# An Enhancement of Earthquake Vulnerability Models for Australian Residential Buildings Using Historical Building Damage

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## ABSTRACT

Geoscience Australia (GA) has developed the Earthquake Risk Model (EQRM) as an open source software for probabilistic earthquake hazard and risk assessment. In the EQRM, earthquake vulnerability models for HAZUS building types are defined with finer subclasses to account for Australian residential building types. An example is the subclass representing a timber framed building with timber walls and a tiled roof. This study aims to determine new building parameter values of earthquake vulnerability models in the EQRM for the Australian residential timber and low-rise unreinforced masonry (URM) buildings using building damage data from two damaging earthquakes: $M_L$ 5.6 Newcastle (1989) and $M_L$ 5.0 Kalgoorlie (2010). The Newcastle damage data is compiled from insurance claim data, from which the economic loss ratio, the ratio of repair cost to replacement cost, is estimated for timber buildings and low-rise URM buildings. The Kalgoorlie damage data is compiled from a detailed population based survey led by GA, from which the economic loss ratio is estimated for low-rise URM buildings. In both instances the loss ratio data is matched to felt ground shaking intensity (Modified Mercalli Intensity). The compiled building damage data are then used as a reference to determine parameter values for the selected building types. The new vulnerability models for the selected building types are compared with the current models, and the effect of the modifications is highlighted and discussed in scenario impact assessments for a building portfolio in Newcastle, Australia.

**Keywords:** EQRM, Vulnerability model, Unreinforced masonry building, Timber building

## INTRODUCTION:

The vulnerability model is a key component of an earthquake risk assessment along with exposure data and a hazard model. The vulnerability models are used to estimate the likelihood of physical damage states and the economic loss at a certain ground shaking intensity (e.g., peak ground acceleration). The models defining the likelihood of physical damage states are often called fragility models. The earthquake vulnerability models are generally developed using analytical models, empirical building damage data or through a heuristic process relying upon expert judgment. Regardless of how the models are developed, empirical data from damaging earthquake events provide the best opportunity to validate and/or refine the existing vulnerability models.

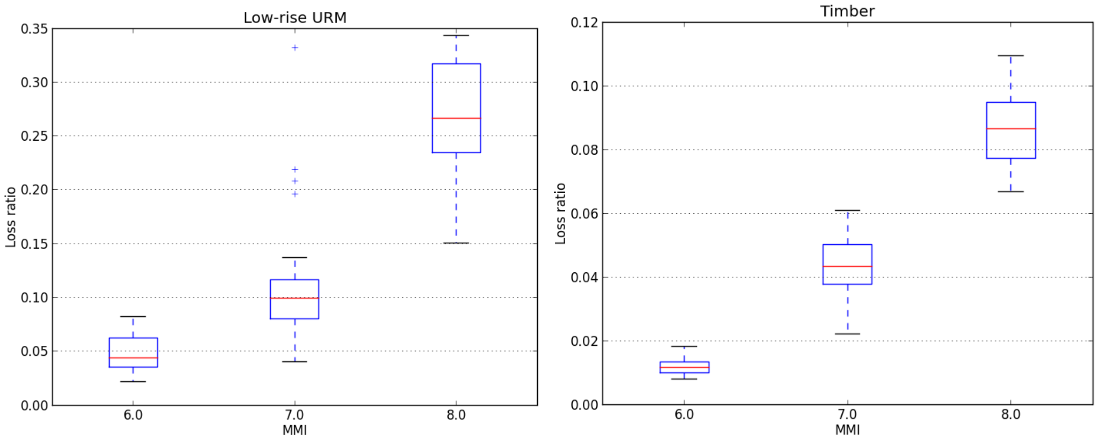
The earthquake vulnerability models for Australian residential buildings are defined in the Earthquake Risk Model (EQRM), which is an open source software for probabilistic earthquake hazard and risk assessment developed by Geoscience Australia (GA) (Robinson et al., 2005). The vulnerability models for Australian residential buildings in the EQRM were initially defined and used to simulate economic loss for the 1989 Newcastle earthquake and the simulated results were found to be consistent with actual economic loss due to the event (Fulford et al., 2002). Since then the models have been further used to perform earthquake risk assessment for major cities in Australia (Sinadinovski et al., 2005). However the building parameter values have not been rigorously reviewed and the vulnerability models have not been compared with either empirical data or models of other countries.

