed post-earthquake damage, and post-earthquake decision (demolish or repair) for 223 buildings was collected. Data were collected in 2014 in collaboration with Christchurch City Council (CCC), Canterbury Earthquake Recovery Authority (CERA), GNS Science, and local engineers. Data were obtained on approximately 88% of the 3-storey and higher reinforced concrete buildings within the CBD, or approximately 34% of all reinforced concrete buildings in the CBD. The study of descriptive statistics and trends of the database confirms that a significant portion of repairable buildings were demolished.

Logistic regression models were developed based on the collected empirical data. From the significance testing, the assessed damage, occupancy type, heritage status, number of floors, and construction year were identified as variables influencing the building-demolition decision. Their effects on the post-earthquake decisions were approximated, and the resulting likelihood of building demolition was estimated for buildings with different attributes. From personal interviews with 9 building owners and owner's representatives, 9 building developers and investors, 5 insurance sector representatives, and 4 local engineers and government authority personnel, it was learned that the local context, such as insurance policy and changes in local legislation, also played a significant role in the decision-making process.

As the first quantitative study that explores the effects of factors on the post-earthquake building demolition decisions, the findings of this study indicates that the damage is not the only factor affecting the post-earthquake decisions on buildings. Incorporation of all influential factors in the probability-of-demolition function would provide better means of estimating expected total loss by considering decision outcome scenarios and associated costs. This would benefit the decision makers with comprehensive and valuable information concerning seismic risk management and strategy. Limitations on this study are discussed and similar studies are suggested reflecting the locality of different communities with seismic risk.

Preface

The research for this thesis was conducted in collaboration with Dr. Ken Elwood, Dr. Stephanie Chang, and Frederic Marquis at the University of British Columbia. The primary data collection was conducted by the author in Christchurch, New Zealand, in collaboration with the research team, Christchurch City Council, Canterbury Earthquake Recovery Authority, and GNS Science. The primary analysis of the research data was conducted by the author.

A synthesis of chapters 3, 4, and 5 of this thesis has been accepted for publication to *11th Canadian Conference on Earthquake Engineering* (Kim, Elwood, Chang & Marquis, 2015). The data collection and analyses were conducted by the author as indicated above, and the paper was written by the author and reviewed by the research team.

This research project received ethics approval for personal interviews and focus group discussion from the University of British Columbia Behavioural Research Ethics Board (Reference no. H14-01332) and from the University of Auckland (UA) Human Participants Ethics Committee (Reference no. 012911).

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List of Symbols

$argmax$	Argument of maximum
B	Regression coefficient or estimator
dm	Damage measure
dv	Decision variable
edp	Engineering demand parameter
im	Intensity measure
k	Number of estimated parameters or degrees of freedom
L	Log of maximum likelihood estimate
LR	Log-likelihood ratio
M_w	Moment magnitude scale
N	Number of samples
P	Probability of an event occurring
tl	Total loss
x	Independent variable
y	Dependent variable
α_E	Importance level for entry
α_R	Importance level for removal
Δ_i	Difference between the minimum AIC value and the AIC value for Model i
$\prod$	Pi function

List of Abbreviations

AIC	Akaike Information Criterion
ATC	Applied Technology Council
BSS	Backward Stepwise Selection
CBD	Central Business District
CCC	Christchurch City Council
CCDU	Christchurch Central Development Unit
CERA	Canterbury Earthquake Recovery Authority
CI	Confidence Interval
CSW	Critical Structural Weakness
DBH	Department of Building and Housing
DEE	Detailed Engineering Evaluation
DI	Damage Indicator
DR	Damage Ratio
DS	Damage Score
EAG	Engineering Advisory Group
ESRI	Environmental Systems Research Institute
EQ	Earthquake
FSS	Forward Stepwise Selection
GDP	Gross Domestic Product
GIS	Geographic Information System

MF	Moment Frame
MFIF	Moment Frame with Infill
MLE	Maximum Likelihood Estimate
NBS	New Building Standard
NZSEE	New Zealand Society for Earthquake Engineering
PBEE	Performance-Based Earthquake Engineering
PEER	Pacific Earthquake Engineering Research
SFRS	Seismic Force Resisting System
SW	Shear Wall
UA	University of Auckland
UBC	University of British Columbia

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Dedication

This thesis is dedicated to my parents, Jong Tack Kim and He Kyong Kang, for their endless support, encouragement, and love for me throughout my life.

Chapter 1: Introduction

This thesis presents a quantitative study of factors influencing the post-earthquake decisions on buildings affected by the 2010-2011 Canterbury Earthquake in Christchurch, New Zealand. Chapter 1 introduces the background of the Canterbury Earthquake and the city's recovery progress and defines the research question, objective, and scope. Chapter 2 reviews literatures on performance-based earthquake engineering principle, post-earthquake decisions, and logistic regression analysis principles. Chapter 3 describes the research data source and collection methodology. Chapter 4 defines the research database and presents descriptive statistics of the database, followed by chapter 5 which presents development of the logistic regression model and probability-of-demolition function. Chapter 6 highlights the local contextual parameters, followed by the conclusion in chapter 7.

1.1 Background of the Canterbury Earthquakes and Recovery Progress

The 2010-2011 Canterbury Earthquake Sequence caused unprecedented losses in Christchurch, New Zealand. Starting with the 4 September 2010 (M_w 7.1) earthquake, the Canterbury region was hit by thousands of earthquakes, including major events that occurred on 26 December 2010 (M_w 4.7), 22 February 2011 (M_w 6.3), 13 June 2011 (M_w 6.0), and 23 December 2011 (M_w 5.8) (Bannister & Gledhill, 2012; Bradley et al., 2014).

The high intensity and large number of ground shaking events caused extensive damage to the Central Business District (CBD) of Christchurch. The Christchurch CBD includes approximately 110 city blocks and green space enclosed by the four avenues: Bealey, Deans, Moorhouse, and Fitzgerald. The area measures approximately 6.2 km^2, which is equivalent to about 60% of the Vancouver downtown peninsula. The citizens of Christchurch suffered from the traumatic experience, disruption in basic needs, and uncertainties due to ongoing aftershocks. The direct impacts of the earthquake sequence include loss of 185 lives, an estimated $NZ 40 billion cost of rebuild (approximately 20% of New Zealand's Gross Domestic Product [GDP]), demolition of approximately 60% of multi-storey reinforced concrete buildings in the CBD, loss of land due to liquefaction, closure of parts of the CBD for over 2 years, and hundreds of thousands of insurance claims (Parker & Steenkamp, 2012). Unlike other major earthquakes in the world, it is estimated that 80% of the economic loss was borne by the insurance industry (Bevere & Grollimund, 2012).

From 22 February to 30 April 2011, a National State of Emergency was declared under the Civil Defence Emergency Management Act (*Civil Defence Emergency Management Act*, 2002). The main focus was to identify dangerous buildings and take required actions (demolition or make-safe work) for immediate public safety. The Canterbury Earthquake Recovery Authority (CERA) was established in March 2011 to lead and facilitate the recovery of the community under the Canterbury Earthquake Recovery Act 2011 (CERA, 2012). One of CERA's roles is to oversee building damage assessments and manage building demolition works. The Christchurch Central Development Unit (CCDU) within CERA was formed to aid the recovery and renewal of the city by planning and executing anchor projects and precincts (CCDU, 2012). Four years after the earthquakes, the community recovery and reconstruction efforts are still ongoing. CERA reported that since September 2010, over 35,000 building consents (i.e. building permits) worth $NZ 9.1 billion have been issued in greater Christchurch and approximately $NZ 7.5 billion in physical rebuilding has been completed (CERA, 2014).

1.2 Research Question and Objective

The consequences of the 2010-2011 Canterbury Earthquakes alerted many urban communities to seismic risk. Considering the performance of reinforced concrete buildings was acceptable and as expected (Kam et al., 2011), the high demolition rate (~60%) of reinforced concrete buildings is surprising. The similarities between New Zealand and North America in the advancement of seismic engineering and building regulations make the information learned from the Canterbury Earthquakes valuable to those who study and live in earthquake-prone cities in USA and Canada.

The research project focuses on the two major questions:

- *What factors, including but not limited to degree of building damage, influence the post-earthquake demolition decisions on buildings?*
- *What is the quantitative relationship between the influential factors and the likelihood of building demolition?*

The aim is to better understand the link between building performance, building characteristics, and post-earthquake decision outcome. Improved understanding of the parameters driving building demolition would provide comprehensive probability-of-demolition functions, which would contribute to further development of the performance-based earthquake engineering methodology.

1.3 Research Framework and Scope

As demonstrated in Figure 1-1, the research involves the following steps to arrive at the findings: development of research question, research scope identification, data collection, database development, descriptive statistics analysis, and logistic regression analysis.

This research focuses on the study of multi-storey (3-storey and higher) reinforced concrete buildings in the Christchurch CBD. Unreinforced masonry buildings are not considered in the study, as those buildings often experienced significant damage which makes demolition decision quite evident.

The developed project database contains empirical data on 223 buildings, including building characteristics, assessed post-earthquake damage, and post-earthquake decisions. It represents approximately 88% of the 3-storey and higher reinforced concrete buildings within the CBD, or approximately 34% of all reinforced concrete buildings in the CBD. Buildings with no, or very limited, available information were excluded from the database.

Statistical descriptive analyses are performed based on the collected empirical database to study the general trends in the study buildings. Then, logistic regression analyses are conducted to identify influencing factors, to develop probability-of-demolition function, and to quantify the relative effects of the factors on the building demolition decision.

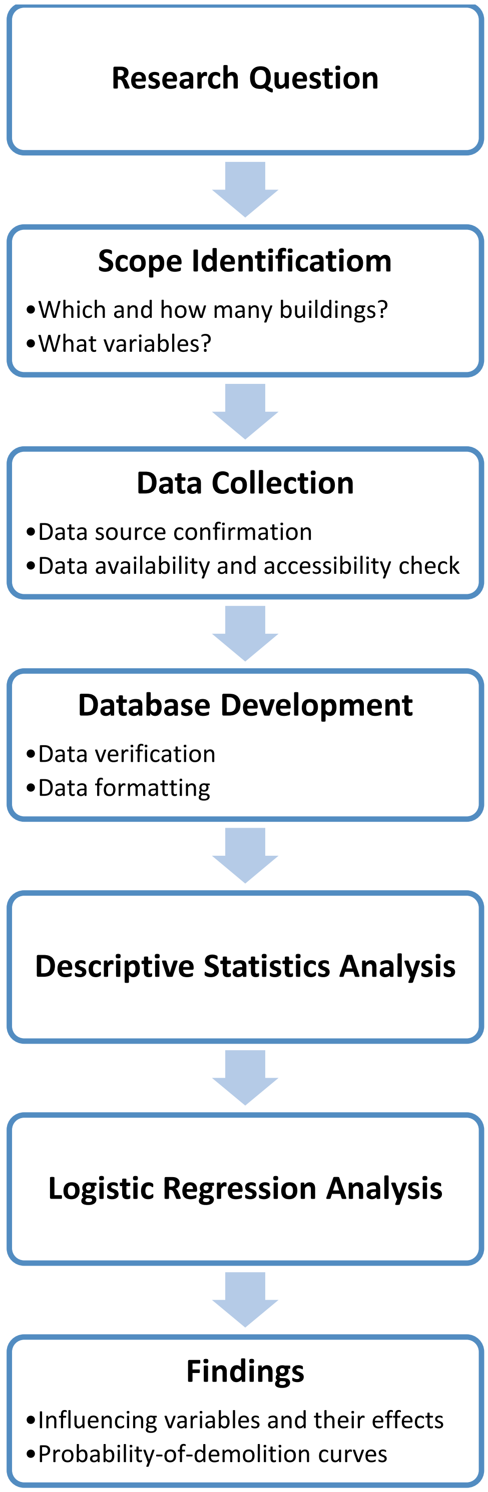

Figure 1-1: Research Framework

Chapter 2: Literature Review

The literature review explores three main topics. Firstly, current performance-based earthquake engineering methodology is reviewed and possible improvements are discussed in line with the research project. Secondly, literature regarding post-earthquake decisions on buildings is reviewed. Lastly, logistic regression analysis principles are presented and its applications in post-disaster empirical studies are introduced.

2.1 Current Performance-Based Earthquake Engineering Methodology

The Pacific Earthquake Engineering Research (PEER)'s performance-based earthquake engineering (PBEE) assessment aims to assist stakeholders in their decision-making in regards to seismic risk management by means of quantification of structural performance (Moehle & Deierlein, 2004). The performance assessment framework consists of four main steps: seismic hazard analysis, structural response analysis, damage analysis, and loss analysis, as shown in Figure 2-1 (Moehle & Deierlein, 2004).

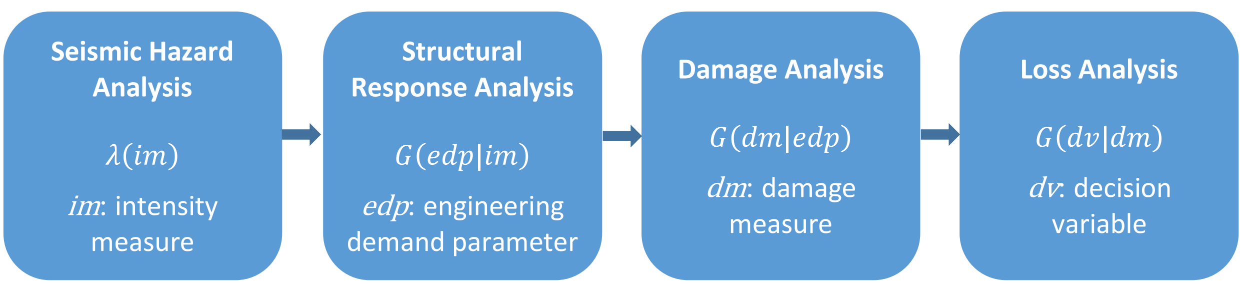

Figure 2-1: Performance Assessment Framework (Moehle & Deierlein, 2004; Yang et al., 2009)

The first step involves evaluation of Intensity Measure ($\boldsymbol{im}$) through probabilistic seismic hazard analysis and characterization of appropriate ground motions. Then, Engineering Demand Parameters ($\boldsymbol{edp}$), such as deformations and accelerations, are calculated by structural response analyses. The third step is to relate Damage Measures ($\boldsymbol{dm}$) to $\boldsymbol{edp}$ through a damage analysis.

The final step is to calculate Decision Variables (dv), which are often expressed in direct dollar losses, downtime, and casualties. Given all the above, the mean annual rate of events with decision variable exceeding a threshold decision variable (dv) value is formulated as follows:

$$\boldsymbol{\lambda}(\mathbf{dv} < \mathbf{DV}) = \int_{\mathbf{im}} \int_{\mathbf{dm}} \int_{\mathbf{edp}} \mathbf{G}(\mathbf{dv}|\mathbf{dm})\ \mathbf{dG}(\mathbf{dm}|\mathbf{edp})\ \mathbf{dG}(\mathbf{edp}|\mathbf{im})|\mathbf{d}\boldsymbol{\lambda}(\mathbf{im})| \tag{2-1}$$

The above equation can also be expressed as:

$$\boldsymbol{\lambda(dv < DV) = \int_{im} G(dv|im)|d\lambda(im)|} \tag{2-2}$$

where,

$$\boldsymbol{G(dv|im) = \int_{dm} \int_{edp} G(dv|dm) dG(dm|edp)\ dG(edp|im)} \tag{2-3}$$

Inspired by the PEER framework, many researchers have focused on developing repair cost analyses of various structural types and components (Yang et al., 2009; Hunt & Stojadinovic 2010; Ramirez et al. 2012).

A study by ATC (2012) applies the PEER framework to obtain the probable consequences such as direct economic losses. By considering either building repair or replacement (demolish and rebuild) options, the study defines the economic losses as building repair cost or replacement cost (including demolition, debris removal, and reconstruction.) The building replacement option is considered only if building is collapsed or predicted repair cost is more than 50% of replacement cost. It is implied that the study assumes building demolition is related to assessed damage and cost of repair.

After earthquake events, there are several possible post-earthquake decision outcomes on damaged buildings: full repair, partial repair, full demolition and walk-away, full demolition and reconstruction, partial demolition, and etc. In this study, two simple cases are considered; repair or demolition. Depending on the outcome, the total economic loss can take different forms. For the case of repair, the incurred costs to building owner include the cost of repair and the cost of downtime (business interruption, loss of rent, etc.). Parts or all of the incurred costs may be recovered from insurance. For the case of demolition, the incurred costs are the cost of demolition and the cost of downtime. Similar to the repair case, the costs may be recovered from insurance by means of building reinstatement or cash payout. The total loss for both scenarios can be summarized as shown in Figure 2-2.

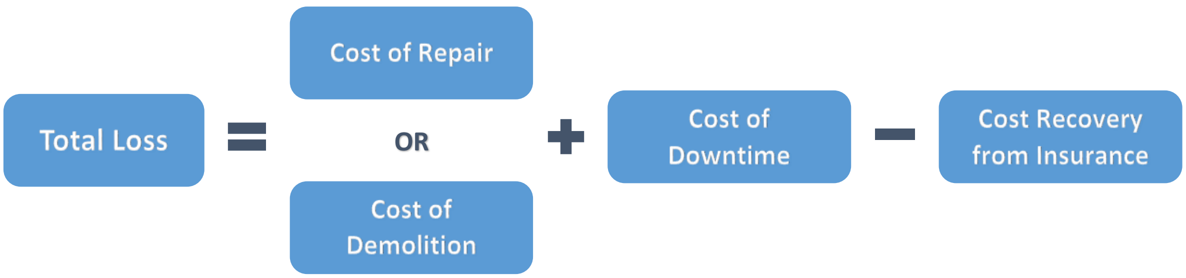

Figure 2-2: Total Economic Loss

The fundamental difference between the two outcomes is the cost of repair compared to the cost of demolition. The demolition cost of a building does not depend on the damage level, while cost of repair, up to certain extent, increases with increasing level of damage. The cost of downtime also differs for the case of repair and demolition. These distinctions depending on the decision outcome should be recognized in the total economic loss estimation. For building owners (or their engineers) who may be end users of the PEER framework, determining total economic loss directly associated with the post-earthquake decision would be a holistic approach in making an informed decision on seismic risks.

Accounting for the two possible outcomes, the conditional probability of total loss ($\boldsymbol{TL}$) exceeding a threshold total loss value (tl) for given $\boldsymbol{dv}$ and $\boldsymbol{im}$ can be expressed as below:

$$\boldsymbol{G(tl|dv,im) = G(tl|repair)P(repair|dv) + G(tl|demolition)P(demolition|dv)} \quad (2\text{-}4)$$

The terms $\boldsymbol{G(tl|repair)}$ and $\boldsymbol{G(tl|demolition)}$ represent the probability of total loss exceeding threshold value given that the building is to be repaired and demolished, respectively. These terms are multiplied by $\boldsymbol{P(repair|dv)}$ and $\boldsymbol{P(demolition|dv)}$ accordingly using the total probability theorem to yield $\boldsymbol{G(tl|dv, im)}$.

The probability of total loss exceeding a threshold value for given $\boldsymbol{im}$ can be expressed as below:

$$\boldsymbol{G(tl|im) = \int_{dv} G(tl|dv, im) dG(dv|im)} \tag{2-5}$$

Then, the mean annual rate of events with total loss exceeding a threshold total loss value is:

$$\boldsymbol{\lambda(tl < TL) = \int_{im} G(tl|im)\, |d\lambda(im)} \tag{2-6}$$

In arriving at the equations **2-4**, **2-5**, and **2-6**, appreciation of the two newly introduced terms, $\boldsymbol{P(repair|dv)}$ and $\boldsymbol{P(demolition|dv)}$, is essential. The concept of $\boldsymbol{P(repair|dv)}$ and $\boldsymbol{P(demolition|dv)}$ are demonstrated in Figure 2-3a. $\boldsymbol{P(demolition|dv)}$ indicates a probability of demolition for a given decision variable. Here, decision variable may be dollar loss associated with damage. Similarly, $\boldsymbol{P(repair|dv)}$ expresses a probability of repair given a decision variable, which is equivalent to $\boldsymbol{1 - P(demolition|dv)}$ when considering two possible outcomes. Figure 2-3b illustrates that the probability-of-demolition curve may be shifted and/or scaled resulting in increase or decrease in the probability of demolition, depending on the effects of variables other than the decision variable.

This research project aims to develop the probability-of-demolition function accounting for various influencing parameters and to explain how each factor would affect the probability-of-demolition curve. This study is unique in its approach to identify factors affecting the building demolition and to quantify their effects on the probability-of-demolition function.

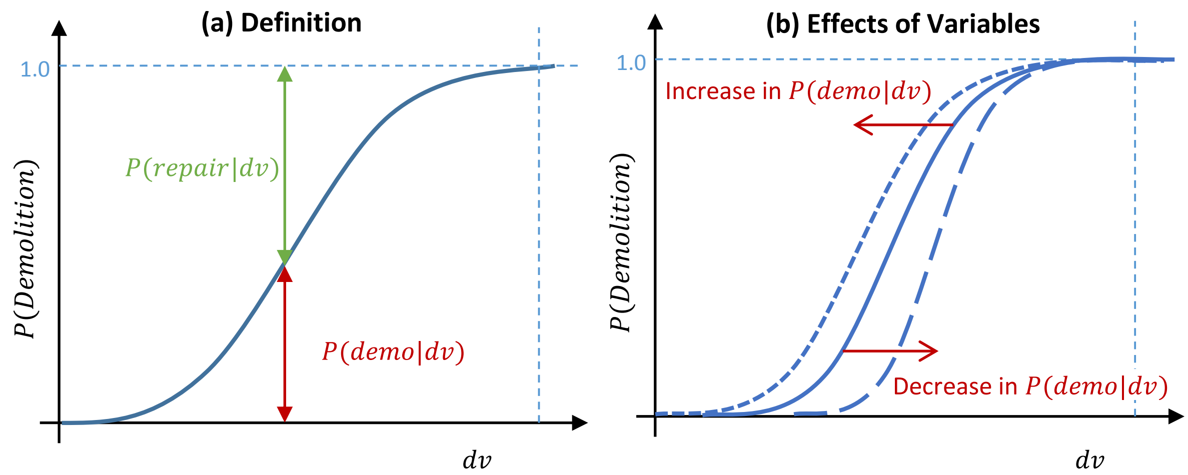

Figure 2-3: Probability-of-Demolition Curve – (a) Definition and (b) Effects of Variables

2.2 Post-Earthquake Decisions on Buildings

The 1994 Northridge Earthquake (M_w 6.7) in California resulted in 57 fatalities and an estimated economic loss of US $40 billion (EQE, 1995; 1997). Among 16,315 non-residential buildings inspected, 57% were found to have no apparent hazard (green placard), 14% in dangerous condition (yellow placard), and only 5% unsafe with collapse risk (red placard) (remaining 24% were unknown). Also, EQE (1995) reported that “over 80% of buildings in the damage database sustained 10% damage or less” in terms of replacement value (the database includes single-family houses.) As conclusive building demolition rate was not reported, the number of repaired and demolished building is inferred from the building permit information reported in EQE (1997). Among the buildings in the city of Los Angeles, 63,138 permits for repair, 19,444 permits for rebuild, and 1,460 permits for demolition were issued. Assuming the total number of permits approximately represents the number of buildings in the city of Los Angeles and that the rebuild permit indicates building demolition and reconstruction, it is inferred that 75% of the buildings in the city of Los Angeles were repaired and 25% were demolished. In addition, it was reported that approximately 75% of the severely damaged apartment buildings were repaired 3 years after the event (Comerio, 1997). Literature on building demolition decision after the Northridge earthquake was not found.

In 1995, a M_w 6.9 earthquake and aftershocks struck the city of Kobe in Japan, costing 6,434 fatalities and an estimated economic loss of US $114 billion (approximately 2.5% of Japan's GDP). More than 256,000 buildings (including fire damage) were damaged from the earthquakes; 41% were completely destroyed, 56% were partially destroyed (destruction of 50% or less), and 3% were burned by fire (City of Kobe, 2010). It was reported that "a large number of affected buildings went into debris disposal even when they were only partially (destruction of 50% or less) damaged directly by the earthquake or by fire" (City of Kobe, 2010). Statistics on number of building demolition/repair were not presented nor the rationale for demolition of partially damaged buildings.

The 2009 L'Aquila Earthquake (M_w 6.3) caused damages to approximately 10,000-15,000 buildings resulting in temporary evacuation of 70,000-80,000 residents in L'Aquila, Italy (Bazzurro et al., 2009). As reported in Polese et al. (2014), depending on the assessed damage and usability rating, varying amount of grants (€/m^2) were provided for repair, strengthening, and seismic retrofit works by the national government. The government's financial support for demolition and reconstruction was allowed for those buildings assessed as unusable and proven to be economically beneficial to do so. Polese et al. (2014) studied the effects of number of floors and building age on the cost of repair, which was observed by means of descriptive statistics on the collected building information. Among heavily damaged reinforced concrete buildings studied, average unit cost of repair generally decreases with increase in number of floors, and higher repair costs were observed for older buildings. Other variables that might also influence the cost of repair or the effects of those variables on the demolition decision outcome were not explicitly explored. Considering low insured loss (14%) (Bevere & Grollimund, 2012) and the central government's heavy involvement in the post-earthquake recovery process, it is inferred that building demolition decision would have been quite straight forward; comparison between the cost of repair and the cost of demolition and reconstruction.

In 2010, the Chilean earthquake (M_w 8.8) and tsunami affected 12.8 million people (75% of national population) causing 571 loss of lives. An estimated economic loss is US $30 billion (approximately 18% of Chile's GDP) and 27% of the loss was insured loss (Bevere & Grollimund, 2012). As a part of the National Reconstruction Plan, the Chilean government authorized recovery grants on 220,000 damaged or destroyed houses (out of 370,000 damaged houses); 52% (115,000 houses) of the eligible houses were repaired and 48% (105,000 houses) required rebuilding (MINVU, 2011). As reported in Comerio (2015), the funding program allowed the eligible owners for several options to choose from: repairing existing houses, purchasing a new house, demolish and build a new house on the same land, build a new house on a new land, or build units in new social-housing developments. Depending on the repairability, owners could choose from the above options and receive subsidy grants. No literature was found regarding how the owners made the decision on their damaged houses.

There exists many literatures discussing various aspects of decision-making on post-disaster recovery, seismic risk mitigation, and structural performance objectives (Zhang et al., 2011; Egbelakin et al., 2011; May, 2004). Very few or no studies, however, have been conducted explicitly on post-earthquake decision-making on damaged buildings with a focus on variables other than level of damage and cost of repair. This research aims to quantitatively demonstrate the role of variables on post-earthquake building demolition decisions.

2.3 Logistic Regression Principles and Application in Empirical Studies

This project uses logistic regression analysis to develop the probability-of-demolition function. Logistic regression principles are briefly discussed, followed by examples of its applications in other empirical studies.

Logistic regression analysis is a probabilistic statistical modeling technique for estimating relationships between a bivariate dependent (or response) variable and independent (explanatory) variables. The probability of the possible outcome is modeled as a function of the independent variables by estimating empirical values of the unknown parameters (regression coefficients). The logistic regression model takes a form of a log function as below:

$$\boldsymbol{ln\left(\frac{P}{1-P}\right) = y = B_0 + B_1x_1 + B_2x_2 + \cdots + B_nx_n} \tag{2-7}$$

$$\boldsymbol{P = \frac{1}{1+e^{-(B_0+B_1x_1+B_2x_2+\cdots+B_nx_n)}}} \tag{2-8}$$

The equation **2-7** is called a logit function and the equation **2-8** is called a logistic function. $\boldsymbol{P}$ is the probability of an event occurring, where $\boldsymbol{y}$ is the bivariate dependent variable. $\boldsymbol{B}$'s are the regression coefficients (or estimators) and $\boldsymbol{x}$'s are the values of the independent variables. From the empirical data, $\boldsymbol{x}$ and $\boldsymbol{y}$ values are known and the regression coefficients are sought.

The process of finding the best relationships between the dependent and independent variables is called "fitting of a model."

$$\boldsymbol{B = arg\,max\left(\prod_{i=1}^{N} P_i^{y_i}(1-P_i)^{1-y_i}\right)} \tag{2-9}$$

The maximum likelihood function (equation **2-9**) finds a set of regression coefficients that maximizes the probability of obtaining the observed set of data. Hence, the resulting group of regression coefficients is a set that allows the model to agree most closely with the observed outcome.

Logistic regression analysis is widely used by researchers in various disciplines to identify factors influencing the outcome and to predict the probability of an outcome. For example, Dabbour (2012) conducted logistic regression analysis on 66,252 single-vehicle collisions that occurred in the states of Ohio and Washington in 2009. The aim was to study the effects of risk factors on the probability of the occurrence of rollover collisions, which would contribute to the informed decision-making for road safety improvement.

Logistic regression analysis has also been used in post-disaster empirical studies. Padgett et al. (2012) studied 44 highway bridges damaged by Hurricane Katrina using logistic regression analysis. Evaluation of hazard intensities and bridge characteristics were conducted to identify important predictors of damage level. Empirical fragility curves for bridge damage states were proposed, and regional risk-based analysis and loss estimation of bridges were suggested.

García-Rodríguez et al. (2008) conducted a study of earthquake-triggered landslide susceptibility after the destructive 2001 El Salvador Earthquakes. Logistic regression model was developed based on 235 samples to determine the important predictors, to estimate the probability of landslide occurrence, and to produce a map of relative landslide susceptibility. A similar study was conducted by Dong et al. (2011) to predict the failure probability of the landslide dams formed after the 1999 Chi-Chi Earthquake, the 2008 Wenchuan Earthquake, and the 2009 Typhoon Morakot. The authors concluded that the proposed models could be used to evaluate the risk and aid in the decision-making for hazard mitigation work.

In these studies, it was emphasized that the empirical logistic regression models are rooted in the characteristics and the locality of the database used, so their application for predictions in other regions and contexts may be limited (García-Rodríguez et al., 2008; Padgett et al., 2012).

Chapter 3: Source of Data and Data Collection Methodology

Chapter 3 presents the sources of the collected data and the data collection methodology in detail. The database was developed by collecting information on building characteristics, assessed post-earthquake damage, and post-earthquake decision (demolish or repair). These data were obtained from and in collaboration with the Christchurch City Council (CCC), the Canterbury Earthquake Recovery Authority (CERA), GNS Science, and from personal interviews for the purpose of this study. These data sources were used to develop, reinforce, and verify the project database. The data collection and database development process took approximately 7 months, with 3 months spent in Christchurch, New Zealand. The following subsections further describe each source.

3.1 Source Databases

The Christchurch City Council (CCC) kindly agreed to support the research project by sharing relevant information from its internal databases. This information included basic building information (address, occupancy type, and name of business), building characteristics (seismic force resisting system, number of floors, construction year, and heritage status), assessed post-earthquake damage information, and building consents (i.e. building permits). The data gathered from CCC became the basis of the project database.

The Canterbury Earthquake Recovery Authority (CERA) also granted controlled access to its internal databases under appropriate confidentiality agreements signed with the research team. Although varies for each building, information available includes basic building information, building decision outcome, current building status, engineering reports, damage assessment information, photographs, and drawings.

3.2 Assessed Damage Information

Post-earthquake building evaluation is a complex methodical process that can have several systems depending on the purpose, scope, and timeline of the assessment. From the day of an earthquake event, the purpose of building evaluation transforms from immediate public safety assessment to usability assessment, repairability assessment, and cost estimations. Similarly, the evaluation develops from visual and superficial inspection to detailed and quantified assessments. Both purpose and scope of the post-earthquake building assessments evolve over time.

In the case of the Canterbury Earthquakes, the following forms were used for damage assessments for buildings in the Christchurch CBD:

- Christchurch Earthquake Rapid Assessment Form – Level 1
- Christchurch Earthquake Rapid Assessment Form – Level 2
- CERA Engineers Risk Assessment Form
- Detailed Engineering Evaluation (DEE) Report
- Detailed Engineering Evaluation (DEE) Summary Table

Table 3-1 below compares the different forms of damage assessments for their purpose, timing, detail and accuracy, data availability for the study, and format of damage assessment data.

The Level 2 Rapid Assessment form was chosen as the main damage assessment information source for the research database as it is most complete across the buildings in the study, readily available, and is suitable for quantitative analysis.

