Damage, Death and Downtime Risk Attenuation in the 2011 Christchurch Earthquake

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ABSTRACT: Following a catastrophic earthquake, 3d (damage, death and downtime) rapid estimates of the extent and severity of losses are desperately needed in order to better aid in post-event response and recovery. A quantitative risk analysis approach is advanced to investigate the 3d loss types for typical New Zealand construction as exemplified by the Redbook building for the 2011 Christchurch earthquake. The results are presented in terms of attenuation curves which show that within the central business district: the expected loss ratio (related to insurance claims) is about 50% of the asset value; the expected chance that someone is killed is 5%; and the expected downtime is 1-year. However, considerable uncertainties also exist, thus one can only be 90% confident that these results will not be higher than: 100% damage, implying collapse is a distinct possibility; 10% chance of fatalities, implying there may also be some deaths and possibly significant injuries; and 2-year downtime due to reconstruction demand surge. These salutary results demonstrate that in spite of structures being well-engineered, *downtime* in particular is unacceptably large. Two methods can be used to solve this problem: to make the structure slightly stronger and more robust through damage avoidance design.

1 INTRODUCTION

Historically, engineers have principally aimed at ensuring life-safety through collapse-prevention due to earthquakes. However, over many years of research and more recently in practice, partial damage, death and downtime losses are gradually being taken into consideration as they turn out to contribute a significant portion of the overall earthquake-induced losses, especially when one considers equivalent monetary value. In this research, the general four-step quantitative risk analysis approach of Mander and Sircar (2011) is extended from the general “all-hazard” based loss model to an earthquake-specific or “scenario-based” 3d loss model.

The well-known “Redbook Building” is considered to be an exemplar of the state-of-the-practice for good structural design in New Zealand (CCANZ, 1998). This building, which is based on using reduced design strength along with ductile detailing, is adopted as the basis for conducting a 3d seismic risk analysis. It will be shown that significant damage can be expected when subjected to the Christchurch earthquakes. Some deaths may also be expected. But it is the downtime that is most worrying aspect, as this is proving to be most undesirable from a building owner’s standpoint. Therefore, three alternative design scenarios are explored and discussed. The first of these is to merely make the building stronger to defray the onset of damage. The second maintains the existing strength, but employs Damage Avoidance Design (DAD) details. While both of these aforementioned strategies are shown to make some improvements in performance along with the reduction in damage, it is finally demonstrated that what is really needed are buildings that are both stronger and have better (damage avoidance) performance attributes.

2 “SCENARIO-BASED” 3d LOSS MODEL

Recently, Mander and Sircar (2011) developed a quantitative risk analysis approach for the loss estimation of structures. The approach develops an equation-based inter-relationship using a four-step procedure between (a) seismic hazard; (b) structural response; (c) damage; and (d) loss. In this research, the "all-hazard" based analysis of Mander and Sircar (2011) is extended to a "scenario-based" risk analysis method. It is well known that for any given specific earthquake there exists an "attenuation relationship" that relates the shaking intensity with respect to the distance to the earthquake's epicentre. Such an attenuation relationship can be substituted into the Mander and Sircar (2011) theory. As shown in Figure 1, the "scenario-based" four-step risk analysis consists of: (a) hazard-intensity attenuation modelling; (b) structural analysis; (c) damage analysis; and (d) loss-attenuation estimation.

Figure 1 shows that each of the four steps are essentially linear when plotted in log-log space. Therefore, a single compound equation may be written to express the interconnection between each of the four graphs.

$$\frac{L}{L_r} = \left|\frac{\theta}{\theta_r}\right|^{c} = \left|\frac{S_a}{S_{ar}}\right|^{bc} = \left|\frac{R}{R_r}\right|^{-abc} \qquad (1)$$

in which r = a reference (scenario) earthquake event; L = a loss ratio; θ = structure drift, an engineering demand parameter (EDP); S_a = spectral acceleration, an intensity measure (IM); R = radial distance from the epicentre of the earthquake; and a, b, c and d are the slopes shown in the four graphs in Figure 1, these are interrelated such that $d = -abc$.

