Identifying vulnerable reinforced concrete buildings in Wellington using a simple assessment methodology

K. Balbirnie, R. Chandramohan, S. Pujol, & J. Wight
University of Canterbury, Christchurch.

ABSTRACT

The application of a simple yet effective method to assess reinforced concrete buildings in New Zealand is discussed. It is proposed that this method be used to identify and prioritise the most vulnerable reinforced concrete buildings in Wellington for retrofit. This method of assessment entails the computation of simple indices representing the fraction of the floor area occupied by columns and walls. It has previously been calibrated to surveys of more than 1000 buildings around the world that have been subjected to strong earthquake ground motion. Buildings in Christchurch with small column and/or wall indices are shown to have performed poorly in the 2010-11 Canterbury earthquakes. The method would have helped identify the PGC and CTV buildings in Christchurch as critically vulnerable structures, while the assessment methodology based on "percent of new building standard" (%NBS), that is widely used in New Zealand practice, did not.

1 INTRODUCTION

The recognition that it is only a matter of time before Wellington experiences a major earthquake has spurred the Wellington City Council to assess and retrofit its most vulnerable buildings. This paper seeks to help identify which reinforced concrete buildings in Wellington need to be prioritised for retrofit before others. Emphasis is placed solely on the structural capacities of buildings, without considering factors such as age, occupancy, importance, cost of strengthening, cost of replacement, and cost of business interruptions.

Methods used in structural design are often not well suited for structural assessment. Design methods are tailored to produce buildings with high probabilities of survival. Assessment methods, on the other hand, are geared towards identifying buildings with small probabilities of survival (Hassan 1997). Design and assessment are, therefore, implicitly concerned with buildings at opposite "tails" of a probability distribution function describing building capacity.

A number of structural assessment methods are used in practice and most of these methods are relatively time and resource-intensive. Given *(i)* the volume of buildings that need to be assessed (not just in New Zealand but around the world); *(ii)* the uncertainties inherent in the prediction of future ground motion; and *(iii)* the potential consequences of building failure, it is the writers' opinion that time and money are often better spent in retrofit and reconstruction rather than assessment and analysis. Recognising that not all older and potentially vulnerable buildings in Wellington can be strengthened at once, it is considered prudent to proceed sequentially, starting from the most vulnerable "earthquake-prone" buildings and gradually progressing towards the less vulnerable ones. Putting this plan into action, however, requires a simple and effective means of identifying the degree of structural vulnerability of a building. For the reasons explained, its format does not need to follow the format of a conventional design method.

2 %NBS AS A STRUCTURAL PERFORMANCE METRIC

The method used to assess buildings in New Zealand entails the computation of the ratio of the estimated lateral strength of the building to that of a new building with similar characteristics built on the same site, known as "percent of new building standard" or "%NBS" (MBIE 2017). Buildings with %NBS values lower than 34% are considered to be "earthquake-prone". Few studies have, however, been conducted to gather empirical evidence supporting the effectiveness of %NBS as a robust metric to identify vulnerable buildings. Adequate studies have not been conducted specifically to evaluate the reliability of %NBS estimates relative to the cost of obtaining them, and to compare the effectiveness of %NBS with respect to alternative metrics.

(i) The differences between the objectives of design and assessment described above; *(ii)* the inherent subjectivity in prescribing inelastic demands in terms of forces (following a force-based assessment framework) rather than displacements; and *(iii)* the significant efforts entailed in estimating the "%NBS of a structure", warrant a systematic evidence-based review of the assessment procedure using %NBS. The authors polled a number of experienced engineers and researchers in New Zealand to gauge their perception of the %NBS metric and encountered a wide and diverging range of opinions. A common criticism was that different structural firms can produce widely different estimates of %NBS for the same building.

