Significance of Various Design and Assessment Parameters on Seismic Collapse Safety Assessment of Reinforced Concrete Frame Buildings

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ABSTRACT

A primary goal of the seismic design requirements of building codes is to protect life safety of building inhabitants during extreme earthquakes. First and foremost, this requires ensuring that the likelihood of structural collapse remains at an acceptably low level. In achieving this goal, the typical approach has been to develop prescriptive and empirical building code requirements for structural strength, stiffness, and deformation capacity. However, for the tall and complex buildings that shape the Hong Kong skyline, or other innovative structural systems, such simplified requirements may not be appropriate, and performance-based design methods may be more suitable.

Performance-based earthquake engineering (PBEE) methods and tools provide a rigorous basis for evaluating building performance. The Pacific Earthquake Engineering Research (PEER) Center has recently developed a comprehensive probabilistic framework for PBEE, as well as detailed procedures for each step of the assessment. PBEE methods are capable of evaluating building performance from damage initiation up to the onset of structural collapse, which is the focus of this paper.

This paper briefly discusses the PEER PBEE collapse risk assessment methodology, and then illustrates the method by assessing the collapse risk of a US building code compliant 8-story reinforced concrete frame building. This paper then focuses on two important aspects of the collapse *assessment method*, namely consideration of structural modeling uncertainties and the effects of ground motion properties (i.e. spectral shape), in order to determine how much these aspects of the assessment method affect the collapse risk predictions. For comparison, this paper then looks at how many aspects of the *structural design* affect the predicted collapse risk.

This study concludes that many aspects of the structural design (building height, framing layout, strength irregularities, etc.) are *have a smaller impact* on the collapse risk prediction, as compared to the aspects of the collapse assessment methodology (structural modeling uncertainties and ground motion properties). This shows that the final collapse risk prediction depends heavily on how one carries out the collapse assessment. This suggests a critical need for developing a *systematic* and *codified* collapse assessment method, especially when performance-based design concepts are included in the development of the new seismic design code. A codified method is essential to ensure that collapse assessments performed by different analysts are comparable.

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PERFORMANCE-BASED EARTHQUAKE ENGINEERING COLLAPSE ASSESSMENT METHODOLOGY

Overview of Method

The Pacific Earthquake Engineering Research (PEER) Center has recently coordinated research efforts to develop a multi-step assessment method to predict structural collapse safety. First, the ground motion hazard is quantified using standard probabilistic seismic hazard analysis, and then appropriate recorded ground motions are selected for use in nonlinear dynamic collapse simulation (Baker and Cornell 2006). Next, the building failure mechanisms are investigated, a structural model is created to simulate structural collapse; nonlinear dynamic collapse simulation is then completed (Haselton 2006, chapter 6) using the Incremental Dynamic Analysis (IDA) approach (Vamvatsikos and Cornell 2002). Non-simulated collapse modes (such as loss of vertical load carrying capacity of the gravity system) are then accounted for using a post-processing approach (not discussed in this paper; see Deierlein and Haselton 2005). Structural modeling uncertainties, such as uncertainties in element plastic rotation capacity, are also incorporated (Haselton 2006, chapter 5). Finally, the ground motion hazard and structural collapse capacity information are combined to compute the conditional collapse probability and the mean annual rate of collapse (Ibarra 2003). These indices can be used to decide if the building collapse risk is at an acceptable level.

Example Collapse Assessment of a Modern 8-story Reinforced Concrete Frame Building

The PEER PBEE collapse assessment method is illustrated in this section using a code-conforming (ICC 2003) reinforced concrete special moment frame building. This structural design and model was developed by the authors in a related study (Haselton 2006, chapter 6) and consists of a perimeter three-bay frame with 20' bay widths, a tributary seismic mass floor area of 7,200 square feet, and a fundamental period (T_1) of 1.71 seconds. This building was designed for a site in the Los Angeles area that has a 2% in 50 year demand of $Sa_{2/50}(1.71s) = 0.57g$ (Goulet et al. 2007). This structural design, and all those presented in this paper, was verified by a practicing engineer to ensure consistency with common design practice.

Figure 1a presents the IDA results for the 8-story structure, as based on 40 ground motion records that were selected to represent large motions that are not near a fault (Haselton 2006, chapter 3; ATC-63 2007, Appendix A). Figure 1b shows these collapse capacities plotted in terms of the cumulative distribution function (CDF). The solid line in a lognormal fit to the empirical CDF, and therefore only reflects the variability associated with differences in the ground motion records such as frequency content ($\sigma_{LN} = 0.39$). The dashed lognormal CDF has the same median as the solid CDF, but has increased variability to account for structural modeling uncertainties ($\sigma_{LN} = 0.60$) (as per Haselton 2006, chapter 5).

