Benchmarking FEMA P-58 performance predictions against observed earthquake data – A preliminary evaluation for the Canterbury earthquake sequence

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ABSTRACT: The Federal Emergency Management Agency (FEMA) in the United States has produced the P-58 guidelines for seismic performance assessment of buildings. This Performance-Based Seismic Assessment procedure aims to quantify earthquake ground shaking, structural demands, component damage and resulting consequences in a logical framework in order to facilitate risk assessment and decision making by a number of stakeholders. The 2010-2011 Canterbury earthquake sequence, and the resulting extensive data sets regarding damaged buildings that were collected, provide a unique opportunity to exercise and evaluate the P-58 guidelines. This paper provides an overview of the authors' methodology to perform such an evaluation, and presents preliminary results from the calculations. Much work remains to critically evaluate these results and to broaden the scope of buildings studied and of impacts predicted. This paper documents some of the key approaches and data sources that will facilitate these next steps.

1 INTRODUCTION

We present preliminary results from an effort to predict performance of buildings in the Christchurch area from the 2010-2011 Canterbury earthquake sequence. Damage and loss predictions are made using the FEMA P-58 methodology (FEMA 2012a), which utilizes detailed predictions of structural response and component-level damage in order to assess impacts. This performance-based assessment approach offers great advantages in that it can explicitly link building properties to potential seismic risk, and it can provide assessments for new construction types without past data regarding their seismic performance (Moehle and Deierlein 2004). There are a number of alternative methods for building loss assessment, such as HAZUS (Kircher et al. 2006) and ATC-13 (Rojahn and Sharpe 1985). These methods are not well suited to handling specific properties of buildings.

While the component fragility functions and the structural response predictions have been calibrated and validated in a number of ways, it is difficult to validate the entire end-to-end prediction. The 2010-2011 Canterbury earthquake sequence provides a valuable set of data on which to calibrate building-level predictions. The M6.2, 22 February 2011 earthquake in particular caused significant damage to buildings in Christchurch, and significant disruption to organisations operating in those buildings.

As such, the post-earthquake data collected regarding damage, losses, and organizational disruption provide a unique opportunity to perform loss estimation validations (Elwood et al. 2015; Fleischman et al. 2014; Lin et al. 2012, 2014).

2 FEMA P-58 ANALYSIS

The FEMA P-58 analysis methodology combines ground motion hazard, structural response and component damage predictions in order to make predictions of building performance under earthquake loads (Figure 1). The calculation approach produces estimates of repair costs, repair times, the number of injuries and fatalities, and the potential for an unsafe placard to be placed on the building. All outputs are in the form of probability distributions, reflecting the substantial uncertainty in these predictions. These output metrics were specified because they facilitate cost-effective risk management decisions when evaluating design of new buildings or risk management actions for existing buildings. The assessment process was developed with assistance from engineering practitioners and researchers, and with input from stakeholder groups including commercial real estate investors, insurers, lenders, attorneys, and architects (FEMA 2012a).

This assessment approach is becoming more common in design and evaluation of buildings worldwide, and has recently been adopted as part of a new building rating system in the United States (www.usrc.org, City of Los Angeles 2015).