Figure 1 shows quantitative information extracted from reports by Beca (2011), Royal Commission (2020), and Kim et al. (2017) for buildings affected by the February 2011 Christchurch Earthquake. The y-axis represents the ratio of estimated cost of repair to total cost of replacement, which can be interpreted as a measure of the sustained damage. A loss ratio of 100% was chosen to represent the PGC and CTV buildings that collapsed during the earthquake. The x-axis represents reported %NBS values for the undamaged buildings, as they would have been computed before the earthquake. In cases for which ranges of ratios or indices were reported in the original sources, median values are plotted.

The lower points (corresponding to repair cost ratios smaller than 30%) indicate some degree of negative correlation, i.e. buildings with larger reported %NBS values required smaller relative repair costs on average. Although MBIE (2017) clearly states that %NBS is to be interpreted solely as an indicator of the likelihood of structural collapse, its observed correlation with incurred damage is not surprising. The points representing the PGC and CTV buildings, in particular, appear to be outliers to this trend because of the decision to plot them at a 100% repair cost ratio. Considering they collapsed and caused significant casualties, however, it is hard to argue that they should be plotted at a different ordinate. More importantly, both the PGC and CTV buildings are observed to possess %NBS values above 34%, indicating that they would not have been flagged as "earthquake-prone" buildings. This highlights the potential shortcomings of the %NBS metric. Recent updates to the procedures used to estimate values of %NBS may lead to better results, but that idea is yet to be tested in a systematic study.

The consequences of failing to correctly identify a seismically vulnerable building (false negatives) are typically a lot more dire than the consequences of incorrectly classifying a good building as structurally deficient (false positives). This suggests that the correct identification of vulnerable buildings should be a more important criterion in the evaluation of structural assessments methods, compared with the rate of false positives. To quote G. Howe (1936), who said in his 1936 study of lessons learned by Japanese structural engineers:

> *"Merely because a building has escaped injury in an earthquake is no guarantee that it is 'earthquake proof.' Only if it is known to have the necessary strength and stiffness can one be sure. It may only have been lucky. Not every soldier who goes into battle is hit. Because he escaped does not prove he was bullet proof."*

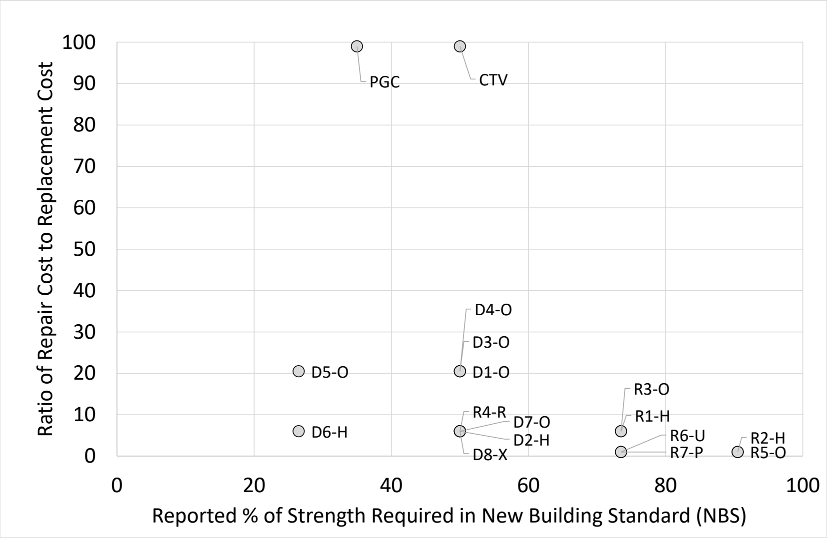

Figure 1: %NBS vs. repair cost ratio for selected Christchurch buildings under the February 2011 earthquake.

From this perspective, one could argue that the data in Figure 1 suggests that buildings with %NBS values below a higher threshold like 60% (not 34%) are likely to be critical and require attention, although the data available are not sufficient to make that claim with confidence yet.