To gauge collapse risk, several indices are commonly utilized[1]. The collapse capacity margin is defined as the ratio of the median collapse capacity and the $Sa_{2/50}(T_1)$ demand; for this building the collapse margin is 1.11. The conditional collapse probability is $P[C| Sa_{2/50}] = 0.44$, when structural modeling uncertainties are included. To compute the mean annual frequency of collapse, the collapse CDF is integrated with the seismic hazard curve for the site and, for this building, we find a

[1] These predictions do not include proper consideration of ground motion spectral shape, and therefore are not considered to be accurate; these are simply presented as a baseline for the later comparisons. The results that are considered to be mst accurate include proper spectral shape and structural modeling uncertainties and are presented in Table 1. In addition, this building is not typical, but actually has the highest collapse risk of the 30 buildings considered in this study.

mean annual frequency of collapse ($\lambda_{collapse}$) of 25.5 x 10^{-4} collapses per year for this building, with structural modeling uncertainties included.

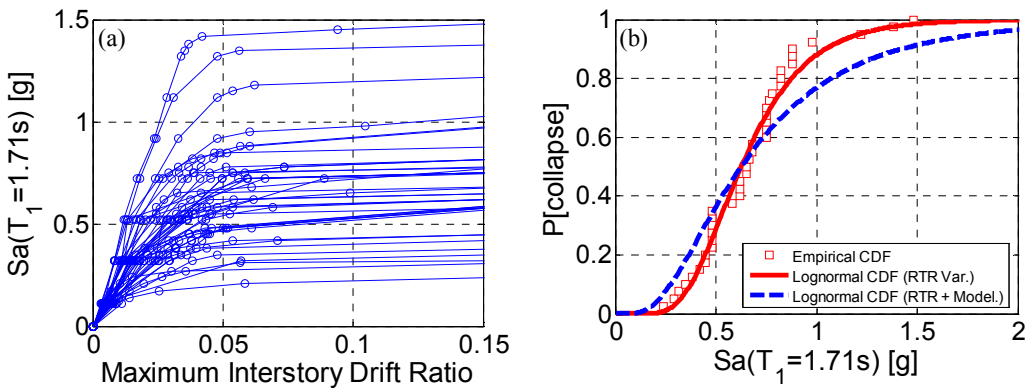

Figure 1. Incremental Dynamic Analysis predictions and collapse capacity CDF for 8-story frame building. The collapse capacity CDF is shown with only record-to-record variability (solid), and also with effects of structural modeling uncertainties also included (dashed).

IMPACTS OF SELECTED ASSESSMENT PARAMETERS ON COLLAPSE RISK ASSESSMENT

Ground Motion Spectral Shape

The collapse predictions in the last section were based on ground motions that were selected without consideration of appropriate spectral shape. Therefore, the results presented in the previous section are preliminary and require modification. Not considering proper ground motion spectral shape is a common oversight in many performance assessments. Baker and Cornell (2006) found that spectral shape is an important consideration for high seismic areas such as California, and the spectral shape can be quantified by a parameter called epsilon (ε), which is a function of building period and is estimated as part of the seismic hazard analysis.

For the example site used in this paper, the mean ε at T_1 = 1.71s is 1.70[2]. Therefore, a second set of ground motions was selected to have this correct ground motion parameter, and then collapse the collapse analyses were repeated to determine the impact that spectral shape (ε) has on the collapse performance assessment. Figure 2a compares the median spectra for these two ground motion sets. Ground motions selected based on ε(1.71s) tend to have a peak at 1.7 seconds and have lower demand at other periods; this suggests that ground motion selected with appropriate epsilon will be less damaging than those selected without regard for spectral shape. Figure 2b shows the collapse capacity CDFs for these two ground motion sets. This shows that the median collapse capacity increases by a factor of 1.6 when the correct ground motion set (the epsilon set) is utilized in the analysis. Table 1 shows the effects of spectral shape on the conditional collapse probability (P[C|

[2] It is an unfortunate coincidence that the period of interest, 1.71 seconds, is numerically the same as the mean ε of 1.70.

