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A STUDY OF FACTORS INFLUENCING POST-EARTHQUAKE DECISIONS ON BUILDINGS IN CHRISTCHURCH, NEW ZEALAND

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ABSTRACT: The consequences of the 2010-2011 Canterbury Earthquakes alerted many urban communities to seismic risk. Considering the performance of reinforced concrete (RC) buildings was acceptable and as expected (Kam et al., 2011), the high demolition rate (~60%) of RC buildings is surprising. In an effort to understand such an outcome, various factors influencing the post-earthquake decisions on buildings (demolition or repair) are explored, focusing on multi-storey RC buildings in Christchurch Central Business District (CBD). Information on building characteristics, assessed post-earthquake damage, and post-earthquake decision (demolish or repair) for 223 buildings was collected and studied. Logistic regression analyses were conducted based on the empirical data to develop probability-of-demolition function accounting for the relative effects of various factors; assessed damage, occupancy type, heritage status, number of floors, and construction year were identified to influence the likelihood of building demolition. From in-person interviews conducted in New Zealand, contextual factors such as insurance policy and changes in legislation were also found to play a significant role in the post-earthquake decisions on buildings.

1. Introduction

The 2010-2011 Canterbury Earthquake Sequence caused unprecedented losses in Christchurch, New Zealand. The most damaging event occurred on 22 February 2011 followed by numerous aftershocks (Bradley et al., 2014), resulting in 185 confirmed fatalities. In addition to the traumatic experience, the direct impacts on the community include $NZ 40 billion in financial loss (or 20% of New Zealand's Gross Domestic Product [GDP]), demolition of approximately 60% of RC buildings in the Christchurch 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). From 22 February to 30 April 2011, a National State of Emergency was declared under the Civil Defence Emergency Management Act (2002) to identify dangerous buildings and take required actions (demolition or make-safe work) for public safety. The Canterbury Earthquake Recovery Authority (CERA) was established to lead and facilitate the recovery of the community (CERA, 2012). One of CERA's roles is to oversee building damage assessments and manage building demolition works in agreement with the building owners. The Christchurch Central Development Unit (CCDU) was formed to aid the recovery and renewal of the city by planning and executing anchor projects (CCDU, 2012). Four years since the earthquakes, the community recovery and reconstruction efforts are still ongoing.

Motivated by the high demolition rate of RC buildings, this study aims to identify variables affecting the post-earthquake decisions on buildings (demolition or repair), focusing on 3-story and higher RC buildings located in the Christchurch CBD. This paper presents a summary of the data collection methodology, description of collected information, and database statistics. Implementation of logistic regression analysis is introduced and the effects of various factors on the decision outcome is demonstrated. In addition, the distinctive local context of Christchurch is discussed.

2. Description of Database

The database was developed by collecting information on building characteristics, assessed post-earthquake damage, and post-earthquake decisions for 223 buildings that are 3-storey and higher RC buildings within the Christchurch CBD. The Christchurch CBD includes approximately 110 city blocks enclosed by the four avenues: Bealey, Deans, Moorhouse, and Fitzgerald. The 223 buildings represent approximately 88% of the 3-storey and higher RC buildings within the CBD (buildings with no or very limited available information were excluded from the database). This represents approximately 34% of all RC buildings in the CBD. The data were obtained from and in collaboration with the Christchurch City Council (CCC), the Canterbury Earthquake Recovery Authority (CERA), GNS science, and local engineers. For buildings for which decision outcome information was unavailable from any of the sources above, building sites were visited to photograph and note the current operational status. The database was completed after an extensive data collection and verification process. The collected information was available in the forms of databases, engineering reports, damage assessment forms, and photographs.

The study database is comprised of information such as building identification information, decision outcome, damage indicators, building condition, seismic force resisting system, duration in cordon (see below), construction year, heritage status, footprint area, number of floors, and type of occupancy. Table 1 summarizes the collected information with descriptions.

Decision Outcome takes three forms; Demolish, Repair, or Unknown. The “Demolish” decision may be made by “Civil Defence”, “CERA”, “Owner”, “CCDU Demolition”, or unknown. The decision by “Civil Defence” refers to buildings that were demolished under the authority of the 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 on such buildings. The decision by “CERA” refers to buildings that were demolished under Sections 38 or 39 of the Canterbury Earthquake Recovery Act (2011) to enable a focused, timely, and expedited recovery. “CCDU Demolition” indicates buildings that were demolished to clear sites for the CCDU’s anchor projects (CCDU, 2012). If not required to be demolished, the building “Owner” may decide to either demolish or repair the buildings. “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 may imply that the decision had not been made or the decision had been made but no actions had been taken yet.

