BUILDING DAMAGE, DEATH AND DOWNTIME RISK ATTENUATION IN EARTHQUAKES

A Thesis

by

YINGHUI HUANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	John B. Mander
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ABSTRACT

Building Damage, Death and Downtime Risk Attenuation in Earthquakes.
(May 2012)
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Whether it is for pre-event prevention and preparedness or for post-event response and recovery of a catastrophic earthquake, estimates of damage, death and downtime (3d) losses are needed by engineers, owners, and policy makers. In this research, a quantitative "scenario-based" risk analysis approach is developed to investigate the 3d losses for buildings. The "Redbook Building" is taken as the typical New Zealand construction exemplar and analyzed for the 22 February 2011 Christchurch Earthquake. Losses are presented in the form of attenuation curves that also include the associated uncertainties. The spatial distribution of 3d damages over the height of buildings is also considered. It is thus shown that it is possible to discriminate between losses that lead to building replacement versus less severe losses that require structures to be repaired.

The 3d loss results show that within the Christchurch city (17 km radial distance from the earthquake epicenter): (a) the expected physical damage loss ratio is about 50% of the property value; (b) the expected probability that someone is killed or seriously injured is about 4%; and (c) the expected downtime for the building being out of service is about 24 weeks. However, when considering various uncertainties, one can have 90% confidence that these loss estimations will be as high as: (a) complete loss (100% physical damage), implying structure has a great chance of collapse; (b) 8% possibility of fatality, implying deaths and significant injuries are likely; and (c) 1-year downtime due to post-event reconstruction demand surge. These informative results demonstrate that even though structures, such as the "Redbook Building", may have been well designed and constructed to contemporary standards, significant damage can still be expected and the downtime loss is particularly large. In order to solve this problem, new building structures should ideally be built stronger, include recentering attributes, and use Damage Avoidance Design (DAD) armoring connection details.

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1. INTRODUCTION

1.1 Motivation and Scope

Damage to constructed facilities, death or injury to occupants and downtime due to repairs or replacement of structures (the 3d losses) when aggregated form the total direct losses arising from a catastrophic earthquake. This thesis investigates the quantification of those losses for multistory buildings using a scenario-based risk framework. It should be noted that indirect losses that affect communities and economies also result, but these are outside the scope of this work. Nevertheless, after a district is struck by a catastrophic earthquake, the estimation of the 3d losses resulting from that event is desperately needed for the overall community response and recovery. In this research, based on the framework of the general “all-hazard” four step risk analysis approach (Mander et al. 2012), a quantitative “scenario-based” 3d loss model is herein developed to explore this issue.

It is well known that for each earthquake there is an attenuation relationship between the ground shaking intensity and the distance from the earthquake epicenter. This research postulates that a similar loss attenuation relationship with respect to the radial distance from the earthquake epicenter can be developed for damage, death and downtime (3d) losses. First, the thesis develops the theory for the estimation of 3d losses. Second, the February 22, 2011 Christchurch (NZ) earthquake ground motions are applied for the “Redbook Building” (CCANZ 1998). Third, a sensitivity study in the

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This thesis follows the style of *Journal of Structural Engineering*.

form of a swing analysis is performed by considering three different types of building alternatives: a 30% stronger model, a more ductile model, and a both stronger and more ductile model. The 3d losses are presented in the form of attenuation curves and associated uncertainties are also included.

In order to consider the spatial distribution of 3d damages over the height of buildings, a proposed "scenario-based" 3d loss model is advanced to combine the "Maximum Loss Model" and the "Average Loss Model'' and is implemented on the "Redbook Building" and the other three derived buildings to investigate the 3d losses. It is thus shown that it is possible to discriminate between losses that lead to building replacement versus less severe losses that require structures to be repaired.

The swing analysis results are also discussed to study the effects of different building enhancements on the repair and replacement losses respectively. It is revealed that the 30% stronger building leads to a decrease in the replacement demands; the DAD armoring detailed building has much less repair costs; and built with strengthening design and DAD construction, the structure can have improvements in reducing both repair and replacement losses and theoretically, buildings beyond the edge of the city (17 km) can almost eliminate the chances of being damaged. Clearly, what is really needed in practice is a building that combines both stronger and more deformable performance attributes.

This thesis is composed of four sections. Following this introductory section in which a literature review is presented, the second section develops the "scenario-based" 3d loss model theory. In the third section the loss modeling approach is refined by taking the spatial distribution of losses over the height of a given building. Finally, the fourth section presents a summary, specific conclusions and recommendations for further research and application for professional practice.

1.2 Literature Review

1.2.1 Background Literature

Natural hazards can impose sudden shocks to the built environment. In catastrophic events structures are damaged and people may suffer risk to life and limb. Following the catastrophic event there are periods of response and recovery. Historically, the extent of damage to constructed facilities has been a prime concern for engineers. Therefore, Dhakal and Mander (2006) proposed a general methodology to estimate the expected annual financial losses due to any natural hazards. This approach is presented by analyzing the seismic financial loss of a highway bridge and it explains the risk in the form of monetary values which can be easily understood by both engineers and other members of the community.

Mander et al. (2012) developed a general quantitative four-step risk analysis approach to estimate the direct damage losses of structures. The four steps are: (a) hazard analysis; (b) structural analysis; (c) damage analysis; and (d) loss estimation. Through this process, the natural hazards can be related to the structure response and to the losses with various uncertainties and post-event price surge taken into consideration. The calculation of the expected annual loss (EAL) was also presented. Using this approach to estimate losses, case studies were conducted to compare the losses of different bridge piers designed to Caltrans, Japan and New Zealand specifications and one bridge to emerging damage avoidance design (DAD) methods.

Historically, life-safety through collapse prevention of structures has been a primary goal of engineers in catastrophic events, such as earthquakes. However, more recently it has been realized that considering life-safety by considering collapse-prevention alone is insufficient. Nowadays, damage, death and downtime losses are gradually becoming the focus of a more comprehensive seismic loss analysis framework. Downtime and business interruption contribute to a significant part of overall seismic losses, especially when aggregated as equivalent financial values. Ghorawat (2011) extended the four-step risk analysis approach to a death loss model and a downtime loss model for highway bridges. Seismic losses of bridges designed according to California and New Zealand specifications were investigated under the 3D loss estimation method. Results showed that the death loss and downtime loss are both greater than the direct physical damage loss; and the downtime loss is especially large, which needs to be paid more attention to and taken more seriously in the future of structural design. It was also demonstrated that DAD details along with recentering design attributes can significantly minimize the 3D seismic damages.

Generally, the seismic damage to a building is considered to be distributed uniformly over the entire height of the structure. This conservative assumption provides an upper-bound and therefore may be termed a “Maximum Loss Model”. However, this is impractical, especially for tall buildings, whose damage is mostly concentrated in lower floors, and often limited to the 1st or 2nd floors. Therefore, to obtain a more realistic result, it is necessary to take the spatial distribution of seismic damages over the height of a building into consideration. Thus, an “Average Loss Model” was proposed by Deshmukh (2011). His approach aggregates the losses of each story to obtain the total damage losses and then averages them to the total number of stories in the building to get the equivalent damage loss of each story. However, the “Average Loss Model” also has disadvantages, since for the most severely damaged stories, the actual damage may be more severe than the averaged equivalent losses; therefore, some stories may collapse without showing this possibility in the “Average Loss Model”.

Deshmukh (2011) used the commercial software SAP2000 to establish building models to analyze the building damage and financial losses for the suites of earthquakes with the incremental dynamic analysis (IDA) method. The building model selected was the 10-story reinforced concrete “Redbook Building” (CCANZ 1998). The ground motions used by Vamvatsikos and Cornell (2002) were applied in that research also and were normalized to spectral acceleration equals to 1g at 1 second of the natural period for 5 percent of damping.

In this research, the four-step quantitative seismic risk analysis approach developed by Mander et al. (2012) is extended from the general “all-hazard” based 3d loss model relating to the annual frequency to a “scenario-based” 3d loss model relating to the radial distance from the epicenter of a particular earthquake. Also, in order to avoid the disadvantages of the “Maximum Loss Model” and the “Average Loss Model”, a proposed “scenario-based” 3d loss model is developed as the combination of the maximum and average loss model. The “Redbook Building” (CCANZ 1998) which is designed using reduced strength for ductility (NZS1170) along with concrete code specified (NZS 3101) ductile detailing has been considered as a building exemplar for standard structural design. In this research, the “scenario-based” 3d loss model is implemented on this building.

1.2.2 Damage

Cornell (1968) proposed an approach to determine the seismic risk at a construction site using peak ground acceleration versus average return period. Formulae which give the required hazard indicators for an earthquake, for example, peak ground acceleration or peak ground velocity, were used to do the calculations. Through the computation, annual frequency, which tells the possibility of exceeding a given value over a specified amount of time, can be obtained. This was a great development in the field of probabilistic seismic hazard analysis.

Kennedy et al. (1980) conducted research to study the safety of the Oyster Creek nuclear power plant. The earthquake was taken as one of the initiating events that could lead to failure of the plant, and comparisons were made between the probability of failure resulting from an earthquake and the probability of failure due to other events. Uncertainties and randomness were treated with careful consideration. A rational methodology was proposed to estimate the variabilities in the incomplete knowledge of structure response, properties of earthquake, structural materials and approximation of the model building. With these estimations, probability of failure of the plant induced by earthquakes then can be evaluated.

Mander et al. (2012) developed a general quantitative four-step risk analysis approach to avoid the use of the customary complex fragility curves to estimate the damage losses of structures. The damage loss is presented by the parameter loss ratio, which is the ratio of repair cost to the total reconstruction cost. The four steps are: (a) hazard analysis; (b) structural analysis; (c) damage analysis; and (d) loss estimation. The first step is to determine the specific seismic hazards at a certain constructed facility site, therefore producing the relationship between the intensity measures (IM) and the annual frequency (f). The second step is to predict the response of the structure to the intensity measures in terms of the engineering demand parameter (EDP), which is commonly taken as the structure drift. The third step is to relate the losses to the engineering demand parameter. In the fourth step, the structural and nonstructural damage can be determined. Mander et al. (2012) showed specifically the four-step approach using Figure 1. The measure of damage levels were divided into five damage stages (DS): (1) DS1 = pre-yield damage; (2) DS2 = nonrepairable damage; (3) DS3 = repairable damage; (4) DS4 = irreparable damage; and (5) DS5 = structure collapse.

When plotted from (1) to (4), the four graphs generate straight lines in log-log space and are inter-related through a compound power equation as follows:

$$\frac{L}{L_{DBE}} = \left|\frac{\theta}{\theta_{DBE}}\right|^{c} = \left|\frac{S_a}{S_{aDBE}}\right|^{bc} = \left|\frac{f}{f_{DBE}}\right|^{\frac{bc}{-k}} \tag{1.1}$$

where $DBE =$design basis earthquake; $L =$loss ratio; $\theta =$ structure drift; S_a = spectral acceleration; f = annual frequency; L_{DBE} = loss ratio for the design basis earthquake; $\theta_{DBE} =$structure drift for the design basis earthquake; S_{aDBE} = spectral acceleration for the design basis earthquake; f_{DBE} = annual frequency for the design basis earthquake, which is taken as 10% in 50 years; k = constant on Figure 1 (a); b = constant on Figure 1 (b); c = constant on Figure 1 (c); d = constant on Figure 1 (d); and k, b, c and d are interrelated as:

$$d = \frac{bc}{-k} \tag{1.2}$$

The empirical loss model is expressed in terms of structural drift as below:

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

where L_c = unit loss, which is normally taken as $L_c = 1.0$; θ_c = structure drift at the onset of complete collapse; L_{on} = loss ratio at the onset of damage state 2; θ_{on} = structure drift at the onset of damage state 2; L_u = loss ratio at the complete collapse of structure, L_u > 1 with a limitation that $L_u \le 1.3$, which assumes a 30 percent cost penalty due to post-disaster price surge arising from widespread demand for materials and labor.

Mander et al. (2012) incorporated variabilities and randomness of the earthquake demand and the structure capacity in the loss model. By using the parameter β to represent the dispersions as shown in Figure 2, the mean value $\bar{y}$ and other fractile values $y_{x\%}$ are related to the median value $\tilde{y}$ by:

$$\bar{y} = \tilde{y}\exp(\frac{1}{2}\beta^2) \tag{1.4}$$

$$y_{x\%} = \tilde{y}\exp(K_x\beta) \tag{1.5}$$

where K_x represents the standard Gaussian random variable. (Note that for the standard deviation that represents the 16th and 84th percentiles $K_x = -1$ and $+1$, respectively).

β_{TL} represents the dispersion in total loss, which is calculated by:

$$\beta_{TL} = \sqrt{\beta_{UL}^2 + c^2 \beta_{RS}^2} \tag{1.6}$$

where β_{UL} accounts for the uncertainties in the loss estimation; and β_{RS} represents total variabilities related to structures, including the randomness in both structural demand β_{RD} and structural capacity β_{RC} .

