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LOSS ASSESSMENT OF TALL BUILDINGS FROM A VULNERABILITY PERSPECTIVE

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Abstract

As the number of tall buildings in seismic areas around the world continues to grow, the ability to perform loss assessments becomes increasingly important. Due to their size, tall buildings house many businesses and/or residents, and any damage to these buildings has the potential to affect a large number of people. Furthermore, these buildings are expensive to build and repair. The financial resources needed to recover from the damage induced by earthquakes are generally not trivial amounts, and thus the ability to realistically model losses in tall buildings becomes essential.

The loss assessment of tall buildings presents unique challenges, including the tendency for significant damage to be concentrated in a few stories rather than distributed throughout the building. The presence of excessive residual drifts in one or a few stories can result in the building being declared a total loss and demolished, even when the levels of damage in the rest of the building are relatively low. Accessibility issues can increase repair costs in a tall building relative to a shorter building as, for example, it is much easier to replace the window on the 2nd story of a 5-story building versus on the 20th story of a 50-story building. The long first-mode periods of tall buildings as well as the significant contribution of higher modes means that the ground motions used to assess the structural response must be carefully considered as both the low frequency and high frequency components of the ground motion affect the response.

The evolution of building design is also an important factor in the loss assessment of tall buildings. The trend in recent years toward performance-based designs and a growing awareness for designs that reduce expected seismic losses play an important role in differentiating the expected losses of newer versus older tall buildings. This is in addition to the effects of advances in building codes and design practice that are typically seen over time, such as improvements in designing for ductility and reducing the risk of connection fractures in steel moment-resisting frames.

This study examines the loss assessment of tall buildings from a vulnerability perspective, drawing on the unique characteristics of tall buildings previously noted. It discusses how the vulnerability characteristics of tall buildings affect the relative seismic risk and uses examples of major cities in North America and New Zealand to illustrate the effects.

Keywords: risk assessment; seismic loss modeling; tall building design; performance-based earthquake engineering

1. Introduction

As the number of tall buildings in seismic areas around the world continues to grow, the ability to perform loss assessments becomes increasingly important. Due to their size, tall buildings house many businesses and/or residents, and any damage to these buildings has the potential to affect a large number of people. Furthermore, these buildings are expensive to build and repair. The financial resources needed to recover from the damage induced by earthquakes are generally not trivial amounts, and thus the ability to realistically model losses in tall buildings becomes essential.

Fig. 1 shows satellite images of the downtown areas of three US cities with significant seismic risk: (a) Los Angeles, CA; (b) San Francisco, CA; and (c) Seattle, WA. Polygons with building footprints are overlaid on the images and are colored according to the number of stories. As demonstrated by Fig. 1 buildings with at least 15 stories (hereby referred to as "tall buildings") comprise a significant portion of the building stock in these cities. Furthermore, tall buildings tend to appear in clusters, and therefore groups of tall buildings are expected to experience similar ground motions, neglecting any local site effects. If these tall building clusters experience strong ground shaking there is the potential for catastrophic consequences given the high concentration of exposure within a relatively small geographical area.