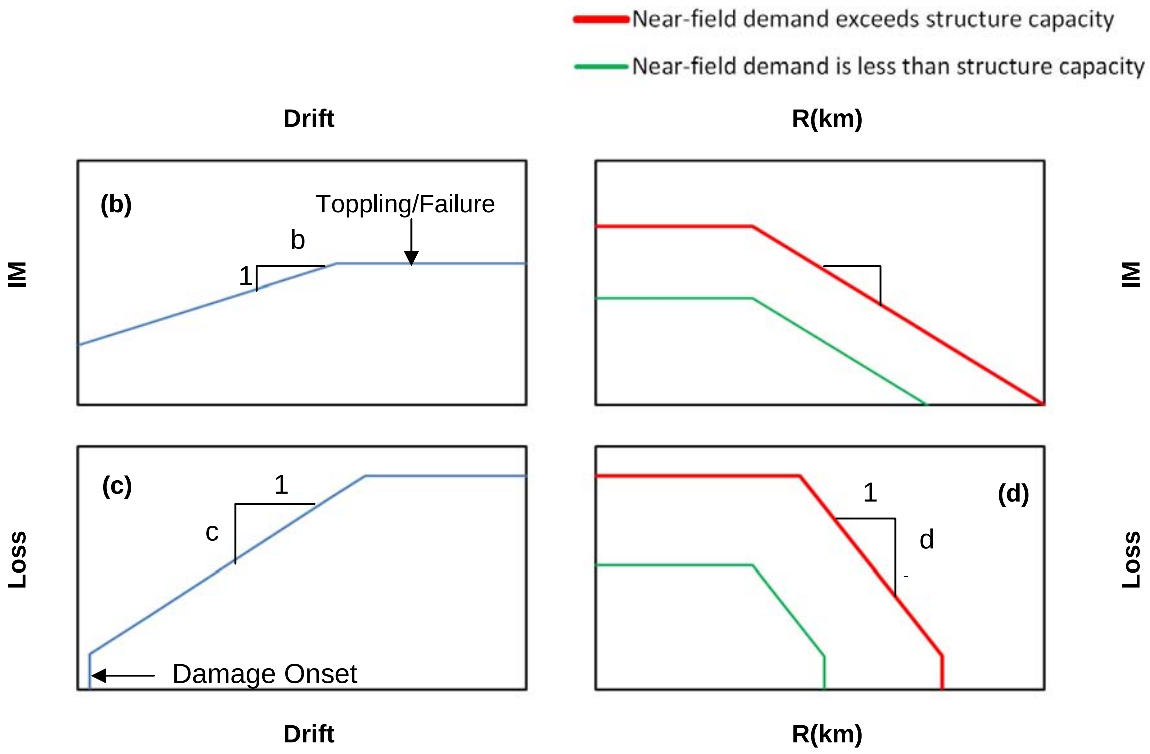

Figure 1: "Scenario-based" 3d Loss Model: (a) seismic hazard intensity-attenuation model; (b) structural analysis; (c) damage analysis; and (d) loss-attenuation estimation

In the first step, instead of associating the intensity measures with annual frequency as Mander and Sircar (2011) proposed, a simple attenuation relationship is proposed that relates the intensity measure with the radial distance from the earthquake epicentre. In the second step, the response of the structure which is exposed to different levels of ground shaking is predicted. In the third step, the structural drift is related to the damage losses. In the fourth step, damage or other losses (such as death and downtime) at a certain radial distance from the earthquake epicentre are modelled.

It should be noted that earthquakes in the near-field (approximately < 8 km) may impose seismic demands that are either greater than the capacity of the structure, or less than the structural toppling/failure capacity, as depicted in Figure 1. This input (in Figure 1a) affects the outcome, as shown in Figure 1d.