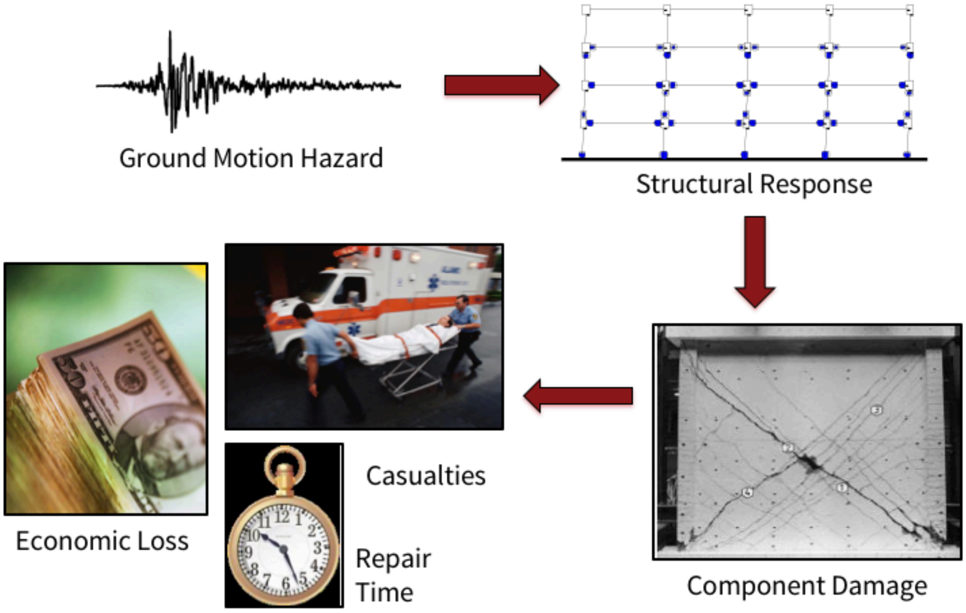

Figure 1: Components of the P-58 analysis methodology (figures courtesy Curt Haselton and Ron Hamburger).

3 BENCHMARKING METHODOLOGY

Figure 2 illustrates the general process used in this benchmarking exercise. Building characteristics and estimates of ground shaking are inputs to a P-58 calculation that then predicts repair costs and repair times. Those predictions are then compared to survey data collected after the earthquakes, which is treated as a benchmark here. The following subsections describe the utilized data in more detail.

3.1 Building characteristics

Building characteristics are derived from the Canterbury Earthquake Building Assessment, CEBA, database (Lin et al. 2014) that includes and joins the rapid damage assessment undertook by Christchurch City Council for assessing the occupational safety (for all types of buildings as Level 1 and Level 2 assessments, depending on the accessibility) and the Detailed Engineering Evaluation (DEE) collected by the Canterbury Earthquake Recovery Authority, CERA, specifically for commercial and multi-storey residential buildings. DEEs include detailed information on the structural characteristics and design of the building, on the condition of the site and on the level and extent of the earthquake-induced damage sustained. A shapefile including the floor footprint area for each building was provided by Christchuch City Council and joined with the CEBA database via GIS.

Data fields currently used in loss predictions are:

- Age of Building
- Building First-Mode Vibration Period

- Building Type and Lateral System (e.g., reinforced concrete shear wall)
- Number of Stories Above and Below Ground
- Floor Footprint Area

The FEMA P-58 approach requires detailed information regarding the contents of the building. For each type of component (e.g., structural components, partitions, mechanical equipment), the type and quantity of component on each floor is needed. These details are estimated by the SP3 software, based on the building characteristics fields specified in the previous paragraph; the building age, occupancy type and building type constrains the type of contents likely to be in a building, and the size of the building constraints the quantity of materials.