Table 3-1: Comparison of Different Forms of Building Damage Assessments

	Purpose	Timing	Detail & Accuracy	Data Availability	Data Format
Level 1 Rapid Assessment	▫ To assess structural damage, hazards, and building safety ▫ To determine level of occupancy ▫ To recommend required make-safe works	Shortly after earthquake events	Increase	Approx. on 100% of study buildings (Level 1 Rapid Assessment used on 11 study buildings*)	Quantitative
CERA Risk Assessment	▫ To assess risk of building collapse			24% of study buildings	Quantitative
Level 2 Rapid Assessment	Same as Level 1 Rapid Assessment			95% of study buildings**	Quantitative
DEE Summary Table	▫ To assess structural damage and losses for insurance purposes ▫ To recommend repair and/or strengthening work required	Typically longer-term		39% of study buildings	Quantitative
DEE Report					Qualitative & Quantitative

* CCC database contains most up-to-date rapid assessment information and often Level 1 Rapid Assessment results were overwritten when Level 2 Rapid Assessment was conducted (scanned copies of Level 1 Rapid Assessments are likely to exist for all buildings).

** Of the 223 buildings in this study, Level 2 Rapid Assessments for 11 buildings were not found, and Level 1 Rapid Assessment information is used instead.

3.2.1 *Christchurch Earthquake Rapid Assessments – Level 1 and Level 2*

Shortly after the Darfield Earthquake on 4 September 2010, CCC adopted NZSEE Rapid Assessment forms (NZSEE, 2009), which are similar to ATC-20 (ATC, 1995) and created the Christchurch Earthquake Rapid Assessment forms (Level 1 and Level 2). These forms can be found in appendix A.1 and A.2.

Both the Level 1 and Level 2 Rapid Assessments were conducted during the period of the national state of emergency declared under the Civil Defence Emergency Management Act (*Civil Defence Emergency Management Act*, 2002) and after all damaging aftershocks, to identify the level of structural damage to buildings, assess building safety and hazards, assign proper level of occupancy, and recommend required make-safe works (shoring, etc.) (NZSEE, 2009).

The Level 1 Rapid Assessments were conducted on all buildings in Christchurch whereas the Level 2 Rapid Assessments were performed on all critical facility buildings (such as hospitals), large buildings (typically multi-storey), and on any other buildings that further and more specific assessments were warranted from the Level 1 Rapid Assessments.

The Level 1 Rapid Assessments were conducted by volunteering groups of structural and civil engineers, architects, and other personnel from the building industry. The Level 2 Rapid Assessments were conducted by volunteering groups of structural, geotechnical, and building services engineers. The assessments were conducted after all subsequent earthquakes by filling in the assessment forms, and the CCC database was updated with the most recent assessment.

Both the Level 1 and Level 2 Rapid Assessments include placard posting and estimated overall building Damage Ratio (DR) as damage indicators (DI). Colored placard posting represents usability of the assessed building; green (or white) for “Inspected,” yellow for “Restricted Use,” and red for “Unsafe.” Damage Ratio is a visual estimate of building damage expressed as a ratio of repair cost to replacement cost, excluding contents. Damage Ratio is expressed in ranged categories of 0-1%, 2-10%, 11-30%, 31-60%, 61-99%, or 100%. As categorical damage indicators, overall damage is assessed by severity: minor/none, moderate, or severe. In addition to all the above, the Level 2 Rapid Assessments contain more detailed lists of structural, nonstructural, and geotechnical damage that can be addressed by indicating the severity of damage with descriptive comments. Placard and Damage Ratio from the Level 2 Rapid Assessments are chosen as damage indicators for this study. More details can be found in sections 4.2.1, 4.2.2, and 4.2.2.

3.2.2 *CERA Engineers Risk Assessment Form*

In addition to the Rapid Assessments, risk assessments were conducted by CERA engineers following major damaging earthquakes (refer to appendix A.3). The risk assessment is a point system based on the type of construction, risk of building collapse, occupancy type, and overall damage ratio from visual inspection. As an emergency assessment for the aftershocks, the risk assessments were conducted to identify buildings with collapse risk and prioritize the make-safe or demolition work. It is, however, unclear which buildings and how many buildings were assessed based on this form. The risk assessment information is obtained for only 24% of the buildings in this study, and the assessed risk score is not used in this study due to the limited availability.

3.2.3 *Detailed Engineering Evaluations*

A Detailed Engineering Evaluation (DEE) is prepared to review the building design and construction, to assess the extent of structural damage, and to understand the potential performance in further earthquakes (EAG, 2012). Necessary repair or strengthening works to restore the functionality and the compliance with the building code are proposed. It may also be used to establish losses for insurance claiming purposes (NZSEE, 2009). DEEs are prepared by engineers contracted by building owners.

As outlined in EAG (2012), the DEE is comprised of qualitative and quantitative assessments, and recommended actions. The qualitative assessment includes: determination of building status and sustained damage, assessment of likely pre- and post-earthquake structural capacity (in terms of %NBS), review of existing documentation, prediction of the likely building performance and damage patterns, and site investigation of collapse hazards and critical structural weaknesses (CSWs). The quantitative assessment is conducted for the buildings with significant damage and for buildings that suffered insignificant damage but are classified as earthquake-prone buildings (%NBS < 33%) according to (*Building Act*, 2004). The purpose is to assess the residual capacity of the damaged buildings and to determine effective repair and/or strengthening work. The quantitative assessment is conducted generally in accordance with NZSEE (2006) with modifications as needed.

The DEEs were collected in two forms: a report and a summary table. The collected DEE summary tables were compiled into one database by GNS Science (Lin et al., 2015). For this study, the compiled DEE summary database is utilized for its convenience in retrieving information on a large number of buildings. Although the submission of the DEE was required by CERA for all nonresidential and apartment buildings in the Christchurch CBD, the collection process left out numerous buildings including buildings demolished early on for public safety by Civil Defence, buildings that were heavily damaged (for which demolition decision was fairly obvious), and small buildings with very minor or no damage. The DEE collection process was stopped in late 2014 as reported in Marquis (2015). The availability of DEE summary table was limited to 39% of the buildings in the study scope.

3.3 Personal Interviews

The research team conducted interviews with 9 building owners and owner's representatives, 9 building developers and investors, 5 insurance sector representatives, and 4 local engineers and government authority personnel. A list of interviewees can be found in appendix B. The interviews were held in Christchurch, Auckland, or Wellington in New Zealand under the conditions of interviewees' consents.

The purpose was to learn about the post-earthquake decision-making process and discover factors influencing the demolition decision that cannot be easily captured or quantified from the CCC and CERA's databases. The outcomes from the interviews are highlighted in chapter 7 and discussed in detail in Marquis (2015) and Marquis et al. (2015).

3.4 Focus Group Discussion for Damage Score Model

As reported in the literature and learned from the personal interviews, many buildings were demolished as they were deemed uneconomic to repair, not because they were dangerous or beyond technical repairability (Miles et al., 2014; Muir-Wood, 2012). It can be inferred that the fate of a damaged building heavily depends on the cost of repair, which is related to the assessed damage. It was not possible to retrieve information on repair costs for a large number of buildings for this study as repair cost information is typically confidential and not included in any of the databases discussed above. Instead, an effort was made to infer repair costs based on available information.

A Damage Score Model was proposed and developed, which aims to integrate the structural, nonstructural, and geotechnical damages from the Level 2 Rapid Assessment into one scoring system, reflecting the relative repair costs incurred due to each type of damage by assigning weights and scales to the damage categories and severities. The Damage Score Model does not assign actual dollar values to the damage categories but ranks them in a relative sense within the scope of the study database. This means that the resulting Damage Scores (DS) do not carry any practical meaning outside of the context of this study.

The research team held a focus group discussion session with experienced local engineers. A list of participants can be found in appendix B. Typical procedures, approaches, and assumptions made during damage assessments were discussed. Each damage category in the Level 2 Rapid Assessment was reviewed for its significance in repair costs. Then, appropriate weights and scales were assigned to each damage category based on participants' judgements and the Damage Score Model was finalized. The outcome of the Damage Score Model is discussed in section 4.2.4.

3.5 Spatial Data Analysis

Geographic Information System (GIS) was used to capture the cordon zone and its change over time relative to the buildings in the study to determine duration each building was in the cordon zone. Further discussion on the cordon can be found in section 4.5. Environmental Systems Research Institute (ESRI)'s software ArcGIS for Desktop (ESRI, 2014) was used to build a spatial database. Christchurch city base map, building footprints and addresses, and CBD cordon outline layers were obtained from publicly available New Zealand Government's online database (Department of Internal Affairs, 2014). Buildings in the research scope were identified and dates the cordon was lifted for each building were acquired. Also, approximate building footprint areas were calculated (section 4.8).

3.6 Foot Survey

For 52 buildings for which decision outcome information was unavailable from any of the data sources described above, building sites were visited to photograph and note the current operational status as of November 2014. Out of 223 buildings, the decisions on 20 buildings could not be determined even after the foot survey. They were not demolished, not occupied, and had no observed activities on the building sites at the time of data collection. It is possible that the decision had not been made or the decision had been made but no actions had been taken yet.

Chapter 4: Description and Statistics of Database

The research database was developed by collecting information on building characteristics, assessed post-earthquake damage, and post-earthquake decisions for 223 buildings satisfying the following criteria: reinforced concrete structural system, 3-storey and higher, and located in the Christchurch CBD. This represents approximately 88% of the buildings meeting the criteria, excluding buildings with no, or very limited, available information.

Figure 4-1 below presents a map of Christchurch CBD identifying the 223 buildings with decision outcomes indicated in different colors.

The database was completed after an extensive data collection and verification process. The sources of the information are described in chapter 3. This chapter defines the collected information and presents descriptive statistics of the buildings in the study.

The research database is comprised of information such as building identification information, decision outcome, demolition decision maker, damage indicators, building conditions (in terms of pre-EQ and post-EQ %NBS), seismic force resisting system, duration in cordon, construction year, heritage status, footprint area, number of floors, and type of occupancy. Rationale for consideration of these variables are discussed in the following subsections. Table 4-1 below summarizes the collected information with descriptions and data sources.

4.1 Decision Outcome and Demolition Decision Maker

In the database, the decision outcome takes three forms: demolish, repair, or unknown. The “Demolish” decision may be made by “Civil Defence,” “CCDU Demolition,” “CERA,” “Owner,” or unknown.

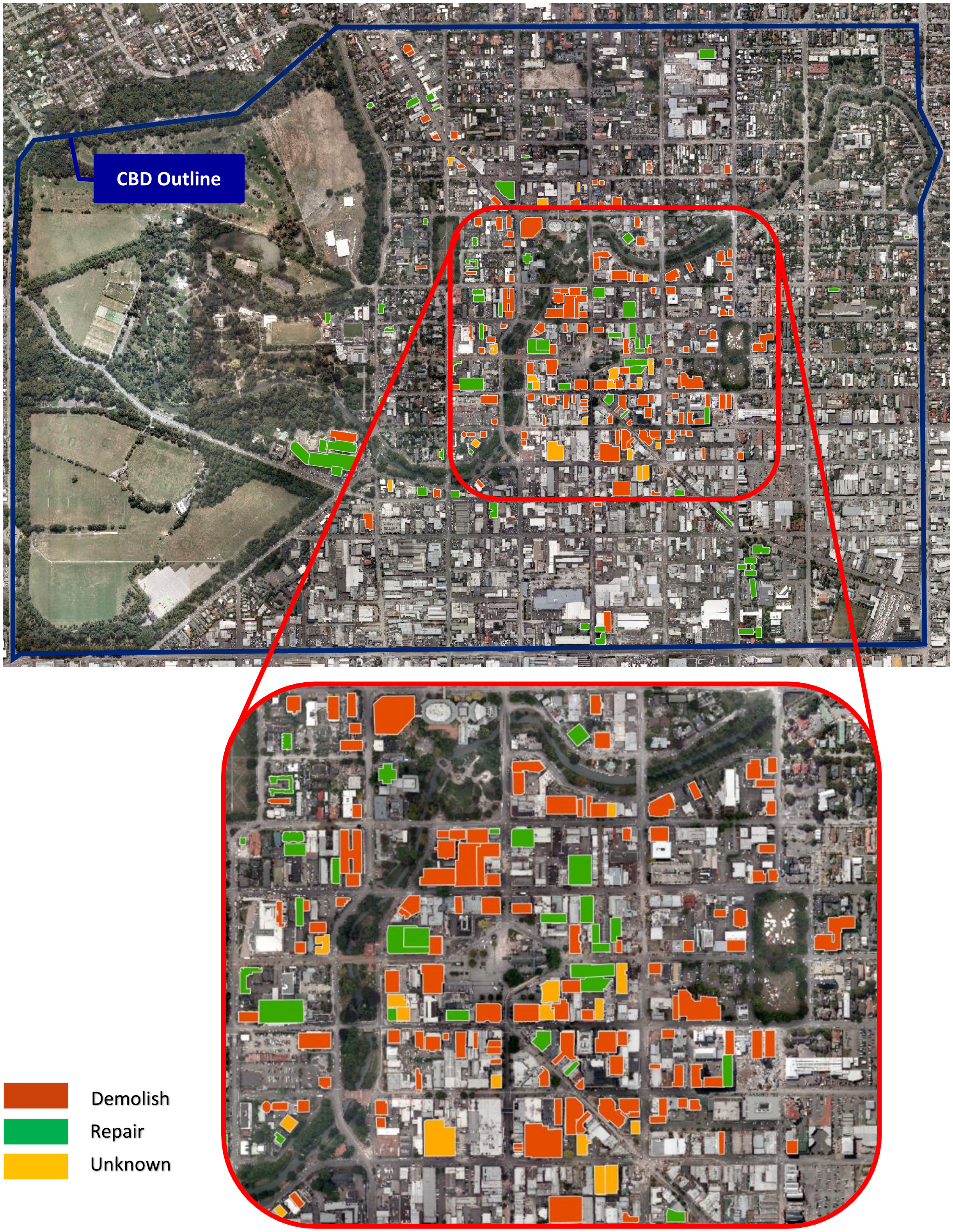

Figure 4-1: Map of Christchurch CBD Showing 223 Study Buildings

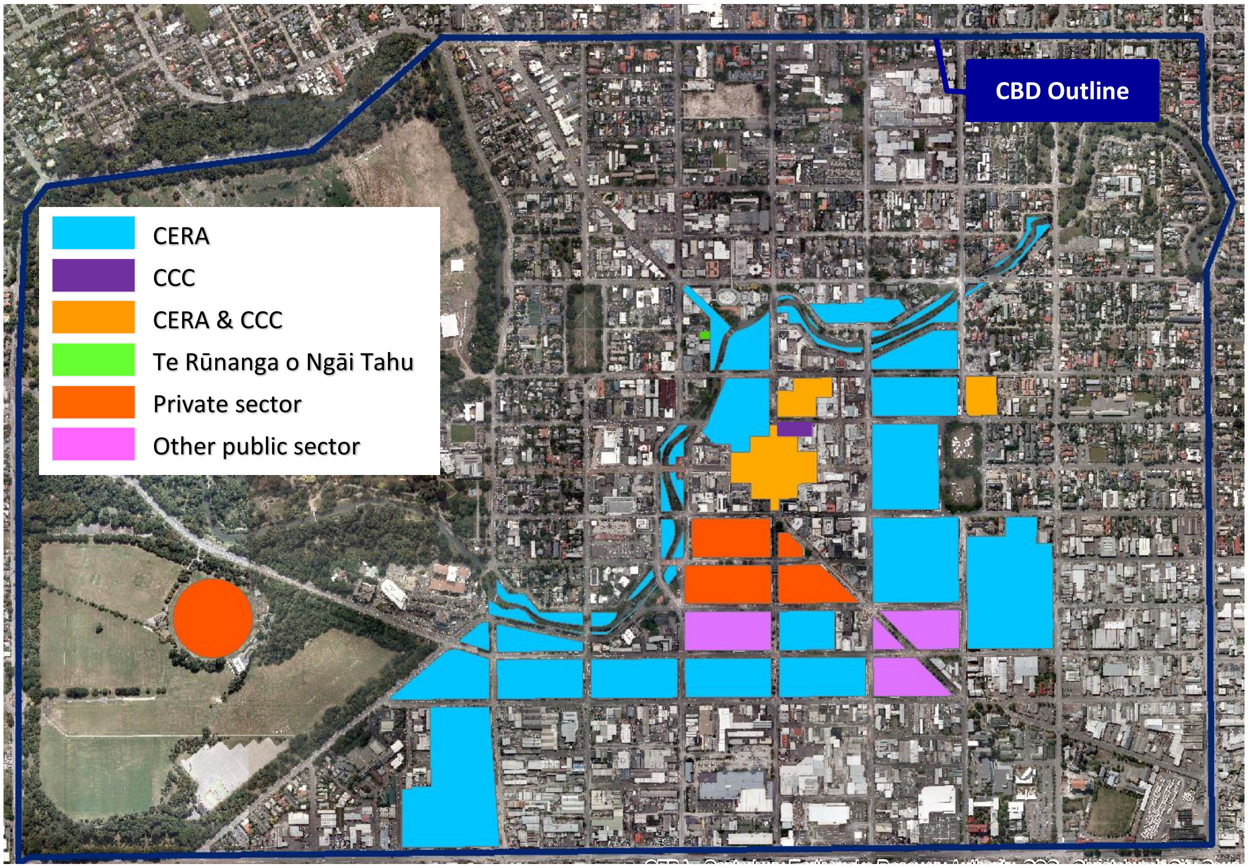

Figure 4-2: Map of Christchurch CBD – Anchor Projects and Precincts (CCDU, 2014)

The decision made by "Civil Defence" refers to buildings that were demolished under the authority of the Civil Defence Emergency Management Act 2002 (*Civil Defence Emergency Management Act*, 2002). These buildings were identified as dangerous and demolished shortly after the earthquake. Due to early and rapid demolition, detailed damage assessments and engineering reports often do not exist for such buildings.

"CCDU Demolition" indicates buildings that were demolished to clear sites for the CCDU's anchor projects (CCDU, 2012). Figure 4-2 illustrates the location and lead agency for the anchor projects in the Christchurch CBD (CCDU, 2014). For the purpose of this study, those buildings that demolition decision was made prior to the release of CCDU's anchor project plan (30 July 2012) are not considered as "CCDU Demolition" even when they fall in the anchor project site.

Table 4-1: Description of Database

Variable	Measure/ Description	Data Source
Address and Business Name	Used for building identification	CCC
Decision Outcome	▫ Demolish ▫ Repair ▫ Unknown	CERA/ Foot survey
Demolition Decision Maker	▫ Civil Defence ▫ CCDU Demolition ▫ CERA ▫ Unknown ▫ Owner	CERA
Damage Indicator		
- Damage Ratio	▫ 0-1% ▫ 11-30% ▫ 61-99% ▫ 2-10% ▫ 31-60% ▫ 100%	Level 2
- Placard	▫ Green ▫ Yellow ▫ Red	Level 2
- Categorical Structural, Nonstructural & Geotechnical Damage	▫ Minor or None ▫ Moderate ▫ Severe	Level 2
- Damage Score	Derived from categorical structural, non-structural, and geotechnical damage	Damage Score Model
Pre-EQ and Post-EQ %NBS	%NBS before and after the earthquakes	DEE
Seismic Force Resisting System (SFRS)	▫ Moment Frame (MF) ▫ MF with Infill (MFIF) ▫ Shear Wall (SW) ▫ Combined MF & SW	CCC/DEE
Duration in Cordon	Number of months from 22 February 2011 to date cordon lifted	GIS Analysis
Construction Year	▫ Pre 1965 ▫ 1992-2003 ▫ 1965-1975 ▫ Post 2003 ▫ 1976-1991	CCC/CERA/DEE
Heritage Status	▫ Heritage ▫ Nonheritage	CCC/CERA
Footprint Area	Measured in m^2	GIS Analysis/DEE
Number of Floors	Number of floors	CCC/DEE
Occupancy Type	▫ Commercial ▫ School ▫ Residential ▫ Public Assembly ▫ Hotel ▫ Government ▫ Post-Secondary ▫ Industrial ▫ Hospital	CCC/CERA/DEE

The decision made by "CERA" refers to buildings that were demolished under Section 38 or 39 of the Canterbury Earthquake Recovery Act 2011 to enable a focused, timely, and expedited recovery of the city (*Canterbury Earthquake Recovery Act*, 2011). Under Section 38, CERA may give a demolition notice to a building owner requiring submission of demolition work plan indicating whether or not the owner intends to carry out the works and specifying the timeline of the demolition works. If the owner fails to notify CERA within 10 days after the demolition notice is given, CERA may commission the demolition works with or without the consent of the owner or occupier, and may recover the costs of carrying out the works from the owner. To facilitate the recovery process, an exemption was given which allows buildings be demolished under Section 38 or 39 without CCC's building consents for demolition works. Under Section 39, CERA may commission urgent demolition works without giving a building owner a notice, in case of sudden emergency (loss of life, injury to a person, damage to property, and damage to the environment) and danger to any works or neighboring property.

If not required to be demolished by the "Civil Defence," "CCDU Demolition," or "CERA," the building "Owner" may decide to either demolish or repair the building. In the study database, demolition of 14 buildings were initiated by building owners while demolished under Section 38 or 39. This indicates the building owners and CERA worked together to enable timely demolition work as building consents are not required if demolished under Section 38 or 39. These cases were identified as owner's decision in this study.

An "Unknown" decision outcome indicates buildings that were not demolished, not occupied, and had no observed activities on site at the time of data collection (November 2014). It is possible that the decision had not been made or the decision had been made but no actions had been taken yet.

4.2 Damage Indicator

In this section, four damage indicators are introduced: Damage Ratio, Placard, Categorical Damage, and Damage Score. The first three damage indicators were retrieved from the Level 2 Rapid Assessment, while Damage Score was derived from Categorical Damage assessment. They are studied as they contain various levels of detail in different formats. Placard indicates usability by color coding while Damage Ratio represents approximate damage to the building in terms of ranges of percentage. Categorical Damage expresses damage severities to structural, nonstructural, and geotechnical components. Damage Score converts the assessed Categorical Damage into a numerical rating system. The four damage indicators are further described in the following subsections.

For 11 building without the Level 2 Rapid Assessment, Damage Ratio and Placard information was obtained from the Level 1 Rapid Assessment instead.

4.2.1 *Damage Ratio*

Damage Ratio (DR) is an estimate of building damage obtained from the Level 2 Rapid Assessment, which is intended to represent an estimate of a ratio of repair cost to replacement cost, excluding contents. Damage Ratio is expressed in six ranged categories: 0-1%, 2-10%, 11-30%, 31-60%, 61-99%, or 100% (there is no separate option for undamaged buildings.) Damage Ratio is not a calculated value, but an approximation of the damage suffered based on the visual inspection. Despite the subjective and approximate nature of this measure, it provides simple and quantitative measure of damage, making it a convenient tool for this study. The collected data is the latest Damage Ratio information available for the study buildings.

4.2.2 *Placard and Usability Category*

Placard posting indicates damage intensity and usability of the assessed building. A green (or inspected) placard represents that there are no restrictions on use or entry, but the structure may need further inspection or repairs. A yellow (or restricted use) placard is given to buildings with safety concerns. Parts of these buildings may be off limits and entry is only allowed for short periods of time. Buildings with red (or unsafe) placards must not be entered and further assessments and risk-mitigation actions are required before any use. Buildings were reassessed after all subsequent earthquakes and may be given different placards. The collected data is the latest placard information available for the study buildings.

The placard posting is further subcategorized depending on the usability. Table 4-2 below summarizes the placard posting and usability subcategory in relation to the damage intensity. For the purpose of this study, placard posting without considering the usability subcategory is used as a Damage Indicator (usability category was not available for 30 buildings). The buildings that were given a red placard due to the risks from adjacent buildings (the usability category of R3) are identified, and the placard postings based on their own damage are assigned for the logistic regression analysis (chapter 5) to ensure the placard damage indicator is solely based on the building damage, not neighbouring building conditions.

For the purpose of assessing the usability of buildings, the placard posting is an efficient and effective measure. Its emphasis on building usability assessment rather than the damage and the small number of placard categories (three) reduce its efficacy as a damage indicator in this study. It may, however, serve as a comparable damage indicator to Damage Ratio. In chapter 5, Damage Ratio and Placard are used in logistic regression analysis and their effects on the analysis results are discussed.

Table 4-2: Christchurch Earthquake Level 2 Assessment Placard and Usability Category

Damage Intensity	Posting	Usability Subcategory
Light Damage; Low Risk	Green; Inspected	G1 – Occupiable, no immediate further investigation required
		G2 – Short term entry
Medium Damage; Medium Risk	Yellow; Restricted Use	Y1 – Short term entry
		Y2 – No entry to parts until repaired or demolished
Heavy Damage; High Risk	Red; Unsafe	R1 – Significant damage: repairs, strengthening possible
		R2 – Severe damage: demolition likely
		R3 – At risk from adjacent premises or from ground failure

4.2.3 *Categorical Damage*

The Level 2 Rapid Assessment contains the categorical assessment of damage in four groups: overall, structural, nonstructural, and geotechnical damage. Each group has subcategories for which inspectors mark for damage severity (minor/none, moderate, or severe) and add comments. Table 4-3 below lists the assessed damage categories.

The advantage of the categorical damage is that it provides very detailed damage assessments, item by item. The list, however, includes items that may not be easily inspected during the rapid assessments, resulting in numerous missing data. Also, the large number of subcategories makes it difficult to use as a building damage indicator in the logistic regression analysis. For this reason, the categorical damage is not directly used as a damage indicator in the analyses, but is used to develop Damage Scores as described in section 4.2.4.

Table 4-3: Christchurch Earthquake Level 2 Assessment Damage Categories

Damage Categories	Subcategory
Overall Damage	Collapse, partial collapse, off foundation
	Building or storey leaning
	Wall or other structural damage
	Overhead falling hazard
	Ground movement, settlement, slips
	Neighbouring building hazard
	Electrical, gas, sewerage, water, hazmats
Structural Damage	Foundations
	Roofs, floors (vertical load)
	Columns, pilasters, corbels
	Diaphragms, horizontal bracing
	Precast connections
	Beam
Nonstructural Damage	Parapets, ornamentation
	Cladding, glazing
	Ceiling, light fixtures
	Interior walls, partitions
	Elevators
	Stairs/exits
	Utilities (e.g., gas, electricity, water)
	Other
Geotechnical Damage	Slope failure, debris
	Ground movement, fissures
	Soil bulging, liquefaction

4.2.4 *Damage Score*

The assessed categorical damages described in section 4.2.2 are fed into the development of the Damage Score Model. The Damage Score Model was developed from the focus group discussion with local engineers (refer to section 3.4) to assign a Damage Score (DS) reflecting the relative repair costs incurred due to each type of damage.

Each damage category's relative contribution to total repair cost is quantified by assigning weights. The weights range from 0 to 100, with the most expensive repair item marked as 100. The damage categories that are not proper indicators of repair cost, or were not inspected during the rapid assessment are given a zero (0), effectively excluding the item from the Damage Score Model. Similarly, numerical values are assigned to each severity category (minor/none, moderate, or severe) to approximate the relative cost of repair work.

The outcome of the focus group discussion on the Damage Score Model is presented in Table 4-4. Among structural elements, damages to the foundations were identified to be the most critical component in building repair cost and was assigned the maximum weight of 100. The participants agreed that geotechnical damages were generally reflected in the foundation assessments and therefore should not be accounted again in Damage Score calculations (zero weights). Nonstructural elements such as elevators and utilities were excluded in the Damage Score Model as they were usually not assessed during the Level 2 Rapid Assessment, often due to power outage. Parapets and ornamentations were also given zero as their repair cost is generally insignificant. Different scales for "High" damage severity were assigned to reflect relative repair cost between the structural (scale of 25) and nonstructural component groups (scale of 10); severe damage to structural components are likely to be more expensive than severe damage to nonstructural components.

It should be noted that the Damage Score Model developed here is based on local engineers' experiences and judgements only. Although not conducted in this study due to lack of access to information, the Damage Score Model may be improved by incorporating approximate unit costs of repair works for each damage category. The underlying concept of the Damage Score offers an ideal damage indicator for this study, but the limitation in the repair cost data inhibits the accuracy of the Damage Score Model.

Using the Damage Score Model, the damage score of a building is calculated by following the four steps:

1) For each damage category, multiply the category weight by the scale for the assessed damage severity. If damage severity is unknown, ignore the damage category.
2) Sum all values from step 1.
3) Count the number of damage categories with known severity. This is referred as "number of included categories."
4) Divide the sum from step 2 by the number of included categories from step 3.

For $\mathbf{n}$ number of damage categories, the damage score is calculated as presented in the equation below.

$$\boldsymbol{Damage\ Score} = \frac{\sum_{i=1}^{n}(\boldsymbol{Category\ Weight_i} \times \boldsymbol{Severity\ Scale_i})}{\boldsymbol{Number\ of\ included\ categories}} \qquad \textbf{(4-1)}$$

"Number of included categories" is entered into the equation to normalize the damage score.

Table 4-4: Damage Score Model

Damage Categories		Weight	Severity Scale		
			Minor/None	Moderate	High
Structural	Foundations	100	1	5	25
	Roof and floor	50			
	Columns, pilasters, and corbels	50			
	Diaphragms and horizontal braces	50			
	Pre-cast connections	50			
	Beams and girders	50			
Nonstructural	Parapets and ornamentations	0	1	5	10
	Claddings and glazing	25			
	Ceilings and light fixtures	25			
	Interior walls and partitions	25			
	Elevators	0			
	Stairs and exits	50			
	Utilities (gas, electricity, water)	0			
Geotech.	Slope failure	0	-	-	-
	Ground movement	0			
	Soil bulging and liquefaction	0			

Based on the described calculation, Damage Score can range from 0 (for completely unknown) to a maximum value of 1000 (when severity is high for all categories). The calculated Damage Score of the buildings in the study ranges from 0 to 781. It is emphasized that Damage Score reflects the relative repair costs among the buildings in the database; there was no attempt to estimate the actual repair costs given the approximate nature of the damage information and the developed model.

As Damage Score is derived based on the categorical damages from the Level 2 Rapid Assessment, Damage Score is compared with Placard and Damage Ratio to observe its correlations with the other two damage indicators for all buildings in the database (Figure 4-3). The solid lines represent average values of Damage Score in each Placard and Damage Ratio category. In general, increase in damage severity corresponds with increase in Damage Score. While average Damage Score is linearly related to Placard, it has an exponential relationship with Damage Ratio. However, significant scatter about the mean is observed, which may be due to the differences in the purpose and scope of the damage indicators.

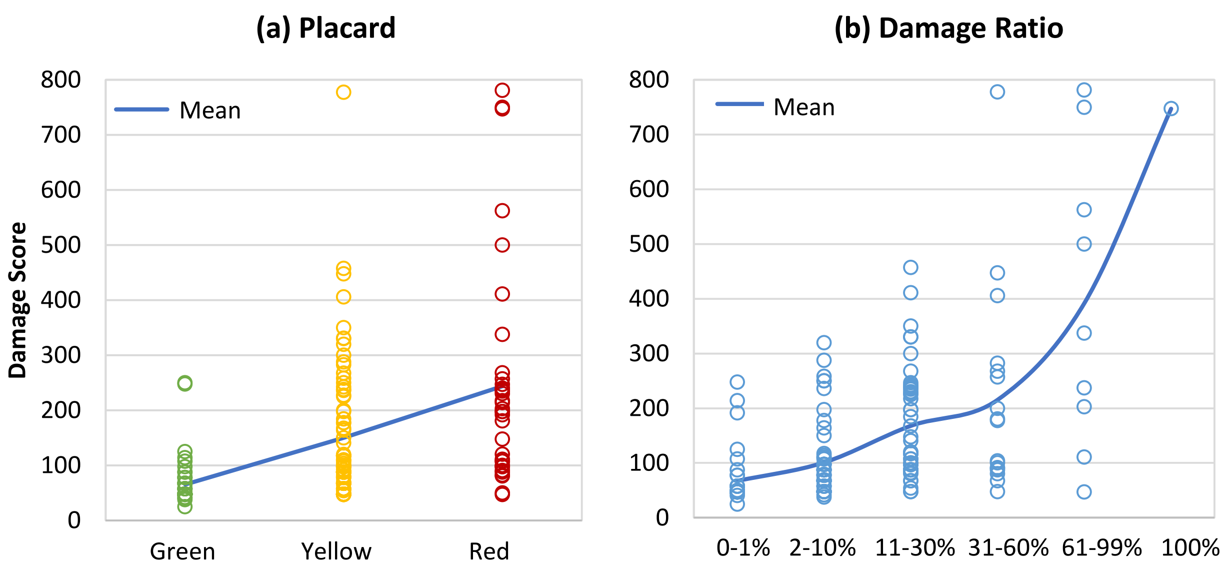

Figure 4-3: Damage Score vs. (a) Placard and (b) Damage Ratio

4.3 Pre- and Post-Earthquake Percentage New Building Standard (%NBS)

The concept of percentage of New Building Standard (NBS) was adopted to approximately measure the structural capacity. Expressed as a percentage, %NBS is the assessed structural performance of an existing building compared with requirements for a new building; a %NBS of 33 or below indicates earthquake-prone building (*Building Act*, 2004) and a %NBS of 67 or higher implies no significant earthquake risk (NZSEE, 2006). As a part of the Detailed Engineering Evaluation (DEE) requirements by CERA, %NBS of a building is determined either in accordance with NZSEE (2006) or by a comparison with current seismic loading standard in New Zealand's structural design standards (NZS1170.5:2004) (DBH, 2012b).