2.1 **“Scenario-based” Physical Loss Model**

The model for calculating the physical damage loss ratio is:

$$\frac{L}{L_c} = \left|\frac{\theta}{\theta_c}\right|^c ; L_{on} \le L \le L_u = 1.3 \tag{2}$$

where L_c = unit loss, which taken as the monetary value of the structure under steady-state (non-disaster) pricing, or as L_c = 1.0 for comparative (unit-price) studies; θ_c = structure drift at the onset of complete collapse; L_{on} = physical loss ratio at the onset of damage state 2; θ_{on} = structure drift at the onset of damage 2; and L_u = physical loss ratio at the complete collapse of structure, $L_u > 1$ with a suggested median value $L_u = 1.3L_c$ presumes a 30% post-event price surge.

2.2 **“Scenario-based” Death Loss Model**

Fault and Event trees are used to analyse the probability of death loss arising from building damage due to the earthquake. The value of the slope in the damage analysis was calibrated using the fault and event trees, and is taken as c = 2.6 as proposed in Ghorawat (2011). The model for calculating the probability of death loss is:

$$\frac{DL}{DL_c} = \left|\frac{\theta}{\theta_c}\right|^c ; DL_{on} \le DL \le DL_u = 0.75 \tag{3}$$

where DL_c = probability of death loss at the onset of complete damage, which is generally taken as DL_c = 0.1 (Mander and Elms 1994); DL_{on} = probability of death loss at the onset of damage; DL_u = probability of death loss of complete damage, which is normally taken as DL_u = 0.75, assuming the maximum occupancy of a building is 75%.

2.3 **“Scenario-based” Downtime Loss Model**

Guided by earlier studies (Mander and Basoz, 1999; and Ghorawat, 2011) a downtime loss model is proposed as

$$\frac{DT}{DT_c} = \left|\frac{\theta}{\theta_c}\right|^c ; DT_{on} \le DT \le DT_u = 150 \tag{4}$$

where DT_c = the downtime at the onset of complete damage; DT_{on} = the downtime at the onset of damage; and DT_u = the downtime at complete damage, which is taken as DT_u = 150 (weeks).

2.4 **Uncertainty and Randomness**

Consider the uncertainty and randomness in the seismic demand and in the establishment of the model, β is used to represent the dispersions through which the median values could be transformed to other fractiles. The dispersion of all combined uncertainty and randomness β_T is given (Kennedy et al. 1980) using the following expression:

$$\beta_T = \sqrt{\beta_D^2 + \beta_U^2 + \beta_C^2} \tag{5}$$

where β_D accounts for the variabilities in demand; β_U accounts for the uncertainty in modelling, which is taken as β_U = 0.25; and β_C accounts for the variabilities in structure capacity, which is taken herein as β_C = 0.2. Further, to account for the overall dispersion in loss with respect to the radial distance from the epicentre, it can be shown that:

$$\beta_{L|R} = \sqrt{\beta_{UL}^2 + c^2 \cdot \beta_T^2} \tag{6}$$

where β_{UL} = 0.35 is assumed to account for the uncertainty in loss (Mander and Sircar, 2011).

3 3d LOSS MODEL CONSIDERING SPATIAL DISTRIBUTION OF LOSSES

A commonly adopted conservative assumption is that the damage of a building is uniformly distributed over the entire height. Thus a "Maximum Loss Model" is defined as:

$$\frac{L_{\max}}{L_c} = \max\left(\left|\frac{\theta_i}{\theta_c}\right|^c\right) \tag{7}$$

$$\left|\frac{\theta_{\max}}{\theta_c}\right| = \left|\frac{L_{\max}}{L_c}\right|^{1/c} \tag{8}$$

where L_{max} = maximum 3d loss ratio; θ_{max} = maximum structure drift in the structure; and θ_i = structure drift of the i^{th} storey.