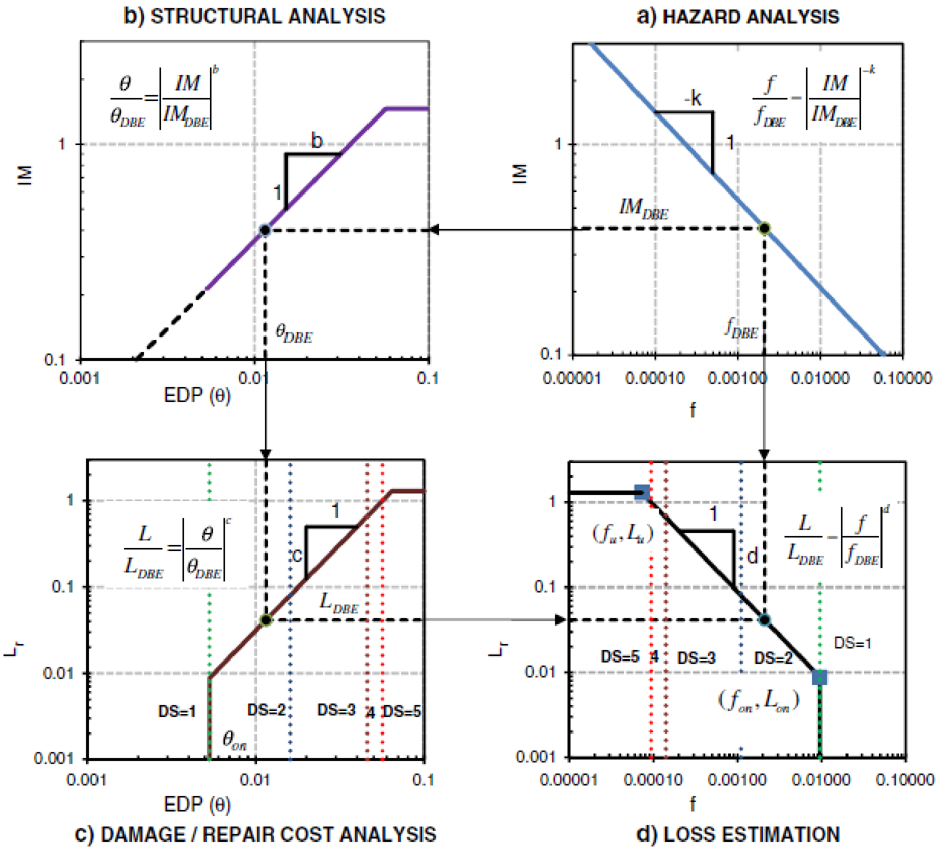


Fig. 1. "All-hazard" based four-step quantitative risk analysis loss model

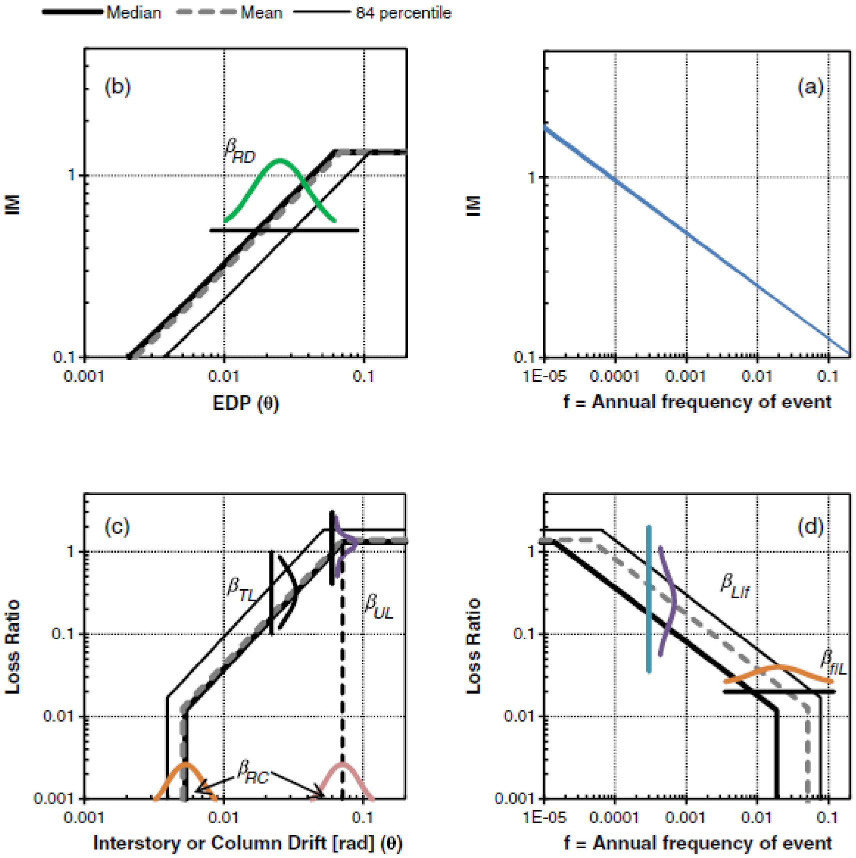


Fig. 2. “All-hazard” based four-step quantitative risk analysis loss model after considering uncertainty and randomness

The total variabilities related to structures β_{RS} is calculated by:

$$\beta_{RS} = \sqrt{\beta_{RD}^2 + \beta_{RC}^2} \tag{1.7}$$

The variability of f_{on} for a given drift $\beta_{f_{on}|\theta}$ is expressed by:

$$\beta_{f_{on}|\theta} = \frac{k}{b}\beta_{RS} = \frac{k}{b}\sqrt{\beta_{RD}^2 + \beta_{RC}^2} \tag{1.8}$$

1.2.3 Death

Except for the direct physical damage of a structure and the associated financial losses, casualties are another important consequence of a catastrophic earthquake.

Mander and Elms (1994) conducted a quantitative risk assessment (QRA) of large structural systems. Unlike the previous first-order-second-moment reliability analysis which was related to damage losses, they focused on the casualties caused by the failure of a large structural system. Multiple fault and event trees were used to develop an approach along with its underlying principles for using the QRA. Typical Fatal Accident Rate (FAR) values summarized by Kletz (1978), Lees (1980), Elms and Mander (1990) were used as a measure of risk. Three case studies were demonstrated to show the applications with the methodology: locomotive engineer hazards, risk exposure to motor vehicle users in earthquakes and risk exposure to occupants of buildings.

Porter et al. (2011) discussed the earthquake-planning scenario of a Mw 7.8 earthquake on the southern San Andreas Fault in 2008. The created scenario led to life and limb losses of 1,800 dead and 53,000 severely injured. Aside from the deaths and injuries directly inflicted by the collapse of buildings and the break-down of lifelines, like water supply, power, wastewater, telecommunications, oil and gas pipelines, the ignited fires also contribute to the casualties. Calculations showed some 1,600 ignited fires which caused 900 deaths among the 1,800 total.

Ghorawat (2011) extended the four-step risk analysis approach to a death loss estimation model of bridges. Bridges designed by Caltrans, Japan, and New Zealand specifications and damage avoidance design method were investigated for the death loss estimation. Calculation of the expected annual death loss was proposed and it can be converted to fatal accident rate (FAR), which is a common measure of fatalities. The death loss in terms of monetary values was then obtained using the Value of Statistical Life (VSL).

1.2.4 Downtime

Comerio (2006) discussed the importance of downtime estimation in loss modeling. Generally, downtime is the time needed to inspect facilities, define the damage levels, plan and complete the repair or reconstruction. Downtime loss is quite difficult to model and quantify, since historically there have not been systematic records following disasters. Rational and irrational components constitute the downtime: the rational elements are construction costs and time which are predictable and quantifiable; and the irrational elements are financing, rearrangement of building operations, human labor availability, and economic uncertainty, which are situation-dependent and difficult to specifically quantify. The information about facilities repairs and reconstruction after the Loma Prieta and Northridge earthquakes was discussed and conclusions were that there are chances that the irrational situation–specific elements of downtime could be estimated and the most influential and dominating factor is financing. University risk management projections on the University of California, Berkeley, were specifically investigated.

Camerio and Blecher (2010) further investigated the irrational downtime of the wood-framed residential buildings after the Loma Prieta and Northridge earthquakes. The residential structures were inspected and determined into three building status: repaired, demolished or rebuilt; and were categorized by tag color, building type and single-family or multifamily. Results showed that the expected downtime for repairing and rebuilding is 2 years and 3.5 years separately; and downtime estimation requires the combination of construction time for repairing the damaged facilities, the mobilization time for different structures, and the local market economy situation at the earthquake area. By estimating these elements in advance, the time needed for a building to be reoccupied can be determined related to the economy situations.

1.3 What then is Particularly New in this Thesis?

(i) As an extension, the general “all-hazard” four-step loss model based on annual frequency is advanced to a “scenario-based” four-step 3d loss model based on the radial distance from the epicenter. Therefore, the 3d losses can be determined directly as loss-specific attenuation relations for a given earthquake.

(ii) Considering the spatial distribution of the seismic damage loss over the height of buildings, especially for tall buildings, proposed “scenario-based” 3d loss models are developed to improve the imprecise estimation of the maximum loss model and the average loss model. It is shown that it is possible to discriminate the building area that requires repairs and total replacement.

(iii) To mitigate the unexpectedly large downtime losses for the benchmark “Redbook Building”, a stronger building, a more ductile building, and a both stronger and more ductile building models are investigated for an appropriate solution for a better structural performance that minimizes losses. Not surprisingly it is confirmed that buildings that are both stronger and more deformable are needed for the future.

2. “SCENARIO-BASED” 3d LOSS MODEL

2.1 Introduction

It is well known that earthquake shaking intensities attenuate as the distance from the earthquake epicenter increases. In the past, various attenuation relationships have been proposed by numerous researchers. For the Christchurch earthquake, the relationship between radial distance from the epicenter and the intensity measures can be determined by actual instrument readings obtained from Geonet. With this attenuation relationship incorporated into the four-step “all-hazard” quantitative risk analysis approach of Mander et al. (2012), a “scenario-based” four-step 3d risk analysis method can be developed. This adopted approach also consists of four parts: (a) hazard intensity-attenuation modeling; (b) structural analysis; (c) damage analysis; and (d) loss-attenuation estimation.

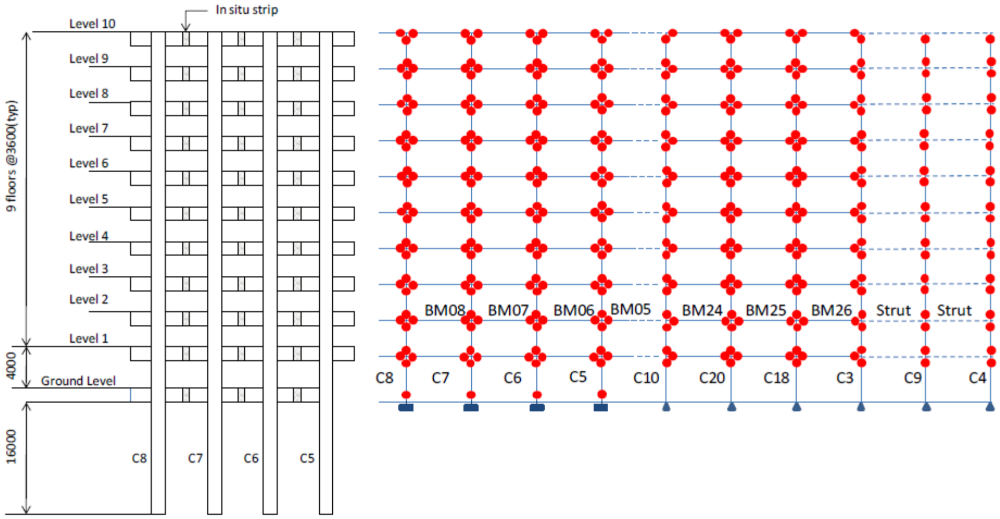
In the hazard intensity-attenuation modeling, instead of the annual frequency as is in the first step of the four-step “all-hazard” risk analysis approach of Mander et al. (2012), the intensity measures are related to the radial distance from the earthquake epicenter. In the second step, the structural responses to different ground shaking intensities are predicted using an engineering demand parameter (EDP); herein this is expressed as the structural interstory drift. In the third step, through the interstory drifts, the damage, death and downtime (3d) losses are estimated. Finally, in the fourth step, the losses are directly related back to the radial distance from the earthquake epicenter; and the subsequent result becomes a loss attenuation relationship – this can be performed for each of the 3d’s.

The 10-story reinforced concrete “Redbook Building” (CCANZ 1998), shown in Figure 3 (Deshmukh 2011), was selected as the structure for analysis in this research. This building was chosen as it conforms to the two relevant current design codes: the loading code (NZS 1170) and the concrete code (NZS 4203). This structure is quite well known as it has also served as the design exemplar used in senior undergraduate reinforced concrete courses over many years at the University of Canterbury.

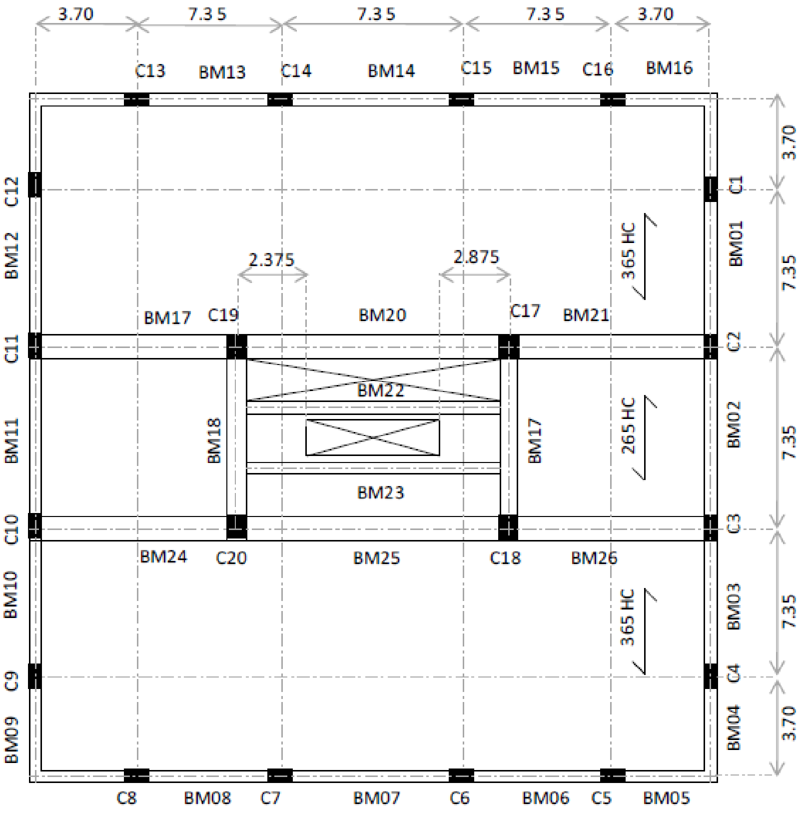
The “scenario-based” 3d loss model is implemented for the “Redbook Building” using the 2011 Christchurch earthquake ground motions. It will be shown that the results for the standard “Redbook Building” indicate that the downtime losses are significant and that in spite of a collapse-prevention design philosophy some deaths may also occur. Therefore, in order to reduce the 3d losses, three methods to improve the building seismic performance are investigated:

(i) Following the Christchurch earthquakes, seismologists and the Department of Building and Housing (DBH) are recommending an increase in seismic coefficient from 0.22g to 0.30g, roughly a 33% increase. Consistent with this proposed increase to more realistically reflect the seismic hazard for Christchurch, the degree of strengthening of “Redbook Building” is assumed to be 30% stronger. The “scenario-based” 3d loss models are then re-applied to the “stronger” building.