$Sa_{2/50}$]) and annual collapse rate ($\lambda_{collapse}$) for this 8-story building and 29 other code-conforming buildings.

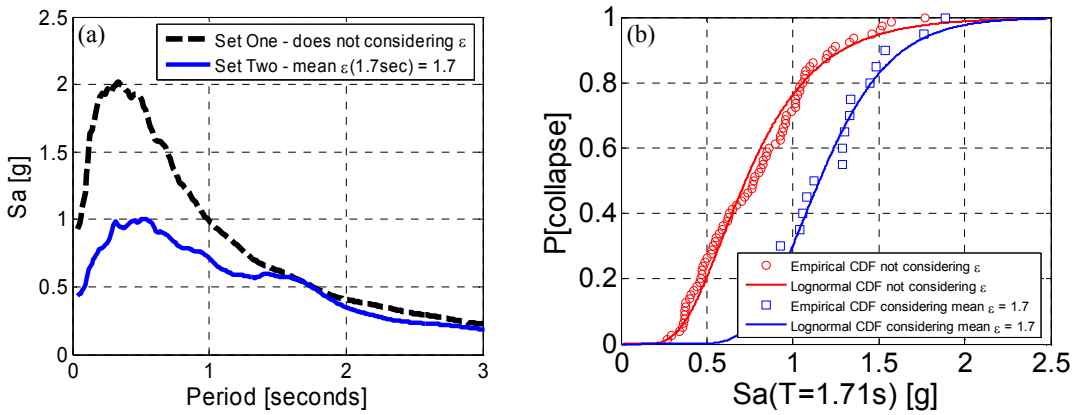

Figure 2. (a) Comparison of median spectra for the ground motion set that was not selection based on ε (Set One; used in the previous section), and the set that was selection to have the proper median ε (Set Two). (b) Comparison of collapse capacity CDFs for ground motion Sets One and Two.

Structural Modeling Uncertainties

As shown in Figure 1b, structural modeling uncertainties primarily add uncertainty to the collapse capacity estimate[3]. These structural modeling uncertainties include the uncertainty in items such as element deformation capacity, element hysteretic deterioration behavior, initial stiffness, etc. These uncertainties greatly impact the results of the collapse risk assessment, especially for modern buildings where the extreme tail of the collapse capacity distribution significantly impacts the annual collapse rate ($\lambda_{collapse}$). Table 1 shows the effects that modeling uncertainties have on the conditional collapse probability (P[C| $Sa_{2/50}$]) and annual collapse rate ($\lambda_{collapse}$) for this 8-story building and 29 other code-conforming buildings.

Impact of Both Assessment Parameters for 30 Structural Designs

In order to come to generalized conclusions regarding how assessment parameters affect predicted collapse risk, it is necessary to look at more than a single structure. To this end, Table 1 presents the design information for 30 different structural designs (design #14 was the 8-story design discussed previously). The designs in this set are all code conforming (ICC 2003), range in height from 1 to 20 stories, have variable bay widths, include both space and perimeter frame systems, and interrogate the possible levels of strength/stiffness irregularity and foundation rotational stiffness.

Table 1 then presents the conditional collapse probabilities and the mean annual rates of collapse for each of the 30 structural designs. To determine how assessment parameters affect predicted collapse risk, the collapse probabilities and rates are computed in three ways: (a) baseline

[3] This observation is valid when the First Order Second Moment assumptions are utilized, as in this study (Haselton 2006, chapter 5). In some cases, structural modeling uncertainties can also affect the median collapse capacity (Liel et al. 2007).

case where the ground motions are selected to have correct spectral shape (ε) and modeling uncertainties are included (the baseline method), (b) a case like (a) but modeling uncertainties are not considered and only record-to-record variabilities are accounted for, and (c) a case like (a) but the ground motions are selected without considering spectral shape (ε) (i.e. ground motion Set One is used).

Table 1. Design documentation, predicted conditional collapse probabilities, and predicted mean collapse rates for 30 reinforced concrete special moment frame structures (Haselton 2006, chapter 6).