As buildings become taller, the conservative assumption that the maximum loss is spread equally over all storeys can lead to a substantial overestimation of total loss. This is because the most severe damage tends to be concentrated within a few floors, typically the lower storeys. Deshmukh (2011) developed a method to address this issue and proposed an "Average Loss Model". This requires the calculation and summation of the loss at each storey of the building and then averaged over the entire height of the building, as follows:

$$\frac{L_{avg}}{L_c} = \frac{\sum_{i=1}^{n} \theta_i^c}{n \cdot \theta_c^c} \tag{9}$$

$$\theta_{avg} = \left(\sum_{i=1}^{n} \frac{\theta_i^c}{n}\right)^{1/c} ; \theta_{\max} \le \theta_c \tag{10}$$

where L_{avg} = average 3d loss ratio (for physical damage loss, $L_{avg} \le 1.0$; for death loss, $DL_{avg} \le 0.1$; and for downtime loss, $DT_{avg} \le 75$); n = total number of storeys of the building; and θ_{avg} = average structure drift in the structure.

In reality, neither the maximum loss model, nor the average loss model will hold universally true for all potential earthquake shaking intensities. For example, under stronger shaking if only one storey is near collapse, then insurers will condemn the entire structure in spite of most other storeys being in pristine condition. This is a case where building replacement is necessary and thus the maximum loss model is applicable.

Therefore, a proposed new loss model is developed by combining the maximum and the average loss models to give a composite conditional loss model. For physical *damage* loss, the proposed model is expressed in terms of whether the building is repaired or replaced as follows:

- The building is *repaired* when:

$$L_{eff} = L_{avg} \quad (L_{on} \le L_{\max} < 1.0) \tag{11}$$

- The building is *replaced* when:

$$L_{eff} = L_{\max} \quad (1.0 \le L_{\max} \le L_u) \tag{12}$$

where L_{eff} = the effective physical damage loss ratio for the proposed physical damage loss model.

Similarly, for the *death* loss, the proposed model is expressed as:

$$DL_{eff} = DL_{avg} \quad (DL_{on} \le DL_{\max} < 0.1) \tag{13}$$

$$DL_{eff} = DL_{\max} \quad (0.1 \le DL_{\max} \le DL_u) \tag{14}$$

where DL_{eff} = the effective probability of death loss for the proposed death loss model.

And for the *downtime* loss, the proposed model is expressed as:

$$DT_{eff} = DT_{avg} \quad (DT_{on} \le DT_{\max} < 75) \tag{15}$$

$$DT_{eff} = DT_{\max} \quad (75 \le DT_{\max} \le DT_u) \tag{16}$$

where DT_{eff} = the effective downtime loss for the proposed downtime loss model.

Other variables to represent the key coordinates in the proposed loss model are calculated by

$$R_{rr} = R_r \left| \frac{L_{rr}}{\overline{L}_r} \right|^{1/d} \tag{17}$$

$$L_{rl} = \overline{L}_r \left| \frac{R_{rr}}{R_r} \right|^{d} \tag{18}$$

where R_{rr} = radial distance from the epicentre of the earthquake corresponding to the 3d loss ratio L_{rr} (for physical damage loss, $L_{rr} = 1.0$; for death loss, $DL_{rr} = 0.1$; for downtime loss, $DT_{rr} = 75$), note that this distance separates repair and replacement outcomes; L_{rl} = 3d loss ratio of the average loss model corresponding to the radial distance from the epicentre of the earthquake R_{rr}.

4 RESULTS AND IMPLICATIONS

From the “scenario-based” 3d loss models, the losses at a certain radial distance from the earthquake epicentre can be easily determined. The well-known 10-storey reinforced concrete “Redbook Building” (CCANZ 1998) was selected as the exemplar structure in this research. The “scenario-based” 3d loss models were implemented for the “Redbook Building” based on the 22 February 2011 Christchurch earthquake. Compared to the maximum loss model, the estimated 3d losses based on the “scenario-based” 3d loss models, considering spatial distribution of damage losses over the height of the buildings, are considerably smaller.

