Improved Estimation of Collapse Risk for Structures in Seismic Regions

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SUMMARY
This paper discusses aspects related to improving collapse risk estimation with an emphasis on reducing both the uncertainty in the estimate and the required computational effort. Collapse risk is measured via the mean annual frequency of collapse (λ_c), which combines the seismic hazard and the structure's collapse fragility (the probability of collapse conditioned on ground motion intensity). Deaggregation of λ_c by intensity is used to identify the intensities that primarily contributing to a structure's λ_c. Finally, a proposed method for estimating λ_c is discussed. This method uses a limited number of intensities to estimate the collapse fragility and provides guidance on the number and level of intensities at which analyses are conducted. Results indicate that in most cases conducting analyses at only two intensities yields adequate estimations of λ_c. This method is applied to a case study of structure and is shown to estimate λ_c efficiently and with reasonable accuracy.

Keywords: collapse, performance-based earthquake engineering, deaggregation

1. INTRODUCTION

While a fundamental objective of building codes has been protection against collapse, the collapse risk of structures has not been explicitly quantified until recently. Advances in computational power and the development and validation of analytical models that capture a structure's behavior as it approaches collapse have made explicit quantification of the collapse risk possible, and the advent of performance-based earthquake engineering has made collapse risk quantification necessary as it is a required component in estimating direct monetary losses, downtime, and fatalities.

This paper discusses aspects related to improving estimation of the collapse risk with an emphasis on reducing both the uncertainty in the estimate and the required computational effort. This paper quantifies collapse risk via the mean annual frequency of collapse (λ_c), which combines the seismic hazard at the site and the structure's collapse fragility (the probability of collapse conditioned on ground motion intensity). Deaggregation of λ_c is discussed and is used to identify the ground motion intensities that primarily contribute to the collapse risk. A method for estimating λ_c is presented that uses λ_c deaggregation to select a limited number of ground motion intensities at which nonlinear response history analyses (RHAs) are conducted and then constructs the collapse fragility curve based on the analysis results. This method is applied to a case study of a four-story steel moment-resisting frame structure, and the computational effort and epistemic uncertainty in the λ_c estimate are compared to the λ_c estimate obtained when the collapse fragility curve is constructed via the commonly used incremental dynamic analysis (IDA) method (Vamvatsikos & Cornell 2002).

2. COLLAPSE RISK ASSESSMENT

A number of metrics exist for quantifying the collapse risk including the probability of collapse at a given ground motion intensity (which is often associated with a specific hazard level) and the collapse margin ratio, which is a ratio of a structure's median collapse intensity to the intensity that has a 2% probability of exceedance in 50 years at the site. The intensity of the ground motion is described by an intensity measure (*IM*) such as the 5%-damped spectral acceleration at the structure's first mode period ($Sa(T_1)$). Metrics that account for both the seismicity at the site and the structural response are desirable because they allow the collapse risk of different structures in different sites to be directly compared. Because the manner in which the seismic hazard varies with intensity (i.e., the shape of the seismic hazard curve) can differ widely between sites, a collapse risk metric that considers only a single ground motion intensity can give a distorted view of the relative collapse risks of structures in different sites compared to the collapse risks measured by λ_c. Therefore, this paper uses λ_c because it considers the site, the structure, and all ground motion intensities that contribute to the collapse risk.

Two components are required to compute λ_c: (1) the seismic hazard curve, which gives the mean annual frequency of exceeding ground motion intensities at the site, and (2) the structure's collapse fragility curve. The collapse fragility curve is integrated over the seismic hazard curve to give λ_c as follows (Medina & Krawinkler 2002)

$$\lambda_c = \int_0^\infty P(C \mid im) \cdot \left| d\lambda_{IM}(im) \right| \tag{2.1}$$

where $P(C \mid im)$ is the probability that the structure will collapse when the ground motion has an intensity *im*, and λ_{IM} is the mean annual frequency of exceedance of ground motion intensity *im*. Eqn. 2.1 can be rewritten as

$$\lambda_c = \int_0^\infty P(C \mid im) \cdot \left| \frac{d\lambda_{IM}(im)}{d(im)} \right| d(im) \tag{2.2}$$

where $d\lambda_{IM}(im)/d(im)$ is the slope of the seismic hazard curve. Eqns. 2.1 and 2.2 are typically solved via numerical integration as a closed-form solution generally does not exist.