A number of alternative metrics to quantify the vulnerability or fragility of a building, have been proposed in the literature. Song (2018), Skok (2014), and Puranam (2019) have evaluated and compared a number of these performance metrics. One of these metrics, known as the Hassan index, is described in the next section and shown to perform better than %NBS in a number of respects despite its relative simplicity.

3 THE HASSAN INDEX

The Hassan index was proposed by Hassan and Sozen (1997). It is a simple yet effective metric that has been calibrated against more than 1000 field observations from earthquakes in China, Haiti, Korea, Nepal, Peru, Taiwan, and Turkey (Sim et al. 2015). Computation of the Hassan index for an RC building requires only the most basic information about its structure: gross dimensions of floor areas and structural elements. The Hassan index (HI), which has also been called Priority index (PI), is computed as the sum of a column index (CI) and a wall index (WI), as shown in Equation 1. The CI and WI of a building are computed according to Equations 2 and 3 respectively.

$$HI = CI + WI \tag{1}$$

$$CI = \frac{\frac{1}{2}\sum A_c}{\sum A_f} \tag{2}$$

$$WI = \frac{\sum A_w + \frac{1}{10}\sum A_{mw}}{\sum A_f} \quad (3)$$

where $\sum A_\mathrm{c}$ represents the summation of cross-sectional areas of columns at the critical level, $\sum A_\mathrm{w}$ represents the summation of cross-sectional areas of RC structural walls at the critical level, $\sum A_\mathrm{mw}$ represents the summation of cross-sectional areas of infill masonry walls at the critical level, and $\sum A_\mathrm{f}$ represents the summation of floor areas above the critical level. The critical level of a building is the level that produces the smallest Hassan index. The critical level for most buildings occurs at the ground floor. WI is calculated individually for both principal floor-plan directions, and the smaller of the two values obtained is chosen as the WI of the building.

The Hassan index has been vetted by a series of studies including O'Brien et al. (2011), Zhou et al. (2013), Shah et al. (2017), Ozcebe et al. (2003), Villalobos et al. (2018), Sim et al. (2015), and Laughery et al. (2020). The data reported by Laughery et al. (2020) are summarised in Figure 2, where the CI and WI for the analysed buildings are plotted on the *x* and *y*-axes respectively, following conventional practice for these indices. Buildings observed to have experienced severe damage under the earthquake are represented by shaded circles. The study considered a building to be severely damaged if it experienced failure of at least one structural element, of the type shown in Figure 3.

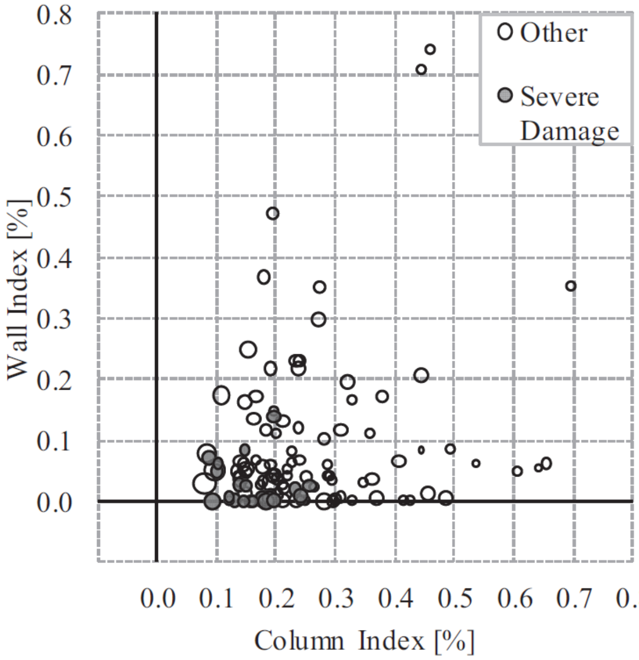

Figure 2: Column index, wall index, and severity of damage sustained by buildings in Taiwan during the 2016 earthquake (Laughery et al. 2020). The diameter of a circle is proportional to the number of stories in the building it represents.