The 3d loss model results show that for the standard “Redbook Building”, within the central business district taken as some 17 km radial distance away from the earthquake epicentre: (i) the expected physical damage loss ratio is about 50% of the asset value; (ii) the expected probability of killing someone is about 3%; and (iii) the expected downtime is 6 months. Considering the randomness and uncertainties, one can have 90% confidence that the losses will not be higher than: (i) 100% physical damage loss ratio; (ii) 5% of probability of death loss; and (iii) 1-year of downtime loss.

When considering the spatial distribution of losses, the analysis results show that for the standard “Redbook Building”, at a 17 km radial distance from the earthquake epicentre: (i) the physical damage loss is about 20%; (ii) the probability of death loss is only 0.7%; and (iii) the downtime loss is about 2 months. Compared to the maximum loss model, it is observed that the estimated losses are significantly reduce when considering spatial distribution of damage over the height of the structure.

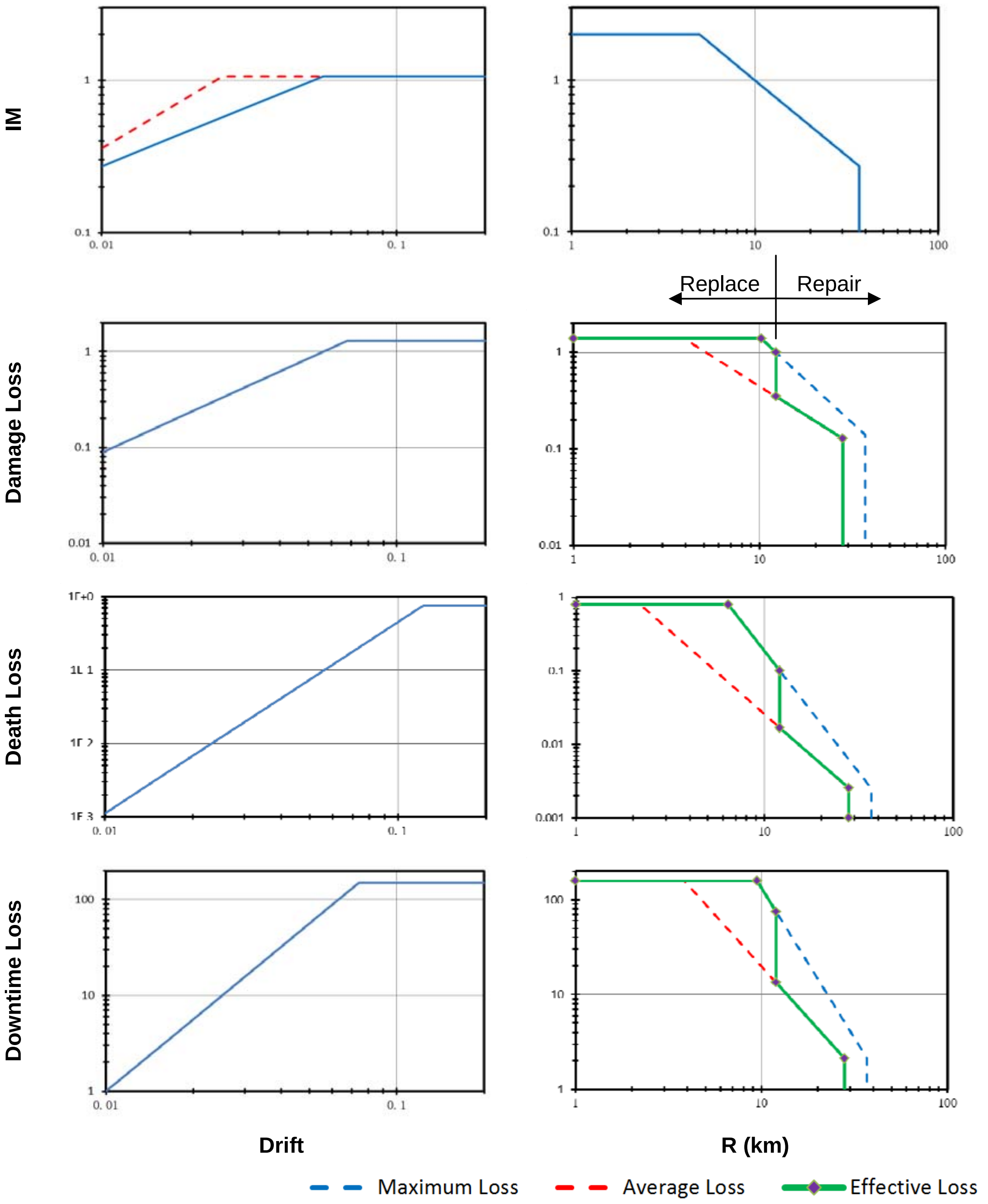

Figure 2: Proposed 3d loss model for standard "Redbook Building"

5 DISCUSSION: WHAT CAN BE DONE TO AMELIORATE LOSSES?

In monetary terms it has been shown that the *downtime* loss is the most significant loss compared to the physical *damage* loss and *death* loss (Ghorawat, 2011). It is therefore necessary to take downtime loss more seriously into consideration in the pre-event analysis and design. To investigate how one might ameliorate losses, and in particular minimize downtime by design, a sensitivity (swing) analysis has been performed. The Cases considered consist of:

(a) Making the building 30% stronger (this degree of strengthening is in keeping with the proposed increase in the seismic hazard for Christchurch);

(b) Making the building more deformable and as damage-free as practicable, without making the building stronger. Using the Damage Avoidance Design (DAD) armouring details along with re-centering attributes as proposed in various recent studies by Rodgers et al. (2008, 2012) and Solberg et al (2008).

(c) A combination of Cases (a) and (b) above.