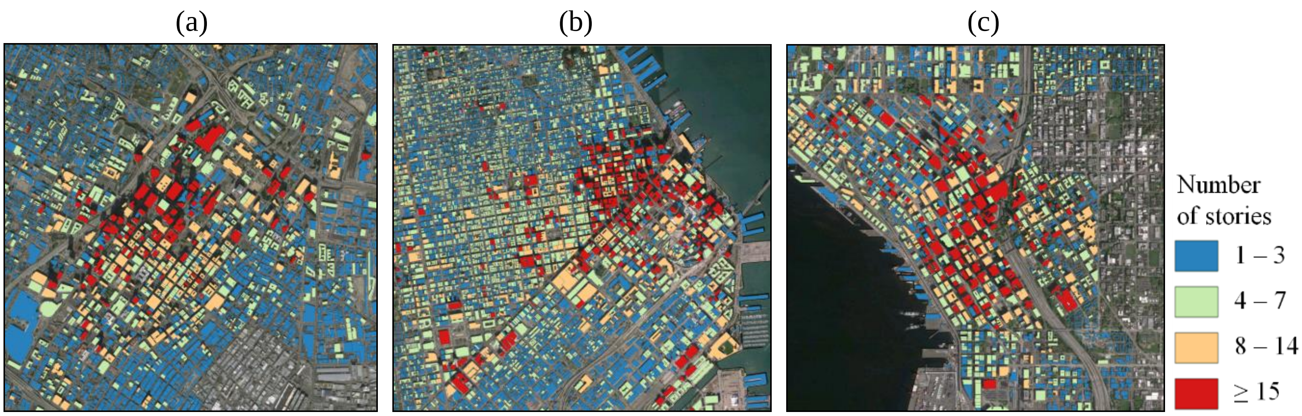

Fig. 1 – Building height distribution in selected US cities: (a) Los Angeles, CA; (b) San Francisco, CA; (c) Seattle, WA.

Severe damage to even a single tall building can also have significant consequences for the surrounding area. Due to the height of tall buildings, the zone impacted by a collapsed tall building and related debris can be large. This was observed in the 22 February 2011 Christchurch earthquake with respect to the 26-story Hotel Grand Chancellor, where fears of collapse due to severe damage sustained in the earthquake caused authorities to initially cordon off a 90-meter radius around the building [1]. Not only were tenants not allowed to access their properties, but even urban search and rescue (USAR) teams were prevented from operating within the area. One week after the earthquake USAR teams were still prevented from accessing buildings within a block in front of the Hotel Grand Chancellor as stabilization works had not been completed. Fortunately the building was eventually stabilized and was later demolished in a controlled fashion, but significant business interruption losses were sustained, including losses to buildings in the surrounding area due to the cordon.

This paper focuses on the loss assessment of tall buildings from a vulnerability perspective, where vulnerability is defined as the expected loss divided by the building replacement cost and conditioned on the ground motion intensity. Factors distinguishing tall buildings from lower-rise buildings are first discussed, and then the evolution of tall building design over time is discussed as it relates to vulnerability. Examples using cities in the North America and New Zealand are provided to highlight these effects.

2. Distinguishing features of tall buildings

From a vulnerability and loss assessment perspective, tall buildings have a number of features that differentiate them from lower-rise buildings. This section discusses the difference in the responses of tall buildings versus lower-rise buildings and how the responses affect the relative vulnerabilities.

2.1 Differences in building response

The PEER Tall Buildings Initiative [2] defines three unique characteristics of a tall building:

1. a fundamental translation period of vibration significantly in excess of 1 second
2. significant mass participation and lateral response in higher modes of vibration
3. slender aspect ratio of the seismic-force-resisting system

The first two characteristics defined above have important implications when selecting ground motions for assessing the seismic performance of tall buildings. Because the response of a tall building has significant participation from multiple modes, the range of periods considered in ground motion selection can be much wider than for a lower-rise building, where only the first couple of modes might be important for the building response. The long first-mode period of tall buildings means that care must be taken to ensure that long-period content is captured in the ground motion records and is not excluded due to the particular features of the accelerometer or the filter frequency used to process recordings, for example. These factors can lead to a lack of suitable ground motions when trying to select hazard-consistent ground motions. Thus, often amplitude- and frequency-modified or even simulated ground motions are used for the performance assessment of tall buildings.