Figure 3: An example of structural damage classified as severe by Laughery et al. (2020).

Studies such as Laughery et al. (2020) have also proposed classification boundaries, represented by lines with a negative slope on the CI-WI plot (as discussed in Section 4), to separate more structurally vulnerable buildings from the others. Nevertheless, a simpler interpretation of the Hassan index would be to prioritise the retrofit and strengthening of buildings lying closer to the origin of the CI-WI plot.

Data presented in the format used in Figure 2 can often be misleading because of circles representing buildings with severe damage overlapping and obscuring circles representing buildings without severe damage. Hence, the same data are also summarised in a bar chart in Figure 4, where the buildings are binned based on their CI + WI values. The chart clearly demonstrates that buildings with smaller CI and WI values plotted closer to the origin are more likely to be severely damaged.

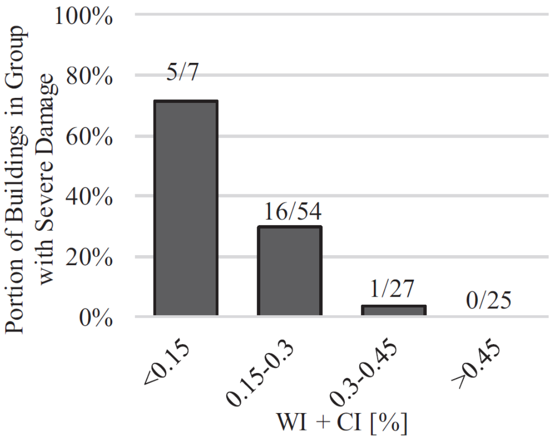

Figure 4: Variation of fraction of buildings with severe damage and relative distance to origin in WI-CI plot for buildings surveyed in Taiwan in 2016 (Laughery et al. 2020).

CI and WI can be interpreted as ratios of proxies for lateral strength and stiffness of a building to a proxy for its total mass, which—for short period buildings—would be affected by a nearly constant linear spectral acceleration demand. Hence, these indices are similar to %NBS in essence, although the computation of %NBS entails more complex estimates of seismic capacity and demand. The advantage of the CI and WI indices is their relative simplicity and the number of studies that have been previously conducted to verify them. Contrasting how little information is required to compute the CI and WI of a building against the complexity of the seismic performance assessment problem, the results presented here (and in the other studies listed above) are rather encouraging.

The Hassan index was originally conceived to assess low-rise buildings with no more than seven stories. Previous studies have demonstrated its performance in assessing buildings in countries such as Haiti, Nepal, and Turkey, in which relatively low quality of materials and workmanship have been reported; as well as buildings in Taiwan, which have higher overall quality (Laughery et al., 2020). Given this precedent, the Hassan index is considered suitable to assess older RC buildings in Christchurch and Wellington. The only caveat is that the buildings analysed in previous studies were mostly monolithic in nature and sufficiently redundant. The applicability of the index to New Zealand buildings with precast floors with insufficient 'seating' and lack of redundancy requires further examination.

4 ASSESSMENT OF CHRISTCHURCH AND WELLINGTON BUILDINGS

The writers have obtained limited but useful information describing the structural layouts of a number of pre-1970s RC buildings in Christchurch and the damage they sustained during the 2010-11 Canterbury earthquakes. The CI and WI values computed for seven of these buildings are plotted in Figure 5. Buildings that sustained severe damage or collapsed are plotted using dark circles. Tables 1 and 2 summarises the characteristics of these buildings, their computed CI and WI values, as well as any assumptions that were made when interpreting the available building information.