The Christchurch City Council mandated seismic strengthening work on the buildings with %NBS rating 33% or below (referred to as earthquake-prone buildings) (CCC, 2010). This means that restoration of an earthquake-prone building is likely to cost more due to the required seismic strengthening work in addition to damage repair compared to other buildings with the same level of damage. Therefore, the %NBS rating is a possible factor affecting the building demolition decision. %NBS information, however, was available for only 35% of the buildings in the database, mainly because the DEEs are not available for all buildings. Details on the city's legislation are discussed in section 6.2.

4.4 Seismic Force Resisting System

Seismic Force Resisting System (SFRS) is a structural system designed to resist lateral loads induced by ground motions. SFRS is considered in this study to observe whether a specific type of SFRS results in more building demolitions, possibly driven by varying structural performance, damage, and associated cost of repair. This study focuses on multi-storey buildings with SFRS of concrete Moment Frame (MF), concrete Shear Wall (SW), concrete Moment Frame with Infill (MFIF), and combined Moment Frame and Shear Wall. Concrete tilt-up structures are not considered in this study as such structures are often popular for one- or two-storey buildings and frequently used steel connections result in different structural behavior and damage compared to the other reinforced concrete structures.

4.5 Duration in Cordon

Immediately after the 22 February 2011 earthquake, a cordon (public exclusion zone) was established, covering most of the built area in the CBD as shown in Figure 4-4. The cordoned area was reduced gradually in 33 phases, and the last cordon was lifted on 27 June 2013, 28 months after the establishment. The duration over which each building was inside the cordon zone may reduce the probability of demolition because the limited public access could facilitate the necessary engineering works on buildings. On the other hand, cordoned-off buildings are more likely to suffer from business interruption, which may lead to loss of tenants especially when the cordon lasts for an extended period. To determine the duration in the cordon zone, the date that the cordon was lifted for each building was obtained from the spatial data analysis (section 3.5) and the number of months in the cordon was calculated.

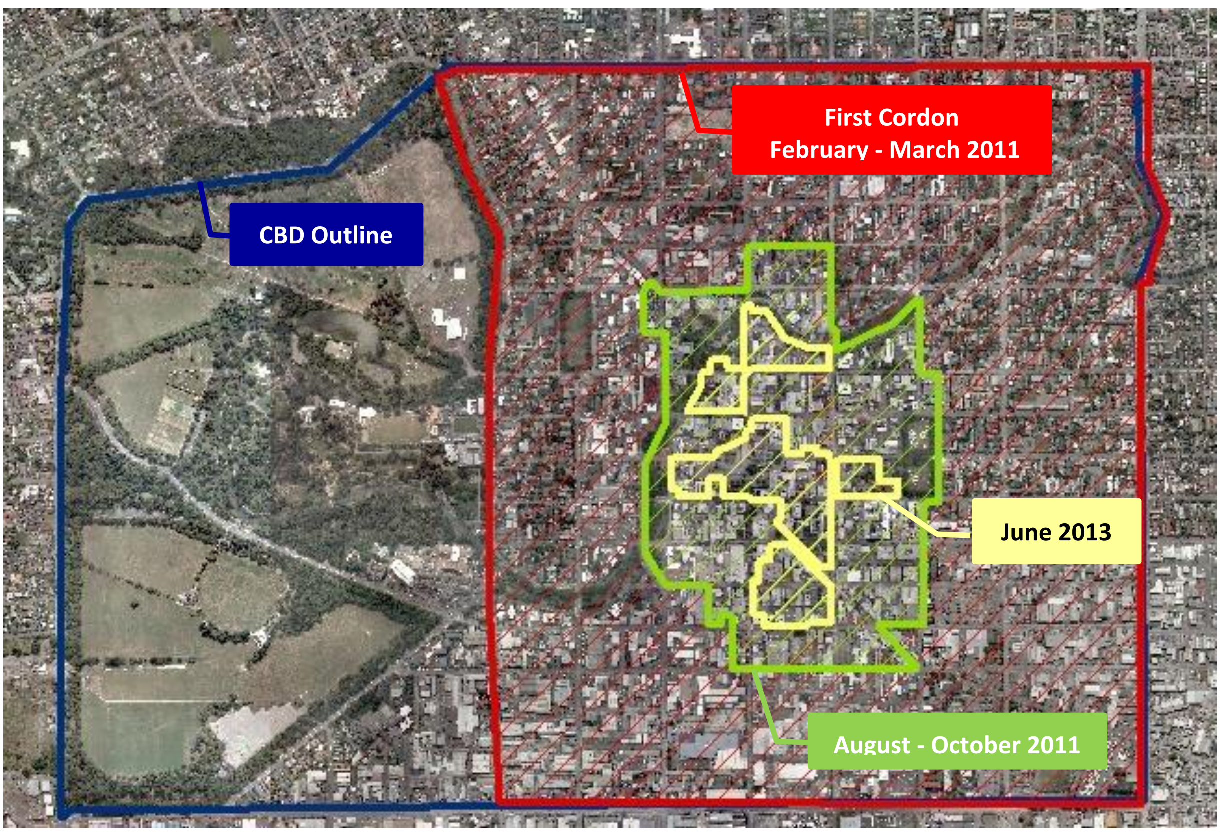

Figure 4-4: Changes in Cordon Zone (showing 3 out of 33 phases)

4.6 Building Construction Year

Building construction year is considered in this study because it indicates the age of building and the building code used for the structural design, which may affect the likelihood of building demolition.

Often, the exact year an old building was built is difficult to find, resulting in an incomplete database. Attempts to estimate the construction year can be challenging and may lead to inaccurate information. An estimation of the construction year in ranges, on the other hand, is relatively easier and more accurate. For this reason, the building construction year is specified in five ranges reflecting the advancement of structural design standards (IPENZ, 2011): pre-1965, 1965-1975, 1976-1991, 1992-2003, or post-2003.

4.7 Heritage Status

Buildings designated as *heritage* in the database refer to those included in the Christchurch City Plan Heritage Groups, Banks Peninsula District Plan Heritage Significance Schedules, or the New Zealand Historic Places Trust Historic Register (CCC, 2007). Although there are various levels associated with the heritage status, buildings were simply recorded as either heritage or nonheritage in the source databases, and hence in the study database as well.

The owners of heritage buildings may apply for and receive financial supports for restoration works from the Heritage Incentives Grant (CCC, 2007) and the Canterbury Earthquake Heritage Buildings Fund (CEHBF, 2012). Therefore, such effort to conserve heritage buildings may decrease the probability of building demolition.

4.8 Footprint Area

The building footprint area is an area defined by the perimeter of the building plan independent of the number of floors above. It is estimated in square meters (m^2) using spatial data analysis software as indicated in section 3.5. The footprint area together with the number of floors indicate the size of a building. These are included in the study to observe the possible influence of the building size on the building demolition.

4.9 Number of Floors

Number of floors above ground is recorded, which approximately relates to building height. As reported in literatures (Polese et al., 2014; Ramirez et al., 2012), a trend of decreasing unit repair cost was observed with increasing number of floors. Decrease in repair cost may decrease the probability of building demolition and therefore, the number of floor variable is considered in this study.

4.10 Occupancy Type

Type of occupancy is categorized into nine groups: commercial, residential, hotel, post-secondary institution, hospital, public assembly, school, government facility, and industrial. Commercial occupancy generally includes office spaces, retail, restaurants, and parking structures. Residential occupancy refers to multi-storey condominiums and apartments.. In New Zealand, schools, hospitals, and post-secondary and public assembly buildings with large capacity are considered as Importance Level 3 or 4, which indicates higher level of importance requiring increased structural performance (DBH, 2012a). Therefore, the occupancy type is considered in the study because it implies the importance of buildings and may affect the likelihood of building demolition. For example, functioning hospitals are crucial after damaging earthquakes, and therefore there may be more in need and effort to restore them. Comparatively, it is speculated that commercial buildings may more likely to be demolished.

4.11 Database Building Statistics

Descriptive statistics are studied to describe the collected database. Frequency distributions of the variables and their relationships with the decision outcome variable (bivariate statistics) are graphically presented and summarized in Figure 4-5Figure 4-12. This allows for simple, yet clear understanding of the characteristics and trends of the buildings in this study. More database building statistics can be found in appendix C.

The 223 buildings in this study represent approximately 88% of the 3-storey and higher reinforced concrete buildings within the Christchurch CBD (approximate total of 254 buildings); buildings with no, or very limited, information were excluded from the database. This represents approximately 34% of all reinforced concrete buildings in the CBD (approximate total of 656 buildings).

As demonstrated in Figure 4-5, 62% of the buildings of interest (138 buildings) were demolished and 29% (65 buildings) were repaired. This is equivalent to demolition of 61% (750,800 m^2) and repair of 30% of total floor space of the buildings considered (1,223,500 m^2), assuming equal plan area for all floors (Figure 4-10c). The outcomes for the remaining 20 buildings (equivalent to 8% of total floor space) were unknown at the time of data collection. Among the demolished buildings, the decisions made by Civil Defence for immediate public safety only account for 2% (3 buildings). Majority of demolition decisions were made by either owners (30%) or CERA (25%), and CCDU demolition accounts for 5%.

Out of the 223 buildings, 35% received green, 46% received yellow, and 19% received red placards (Figure 4-6a). Among the green placarded buildings, 35% were demolished. Of the 135 buildings (61%) assessed to have a relatively low Damage Ratio of 10% or less, 47% (63 buildings) were demolished (Figure 4-6b). Similarly, 117 buildings (57%) received low Damage Scores of 100 or less, and 50% of them (59 buildings) were demolished (Figure 4-6c). It can thus be inferred that a significant number of reinforced concrete buildings with relatively low damage were demolished.

While 28~30% of the study buildings were not assessed for geotechnical damages, the majority of the buildings (61~69%) were assessed to have minor or no slope failure, ground movement, and soil bulging and liquefaction damages (Figure 4-7).

In terms of building characteristics, heritage buildings account for 16% of the database (Figure 4-8a) and it is observed that heritage buildings have lower likelihood of demolition compared to nonheritage buildings. Moment frame (39%) and shear wall (44%) structural systems are almost equally common in the Christchurch CBD (Figure 4-8b). It is found that higher rate of moment frame buildings (75%) were demolished compared to shear wall buildings (49%). A significant number of buildings are low and mid-rise buildings (Figure 4-8c). Demolition rate increases as the number of floor increases; 57% for 3-5 storey, 68% for 6-12 storey, and 73% for 13-22 storey buildings.

Commercial occupancy is dominant (69%) and residential and hotel buildings account for 10% and 9%, respectively (Figure 4-9a). High rate of demolition is observed for commercial (74%) and government buildings (75%) compared to demolition rates for residential (36%), hotel (47%), and hospital (38%) buildings. Representing only 7% of the study buildings, majority of post-secondary, public assembly, school, and industrial buildings were repaired (78~100%). Buildings constructed before 1975 account for 45% of the database and 65% of those buildings were demolished; 59% of the buildings constructed after 1975 were demolished (Figure 4-9b). Buildings that were in the cordon zone for more than 1 year account for 58% of the database, and 76% of them were demolished (Figure 4-9c).

The majority of buildings (78%) have a building footprint area of less than 1,000 m^2, and 65% of those buildings were demolished (Figure 4-10a). Total floor area was calculated assuming equal plan area for all floors (building footprint area multiplied by number of floors.) As shown in Figure 4-10b, 32% of the buildings have total floor area of 4,000 m^2 or less and 62% of those buildings were demolished. Figure 4-10c presents the total floor area categorized by occupancy types. Out of 683,000 m^2 of total commercial floor area in the study, 74% (119,600 m^2) was demolished. On the other hand, 67% (163,500 m^2) of total institutional and industrial floor area was repaired.

As shown in Figure 4-11, DEE summary table was collected for 87 buildings (39%) of the study buildings, and 87% (76 buildings) and 90% (78 buildings) of those buildings were assessed for Pre-EQ and Post-EQ %NBS ratings, respectively. Of the buildings with DEE summary table, 59% were repaired, while only 29% of the total study buildings were repaired. It is inferred that the buildings with DEE summary table are more likely to be repaired.

Figure 4-12 compares the assessed damage (Placard and Damage Ratio) statistics for the two sets of data: all 223 study buildings and 87 buildings with DEE summary table available. It is apparent that greater portion of the buildings with DEE summary table were assessed for minor damage; 56% received green placards compared to 35% for the entire database, and 81% were assessed for Damage Ratio of 10% or less compared to 61% for the entire database. From Figure 4-11 and Figure 4-12, it can be concluded that the buildings with DEE summary table do not represent the overall database, statistically; those buildings had less damage and are more likely to be repaired.

Considering only buildings with pre- and post-EQ %NBS ratings (Figure 4-13), the demolition rate is lowest (< 11%) among those buildings with %NBS > 66% and highest (33%) for buildings with %NBS ≤ 33%. This is most likely due to the city's earthquake-prone building policy, which mandates seismic strengthening work on buildings with %NBS ≤ 33% and hence increases the cost of restoration (repair and strengthening). More discussion on the city's policy is provided in section 6.2.

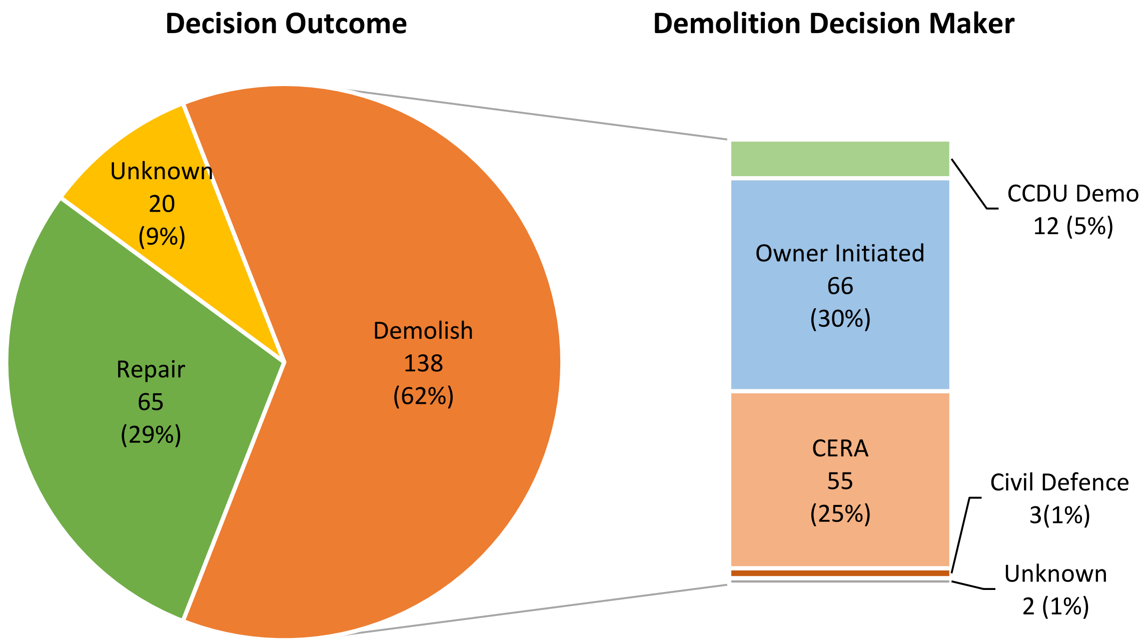

Figure 4-5: Building Decision Outcome Statistics – Decision Outcome and Demolition Decision Maker

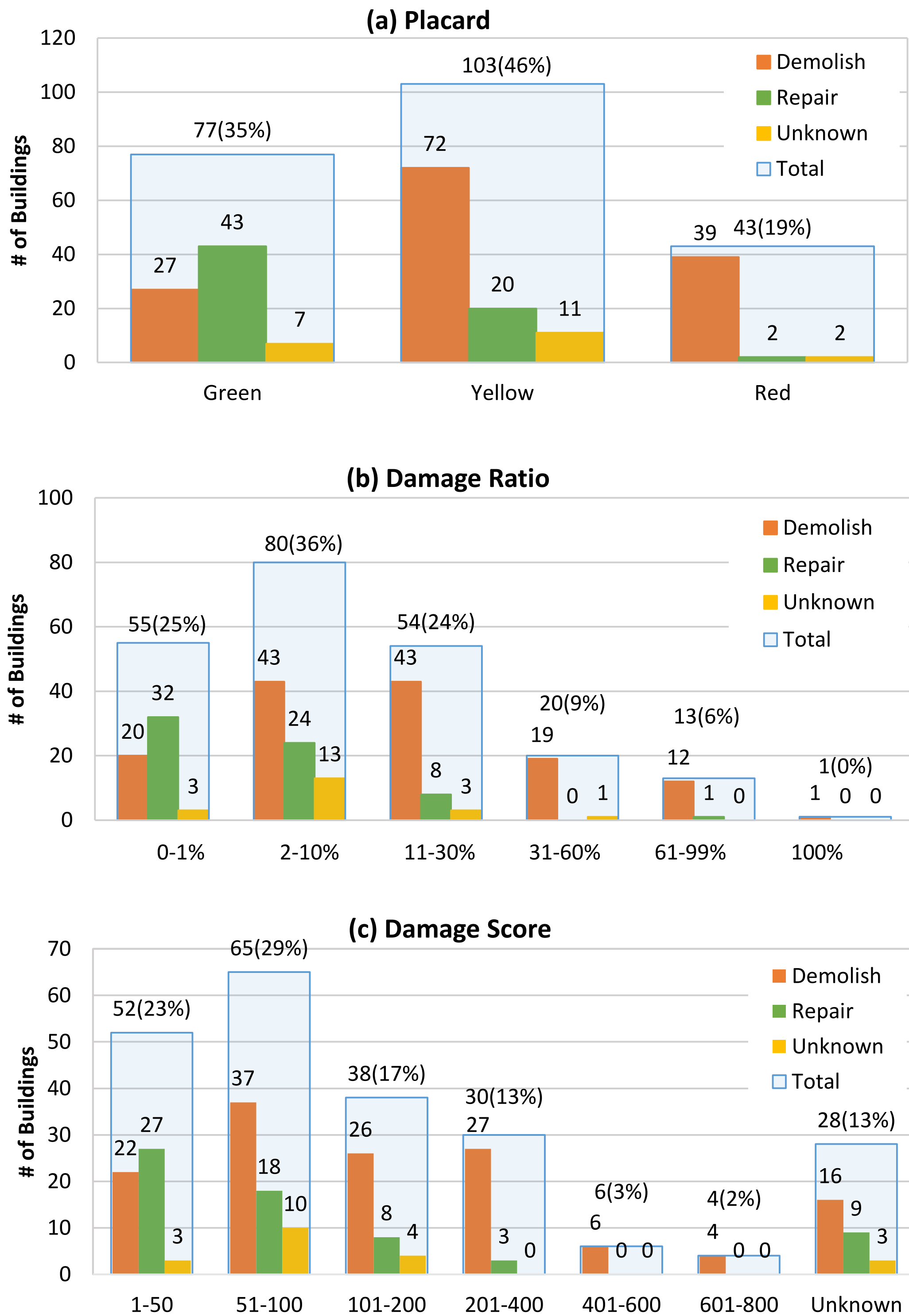

Figure 4-6: Damage Indicator Statistics – (a) Placard, (b) Damage Ratio, and (c) Damage Score

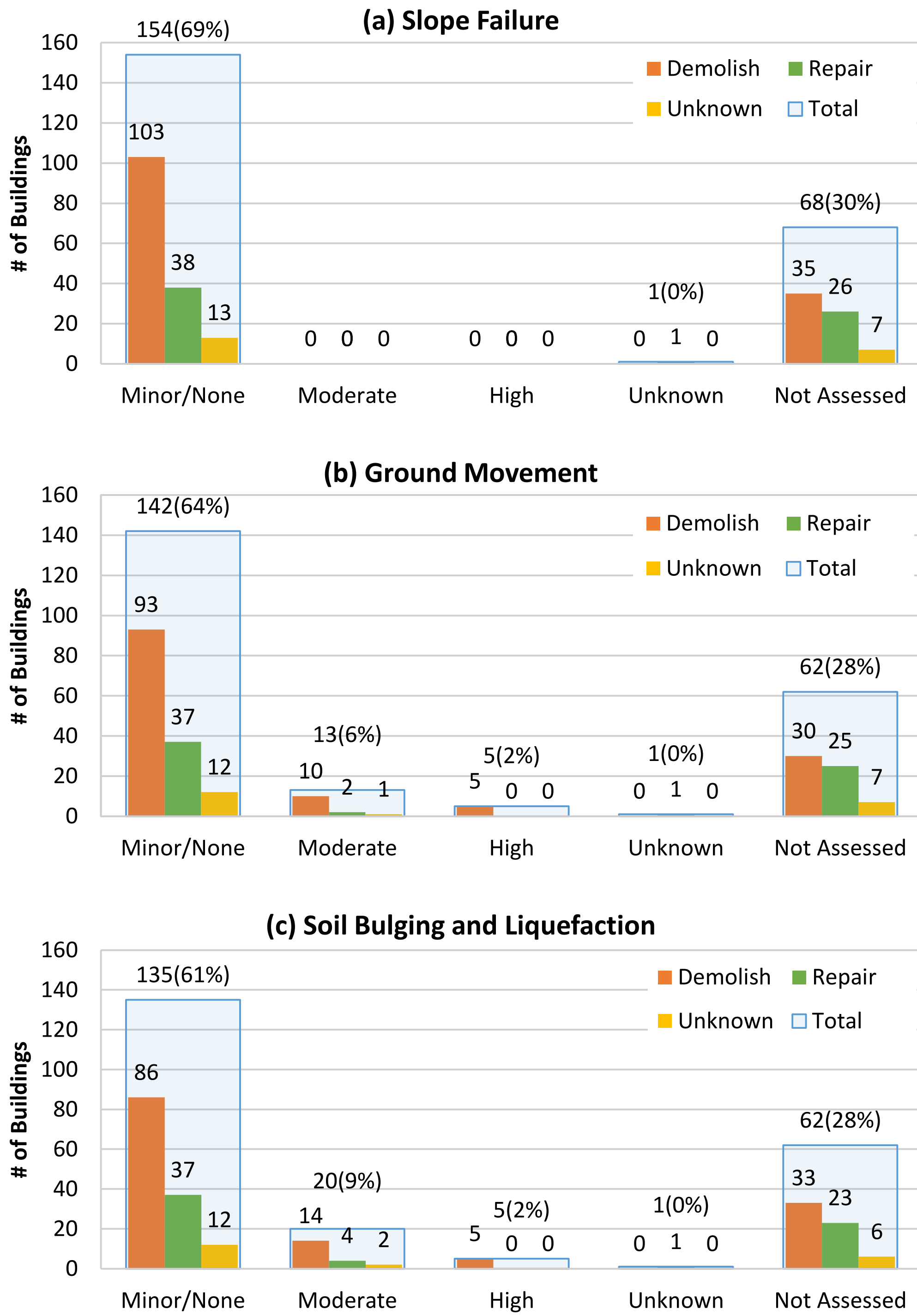

Figure 4-7: Geotechnical Damage Statistics – (a) Slope Failure, (b) Ground Movement, and (c) Soil Bulging and Liquefaction

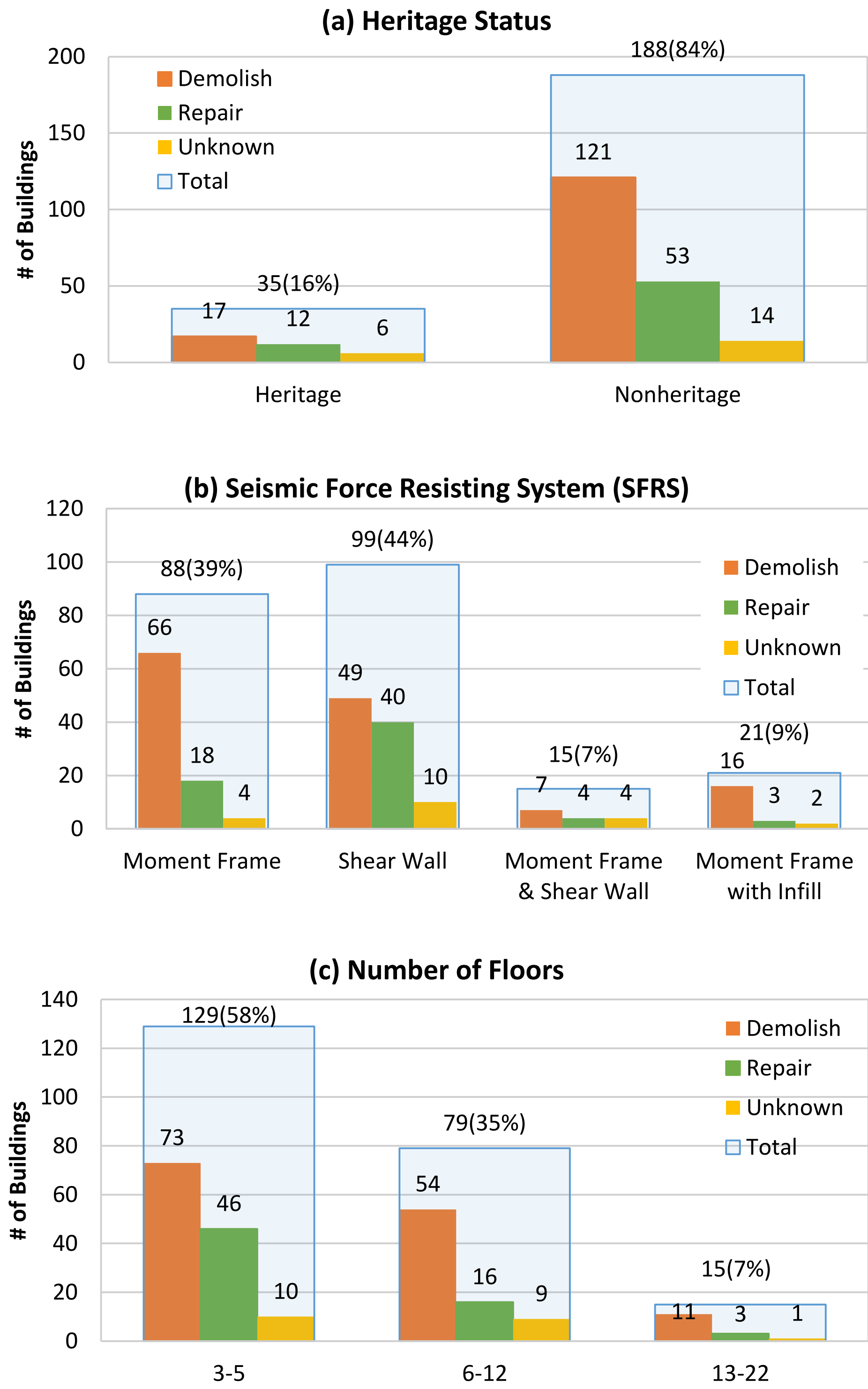

Figure 4-8: Building Statistics – (a) Heritage Status, (b) Seismic Force Resisting System, and (c) Number of Floors

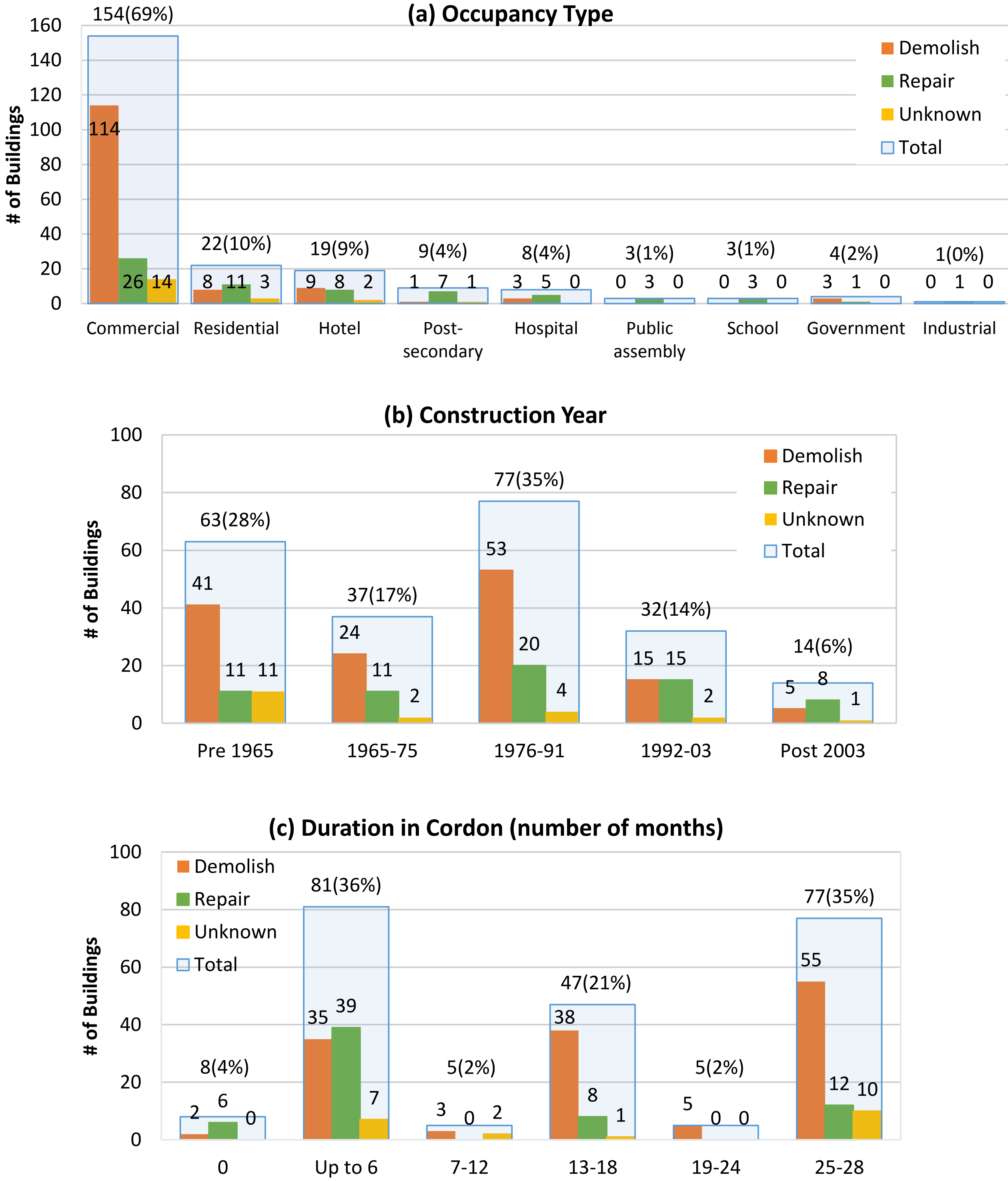

Figure 4-9: Building Statistics – (a) Occupancy Type, (b) Construction Year, and (c) Duration in Cordon