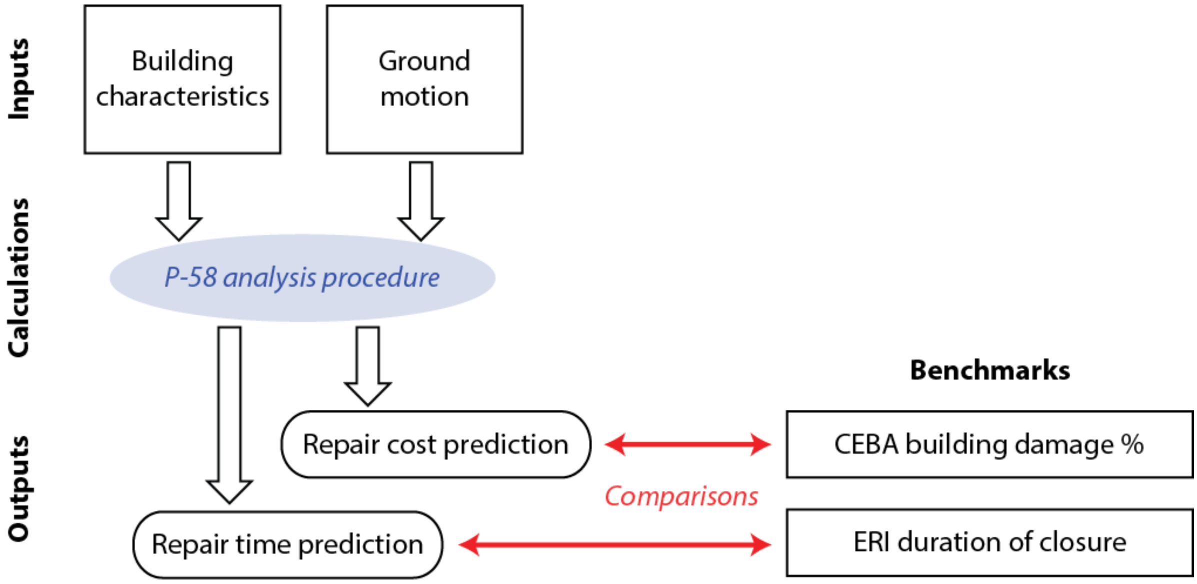

Figure 2: Process used for benchmarking evaluations. Rectangles are inputs to the analysis, the ellipse is the P-58 calculation, and rounded rectangles are outputs from the P-58 calculation.

3.2 Ground motion

The ground motion at each building location during the M6.2, 22 February 2011 Christchurch earthquake is estimated from Bradley (2012). That study used 19 strong motion recordings in the Christchurch area, and empirical ground motion predictions that account for distance to the earthquake and local site conditions, to make a prediction of shaking throughout the region. Ground motion intensity is quantified via response spectra, and for each location of interest the spectral acceleration at the building's first mode period and the peak ground acceleration (PGA) are used to predict building damage. Estimated ground motion from the 4 September 2010 Darfield earthquake is also available and will be used to predict performance of the same buildings in ongoing work.

3.3 P-58 analysis procedure

3.3.1 *Structural response predictions*

Structural response predictions are made using the simplified method approach of FEMA P-58. The structural system and building height are used to estimate an elastic deflected shape for the building under earthquake excitation, and the building period and estimated yield strength are used to estimate the magnitude of displacements and accelerations that the building is predicted to see under the specified ground motion.

3.3.2 *Component damage and repair costs*

For each component specified to be in the building, fragility data is taken from the P-58 component fragility database (FEMA 2012b). This database specifies the damage states that a given component can take, the demand parameter (e.g., displacement or acceleration) that predicts that damage, and provides a fragility function for predicting occurrence or exceedance of that damage state. Also included in the fragility database are predictions of the cost and amount of time it would take to repair that damage. Costs and repair times are specified in the form of probability distributions, and the costs and repair times scale with the number of damaged components to reflect that per-unit costs will decrease if a greater number of units require repair. Component fragility and repair cost data is based primarily on United States construction data, and applicability to New Zealand construction will be evaluated as the project progresses.

3.4 **Repair cost and repair time outputs**

The FEMA P-58 methodology utilizes a Monte Carlo procedure to simulate realizations of all the above analysis stages, in order to capture uncertainties at each stage. To quantify building-level repair costs, the component-level repair costs are summed. To quantify building-level repair times, a more complex aggregation is performed. Repair times can be computed using P-58 by assuming that repairs on each floor take place in parallel (so that the longest-time-to-repair floor governs the building repair) or to occur one floor at a time. Additionally, a more complex repair and recovery time calculation, following the REDi procedure (Arup 2013), is performed. These simulations, and the final aggregation of results, is performed here using the SP3 software tool.

3.5 **Benchmarks**

The CEBA database includes a field estimating the percentage building damage, collected during Building Safety Evaluation (tagging) procedures. These ratios reflect the extent of building volume damaged rather than the repair cost as a percentage of the building value (Bocchini et al. 2015), but they are used in this initial study as an imperfect proxy for repair cost.

The Economics of Resilient Infrastructure, ERI project (Seville et al. 2014) captured survey data from 541 organisations from across Greater Christchurch, between July and December 2013, approximately two and a half years after the February earthquake. The survey captured information on more than 200 different variables including organisation demographics, impact measures, pre-event mitigation measures, post-event business changes, adaptation measures, and financial information. Organisations included belonged to one of 17 industry sectors and covered a range of business sizes, ages, organisational ownership structures, and locations (Brown et al. 2015). In this initial study we are using the organization's duration of closure as a benchmark to compare the repair time predictions, though there are opportunities for much more refined analysis of this data in future stages of the work.