The response of low-rise buildings tends to be dominated by the first mode of vibration, and thus the story drift ratios are often relatively similar along the height of low-rise buildings responding elastically or with low levels of nonlinearity in the structural members. In such cases the damage to structural and non-structural drift-sensitive components, which can represent well over 50% of the total building value in commercial and residential buildings [3], can be fairly well distributed along the height of the building. In contrast, for tall buildings the significant participation of higher modes in the response often leads to a non-uniform distribution of story drift ratios along the height. This is demonstrated in Fig. 2, which shows the mean story drift ratios along the height of a 40-story steel moment-resisting frame (MRF) structure designed according to the 1973 Uniform Building Code (UBC) for a site in San Francisco, CA. The mean story drift ratios are obtained via nonlinear response history analyses using ground motions where the 5%-damped spectral acceleration at a period to 5 seconds (Sa(5 s)) is equal to 0.1 g, which is associated with a return period of approximately 400 years at the design site. Details about the design and modeling of the MRF as well as the ground motion selection are provided by Molina Hutt et al. [4]. As shown in Fig. 2, the story drift ratios for this particular building tend to be significantly higher in the upper third of the building, especially for stories 30 through 35.

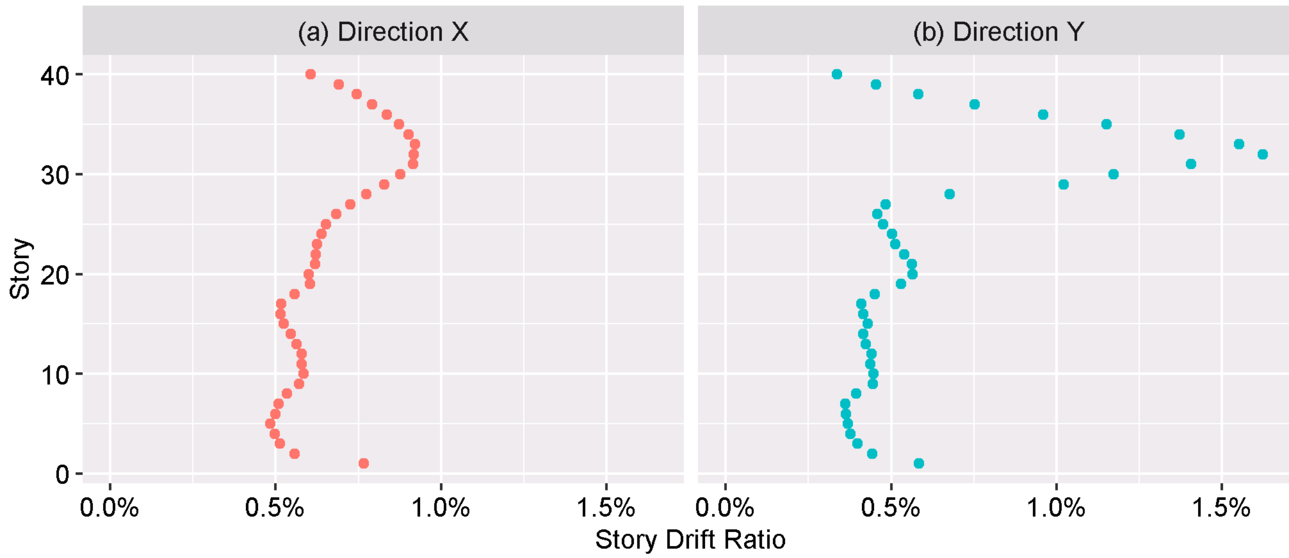

Fig. 2 – Mean story drift ratios for Sa(5 s) = 0.1 g: (a) Direction X; (b) Direction Y. Note: Direction X is 80 ft (24.4 m) in plan while Direction Y is 120 ft (36.6 m) in plan [4]

The concentration of large story drift ratios in just a few stories of a tall building was also observed by researchers who conducted loss assessments on modern tall buildings, including Shome et al. [5], who evaluated a 42-story reinforced concrete (RC) core-wall structure and a 42-story RC dual-system structure, and Ramirez et al. [6], who evaluated RC MRF structures between 1 and 20 stories. Ramirez et al. also noted that the concentration of large story drift ratios in tall buildings tends to increase with increasing ground motion intensity.