This study aims to enhance the vulnerability models for Australian residential timber and low-rise URM buildings using building damage data from two damaging earthquakes: $M_L$ 5.6 Newcastle (1989) and $M_L$ 5.0 Kalgoorlie (2010). The Newcastle damage data is compiled from insurance claim data, from which the economic loss ratio is estimated for timber buildings and low-rise URM buildings (Maqsood and Edwards, 2013). The Kalgoorlie damage data is compiled from a detailed population based survey led by GA, from which the economic loss ratio is estimated for URM buildings (Edwards et al., 2010). In both instances the loss ratio data is matched to felt ground shaking intensity (Modified Mercalli Intensity). The compiled building damage data are then used as a reference to determine parameter values for the selected building types. The new vulnerability models for the selected building types are compared with the current models, and the effect of the modifications is highlighted and discussed in scenario impact assessments for a building portfolio in Newcastle, Australia.

## BUILDING DAMAGE DATA:

Building damage data are compiled from two damaging earthquake events in Australia: $M_L$ 5.6 Newcastle (1989) and $M_L$ 5.0 Kalgoorlie (2010).

The Newcastle damage data is compiled from insurance claim data, from which the economic loss ratio is estimated for two building types: timber buildings and low-rise URM buildings. Since the insurance claim data does not contain any geospatial information except the name of the suburb, the loss ratios for each building type are averaged at each suburb. Similarly associated ground shaking intensity is estimated by spatial averaging the felt MMI at each suburb (IEAust, 1990) and then rounded to the nearest MMI. Figure 1 shows boxplots of the estimated loss ratios of low-rise URM and timber buildings at three different MMI values. The box denotes the interquartile range between the first and third quartiles, and the line within the box denotes the median; whiskers denote the lowest and highest values within 1.5 times interquartile range from the first and third quartiles, respectively. Not surprisingly, low-rise URM buildings are found to have suffered more damage than timber buildings.



(a) Low-rise URM buildings (b) Timber buildings

Figure 1. Loss ratio of buildings from the Newcastle event

Following the Kalgoorlie earthquake (20 April, 2010) GA led a collaborative population-based survey to capture detailed information on the performance of older unreinforced masonry buildings that were significantly affected by the event. The survey captured detailed information on building attributes and the extent of damage regardless of whether damage was sustained or not. The felt intensity was also assessed using non-damage related metrics where possible, which was greatly assisted by interview of building occupants who were present at the time of the event. The collected building damage data was subsequently combined with costing information to estimate a loss ratio for each building surveyed. Figure 2 shows a boxplot of loss ratio of URM buildings from Kalgoorlie damage data at two MMI values. It is not surprising to see wider spread in Kalgoorlie than Newcastle given the fact that Newcastle data is aggregated at each suburb while Kalgoorlie data is at individual building level.

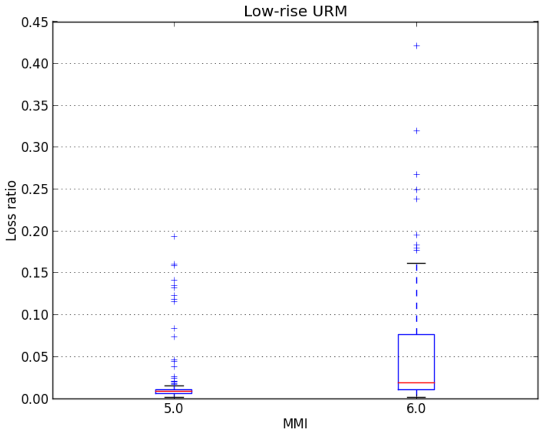


Figure 2. Loss ratio of low-rise URM buildings from the Kalgoorlie event

To determine parameter values of vulnerability models in the EQRM, mean loss ratios were chosen as point estimates from the building damage data as summarised in Table 1. Note that the mean loss ratios of URM buildings at MMI 6 from the two events are close to each other.