Shortly after the September 2010 earthquake, CCC adopted NZSEE Rapid Assessment forms (Level 1 and Level 2) (NZSEE, 2009) similar to ATC-20 (ATC, 1995). Groups of engineers surveyed buildings in Christchurch after all subsequent earthquakes by filling in the assessment forms. Both Level 1 and Level 2 Rapid Assessments include Placard posting and estimated overall building Damage Ratio as damage indicators. Placard posting represents usability of the assessed building; green for “Inspected”, yellow for “Restricted Use”, and red for “Unsafe”. Damage Ratio (DR) is an estimate of building damage as a ratio of repair cost to replacement cost (excluding contents) and it is expressed in ranges 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, and severe. In addition to all the above, the Level 2 Raid Assessment contains detailed lists of structural, nonstructural, and geotechnical damage, indicating the severity with descriptive comments. Placard and Damage Ratio from the Level 2 Rapid Assessments are chosen as damage indicators for this study.

Table 1: Description of Collected Data

Variable	Measure/ Description		
Address and Business Name	(Used for building identification)		
Decision Outcome	Demolish	Repair	Unknown
Demolition Decision Made by	Civil Defence CERA Owner	CCDU Demolition Unknown	
Damage Indicator	**Damage Ratio**	**Placard**	**Categorical Damage**
	0-1% 2-10% 11-30% 31-60% 61-99% 100%	Green Yellow Red	Minor or None Moderate Severe
Pre-EQ and Post-EQ %NBS	%NBS before and after the earthquakes		
Seismic Force Resisting System (SFRS)	Moment Frame (MF) Shear Wall (SW)	MF with Infill (MFIF) Combined MF & SW	
Duration in Cordon	Number of months from 22 February 2011 to date cordon lifted		
Construction Year	Pre 1965 1965-1975 1976-1991	1992-2003 Post 2003	
Heritage Status	Heritage	Nonheritage	
Footprint Area	Measured in m^2		
Number of Floors	Number of floors		
Occupancy Type	Commercial Residential Hotel Government	School Post-secondary Hospital Public assembly Industrial	

As an approximate measure of structural capacity, the concept of percentage of New Building Standard (NBS) was adopted. %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 in accordance with NZSEE (2006), or by a comparison with current seismic loading standard in NZS1170.5:2004 (DBH, 2012). CCC mandated seismic strengthening work on the buildings with %NBS ≤33% (earthquake-prone buildings) (CCC, 2010). Therefore, %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 DEE's were not available for all buildings.

Immediately after the 22 February 2011 earthquake, a cordon (public exclusion zone) was established covering the most of the built area in the CBD. The cordoned area was reduced gradually in 33 phases and the last cordon was lifted on 27 June 2013, 28 months after the establishment. To determine how long each building was inside the cordon and had restricted public access, the date that cordon was lifted for each study building was obtained and the number of months inside the cordon was calculated.

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). 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. Although there are various levels associated with heritage status, it is simply recorded in the database as either heritage or nonheritage.

Type of occupancy is categorized into commercial, residential, hotel, school, post-secondary, hospital, government, public assembly, and industrial. Commercial occupancy generally includes office spaces, retails, restaurants, and parking structures. Residential occupancy refers to multi-storey condominiums and apartments.

This study focuses on buildings with seismic force resisting system of concrete moment frame (MF), concrete shear wall (SW), concrete moment frame with infill (MFIF), and combined MF and SW. Construction year is specified in 5 ranges reflecting changes in design standards; Pre 1965, 1965-1975, 1976-1991, 1992-2003, or Post 2003. The number of floors above ground and building footprint area (estimated in m^2) are also recorded.