(ii) Another method to reduce damage is to modify the connection details conforming to the principles of self-centering and Damage Avoidance Design (DAD) to



(a) Elevation *(b) Extended 2D structural model developed in SAP2000*



(c) Plan of Redbook Building

Fig. 3. Prototype “Redbook Building”: (a) elevation; (b) extended 2D structural model developed in SAP 2000; and (c) plan of “Redbook Building”

make the building more ductile and as damage-free as practicable. Thus the same structure strength is kept the same as for the benchmark “Redbook Building”, but the construction is assumed to be modified to employ DAD armoring details with re-centering attributes. This has been proposed in various recent studies by Rodgers et al (2008, 2012) and Solberg et al (2008). This relatively weak but more robust building is also to be analyzed for the 3d damage losses and compared with the benchmark “Redbook Building”.

(iii) A stronger and more robust structure with DAD details combining the above two cases is also studied.

All the 3d loss results of the four different types of buildings are presented in graphs which have three lines drawn at the 16th, 50th, and 84th percentile band that demonstrates the wide range of outcomes that can potentially occur. Summaries of the expected and 90% confidence 3d losses at 17 km away from the earthquake epicenter are also presented in tables.

2.2 “Scenario-based” 3d Loss Model

The quantitative risk analysis approach proposed by Mander et al. (2012) for loss estimation of structural damage is first considered and adapted from an “all-hazard” based analysis to a “scenario-based” risk analysis. Figure 4 presents four graphs each plotted in log-log scale. The graphs are interconnected by a relationship that can be expressed as:

$$\frac{L_i}{L_{ri}} = \left|\frac{\theta}{\theta_r}\right|^{c_i} = \left|\frac{S_a}{S_{ar}}\right|^{bc_i} = \left|\frac{R}{R_r}\right|^{-abc_i} \tag{2.1}$$

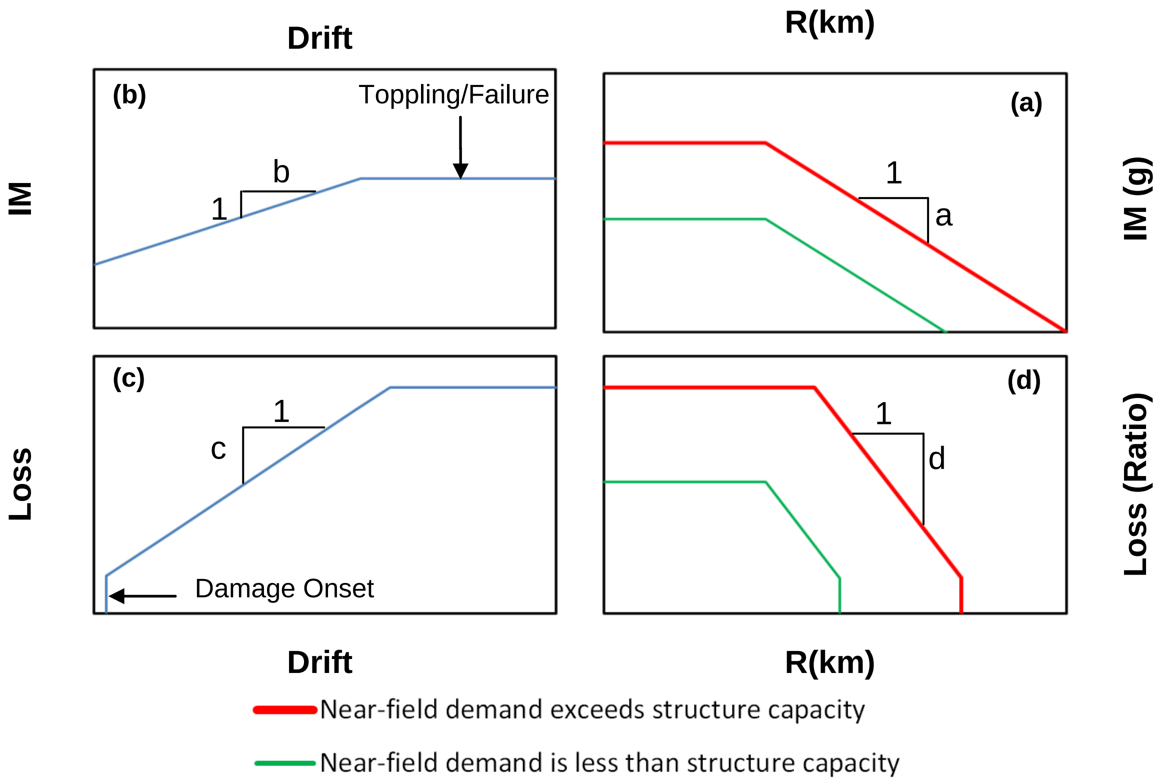


Fig. 4. "Scenario-based" 3d loss model: (a) seismic hazard intensity-attenuation model; (b) structural analysis; (c) damage analysis; and (d) loss-attenuation estimation

where $r =$ a reference (scenario) earthquake event; $i = i^{th}$ damage state, where $i = 1, i = 2$, and $i = 3$ stand for damage loss, death loss and downtime loss, respectively; $L_i =$ seismic loss of i^{th} damage state; $\theta =$ structure drift; $S_a =$ spectral acceleration, an intensity measure (IM); $R =$ radial distance from the earthquake epicenter; L_{ri} = seismic loss for the reference earthquake of i^{th} damage state; θ_r = structure drift for the reference earthquake; S_{ar} = spectral acceleration for the reference earthquake; R_r = radial distance from the earthquake epicenter for the reference earthquake; and a, b, c_i and d_i are the slopes shown in the four graphs in Figure 4, which are interrelated as:

$$d_i = -abc_i \tag{2.2}$$

A hazard intensity attenuation model proposed for the 2011 Christchurch earthquake is shown in Figure 5 and used in this research. The general form of this equation can be formally expressed as:

$$\frac{S_a}{S_{ar}} = \left|\frac{R}{R_r}\right|^{-a} \; ; \; S_a \leq S_{ar} \tag{2.3}$$

where $R_r =$ "corner" distance such that $S_a \leq S_{ar}$; and $a = 1$ for the Christchurch earthquake. Note that the plateau in Figure 4 (a) represents the near-field seismic demands, when $R \leq R_r$, thus $S_a = S_{ar}$.

The loss model in Figure 4 (c) is expressed by:

$$\frac{L_i}{L_{ci}} = \left|\frac{\theta}{\theta_c}\right|^{c_i} ; L_{oni} \leq L_i \leq L_{ui} \tag{2.4}$$

where $L_{ci} = i^{th}$ damage state loss at the onset of complete collapse; $\theta_c =$ structure drift at

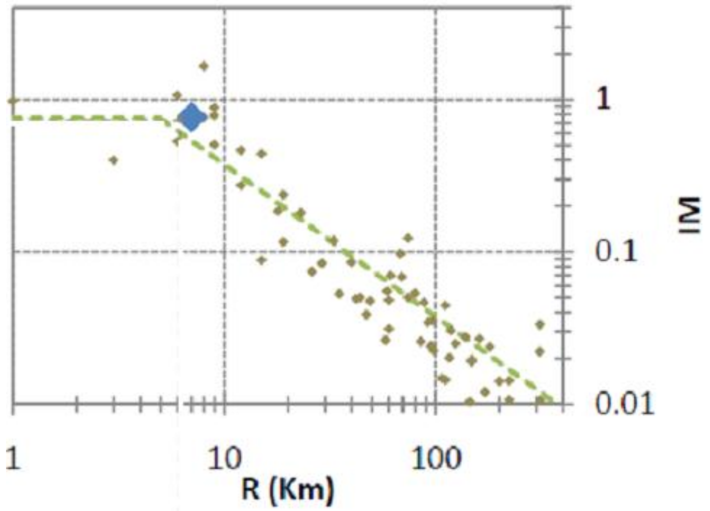


Fig. 5. Hazard intensity attenuation model

the onset of complete collapse; $L_{ui} = i^{th}$ damage state loss at the complete collapse of structure; $L_{oni} = i^{th}$ damage state loss at the onset of damage, which is calculated by:

$$\frac{L_{oni}}{L_{ci}} = \left|\frac{\theta_{on}}{\theta_c}\right|^{c_i} \tag{2.5}$$

where $\theta_{on} =$ structure drift at the onset of damage.

The collapse criteria is defined the same as the onset of damage state 5 as used in HAZUS, which is the global instability or collapse, whichever comes first. For the "Redbook Building", the slope c_i in Figure 4 (c), the median loss values at the onset of complete collapse $\tilde{L}_{ci}$ and the median loss values at complete collapse $\tilde{L}_{ui}$ are taken as:

- for $i = 1$, the parameters used for the physical damage loss are:

  $c_1 = 1.4$, (Deshmukh 2011);

  $\tilde{L}_{c1} = 1.0$, (Mander et al. 2012);

  $\tilde{L}_{u1} = 1.5$;

- for $i = 2$, the parameters used for the death loss are:

  $c_2 = 2.6$, which is calibrated using fault and event trees;

  $\tilde{L}_{c2} = 0.1$, (Mander and Elms 1994);

  $\tilde{L}_{u2} = 0.5$;

- for $i = 3$, the parameters used for the downtime loss are:

  $c_3 = 2.5$, (Ghorawat 2011);

  $\tilde{L}_{c3} = 75$ (weeks), (Ghorawat 2011);

$\tilde{L}_{u3} = 200$ (weeks);

Note $\tilde{L}_{u1} = 1.5$ is a higher value than the value of $\tilde{L}_{u1} = 1.3$ that was suggested by Mander et al. (2012). This increase is based on a cost estimation that follows the 2011 Christchurch earthquakes. In that event there has been considerable cost associated with deconstructing damaged structures prior to commencing reconstruction.

Considering the aleatory variabilities in the seismic demand and structure capacity as well as the epistemic uncertainties associated with construction estimates a lognormal distribution is assumed. This is a two parameter model characterized by a median and a lognormal standard deviation commonly referred to as the dispersion factor, β.

As is proposed by Mander et al. (2012), the dispersion in total losses β_{TL} is calculated by:

$$\beta_{TL} = \sqrt{\beta_{UL}^2 + c^2 \beta_{RS}^2} \tag{2.6}$$

where β_{UL} accounts for the uncertainties in the loss estimation, which is taken as $\beta_{UL} = 0.4$; and β_{RS} represents total variabilities related to structures.

The total variabilities related to structures β_{RS} can be calculated by:

$$\beta_{RS} = \sqrt{\beta_{RD}^2 + \beta_{RC}^2} \tag{2.7}$$

where β_{RD} accounts for the randomness in structural demand, which is taken as $\beta_{RD} = 0.43$(Mander et al. 2012); and β_{RC} accounts for the randomness in structural capacity, which is taken as $\beta_{RC} = 0.2$ (Solberg et al. 2008).

For i^{th} damage state, the median loss value for the reference earthquake $\tilde{L}_{ri}$ is calculated by:

$$\tilde{L}_{ri} = \tilde{L}_{ci} \left| \frac{\theta_r}{\theta_c} \right|^{c_i} \tag{2.8}$$

Then the corresponding mean loss values for i^{th} damage state are calculated by:

$$\bar{L}_{ri} = \tilde{L}_{ri} \exp(0.5\beta_{TL}^2) \tag{2.9}$$

$$\bar{L}_{oni} = \bar{L}_{ri} \left| \frac{\bar{R}_{oni}}{R_r} \right|^{d_i} \tag{2.10}$$

$$\bar{L}_{ui} = \tilde{L}_{ui} \exp(0.5\beta_{UL}^2) \tag{2.11}$$

where $\bar{L}_{ri}$ is the mean loss value for the reference earthquake; $\bar{L}_{oni}$ and $\bar{L}_{ui}$ are the mean loss values at the onset of damage and at the complete collapse of structure, respectively; and $\tilde{R}_{oni}$ and $\bar{R}_{oni}$ are the median and mean values of the radial distance from the earthquake epicenter at the onset of damage respectively which are given by:

$$\tilde{R}_{oni} = R_r \left| \frac{\tilde{L}_{oni}}{\tilde{L}_{ri}} \right|^{1/d_i} \tag{2.12}$$

$$\bar{R}_{oni} = R_r \left| \frac{\bar{L}_{oni}}{\bar{L}_{ri}} \right|^{1/d_i} \tag{2.13}$$

$\tilde{R}_{ui}$ and $\bar{R}_{ui}$ are the median and mean values of the radial distance from the earthquake epicenter at complete collapse of structure respectively which are calculated by:

$$\tilde{R}_{ui} = R_r \left| \frac{\tilde{L}_{ui}}{\tilde{L}_{ri}} \right|^{1/d_i} \tag{2.14}$$

$$\bar{R}_{ui} = R_r \left| \frac{\bar{L}_{ui}}{\bar{L}_{ri}} \right|^{1/d_i} \tag{2.15}$$

2.3 Results

The “scenario-based” 3d loss model is earthquake specific; therefore, the 3d losses for the Christchurch earthquake at a certain radial distance from the earthquake epicenter can be determined easily as shown in this research. Though the damage, death and downtime losses are all important aspects needed to be considered for structure designs, previous studies done by Ghorawat (2011) has shown that downtime loss is the most significant loss compared to the physical damage loss and death loss. It is therefore necessary to take downtime loss more seriously into consideration in the pre-event analysis and design. To explore how to better ameliorate losses, particularly the downtime loss by design, four different types of buildings are investigated with the “scenario-based” 3d loss model through a sensitivity analysis as shown in Figure 6 to Figure 9. Results are demonstrated in terms of attenuation curves, showing median values and 16th and 84th percentile values.

The 3d loss model results show that for the standard “Redbook Building” in Figure 6, within the Christchurch city, taken at some 17 km radial distance away from the earthquake epicenter following the inter-graph dashed line: (i) the median physical damage loss ratio is about 30%; (ii) the median probability of loss of life is about 1.5%; and (iii) the median downtime loss is 12 weeks. The 84th percentile seismic losses are: (i)

90% physical damage loss ratio; (ii) 6% probability of death loss; and (iii) 40 weeks of downtime loss.

In Figure 7, the median values indicate that for the 30% stronger model at 17 km: (i) the physical damage loss ratio is about 20%; (ii) the probability of death loss is less than 1%; and (iii) the downtime loss is about 5 weeks. The 84th percentile values are: (i) 55% damage loss; (ii) 2% probability of death loss; and (iii) 20 weeks of downtime loss.