4 **PRELIMINARY RESULTS**

While the loss assessment work is ongoing as the input data is refined and the calculation outputs are evaluated, a few preliminary results are presented here to indicate the types of loss metrics available and the evaluations that can be performed. Results are shown here for a sample of 10 buildings near the Christchurch CBD (see Figure 3). These buildings all had reasonably complete information regarding their characteristics, and also had tenants who participated in a survey on business disruption as part of the ERI project (Seville et al. 2014).

Figure 4 shows a comparison of the FEMA P-58 predictions of mean repair costs versus CEBA building damage for the sample buildings with relevant data available. While the comparison metrics are not exactly aligned and there are a number of significant limitations with the analysis, there is some correspondence between predictions and results. In addition to a total building repair cost metric, the P-58 analysis also produces breakdowns of repair cost by component type (e.g., structural components, partitions, mechanical equipment) as well as collapse and residual drift; these breakdowns are being studied and will also be evaluated versus corresponding fields from the CEBA database describing the various types of damage observed in each building.

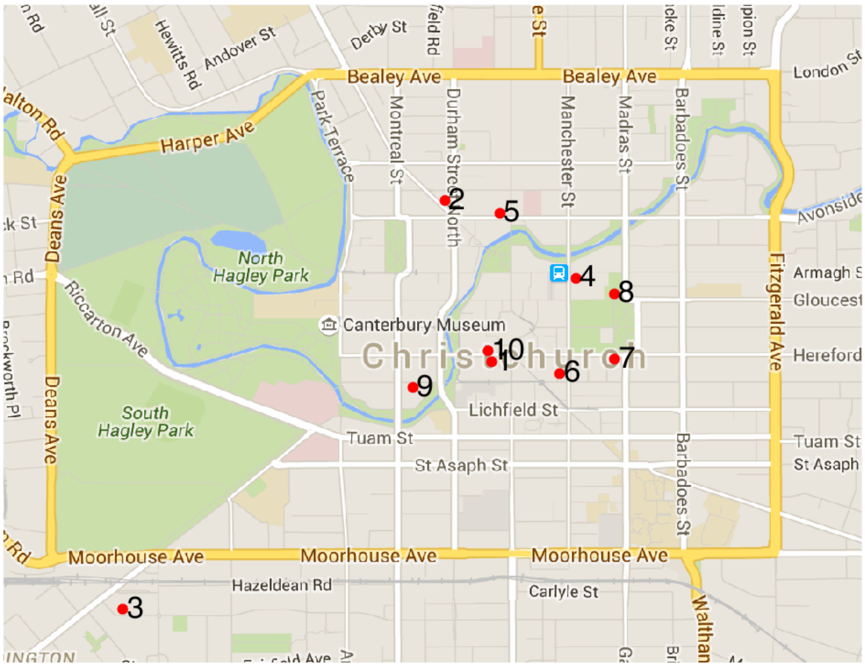

Figure 3: Map of the Christchurch Central Business District, and locations of ten example buildings considered here.