3. Database Statistics

Various descriptive statistics of the collected information are summarized in Figure 1 through Figure 4. Detailed information on the collected database can be found in Kim (2015). As demonstrated in Figure 1, 62% of the buildings of interest (138 buildings) were demolished and 29% (65 buildings) were repaired. This is equivalent to demolition of 61% and repair of 30% of total floor space of the buildings considered (1,223,500 m^2), assuming equal plan area for all floors (number of floors multiplied by the footprint area). The outcomes for the remaining 20 buildings 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). Out of 223 buildings, 35% received green, 46% received yellow, and 19% received red placards; 35% of the green placarded buildings were demolished (Figure 2a). Of 135 buildings (61%) assessed to have relatively low Damage Ratio of 10% or less, 47% (63 buildings) were demolished (Figure 2b). It can thus be inferred that a significant number of reinforced concrete buildings with relatively low damage were demolished. Figure 2c and Figure 2d present damage statistics for those buildings with DEE (which contains assessed %NBS). In comparison with the study database, greater portion of this subgroup buildings were assessed to suffer minor damage; 56% received green placards and 81% were assessed for Damage Ratio of 10% or less. Also, it is apparent that the demolition rate of the subgroup is much lower than that of the 223 study buildings. Considering only buildings with pre-EQ or post-EQ %NBS (65% of the study buildings are missing %NBS information), the demolition rate is lowest (<11%) among those buildings with %NBS > 66% and highest (33%) for buildings with %NBS ≤ 33% (Figure 3).

In terms of building characteristics (Figure 4), 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. Heritage buildings account for 16% of the database and it is seen that heritage buildings have lower likelihood of demolition. The majority of buildings (78%) have footprint area of less than 1000 m^2, and 65% of those buildings were demolished.

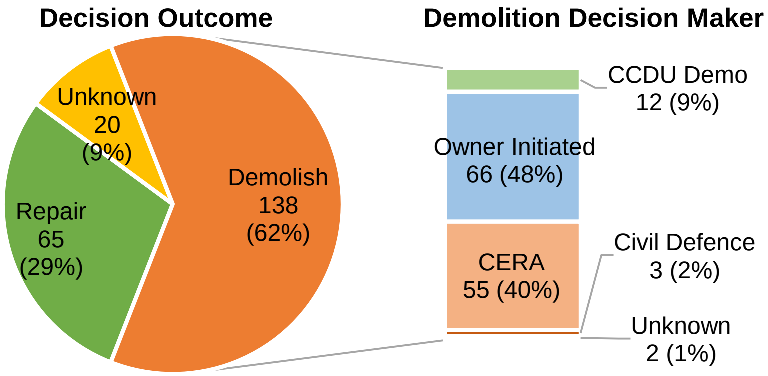

Figure 1: Building Decision Statistics – Decision Outcome and Demolition Decision Maker