In Figure 8, for the more ductile building, the damage area begins at just around the 17 km radial distance from the earthquake epicenter, which means that buildings at this distance from the earthquake epicenter can possibly avoid the chances of being damaged.

In Figure 9, for the stronger and more ductile building, obviously, the structures can still work well and guarantee safety at and beyond this distance (17 km) from the earthquake epicenter.

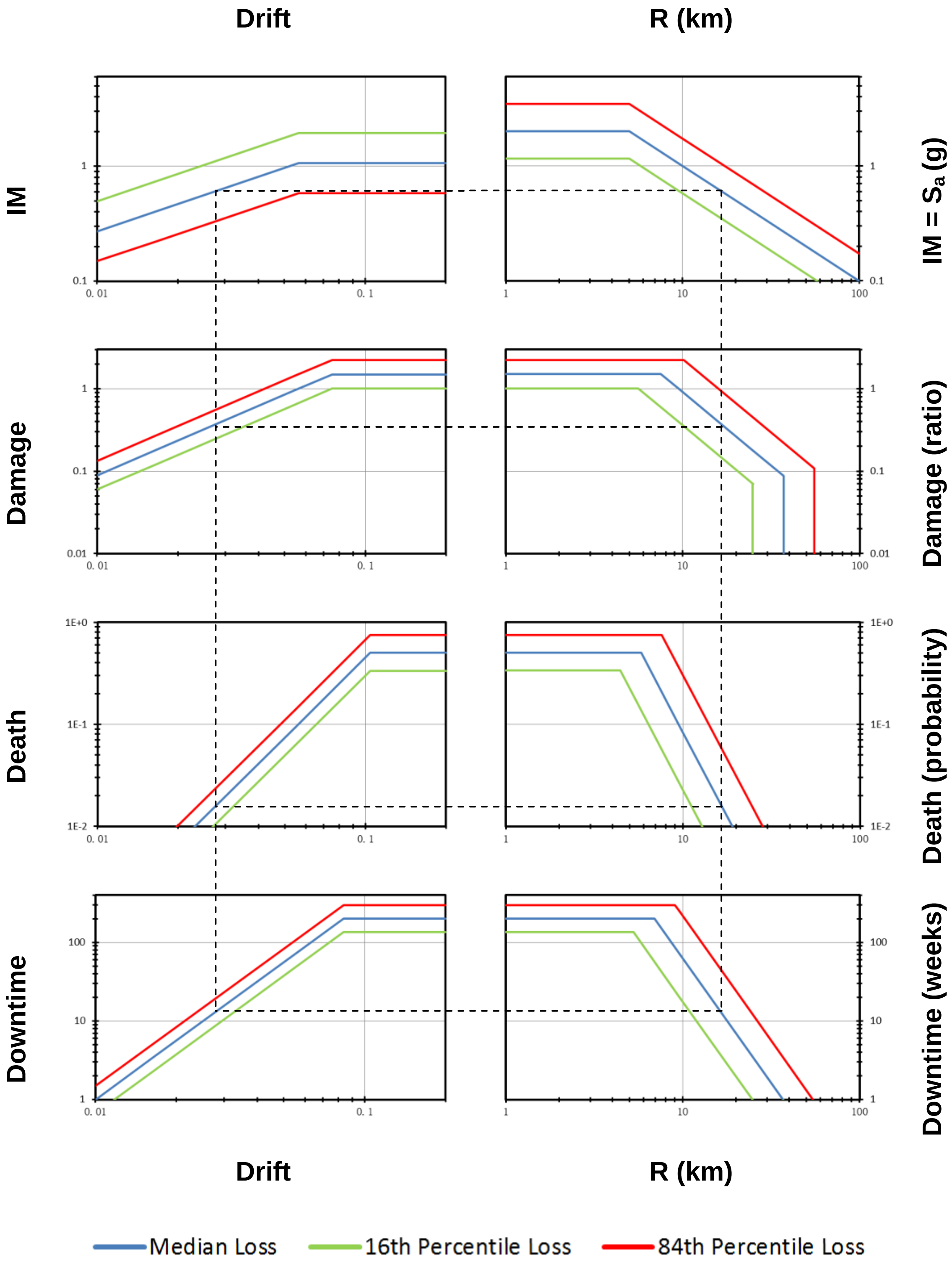


Fig. 6. **“Scenario-based” 3d loss analysis for the “Redbook Building” with 16th percentile, median and 84th percentile values**

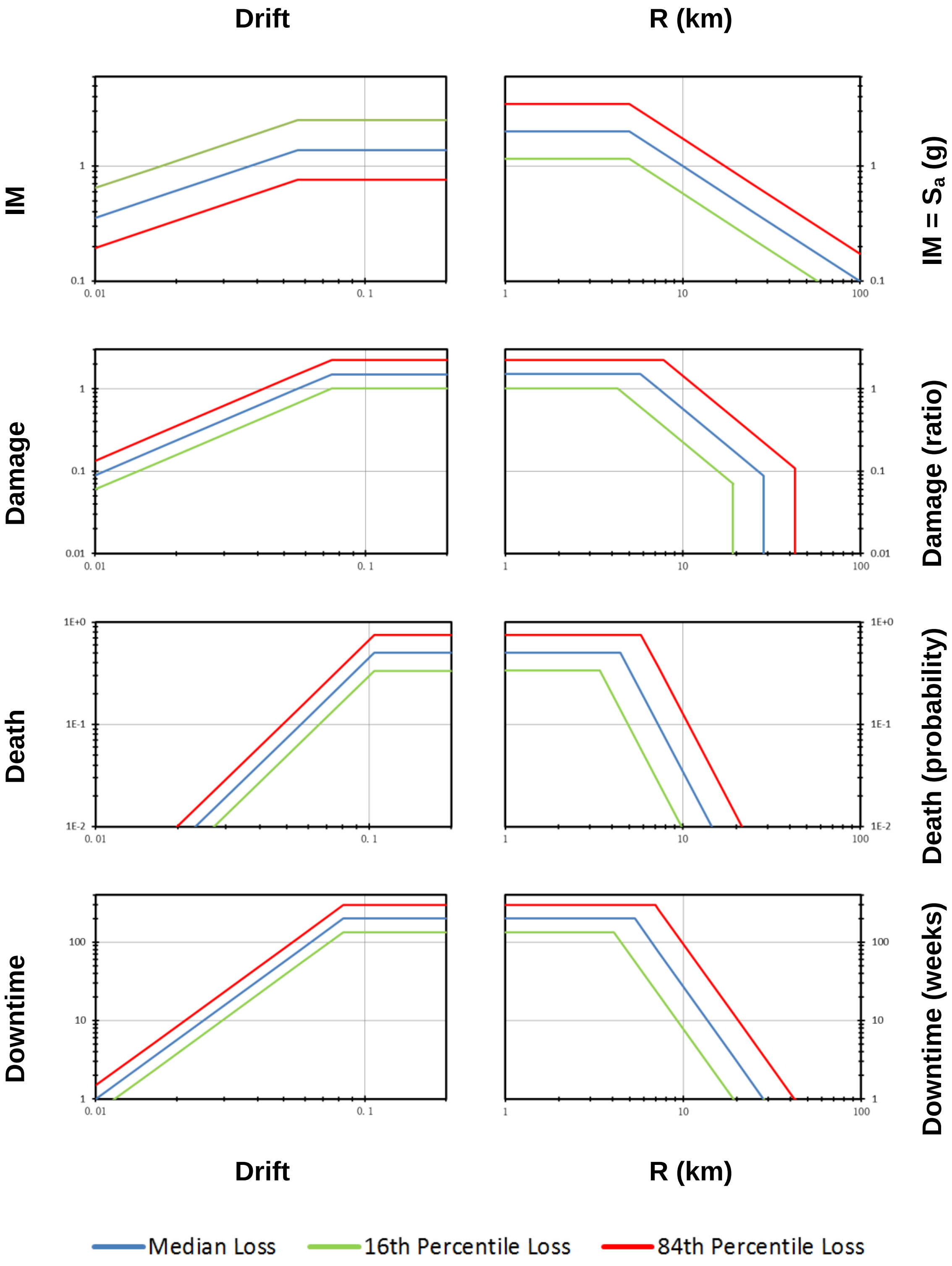


Fig. 7. “Scenario-based” 3d loss analysis for 30% stronger building with 16th percentile, median and 84th percentile values

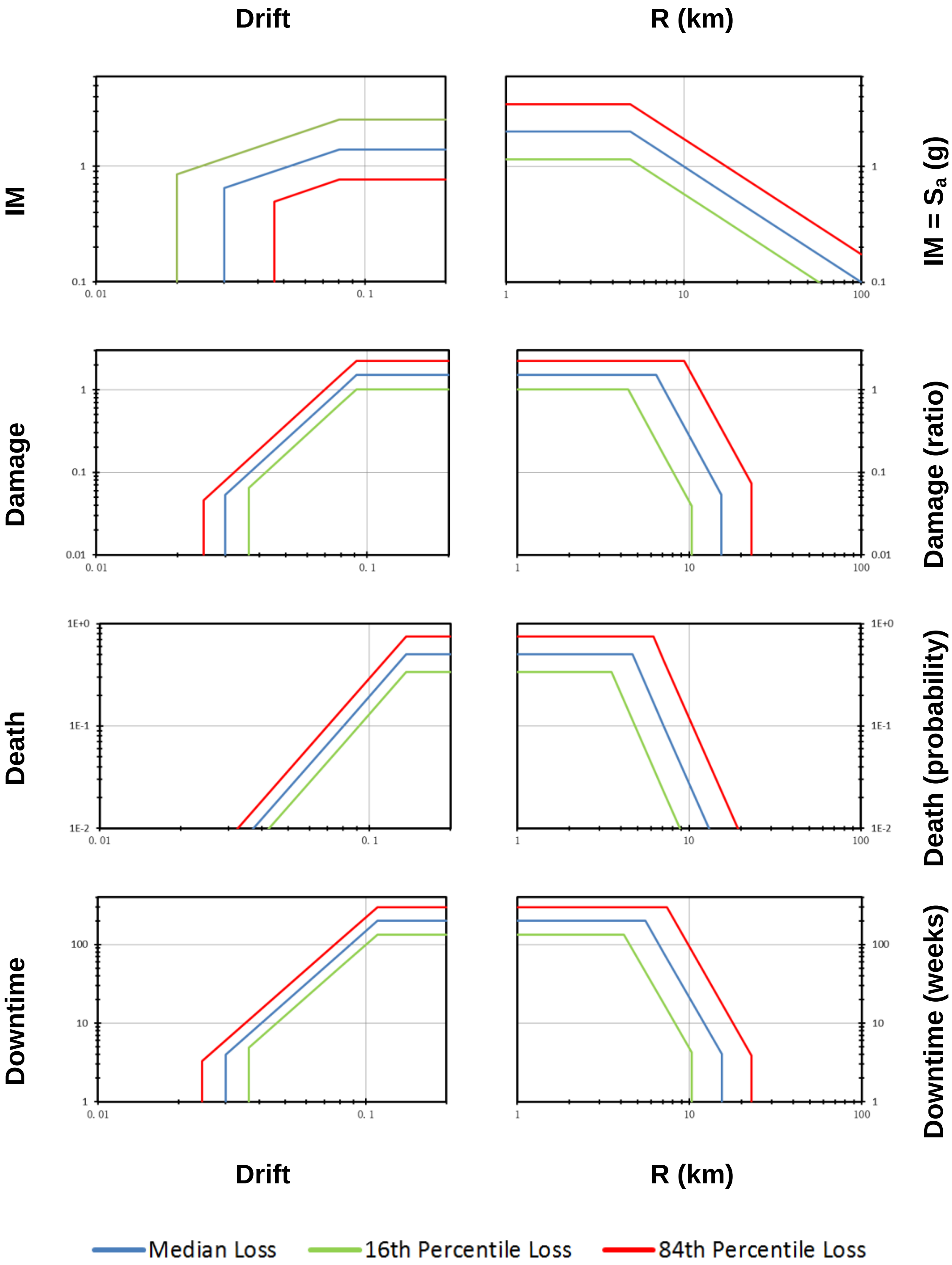


Fig. 8. "Scenario-based" 3d loss analysis for DAD detailed "Redbook Building" with 16th percentile, median and 84th percentile values

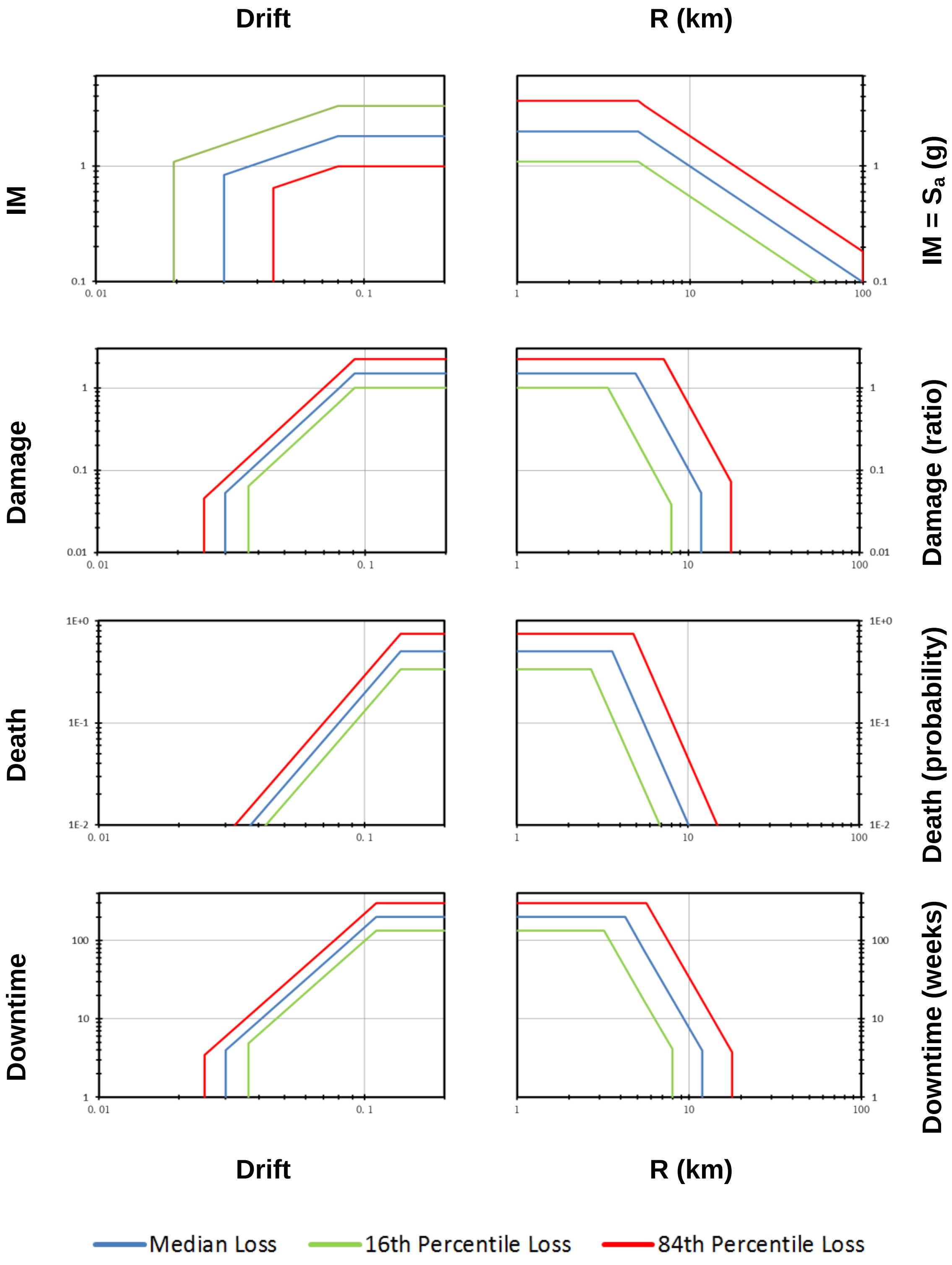


Fig. 9. "Scenario-based" 3d loss analysis for 30% stronger and more ductile building with 16th percentile, median and 84th percentile values