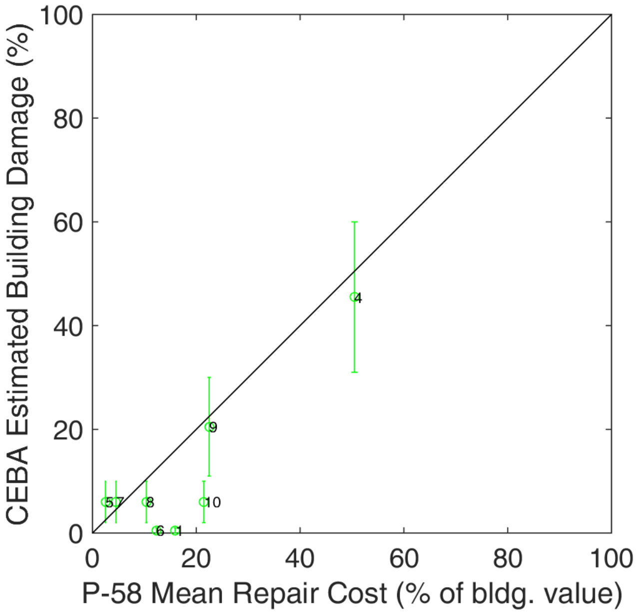

Figure 4: FEMA P-58 predictions of mean loss given the M6.2, 22 February 2011 earthquake ground motion, plotted versus CEBA estimated damage. Units are repair costs as a percentage of total building value. Vertical axis values of the plotted circles are the midpoints of the reported range, and error bars indicate the extent of the range. Horizontal axis values indicate the mean repair cost prediction from P-58 (i.e., the variability in predictions is not reflected).

Figure 5 shows a comparison of recovery time predicted using FEMA P-58 and REDi, versus duration of closure times reported by organizations in the ERI survey. We note that there are a number of buildings with large predicted recovery times but small ERI closure times—this is generally because the organizations in those buildings were able to relocate and resume operations prior to their original building being repaired; future analysis will address this discrepancy that results from the inconsistent comparison metrics.

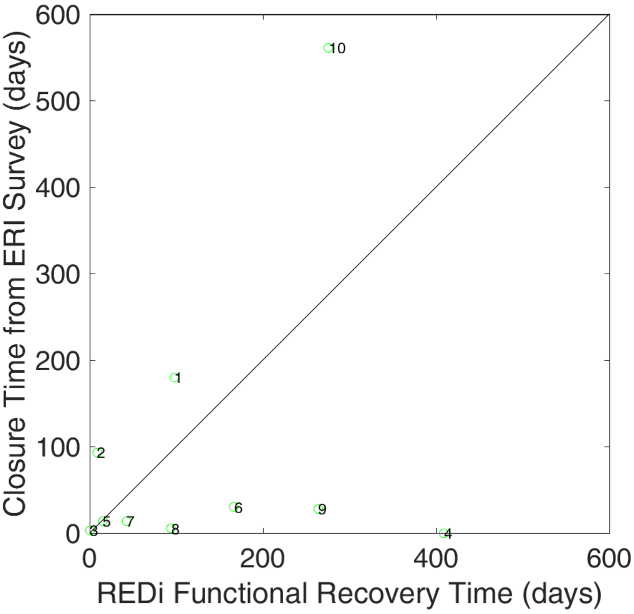

Figure 5: Predictions of mean functional recovery time given the M6.2, 22 February 2011 earthquake ground motion, plotted versus ERI closure time.

There are a number of limitations to the results presented above. A few key limitations are (1) The repair cost predictions do not consider effects of liquefaction, which will be significant in some cases, and have very limited treatment of building collapses. (2) The recovery time predictions do not consider important effects such as location within the CBD cordon and organizations that relocated to other buildings. (3) Uncertainties in both the P-58 predictions and the survey data benchmarks is not being treated rigorously and comprehensively.

Given the limited information used to the produce the performance predictions, the mismatches between predicted and benchmark metrics, and the above analysis limitations, the degree of correspondence of predictions and benchmarks in Figures 4 and 5 is reasonable. As the calculations are refined and additional dimensions of the data are explored, we are optimistic that we will find a number of interesting insights regarding the P-58 prediction methodology and regarding the relationship between building properties and seismic performance.

5 CONCLUSIONS

Preliminary results have been shown from an effort to use the FEMA P-58 seismic loss assessment methodology to predict damage and repair costs to buildings under the M6.2, 22 February 2011 Christchurch earthquake. Building properties are used to populate models and predict damage, and the predictions are then compared to evaluations of the buildings and tenant organizations after the earthquake.

Preliminary results from a small subset of buildings indicates that the P-58 predictions are generally consistent with observed data. Moving forward, the authors will perform more comprehensive evaluations on a larger set of buildings, and will continue to collect relevant data from any parties willing and able to share them. The results have the potential to provide insights about the degree to which the P-58 predictions quantify the impact of building-specific properties.

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