2.2 Differences in building vulnerability

The concentration of large story drift ratios seen in tall buildings has important implications for building vulnerability and loss assessment, as it leads to a large proportion of damage and overall building loss coming from a relatively small number of stories. Ramirez et al. [6] observed that damage concentration was actually beneficial for tall buildings from a vulnerability perspective as, compared to shorter buildings, the damaging drifts were limited to a smaller fraction of the building, and thus normalized repair costs were reduced. However, they also noted that this concentration of damage leads to a higher risk of sidesway collapse in taller buildings compared to shorter buildings. The concentration of damage in tall buildings is not only limited to cases in which the ground motion is strong enough to cause large story drift ratios, as Shome et al. [5] observed that even when tall building losses were dominated by nonstructural losses (due to small story drift ratios at low ground motion intensities) there was still a significant concentration of damage in just a few stories. Their analyses found that at low ground motion intensities both the core-wall and dual-system structures had losses concentrated in the top few stories, which were driven by a whiplash effect.

Between the extremes of no damage and total collapse, building stakeholders must determine whether a damaged building is economical to repair or whether it is better to demolish it. In many cases the decision to repair versus demolish is obvious, but there are cases in which the cost to repair the damage can be similar to the total building value. This is of particular importance for tall buildings where a few stories may have severe damage while the majority of stories may have relatively low levels of damage. Considering the former case from a purely damage-based perspective and ignoring repair costs, the overall damage ratio of the building (i.e. the average damage ratio over all stories in the building) may only be a moderate value; however, the costs associated with repairing the severely damaged stories can be so significant that it becomes more economical to demolish the building. The 2010 – 2011 Canterbury earthquake sequence in New Zealand provides some examples of tall buildings that were demolished due to damage sustained during the earthquakes, which are shown in Fig. 3:

- The 26-story Hotel Grand Chancellor seen in Fig. 3(a) was demolished after a local failure at the base of a shear wall during the 22 February 2011 event caused the southeast corner at the top of the structure to displace 0.8 m (2.6 ft) vertically and 1.3 m (4.3 ft) laterally [7].
- The 20-story Clarendon Tower seen in Fig. 3(b) was demolished after it sustained extensive cracking in the floor diaphragms, leading to fears that support for the some of the floor system might be lost, as well as damage caused by frame elongation [7]. The frame damage was most extensive at the mid-height stories, where peak story drift ratios were estimated to reach between 1.3% and 2.8% [8, 9].
- The 22-story PricewaterhouseCoopers building seen in Fig. 3(c) was demolished after it was deemed too costly to repair. As with the Clarendon Tower, the most severe damage occurred at the mid-height stories. Structural damage to the PricewaterhouseCoopers building included the formation of plastic hinges in the beams of the RC frame on levels 6 through 8 [10].

(a) (b) (c)