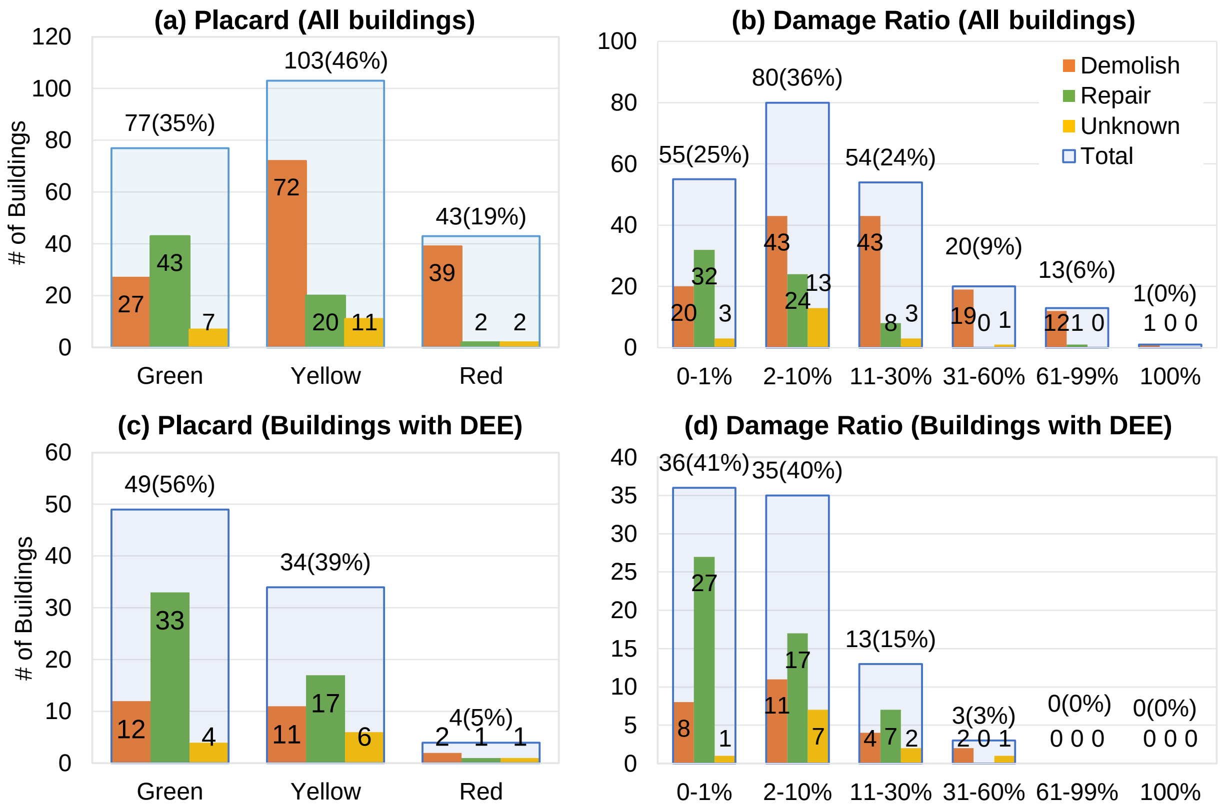

Figure 2: Building Damage Statistics – (a) Placard on all buildings, (b) Damage Ratio on all buildings, (c) Placard on buildings with DEE, and (d) Damage Ratio on buildings with DEE

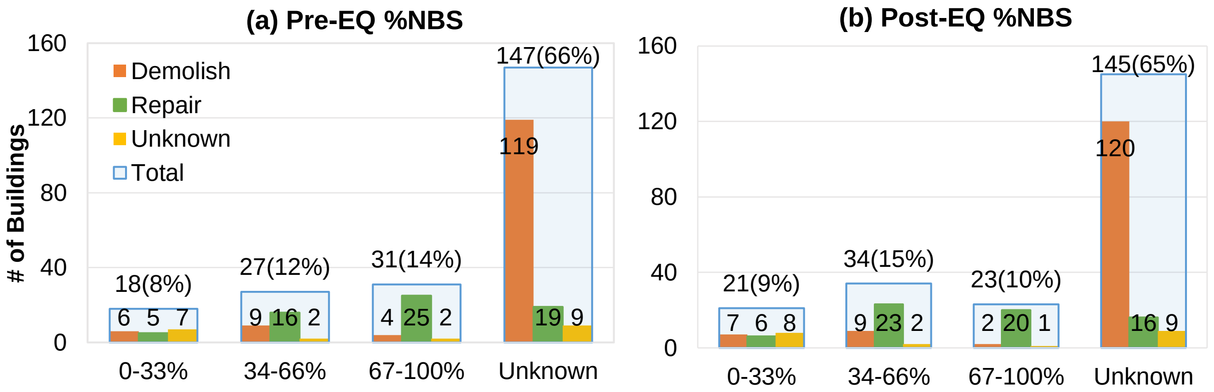

Figure 3: Building Structural Capacity Statistics – (a) Pre-EQ %NBS and (b) Post-EQ %NBS

Low and mid-rise buildings are dominant and 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. Moment frame (40%) and shear wall (44%) structural systems are equally common in Christchurch CBD. It is found that higher rate of moment frame buildings (75%) were demolished compared to shear wall buildings (49%). Buildings that were in cordon zone for more than a year account for 58% of the database, and 76% of them were demolished. Commercial occupancy is dominant (69%), followed by residential (10%) and hotel buildings (9%). High rate of demolition is observed for commercial (74%) and government buildings (75%) compared to 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%).