Table 1. Mean loss ratio estimated from the two historical building damage data

| | MMI 5 | MMI 6 | MMI 7 | MMI 8 |
|---|---|---|---|---|
| Low-rise URM (Newcastle) | - | 0.047 | 0.110 | 0.270 |
| Low-rise URM (Kalgoorlie) | 0.019 | 0.062 | - | - |
| Timber (Newcastle) | - | 0.012 | 0.043 | 0.085 |

## VULNERABILITY MODELS IN THE EQRM:

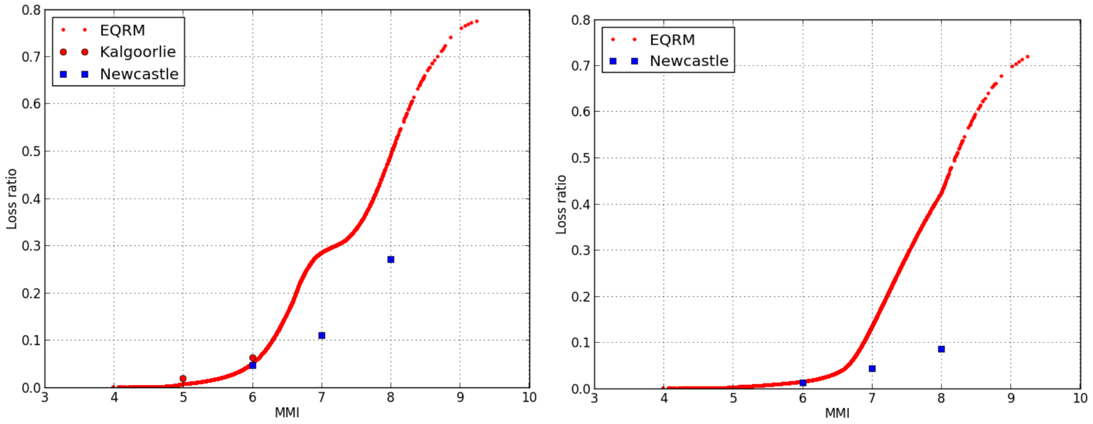
As of this writing there are two ways of defining vulnerability models in the EQRM: the first is to input parameter values required for an engineering approach primarily based on the capacity spectrum method, and the second is to directly input MMI-based vulnerability models.

In the engineering approach, the building response is computed using the capacity spectrum method applied to a generalised Single-Degree-Of-Freedom (SDOF) model of the building, which is similar to the HAZUS methodology (NIBS, 2003). The computed building response is subsequently used in computing the likelihood of physical damage states and the economic loss associated with three building components: structural, non-structural drift-sensitive and non-structural acceleration-sensitive. The total loss is estimated as the sum of the loss of each component. While both the HAZUS methodology and EQRM use the capacity spectrum method, there are key differences between the demand spectra used. HAZUS scales a generalised spectral shape similar to design spectrum for each earthquake event, whereas EQRM uses a response spectrum predicted from the selected ground motion model(s) for the event. This would lead to differences in predicted building responses.

In the EQRM, earthquake vulnerability models for HAZUS building types are defined with finer subclasses to account for Australian residential building types. For example, five subclasses are defined for Australian timber frame buildings based on the combination of wall and roof materials (e.g., W1TIMBERTILE represents timber frame building with timber walls and tiled roof). The parameter values for the Australian buildings were determined primarily from engineering judgment with reference to parameter values provided by HAZUS and some experimental data.

Because both sets of building damage data do not have detailed information about wall and roof materials, in this study we determine new parameter values for vulnerability models of URMLMEAN (low-rise URM with any wall and roof materials) and W1MEAN (timber frame with any wall and roof materials) defined in the EQRM.

A large number of ground motions are simulated using the Toro et al. (1997) ground motion model for a scenario event of $M_W$ 5.6 and Joyner-Boore distance 10km. In this study a single set of magnitude and distance is used along with mean capacity curves of the buildings and no site amplification to get smooth vulnerability curves for the buildings. For the ground-motion-to-intensity conversion the equation derived by Atkinson and Kaka (2007) is used. For each simulation the loss ratio is computed. Figures 3(a) and 3(b) show the computed current vulnerability curves for URMLMEAN and W1MEAN respectively. It is clear that the current vulnerability models predict higher than the actual loss for intensities greater than MMI 6.