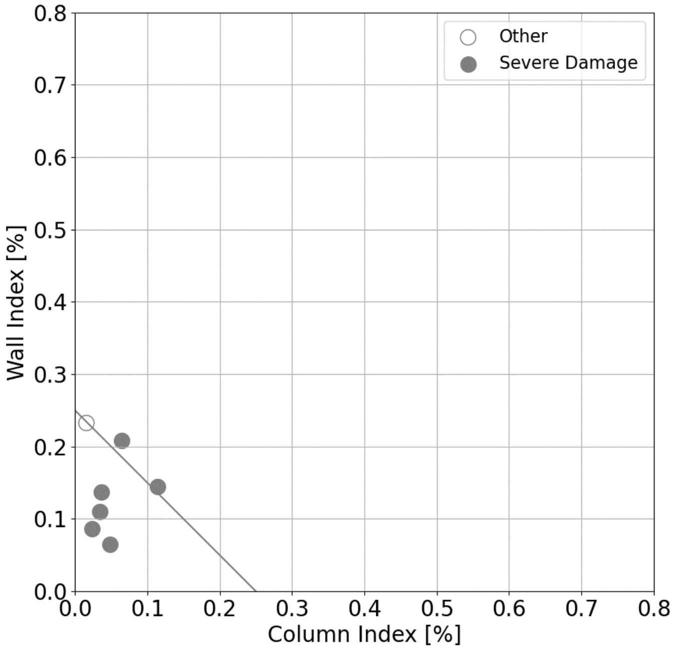

Figure 5: Column index, wall index, and severity of damage sustained by Christchurch buildings under by the 2010-11 Canterbury earthquakes.

The scarcity of the Christchurch building data plotted in Figure 5 is evident when compared with the Taiwan building data from Figure 2. Nevertheless, even the limited data in Figure 5 support the interpretation that buildings plotted closer to the origin of the CI-WI plot are more vulnerable to severe damage.

Analogous to the definition of "earthquake-prone" buildings as those with %NBS values lower than 34%, different boundaries could be envisioned on the CI-WI plot to separate the most vulnerable buildings from the others. Nevertheless, no boundary will be perfect on account of (i) the range of structural characteristics not considered in the computation of CI and WI; (ii) the uncertainty in the intensity of ground motions the buildings are likely to experience; and (iii) the uncertainty in the definition of the term "vulnerability". In reality, any boundary drawn to distinguish vulnerable buildings from others would also need to consider social, political, and economic factors. Alternatively, it would be prudent to envision a linear boundary with a negative slope and located close to the origin of the CI-WI plot that classifies buildings located closest to the origin as more vulnerable. This boundary could then be moved further away from the origin as the most critical buildings are gradually strengthened, as resources and political will become available, and as a function of the perceived local seismic hazard. Hassan and Sozen (1997) suggested the "domain" represented by Equation 4 to identify the most vulnerable buildings in a large inventory of old RC structures, which has been plotted in Figures 5 and 6.

$$CI + WI < 0.25 \tag{4}$$

The CI and WI values of the PGC and CTV buildings are computed to lie in the domain defined by Equation 4, which correctly classifies them as vulnerable buildings. This result suggests that the Hassan index can perform better than %NBS (as reported by the cited sources), which failed to classify the two buildings as "earthquake-prone." The CI and WI indices of buildings #1, #2, #3, and #5 in Table 1, that experienced severe damage, were also found to lie within or close to the domain that would correctly classifying them as more vulnerable.

In statistical terms, the Hassan index could be considered a simpler predictive model with a larger bias (lower accuracy), but a smaller variance (better precision). %NBS, on the other hand, would represent a more complex predictive model with a smaller bias (better accuracy), but a larger variance (lower precision). The variability in %NBS estimates reported by different structural firms assessing the same building is simply a reflection of its large variance. Conventional thinking often considers the more complex model to be superior because of its lower bias or better accuracy. Nevertheless, the statistically optimal model would be the one with the lowest bias and variance. In this case, the lower apparent bias and variance of the Hassan index despite its relative simplicity, renders it difficult to justify the continued use of %NBS as the sole basis to identify seismically vulnerable buildings, without sufficient supporting studies and evidence.