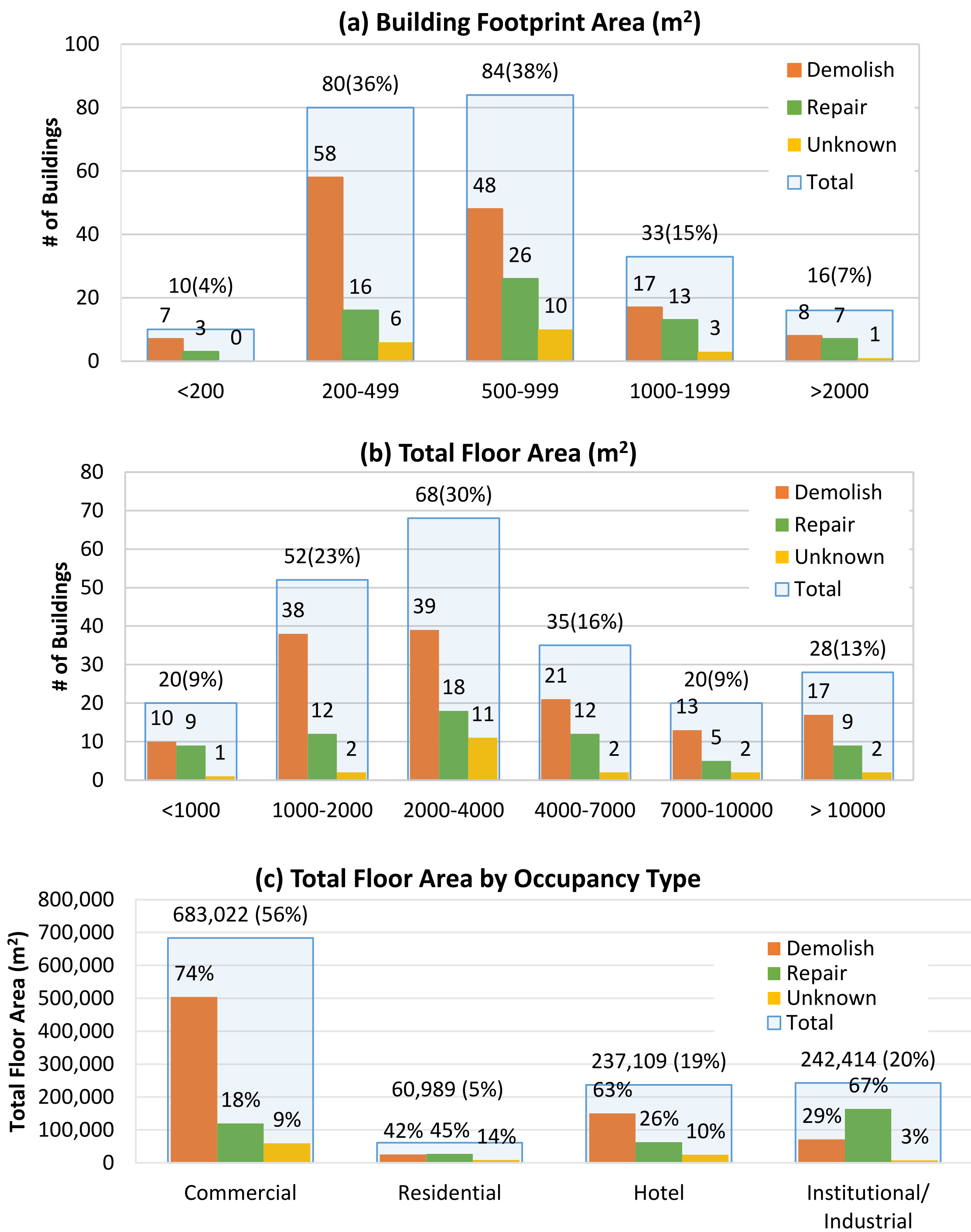

Figure 4-10: Building Area Statistics – (a) Footprint Area, (b) Total Floor Area, and (c) Total Floor Area by Occupancy Type

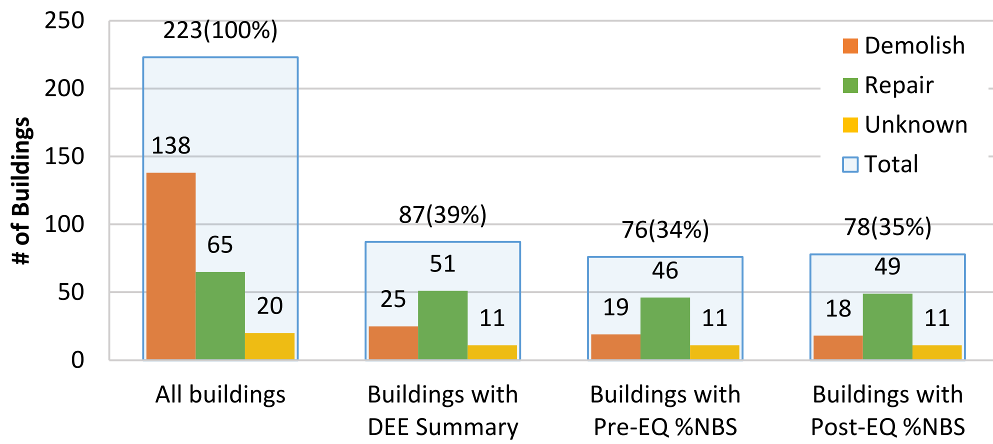

Figure 4-11: Building Data Availability - All Buildings, Buildings with DEE Summary Table, Buildings with Pre-EQ %NBS Data, and Buildings with Post-EQ %NBS Data

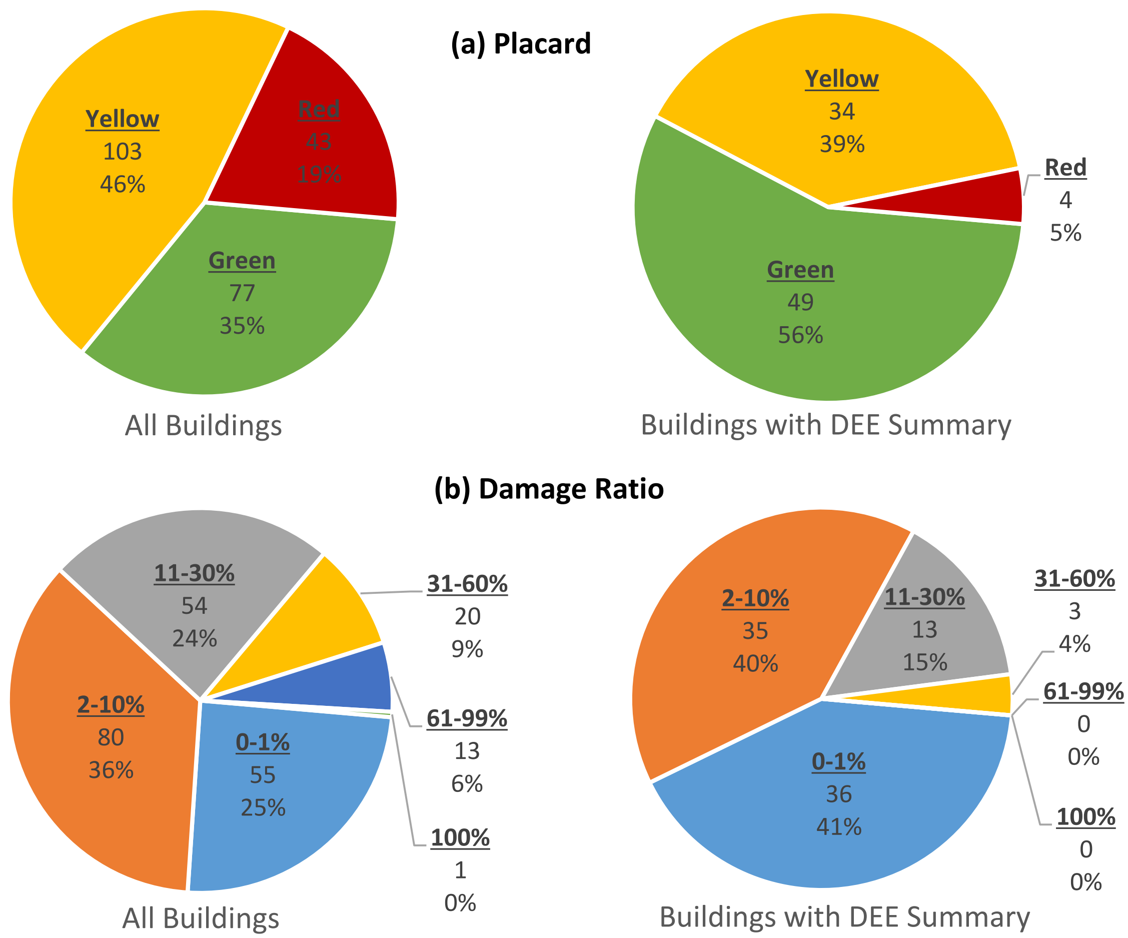

Figure 4-12: All Buildings vs Buildings with DEE Summary Table – (a) Placard and (b) Damage Ratio

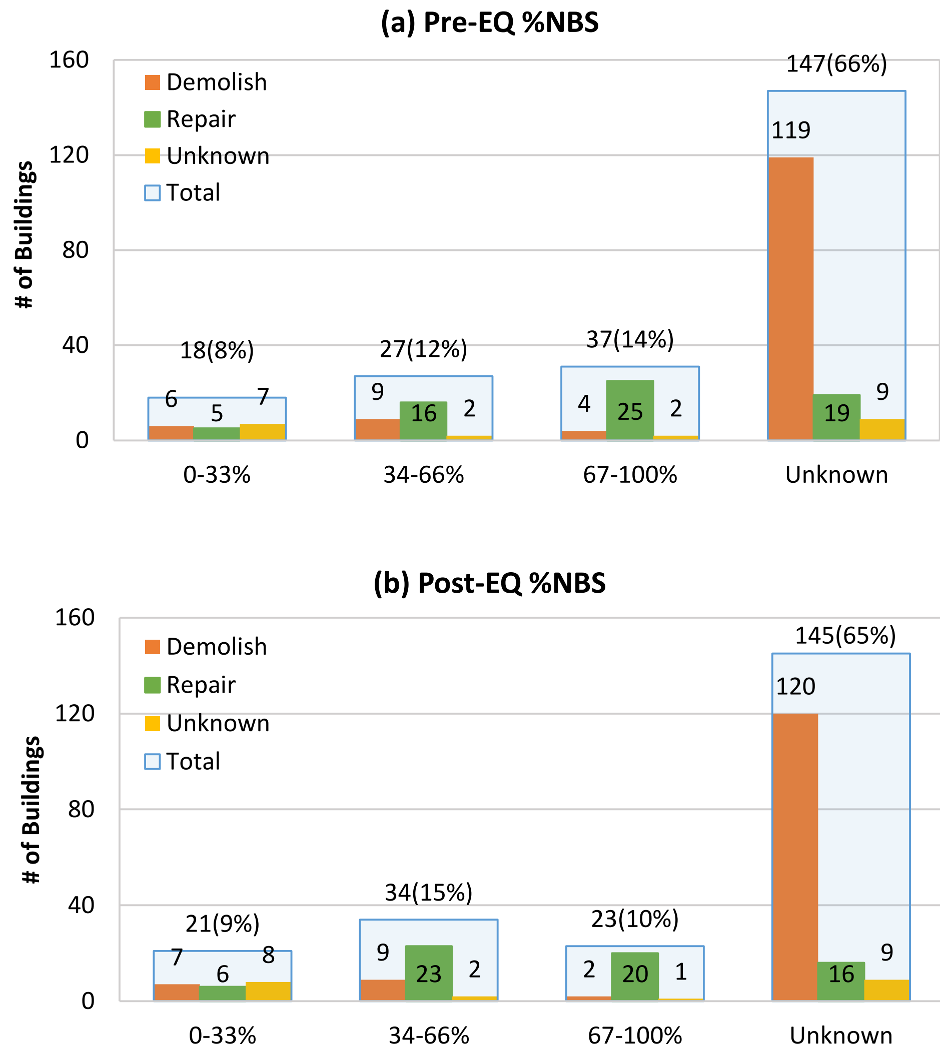

Figure 4-13: Building Seismic Capacity Statistics - (a) Pre-EQ %NBS and (b) Post-EQ %NBS

Chapter 5: Logistic Regression Model

The bivariate statistics presented in section 4.11 describe the relationships between pairs of variables; individual independent variables with the decision outcome (dependent) variable. In chapter 5, logistic regression analyses are presented to encompass simultaneous and relative effects of the independent variables on the dependent variable.

Chapter 5 describes the development of logistic regression models based on the collected data described in chapter 4. Utilizing two different methods (Forward and Backward Stepwise Selection methods) and three different damage indicators (Placard, Damage Ratio, and Damage Score), total of six models were developed. Then, they were tested for goodness-of-fit and screened for quality to arrive at the best model. Probability-of-demolition function from the final logistic regression model is presented and its interpretation is discussed. Separate logistic regression models considering the %NBS variable are also examined.

The basic principles of logistic regression analysis were discussed in section 2.3. The statistical analysis software used for the project is IBM® SPSS® Statistics 22

5.1 Objective and Scope of Logistic Regression Model Analysis

The main objective of the logistic regression model analysis is to explicitly quantify the influence of potential explanatory variables on the probability of building demolition. The aim is to express the results in terms of probability of demolition given a set of influencing factors. Although the empirical equation developed here may be used to predict the probability of building demolition, the database scope and local context should be carefully considered before using the model for prediction in other settings. Such limitation is further discussed in section 7.2.

The scope of the logistic regression model analysis is the same as the research scope: 3-storey and higher concrete buildings in the Christchurch CBD. Logistic regression models are established based on the research database with a few exceptions. The buildings with *unknown* decision outcome (20 buildings) are excluded, as such buildings do not provide any meaningful information for the analysis. The buildings demolished under *CCDU Demolition* (12 buildings) are also left out because the decision outcome on such buildings is solely based on the city's development plan, irrespective of the variables under consideration.

5.2 Description of Logistic Regression Model

The basic principles of logistic regression analysis were discussed in section 2.3. For more details on logistic regression analysis and model building procedure using SPSS, refer to Hosmer et al. (2013) and IBM Corp.(2013).

In logistic regression models, the independent variables can be both categorical and scalar. The categorical variables are coded using dummy (or design) variables. Each dummy variable is given a value of either 0 or 1, and a combination of the dummy variables defines class membership of the independent variable. If a categorical variable has n possible values, $n\text{-}1$ dummy variables are introduced. For example, the *Placard* variable has three categories (green, yellow, and red). As these are discrete categorical values, two dummy variables are introduced and coded as shown in Table 5-1. When there are two possible groups in a categorical variable, each group is simply assigned a value of either 0 or 1.

Table 5-1: Dummy Variable Coding for Placard

Placard	Dummy 1	Dummy 2
Green	1	0
Yellow	0	1
Red	0	0

While the *Occupancy Type* variable has 9 categories, the majority of the study buildings is commercial occupancy (Figure 4-9a). A large number of categories may result in relatively small or zero number of observations in each category, which is the most common reason for convergence failure of a logistic regression model (Altman et al., 2003). For numerical stability and succinctness of the model, the *Occupancy Type* variable is reduced to two categories: Commercial and Residential/Hotel/Institutional/Industrial. Similarly, the MFIF and Combined MF/SW categories for the *SFRS* variable are grouped together, resulting in three categories and two dummy variables.

For the *Construction Year* variable, which is in categorical ranges, the median value for each range was selected as its representative scalar value.

Due to the small number of observations in the 100% *Damage Ratio* category, the categorical (and ordinal) *Damage Ratio* variable caused model instability (Altman et al., 2003). In an effort to resolve the issue, the *Damage Ratio* variable was converted to a linear scalar variable (1 to 6). To investigate the validity of such conversion, two univariate regression models were developed relating the *Decision Outcome* (dependent variable) with the two different types of the *Damage Ratio* variable: first model with categorical variable and second model with scalar variable. The probability of demolition from those two models are compared in Table 5-2. It is shown that the two predictions of the probability of demolition are generally in agreement with minor differences at higher damage ratios. In addition, the Level 2 Rapid Assessment form includes Damage Ratio in the form of categories (tick box for each range) and it is more likely that the inspectors consider Damage Ratio ranges as relative linear scale than as numerical ranges. Therefore, it is confirmed that the linear scale is a reasonable approximation, and such change in the variable type does not significantly affect the model outcome.

Table 5-2: Comparison of Categorical and Scalar Damage Ratio Variable - Probability of Demolition

Variable Type	**Damage Ratio**					
	0-1%	2-10%	11-30%	31-60%	61-99%	100%
Categorical	38%	64%	84%	100%	92%	100%
Scalar	38%	64%	84%	94%	98%	99%

Table 5-3 summarizes the coded values for all variables.

The *Pre-EQ %NBS* and *Post-EQ %NBS* variables are not included in the logistic regression model due to lack of available data for a sufficient number of buildings. Instead, the importance of the variables are studied separately in section 5.8.

5.3 Logistic Regression Model Building Strategy

Among various model-building strategies, stepwise variable selection methods are chosen. The main advantage of the stepwise selection methods is that they are useful when important variables are not known from previous studies, and their relation with the outcome variable is not well understood (Hosmer et al., 2013). This aspect gives a substantial advantage since the core objective of the logistic regression analysis is to identify the factors influencing the building decision outcome. In addition, the stepwise selection methods are effective and efficient in screening many variables and fitting various models concurrently.

The stepwise selection methods utilize significance testing rules when determining inclusion or exclusion of independent variables in models. Depending on the type of methods, such decision rules vary among probability of likelihood ratio statistics, score statistics, and Wald statistics. Studies have shown that there are no significant differences among different types of tests (Hosmer et al., 2013). The stepwise selection methods used in this analysis are described in the following subsections.

Table 5-3: Logistic Regression Model Variables

<table>
<tr><th>Variable Type</th><th>Variable Name</th><th>Notation</th><th colspan="2">Values</th><th>Value Label</th><th>Measure</th></tr>
<tr><td rowspan="2">Dependent</td><td rowspan="2">Decision Outcome</td><td rowspan="2">y</td><td colspan="2">0</td><td>Demolish</td><td rowspan="2">Categorical</td></tr>
<tr><td colspan="2">1</td><td>Repair</td></tr>
<tr><td rowspan="30">Independent</td><td>Footprint Area</td><td>x_1</td><td colspan="3">Numeric [m^2]</td><td>Scale</td></tr>
<tr><td rowspan="5">Construction Year</td><td rowspan="5">x_2</td><td colspan="2">1932</td><td>Pre 1965</td><td rowspan="5">Scale</td></tr>
<tr><td colspan="2">1970</td><td>1965-1975</td></tr>
<tr><td colspan="2">1984</td><td>1976-1991</td></tr>
<tr><td colspan="2">1998</td><td>1992-2003</td></tr>
<tr><td colspan="2">2007</td><td>Post 2003</td></tr>
<tr><td rowspan="2">Heritage Status</td><td rowspan="2">x_3</td><td colspan="2">0</td><td>Heritage</td><td rowspan="2">Categorical</td></tr>
<tr><td colspan="2">1</td><td>Nonheritage</td></tr>
<tr><td rowspan="4">SFRS</td><td rowspan="4">x_4, x_5</td><td>x_4</td><td>x_5</td><td></td><td rowspan="4">Categorical</td></tr>
<tr><td>1</td><td>0</td><td>MF</td></tr>
<tr><td>0</td><td>0</td><td>SW</td></tr>
<tr><td>0</td><td>1</td><td>MFIF, MF&SW</td></tr>
<tr><td rowspan="2">Occupancy Type</td><td rowspan="2">x_6</td><td colspan="2">0</td><td>R/H/I</td><td rowspan="2">Categorical</td></tr>
<tr><td colspan="2">1</td><td>Commercial</td></tr>
<tr><td>Number of Floors</td><td>x_7</td><td colspan="3">Numeric</td><td>Scale</td></tr>
<tr><td>Duration in Cordon</td><td>x_8</td><td colspan="3">Numeric [months]</td><td>Scale</td></tr>
<tr><td rowspan="4">Placard</td><td rowspan="4">x_9, x_{10}</td><td>x_9</td><td>x_{10}</td><td></td><td rowspan="4">Categorical</td></tr>
<tr><td>1</td><td>0</td><td>Green</td></tr>
<tr><td>0</td><td>1</td><td>Yellow</td></tr>
<tr><td>0</td><td>0</td><td>Red</td></tr>
<tr><td rowspan="6">Damage Ratio</td><td rowspan="6">x_{11}</td><td colspan="2">1</td><td>0-1%</td><td rowspan="6">Scale</td></tr>
<tr><td colspan="2">2</td><td>2-10%</td></tr>
<tr><td colspan="2">3</td><td>11-30%</td></tr>
<tr><td colspan="2">4</td><td>31-60%</td></tr>
<tr><td colspan="2">5</td><td>61-99%</td></tr>
<tr><td colspan="2">6</td><td>100%</td></tr>
<tr><td>Damage Score</td><td>x_{12}</td><td colspan="3">Numeric</td><td>Scale</td></tr>
</table>

5.3.1 *Forward Stepwise Selection*

The Forward Stepwise Selection (FSS) method performs variable entry testing based on the significance of the score statistics and variable removal testing based on the probability of likelihood ratio statistics on the maximum partial likelihood estimates. The general steps are described below:

1) The candidate independent variables are tested for inclusion one at a time based on the significance level (p-value) of the score statistics. The variable with the smallest p-value being less than the specified importance level for entry (α_E) is included in the model.
2) After each entry, the variables that are entered into the model are tested against removal criteria. For each included variable, the significance of change in the log-likelihood is determined. The log-likelihood ratio (LR) is expressed as $LR_j = -2(L_j - L)$, where L is the log of maximum likelihood estimates (MLE) of the current full model and L_j is the log of MLE of the model excluding one variable at a time. The variable with the largest p-value being greater than the specified importance level for removal (α_R) is removed from the model.
3) The model is updated and the remaining variables in the model are tested based on the most current model. After all included variables are tested for removal, all steps are repeated to evaluate the remaining candidate variables. The procedure ends when all variables are assessed based on the entry and removal criteria or when the current model is the same as the previous model.

5.3.2 *Backward Stepwise Selection*

Backward Stepwise Selection (BSS) method conducts variable removal testing based on the probability of the likelihood ratio statistics on the maximum partial likelihood estimates and variable entry testing based on the significance of the score statistics. The main difference to the FSS method is that the iteration procedure starts with all independent variables included in the model, and the variables are tested for removal one at a time. The general steps are described below:

1) All independent variables are entered into the model as a start. Then, the variables are tested for removal one at a time based on the significance level (p-value) of log-likelihood ratio, $\boldsymbol{LR_j} = -\boldsymbol{2}(\boldsymbol{L_j} - \boldsymbol{L})$. The variable with the largest p-value being greater than the specified importance level for removal (α_R) is removed from the model. The model is updated and the remaining variables in the model are tested based on the most current model.
2) After all included variables are tested for removal, the variables not in the model are checked for inclusion one at a time based on the significance level (p-value) of the score statistics. The variable with the smallest p-value being less than the specified importance level for entry (α_E) is included in the model.
3) If the updated model is not the same as any of the previous models, all previous steps are repeated. The procedure ends when all variables are assessed based on the entry and removal criteria or when the current model is the same as the previous model.

Due to the fundamental difference in the variable selection procedure, the two methods may produce different models. Both methods are used to explore and compare different model results. If the two methods generate the same model results, it would imply that the selected variables and the resulting models are robust. For both the FSS and BSS methods, the p-values of 0.05 and 0.10 are used for entry (α_E) and for removal (α_R), respectively.

For each damage indicator (*Placard*, *Damage Ratio*, and *Damage Score*), two sets of models are developed using FSS and BSS methods. Descriptive names are given to each model. Model PLF indicates model with *PLacard* as a DI using Forward Stepwise Selection method. Similarly, Model DRB indicates model with *Damage Ratio* as a DI using Backward Stepwise Selection method. Model DSF and Model DSB refer to *Damage Score* models with Forward and Backward Stepwise

Selection methods, respectively. The variable selection methods and the considered variables for the six models are summarized in Table 5-4 below.

Table 5-4: Logistic Regression Model Description

Model			PLF	PLB	DRF	DRB	DSF	DSB
Variable Selection Method			FSS	BSS	FSS	BSS	FSS	BSS
Considered Variables	Footprint Area	X_1	✓	✓	✓	✓	✓	✓
	Construction Year	X_2	✓	✓	✓	✓	✓	✓
	Heritage Status	X_3	✓	✓	✓	✓	✓	✓
	SFRS	X_4, X_5	✓	✓	✓	✓	✓	✓
	Occupancy Type	X_6	✓	✓	✓	✓	✓	✓
	Number of Floors	X_7	✓	✓	✓	✓	✓	✓
	Duration in Cordon	X_8	✓	✓	✓	✓	✓	✓
	Placard	X_9, X_{10}	✓	✓				
	Damage Ratio	X_{11}			✓	✓		
	Damage Score	X_{12}					✓	✓

✓: Variable considered for inclusion

5.4 Model Outcome

Logistic regression analyses are conducted for the six models as described in Table 5-4 above. Through iteration steps as described in section 5.3, the regression coefficients and the log-likelihood ratios are determined and summarized in Table 5-5, Table 5-6, and Table 5-7. The values from the last iteration step (in red) represent the final values for each model. Table 5-8 summarizes and compares the selected independent variables among the six models.

Table 5-5: Logistic Regression Model Coefficients – Model PLF and PLB (Placard)

Iteration Steps		Null	Model PLF				Model PLB			
			PLF_1	PLF_2	PLF_3	PLF_4	PLB_1	PLB_2	PLB_3	PLB_4
Intercept	x_0	-0.66	-2.97	-1.74	-0.36	0.31	-33.21	-34.28	-35.30	-42.19
Footprint Area	x_1						0.00			
Construction Year	x_2						0.02	0.02	0.02	0.02
Heritage Status	x_3						-1.42	-1.47	-1.35	-1.41
SFRS	x_4					-1.08	-0.92	-0.91	-0.93	
	x_5					-1.00	-0.75	-0.75	-0.79	
Occupancy Type	x_6			-1.80	-2.24	-2.10	-1.95	-1.98	-2.09	-2.19
Number of Floors	x_7				-0.22	-0.25	-0.23	-0.23	-0.25	-0.23
Duration in Cordon	x_8						-0.01	-0.01		
Placard	x_9		3.74	3.48	3.58	3.54	3.61	3.67	3.68	3.73
	x_{10}		1.76	1.86	2.14	2.00	2.17	2.22	2.19	2.33
-2 Log-Likelihood (-2LL)		245.0	188.5	167.7	157.5	151.0	144.4	144.5	144.9	149.2
No. of included variable		0	1	2	3	4	8	7	6	5

Table 5-6: Logistic Regression Model Coefficients – Model DRF and DRB (Damage Ratio)

Iteration Steps		Null	Model DRF					Model DRB			
			DRF_1	DRF_2	DRF_3	DRF_4	DRF_5	DRB_1	DRB_2	DRB_3	DRB_4
Intercept	x_0	-0.66	0.72	2.95	4.19	-35.39	-45.48	-39.93	-40.33	-41.30	-45.48
Footprint Area	x_1							0.00	0.00		
Construction Year	x_2					0.02	0.03	0.02	0.02	0.02	0.03
Heritage Status	x_3						-1.65	-1.49	-1.47	-1.54	-1.65
SFRS	x_4							-0.79	-0.80	-0.80	
	x_5							-0.38	-0.39	-0.40	
Occupancy Type	x_6		-2.13	-1.97	-2.24	-2.19	-2.10	-1.97	-2.00	-2.04	-2.10
Number of Floors	x_7				-0.20	-0.23	-0.20	-0.22	-0.22	-0.22	-0.20
Duration in Cordon	x_8							0.00			
Damage Ratio	x_{11}			-1.09	-1.04	-1.04	-1.16	-1.10	-1.10	-1.12	-1.16
-2 Log-Likelihood (-2LL)		245.0	204.8	170.8	161.1	155.1	149.3	146.0	146.0	146.2	149.3
No. of included variable		0	1	2	3	4	5	8	7	6	5

Table 5-7: Logistic Regression Model Coefficients – Model DSF and DSB (Damage Score)

Iteration Steps		Null	Model DSF		Model DSB		
			DSF_1	DSF_2	DSB_1	DSB_2	DSB_3
Intercept	X_0	-0.68	0.86	2.09	-36.21	-36.22	-29.51
Footprint Area	X_1				0.00	0.00	0.00
Construction Year	X_2				0.02	0.02	0.02
Heritage Status	X_3				-0.80	-0.81	
SFRS	X_4				-1.15	-1.15	-1.17
	X_5				-0.75	-0.74	-0.73
Occupancy Type	X_6		-2.29	-2.17	-2.00	-1.99	-2.02
Number of Floors	X_7				-0.23	-0.23	-0.25
Duration in Cordon	X_8				0.00		
Damage Score	X_{12}			-0.01	-0.01	-0.01	-0.01
-2 Log-Likelihood (-2LL)		212.2	174.1	151.3	129.7	129.7	131.2
No. of included variable		0	1	2	8	7	6

Table 5-8: Logistic Regression Model Outcome - Summary of Selected Variables

Selected Variables		Model					
		PLF	PLB	DRF	DRB	DSF	DSB
Footprint Area	X_1						✓
Construction Year	X_2		✓	✓	✓		✓
Heritage Status	X_3		✓	✓	✓		
SFRS	X_4, X_5	✓					✓
Occupancy Type	X_6	✓	✓	✓	✓	✓	✓
Number of Floors	X_7	✓	✓	✓	✓		✓
Duration in Cordon	X_8						
Placard	X_9, X_{10}	✓	✓				
Damage Ratio	X_{11}			✓	✓		
Damage Score	X_{12}					✓	✓

✓: Variable included in model

From the six logistic regression model outcomes, the following observations are made:

- Damage indicator variable (*Placard*, *Damage Ratio*, or *Damage Score*) is included in all six models. This means the assessed damage is influential in the probability of demolition, which is expected and reasonable.
- *Occupancy Type* variable is also included in all six models, indicating that the variable is influential.
- *Footprint Area*, *Construction Year*, *Heritage Status*, *SFRS*, and *Number of Floors* variables are included in at least one model.
- The two models with *Damage Ratio* (Model DRF and DRB) result in the same included variables and the same regression coefficients. This means that the selected variables strongly influence the decision outcome and that the model is robust.

The six models are tested and screened in section 5.5 and section 5.6 for final model selections. More discussion of the selected final model can be found in section 5.6.

5.5 Model Fit Test

The six models are tested to ensure the developed models properly represent the observed data. This is done using the Hosmer-Lemeshow goodness-of-fit test, which assesses whether or not the observed outcome matches with the predicted outcome in subgroups of the model population by conducting a chi-square test on the contingency table (Hosmer et al., 2013). The contingency table is created by classifying the binary outcome with a number of subgroups. Each group contains approximately equal population and is partitioned by the percentiles of the predicted probability. Here, 10 subgroups are created for each model, resulting in 2x10 contingency tables. Table 5-9 presents the contingency table for Model DRF as an example.

Table 5-9: Hosmer-Lemeshow Contingency Table for Model DRF

Subgroup	Outcome = Demolish		Outcome = Repair		Total
	Observed	Expected	Observed	Expected	
1	19	18.8	0	0.2	19
2	18	18.4	1	0.6	19
3	18	18.0	1	1.0	19
4	16	16.0	2	2.0	18
5	18	17.9	4	4.1	22
6	17	13.9	2	5.1	19
7	6	11.4	14	8.6	20
8	9	6.8	10	12.2	19
9	5	3.6	14	15.4	19
10	0	1.2	17	15.8	17

Using the contingency table, the Hosmer-Lemeshow goodness-of-fit statistic is calculated on the models and its significance value (p-value) is obtained. Detailed mathematics of the statistics can be found in the literature (Hosmer et al., 2013).

As suggested in the literature, however, the p-value from the model goodness-of-fit test should not be used to determine the relative performance of different models. Rather, it is used to check the goodness-of-fit of each model. Generally, the p-value less than 0.05 indicates that the model has a poor fit.

Table 5-10 summarizes the chi-square statistics and the p-values of the six models. Except for the Model DSB, all models have the p-value greater than 0.05, indicating a good fit.

Table 5-10: Hosmer-Lemeshow Goodness-of-Fit Test

	PLF	PLB	DRF	DRB	DSF	DSB
Chi-Square	8.94	10.42	12.09	12.09	6.917	21.53
p-value	0.35	0.24	0.15	0.15	0.55	0.01

5.6 Model Selection

Akaike Information Criterion (AIC) is a measure of the relative quality of a statistical model for a given set of data. It provides a relative estimate of the information lost when a selected model is used to represent the process that generates the data (Akaike, 1974). The AIC value is calculated using the equation shown below:

$$\boldsymbol{AIC = 2k - 2\, ln(L)} \tag{5-1}$$

$\mathbf{L}$ is the maximum likelihood estimate of the model and $-2\ln(\mathrm{L})$ is equivalent to ***-2 Log-Likelihood*** presented in Table 5-5, Table 5-6, and Table 5-7. $\boldsymbol{k}$ is the number of estimated parameters, which is equivalent to the number of degrees of freedom.

Increasing the number of estimated parameters improves the goodness-of-fit of the model. At the same time, however, it complicates the statistical model and may lead to model overfitting, which describes random error instead of the true relationship. Therefore, overfitting may exaggerate the noise and exacerbate the model performance. By adding the $\mathbf{k}$ term, the AIC accounts for the trade-off between the goodness-of-fit and the complexity of the model. Therefore, the model with the lowest AIC value is preferred.