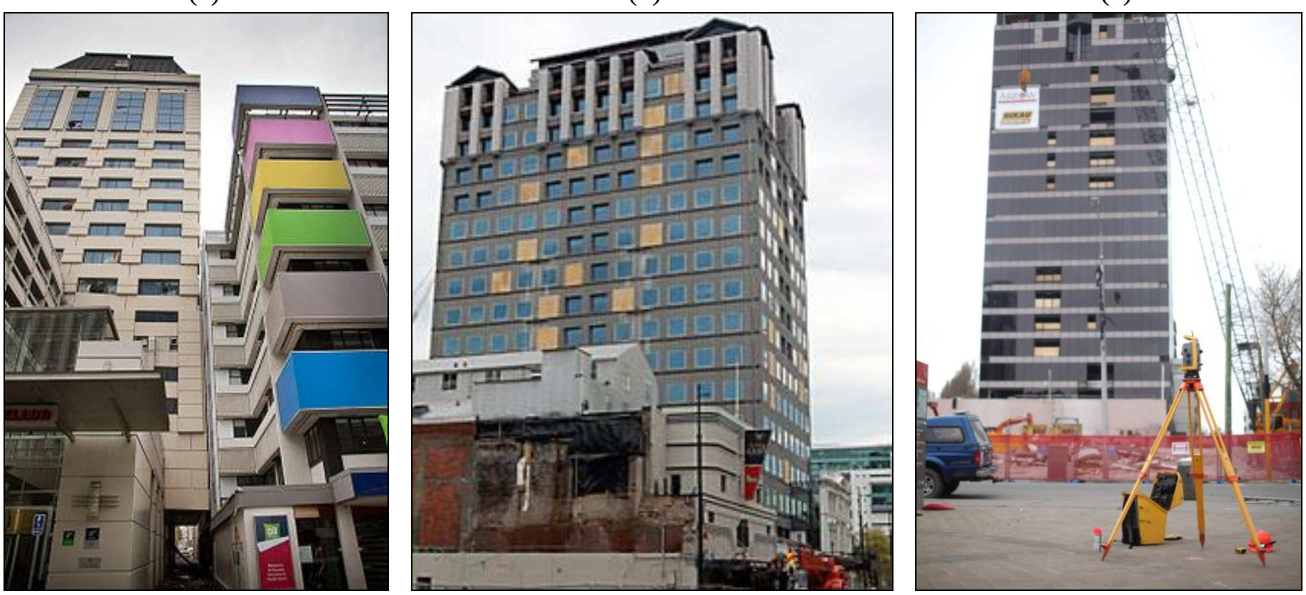

Fig. 3 – Buildings damaged during the 2010 – 2011 Canterbury earthquake sequence that were subsequently demolished: (a) Hotel Grand Chancellor[1]; (b) Clarendon Tower[2]; (c) PricewaterhouseCoopers building[3]

Some analytical studies have compared the vulnerabilities of tall versus shorter buildings. Many of these studies evaluate the average annual loss (AAL), which is the average loss expected in one year and depends on both the building vulnerability and the seismic hazard at the site. Jayaram et al. [11] compared the AAL and 500-year return period loss values of 20- and 40-story steel MRFs in Los Angeles, CA for both modern and 1970s-era buildings. They found that for both loss metrics the loss ratio (i.e. loss normalized by building replacement cost) of the 40-story building was approximately 90% of the loss ratio of the 20-story building, given that both buildings were designed in the same era. Ramirez et al. [6] compared losses for modern RC MRFs of 1, 2, 4, 8, 12 and 20 stories in Los Angeles, CA, using the AAL and the loss conditioned on the ground motion intensity associated with the design basis earthquake (DBE) for each structure, which was approximately equal to the intensity with a 10% probability of exceedance in 50 years. They found that with the exception of the one-story buildings the loss ratios associated with the DBE tended to decrease with height. They attributed this trend to the

[1] https://en.wikipedia.org/wiki/Hotel_Grand_Chancellor,_Christchurch

[2] http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/6567773/Clarendon-Tower-a-horror-story

[3] http://www.foxsurvey.co.nz/2012/06/demise-of-the-pwc

concentration of large drift demands and associated damage in taller buildings, which reduced normalized repair costs. When looking at AAL the trend was not as clear, as the AAL generally increased from one to four stories, was similar for four and eight stories, and then decreased beyond eight stories.

When comparing the vulnerabilities of a similar class of buildings (where similar refers to the location, structural system, and design and construction practices), one might expect tall buildings to be less vulnerable than shorter buildings at low to moderate levels of ground shaking, given the reduction in normalized repair costs from damage concentration observed by Ramirez et al. [6]. However, as the shaking intensifies the damage concentration in tall buildings can eventually become less beneficial as it leads to increasing probabilities of the building being a total loss, either from damage or residual drifts that are uneconomical to repair or from collapse. Thus one might expect that for very high levels of ground shaking tall buildings may be more vulnerable than shorter buildings.