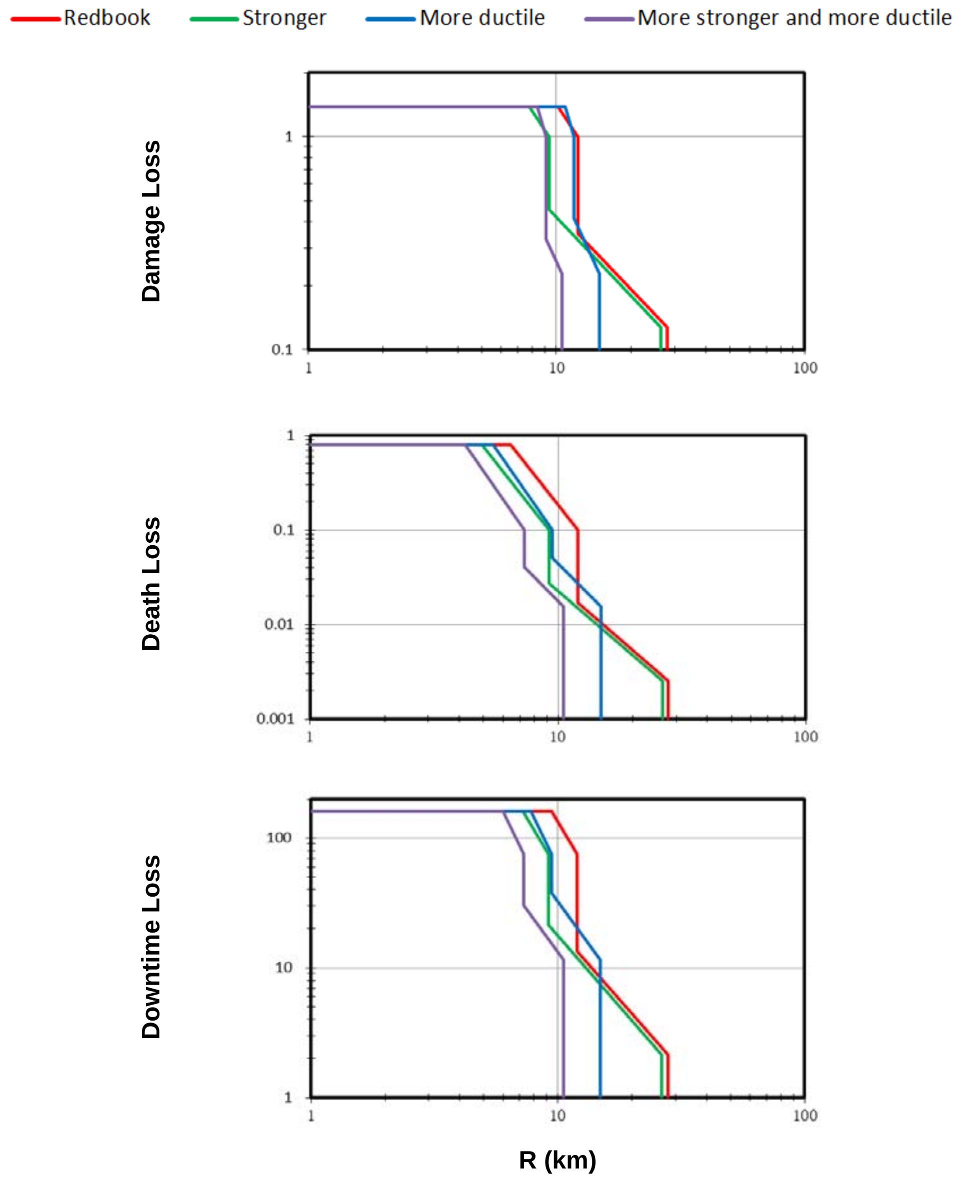

Figure 3: Proposed 3d loss model results for different buildings

Results of this swing analysis are presented in Figure 3. When compared with the "Redbook Building" as the benchmark, one can observe that for Case (a) the stronger building: (i) the physical damage loss ratio declined to about 20%; (ii) the probability of death loss reduces to 0.4%; and (iii) the downtime loss is about 1 month. The values indicate that the building with a stiffer construction can clearly decrease the damage losses, especially the downtime loss. For Case (b), the more ductile building, the 17 km radial distance from the earthquake epicentre is just at the onset of the damage loss area, which means that no damage is done to the building is possible. However, at distances closer than 17 km complete damage requiring replacement is not really improved. For Case (c), where the building is both strengthened and detailed to avoid damage, both replacement and repairs are reduced.

The swing analysis indicates that a stronger building will help inhibit collapse and thus reduce replacement losses, but repairs are still required at moderate distances from the epicentre (R > 9 km). A more deformable (DAD) construction is evidently more effective in reducing the repair losses, but under severe shaking replacements may still be necessary; there is no substitution for strength when complete toppling/collapse/replacement is concerned.

However, the more ductile building is noticeably more effective in decreasing the earthquake inflicted damage and almost eliminates the need for building repairs. Therefore, to reduce the need for both *replacements* and *repairs*, structures need to be respectively made both *stronger* and *more deformable* (with DAD details). The stronger and more ductile building can achieve the best performance and have the minimum 3d losses compared to the other three types of buildings.

For the case of modifying the “Redbook Building” by increasing the strength by 30 percent, plus altering the connections to armoured DAD details, all damage beyond 10 km from the epicentre can theoretically be eliminated. To reduce this entirely the building would need to be made stronger again.

6 CONCLUSION

By making a building stronger by design, the need for complete replacement is reduced, but damage and thus repairs along with the inevitable downtime can still be expected. Conversely, by making a building more deformable, the need for repairs will be reduced, but toppling or complete failure will only be eliminated if the building is also made stronger.

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