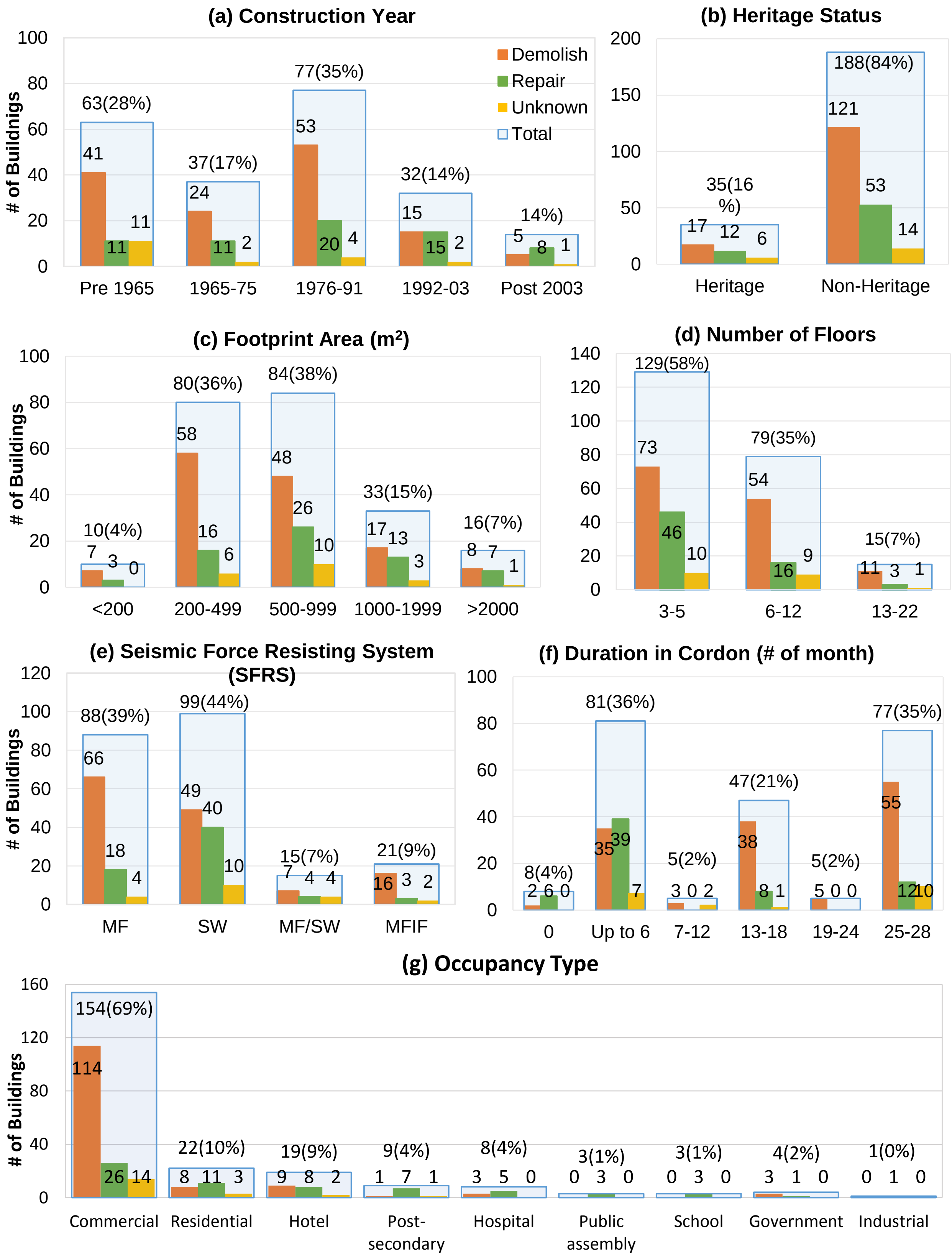

Figure 4: Building Characteristics Statistics – (a) Construction year, (b) Heritage Status, (c) Footprint area, (d) Number of floors, (e) SFRS, (f) Duration in cordon, and (g) Occupancy type

4. Logistic Regression Analysis

Logistic regression is a probabilistic statistical method for estimating relationships between a bivariate dependent (or response) variable, y, and independent (explanatory) variables, x. The probability of the possible outcome, P, is modeled as a function of the independent variables by estimating empirical values of the unknown parameters (regression coefficients), B. The logistic regression function is expressed as:

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

In this study, logistic regression analysis is used to develop an empirical equation and quantify the influence of various factors on the probability of building demolition. Although the developed empirical equation may be used to predict the probability of building demolition, the database scope and local context should be carefully considered.

Logistic regression models are established based on the previously described database with a few exceptions. The buildings with “Unknown” decision outcome (20 buildings) are excluded as such buildings do not provide any meaningful information. 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 in consideration. Although pre-EQ and post-EQ %NBS are possible influencing factors, they are not included in the logistic regression model development due to lack of available information. The effect of %NBS on the decision outcome is discussed in Kim (2015).