2.1 Relationship between λ_c and probability of collapse

The mean annual frequency of collapse λ_c describes the mean rate of collapse per year. The probability of collapse over *t* years can be computed via the following equation, assuming the occurrence of earthquakes in time follows a Poisson process

$$P_c(over\ t\ years) = 1 - \exp(-\lambda_c t) \tag{2.3}$$

2.2 Collapse fragility curve

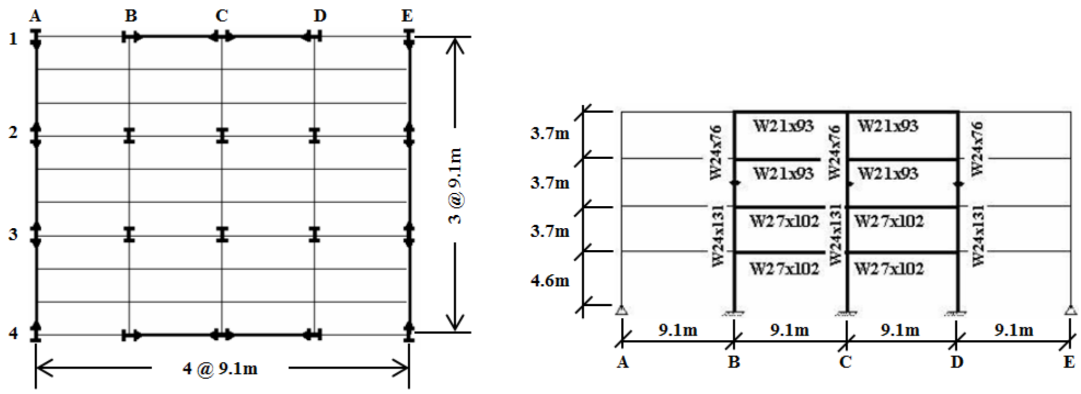
The most significant computational effort in collapse risk assessment is associated with obtaining the collapse fragility curve, which describes the structure's probability of collapse as a function of ground motion intensity. An approach that has been used extensively in recent years to obtain the collapse fragility curve (e.g., Zareian & Krawinkler 2007; Haselton et al. 2008) is to identify the collapse intensity (the minimum ground motion intensity that causes the structure to collapse) of each ground motion in a set of ground motions and then fit a cumulative distribution function to the collapse intensities. The lognormal distribution is widely used for the collapse fragility curve as previous studies have concluded, based on goodness-of-fit tests, that collapse intensities can be assumed to be lognormally distributed (Ibarra & Krawinkler 2005; Bradley & Dhakal 2008; Ghafory-Ashtiany et al. 2011). The collapse intensity, which is dependent on both the structure and the ground motion, is typically found using IDA (Vamvatsikos & Cornell 2002). For each ground motion, this process involves repeating nonlinear RHAs of the structure with the ground motion scaled to increasing intensity levels until collapse occurs. Once a ground motion intensity is encountered that causes collapse, additional analyses are typically performed within the last interval of intensities to determine the collapse intensity within a specified tolerance.

3. CASE STUDY

This section presents the structure, site, and ground motions used in the collapse risk assessment case study and discusses the results. In this study collapse is defined as lateral dynamic instability, which is commonly called the sidesway mode of collapse. Loss of vertical carrying capacity is not considered.

3.1 Structure and modeling

This study uses a four-story office building that resists lateral loads with steel special moment frames (SMFs) (Lignos et al. 2011). The SMFs include reduced beam sections (RBS) and were designed in accordance with the 2003 International Building Code (ICC 2003) and the 2005 AISC seismic provisions (AISC 2005a, b) using design spectral ordinates S_{DS} and S_{D1} of 1.0 g and 0.6 g, respectively. Fig. 3.1(a) shows the plan view of the structure. Fig. 3.1(b) shows an elevation of the SMFs along lines 1 and 4, which are the focus of this case study. The first three modal periods of these frames are 1.33 s, 0.43 s, and 0.22 s, respectively.