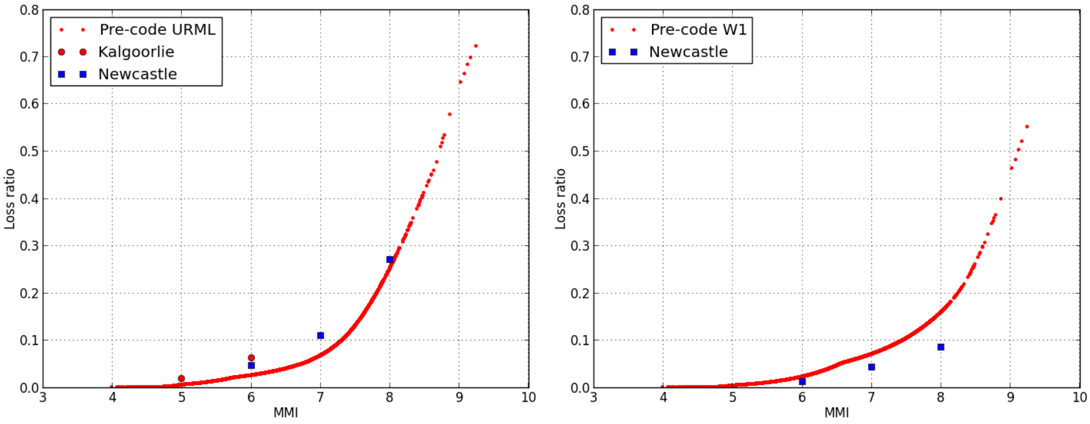
(a) URMLMEAN (b) W1MEAN

Figure 3. Computed vulnerability curves using the current parameter values

## DETERMINATION OF NEW PARAMETER VALUES OF THE VULNERABILITY MODELS:

Because more than twenty parameters are used to compute damage outcomes in the EQRM, there can be numerous combinations of parameter values that fit vulnerability models to the reference data. We focus on the parameter values of capacity curves and damage state thresholds while keeping the values of other parameters constant. This study does not attempt to adjust parameter values to provide a mathematical best-fit model to the reference data. Instead values of the selected parameters are adjusted by trial-and-error until the computed vulnerability curve visually matches the empirical data overall. Note that the calibration of vulnerability model in the EQRM is subject to the following selections: 1) ground motion model(s) 2) ground-motion-to-intensity conversion equation 3) magnitude and distance of the scenario event 4) site amplification 5) uncertainty in ground motions 6) uncertainty in the capacity curves of buildings. The resulting parameter values determined for the vulnerability models would differ for different selections of the aforementioned inputs into the process which seeks to match empirical loss observations.

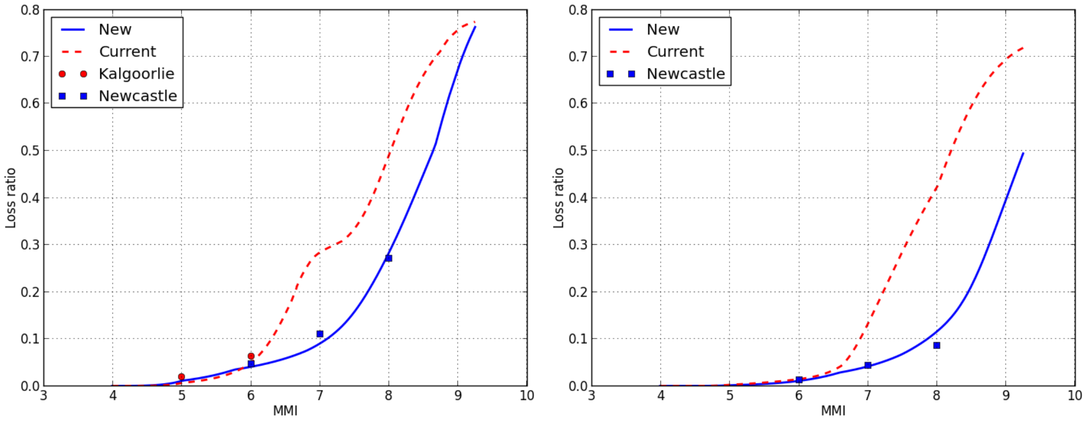
First we compute vulnerability curves of HAZUS building types corresponding to the URMLMEAN and W1MEAN, which are pre-code URML (non-seismically designed low-rise URM buildings) and pre-code W1 (non-seismically designed wood light-frame buildings), respectively in the HAZUS building classification. Figure 4 shows the computed vulnerability curves along with the building damage data. The vulnerability curve of pre-code URML predicts lower than the building damage data on average, while pre-code W1 predicts higher than the data. Nevertheless they are closer to the reference data than the corresponding Australian models thus the capacity parameter values of the HAZUS building types were adopted for the Australian residential buildings.