Table 1. Expected 3d losses at R = 17 km for four different types of buildings

Buildings	Damage Loss	Death Loss	Downtime Loss (weeks)
Redbook Building (benchmark)	50%	4%	24
30% Stronger Building	30%	1%	18
More Ductile Building	—	—	—
Stronger and More Ductile Building	—	—	—

Table 2. 90% Confidence 3d losses at R = 17 km for four different types of buildings

Buildings	Damage Loss	Death Loss	Downtime Loss (weeks)
Redbook Building (benchmark)	100%	8%	50
30% Stronger Building	60%	2%	30
More Ductile Building	—	—	—
Stronger and More Ductile Building	—	—	—

2.4 Discussion

The expected and 90% confidence 3d losses at R = 17 km are summarized in Table 1 and Table 2 seperately. The 3d loss model results show that for the standard "Redbook Building", at some 17 km radial distance away from the earthquake epicenter: (i) the expected physical damage loss ratio is about 50% of the asset value; (ii) the expected probability of loss of life is about 4%; and (iii) the expected downtime is 24 weeks. Considering the randomness and uncertainties, one can have 90% confidence that the 3d losses will not be higher than: (i) 100% physical damage loss ratio; (ii) 8% probability of death loss; and (iii) 1-year of downtime loss.

For the 30% stronger model: (i) the expected physical damage loss ratio declined to about 30%; (ii) the expected probability of death loss is about 1%; and (iii) the expected downtime loss is about 18 weeks. After comparing the results of the "Redbook Building" with the stronger building, one can see that the building with a stronger construction can clearly decrease the losses. For the more ductile and both stronger and more ductile building, the seismic losses at this distance can essentially be eliminated.

2.5 Conclusions

Based on the research conducted in this section, the following conclusions are drawn:

(1) With the "scenario-based" 3d loss model the 3d seismic losses at a certain radial distance from the earthquake epicenter can be easily determined for a specific earthquake scenario.

(2) Making a building stronger can help moderately reduce the seismic losses, but seismic resistance can be more effectively improved if the structure is constructed with proper DAD armoring details which could almost eliminate the buildings from the chances of being damaged at the edge of the Christchurch city (17 km away from the earthquake epicenter). However, what really needs to be done is to increase the structural strength and also apply proper DAD armoring details at the same time, which can make buildings achieve the best performance attributes.

3. “SCENARIO-BASED” 3d LOSS MODEL CONSIDERING SPATIAL DISTRIBUTION OF LOSSES

3.1 Introduction

A commonly adopted conservative assumption is that the damage of a building is uniformly distributed over the entire height of the structure, which is the concept in the “Maximum Loss Model”. The conservative influence of this assumption on the loss estimation is pretty significant when it comes to tall buildings, whose most severe damage is basically concentrated on the lower floors. To address this issue, Deshmukh (2011) developed another method, the “Average Loss Model”, which requires the calculation and summation of the damage loss of every single story of the building and then averages the total damage loss to the entire height of the building. Neither of those two methods can achieve the best results when applied in practice: the “Maximum Loss Model” provides a conservative result; and the “Average Loss Model” leads to a smaller loss estimation than its practical value for the most severely damaged stories when averaging the total loss to all the floors.

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 story is near collapse, then insurers will condemn the entire structure in spite of most other stories being in pristine condition. This is a case where building replacement is necessary and thus the maximum loss model is applicable. Hence, a proposed “scenario-based” 3d loss model is developed by adding a conditional loss model and combining the above two models with proper consideration of the spatial distribution of the seismic losses over the height of buildings.

The case study of this section also investigates the behavior of the four different types of buildings in Section 2 for Christchurch earthquakes with the proposed "scenario-based" 3d loss model considering spatial distribution of losses over the height of buildings. Compared to the results in Section 2, 3d losses are significantly reduced with this proposed 3d loss model. Results of the four different buildings are compared and hence the effects of different structure enhancement methods on the 3d seismic losses are explored and discussed.

3.2 "Scenario-based" 3d Loss Model Considering Spatial Distribution of Losses

The "Maximum Loss Model" assumes the seismic losses of the most severely damaged story are uniformly distributed over the total height of the building, which is expressed as:

$$\frac{L_{\max i}}{L_{ci}} = \max\left(\left|\frac{\theta_k}{\theta_c}\right|^{c_i}\right) \tag{3.1}$$

$$\left|\frac{\theta_{\max i}}{\theta_c}\right| = \left|\frac{L_{\max i}}{L_{ci}}\right|^{1/c_i} \tag{3.2}$$

where $L_{\max i} =$ maximum loss for the i^{th} damage state; $\theta_{\max i} =$ maximum structure drift in the structure for the i^{th} damage state; and $\theta_k =$ structure drift of the k^{th} story.

The "Average Loss Model" aggregates the seismic losses of each story of the building and then averages the total losses over the whole number of stories of the building, which is expressed as:

$$\frac{L_{avgi}}{L_{ci}} = \frac{\sum_{k=1}^{n} \theta_k^{c_i}}{n \cdot \theta_c^{c_i}} \tag{3.3}$$

$$\theta_{avgi} = \left(\sum_{k=1}^{n} \frac{\theta_k^{c_i}}{n} \right)^{1/c_i} ; \theta_{\max i} \le \theta_c \tag{3.4}$$

where $L_{avgi} =$ average loss for the i^{th} damage state; $n =$ total number of stories of the building; and $\theta_{avgi} =$ average structure drift in the structure for the i^{th} damage state.

For i^{th} damage state, L_{avgi} is bounded by:

- for $i = 1$, the average physical damage loss ratio L_{avg1} is bounded by:

$$L_{avg1} \le 1.0$$

- for $i = 2$, the average probability of death loss L_{avg2} is bounded by:

$$L_{avg2} \le 0.1$$

- for $i = 3$, the average downtime loss L_{avg3} is bounded by:

$$L_{avg3} \le 75 \text{ (weeks)}$$

The proposed "scenario-based" 3d loss model shown in Figure 10 is developed by combining these above two models and adding a conditional loss model which can also be used to discriminate seismic losses that require building repairs and replacement.

For i^{th} damage state, the conditional loss model can be expressed as:

- for $i = 1$ (the physical damage loss):

The building is repaired when:

$$L_{eff1} = L_{avg1} \qquad (L_{on1} \le L_{\max1} < 1.0) \tag{3.5}$$

The building is replaced when:

$$L_{eff1} = L_{\max 1} \qquad (1.0 \le L_{\max 1} \le L_{u1}) \tag{3.6}$$

where $L_{eff1} =$ the effective physical damage loss for the proposed loss model.

- for $i = 2$ (the death loss):

  The building is repaired when:

$$L_{eff2} = L_{avg2} \qquad (L_{on2} \le L_{\max 2} < 0.1) \tag{3.7}$$

The building is replaced when:

$$L_{eff2} = L_{\max 2} \qquad (0.1 \le L_{\max 2} \le L_{u2}) \tag{3.8}$$

where $L_{eff2} =$ the effective death loss for the proposed loss model.

- for $i = 3$ (the downtime loss):

  The building is repaired when:

$$L_{eff3} = L_{avg3} \qquad (L_{on3} \le L_{\max 3} < 75) \tag{3.9}$$

The building is replaced when:

$$L_{eff3} = L_{\max 3} \qquad (75 \le L_{\max 3} \le L_{u3}) \tag{3.10}$$

where $L_{eff3} =$ the effective downtime loss for the proposed loss model.

Other variables to develop the key coordinates in the proposed loss model for the i^{th} damage state are calculated by:

$$R_{rri} = R_r \left| \frac{L_{rri}}{\overline{L}_{ri}} \right|^{1/d_i} \tag{3.11}$$

$$L_{rli} = \overline{L}_{ri} \left| \frac{R_{rri}}{R_r} \right|^{d_i} \tag{3.12}$$

where R_{rri} = radial distance from the earthquake epicenter corresponding to the loss L_{rri}, which is taken as 1.0, 0.1 and 75 respectively for $i=1$, $i=2$, and $i=3$; L_{rli} = corresponding loss in the average loss model to the radial distance from the earthquake epicenter R_{rri}.

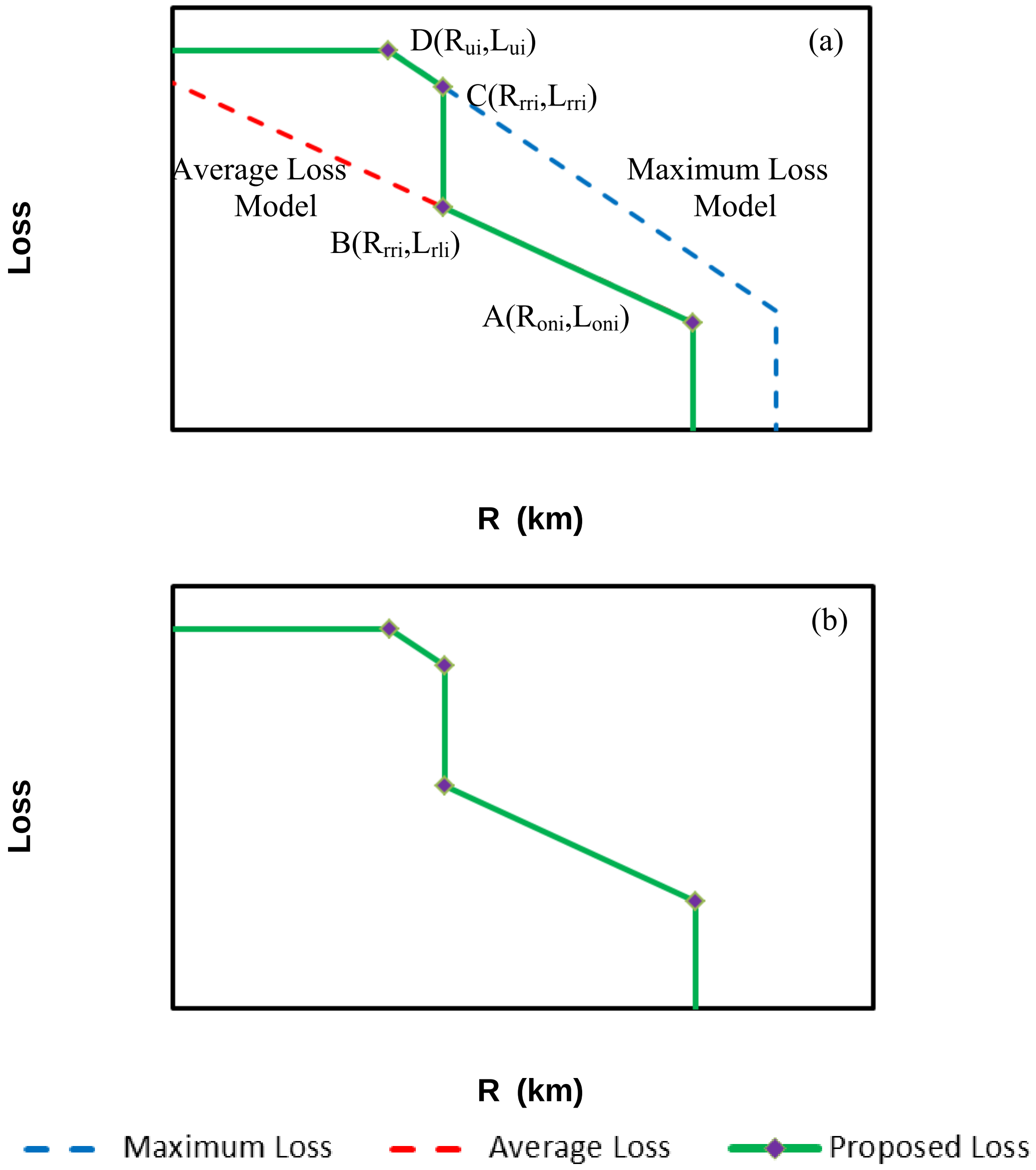


Fig. 10. The proposed "scenario-based" 3d loss model: (a) key points to develop the proposed loss model; and (b) proposed loss model

3.3 Results

The “scenario-based” 3d loss model considering spatial distribution of damage losses over the height of buildings is also applied to the four different types of buildings in Section 2. The four-step process to develop the proposed 3d loss model in median values for the “Redbook Building” is shown in Figure 11. Expected 3d losses transferred from the median 3d losses for those four different buildings are presented in Figure 12, Figure 13, Figure 14 and Figure 15 separately. Figure 16 presents the expected losses of the four different buildings after considering spatial distribution of seismic losses over the height of buildings in one figure.

Figure 11 presents the four-step process to develop the proposed “scenario-based” 3d loss model using the standard “Redbook Building” as the exemplar. As marked in the figure, building area that requires repairs and replacement can be discriminated.