(a) (b)

Figure 3.1 4-story steel structure: (a) plan view and (b) elevation view on line 4

Due to symmetry, only one of the SMFs was modeled in OpenSees (2009). The frame members were modeled as elastic elements with nonlinear rotational springs at their ends as discussed by Lignos et al. (2011). The rotational springs utilize a modified version of the Ibarra-Medina-Krawinkler deterioration model (Ibarra & Krawinkler 2005) that includes rules for stiffness and strength deterioration, including in-cycle strength deterioration. Specific details of the deterioration model and the deterioration parameters used for the rotational springs are provided by Lignos and Krawinkler (2011). A leaning column carrying gravity loads was connected to the SMF by axially rigid elements pinned at both ends to simulate P-Δ effects.

3.2 Site and seismic hazard

The Bulk Mail Center (33.996° N, −118.162° W) near Los Angeles, California, USA is selected as the site. It represents a typical site in urban California with high seismicity that is not dominated by unusually strong near-fault effects (Haselton et al. 2008). The seismic hazard curve for $Sa(T_1)$ is obtained via the Java Ground Motion Parameter Calculator from the USGS (2011). Because hazard curves are only available for select periods, the seismic hazard curve for T = 1.33 s was obtained via linear interpolation of the T = 1 s and T = 2 s hazard curves in log-log domain and then modified by a site amplification factor of 1.5 to adjust the values to NEHRP site class D, the soil condition at the site

(Haselton et al. 2008). The resulting seismic hazard curve for T_1 = 1.33 s is shown in Fig. 3.2 and describes the mean annual frequency (λ_{Sa}) of exceeding $Sa(T_1)$ values at the site.

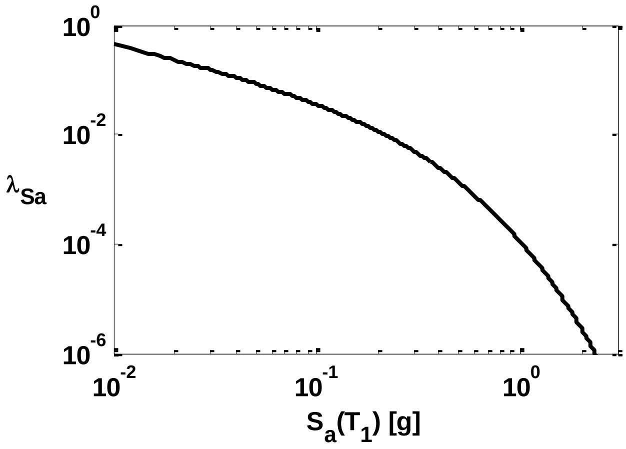


Figure 3.2 Seismic hazard curve

3.3 Ground motions

The ground motion set used in this study consists of 137 acceleration records (each with two horizontal components) selected from the PEER NGA database (Power et al. 2008). The set is comprised of all records in the NGA (excluding those from dam abutments) that were recorded at NEHRP class C or D sites, were produced by strike-slip, reverse, or reverse-oblique faults, and fall within a specified range of magnitude ($6.93 \leq M_w \leq 7.62$) and Joyner-Boore distance ($0 \leq R_{jb} \leq 27$ km). The magnitude and distance ranges approximate the site's main hazard contributors at long return periods, and the fault types are consistent with those dominating the site's hazard (Haselton et al. 2008). The ground motion set includes records with a variety of characteristics, including pulse-like (records affected by forward directivity) and non-pulse-like records as seven faults are located within 20 km of the site.

3.4 Collapse risk assessment and λ_c deaggregation

The collapse intensity of each ground motion was found using IDA, and the resulting collapse fragility curve is shown in Fig. 3.3 using $IM = Sa(T_1)$. The 274 collapse intensities are fit with a lognormal distribution, resulting in a median collapse intensity of 0.96 g and a lognormal standard deviation (σ_{ln}, also commonly denoted as β) of 0.39. The lognormal fit passes the Kolmogorov-Smirnov test (Benjamin & Cornell 1970) at the 5% confidence level and is a good fit for the data based on Fig. 3.3.