(a) Pre-code URML (b) Pre-code W1

Figure 4. Comparison of computed vulnerability curves of HAZUS building types with the building damage data

Because the contribution of the non-structural acceleration sensitive component to the total loss ratio is the largest where a large discrepancy exists in Figure 4, parameter values of the damage state thresholds of non-structural acceleration sensitive components are adjusted by trial-and-error until the computed vulnerability curve agrees well to the reference data overall. For URMLMEAN the damage state threshold values of HAZUS building type pre-code URML are decreased to push the vulnerability curve up to the reference data. Similarly the threshold values of the HAZUS building type pre-code W1 are increased to pull the vulnerability down for W1MEAN. Figure 5 shows the adjusted vulnerability curves for the two building types along with the building damage data.



(a) URMLMEAN (b) W1MEAN

Figure 5. Comparison of the current and new vulnerability curves for Australian residential buildings with the building damage data

## EFFECT OF NEW VULNERABILITY MODELS TO PORTFOLIO RISK:

To illustrate the effect of the new vulnerability models, a portfolio of buildings in Newcastle is created with a slight modification from the portfolio used for the Newcastle earthquake risk assessment (Fulford et al., 2002). All subclasses of low-rise URM buildings are changed to URMLMEAN, and all subclasses of timber buildings are changed to W1MEAN, which results in 4175 of W1MEAN and 725 URMLMEAN buildings in the portfolio.

Two scenario events are considered: $M_W$ 5.35 (the same as the estimated magnitude of the Newcastle event) and $M_W$ 6.5. Median ground motions are generated for the two scenario events and the economic loss for each building is computed. The MMI range within one standard deviation from the mean is from 5.4 to 6.2 for the $M_W$ 5.35 and from 7.9 to 8.3 for the $M_W$ 6.5 scenario event, respectively. Table 2 summarises computed loss ratios for the building portfolio from the two scenario events. For the $M_W$ 5.35 event the difference of loss ratio between the current models and the new models is not large, mainly because of the similarity between the two models at the estimated MMI range (see Figure 5a). For the larger magnitude event the difference between the two models is significant because of the dominance of timber buildings in the portfolio and large difference between the current and new models at higher intensities of shaking (see Figure 5b). For more severe earthquakes with stronger ground motions the reduction in predicted losses between current and the new models will be greater as can be expected from the change in the vulnerability relationships at stronger shaking. It follows that the use of the new models will result in lower predictions of earthquake risk for communities comprised of these buildings.

Table 2. Estimated loss ratio for the building portfolio from the two scenario events

| | | Low-rise URM | Timber | All |
|---|---|---|---|---|
| Scenario event ($M_W$ 5.35) | Current models | 0.074 | 0.021 | 0.026 |
| | New models | 0.042 | 0.017 | 0.020 |
| Scenario event ($M_W$ 6.5) | Current models | 0.362 | 0.494 | 0.479 |
| | New models | 0.230 | 0.079 | 0.095 |

## CONCLUSIONS:

New parameter values are determined for the vulnerability models of two Australian residential building types (W1MEAN and URMLMEAN) using the compiled data from two recent historical damaging events in Australia. The effect of the new vulnerability models is illustrated in the risk assessment of a building portfolio in Newcastle where a noticeable difference is observed for a large magnitude scenario event. New vulnerability models can be used as reference curves to adjust other vulnerability models for Australian residential buildings, which will be implemented in future revisions of the EQRM.

## ACKNOWLEDGEMENT:

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