The difference between the minimum AIC value and the AIC value for Model i ($\Delta_{\boldsymbol{i}}= \boldsymbol{AIC_{min}} - \boldsymbol{AIC_i}$) may be used to express the likelihood of Model i being the best model. As a rule of thumb, Δ_i between 0 and 2 implies substantial evidence that Model i may be the best model, Δ_i between 4 and 7 suggests considerably less support, and Δ_i greater than 10 indicates essentially no evidence that Model i may be the best model (Burnham & Anderson, 2002).

While candidate models are ranked based on the magnitude of the AIC values, the relative strength of a model can be quantified using the relative likelihood (Burnham & Anderson, 2002).

$$Relative\ Likelihood = e^{(AIC_{min} - AIC_i)/2} \quad (5\text{-}2)$$

For example, based on equation **5-2**, relative likelihood of Model PLF compared to Model PLB (minimum AIC value between the two models) is calculated as $e^{(163-165)/2} = \mathbf{0.37}$. This can be interpreted as Model PLF is 0.37 times as probable as Model PLB to minimize the information loss.

Table 5-11 below presents the calculated AIC values, Δ_i, and relative likelihoods for the six models. Δ_i and relative likelihoods are calculated by comparing two models with the same damage indicator.

Table 5-11: Logistic Regression Model AIC, Delta AIC, and Relative Likelihood

Selected Variables	Model					
	PLF	PLB	DRF	DRB	DSF	DSB
-2 Log-Likelihood (LL)	151.0	149.2	149.3	149.3	151.3	131.2
No. of estimated parameters, k	7	7	6	6	3	8
AIC	165	163	161	161	157	147
Δ_i	2	0	0	0	10	0
Relative Likelihood	0.368	1	1	1	0.007	1

The AIC, Δ_i, and relative likelihood values, together with the goodness-of-fit results in Table 5-10, are used to identify the preferred model for each damage indicator. For Placard DI, Model PLB is chosen since it has lower AIC value compared to Model PLF (although difference is marginal). Also, Model PLB includes the same variables as Model DRF and DRB. For *Damage Ratio* DI, coefficients for Model DRF are the same as Model DRB, as demonstrated in section 5.5. For *Damage Score* DI, Model DSF is chosen even with higher AIC value, because Model DSB failed the goodness-of-fit test in section 5.5.

Table 5-12 below summarizes the regression coefficients and the p-values for the independent variables, -2 Log-Likelihood values, goodness-of-fit p-values, and the AIC values for the chosen three models. For the rest of the discussion, the last letter “F” and “B” are dropped and the chosen models are simply referred to as Model PL, DR, and DS. A regression coefficient of zero means that the corresponding variable is found to have a significance value greater than 0.05 and therefore is not included in the final model.

Table 5-12: Final Logistic Regression Model Summary*

Final Model			PL		DR		DS	
			B	p-value	B	p-value	B	p-value
Independent Variables	Intercept	x_0	-42.19	-	-45.48	-	2.09	-
	Footprint Area	x_1	0	> 0.05	0	> 0.05	0	> 0.05
	Construction Year	x_2	0.02	0.02	0.03	0.01	0	> 0.05
	Heritage Status	x_3	-1.41	0.04	-1.65	0.02	0	> 0.05
	SFRS	x_4	0	> 0.05	0	> 0.05	0	> 0.05
		x_5	0	> 0.05	0	> 0.05	0	> 0.05
	Occupancy Type	x_6	-2.19	0.00	-2.10	0.00	-2.17	0.00
	Number of Floors	x_7	-0.23	0.00	-0.20	0.01	0	> 0.05
	Duration in Cordon	x_8	0	> 0.05	0	> 0.05	0	> 0.05
	Placard	x_9	3.73	0.00	-	-	-	-
		x_{10}	2.33	0.01	-	-	-	-
	Damage Ratio	x_{11}	-	-	-1.16	0.00	-	-
	Damage Score	x_{12}	-	-	-	-	-0.01	0.00
-2 Log-Likelihood (-2LL)			149.2		149.3		151.3	
No. of included variable			5		5		2	
Goodness-of-Fit p-value			0.24		0.15		0.55	
AIC			163		161		157	

* Dependent variable: decision outcome

In both Model PL and Model DR, *Occupancy Type*, *Heritage Status*, *Number of Floors*, and *Construction Year* variables are identified to be statistically significant with p-value less than 0.05, in addition to the damage indicator variable. Model DS identifies *Damage Score* and *Occupancy Type* variables as being important. Damage indicator and *Occupancy Type* variables are consistently found to be important in all three models, implying robustness of their effects on the demolition decision outcome.

The signs of the regression coefficients indicate the directions of the influence, that is, whether a unit increase of a variable increases or decreases the probability of demolition. The sign depends on the coding of the dependent and independent variables during the model building steps. For example, in this study, the negative regression coefficient for the *Damage Ratio* variable indicates that a positive change of the variable (increase in *Damage Ratio*) increases the probability of demolition.

Among the final three models, Model DR seems to be the best model for the following reasons:

- The AIC value of Model DR is smaller than that of Model PL, while Model PL and Model DR included the same variables and presented similar results. This indicates that Model DR is better than Model PL.
- Model DS indicates that *Occupancy Type* is the only variable that is important other than *Damage Score*. Realistically and intuitively, there are likely to be other variables influencing the odds ratio of building demolition, in which case relevant variables should be included in the model regardless of their statistical significance (Hosmer et al., 2013). For this reason, it is unlikely that Model DS would be the best model.
- Damage Ratio is more refined measure of damage and less biased by external factors compared to Placard. Also, Damage Ratio is likely to have less inherent uncertainty compared to Damage Score; Damage Ratio is one overall estimate of damage while Damage Score is a collection of multiple estimates with their own uncertainty. Thus, it is inferred that Model DR is better than Model PL and Model DS.
- While two different variable selection methods are used, Model DRF and Model DRB resulted in the same variables with the same regression coefficients. This indicates that Model DR and its selected variables are more robust than Model PL and Model DS; models

with Placard (PLF and PLB) and Damage Score (DSF and DSB) resulted in different selected variables for different variable selection methods.

Therefore, Model DR is selected to be the best model and the following discussion focuses on Model DR.

5.7 Probability of Demolition

From the logistic regression analysis results, a function representing how the probability of demolition varies with level of damage and other independent variables can be derived. The regression coefficients from the established logistic regression model (Model DR) (Table 5-12) are substituted into the equations **2-7** and **2-8** to obtain the probability-of-demolition function as below:

$$\boldsymbol{ln}\left(\frac{\boldsymbol{P}}{\boldsymbol{1-P}}\right) = \boldsymbol{y} = -\mathbf{45.48} + \mathbf{0.03}\boldsymbol{x_2} - \mathbf{1.65}\boldsymbol{x_3} - \mathbf{2.10}\boldsymbol{x_6} - \mathbf{0.2}\boldsymbol{x_7} - \mathbf{1.16}\boldsymbol{x_{11}} \quad \textbf{(5-3)}$$

$$\text{Probability of Demolition} = 1 - \mathrm{P} = \frac{1}{1+e^{-45.48+0.03x_2-1.65x_3-2.1x_6-0.2x_7-1.16x_{11}}} \quad \textbf{(5-4)}$$

Note that the logistic regression model was coded so that $\boldsymbol{P}$ in the above function is the probability of repair and $\boldsymbol{1-P}$ is the probability of demolition (Table 5-3).

For visualization focusing on the level of damage, 2-dimensional probability-of-demolition curve is plotted against *Damage Ratio* by assuming a reference set of independent variables (fixed values of $\boldsymbol{x_2}$, $\boldsymbol{x_3}$, $\boldsymbol{x_6}$, and $\boldsymbol{x_7}$) (Figure 5-1). This curve is referred to as reference curve in the following discussion. The reference values of the independent variables are chosen at their median values from the database, and these are presented in Table 5-13.

Table 5-13: Reference Values for Independent Variables

Variable Name	Variable	Reference Value
Construction Year	x_2	1984
Heritage Status	x_3	Nonheritage
Occupancy Type	x_6	Commercial
Number of Floors	x_7	5-storey
Damage Ratio	x_{11}	2-10%

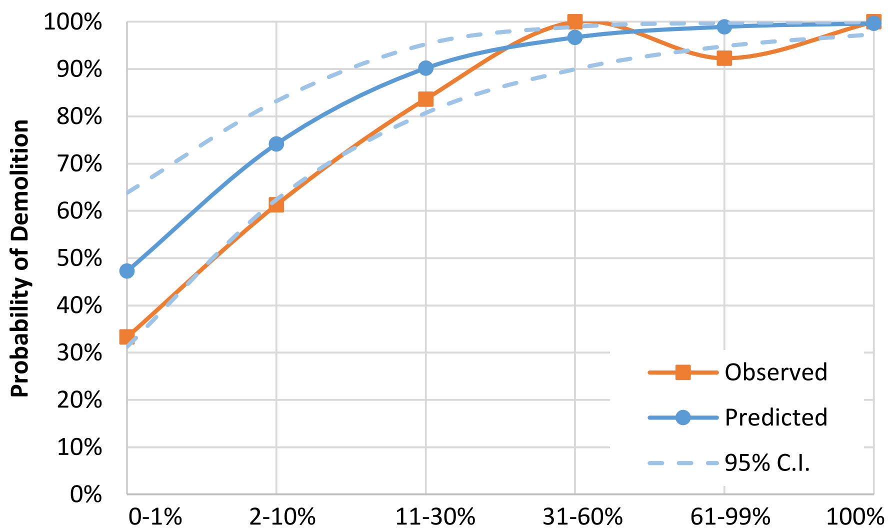

Figure 5-1: Probability of Demolition vs. Damage Ratio

The observed probability-of-demolition curve in Figure 5-1 is produced by calculating the frequency of observed demolition outcome for each level of damage (referred to as cross-tabulation). The 95% confidence intervals (CI) for the predicted probability-of-demolition are calculated as follows:

1) Fitted value (y) is calculated by substituting reference values of the independent variables and a *Damage Ratio* value into equation **5-3**.

2) Standard error of the fitted value (S.E. fit) is calculated using R (The R Core Team, 2014); SPSS does not have a readily available option for this calculation.
3) Upper limit (UL) and lower limit (LL) for 95% confidence of the probability of demolition are calculated as $\frac{1}{1+e^{(\text{fitted y}\pm 1.96\text{S.E.fit})}}$.
4) The above calculations are conducted for the six values of *Damage Ratio* variable.

The drop in the observed probability of demolition at *Damage Ratio* of 61-99% is exaggerated by the small number of observations in that category.

Figure 5-1 shows that the logistic regression model prediction is generally in good agreement with the observed probability of demolition (within 95% CI). As expected, both the predicted and observed probability-of-demolition curves indicate that the likelihood of demolition increases with severity of building damage. It is found that the probability of demolition (for both observed and predicted) for the lowest levels of damage are already quite high ranging from 31% to 47%. It should be noted that the likelihood of an undamaged building being demolished is very low (except for the buildings demolished under CCDU demolition, which were excluded from the analysis) because insurance claim is triggered by the assessed damage. Although *Damage Ratio* of 0-1% is supposed to include the buildings with no damage (as there is no option for “no damage” in the assessment form), the high demolition rate for the buildings with 0-1% *Damage Ratio* suggests that the majority of those buildings are likely to had some degree of damage.

Since the predicted probability-of-demolition curve is based on the arbitrarily chosen, median conditions of the independent variables (reference values), the change in the probability of demolition due to the change in damage severity (slope of the curve) is more informative than the absolute values of the probability of demolition. With all other variables being equal, varying *Damage Ratio* from 0-1% to 11-30% and to 100% would raise the likelihood of demolition by 43% and 52%, respectively. The changes in the probability of demolition is summarized in Table 5-14, which is read from row to column and the values are subtraction of the two probabilities.

Table 5-14: Change in Probability of Demolition

Damage Ratio	0-1%	2-10%	11-30%	31-60%	61-99%	100%
0-1%	0%	27%	43%	49%	52%	52%
2-10%	-27%	0%	16%	23%	25%	26%
11-30%	-43%	-16%	0%	7%	9%	9%
31-60%	-49%	-23%	-7%	0%	2%	3%
61-99%	-52%	-25%	-9%	-2%	0%	1%
100%	-52%	-26%	-9%	-3%	-1%	0%

The reference curve in Figure 5-1 may be shifted and/or scaled by varying one independent variable at a time. By observing the changes in the curve, the effects of independent variables on the demolition decision can be determined. This is demonstrated in Figure 5-2.

Generally speaking, older, taller, nonheritage, commercial buildings have higher probability of demolition for a given *Damage Ratio*. Such effects of the independent variables, however, diminish with increase in assessed damage. That is, when a building experiences severe damage, other influencing variables become less important in the demolition decision. The effects of unit change of the independent variables on the probability of demolition can be quantified by the magnitude of the regression coefficients as seen in Table 5-12 and discussed in section 5.6.

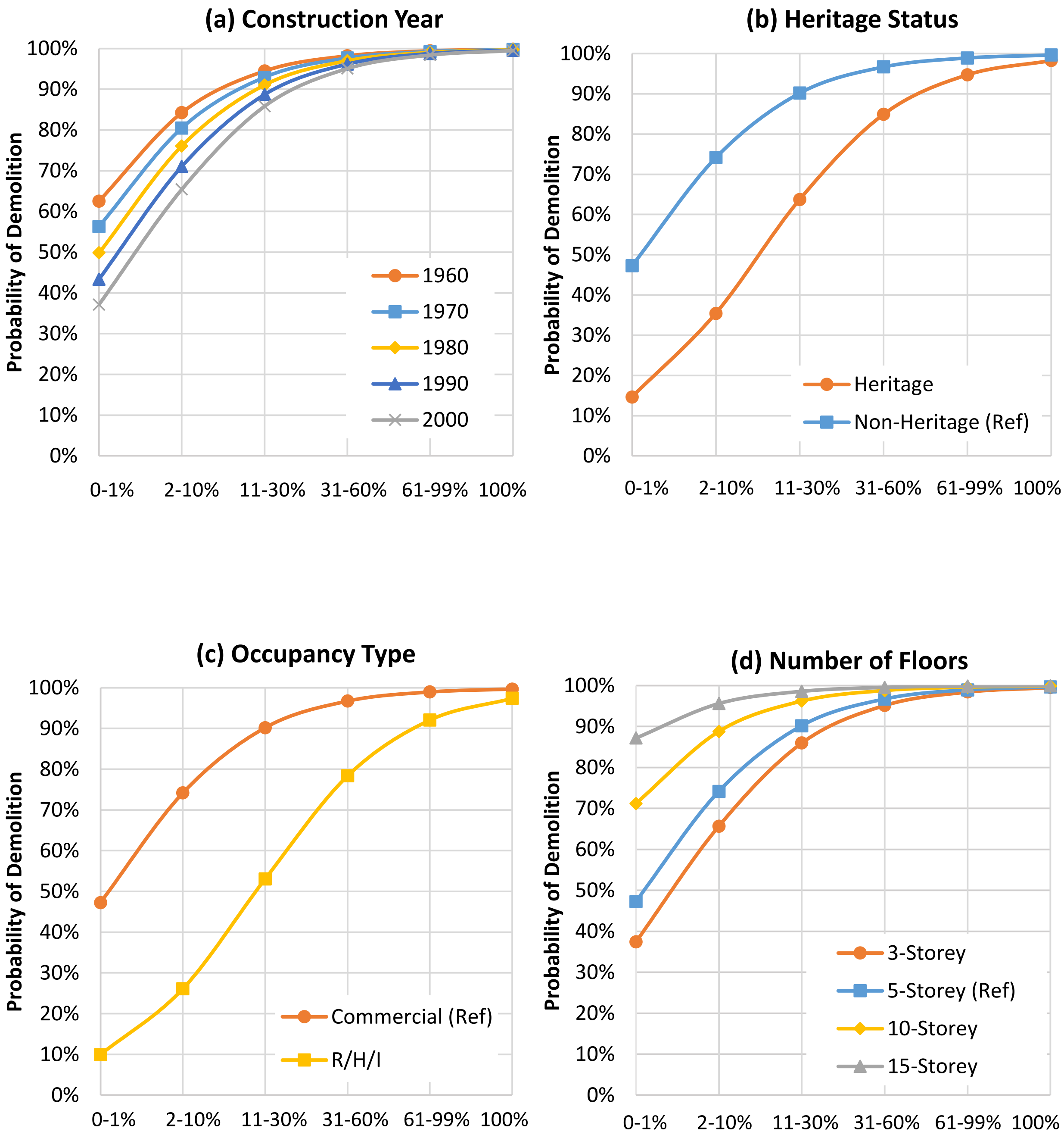

Figure 5-2: Probability of Demolition vs. Damage Ratio – Varying (a) Construction Year, (b) Heritage Status, (c) Occupancy Type, and (d) Number of Floors

5.8 Logistic Regression Model with %NBS Variable

Due to the high rate of missing values (65%), the *Pre-EQ %NBS* and *Post-EQ %NBS* variables were not included in the development of the logistic regression model. As discussed in section 4.3, the %NBS variables as an indicator of a building's seismic capacity may affect the demolition decision due to the city's earthquake-prone building policy. To consider their effects, several methods for handling the missing value problem are considered.

The most common and simple method is the case-wise deletion method, also known as complete-case-analysis, which discards any data with missing information (Little & Rubin, 2002). This method assumes that the missing data are completely random, which means that the missing %NBS information should not be related to the decision outcome or any other independent variables. %NBS information was collected as a part of the DEE requirements by CERA, but the DEEs for numerous buildings were not collected, including for those buildings demolished early on for public safety by the Civil Defence team, those that were heavily damaged and for which the demolition decision was fairly obvious, and small buildings with very minor or no damage. The statistics of the buildings with %NBS data were observed to be different from the study database in terms of assessed damage and the likelihood of demolition; higher portion of the buildings with %NBS data experienced minor damage and were repaired. These reasons are related to the damage state and building characteristics, and therefore the "missing at random" assumption is not satisfied. Since the deleted data differ systematically from the rest of the database, the estimates may be seriously biased (Little & Rubin, 2002). Moreover, due to a significantly smaller sample size (59 buildings) after the deletion, the predictive power of the model may be lost considerably (Schafer, 1999).

With these cautions in mind, the case-wise deletion method was used nonetheless to develop logistic regression models on the subset. Two models were developed using the forward stepwise variable selection approach and Damage Ratio as a damage indicator (as described in section 5.3). As summarized in Table 5-15, *Occupancy Type*, *Number of Floors*, and *Pre-EQ%NBS* or *Post-*

EQ%NBS variables are identified as important, whereas *Damage Ratio* variable is not found to be influential. This is probably because 80% of the buildings with the %NBS data have *Damage Ratio* of 10% or less and none of them has *Damage Ratio* greater than 60% (refer to section 4.11). This may imply that the models based on the subset are biased and/or estimation power is lost significantly. Statistical correlations between the *%NBS* with the *Damage Ratio* were not observed (Pearson correlation coefficients of -0.05 and -0.19 for *Pre-EQ%NBS* or *Post-EQ%NBS,* respectively).

Table 5-15: Logistic Regression Model with %NBS Summary – Case-Wise Deletion Method

			Pre-EQ %NBS		Post-EQ %NBS	
			B	**p-value**	**B**	**p-value**
Independent Variables	Intercept	x_0	3.44	-	3.73	-
	Footprint Area	x_1	0	> 0.05	0	> 0.05
	Construction Year	x_2	0	> 0.05	0	> 0.05
	Heritage Status	x_3	0	> 0.05	0	> 0.05
	SFRS	x_4	0	> 0.05	0	> 0.05
		x_5	0	> 0.05	0	> 0.05
	Occupancy Type	x_6	-2.91	0.02	-2.43	0.05
	Number of Floors	x_7	-0.78	0.00	-0.65	0.00
	Duration in Cordon	x_8	0	> 0.05	0	> 0.05
	Damage Ratio	x_{11}	0	> 0.05	0	> 0.05
	Pre-EQ %NBS	x_{13}	8.62	0.00	-	-
	Post-EQ %NBS	x_{14}	-	-	7.01	0.01
-2 Log-Likelihood (-2LL)			32		38	
Goodness-of-Fit p-value			0.94		0.96	
AIC			40		46	
No. of cases considered			59		61	
No. of included variable			3		3	

Another approach was taken to assess whether *Pre-EQ %NBS* and *Post-EQ %NBS* variables are of importance to the probability of demolition. The steps are as follows:

1) A logistic regression model is created by fitting the "best model" based on all buildings excluding %NBS variable (determined in section 5.6) on the subset of database whose records of %NBS are available. Here, fitted means that the selected variables from the "best model" are entered into the logistic regression analysis of the subset of database, without considering the significance of the selected variables.
2) Another logistic regression model is created by adding the %NBS variable to the "best model" and fitting on the subset of the database whose records of %NBS are available.
3) These two subset models are compared to determine whether the inclusion of %NBS variable affects and/or improves the model performance.

The above procedure is conducted based on Model DR for *Pre-EQ %NBS* and *Post-EQ %NBS* variables. When Model DR is fitted on the *Post-EQ %NBS* subset, the resulting model becomes unstable with large standard error. This is likely due to the absence of heritage buildings that were demolished; zero observation in a categorical variable may cause nonconvergence problem (Altman et al., 2003). For this reason, the rest of the discussion focuses on Model DR, which is fitted on *Pre-EQ %NBS* subset. Table 5-16 summarizes the considered logistic regression model results. **DR_Pre%NBS** indicates the Model DR fitted on the *Pre-EQ %NBS* subset, and the following **a** and **b** represent whether %NBS variable is added to the model or not (Step 1 and 2, respectively).

It can be seen that the p-values of the *Heritage Status*, *Construction Year*, and *Damage Ratio* variables are greater than 0.05, which means they now become less important when fitted on the subset. The added *Pre-EQ %NBS* variable is found to be important with the p-value of 0.01. Intuitively and logically, the fact that Damage Ratio is insignificant is unlikely to be true. This implies that the models based on the subset are strongly biased, possibly because 80% of the buildings with the %NBS data have *Damage Ratio* of 10% or less and none of them has *Damage Ratio* greater than 60%.

Nonetheless, the model goodness-of-fit is acceptable for both models, and the AIC value is smaller when the subset model includes %NBS variable. These imply that the %NBS variable is important when the model is based on the subset data, and the inclusion of %NBS variable improves the subset model performance (smaller AIC value). From this, it is inferred that %NBS may play a significant role in the probability of demolition when included in the global model. It should be noted, however, that the models based on the subset are not reliable in identifying influencing variables nor in quantifying their effects on the probability of demolition due to lack of available information.

Table 5-16: Logistic Regression Model with %NBS Summary – Model DR on Pre-EQ %NBS Subset

			DR_Pre%NBS_a		DR_Pre%NBS_b	
			B	**p-value**	**B**	**p-value**
Independent Variables	Intercept	x_0	-96.1	-	-57.0	-
	Construction Year	x_2	0.05	0.01	0.03	0.17
	Heritage Status	x_3	-1.46	0.37	-1.73	0.52
	Occupancy Type	x_6	-2.69	0.03	-2.64	0.06
	Number of Floors	x_7	-0.53	0.01	-0.77	0.00
	Damage Ratio	x_{11}	-0.74	0.19	-0.77	0.22
	Pre-EQ %NBS	x_{13}	-	-	8.44	0.01
-2 Log-Likelihood (-2LL)			37.0		27.8	
Goodness-of-Fit p-value			0.93		0.88	
AIC			49		42	
No. of cases considered			59		59	
No. of included variable			5		6	

Although not explored in this study, another common method for treating missing information is multiple imputation method. This method is used to complete the dataset by generating values for missing data based on the statistical distribution of the available information. Similar to the case-wise deletion method, however, without satisfying the "missing at random" assumption, it may also be misleading, because it fails to take the missing value mechanism into account.

Chapter 6: Discussion of Local Context Factors

In addition to the quantitative factors discussed previously, the local context and background should also be considered for comprehensive understanding of the post-earthquake decisions on buildings.

In-person interviews (with 9 building owners and owner's representatives, 9 building developers and investors, 5 insurance sector representatives, and 4 local engineers and government authority personnel) revealed the complexity of the post-earthquake decision-making process, which is discussed further in Marquis (2015) and Marquis et al. (2015). This section highlights the two most distinct local contextual factors that affected the building demolition decisions in Christchurch, New Zealand.

6.1 Insurance

Approximately 80% of the economic loss from the Canterbury Earthquakes was borne by the insurance industry (Bevere & Grollimund, 2012), and therefore the insurance policy poses as an important variable in the post-earthquake decisions on buildings. The majority of commercial buildings in Christchurch were insured under a reinstatement policy including all 15 case studies buildings studied by Marquis (2015), which entitles the owner to a building in a "condition as new" while being limited to a maximum insurer's liability (sum insured). It was learned that issues such as appropriate repair extent, methodology, and costs covered under the policy caused disagreements between the owners and the insurers, which often delayed the claiming process. Some building owners expressed their frustration during the process and its influence on their decision-making process. In addition, the interviews revealed that the sum insured amount was found to be lower than the actual rebuild or replacement cost for many buildings, possibly due to the post-earthquake inflation in construction and demolition costs and the inadequate pre-earthquake valuation of the buildings. As reported in Marquis et al. (2015), only 2 out of 15 case study buildings are estimated to have sufficient coverage to rebuild.

Prolonged and often complex insurance claiming process and the inadequate sum insured amount led technically viable repair (and strengthening) works to be considered uneconomical. Once a building was deemed as an “economic total loss,” both the insurer and the building owner preferred to agree on a cash settlement payout, leading to the more convenient outcome of building demolition rather than the more financially risky building repair.

Although attempted, insurance information could not be collected on large number of buildings, mainly due to confidentiality issue and limited data availability; for the 15 case study buildings in Marquis (2015), insurance information could be obtained under each building owner’s permission. If collected and analyzed, type of insurance policy and quantified insurance coverage information (e.g. sum insured amount) would have been strong candidate variables affecting the building demolition decision; these variables are likely to improve the performance of the logistic regression model. Collaborative research work with insurance industry might enable the collection of insurance data for future studies.

6.2 Changes in Local Legislation

Following the September 2010 earthquake, the Christchurch City Council revised its earthquake-prone building policy, recommending that building strengthening work shall aim to meet 67% NBS, raising the target from a prior required minimum of 34% NBS (CCC, 2010). Until the Supreme Court finally ruled in December 2014 (after a High Court decision in 2013) that property owners and insurers are only required to strengthen buildings up to 34% NBS, many building owners and insurers were uncertain as to whether the change in the earthquake-prone building policy was enforceable and, if it was, who was required to pay for the additional strengthening costs.

Furthermore, to account for the heightened level of seismicity in Canterbury region, an amendment to the New Zealand Building Code was published after the February 2011 Earthquake (DBH, 2011) resulting in a 36% increase in the basic seismic design load for Christchurch. This revision effectively lowered the %NBS rating of many existing buildings in the region. For example, a building constructed in 2010 to comply with the Building Code could have a capacity of just 73% NBS based on the new seismic design load.

These changes in the local legislation have had a substantial influence on the cost of repair and strengthening work. Also, the tenants have become more vigilant as to building performance, seeking buildings with a higher %NBS rating. These left the buildings rated below 67 %NBS with the insecurity of their future profitability. All of these factors may have led to more building demolitions than would have happened without such changes.

Chapter 7: Conclusion

The 2010-2011 Canterbury Earthquake Sequence extensively disrupted the built environment of the city of Christchurch. In order to investigate the high demolition rate relative to the assessed damage of reinforced concrete buildings in the Christchurch CBD, this research sought to determine the influence of various factors on post-earthquake building demolition decisions. The empirical database was developed by collecting information for 223 buildings, and logistic regression analyses were conducted. The variables affecting the demolition decision were identified, and their effects on the probability of building demolition were estimated. In addition, major qualitative factors affecting the post-earthquake decision were discussed.

7.1 Major Findings and Contributions

This research is the first study that quantitatively explains the effects of various factors, including the level of damage, on the post-earthquake building demolition decisions. The findings of this study indicate that damage is not the only factor affecting the building demolition decision and highlights that more attention should be paid to other variables.

The descriptive statistics demonstrated that a significant number of reinforced concrete buildings with relatively low assessed damage were demolished. It was inferred that there may be other variables affecting the demolition decision, which relates back to the research question: *what factors, including but not limited to degree of building damage, influence the post-earthquake demolition decisions on buildings?*

The logistic regression analysis results implied that the assessed damage, construction year, heritage status, number of floors, and occupancy type influenced the likelihood of building demolition. As anticipated, increase in building damage and building age increased the probability of demolition. Heritage buildings showed lower probability of demolition, which is rationale considering the heritage conservation policy. Commercial buildings were more likely to be demolished compared to residential, hotel, industrial, and institutional buildings. Opposed to the assumption made, the increase in the number of floors increased the probability of demolition. This trend may be exaggerated by the small number of tall buildings in the study database. Also, it may partly be because of the change in the public's perception on seismic risk after the collapse of the two large buildings, which claimed the greatest number of lives. In-person interviews with building owners revealed that some tenants have shown preference for low-rise over high-rise buildings after the earthquakes. On the contrary to the initial conjecture that duration in cordon may play a significant role, the logistic regression models did not identify it to be important. Building footprint area and seismic force resisting system were found to be insignificant in the probability of building demolition. While data limitations precluded reliable analysis of the role of pre- and post- earthquake seismic capacity (%NBS), available evidence suggests that %NBS as an indication of structural capacity may have affected the building demolition decision as well; buildings with lower %NBS rating are expected to have higher probability of demolition.

The probability-of-demolition function accounting for the effects of various factors was obtained from the logistic regression analysis (equation **5-4**), and the probability-of-repair function can be easily calculated assuming there are only two possible outcomes. The two functions represent $\boldsymbol{P}(\boldsymbol{demolition}|\boldsymbol{dv})$ and $\boldsymbol{P}(\boldsymbol{repair}|\boldsymbol{dv})$ in equation **2-4**, where interpreted as the probability of demolition or repair given $\mathbf{dv}$ (repair cost in the form of Damage Ratio) for a given set of conditions on Occupancy Type, Heritage Status, Construction Year, and Number of Floors (i.e. the variables identified in the logistic regression analysis.) That is, the probability-of-demolition or repair functions are conditioned upon $\mathbf{dv}$, which is now a vector with 5 variables. Further study is needed to develop total loss functions for both demolition and repair decision outcomes ($\boldsymbol{G}(\boldsymbol{tl}|\boldsymbol{demolition})$ and $\boldsymbol{G}(\boldsymbol{tl}|\boldsymbol{repair})$), with consideration of cost of repair, demolition, and downtime, and cost recovery from insurance. Then, the 4 functions combined using the total probability theorem (equation **2-4)** would yield the probability of total loss exceeding a threshold value. This modified approach to the PBEE's loss analysis would provide means of predicting total loss, which considers both decision outcome scenarios and their influencing variables. This would benefit the decision makers with more comprehensive and valuable information concerning seismic risk management and strategy.

7.2 Limitations and Further Research Opportunities

The outcomes (influential variables and their effects on the likelihood of demolition) of the logistic regression model presented in this thesis are based on a case study of the city of Christchurch, and these outcomes depend on the characteristics and the locality of the utilized database. That is, the model developed on the buildings in the Christchurch CBD may or may not provide reasonable predictions when applied to other earthquake-prone communities. Trends in the building characteristics (such as common structural system, occupancy type, building height, and heritage status) may differ from one city to the other. In terms of the locality of the database, the interviewees stressed that the insurance policies and the changes in the local legislation were important during their decision-making processes. Therefore, it is crucial to recognize the inherent variations among different regions and to carefully consider the limitations when applying the logistic regression model from this study to different locations. For the communities with histories of damaging earthquakes, it is recommended to conduct similar studies as presented in this thesis for better understanding of the losses due to damaging earthquakes. Communities without historic data could also benefit from various case studies with different local context factors.

With such cautions in mind, it is speculated that the logistic regression model developed here (Model DR) may be used to predict a probability of demolition of buildings in Wellington, New Zealand. Wellington is New Zealand's second most populated city with well-known seismic risks. Compared to Christchurch, building regulations and policies, insurance, and building characteristics may be quite similar (a survey of the insurance market is needed as insurance policy may be changing after the Canterbury Earthquakes.) Damage indicator may be predicted using a separate damage prediction model developed based on Wellington's expected seismicity. Information on construction year, heritage status, number of floors, and occupancy type are relatively easy to collect. Then, Model DR could be used to predict the likelihood of demolition of buildings, and the findings could be used in assessing the seismic risk, loss, and resilience of the community.