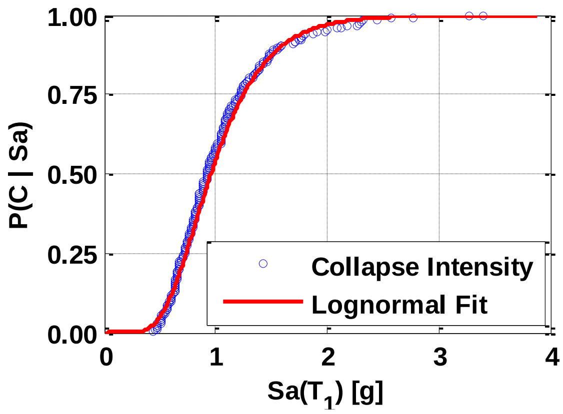


Figure 3.3 Collapse fragility curve

A 4th-order polynomial was fit to the seismic hazard curve in log-log domain and used to compute λ_c according to Eqn. 2.2. This resulted in λ_c = 3.4x10^{-4}, which gives a 1.7% probability of collapse in 50 years according to Eqn. 2.3. The individual terms in Eqn. 2.2 are plotted with respect to $Sa(T_1)$ in Fig. 3.4: the collapse fragility curve (Fig. 3.4(a)), the slope of the seismic hazard curve (Fig. 3.4(b)), and the λ_c deaggregation curve (Fig. 3.4 (c)), which is the product of the collapse fragility curve and the slope of the seismic hazard curve. Eqn. 2.2 shows that the area under the λ_c deaggregation curve equals λ_c (i.e., integrating the λ_c deaggregation curve with respect to intensity gives λ_c).

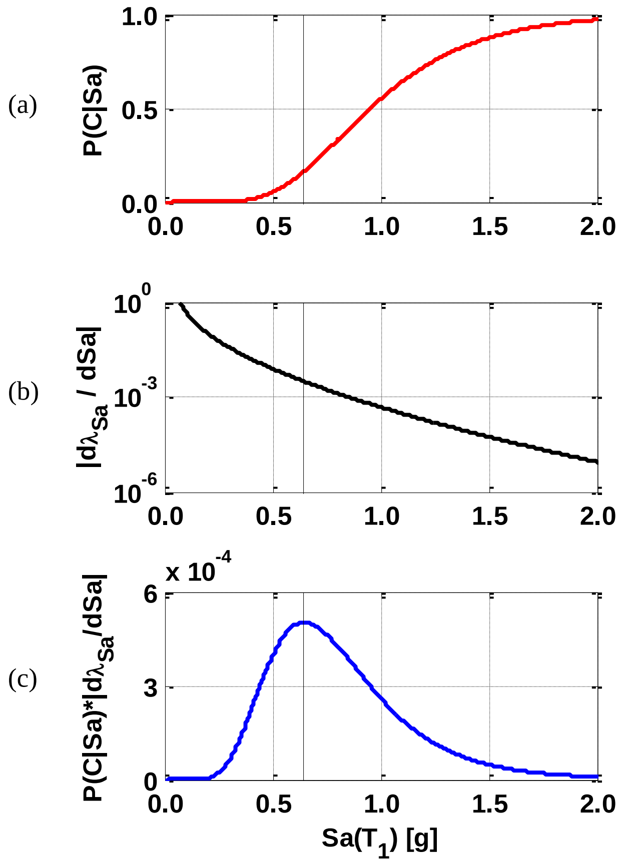


Figure 3.4 Collapse risk assessment: (a) collapse fragility curve, (b) slope of the seismic hazard curve and (c) λ_c deaggregation curve

The λ_c deaggregation curve is a useful tool for identifying which intensities contribute most to the collapse risk. Ground motions intensities with higher ordinates in the λ_c deaggregation curve indicate higher contributions to λ_c. Fig. 3.4(c) shows that the largest collapse risk contribution (the peak of the λ_c deaggregation curve) for the case study occurs at an intensity of 0.65 g. This intensity is denoted by a vertical line in the plots of Fig. 3.4 and is associated with a probability of collapse of only 16%. Intensities associated with the lower half of the collapse fragility curve dominate the collapse risk as 73% of λ_c comes from intensities less than the median collapse intensity of 0.96 g (i.e., the area under the λ_c deaggregation curve between 0 and 0.96 g is 73% of λ_c). This occurs because the steep slope of the hazard curve at these intensities outweighs the corresponding small probabilities of collapse. This finding is typical for a variety of structures and sites, as the largest contributions to λ_c were associated with intensities in the lower half of the collapse fragility curve for structures in New Zealand (Bradley & Dhakal 2008), Los Angeles, California, USA (Haselton et al. 2008; Ibarra & Krawinkler 2005), and other seismically active sites throughout the USA (Eads et al. 2012a).