Figure 12 shows the expected 3d losses for the “Redbook Building”. At a 17 km radial distance from the earthquake epicenter: (i) the expected physical damage loss is about 25%; (ii) the probability of death loss is only 1%; and (iii) the downtime loss is about 8 weeks. Clearly, compared to the maximum loss model in the blue dashed line, the estimated 3d losses are significantly reduced after considering the spatial distribution of damage losses over the height of the structure.

In Figure 13, it shows that after making the building stronger, it does not make too much difference in the average loss model results compared to the “Redbook Building”, but the maximum loss has a noticeable decrease. Therefore, in the proposed loss model, the loss cost does not reduce too much before the building completely collapses, but the reconstruction district is narrowed to a smaller area, thus the replacement losses are reduced.

In Figure 14, it shows that for more deformable building, the radial distance from the earthquake epicenter at onset of damage is about 15 km. Hence, at a 17 km radial distance from the earthquake epicenter, the structures may either need some mild repairmen or still be able to perform perfectly well. Even though the demands for repairmen are evidently reduced, the replacement loss does not have that much improvement.

Figure 15 presents the 3d losses of the both stronger and more ductile building model. The radial distance from the earthquake epicenter at onset of damage is about 11 km and at onset of complete collapse is about 9 km. It distinctly displays that this type of building has the minimum 3d losses in terms of both repairmen and replacement cost.

Figure 16 provides a comparison of the expected seismic losses of the four different types of buildings on one graph for each of the 3d loss types.

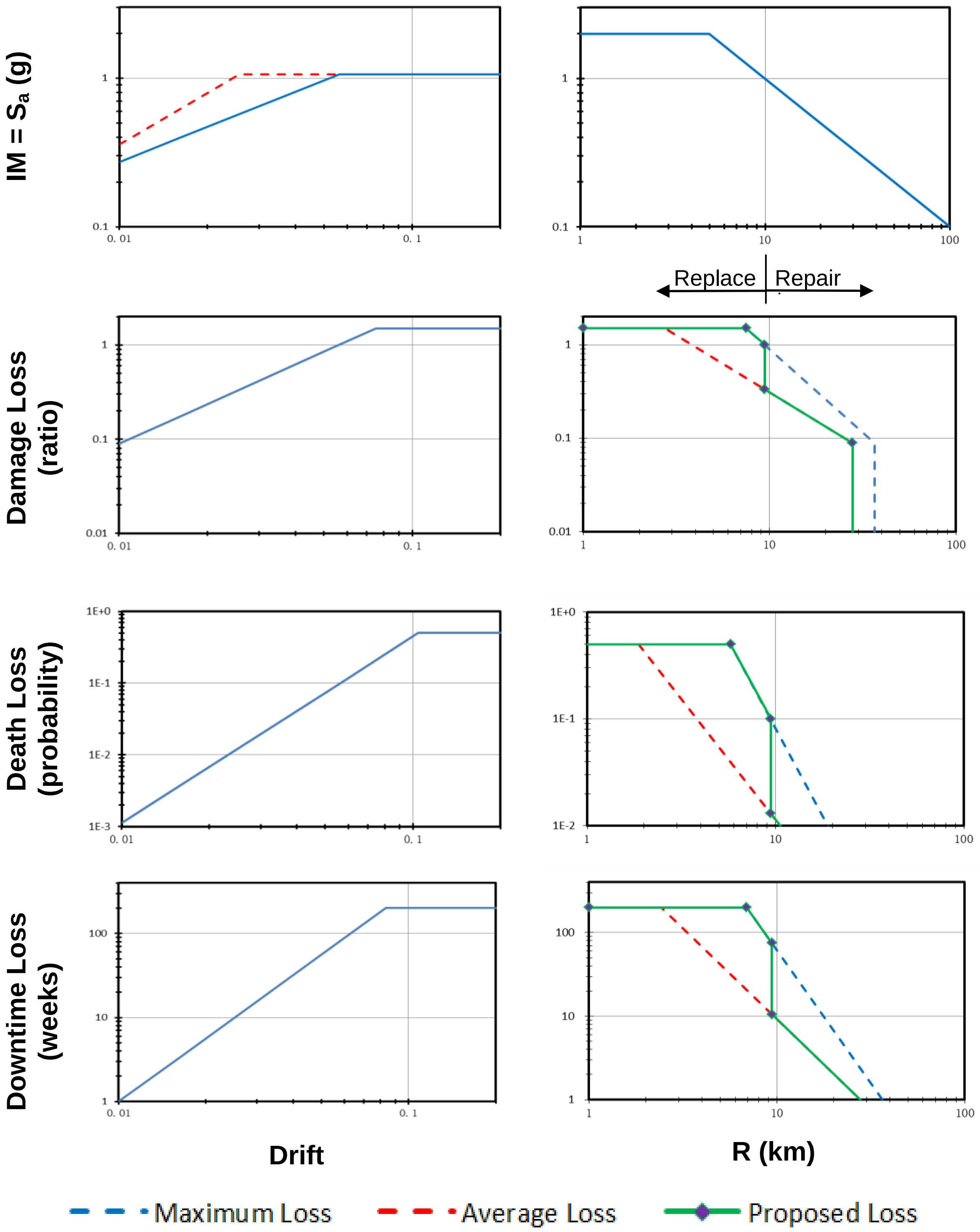


Fig. 11. Proposed “scenario-based” four-step 3d loss model developed for the standard “Redbook Building”

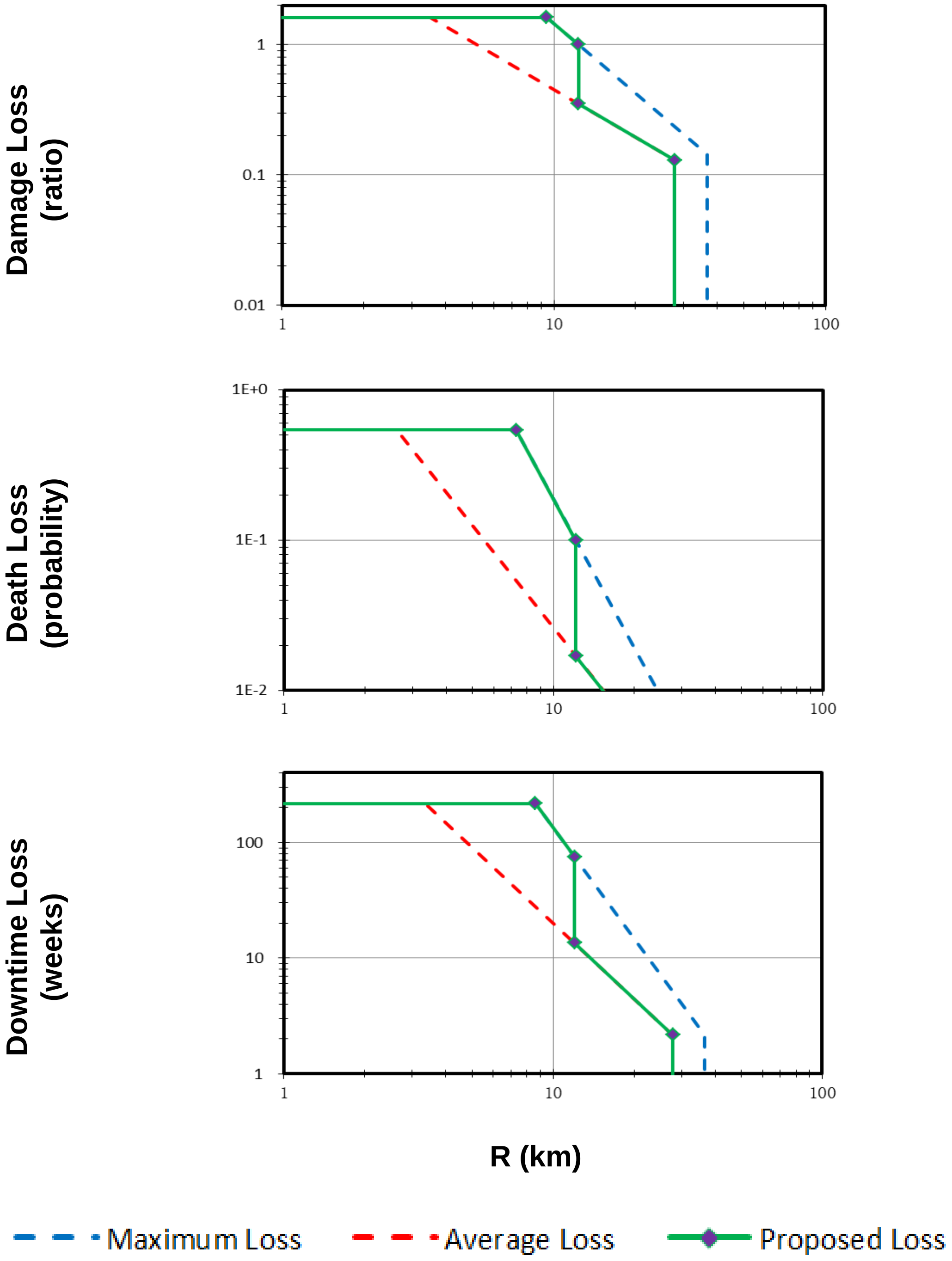


Fig. 12. Expected losses of proposed "scenario-based" 3d loss model estimation for the standard "Redbook Building"

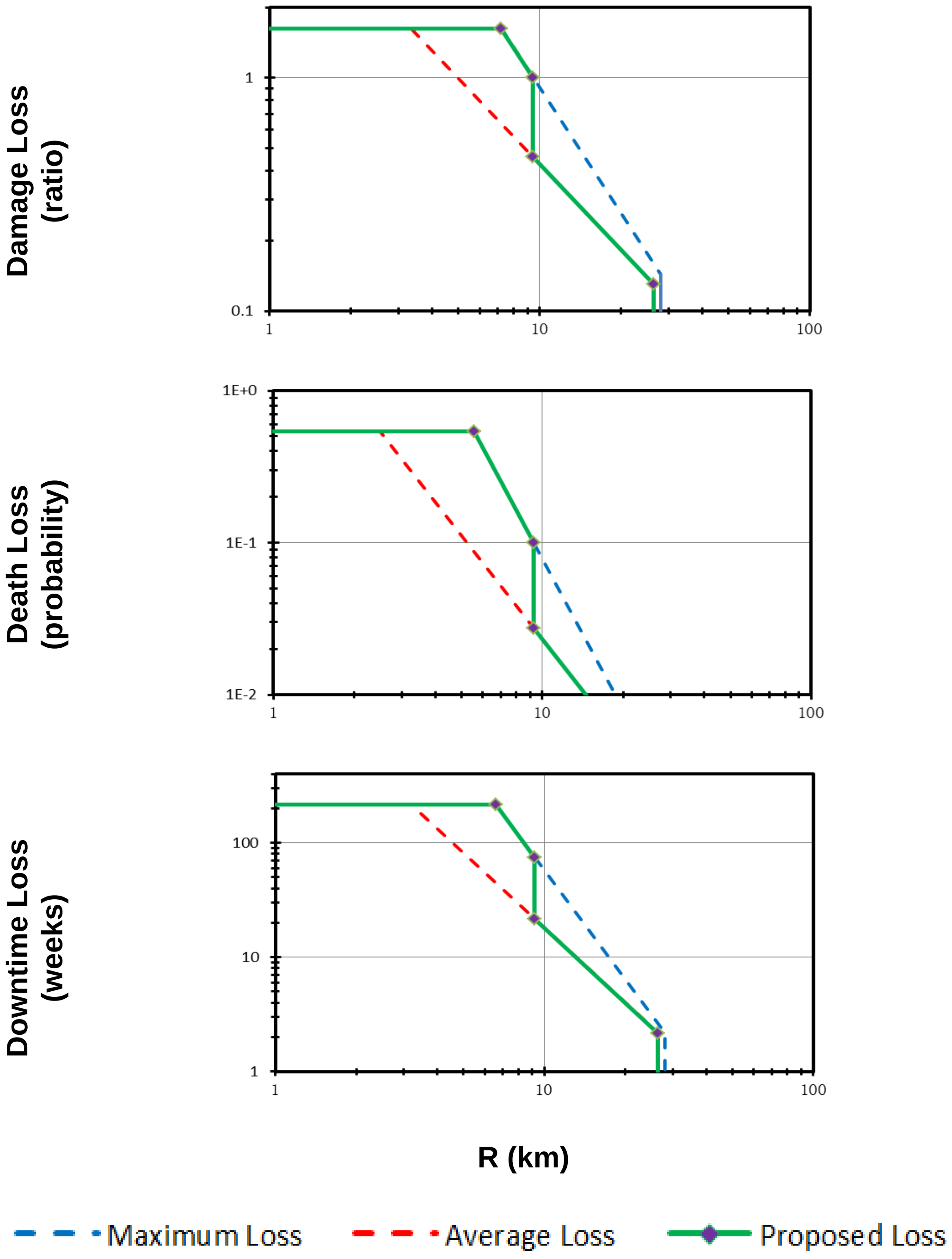


Fig. 13. Expected losses of proposed "scenario-based" 3d loss model estimation for 30% stronger building