Significant portion of time and effort for this study was spent on data collection and information verification process. While having access to the two major databases (CCC and CERA) and several other sources, a number of inconsistent information was found and verifying and correcting them were difficult and time consuming, especially when structural drawings and design reports were not found. Development of an overall database compiling the building information (such as address, owner contact details, structural type, number of floors, construction year, design building code, existence of structural strengthening, design drawings and reports, etc.) would enhance the accessibility and accuracy of the building data, which is especially important during the assessments of damaged structures. In addition, when such database can be easily linked with multiple damage assessments, it would be valuable for various post-earthquake empirical studies.

During the focus group session with the local engineers, it was learned that the outcomes of the Level 1 and Level 2 Rapid Assessments were likely to be very subjective depending on the inspectors. Although the inherent subjectivity of the visual assessments are recognized, it may be reduced by further developing the assessment forms, and implementing building assessment training program. For example, lack of options such as "no damage" and "damage unknown" may lead to different markings on the assessment form; some inspectors may leave the assessment item blank while others may check the "none/minor." When the assessment forms are well-defined and the inspectors comprehend the assessment protocols, the accuracy, efficiency, and effectiveness of the rapid damage assessments will be improved, which is paramount for public safety, rapid recovery of the city, and future research in seismic engineering.

Another opportunity for future research is on the assessment of the residual structural capacity. The absence of proper guidelines for residual capacity assessment and ongoing aftershocks aggravating the damage resulted in great uncertainties in repairability of buildings. This may have delayed the decision-making process and the recovery of the city, and increased the building demolition rate. Development of a systematic procedure for residual capacity assessment will greatly contribute to the resilience of the earthquake-prone communities.

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Appendix A – Building Assessment Forms

A.1 - Christchurch Earthquake Assessment Form – Level 1

Christchurch Eq. RAPID Assessment Form - LEVEL 1

Inspector Initials		Date of Inspection		Exterior Only	
Territorial Authority	Christchurch City	Time		Exterior and Interior	

Building Name

Short Name

Address

GPS Co-ordinates S° E°

Contact Name

Contact Phone

Storeys at and above ground level　　Below ground level

Total gross floor area (m²)　　Year built

No of residential Units

Photo Taken　Yes　No

Type of Construction

- ☐ Timber frame
- ☐ Steel frame
- ☐ Tilt-up concrete
- ☐ Concrete frame
- ☐ RC frame with masonry infill
- ☐ Concrete shear wall
- ☐ Unreinforced masonry
- ☐ Reinforced masonry
- ☐ Confined masonry
- ☐ Other:

Primary Occupancy

- ☐ Dwelling
- ☐ Other residential
- ☐ Public assembly
- ☐ School
- ☐ Religious
- ☐ Commercial/ Offices
- ☐ Industrial
- ☐ Government
- ☐ Heritage Listed
- ☐ Other

Investigate the building for the conditions listed below:

Overall Hazards / Damage	**Minor/None**	**Moderate**	**Severe**	**Comments**
Collapse, partial collapse, off foundation	☐	☐	☐	
Building or storey leaning	☐	☐	☐	
Wall or other structural damage	☐	☐	☐	
Overhead falling hazard	☐	☐	☐	
Ground movement, settlement, slips	☐	☐	☐	
Neighbouring building hazard	☐	☐	☐	
Other	☐	☐	☐	

Choose a posting based on the evaluation and team judgement. Severe conditions affecting the whole building are grounds for an UNSAFE posting. Localised Severe and overall Moderate conditions may require a RESTRICTED USE. Place INSPECTED placard at main entrance. Post all other placards at every significant entrance.

INSPECTED *GREEN* ☐　　RESTRICTED USE *YELLOW* ☐　　UNSAFE *RED* ☐

Record any restriction on use or entry:

Further Action Recommended:

Tick the boxes below only if further actions are recommended

- ☐ Barricades are needed (state location):
- ☐ Level 2 or detailed engineering evaluation recommended
  - ☐ Structural　☐ Geotechnical　☐ Other:
- ☐ Other recommendations:

Estimated Overall Building Damage (Exclude Contents)

None	☐		
0-1 %	☐	31-60 %	☐
2-10 %	☐	61-99 %	☐
11-30 %	☐	100 %	☐

Sign here on completion

Date & Time

ID

Inspection ID ________ (Office Use Only)

(Retrieved from CCC)

A.2 - Christchurch Earthquake Assessment Form – Level 2

Christchurch Eq RAPID Assessment Form - LEVEL 2

Inspector Initials ______ Date ______ **Final Posting** (e.g. UNSAFE) ______
Territorial Authority Christchurch City Time ______

Building Name
Short Name ______
Address ______
GPS Co-ordinates S° ______ E° ______
Contact Name ______
Contact Phone ______
Storeys at and above ground level ______ Below ground level ______
Total gross floor area (m^2) ______ Year built ______
No of residential Units ______
Photo Taken Yes No

Type of Construction
- ☐ Timber frame
- ☐ Steel frame
- ☐ Tilt-up concrete
- ☐ Concrete frame
- ☐ RC frame with masonry infill
- ☐ Concrete shear wall
- ☐ Unreinforced masonry
- ☐ Reinforced masonry
- ☐ Confined masonry
- ☐ Other:

Primary Occupancy
- ☐ Dwelling
- ☐ Other residential
- ☐ Public assembly
- ☐ School
- ☐ Religious
- ☐ Commercial/ Offices
- ☐ Industrial
- ☐ Government
- ☐ Heritage Listed
- ☐ Other

Investigate the building for the conditions listed on page 1 and 2, and check the appropriate column. A sketch may be added on page 3

Overall Hazards / Damage	Minor/None	Moderate	Severe	Comments
Collapse, partial collapse, off foundation	☐	☐	☐	
Building or storey leaning	☐	☐	☐	
Wall or other structural damage	☐	☐	☐	
Overhead falling hazard	☐	☐	☐	
Ground movement, settlement, slips	☐	☐	☐	
Neighbouring building hazard	☐	☐	☐	
Electrical, gas, sewerage, water, hazmats	☐	☐	☐	

Record any existing placard on this building: Existing Placard Type (e.g. UNSAFE) ______

Choose a new posting based on the new evaluation and team judgement. Severe conditions affecting the whole building are grounds for an UNSAFE posting. Localised Severe and overall Moderate conditions may require a RESTRICTED USE. Place INSPECTED placard at main entrance. Post all other placards at every significant entrance. Transfer the chosen posting to the top of this page.

INSPECTED			RESTRICTED USE			UNSAFE			
GREEN	*G1*	*G2*	*YELLOW*	*Y1*	*Y2*	*RED*	*R1*	*R2*	*R3*

Record any restriction on use or entry:

Further Action Recommended:

Tick the boxes below only if further actions are recommended
- ☐ Barricades are needed (state location):
- ☐ Detailed engineering evaluation recommended
  - ☐ Structural ☐ Geotechnical ☐ Other:
- ☐ Other recommendations:

Estimated Overall Building Damage (Exclude Contents)

None	☐		
0-1 %	☐	31-60 %	☐
2-10 %	☐	61-99 %	☐
11-30 %	☐	100 %	☐

Sign here on completion ______
Date & Time ______
ID ______

Inspection ID: __________ (Office Use Only)

Structural Hazards/ Damage	Minor/None	Moderate	Severe	Comments
Foundations	☐	☐	☐	
Roofs, floors (vertical load)	☐	☐	☐	
Columns, pilasters, corbels	☐	☐	☐	
Diaphragms, horizontal bracing	☐	☐	☐	
Pre-cast connections	☐	☐	☐	
Beam	☐	☐	☐	
Non-structural Hazards / Damage				
Parapets, ornamentation	☐	☐	☐	
Cladding, glazing	☐	☐	☐	
Ceilings, light fixtures	☐	☐	☐	
Interior walls, partitions	☐	☐	☐	
Elevators	☐	☐	☐	
Stairs/ Exits	☐	☐	☐	
Utilities (eg. gas, electricity, water)	☐	☐	☐	
Other	☐	☐	☐	
Geotechnical Hazards / Damage				
Slope failure, debris	☐	☐	☐	
Ground movement, fissures	☐	☐	☐	
Soil bulging, liquefaction	☐	☐	☐	

General Comment ______________________________

Usability Category

Damage Intensity	Posting	Usability Category	Remarks
Light damage *Low risk*	Inspected (Green)	G1. Occupiable, no immediate further investigation required	
		G2. Occupiable, repairs required	
Medium damage *Medium risk*	Restricted Use (Yellow)	Y1. Short term entry	
		Y2. No entry to parts until repaired or demolished	
Heavy damage *High risk*	Unsafe (Red)	R1. Significant damage: repairs, strengthening possible	
		R2. Severe damage: demolition likely	
		R3. At risk from adjacent premises or from ground failure	

Sketch (optional)
Provide a sketch of the entire building or damage points. Indicate damage points.

Recommendations for Repair and Reconstruction or Demolition (Optional)

3 *Inspection ID: __________ (Office Use Only)*

(Retrieved from CCC)

A.3 - CERA Engineers Risk Assessment Form

PLACARDED BUILDINGS
RISK ASSESSMENT

Existing Placard ______________

ADDRESS: ________________________________

OTHER: ________________________________

Type of Construction (Tick Only One)

- ☐ Timber frame
- ☐ Steel frame
- ☐ Tilt-up concrete
- ☐ Concrete frame
- ☐ RC frame with masonry infill
- ☐ Concrete shear wall
- ☐ Unreinforced masonry
- ☐ Confined masonry
- ☐ Other: ___________________________

Detached ☐ Semi detached ☐ Fully Attached ☐

Risk of building collapsing or part of building collapsing onto adjacent property or public space.

Low ☐ Moderate ☐ Severe ☐

Risk of building collapsing or part of building collapsing into itself or onto its own property only.

Low ☐ Moderate ☐ Severe ☐

Potential occupancy of Public space and/or adjacent building

(cul-de-sac, planted area → low), (collector road, house, isolated shop → moderate), (arterial, shopping mall, grandstand → severe)

Low ☐ Moderate ☐ Severe ☐

Overall building damage 0 – 25% ☐ 25 – 50% ☐
50 – 75% ☐ 75 – 100% ☐ RISK#: _____

Building or part of the building is damaged and assessed as having an earthquake strength of less than 33% NBS Yes ☐ No ☐

Partial deconstruction will remove danger Yes ☐ No ☐

Full demolition will remove danger Yes ☐ No ☐

Comments (including barricade and any other urgent requirements): ____________________________

____

____

____

____

Assessors Signature: _______________ **Time:** _______ **Reviewers Signature:** _______________ **Time:** _______

Assessors Name: _________________ **Date:** __/__/__ **Reviewers Name:** _________________ **Date:** __/__/__

Risk Assessment Scorecard

Type of Construction (Tick Only One)

Timber frame	5
Steel frame	5
Tilt-up concrete	15
Concrete frame	10
RC frame with masonry infill	15
Concrete shear wall	5
Unreinforced masonry	50
Confined masonry	15

Risk of building collapsing or part of building collapsing onto adjacent property or public space.

Low	15
Moderate	20
Severe	100

Risk of building collapsing or part of building collapsing into itself or onto its own property only.

Low	5
Moderate	10
Severe	50

Potential occupancy of Public space and/or adjacent building

(cul-de-sac, planted area → low), (collector road, house, isolated shop → moderate), (arterial, shopping mall, grandstand → severe)

Low	20
Moderate	50
Severe	200

Overall building damage

0 – 25%	5
25 – 50%	20
50 – 75%	50
75 – 100%	100

Retrieved from CERA Database

A.4 - Detailed Engineering Evaluations – Summary Table

Detailed Engineering Evaluation Summary Data V1.14

Location

Building Name:
Unit No: Street
Building Address:
Legal Description:
Degrees Min Sec
GPS south:
GPS east:
Building Unique Identifier (CCC):

Reviewer:
CPEng No:
Company:
Company project number:
Company phone number:
Date of submission:
Inspection Date:
Revision:
Is there a full report with this summary?

Site

Site slope:
Soil type:
Site Class (to NZS1170.5):
Proximity to waterway (m, if <100m):
Proximity to clifftop (m, if < 100m):
Proximity to cliff base (m,if <100m):

Max retaining height (m):
Soil Profile (if available):
If Ground improvement on site, describe:
Approx site elevation (m):

Building

No. of storeys above ground: single storey = 1
Ground floor split?
Storeys below ground
Foundation type:
Building height (m):
Floor footprint area (approx):
Age of Building (years):

Ground floor elevation (Absolute) (m):
Ground floor elevation above ground (m):
if Foundation type is other, describe:
height from ground to level of uppermost seismic mass (for IEP only) (m):
Date of design:

Strengthening present?
If so, when (year)?
And what load level (%g)?
Brief strengthening description:

Use (ground floor):
Use (upper floors):
Use notes (if required):
Importance level (to NZS1170.5):

Gravity Structure

Gravity System:
Roof:
Floors:
Beams:
Columns:
Walls:

Lateral load resisting structure

Lateral system along:		Note: **Define along and across in detailed report!**		
Ductility assumed, μ:				
Period along:		#N/A enter height above at H31 and lateral system	estimate or calculation?	
Total deflection (ULS) (mm):			estimate or calculation?	
maximum interstorey deflection (ULS) (mm):			estimate or calculation?	
Lateral system across:				
Ductility assumed, μ:				
Period across:		#N/A enter height above at H31 and lateral system	estimate or calculation?	
Total deflection (ULS) (mm):			estimate or calculation?	
maximum interstorey deflection (ULS) (mm):			estimate or calculation?	

Separations:

north (mm):		leave blank if not relevant
east (mm):		
south (mm):		
west (mm):		

Non-structural elements

Stairs:		
Wall cladding:		
Roof Cladding:		
Glazing:		
Ceilings:		
Services(list):		

Available documentation

Architectural		original designer name/date	
Structural		original designer name/date	
Mechanical		original designer name/date	
Electrical		original designer name/date	
Geotech report		original designer name/date	

Damage

Site:
(refer DEE Table 4-2)

Site performance:		Describe damage:	
Settlement:		notes (if applicable):	
Differential settlement:		notes (if applicable):	
Liquefaction:		notes (if applicable):	
Lateral Spread:		notes (if applicable):	
Differential lateral spread:		notes (if applicable):	
Ground cracks:		notes (if applicable):	
Damage to area:		notes (if applicable):	

Building:

	Current Placard Status:			
Along	Damage ratio:		Describe how damage ratio arrived at:	
	Describe (summary):			

Across | Damage ratio: |
Describe (summary): |

$$Damage\_Ratio = \frac{(\%NBS(before) - \%NBS(after))}{\%NBS(before)}$$

Diaphragms	Damage?:		Describe:
CSWs:	Damage?:		Describe:
Pounding:	Damage?:		Describe:
Non-structural:	Damage?:		Describe:

Recommendations

Level of repair/strengthening required:		Describe:	
Building Consent required:		Describe:	
Interim occupancy recommendations:		Describe:	

Along	Assessed %NBS before e'quakes:		##### %NBS from IEP below	If IEP not used, please detail assessment methodology:
	Assessed %NBS after e'quakes:			
Across	Assessed %NBS before e'quakes:		##### %NBS from IEP below	
	Assessed %NBS after e'quakes:			

IEP **Use of this method is not mandatory - more detailed analysis may give a different answer, which would take precedence. Do not fill in fields if not using IEP.**

Period of design of building (from above): 0

h_n from above: m

Seismic Zone, if designed between 1965 and 1992:

not required for this age of building

not required for this age of building

	along	across
Period (from above):	0	0
(%NBS)nom from Fig 3.3:		

Note:1 for specifically design public buildings, to the code of the day: pre-1965 = 1.25; 1965-1976, Zone A =1.33; 1965-1976, Zone B = 1.2; all else 1.0

Note 2: for RC buildings designed between 1976-1984, use 1.2

Note 3: for buildngs designed prior to 1935 use 0.8, except in Wellington (1.0)

	along	across
Final $(\%NBS)_{nom}$:	**0%**	**0%**

2.2 Near Fault Scaling Factor

Near Fault scaling factor, from NZS1170.5, cl 3.1.6:

	along	across
Near Fault scaling factor (1/N(T,D), **Factor A**:	#DIV/0!	#DIV/0!

2.3 Hazard Scaling Factor

Hazard factor Z for site from AS1170.5, Table 3.3:

Z_{1992}, from NZS4203:1992

Hazard scaling factor, **Factor B**: #DIV/0!

2.4 Return Period Scaling Factor

Building Importance level (from above):

Return Period Scaling factor from Table 3.1, **Factor C**:

	along	across
2.5 Ductility Scaling Factor — Assessed ductility (less than max in Table 3.2)		
Ductility scaling factor: =1 from 1976 onwards; or =k_μ, if pre-1976, from Table 3.3:		
Ductity Scaling Factor, **Factor D**:	0.00	0.00
2.6 Structural Performance Scaling Factor: Sp:		
Structural Performance Scaling Factor **Factor E**:	#DIV/0!	#DIV/0!
2.7 Baseline %NBS, $(NBS\%)_b = (\%NBS)_{nom}$ x A x B x C x D x E — **$\%NBS_b$:**	**#DIV/0!**	**#DIV/0!**

Global Critical Structural Weaknesses: (refer to NZSEE IEP Table 3.4)

3.1. Plan Irregularity, factor A: 1

3.2. Vertical irregularity, Factor B: 1

3.3. Short columns, Factor C: 1

3.4. Pounding potential

Pounding effect D1, from Table to right:

Height Difference effect D2, from Table to right:

Therefore, Factor D: 0

3.5. Site Characteristics 1

Table for selection of D1	Severe	Significant	Insignificant/none
Separation	0<sep<.005H	.005<sep<.01H	Sep>.01H
Alignment of floors within 20% of H	**0.7**	**0.8**	**1**
Alignment of floors not within 20% of H	**0.4**	**0.7**	**0.8**

Table for Selection of D2	Severe	Significant	Insignificant/none
Separation	0<sep<.005H	.005<sep<.01H	Sep>.01H
Height difference > 4 storeys	0.4	0.7	1
Height difference 2 to 4 storeys	0.7	0.9	1
Height difference < 2 storeys	1	1	1

	Along	Across
3.6. Other factors, Factor F — For ≤ 3 storeys, max value =2.5, otherwise max valule =1.5, no minimum		
Rationale for choice of F factor, if not 1	Roof bracing compressive strut connection capacity	

Detail Critical Structural Weaknesses: (refer to DEE Procedure section 6)

List any: Refer also section 6.3.1 of DEE for discussion of F factor modification for other critical structural weaknesses

	Along	Across
3.7. Overall Performance Achievement ratio (PAR)	**0.00**	**0.00**
4.3 PAR x (%NBS)b: PAR x Baselline %NBS:	**#DIV/0!**	**#DIV/0!**
4.4 Percentage New Building Standard (%NBS), (before)		**#DIV/0!**

Official Use only:

Accepted By

Date:

Site slope	flat	
	slope < 1in 10	
	slope < 1in 5	
	slope >1 in 5	

Soil type	silt	
	silty sand	
	sandy silt	
	peat	
	gravel	
	mixed	

Site Class	A	
	B	
	C	
	D	
	E	

Importance	IL1	1
	IL2	2
	IL3	3
	IL4	4

CSWs	Severe	0.4
	Significant	0.7
	Insignificant	1
	None	1

yes/no	yes
	no

foundation_type_list	isolated pads, no tie beams
	strip footings
	pads with tie beams
	mat slab
	raft slab
	driven precast piles
	driven steel piles
	timber piles
	bored cast-insitu concrete piles
	driven bulb piles
	steel screw piles
	CFA piles
	other (describe)

gravity system	load bearing walls
	frame system

roof	concrete	slab thickness (mm)
	other (note)	describe system
	steel framed	rafter type, purlin type and cladding
	steel truss	truss depth, purlin type and cladding
	timber framed	rafter type, purlin type and cladding
	timber truss	truss depth, purlin type and cladding

floors	composite concrete in steel deck	tray type and overall thickness (mm)
	concrete flat slab	slab thickness (mm)
	concrete waffle slab	slab thickness (mm)
	non-composite concrete in steel decl	tray type, overall thickness and reinforcement type
	other (note)	describe sytem
	precast concrete toppingless	unit type and depth (mm), diaphragm connectors
	precast concrete with topping	unit type and depth (mm), topping thickness and reinforcement t
	steel deck	type
	timber	joist depth and spacing (mm)

beams	cast-insitu concrete	overall depth x width (mm x mm)
	none	overall depth x width (mm x mm)
	precast concrete	overall depth (mm)
	rivetted plate girder	overall depth (mm)
	steel non-composite	beam type
	steel composite	beam and connector type
	timber	type
	other (note)	describe system

columns	brick masonry	typical dimensions (mm x mm)
	cast-insitu concrete	typical dimensions (mm x mm)
	cast-iron	typical dimensions (mm x mm)
	load bearing walls	typical dimensions (mm x mm)
	other (note)	typical dimensions (mm x mm)
	precast concrete	typical dimensions (mm x mm)
	stone masonry	typical dimensions (mm x mm)
	structural steel	typical dimensions (mm x mm)
	timber	typical dimensions (mm x mm)

walls	non-load bearing	
	fully filled concrete masonry	thickness (mm)
	partially filled concrete masonry	thickness (mm)
	load bearing concrete	thickness (mm)
	load bearing brick	thickness (mm)
	load bearing stone	thickness (mm)

lateral systems	concrete frame with infill	note total length of wall at ground (m):
	concrete shear wall	enter wall data in "IEP period calcs" worksheet for period calcula
	damage avoidance system	describe system
	ductile concrete moment frame	note typical bay length (m)
	fully filled CMU	note total length of wall at ground (m):
	lightweight timber framed walls	note typical wall length (m)
	multi-level tilt panel	note total length of wall at ground (m):
	non-ductile concrete moment frame	note typical bay length (m)
	other (note)	describe system
	partially filled CMU	note total length of wall at ground (m):
	rivetted steel moment frame	note typical bay length (m)
	single level tilt panel	note total length of wall at ground (m):
	steel concentric braced frame	note typical frame sizes and bay length (m)
	steel eccentric braced frame	note typical frame sizes and bay length (m)
	steel frame with infill	note typical frame sizes and bay length (m)
	timber moment frame	note typical bay length (m)
	unreinforced masonry bearing wall - l	note wall thickness and cavity
	unreinforced masonry bearing wall - :	note wall thickness and cavity
	welded and bolted steel moment fran	note typical bay length (m)

est_calc	estimated
	calculated

placard_status	red
	yellow
	green

Building Use	commercial	
	educational	
	institutional	
	multi-unit residential	
	parking	
	retail	
	other (specify)	
	public	

Documentation	full
	none
	partial

Stairs	cast insitu	notes
	other (specify)	describe
	precast, full flight	describe supports
	precast, half height	describe supports
	steel	describe supports
	timber	describe supports

Cladding	brick or tile	describe (note cavity if exists)
	curtain wall system	estimate movement allowance
	other heavy	describe
	exposed structure	describe
	other light	describe
	plaster system	describe
	precast panels	thickness and fixing type
	profiled metal	describe

Unreinforced masonry
Concrete Block
Masonry veneer
Glass curtain wall
Tilt panel
Concrete panel
Lightweight concrete panel
Stucco
Fibre cement panel
Weatherboard
Profiled metal
Plywood
EIFS

Glazing	aluminium frames
	other (specify)
	steel frames
	timber frames

Ceilings	fibrous plaster, fixed
	heavy tiles
	light tiles
	none
	strapped or direct fixed
	plaster, fixed
	sprayed

pounding damage	moderate
	none
	severe

Roof Cladding	Heavy tiles	describe
	Membrane	substrate
	Metal	describe
	Other (specify)	describe
	Profiled composite materi	describe
	Profiled fibre cement	describe
	Shingles or shakes	describe

age_list	Pre 1935
	1935-1965
	1965-1976 zone
	1976-1992 zone
	1992-2004
	2004-

zone_list	A
	B
	C

IEP Soil Types

From NZS1170.5:2004	A or B rock
	C shallow soil
	D soft soil
	E very soft soil

From NZS4203:1992,	a) Rigid
	b) Intermediate

Ground damage

Settlement	none observed 0-25mm 25-100mm 100-200mm more than 200mm
Differential settlement	none observed 0-1:350 1:350-1:250 1:250-1:150 1:150 or more
liquefaction_vol	none apparent 0-2 m³/100m² 2-5 m³/100m² 5-10 m³/100m² more than 10 m³/100m²
Lateral_spread	none apparent 0-50mm 50-250mm 250-500mm more than 500mm
lateral_spread_differenti	none apparent 0-1:400 1:400-1:100 1:100-1:50 more than 1:50
Cracks	none apparent 0-20mm/20m 20-100mm/20m 100-200mm/20m more than 200mm/20m
Damage to area	none apparent slight moderate to substantial (1 in 5) widespread to major (in in 3 to most)

ype

ation

Recommendations

repair_list	none minor non-structural minor structural significant structural significant structural and strengthening demolition
interim_list	full occupancy partial occupancy do not occupy

CSW severity	severe significant insignificant

Retrieved from CERA Database

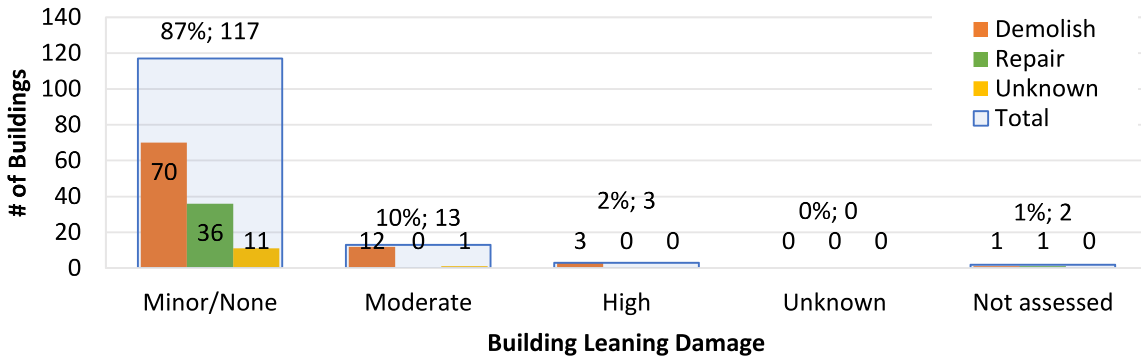
Appendix B – List of Participants

		Participant	Position/Title	Company	Interview Date
Personal Interview Participants	Owners/ Representatives	**Connal Townsend**	Chief Executive	Property Council of New Zealand	14 October 2014
		Darren Moses	Unit Manager	Christchurch City Council	29 October 2014
		David Meates	Chief Executive	Canterbury District Health Board	24 September 2014
		Gary Jarvis	Group Operations Manager	Heritage Hotel Management	13 October 2014
		Jeff Field	University Registrar	University of Canterbury	26 September 2014
		Josie Ogden-Schroeder	Chief Executive	YMCA Christchurch	25 September 2014
		Mark Youthed	Senior Commercial Asset Manager	Knight Frank	24 September 2014
		Miles Romanes	Project Manager	Pace Project Management	24 September 2014
		Participant 1	Structural Engineer	-	23 September 2014
	Building Developers / Property Investors	**Chris Gudgeon**	Chief Executive	Kiwi Income Property Trust	15 October 2014
		Ernest Duval	Trust Manager/CEO	ETP/Fortis Construction	24 September 2014
		Glen Boultwood	Fund Manager	Eureka Funds	15 October 2014
		Lisle Hood	Property Investor	Business Building Systems	22 October 2014
		Miles Middleton	Property Investor	Viewmount Orchards	25 September 2014
		Participant 2	General Manager	-	5 November 2014
		Peter Rae	Chairman and Managing Director	Peter Rae Industries	23 September 2014
		Philip Burdon	Property Investor and Developer	-	5 November 2014
		Shaun Stockman	Managing Director	KPI Rothschild Property	22 September 2014

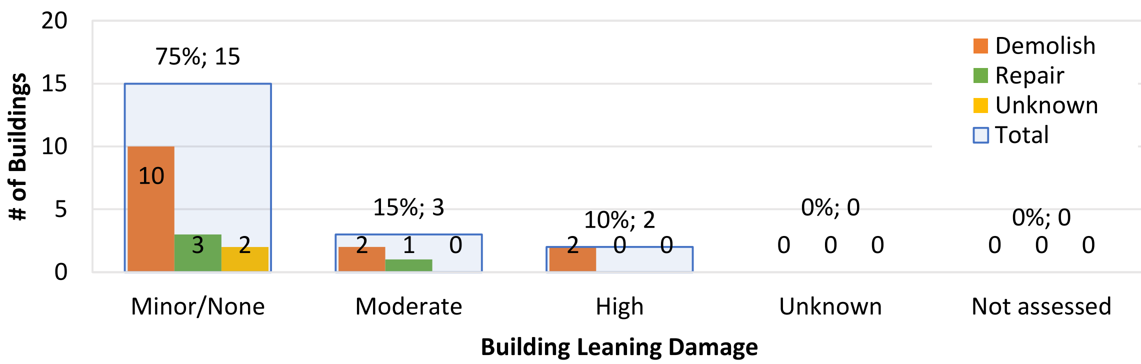
		Participant	Position/Title	Company	Interview Date
	Insurance	**Jimmy Higgins**	Executive GM – Earthquake Programme	Vero NZ	15 October 2014
	Insurance	**John Lucas**	Insurance Manager	Insurance Council of New Zealand	17 October 2014
	Insurance	**Murray Spicer**	Engineer acting for insurers	MacDonald Barnett	14 October 2014
	Insurance	**Simon Foley**	Distribution Manager	Zurich New Zealand	15 October 2014
	Insurance	**Storm McVay**	Executive Broker	Crombie Lockwood	22 September 2014
	Government Authorities	**John O'Hagan**	Lead Engineer–Significant Buildings Unit	CERA	22 October 2014
	Government Authorities	**John Snook**	Structural Engineer	CERA	30 September 2014
	Government Authorities	**Participant 3**	-	CERA	26 September 2014
	Government Authorities	**Steve McCarthy**	Regulatory Services Manager	CCC	26 September 2014
Focus Group Participants	Structural Engineers	**Sean Gardiner**	Business Unit Leader	Spiire	12 November 2014
Focus Group Participants	Structural Engineers	**Paul Campbell**	Building Structures Leader	Opus International Consultants Ltd	12 November 2014
Focus Group Participants	Structural Engineers	**David Whittaker**	Technical Director	BECA	12 November 2014
Focus Group Participants	Structural Engineers	**Craig Lewis**	Managing Director	Lewis Bradford Consulting Engineers	12 November 2014
Focus Group Participants	Structural Engineers	**Dave Brunsdon**	Director/Lead Researcher	Kestrel Group/Resilient Organizations	12 November 2014

Appendix C – Additional Database Building Statistics

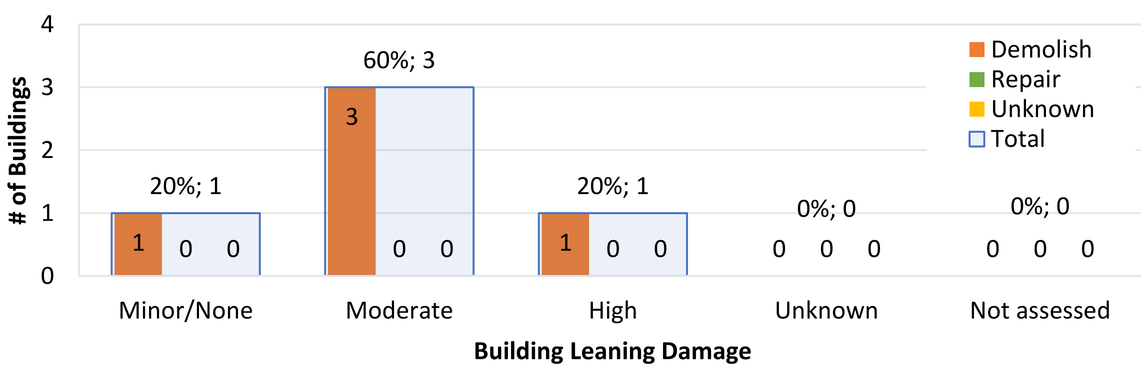
Buildings with Minor/None Soil Bulging and Liquefaction Damage vs Building Leaning Damage