4. METHOD FOR ESTIMATING λ_c

As mentioned in Section 2.2, obtaining the collapse fragility curve is the most computationally demanding part of calculating λ_c. Though the collapse fragility curve is typically constructed by fitting a lognormal distribution to the collapse intensities of a set of ground motions, this is neither the only method nor the most computationally efficient method. The method for estimating λ_c discussed in this section was proposed by Eads et al. (2012b) and does not require finding each ground motion's collapse intensity, which involves significant computational effort. Instead, this method obtains a limited number of points on the collapse fragility curve and estimates the collapse fragility curve based on these points. Because the collapse fragility curve describes the structure's probability of collapse as a function of ground motion intensity, a point on the curve is estimated as the fraction of ground motions that cause collapse when scaled to a given intensity. By using more ground motions at limited intensities, the proposed method can reduce the uncertainty in the collapse risk estimates and the computational effort involved. To obtain a good estimate of λ_c, the proposed method concentrates on obtaining good estimates of the collapse fragility curve at intensities with significant contributions to λ_c. Given a structure and a seismic hazard curve, the proposed method uses an initial estimate of the collapse fragility curve to identify intensities with significant contributions to λ_c, updates the fragility curve based on the results of RHAs at the significant intensities, and updates the estimate of λ_c. The remainder of this section presents this method, applies it to the case study, and compares the computational effort and level of uncertainty in the λ_c estimate to the estimate obtained via the typical method involving IDA.

4.1 Steps of the proposed method

The proposed method to estimate λ_c is summarized as follows (Eads et al. 2012b):

1. Obtain an initial estimate of the collapse fragility curve assuming a lognormal probability distribution by estimating the median collapse intensity and the dispersion (i.e., the logarithmic standard deviation σ_{lnIM}). Any approximate method can be used to obtain the estimate, such as those presented by Shafei et al. (2011), Han et al. (2010), or Equation 4-4 in FEMA P440A (ATC 2009). Eads et al. (2012b) demonstrated that an accurate initial estimate of the collapse fragility curve is not necessary.
2. Using the collapse fragility curve estimated in Step 1 and the seismic hazard curve at the site, calculate λ_c using Eqn. 2.2 and obtain the λ_c deaggregation as shown in Fig. 3.4(c). Identify the intensity at which the cumulative contribution to λ_c is approximately 90% (i.e., the intensity at which the area under the λ_c deaggregation curve between zero and this intensity is 90% of λ_c). Call this intensity IM_1.
3. Conduct RHAs using ground motions scaled to intensity level IM_1 and estimate $P(C \mid IM_1)$ as the fraction of motions causing the structure to collapse. The motions should be consistent with the magnitude, distance, focal mechanisms, and site conditions from the probabilistic seismic hazard analysis (PSHA) deaggregation at the hazard level associated with IM_1. One can also consider other features such as ε (the number of logarithmic standard deviations between the spectral acceleration of a ground motion and the spectral acceleration predicted by a ground motion attenuation relationship at a given period), which has been shown to affect collapse risk assessment (Haselton et al. 2011). Additional information on record selection can be found in Baker & Cornell (2006).
4. Using the point (IM_1, $P(C \mid IM_1)$) and the dispersion estimate from Step 1, obtain an estimate of the collapse fragility curve assuming a lognormal probability distribution. Use this estimate of the collapse fragility curve and the seismic hazard curve to calculate λ_c using Eqn. 2.2 and obtain the λ_c deaggregation. Identify the intensity at which the cumulative contribution to λ_c is approximately 35% (i.e., the intensity at which the area under the λ_c deaggregation curve between zero and this intensity is 35% of λ_c). Call this intensity IM_2.
5. Repeat Step 3 using IM_2 to obtain $P(C \mid IM_2)$. Note that the ground motions used at IM_2 are not necessarily the same as those used at IM_1.