It is important to understand that the general expectations about the relative vulnerabilities outlined above are not strict rules and that the vulnerabilities of tall versus shorter buildings can be influenced by a number of factors. For example, from a structural perspective the ductility and particular structural system can play a role. A non-ductile building is expected to have a higher probability of collapse compared to a ductile building, so the vulnerability of a non-ductile tall building would therefore increase much faster and drive the point at which short and tall vulnerabilities are similar to a lower ground motion intensity compared to a ductile tall building. The structural system can also affect the relativity. One example is the difference between perimeter frames versus space frames, as the structural damage in perimeter frames tends to be more concentrated. In the Ramirez et al. study [6] of modern RC MRFs, they found that damage concentration resulted in a 15% reduction in losses for perimeter frames compared to space frames at the DBE level. However, in a study of 1960s-era non-ductile RC MRFs Ramirez and Miranda [12] found that the DBE-level losses and AALs were higher for perimeter frames compared to space frames for 4-story, 8-story and 12-story structures, but not for 2-story structures. For the 12-story structure, which was the tallest structure they investigated, the loss at the DBE level was approximately 50% greater for the perimeter frame, and the AAL was almost double that of the space frame. The reason for this reversal in trend compared to the modern structures is that the non-ductile design of the 1960s-era buildings contributed to a significantly greater risk of collapse, and the damage concentration seen in perimeter frames further increased the collapse risk as the structural members had limited deformation capacity between the onset of yield and brittle failure. When comparing the vulnerability of the 2-story to the 12-story structures using the ratio of AAL values, the space frames had a ratio of approximately 3:1 while the perimeter frames had a ratio of approximately 1.5:1. These examples highlight that the relative vulnerability of buildings can be quite sensitive to the particular features of the structures considered and the particular intensity level or loss metric.

In addition to structural properties, the particular location can also affect the relative vulnerability, as local site effects such as soil type and presence of a basin, the distance from seismic sources, and source magnitudes can all influence the response of tall versus shorter buildings. The 1985 Mexico City earthquake is a prime example of this as the level of damage was highly correlated with local soil conditions as well as the building height. The highest building damage occurred within the basin where soft clay layers significantly amplified the ground motions, with buildings between approximately 6 and 18 stories experiencing the most severe damage. Seed et al. [13] found that the degree of amplification and the frequencies that were amplified could vary significantly with small changes in the shear wave velocity of the clay, even for sites with similar soil depths and stiffness values. Thus, the local site effects can cause buildings within a certain period range to experience relatively weaker or stronger shaking compared to other period ranges, which influences the relative vulnerability. The source distances and magnitudes also affect the frequency content of the ground motions, which is reflected in ground motion prediction models, and can affect the duration of strong shaking as well.

3. Evolution of tall building design

The evolution of tall building design over time can play a significant role in the vulnerability of tall buildings. In more recent years the trend toward performance-based designs and a growing awareness for designs that reduce expected seismic losses play an important role in differentiating the expected losses of newer versus older tall buildings. Advances in building codes and design practice that are typically seen over time, such as improvements in designing for ductility and reducing the risk of connection fractures in steel moment-resisting frames, also impact the vulnerability.

A number of researchers have investigated the vulnerability of tall buildings as it relates to the evolution of building design. Molina Hutt et al. [4] conducted a loss assessment of an archetypical 40-story steel MRF structure designed according to the 1973 UBC for a site in downtown San Francisco, CA. They found that the collapse risk of this building was five to seven times greater than the collapse risk implied by modern building codes for new buildings. For ground motion intensities greater than Sa(5 s) = 0.14 g, which is associated with a 400-year return period at the site, the expected losses were dominated by structural collapse. Steel MRFs designed in the western US during this era are particularly vulnerable due to their susceptibility to brittle failure at column splices and to fracture at beam-column moment connections, as was observed in the 1994 Northridge earthquake.