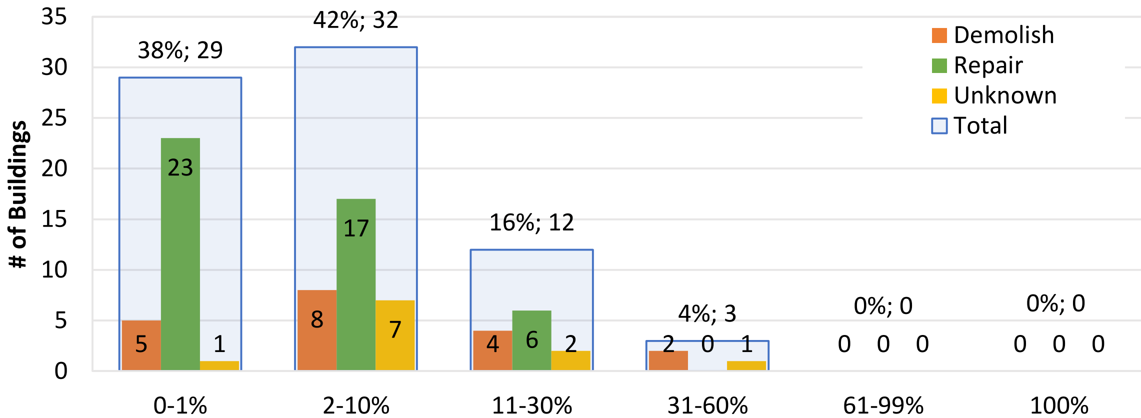
Buildings with Moderate Soil Bulging and Liquefaction Damage vs Building Leaning Damage



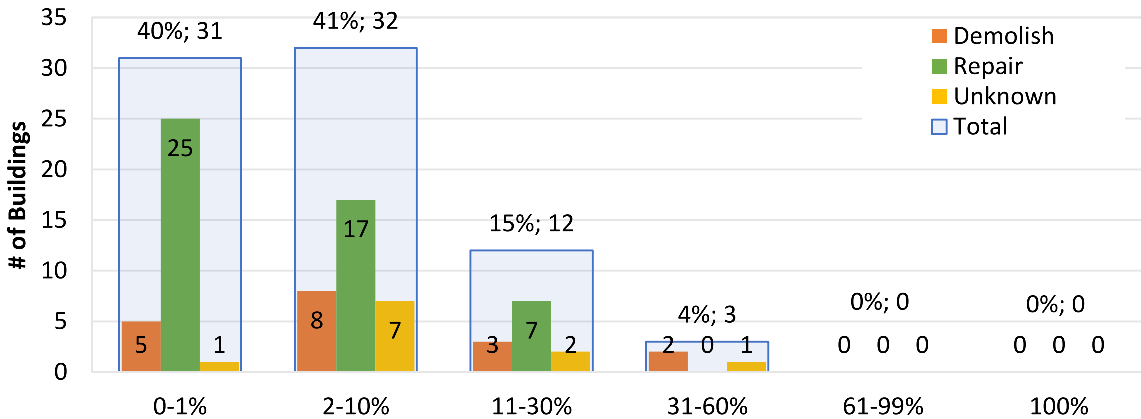
Buildings with High Soil Bulging and Liquefaction Damage vs Leaning Damage



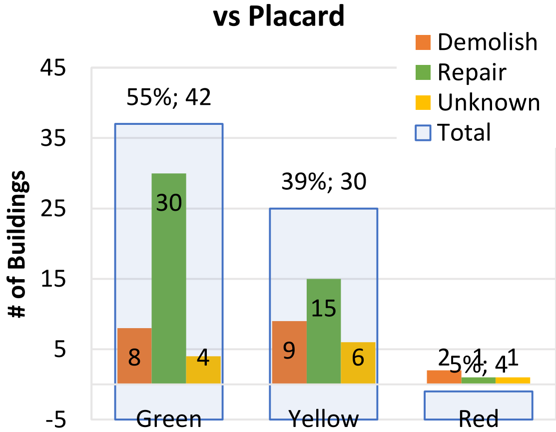
Buildings with Pre-EQ %NBS Data vs Damage Ratio



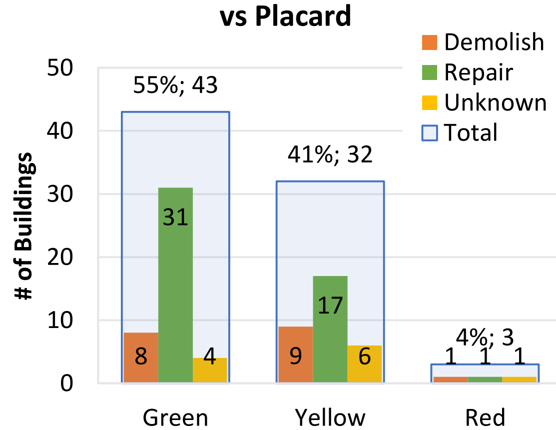
Buildings with Post-EQ %NBS Data vs Damage Ratio

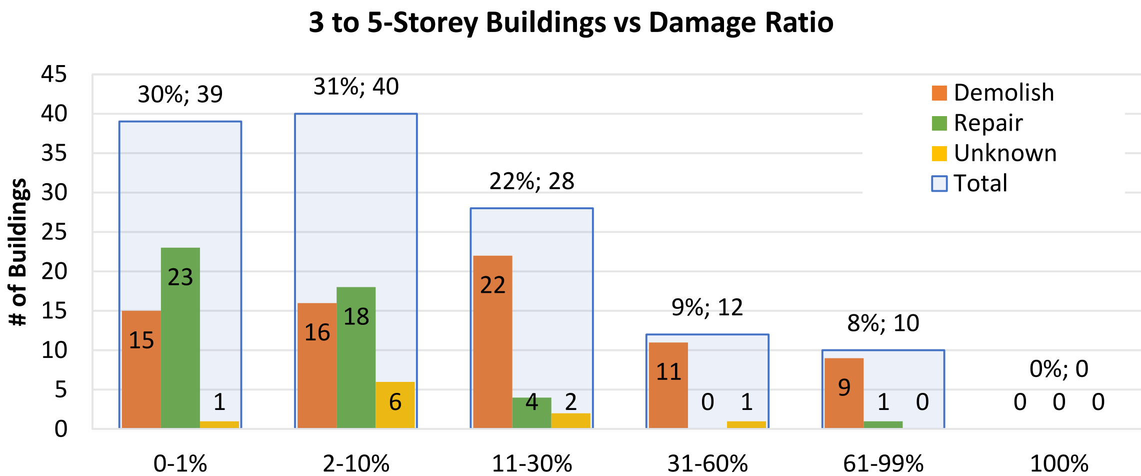


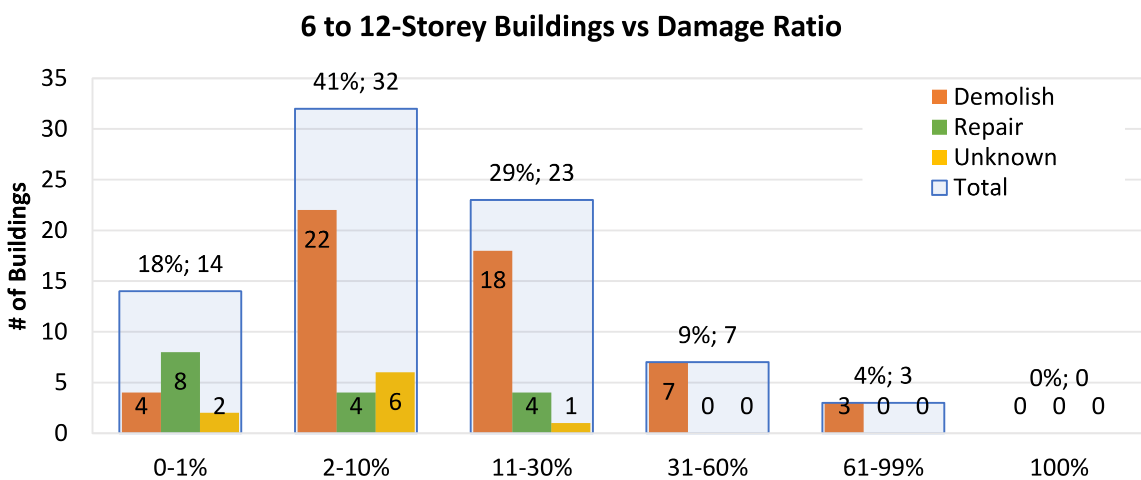
Buildings with Pre-EQ %NBS Data vs Placard

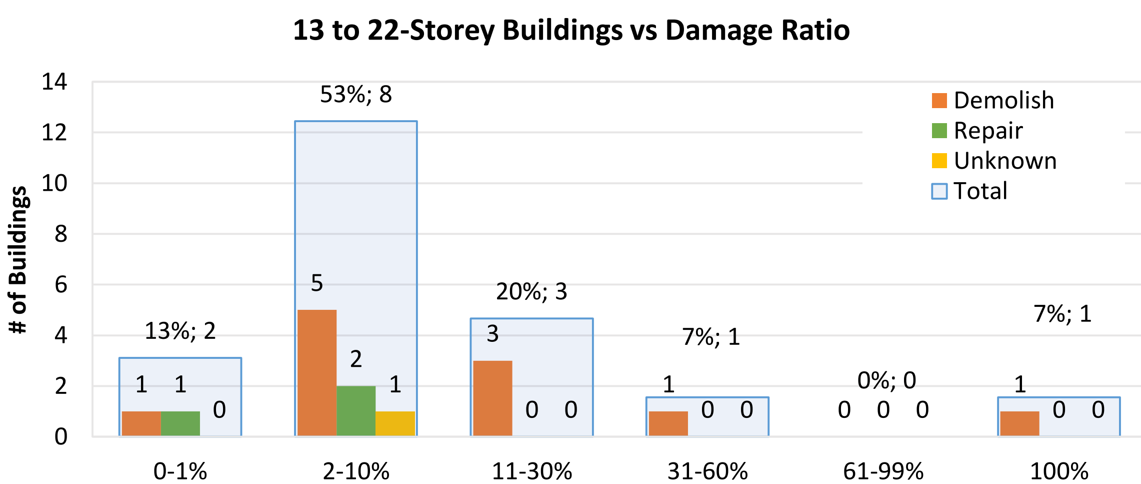


Buildings with Post-EQ %NBS Data vs Placard

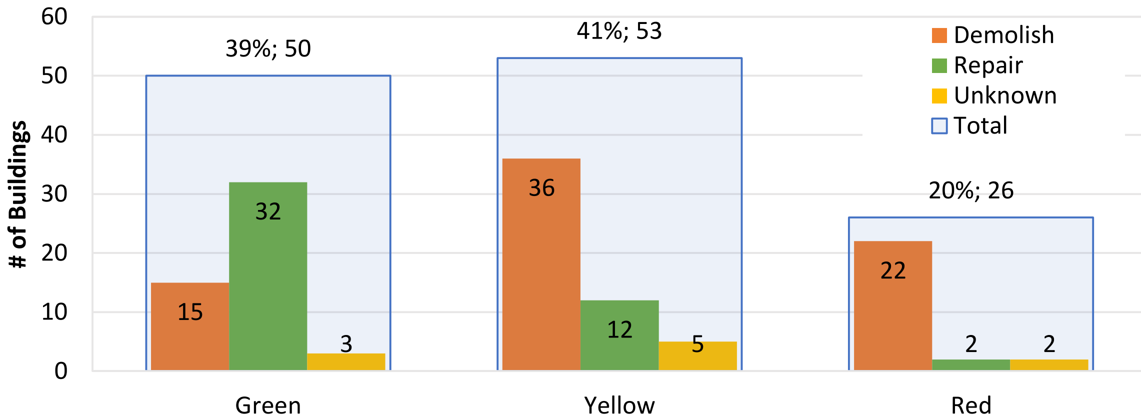



3 to 5-Storey Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
30%; 39
31%; 40
22%; 28
9%; 12
8%; 10
0%; 0
15 23 1
16 18 6
22 4 2
11 0 1
9 1 0
0 0 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%

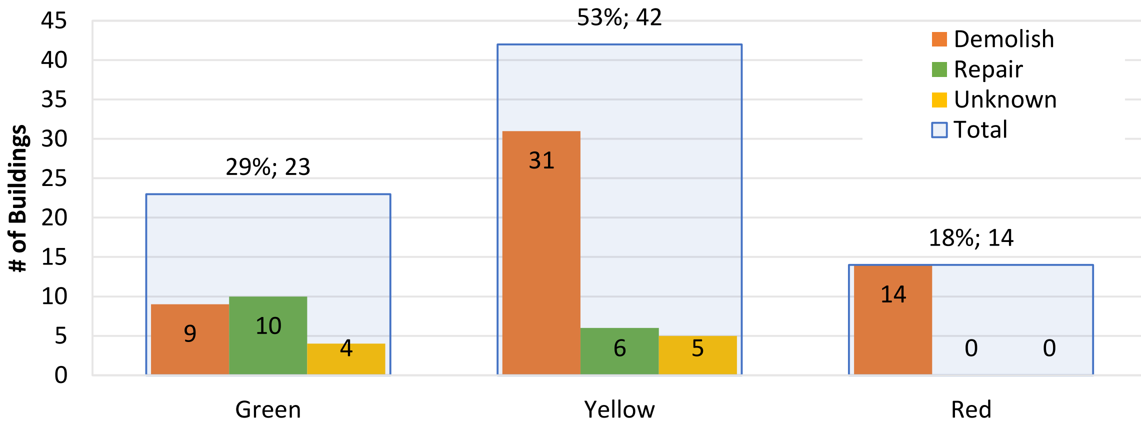

6 to 12-Storey Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
18%; 14
41%; 32
29%; 23
9%; 7
4%; 3
0%; 0
4 8 2
22 4 6
18 4 1
7 0 0
3 0 0
0 0 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%


13 to 22-Storey Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
13%; 2
53%; 8
20%; 3
7%; 1
0%; 0
7%; 1
1 1 0
5 2 1
3 0 0
1 0 0
0 0 0
1 0 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%

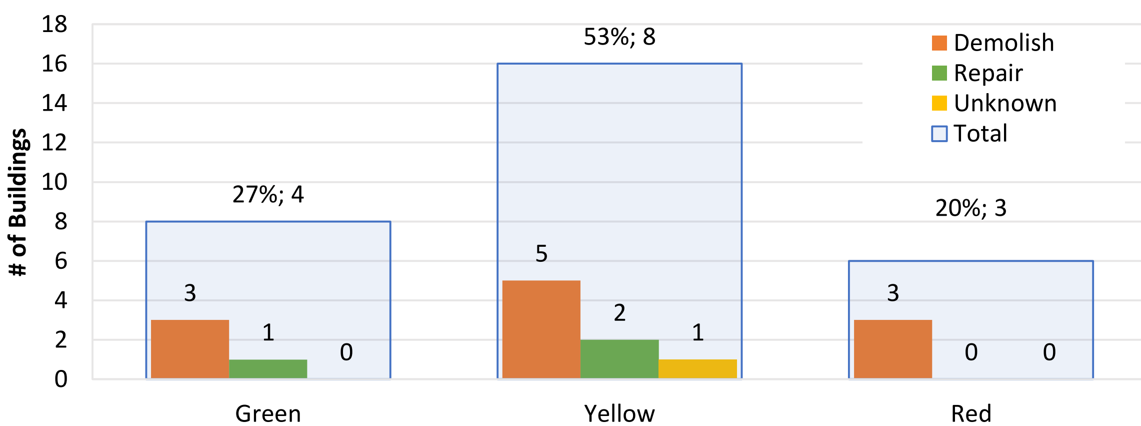
3 to 5-Storey Buildings vs Placard

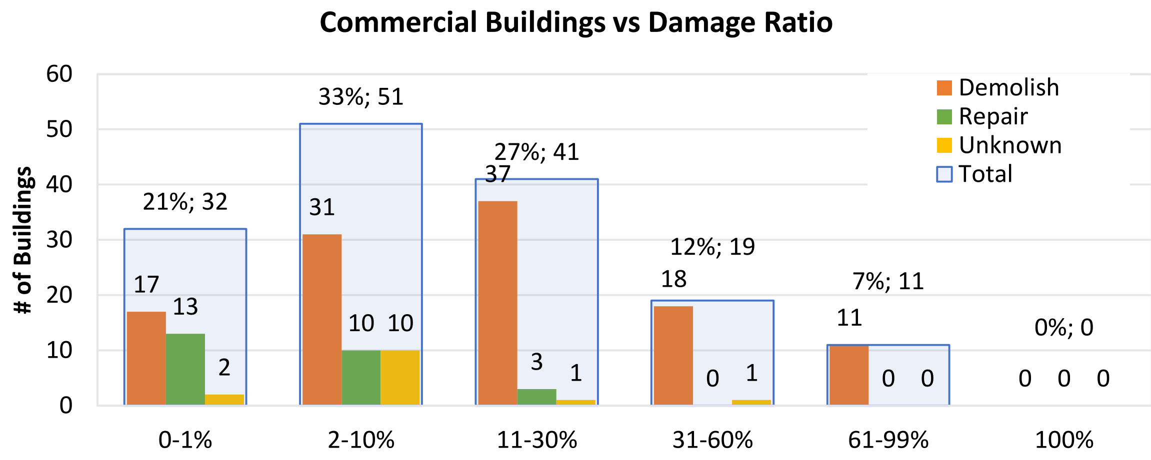


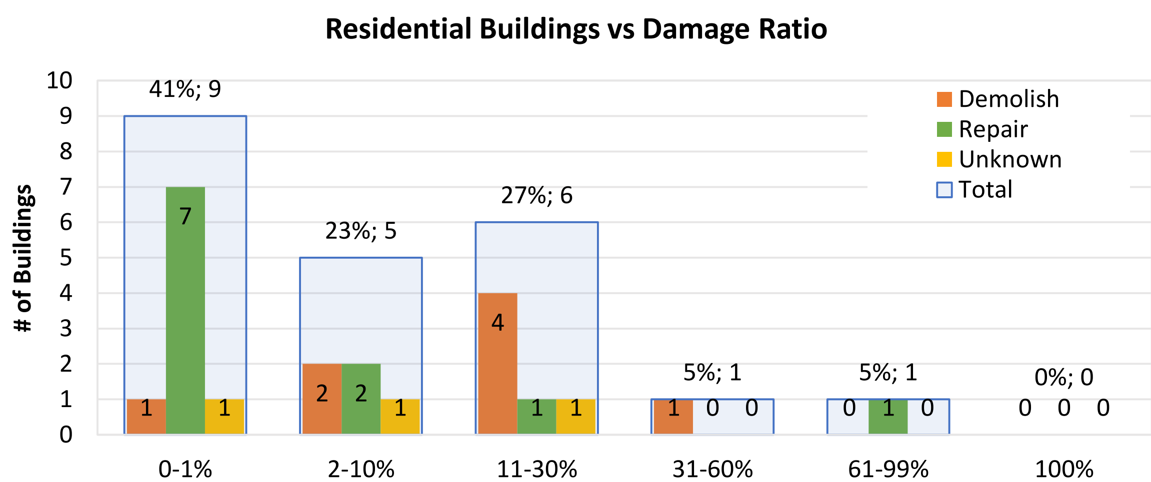
6 to 12-Storey Buildings vs Placard

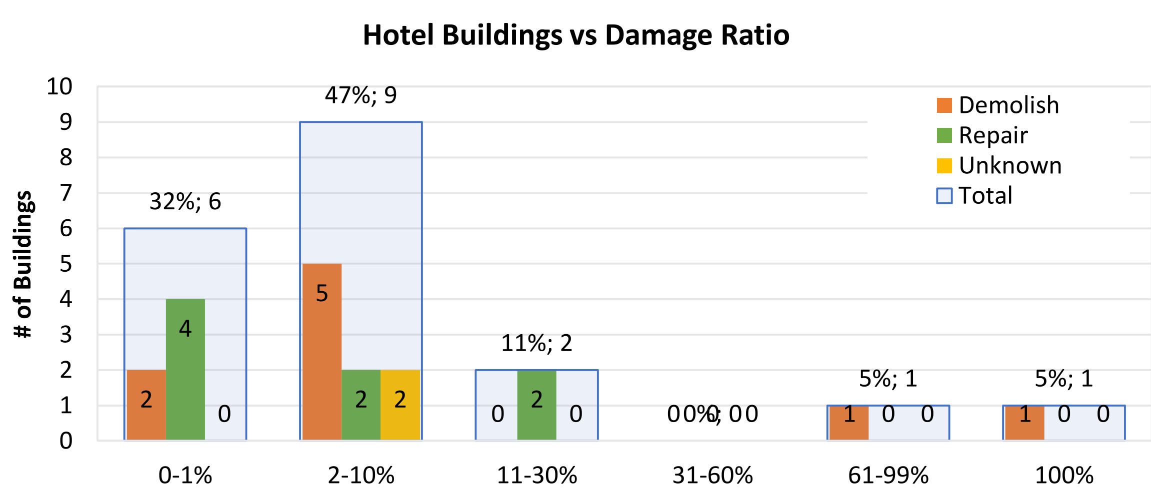


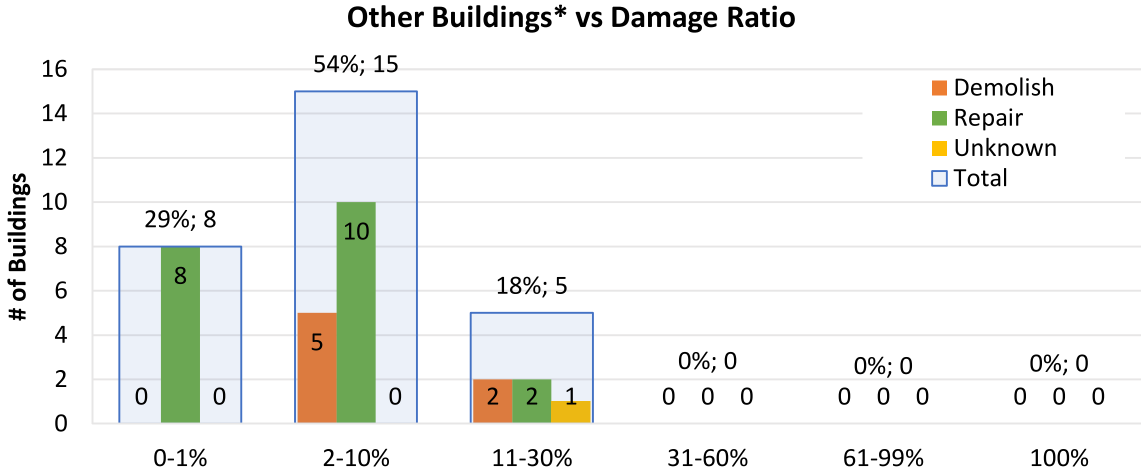
13 to 22-Storey Buildings vs Placard



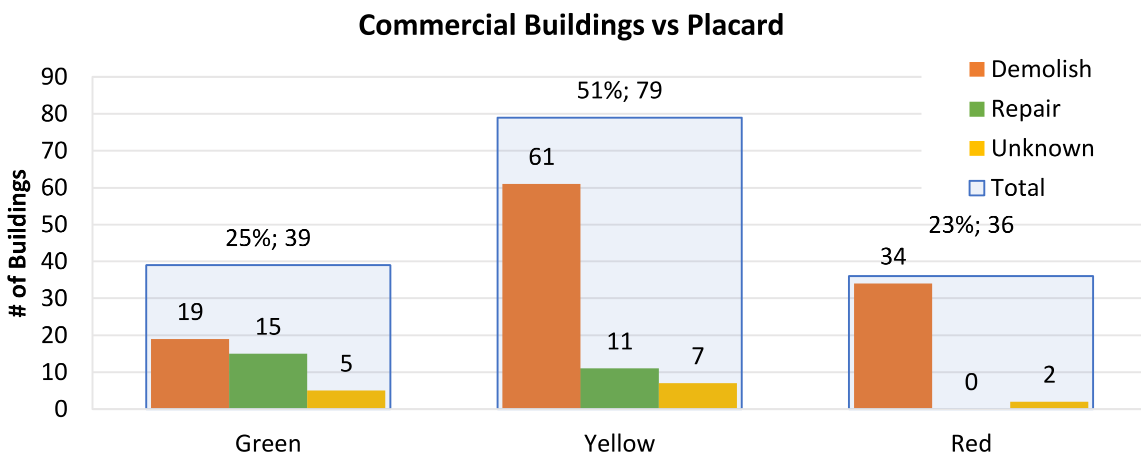

Commercial Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
21%; 32
33%; 51
27%; 41
12%; 19
7%; 11
0%; 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%

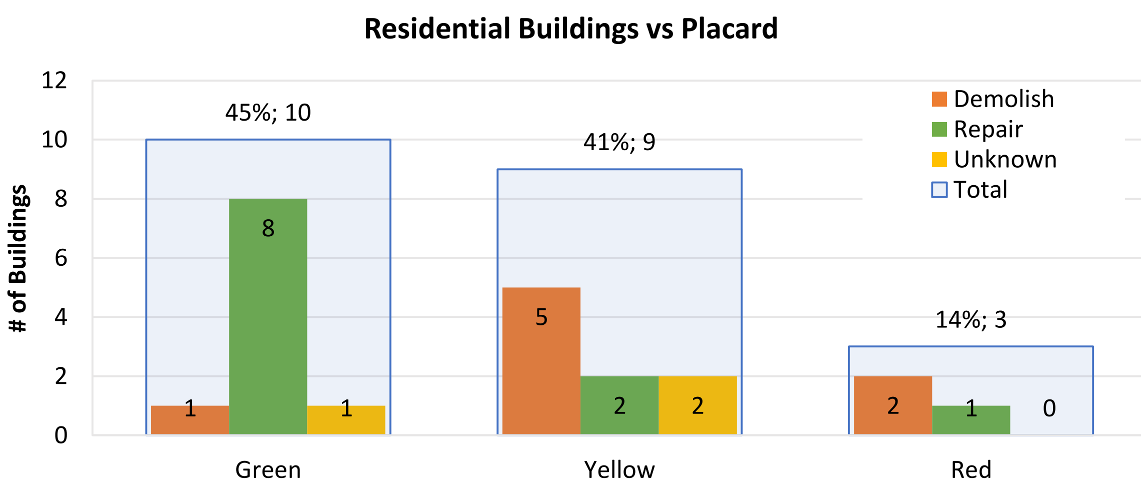

Residential Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
41%; 9
23%; 5
27%; 6
5%; 1
5%; 1
0%; 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%


Hotel Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
32%; 6
47%; 9
11%; 2
5%; 1
5%; 1
0-1%
2-10%
11-30%
31-60%
61-99%
100%

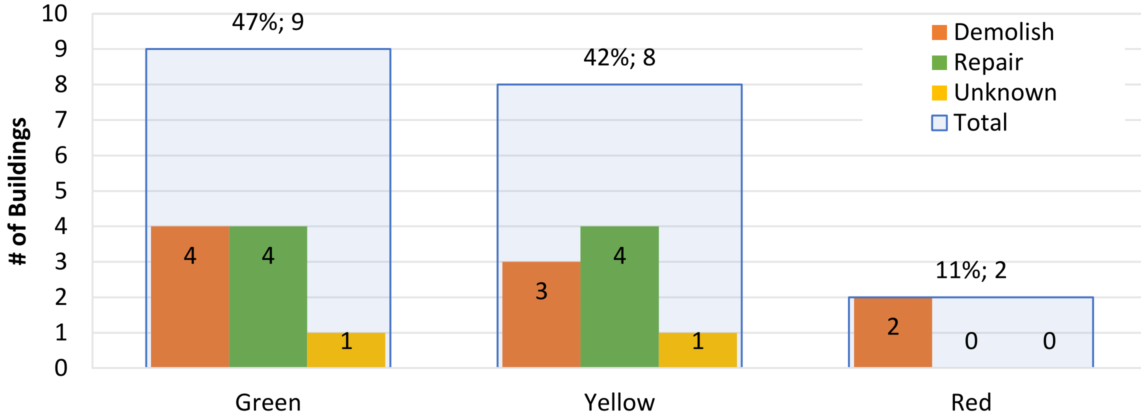


*All buildings not classified as commercial, residential, or hotel

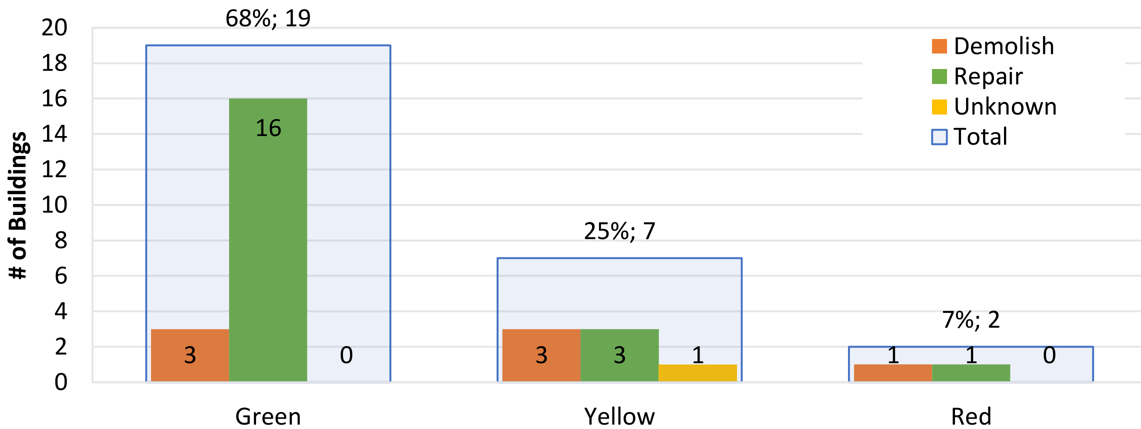




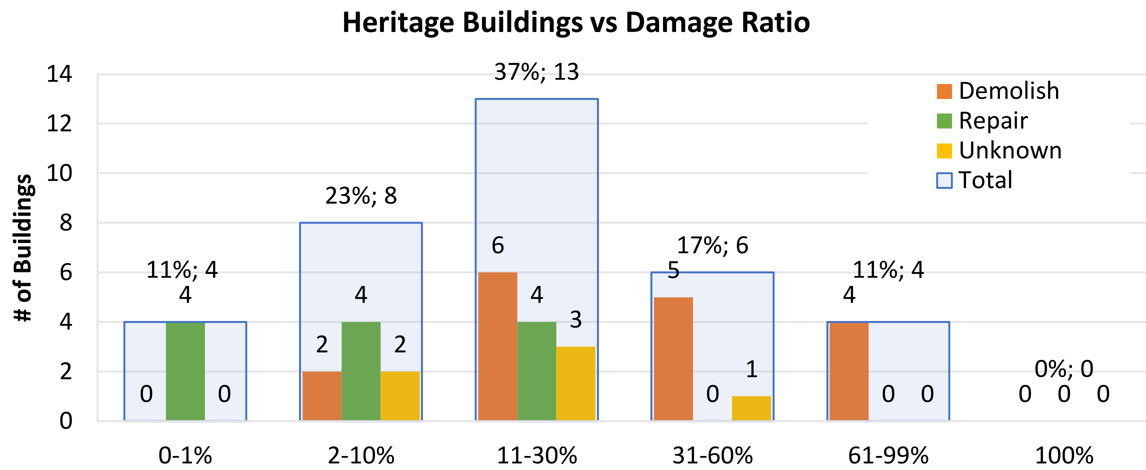
Hotel Buildings vs Placard



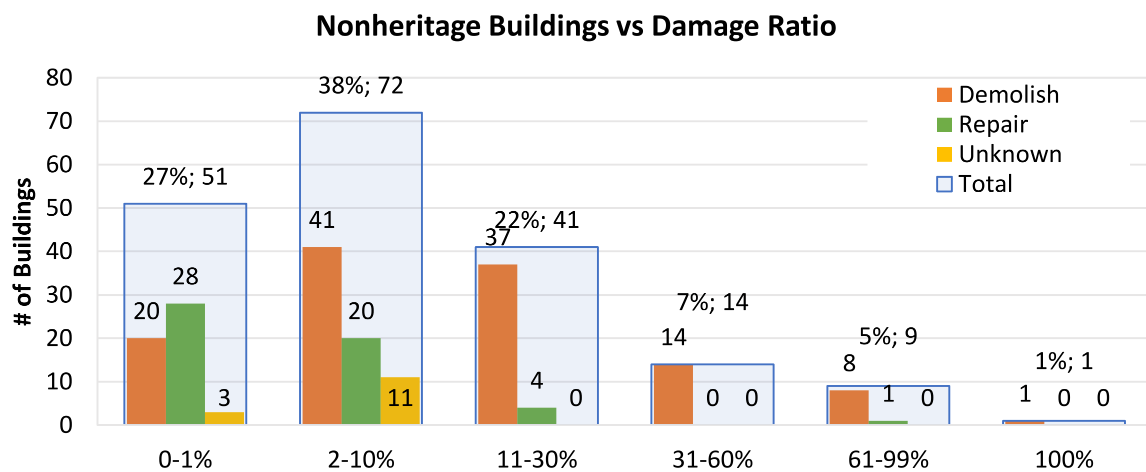
Other Buildings* vs Placard



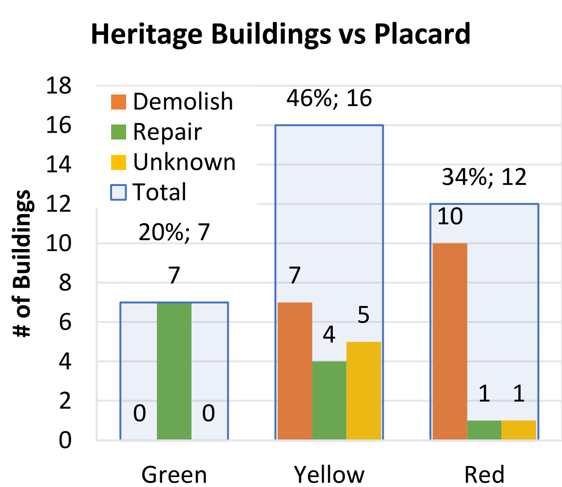
*All buildings not classified as commercial, residential, or hotel