Structural plans were also obtained for a number of RC buildings in Wellington, most of which were built in the 1970s or before. CI and WI values computed for 13 of them are plotted in Figure 6. Additional information regarding these buildings is provided in Table 2. Seven out of the 13 buildings were found to lie within or at the boundary of the domain represented by Equation 4, indicating that they are likely to be more vulnerable. Although building #8, which was built in the 90s, might possess adequate detailing (a factor not considered in the computation of CI and WI that would make it less critical), the older buildings built in the 70s or earlier (buildings #6, #9, #11, #12, #15, and #18) are likely to be deficient. It would be considered prudent to alert occupants and prioritise these buildings for immediate attention. School buildings, in particular, should be addressed with urgency to avoid a repeat of the CTV building tragedy. The fact that 3 of these vulnerable buildings have already been retrofitted to some degree offers encouragement and lends support to the system of classifying buildings as "earthquake-prone" based on %NBS. Nevertheless, the failure of the %NBS metric (as reported by the cited sources) to classify correctly the PGC and CTV buildings in Christchurch as "earthquake-prone" indicates it has room for improvement. As mentioned before, recent updates to the methods used to estimate %NBS may yield more reliable results, but that is yet to be tested through a systematic review of observations from past earthquakes. In the meantime, it may be prudent to include the Hassan Index as part of current Initial Evaluation Procedures (IEP). The local seismic hazard could be considered in the assessment as suggested by Laughery et al. (2020).

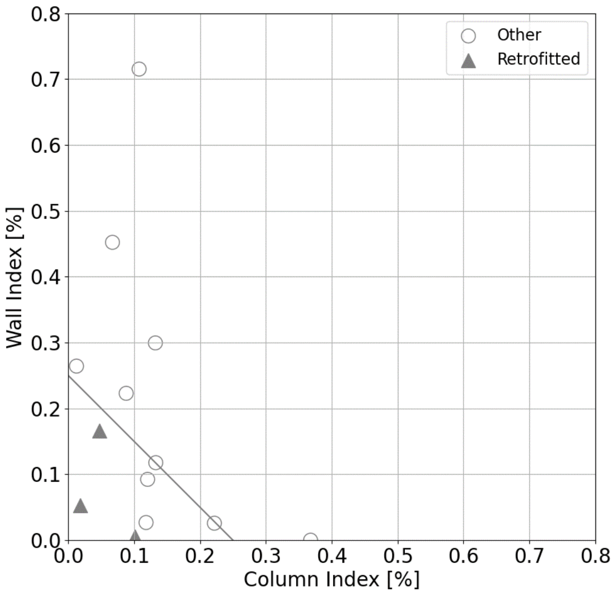

Figure 6: Column and wall indices of Wellington buildings.

5 CONCLUSION

%NBS (percent of new building standard) is the metric currently used to identify “earthquake-prone” buildings in New Zealand. The limited data analysed as part of this study indicate that the %NBS metric requires more systematic calibration before it can be used with confidence to identify the most vulnerable buildings from a large inventory of older buildings. In particular, published estimates of %NBS for the PGC and CTV buildings in Christchurch were observed to be greater than 34%, which indicates they would not have been classified as “earthquake-prone” before their collapse in the 2011 Canterbury earthquake. Recent updates to the procedures used to estimate %NBS may lead to more reliable results, but that is yet to be demonstrated though a systematic study.

The Hassan index is a simple metric that has been vetted and calibrated by a number of previous studies and shown to be able to identify effectively seismically vulnerable RC buildings. The Hassan index was computed for a number of older RC buildings in Christchurch and Wellington as part of this study, and it was shown to identify correctly the PGC and CTV as well as other buildings to be structurally deficient. Weighing the ease of computing this index against the quality of its results, it is suggested that this index be used as part of an Initial Evaluation Procedure to identify older RC buildings in Wellington that need to be prioritised for strengthening.