Among various model-building strategies, Forward and Backward Stepwise variable selection methods are chosen (variable p-value <0.05 for entry and >0.1 for removal). The main advantage is that it is 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). A final model is chosen based on Hosmer-Lemeshow Goodness-of-Fit test (model significance >0.05) and Akaike Information Criterion (AIC) (lower AIC value represents better performance) (Hosmer et al., 2013; Akaike, 1974).

$$ln\left(\frac{P}{1-P}\right) = y = -45.48 + 0.03x_2 - 1.65x_3 - 2.10x_6 - 0.2x_7 - 1.16x_{11} \tag{2}$$

Equation 2 presents the logistic regression function from the selected best model, which includes an intercept and five regression coefficients for the variables that are found to be important (p-value <0.05): construction year(x_2), heritage status(x_3), occupancy type(x_6), number of floors(x_7), and Damage Ratio(x_{11}). Here, P and $1-P$ represent the probability of repair and the probability of demolition, respectively. Detailed discussion on the logistic regression model development and interpretation can be found in Kim (2015).

Figure 5 presents predicted and observed probability-of-demolition curves against Damage Ratio. The predicted probability-of-demolition and its 95% confidence interval curves are generated based on arbitrarily chosen conditions on the other four variables (commercial occupancy, nonheritage, 5-storey high, and construction year of 1984). This is referred to as a reference curve. The drop in the observed probability of demolition at 61-99% Damage Ratio is exaggerated by the small number of observations in that category. The predicted probability of demolition indicates that the likelihood of demolition increases with severity of building damage, which is in agreement with the observed probability of demolition.

Since these curves are based on arbitrary conditions for the independent variables, change in probability of demolition due to change in Damage Ratio (slope of the curve) is more informative than the absolute value of probability of demolition. With all other variables being equal, increasing Damage Ratio from 0-1% to 2-10% would raise the likelihood of demolition by 27%. Similarly, compared to buildings assessed to experience 0-1% Damage Ratio, the probability of demolition increases by 43%, 49%, 52%, and 52% for Damage Ratio of 11-30%, 31-60%, 61-99%, and 100%, accordingly.

The reference curves may be shifted and/or scaled by varying one independent variable at a time. By observing the changes in the curves, the effects of independent variables on the demolition decision can be demonstrated as shown in Figure 6. 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 variables such as occupancy type, heritage status, number of floors, and construction year become less important in the likelihood of building demolition.