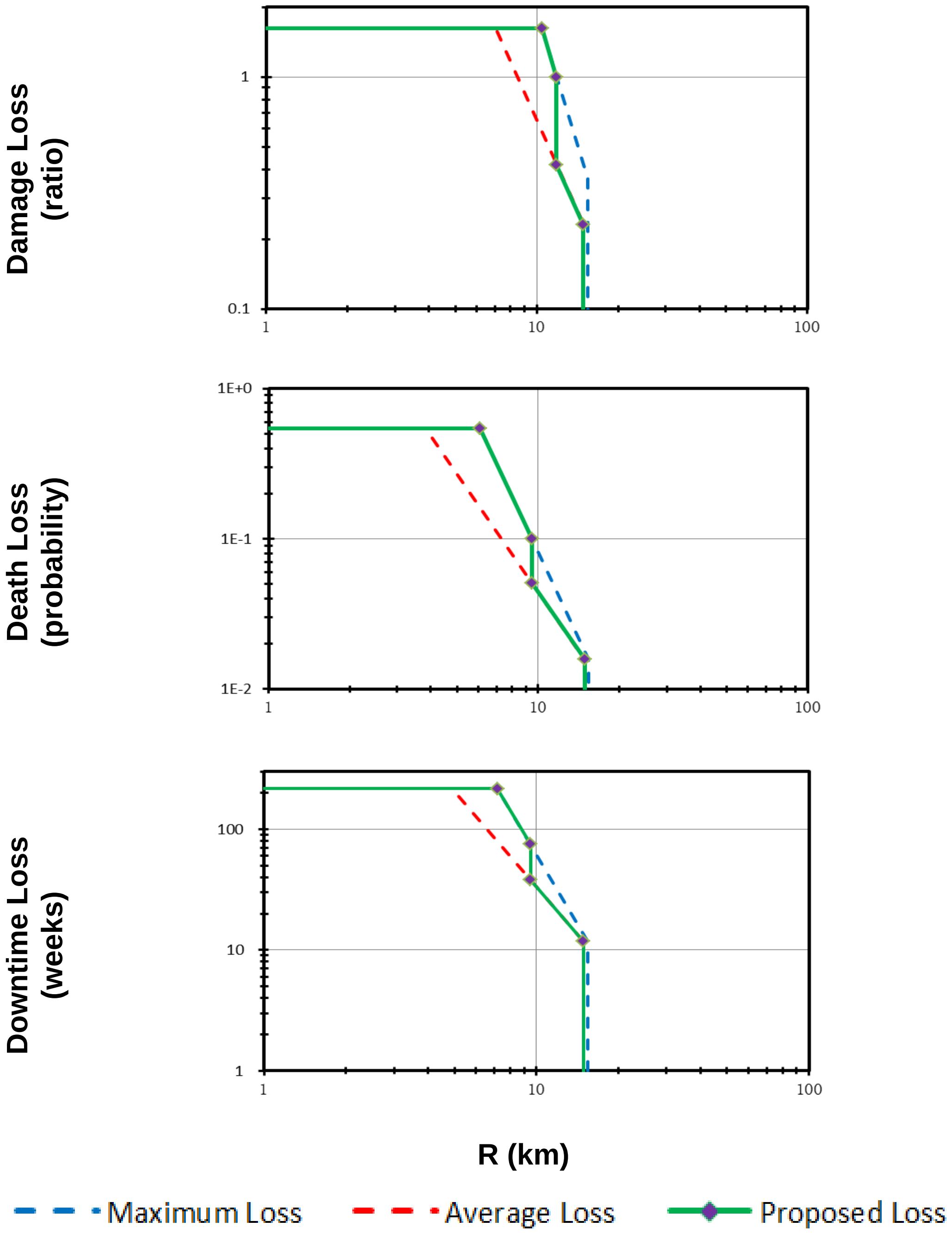


Fig. 14. Expected losses of proposed "scenario-based" 3d loss model estimation for more ductile building

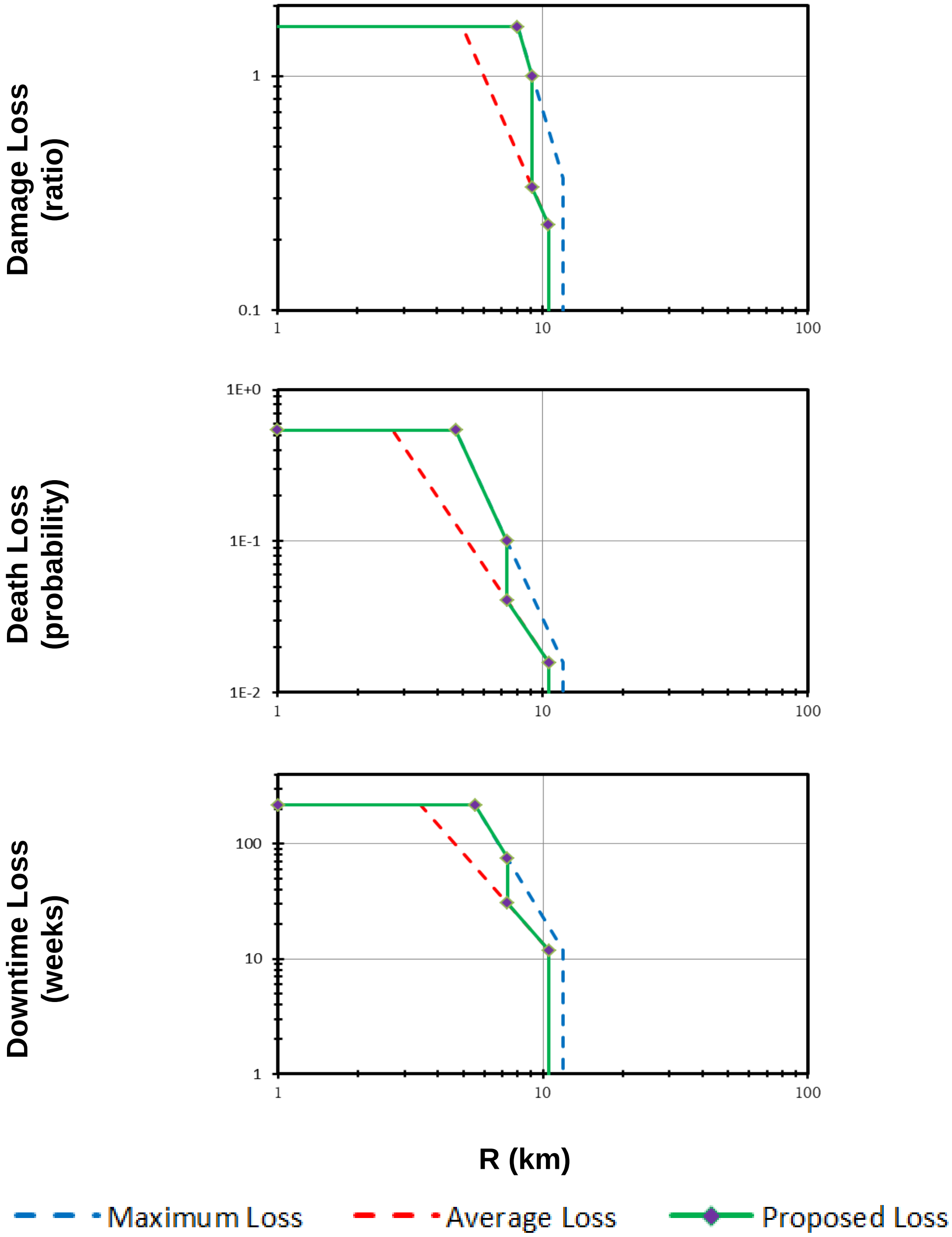


Fig. 15. Expected losses of proposed "scenario-based" 3d loss model estimation for stronger and more ductile building

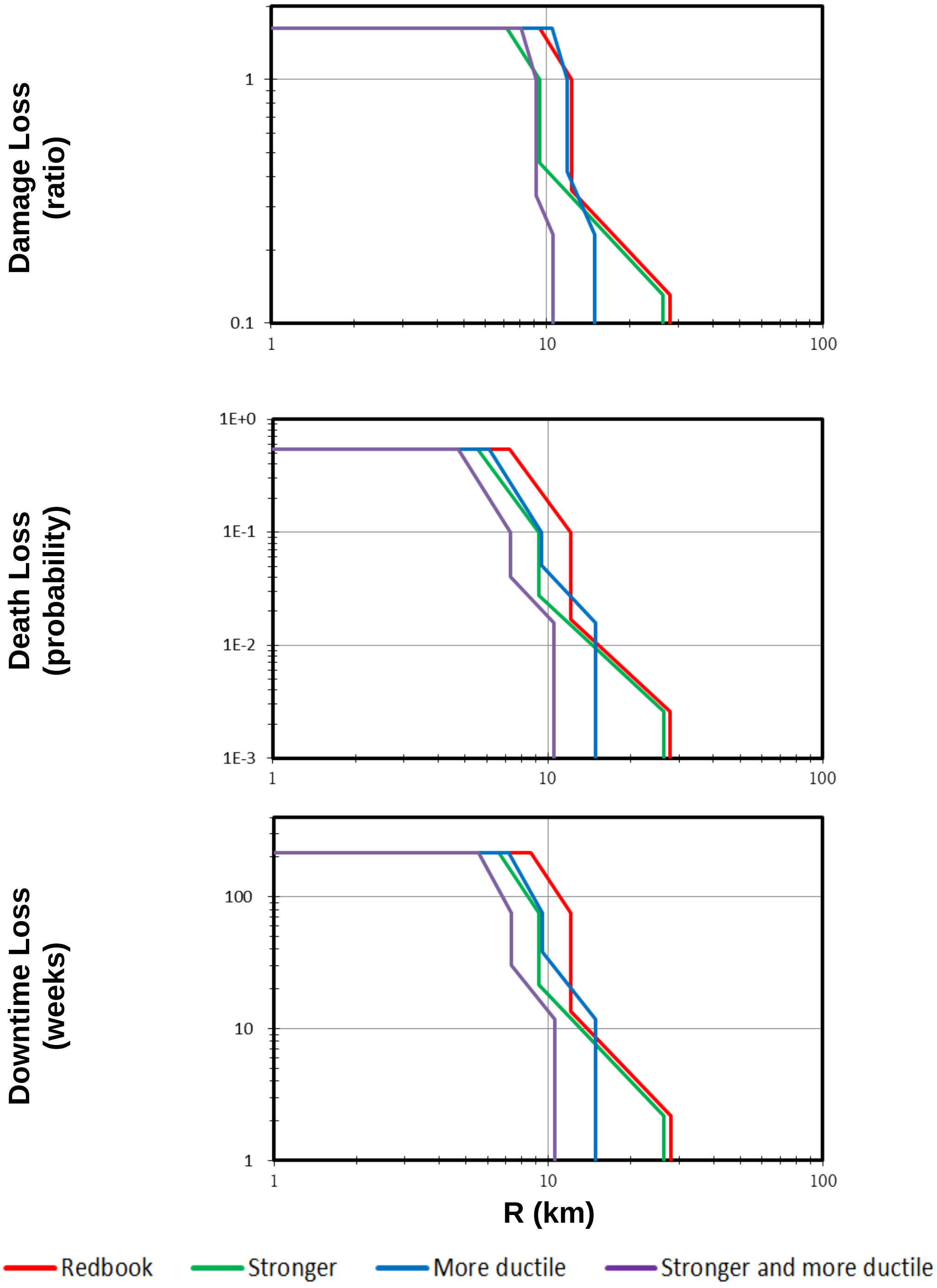


Fig. 16. Comparison of expected loss estimation results of proposed "scenario-based" 3d loss model including effects of spatial distribution of losses over height of buildings for four different types of building models

3.4 Discussion

Shown in Table 3 are the expected 3d losses at a radial distance of 17 km for the "Redbook Building" with and without considering the spatial distribution of losses over the height of buildings. After considering the spatial distribution of losses: (i) the damage loss is reduced from 50% to about 25%; (ii) the probability of death loss is reduced to about 1%; and (iii) the downtime is reduced to about 8 weeks. Therefore, the percent reduced for damage loss, death loss and downtime loss after considering the spatial distribution of losses are 50%, 75%, and 67% separately. Therefore, the estimation of seismic losses is significantly reduced after using the proposed loss model.

Table 4 presents a summary of the expected 3d seismic losses at 17 km from the earthquake epicenter for the four different types of buildings considering the spatial distribution of losses. Compared to the maximum results in Table 1, the 30% stronger building proves to be: (i) the damage loss ratio is reduced from 30% to 20%; (ii) the fatality is reduced to less than 1%; and (iii) the downtime loss is reduced from 18 weeks to 5 weeks. Clearly, the downtime loss decreases the most, which is about a 72% reduction. Therefore, after considering the spatial distribution of losses, for both the "Redbook Building" and the 30% stronger building, the downtime loss reduces the most (about 70%) compared to the damage loss and the death loss.

Table 5 shows the radial distance from the earthquake epicenter at the onset of repair as well as the onset of replacement for the four types of buildings. The onset of repair is 26 km and 15 km for the stronger building and the more ductile building respectively. Compared to the 28 km of "Redbook Building", clearly, the more ductile

Table 3. Expected 3d losses at R = 17 km for the "Redbook Building" with and without considering the spatial distribution of losses

Damage States	Not Consider	Consider	Percent Reduced
Damage Loss (ratio)	50%	25%	50%
Death Loss (probability)	4%	1%	75%
Downtime (weeks)	24	8	67%

Table 4. Expected 3d losses at R = 17 km for four different types of buildings considering the spatial distribution of losses

Buildings	Damage Loss	Death Loss	Downtime (weeks)
Redbook Building (benchmark)	25%	1%	8
30% Stronger Building	20%	1%	5
More Ductile Building	—	—	—
Stronger and More Ductile Building	—	—	—

Table 5. Radial distance from the earthquake epicenter at the onset of repair and onset of replacement for four different types of buildings

Buildings	Onset of Repair (km)	Onset of Replacement (km)
Redbook Building (benchmark)	28	12.3
30% Stronger Building	26	9.5
More Ductile Building	15	11.9
Stronger and More Ductile Building	11	9.2

building is more effective in reducing the earthquake inflicted damaged area.

The onset of replacement is 9.5 km for the stronger building and 11.9 km for the more ductile building. Therefore, there is almost no improvement in the building replacement comparing the more ductile building with the “Redbook Building” for which the onset of replacement also happens at near 12 km; and making the building stronger only moderately reduces the replacement losses.

For the both stronger and more ductile building, the distance that requires the building repair and replacement is 11 km and 9.2 km separately. Clearly, the stronger and more ductile building can evidently reduce the both repair and replacement losses and it can almost eliminate the need for repairs, since the onset of repair and the onset of replacement are at very close distances. This implies that this type of building will either perform well or suffer complete collapse directly under strong ground shaking intensities. Clearly, to remedy the collapse potential one must design the building even stronger.

3.5 Discussion of Societal Effects

Figure 17 presents a (Google) map of the Christchurch city region out to some 17 km from the epicenter of the February 22, 2011 Christchurch earthquake. The central business district (CBD) of Christchurch is shown by the white 1 mile × 1 mile square in the center of the map. The built up metropolitan region is mostly within 17 km from the earthquake epicenter, marked by the blue circular arc.

The damage loss shown in Figure 16 indicates that for the benchmark “Redbook Building”, one would expect the onset of moderate damage and the need for repairs to begin at within 28 km, while the expected onset of replacement to occur at about 12 km.