Design Information						Baseline (correct) - With Modeling Uncertainties and Correct Spectral Shape		Comparison - Without Modeling Uncertainties		Comparison - Without Correct Spectral Shape (ground motion Set One)	
Design Number	No. of stories	Bay Width [ft]	Framing System	Strength/ Stiffness Distribution Over Height	Foundation Fixity Assumed in Design [a]	$P[C\|Sa_{2/50}]$	λ_{col} [10^{-4}]	$P[C\|Sa_{2/50}]$	λ_{col} [10^{-4}]	$P[C\|Sa_{2/50}]$	λ_{col} [10^{-4}]
1	1	20	Space	A	GB	0.10	2.6	0.03	0.4	0.20	7.3
2					P	0.07	1.7	0.01	0.2	0.16	4.7
3					F	0.10	2.6	0.03	0.4	0.20	7.3
4			Perimeter	A	GB	0.20	7.0	0.09	1.4	0.36	17.3
5	2	20	Space	A	GB	0.04	1.0	0.00	0.1	0.10	2.6
6					P	0.04	1.0	0.00	0.1	0.09	2.2
7					F	0.08	2.0	0.02	0.3	0.15	4.8
8			Perimeter	A	GB	0.12	3.4	0.03	0.6	0.23	8.7
9	4	20	Perimeter	A	GB	0.13	3.6	0.03	0.6	0.28	11.3
10				B	GB	0.09	2.5	0.02	0.4	0.22	8.1
11			Space	A	GB	0.07	1.7	0.01	0.2	0.17	5.4
12		30	Perimeter	A	GB	0.08	2.1	0.01	0.3	0.22	8.2
13			Space	A	GB	0.03	0.7	0.00	0.1	0.09	2.5
14	8	20	Perimeter	A	GB	0.19	6.3	0.08	1.3	0.44	25.5
15		20	Space	A	GB	0.09	2.4	0.01	0.3	0.29	11.5
16				B	GB	0.09	2.5	0.01	0.3	0.25	9.2
17				C (65%)[b]	GB	0.08	2.3	0.01	0.3	0.24	10.0
18				C (80%)[b]	GB	0.05	1.7	0.00	0.2	0.20	8.7
19				C (65%)[c]	GB	0.14	4.3	0.04	0.8	0.35	16.8
20				C (80%)[c]	GB	0.15	4.6	0.05	0.9	0.35	16.8
21	12	20	Perimeter	A	GB	0.16	5.2	0.05	0.9	0.39	20.3
22		20	Space	A	GB	0.15	4.7	0.05	0.8	0.33	15.5
23				B	GB	0.11	3.1	0.02	0.5	0.29	12.6
24				C (65%)[b]	GB	0.12	3.2	0.03	0.5	0.30	12.1
25				C (80%)[b]	GB	0.12	3.1	0.02	0.5	0.33	14.0
26				C (65%)[c]	GB	0.16	4.5	0.04	0.8	0.38	18.1
27				C (80%)[c]	GB	0.15	4.9	0.05	0.9	0.36	18.0
28		30	Space	A	GB	0.07	2.1	0.01	0.3	0.24	8.5
29	20	20	Perimeter	A	GB	0.13	3.7	0.03	0.6	0.31	13.4
30		20	Space	A	GB	0.08	2.0	0.01	0.3	0.23	9.0
					Average:	0.11	3.1	0.03	0.5	0.26	11.0

a - Fixity assumed only in the design process. OpenSees models use expected grade beam, basement column, and soil stiffnesses.
b - Only first story designed to be weak.
c - First and second stories designed to be weak.
A - Expected practitioner design; strength and stiffness stepped over height as would be done in common design practice.
B - Conservative uniform design; strength, size, nor concrete strength stepped down over the height of the building.
C (%) - Weak story; done by sizing the target weak story(ies) based on code requirements and then strengthening stories above. % is the percentage of strength in the weak story(ies) as compared to the stories above.
F - Fixed.
GB - "Grade Beam" - this considers the rotational stiffness of the grade beam and any basement columns.
P - Pinned.

Table 1 shows that both spectral shape and modeling uncertainties have important impacts on predicted collapse risk. The average collapse probabilities and rates for these 30 structures can be summarized as follows:

a) Baseline correct case: $P[C|\ Sa_{2/50}] = 0.11$, $\lambda_{collapse} = 3.1\text{x}10^{-4}$ collapses/year
b) Without modeling uncertainty: $P[C|\ Sa_{2/50}] = 0.03$, $\lambda_{collapse} = 0.5\text{x}10^{-4}$ collapses/year
c) Without proper spectral shape (ε): $P[C|\ Sa_{2/50}] = 0.26$, $\lambda_{collapse} = 11.0\text{x}10^{-4}$ collapses/year

This shows that neglecting structural modeling uncertainties will lead to an *underestimation* of $\lambda_{collapse}$ by a *factor of six*. Similarly, neglecting proper spectral shape (ε) will lead to an *overestimation* of $\lambda_{collapse}$ by a *factor of three*.