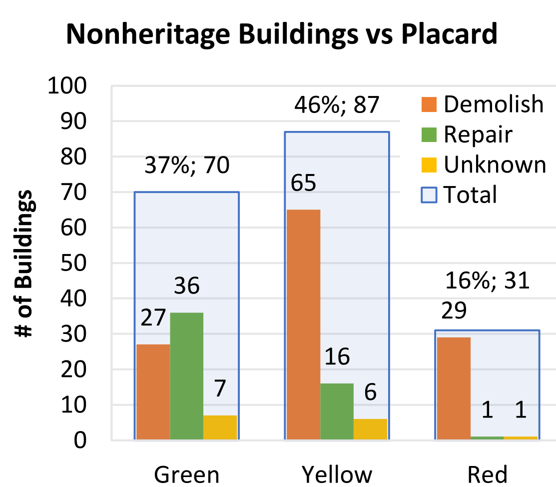
Heritage Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
11%; 4
23%; 8
37%; 13
17%; 6
11%; 4
0%; 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%



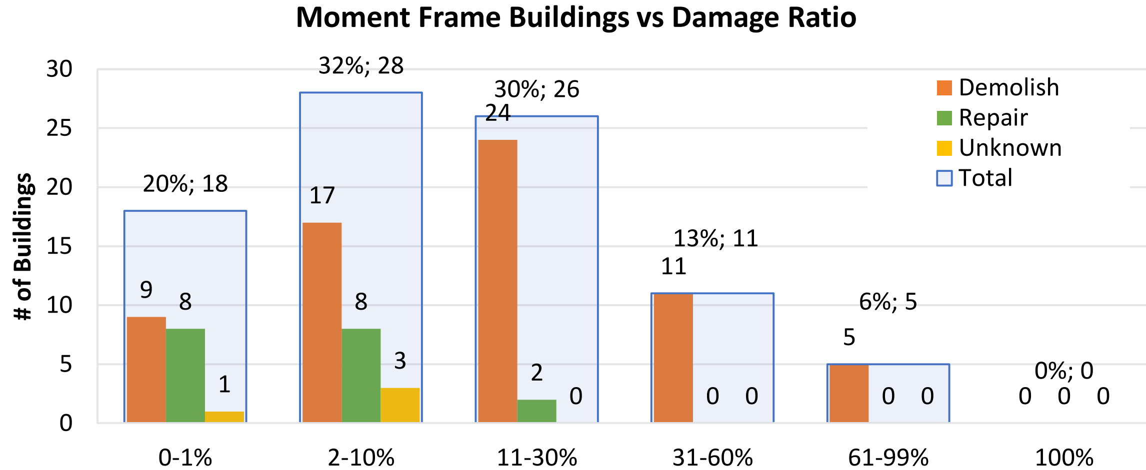
Nonheritage Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
27%; 51
38%; 72
22%; 41
7%; 14
5%; 9
1%; 1
0-1%
2-10%
11-30%
31-60%
61-99%
100%

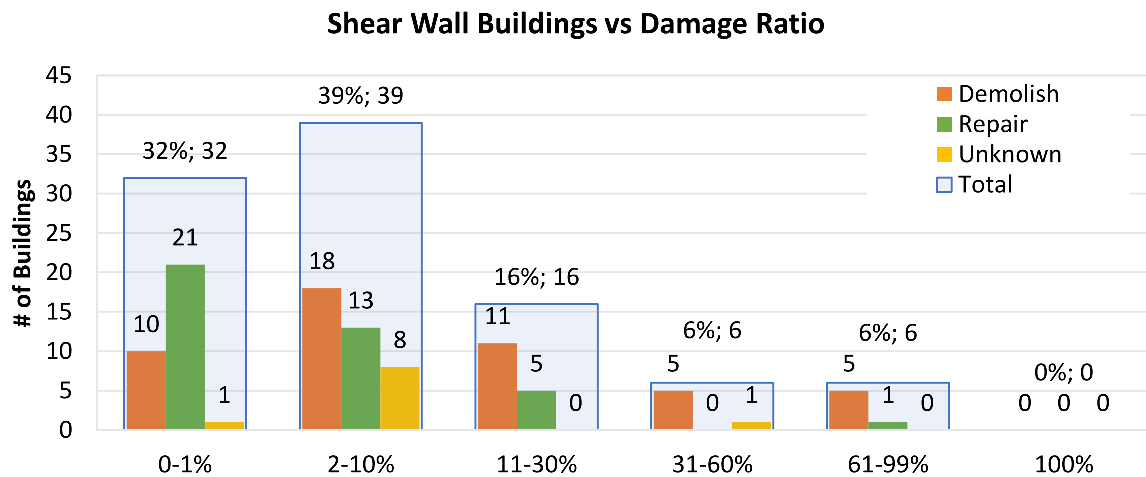


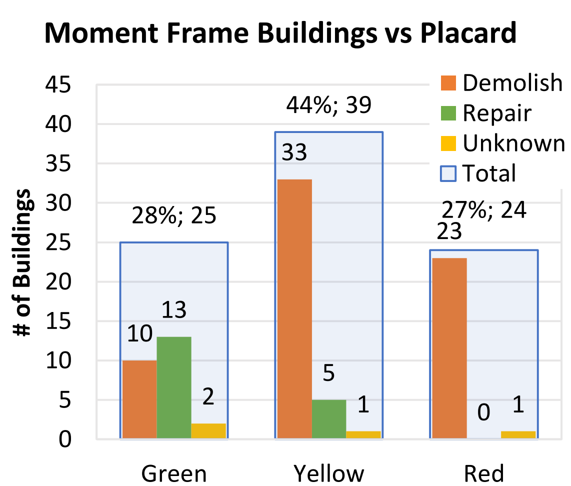
Heritage Buildings vs Placard
# of Buildings
Demolish
Repair
Unknown
Total
20%; 7
46%; 16
34%; 12
Green
Yellow
Red

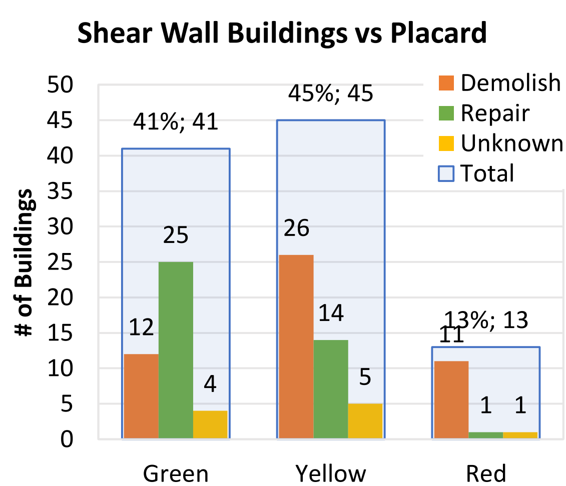


Nonheritage Buildings vs Placard
# of Buildings
Demolish
Repair
Unknown
Total
37%; 70
46%; 87
16%; 31
Green
Yellow
Red

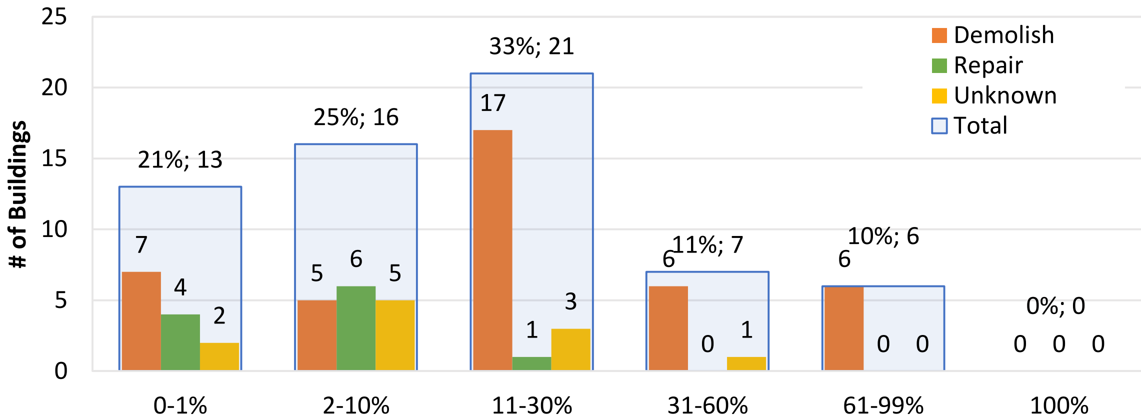

Moment Frame Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
20%; 18
32%; 28
30%; 26
13%; 11
6%; 5
0%; 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%


Shear Wall Buildings vs Damage Ratio
# of Buildings
Demolish
Repair
Unknown
Total
32%; 32
39%; 39
16%; 16
6%; 6
6%; 6
0%; 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%

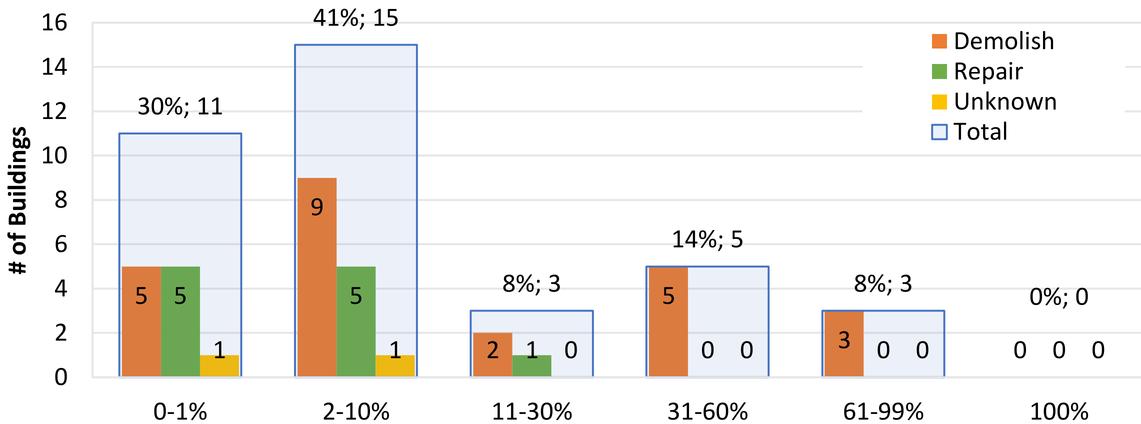

Moment Frame Buildings vs Placard
# of Buildings
Demolish
Repair
Unknown
Total
28%; 25
44%; 39
27%; 24
Green
Yellow
Red


Shear Wall Buildings vs Placard
# of Buildings
Demolish
Repair
Unknown
Total
41%; 41
45%; 45
13%; 13
Green
Yellow
Red

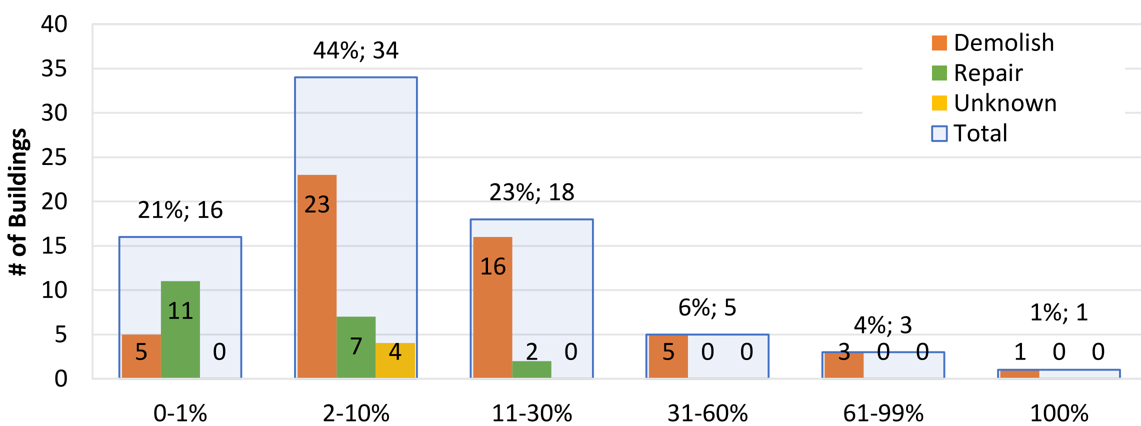
Pre 1965 Buildings vs Damage Ratio

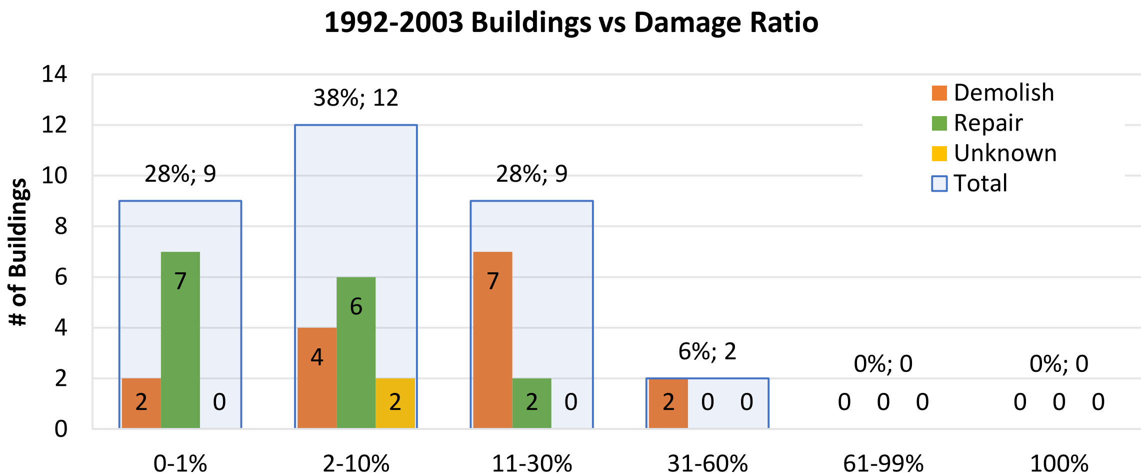


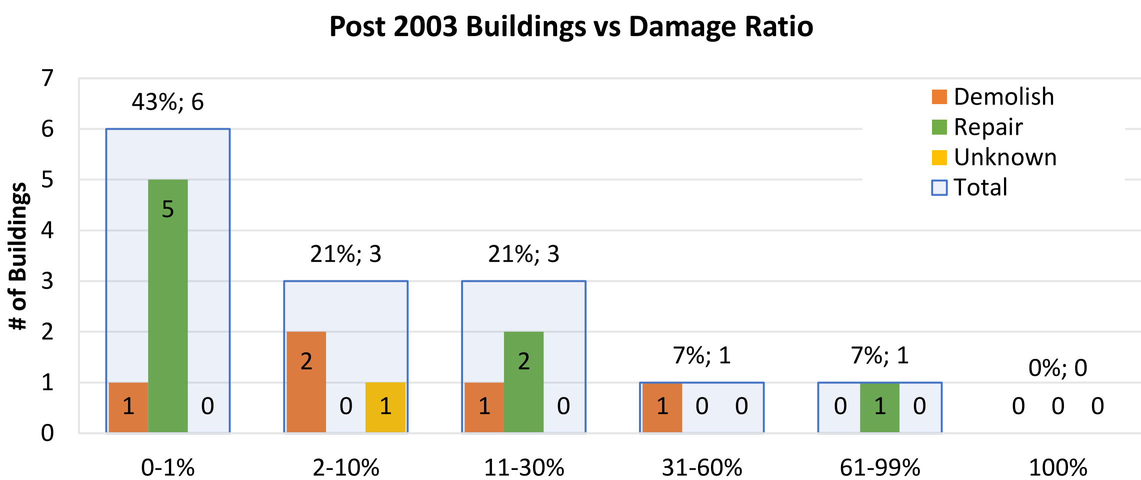
1965-1975 Buildings vs Damage Ratio



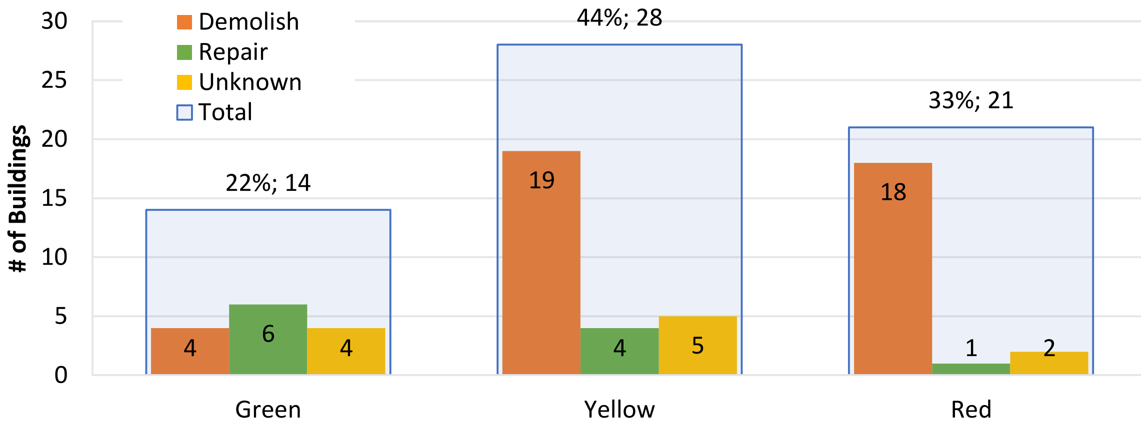
1976-1991 Buildings vs Damage Ratio



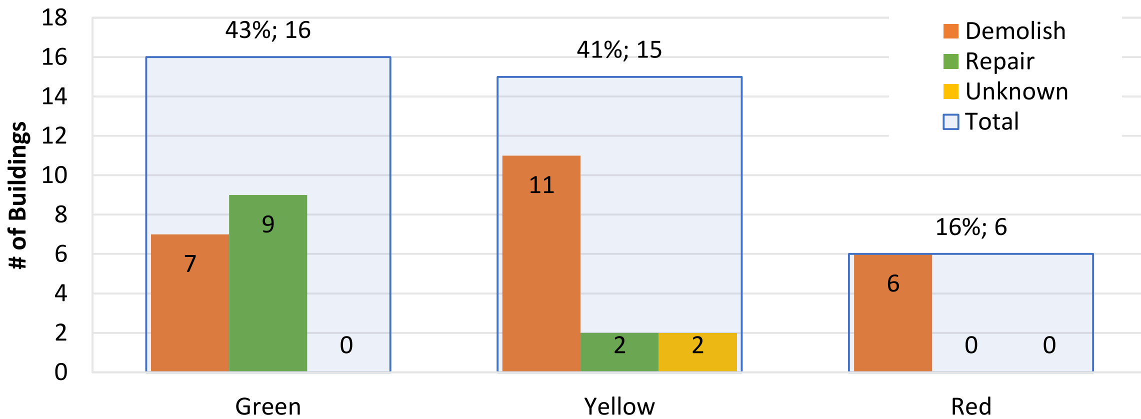

1992-2003 Buildings vs Damage Ratio
# of Buildings
14
12
10
8
6
4
2
0
Demolish
Repair
Unknown
Total
28%; 9
38%; 12
28%; 9
6%; 2
0%; 0
0%; 0
2 7 0
4 6 2
7 2 0
2 0 0
0 0 0
0 0 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%


Post 2003 Buildings vs Damage Ratio
# of Buildings
7
6
5
4
3
2
1
0
Demolish
Repair
Unknown
Total
43%; 6
21%; 3
21%; 3
7%; 1
7%; 1
0%; 0
1 5 0
2 0 1
1 2 0
1 0 0
0 1 0
0 0 0
0-1%
2-10%
11-30%
31-60%
61-99%
100%

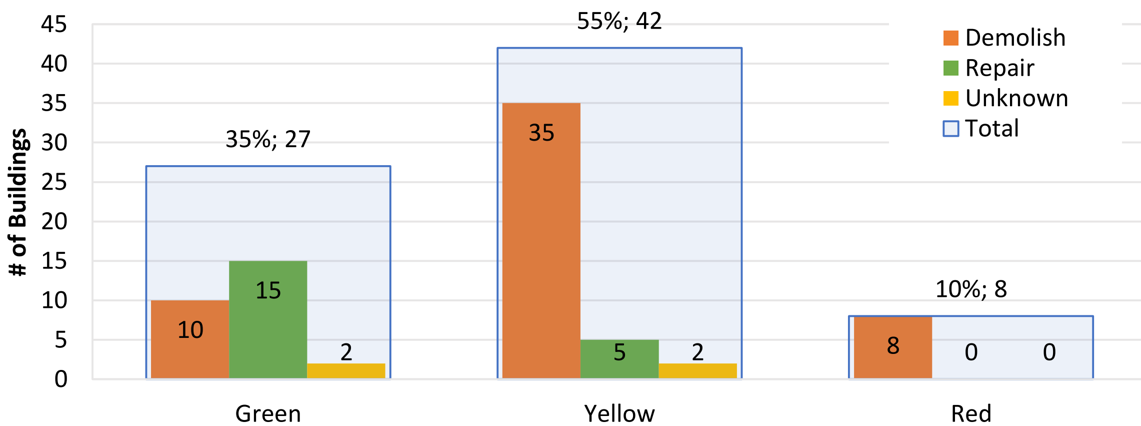
Pre 1965 Buildings vs Placard

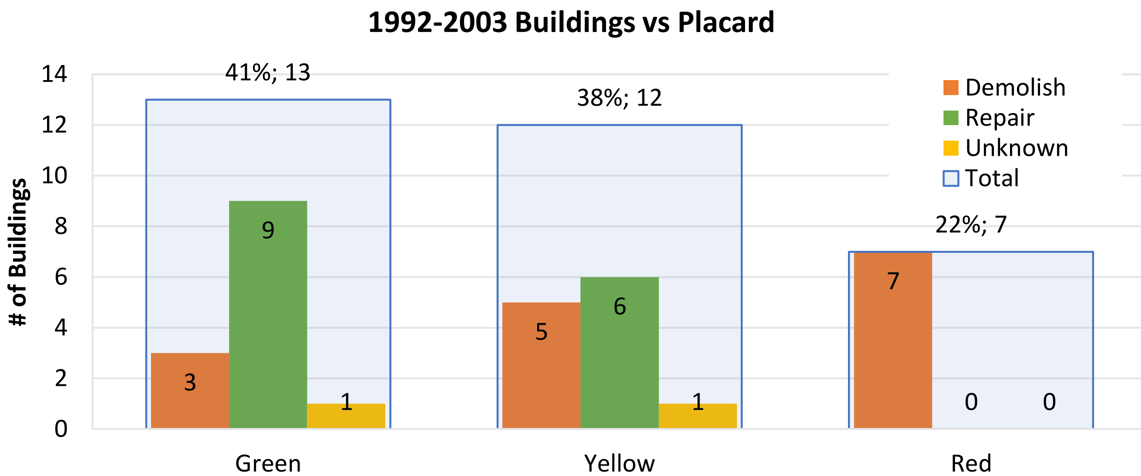


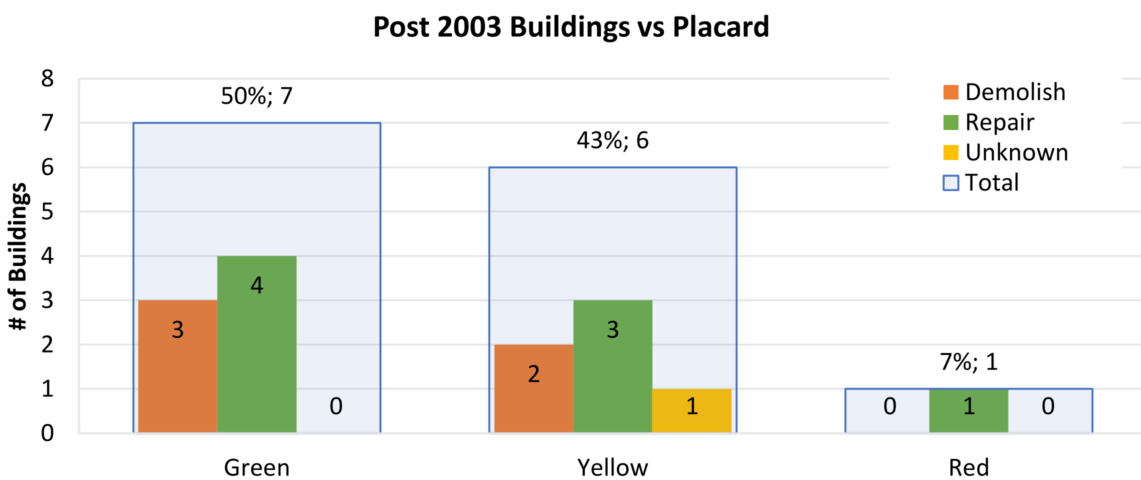
1965-1975 Buildings vs Placard

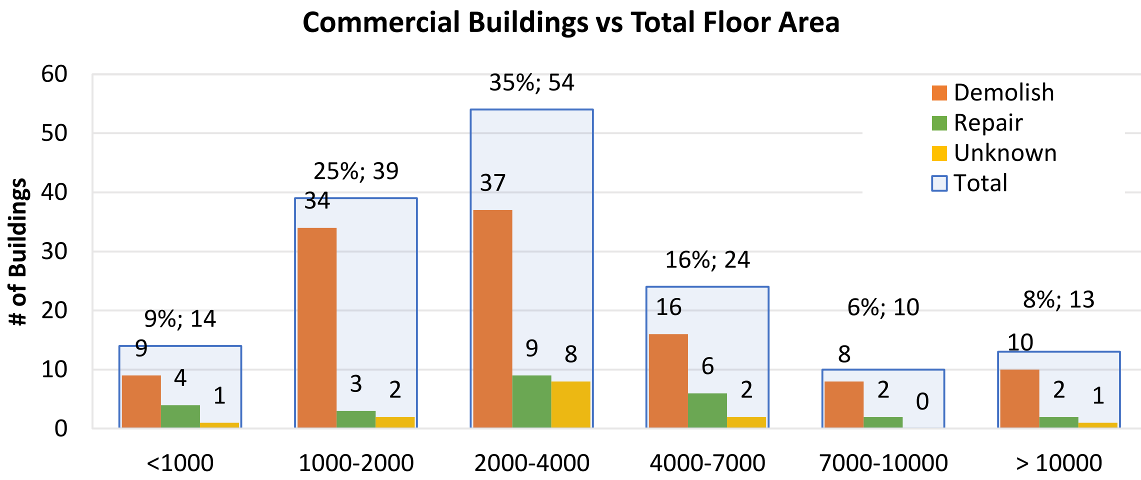


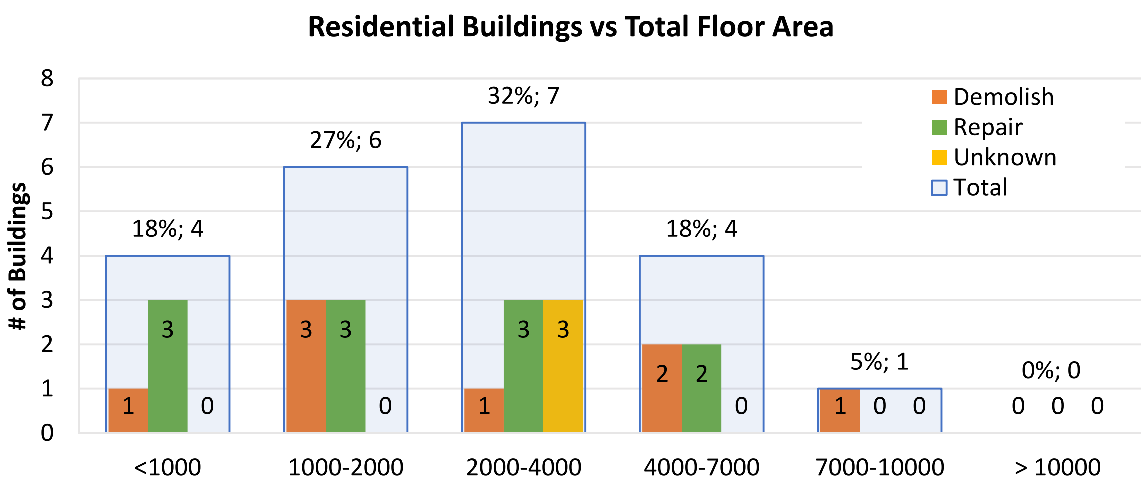
1976-1991 Buildings vs Placard

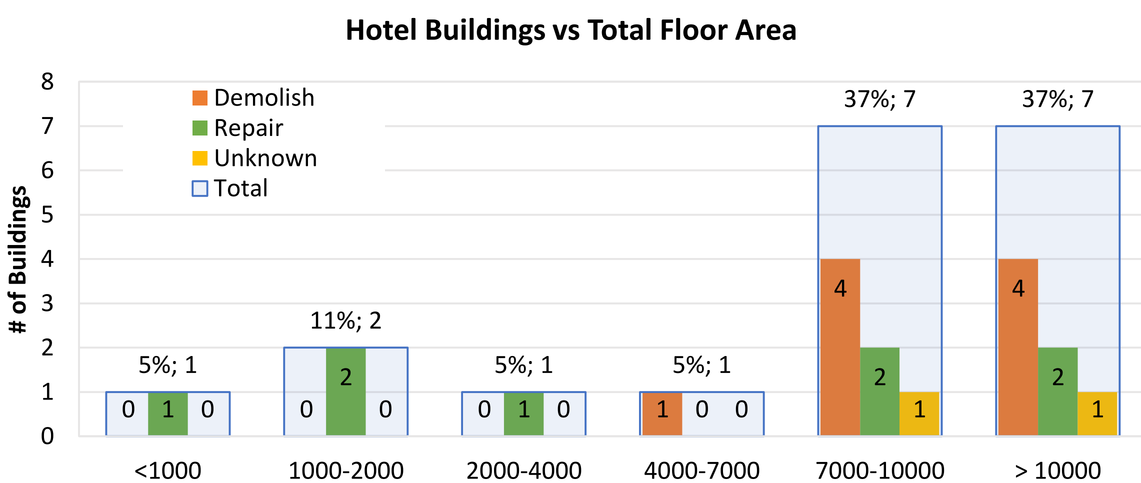



1992-2003 Buildings vs Placard
# of Buildings
14
12
10
8
6
4
2
0
41%; 13
38%; 12
22%; 7
9
3
1
6
5
1
7
0
0
Green
Yellow
Red
Demolish
Repair
Unknown
Total


Post 2003 Buildings vs Placard
# of Buildings
8
7
6
5
4
3
2
1
0
50%; 7
43%; 6
7%; 1
4
3
0
3
2
1
0
1
0
Green
Yellow
Red
Demolish
Repair
Unknown
Total


Commercial Buildings vs Total Floor Area
# of Buildings
60
50
40
30
20
10
0
Demolish
Repair
Unknown
Total
9%; 14
25%; 39
35%; 54
16%; 24
6%; 10
8%; 13
<1000
1000-2000
2000-4000
4000-7000
7000-10000
> 10000


Residential Buildings vs Total Floor Area
# of Buildings
Demolish
Repair
Unknown
Total
18%; 4
27%; 6
32%; 7
18%; 4
5%; 1
0%; 0
<1000
1000-2000
2000-4000
4000-7000
7000-10000
> 10000


Hotel Buildings vs Total Floor Area
# of Buildings
Demolish
Repair
Unknown
Total
5%; 1
11%; 2
5%; 1
5%; 1
37%; 7
37%; 7
<1000
1000-2000
2000-4000
4000-7000
7000-10000
> 10000