6 ACKNOWLEDGEMENTS

Eldhose Paulose was instrumental in the search for Christchurch building drawings and his help is greatly appreciated.

This project was (partially) supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. This is QuakeCoRE publication number 0656.

Table 1: Details of studied buildings in Christchurch.

ID	CI%	WI%	Floors above critical	Area (m^2)	Damage	Construction year	Retrofit	Location	Key assumptions
1	0.11	0.15	5 + Part. Floor	2203	Severe	Unknown	Unknown	Christchurch	Roof taken as half typical floor area.
2	0.06	0.21	8	2601	Severe	Unknown	Unknown	Christchurch	
3	0.03	0.11	4 + Part. floor	1713	Severe	1964	NA	Christchurch	Unconfined blockwork is taken with a coefficient of 0
4	0.03	0.23	5	2484	Other	Unknown	Unknown	Christchurch	Only exterior walls considered, not enough information obtained about interior walls. Plans for 2nd storey assumed typical.
5	0.03	0.11	7	3934	Severe	Unknown	Unknown	Christchurch	Walls with labels consistent with labels of columns and beams assumed to be RC. Public images indicate a floor was added.
CTV	0.04	0.14	5	3665	Collapse	1986	NA	Christchurch	
PGC	0.02	0.09	4 + Part. floor	3617	Collapse	1966	NA	Christchurch	

Notes: Wall openings (windows and doors) were ignored in calculations of wall cross-sectional areas. Masonry (of any type) was considered only if confined by RC elements along all edges. For curved walls and walls not parallel to either of the principal floor-plan axes, their projections along said axes were used to calculate WI. WI refers to the floor-plan direction associated with the smaller amount of wall.

'Part. floor' refers to a partial floor at the top of the building and with a floor-plan area smaller than the area of the typical floor plan.

Table 2: Details of studied buildings in Wellington.

ID	CI%	WI%	Floors above critical	Area (m^2)	Damage	Construction year	Retrofit	Location	Key assumptions
6	0.13	0.12	3	7863	NA	1960	Not Retrofitted	Wellington	
7	0.37	0.00	3	383	NA	1941	Not Retrofitted	Wellington	Thickness of walls assumed to be 0.25 m
8	0.02	0.05	6	2266	NA	1997	Retrofitted	Wellington	More modern building may have adequate detailing. Projections used for diagonal walls.
9	0.12	0.09	6	3083	NA	1965	Not Retrofitted	Wellington	
10	0.01	0.26	6	2014	NA	1964	Not Retrofitted	Wellington	
11	0.05	0.17	4	580	NA	1963	Retrofitted	Wellington	Masonry confined by frame included with coefficient of 1/10, unconfined ignored
12	0.22	0.03	5	1260	NA	1924	Not Retrofitted	Wellington	Confined brick masonry taken with a coefficient of 1/10, unconfined ignored
13	0.09	0.22	5	285	NA	1967	Not Retrofitted	Wellington	
14	0.11	0.72	5	292	NA	1967	Not Retrofitted	Wellington	
15	0.10	0.01	6	1955	NA	1972	Retrofitted	Wellington	Light steel framing on a small wall on each floor ignored
16	0.13	0.30	4	878	NA	1957	Not Retrofitted	Wellington	Approximated curved walls using projections
17	0.07	0.45	7	4979	NA	1967	Not Retrofitted	Wellington	
18	0.12	0.03	7 + Part. floor	4160	NA	1973	Not Retrofitted	Wellington	

Notes: Wall openings (windows and doors) were ignored in calculations of wall cross-sectional areas. Masonry (of any type) was considered only if confined by RC elements along all edges. For curved walls and walls not parallel to either of the principal floor-plan axes, their projections along said axes were used to calculate WI. WI refers to the floor-plan direction associated with the smaller amount of wall.

'Part. floor' refers to a partial floor at the top of the building and with a floor-plan area smaller than the area of the typical floor plan.