In a related study Molina Hutt compared the relative vulnerability of 1970s-era versus modern steel MRF buildings in downtown San Francisco, CA, this time using 50-story structures. The 1973 UBC was again used to design the 1970s archetype while the 2012 International Building Code (IBC) was used to design the modern archetype. Major differences in the designs of these buildings include the use of space frames for the 1970s archetype versus perimeter frames for the modern archetype, the presence of fracture-prone beam-column moment connections in the 1973 design versus reduced beam sections in the 2012 design that encourage strong column-weak beam behavior, an increase in design forces from 1973 to 2012 resulting in the modern archetype having an effective design base shear approximately double that of the 1970s archetype, and the lack of code-required drift limitations in the 1973 UBC. However, drift limits of 0.0025 under wind and 0.005 under seismic loads were used in the design of the 1970s-era structure as engineers indicated this was the practice at the time. The design and modeling of the structures were consistent with what is described in [14], except 2D structural models were employed and expected values were used for structural component properties instead of randomly simulating the values. At each intensity level of interest the ground motions were selected using a conditional spectrum conditioned at 5 seconds, which was constructed using hazard deaggregations obtained from the USGS (geohazards.usgs.gov). Loss assessment was performed using SP3 (hbrisk.com). As expected, the 1970s archetype is significantly more vulnerable than the modern archetype. The 1970s archetype has a much higher collapse risk, due largely to the vulnerabilities described for the 40-story structure in the Molina Hutt et al. study [4].

Fig. 4 compares the loss breakdown as a function of ground motion intensity for the 1970s archetype versus the modern archetype. The expected losses are broken down into three components: losses due to non-collapse where the building is (1) damaged and repaired, or (2) demolished due to excessive residual drifts that are uneconomical to repair, and (3) losses due to collapse. The expected component losses are computed as the expected value of loss given the building response multiplied by the probability of that building response (i.e. either the structure not collapsing and being repairable, the structure not collapsing but being demolished, or the structure collapsing). The contribution from each component is computed as the expected component loss normalized by the sum of losses from all three components. The larger collapse risk of the 1970s archetype is evident in Fig. 4. At a ground motion intensity of Sa(5 s) = 0.1 g, which is associated with a 200-year return period at the site, over 50% of the loss for the 1970s archetype is due to collapse, whereas the modern archetype has a negligible amount of loss due to collapse. Instead, the losses for the modern archetype at this intensity are due mostly to repairable damage (approximately 75%). Fig. 4(b) highlights that while collapse is not a significant contributor to the losses of the modern archetype at low to moderate intensities, there is a significant component of the loss coming from demolition. For intensities greater than Sa(5 s) = 0.2 g, which is associated with an 800-year return period at the site, the losses from demolition are actually larger than the losses from repairable damage. Even though the structure has only a 1% probability of collapsing at an intensity of Sa(5 s) = 0.2 g, it has a 45% probability of being demolished due to excessive residual drifts. The low probability of collapse is great from a life-safety perspective, but the significant probability of demolition may be concerning from an economic and societal perspective.