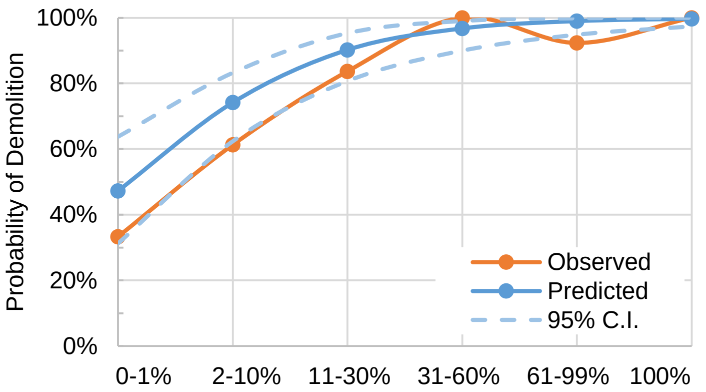

Figure 5: Predicted and Observed Probability of Demolition Curves

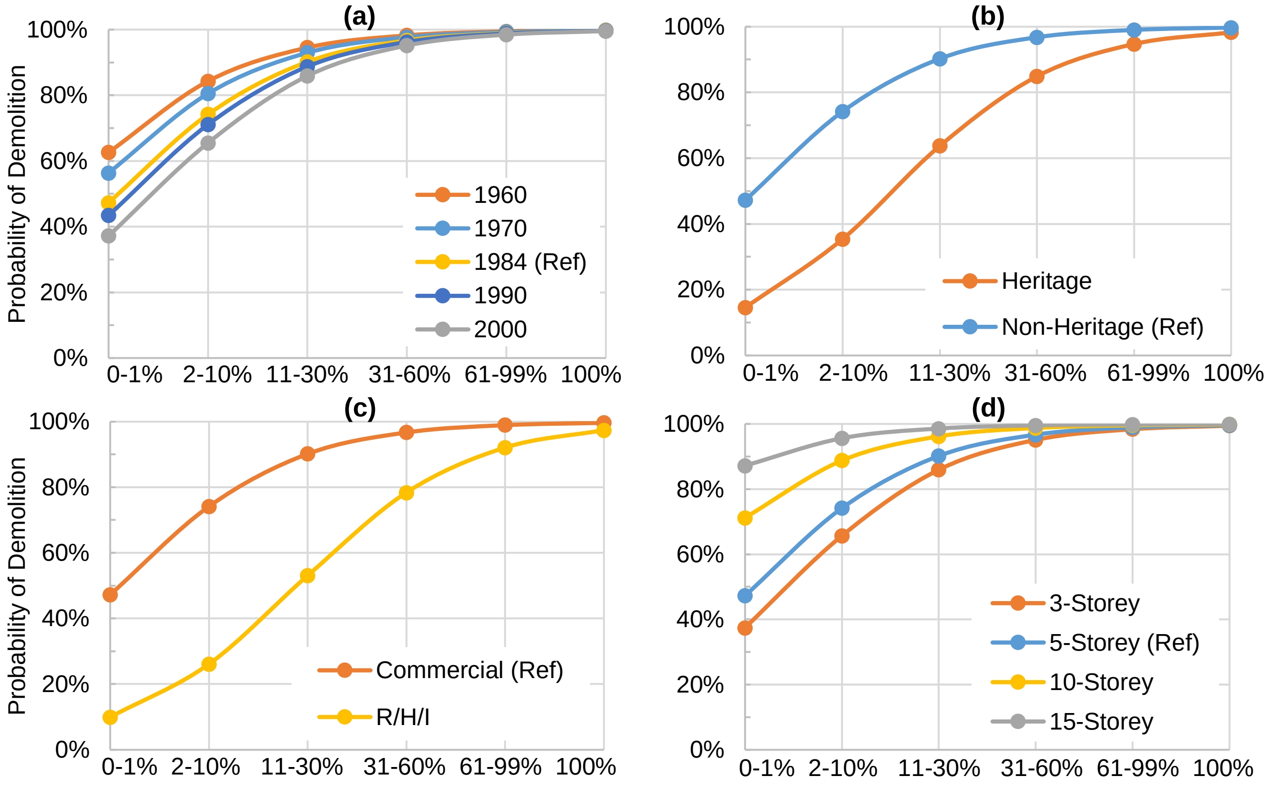

Figure 6: Probability of Demolition vs. Damage Ratio; Varying (a) Construction Year, (b) Heritage Status, (c) Occupancy Type, and (d) Number of Floors

5. Other Local Context Factors

In addition to the quantitative factors discussed previously, the local context and background are also studied for comprehensive understanding of the post-earthquake decisions on buildings. While it was not possible to obtain quantitative data, it was recognized that other contextual factors may have influenced the decision-making process. In-person interviews were conducted with building owners and owner's representatives, property managers, engineers, insurance industry representatives, and government authority personnel. The interviews revealed the complexity of the post-earthquake decision-making process, which is discussed further in Marquis et al. (2015). This section highlights the two important local contextual factors that affected the building demolition decisions in Christchurch.

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. The majority of commercial buildings in Christchurch were insured under reinstatement policy, which entitles the owner to a building in a “condition when 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. In addition, the outcome of the Canterbury Earthquakes has shown that the sum insured was lower than the actual rebuild or replacement cost for most of the commercial buildings. Prolonged and often complex insurance claiming process and the inadequate sum insured amount led many technically viable repair and/or 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.

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 compared to a previous 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 left with uncertainty as to whether the change 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% in comparison with the new seismic design load requirements. 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.

6. Lessons and Conclusions

Despite numerous studies on building performance during earthquakes, there has been no attempt to quantitatively assess the effects of various factors on the building demolition decision. This paper presented the study of factors influencing the post-earthquake decisions on buildings (demolition or repair). Descriptive statistics and logistic regression analyses were conducted based on the empirical data collected from Christchurch, New Zealand. In addition to damage level, occupancy type, heritage status, number of floors, and construction year were found to influence the likelihood of building demolition, especially when the assessed damage was relatively low. Local context factors, such as insurance policy and changes in legislation, were also recognized to play a significant role in the decision-making process. It is concluded that the high demolition rate of RC buildings in Christchurch would be explained when such influencing factors are considered altogether. The findings from this study infers that the current performance-based earthquake engineering methodology may be further developed by considering influential parameters (in addition to damage measure) on the likelihood of demolition when assessing losses. More studies are suggested to identify influencing factors and their effects on the building demolition, reflecting the locality of different communities with seismic risk.

7. Acknowledgements

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