7 REFERENCES

Beca Carter Hollings & Ferner Ltd. (2011) "Investigation into the Collapse of the Pyne Gould Corporation Building on 22nd February 2011," Report for Department of Building and Housing (DBH), New Zealand.

Canterbury Earthquakes Royal Commission (2020) "Volume 6: Canterbury Television Building (CTV)," Report, Department of Internal Affairs, New Zealand.

Donmez C., and Pujol, S. (2005) "Spatial Distribution of Damage Caused by the 1999 Earthquakes in Turkey," Earthquake Spectra, Vol.21, No.1.

Hassan A.F., and M. A. Sozen (1997), "Seismic Vulnerability Assessment of Low-Rise Buildings in Regions with Infrequent Earthquakes," ACI Structural J., Vol.94, Issue 1.

Howe G. (1936) "Requirements for Buildings to Resist Earthquakes," U.S. Steel Products Co., New York.

Kim, J., Elwood K., Marquis F., Chang S., (2017) "Factors Influencing Post-Earthquake Decisions on Buildings in Christchurch, New Zealand," Earthquake Spectra, Volume 33, No. 2.

Laughery, L. et al. (2020), "Evaluation of Seismic Vulnerability Indices for Low-Rise Reinforced Concrete Buildings Including Data from the 6 February 2016 Taiwan Earthquake," Journal of Disaster Research Vol.15 No.1, 2020.

MBIE. (2017). The Seismic Assessment of Existing Buildings Part A: Assessment Objectives and Principles. Ministry of Business, Innovation, and Employment. www.eq-assess.org.nz

O'Brien, P., Eberhard, M., Haraldsson, O., Irfanoglu, A., Lattanzi, D., Lauer, S., and Pujol, S. (2011) "Measures of the Seismic Vulnerability of Reinforced Concrete Buildings in Haiti," Earthquake Spectra, Vol.27, Issue S1.

Ozcebe, G., Ramirez, J., Wasti, S.T., Yakut, A. (2003) "1 May 2003 Bingol Earthquake – Engineering Report," Report to U.S. National Science Foundation (NSF) and Scientific and Technical Research Council of Turkey (TUBITAK).

Puranam A., Irfanoglu A., Pujol S., Chiou TC. and Hwang SJ. (2019) "Evaluation of seismic vulnerability screening indices using data from the Taiwan Earthquake of 6 February 2016," Bulletin of Earthquake Engineering 17(4).

Shah, P., Pujol, S., Kreger, M., Irfanoglu, A. (2017) "2015 Nepal Earthquake," Concrete INternational, Vol. 39, No. 3.

Sim, C., Song, C. , Skok, N. , Irfanoglu, A. , Pujol, S., and Sozen, M. (2015) "Database of low-rise reinforced concrete buildings with earth-quake damage," https://datacenterhub.org/resources/ [accessed January 18, 2019].

Skok, N.R. (2014) "Evaluation of Collapse Indicators for Seismically Vulnerable Reinforced Concrete Buildings," MS Thesis, Purdue University.

Song, C. (2018) "Collapse Assessment of Vulnerable Reinforced Concrete Structures under Earthquakes," PhD Thesis, Purdue U.

Sozen M.A. (2014) "Surrealism in Facing the Earthquake Risk," in: Ilki A., Fardis M. (eds) Seismic Evaluation and Rehabilitation of Structures. Geotechnical, Geological and Earthquake Engineering, Vol 26. Springer.

Villalobos E., Sim C., Smith-Pardo JP., Rojas P., Pujol S. and Kreger ME. (2018) The 16 April 2016 Ecuador earthquake damage assessment survey. Earthquake Spectra 34(3).

Zhou, W., Zheng, W., and Pujol, S. (2013) "Seismic Vulnerability of Reinforced Concrete Structures Affected by the 2008 Wenchuan Earthquake," Bulletin of Earthquake Engineering, Vol.11, Issue 6.