6. Assuming a lognormal distribution, update the collapse fragility curve estimate by using the points (IM_1, $P(C \mid IM_1)$) and (IM_2, $P(C \mid IM_2)$). Note that here the dispersion estimate used in Steps 1 and 4 is no longer used.
7. Using the collapse fragility curve from Step 6 and the seismic hazard curve, calculate λ_c using Eqn. 2.2.

If the points in Step 6 are close together on the collapse fragility curve or the *IM* levels do not have significant contributions to λ_c, conducting RHAs at a third intensity and updating the collapse fragility and λ_c estimates based on the results is suggested. A third point on the collapse fragility curve is also useful for determining how well the fitted fragility curve captures the data and deciding whether to run more RHAs to improve the estimate. The third intensity, IM_3, should be selected so that it (a) is not near regions of the collapse fragility curve and the λ_c deaggregation estimated by the first two *IM* levels, and (b) has significant contribution to λ_c based on the λ_c deaggregation.

4.2 Discussion

The proposed method is very general and can be used with any *IM* such as $Sa(T_1)$ or even a vector *IM* such as $Sa(T_1)$ and ε. Baker and Cornell (2005) provide more information about the advantages and use of a vector IM. By limiting the RHAs to two intensity levels, the proposed method significantly reduces the computational effort involved in obtaining the collapse fragility curve. Furthermore, since RHAs are performed at only two intensity levels, more ground motions than the number typically used can be considered, which leads to a significant reduction in the statistical (epistemic) uncertainty in the collapse fragility curve and in λ_c while still reducing the computational effort. The reader is referred to Eads et al. (2012b) for an extended discussion of statistical uncertainty in the collapse fragility curve and in λ_c as a function of the number of ground motions used in analysis.

Another important advantage of the proposed two-point approach, compared to performing a set of IDAs to collapse, is that more attention can be paid to selection and scaling of the ground motions to the hazard levels associated with the two *IM* values. Ideally, one should select different ground motions for each of these two intensity levels consistent with PSHA deaggregation results to identify the magnitude, distance, focal mechanism, and ε distributions at these intensity levels. This approach avoids the shortcoming in IDA of using identical ground motions at different hazard levels, which disregards differences in duration and other ground motion characteristics at varying intensity levels.

4.3 Application to case study

The proposed method was applied to the case study. Only two intensity levels were used to construct the collapse fragility curve (i.e., a third intensity level was not included to improve the λ_c estimate if the two intensities were close together), and the same set of ground motions was used for both intensity levels. Confidence intervals on the λ_c estimate are presented in Fig. 4.1 as a function of the numbers of RHAs performed. For the proposed method, the number of ground motions (N) used to estimate each point on the collapse fragility curve is equal to half the number of RHAs. The 95% confidence interval for a given number of RHAs is constructed using the percentile method with 1,000 bootstrap simulations (Efron & Tibshirani 1993). In each bootstrap simulation, a random sample of N ground motions is used to construct the collapse fragility curve according to the proposed method and then that fragility curve is used to calculate λ_c. Fig. 4.1 also shows confidence intervals on the λ_c estimate when constructing the collapse fragility curve by performing IDAs in 0.1 g increments until collapse occurs and then finding the collapse intensity within a tolerance of 0.01 g using the bisection method. Using this approach (herein referred to as the full IDA), an average of 15 RHAs were required to find the collapse intensity for each ground motion in the case study. Therefore, the number of ground motions used in this approach is one-fifteenth the number of RHAs. Fig. 4.1 shows that for the case study the mean λ_c estimates of the two methods are not significantly different and, more importantly, for the same number of RHAs the proposed method has significantly less uncertainty due to the ground motion sample size than the full IDA.