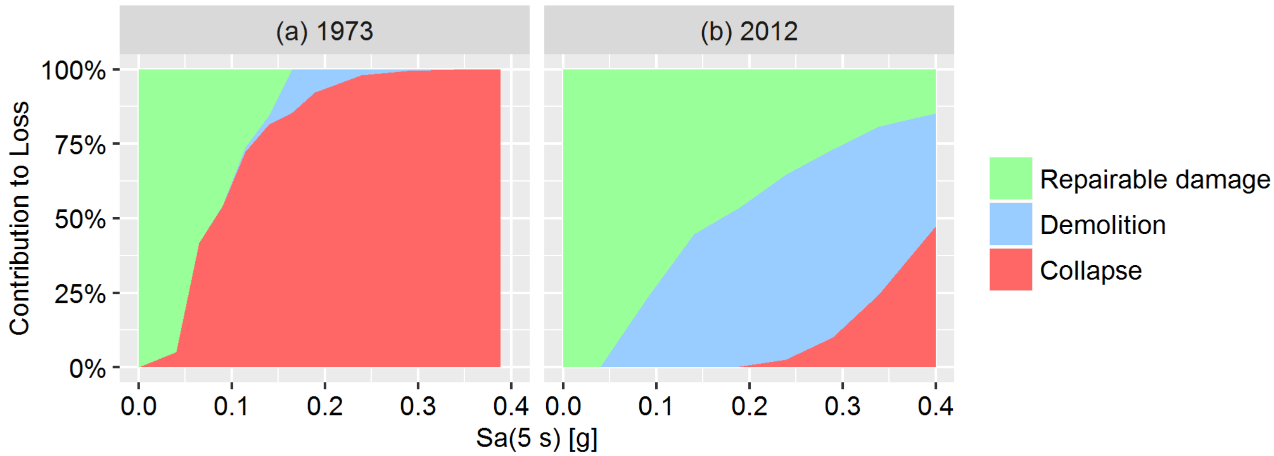

Fig. 4 – Breakdown of loss by component as a function of ground motion intensity for 50-story steel MRF in San Francisco, CA for buildings designed in different years: (a) 1973; (b) 2012.

Jayaram et al. [11] also compared the relative vulnerabilities of modern versus 1970s-era steel MRFs. They made comparisons for both 20-story and 40-story structures located in Los Angeles, CA. The 1970s-era buildings were designed according to the 1973 UBC while the modern buildings were designed according to the 2006 IBC. As in the Molina Hutt study, a drift limit was imposed for the 1973 design as it was the practice at the time, even though it was not required by the code. Jayaram et al. found that the AAL and 500-year return period losses were approximately 45% and 35% greater, respectively, for the 1970s-era structures compared to a modern structure of the same height.

Finally, as part of the PEER Tall Buildings Initiative [2] the vulnerabilities of tall buildings designed using the prescriptive approach of modern buildings codes (in this case the 2006 IBC) were compared to those designed using performance-based guidelines. The performance-based design guidelines were developed with the aim of improving the seismic performance of tall buildings and include additional serviceability requirements. They also enable the design of systems that are precluded by some building codes, such as those with innovative structural systems or those that exceed height requirements. The building designs and loss assessments were conducted for a site in Los Angeles, CA, and three different structural configurations were examined: a 42-story RC core-wall structure, a 42-story RC dual-system structure and a 40-story buckling-restrained braced (BRB) steel frame structure. Analytical loss assessments conducted by Shome et al. [5] showed that both the AAL and the return period loss ratios were lower for the buildings designed according to PEER’s performance-based guidelines than those designed according to the code. For the dual-system structure the performance-based design resulted in an approximately 10% reduction in the AAL compared to the code-based design, while for both the core-wall and BRB frame systems the performance-based designs resulted in an approximately 20% reduction in AAL. Similar loss reductions were observed at the 500-year return period.

4. Conclusions

This paper examined the loss assessment of tall buildings from a vulnerability perspective. Distinguishing features of tall buildings were highlighted, including the long first-mode periods and the significant contribution of higher modes in the structural response. The tendency for losses to concentrate in a few stories of a tall building was discussed. While damage concentration can reduce the vulnerability at low to moderate ground motion intensities where the structural damage is minor, it can also increase the vulnerability of structures at high levels of ground motion intensity due to higher probabilities of collapse or demolition due to excessive residual drifts. The ductility of the structure can also affect whether the damage concentration is beneficial from a vulnerability perspective. Several studies were cited that found normalized losses of similar structures typically decrease with building height; however, it was cautioned that a number of factors can influence the relative vulnerabilities. The 1985 Mexico City earthquake was used as an example, as the most severe damage was typically observed in mid- to high-rise structures due to the basin amplifying certain frequencies in the ground motion. The evolution of building design as it affects tall building vulnerability was also discussed. It was shown that while modern structures may have reduced vulnerabilities due to better designs and lower collapse risks, demolition of these structures due to excessive residual drifts can still contribute significantly to the losses. Finally, a study was cited that compared the vulnerabilities of tall buildings designed by modern building codes versus those designed by performance-based guidelines. This study found that buildings designed with the performance-based guidelines were approximately 10% to 20% less vulnerable.

5. Acknowledgements

Any opinions, findings and conclusions or recommendations expressed in this manuscript are those of the authors and do not necessarily reflect those of Risk Management Solutions, Inc.

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