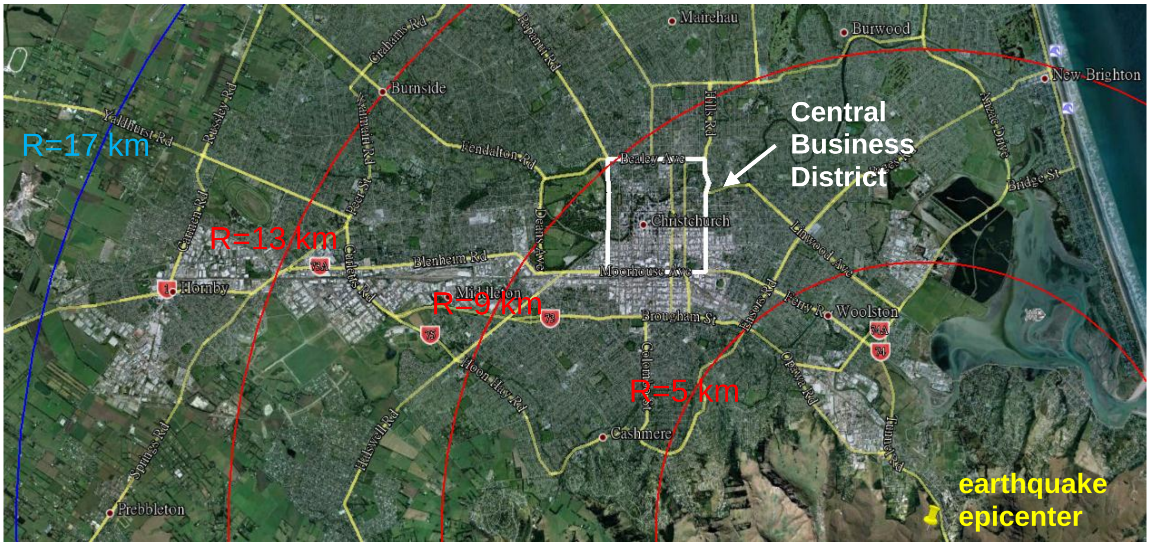


Fig.17. Christchurch district map

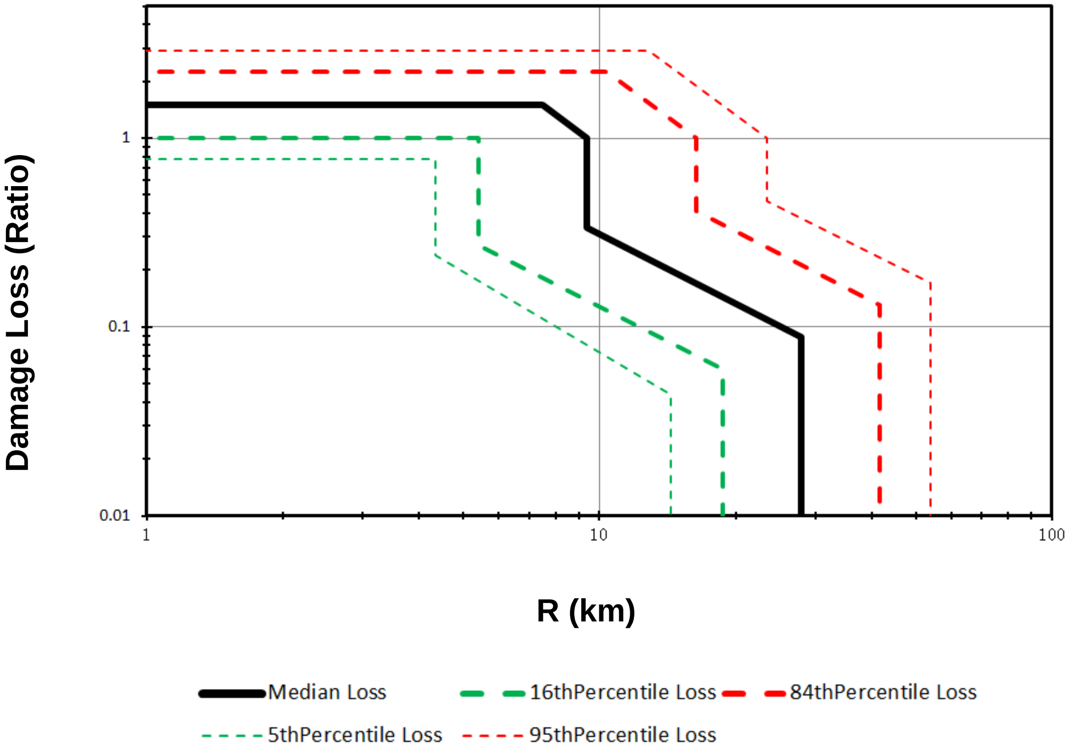


Fig.18. Various percentile damage loss for the “Redbook Building”

However, that figure does not indicate the extent of the uncertainties in these damage estimates. Therefore, given various aleatory and epistemic uncertainties, the contours showing 5th, 16th, 84th, 95th percentile damage losses are plotted in Figure 18 which indicates that:

(i) The onset of repairs may occur between 14 km to 54 km, which demonstrates that one can have 95% confidence to ensure that no building will suffer any earthquake inflicted damage beyond 54 km and the structures within 14 km definitely need to be seriously inspected and most likely repaired; and a moderate confidence may tell that buildings located from 18 km and 42 km have some possibilities of structure yielding damage.

(ii) Similarly, there is 95% possibility of a nearly 20 km (from 5 km to 25 km) transition area, from building repairs to structure reconstruction commencement; and the onset of replacement is possible up to some 17 km away from the epicenter, but there is a high likelihood that within 5 km replacement will be a certainty.

It is of interest to note that for a certain district, the closer the distance to the "onset of damage" is to the earthquake epicenter, the less the damaged land area (and hence fewer buildings) is to be expected. Therefore the cumulative seismic losses will be less. To consider this more formally, the regional seismic loss integral of the area at a certain radial distance from the epicenter in terms of the regional loss per km wide band can be expressed as:

$$L_{region} = \theta LR \tag{3.13}$$

where $\theta =$ angle of an arc within a city's limits.

Recalling the general loss model is expressed by:

$$L = L_r \left| \frac{R}{R_r} \right|^d ; L \leq L_r \tag{3.14}$$

Substituting Eq. (3.14) into Eq. (3.13) gives:

$$L_{region} = \theta \frac{L_r}{R_{ra}^{d_a}} R^{d_a+1} \;;\; R_{on} \leq R \leq R_{rr} \tag{3.15}$$

$$L_{region} = \theta \frac{L_r}{R_{rm}^{d_m}} R^{d_m+1} \;;\; R_{rr} \leq R \leq R_r \tag{3.16}$$

$$L_{region} = \theta L_r R \;;\; R < R_r \tag{3.17}$$

in which d_a = the slope in the average loss model; R_{ra} = the radial distance from the epicenter for the reference earthquake in the average loss model; d_m = the slope in the maximum loss model; R_{rm} = the radial distance from the epicenter for the reference earthquake in the maximum loss model.

Suppose that the City of Christchurch has many buildings similar to the "Redbook Building" as analyzed herein. With respect to the February 22, 2011 earthquake there is an exposure arc of some 90 degrees encompassing the city, thus $\theta = \frac{\pi}{2}$. Substitute the results for the "Redbook Building" in Eq (3.15), Eq (3.16) and (3.17) and plotting gives the graph shown in Figure 19.

From Figure 19 it is of interest to note that the city of Christchurch could not be more unlucky. This is because the CBD is located in a band from 5 km to 9 km from the epicenter where the losses are greatest as given by Eq (3.17). Beyond 9 km the loss per km as one moves further away from the epicenter is almost constant. This is because while the rate of loss attenuates with distance, the area exposed increases and the product of the two remains almost the same. This interesting finding has much significance for the insurance industry where claims will be geographically dispersed.

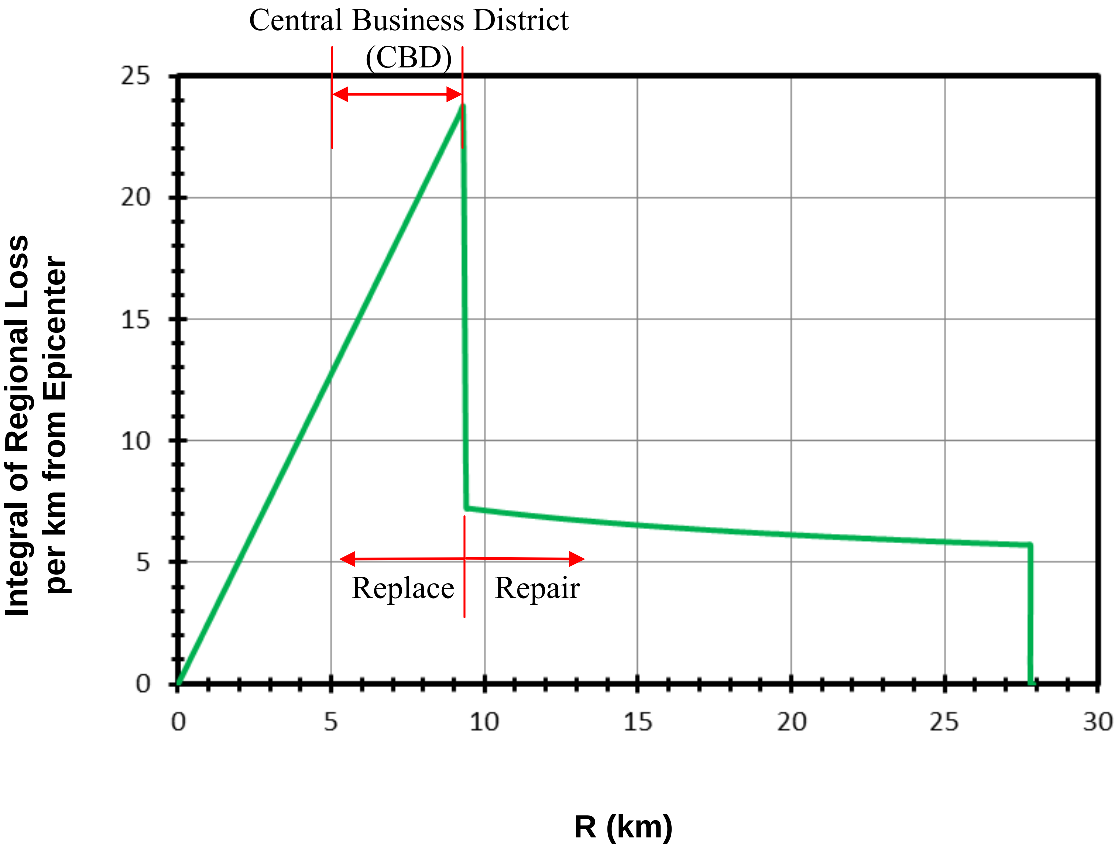


Fig. 19. Regional loss for the "Redbook Building"

3.6 Conclusions

Based on the research conducted in this section, the following conclusions are drawn:

(1) Compared to the maximum loss model, the estimated 3d losses based on the "scenario-based" 3d loss model considering spatial distribution of damage losses over the height of buildings are considerably smaller.

(2) Making a building stronger can inhibit structure collapse and therefore reduce the replacement losses, but repairs are still needed and have not been improved too much. For a more deformable building, it has distinct advantage in mitigating the damages and thus reducing the necessity for repairs, but the reconstruction should still be expected with severe ground shaking intensities. The buildings' performance and earthquake resistance can be conspicuously improved with a strengthening design and a DAD construction and the 3d losses can thus be reduced both in repair and replacement costs.

(3) When considering an area wide insurance or regional loss portfolio, as one moves away from the epicenter there is a linear increase in the aggregated losses due to complete replacement. However, beyond a certain distance (R_{rr}), repairs (rather than replacement) are only necessary. In spite of this the total values of those losses per km wide band (as measured from the epicenter) remain almost constant until suddenly they fail off.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary

Rapid seismic loss estimation is needed for the designers and owners, which enables them to be better aware of the possible financial losses so that the government and communities then are able to be better prepared for the possible 3d losses in advance. The “scenario-based” four-step 3d loss model is advanced based on the quantitative risk analysis approach developed by Mander et al. (2012). Spatial distribution of losses over the height of buildings is also taken into consideration; and the “scenario-based” 3d loss model is improved for tall building loss estimation. The seismic losses of “Redbook Building” for the February 2011 Christchurch Earthquake is examined using this method. Results show that buildings will have severe physical damage; deaths and injuries can also occur; and what needs to be paid particularly attention to is the downtime loss, which is unacceptably large and most undesirable. Therefore, except for the standard “Redbook Building”, three alternative design solutions are also studied. The first solution is to make the building stronger to increase the structure resistance to earthquake damage. The second is to keep the original structure strength and construct with more ductile details using Damage Avoidance Design (DAD). Even though both cases are shown to have good effects in reducing damage losses and improve structure performance, it is demonstrated that making structures both stronger and more deformable is the best means of limiting losses.

4.2 Conclusions

Based on this research, the following conclusions can be made:

(1) Given a specific scenario earthquake, the “scenario-based” 3d loss model works well for estimating the 3d seismic losses at a certain radial distance from the earthquake epicenter, from which a loss attenuation estimation model can be developed for that earthquake scenario.

(2) Compared to the maximum loss model, after considering spatial distribution of damage losses over the height of the buildings, the estimated 3d losses based on the “scenario-based” 3d loss models are considerably smaller.

(3) A 30% stronger building has little effect on the 3d losses before the structure collapses, which can barely help with the repair loss; but it can help inhibit building toppling, which can reduce the reconstruction demands. A more deformable building is conspicuously effective in preventing damage and thus reducing the repair needs; however, in case of severe ground shakings, structure collapse should still be expected and taken seriously. Overall, it is obvious that a strengthening building with proper DAD armoring details can achieve the best performance and has minimum 3d losses compared to the other three types of buildings.

(4) The integral of damage loss per unit distance was studied with implications for insurance underwriters. For regional loss per km from the epicenter, the building replacement loss increases uniformly with the radial distance from the earthquake epicenter; and a constant loss rate trend shows to happen for the repair cost.

4.3 Recommendations

The following aspects may be necessary for future study:

(1) Theoretical 3d loss results obtained from the model are required to be verified in practice.

(2) Experimental investigations are needed to verify the effects of the different building enhancement methods on the seismic losses.

(3) Detailed investigations on the 3d losses are required, since they are not only related to the ground shaking intensities, the usage of a structure also has significant effects on the 3d losses. For example, the number of people and values of expensive equipment are different for a residential building and a scientific lab.

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