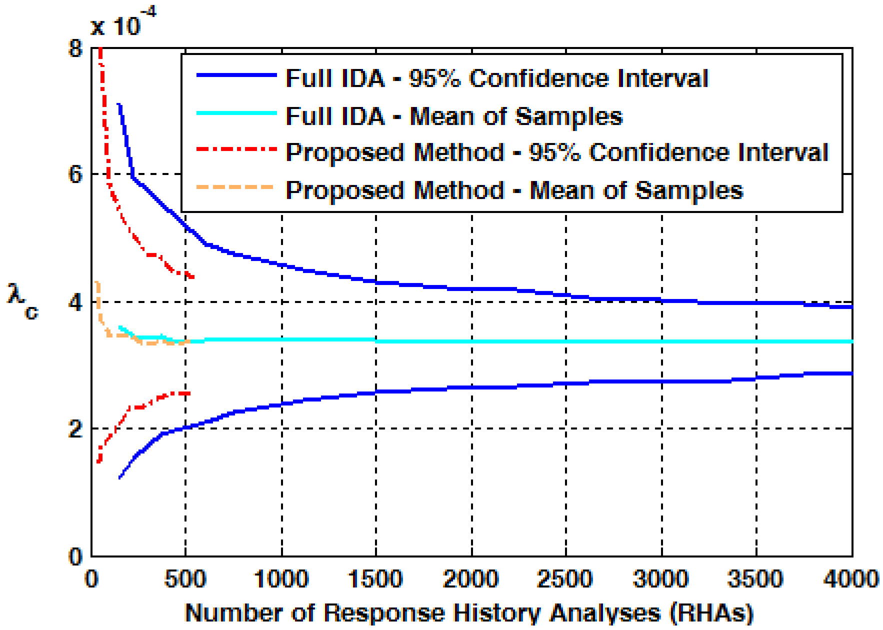


Figure 4.1 95% confidence intervals for λ_c as a function of the number of RHAs

Table 4.1 summarizes the computational effort and margins of error in estimating λ_c for the case study using the proposed and full IDA methods. The margin of error is computed as half the width of the 95% confidence interval normalized by the value of λ_c computed in Section 3.4. Also shown in this table is the number of ground motions employed by each method. It can be seen that for that same margin of error, the proposed method requires significantly less computational effort than the full IDA method (e.g., for a margin of approximately 50%, the full IDA method requires three times as many RHAs as the proposed method). The case study results also demonstrate that the proposed method can be both less computationally demanding and less uncertain than the full IDA method. For example, estimating λ_c using the full IDA method with 30 ground motions requires 450 RHAs and gives a margin of error of 50%, whereas using the proposed method with 150 ground motions requires only 300 RHAs (33% less computational effort) for a margin of error of 35% (30% less uncertainty).

Table 4.1 Computational effort and uncertainty when estimating λ_c using the proposed and full IDA methods

Number of Response History Analyses (RHAs)	Margin of Error in λ_c		Number of Ground Motions (N)	
	Proposed	Full IDA	Proposed	Full IDA
150	49%	82%	75	10
300	35%	57%	150	20
450	28%	50%	225	30

5. SUMMARY AND CONCLUSIONS

Components of collapse risk assessment, including the collapse fragility curve, mean annual frequency of collapse (λ_c), and probability of collapse over a given period of time, have been presented and discussed. Deaggregation of λ_c, which is a powerful tool for identifying the ground motion intensities that primarily contribute to the λ_c of a structure, has also been discussed. Results of this paper and other studies indicate that for a variety of structures and locations, λ_c is typically dominated by ground motion intensities associated with the lower half of collapse fragility curve. It is therefore suggested that rather than emphasizing estimation of the median collapse intensity as is typically done, emphasis should be placed on the lower half of the collapse fragility curve and, in particular, on those ground motion intensities identified through a λ_c deaggregation that primarily contribute to the collapse risk.

A method for estimating the collapse fragility curve and λ_c has also been presented. Instead of conducting response history analyses (RHAs) at many intensity levels using relatively small sets of ground motions as is typically done, the proposed method suggests using larger sets of ground motions but conducting RHAs only at two intensity levels corresponding to intensities that primarily contribute to λ_c. By using more ground motions the proposed method reduces the uncertainty in the results, and it significantly reduces the number of RHAs and hence the computational effort by only performing analyses at two intensity levels. Case study results show that for a 50% margin of error in the λ_c estimate, the proposed method reduces the number of RHAs by approximately 66% when compared an IDA method that finds the collapse intensity of each record. The case study results also show that for the same number of RHAs (150) as the IDA method, the proposed method reduces the margin of error in the λ_c estimate from approximately 80% to 50%.

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