IMPACTS OF VARIATIONS IN STRUCTURAL DESIGN ON COLLAPSE RISK ASSESSMENT, AND COMPARISON TO EFFECTS OF ASSESSMENT PARAMETERS

The previous section presented 30 structural designs and then looked at how the assessment parameters impacted the collapse risk assessment for each of the designs. Another interesting question is how the collapse risk varies between each of the code-conforming designs.

The baseline results from Table 1 show that the mean $P[C|\ Sa_{2/50}] = 0.11$, with a range of 0.03 to 0.20. In addition, the mean $\lambda_{collapse} = 3.1\text{x}10^{-4}$ collapses/year, with a range of $0.7\text{x}10^{-4}$ to $7.0\text{x}10^{-4}$. If we look at the ratios between the mean/minimum and maximum/mean of $\lambda_{collapse}$ for the 30 different designs, they are a *factor of four* and a *factor of two*, respectively. For comparison, the modeling uncertainties changed the $\lambda_{collapse}$ by a factor of six and the spectral shape (ε) effect changed the $\lambda_{collapse}$ by a factor of three.

In order to make a slightly clearer comparison, Table 2 compares the design changes individually (i.e. space versus perimeter frame, etc.) rather than looking at the range of results for 30 buildings. This table includes both the assessment parameters and the design aspects, and then ranks each item based on the amount it changes the estimate of $\lambda_{collapse}$. This table shows that the aspects of the assessment methodology, the structural modeling uncertainties and consideration of spectral shape, are *more important than any one of the design parameters* considered in this study. Of the design parameters investigated, the building height has the most important affect on collapse performance. The next most important consideration is the difference between space and perimeter frame buildings. The next three design parameters (assumed foundation fixity, conservative design, and weak-story designs) have minimal effect, and bay spacing has no measurable effect on collapse performance. It should be noted that these observations are limited to the scope of this study, with this study only being based on code conforming seismically detailed reinforced concrete frame buildings.

Table 2. Comparison of how each design and assessment parameter affects the collapse risk prediction.

	Average values for each of the cases considered		
Design or Assessment Parameter	**Margin against 2% in 50 motion**	**$\lambda_{collapse}$ [10^{-4}]**	**P[C|$Sa_{2/50}$]**
Inclusion of structural modeling uncert.[a] (with and without)	1.6, 1.6	11.0, 2.8	26%, 16%
Spectral shape considerations (correct method and baseline)	2.3, 1.6	3.1, 11.0	11%, 16%
Building height[b]	1.6, 2.0	12.4, 5.7	28%, 17%
Space versus perimeter frame	1.7, 1.3	8.6, 16.1	22%, 33%
Foundation fixity in design (pinned versus fixed)	1.9, 1.6	3.5, 6.1	12%, 18%
Strength irregularity (65% versus 100% strength ratios)	1.2, 1.4	17.5, 13.5	37%, 31%
Uniform size and reinf. over height versus baseline design	1.6, 1.4	10.0, 12.8	25%, 30%
Bay spacing (20' versus 30' spacing)	virtually no change		

a - The structural uncertainties do not affect the median collapse capacity because we are using the mean estimate method. If we instead did predictions at a given prediction confidence level, this value would be greater than 1.0.
b - The comparison differs for building height because there are six height levels. The values reported here are the average and the best-case.

SUMMARY AND CONCLUSIONS

This paper shows that many aspects of the collapse assessment methodology (structural modeling uncertainties and ground motion spectral shape) *have a larger impact* on the collapse risk prediction, as compared to any one aspect of the structural design (building height, framing layout, strength irregularities, etc.). This does not mean that this collapse assessment methodology is incapable of distinguishing how structural design differences affect collapse risk; Haselton (2006, chapter 7) has shown that this collapse methodology can be beneficial for this purpose. Rather, this finding shows that a consistent assessment method is required, if relative comparisons are to be meaningful.

This observation has important implications for those developing seismic codes and building regulations, as is currently being done in Hong Kong. If these design codes allow for performance-based design, then development of a *systematic codified* assessment method is essential. Such a codified method is needed to ensure that performance assessments completed by different analysts are comparable. As mentioned above, without such a codified assessment method, the structural simulation results would depend more on how one carries out the assessment and less on how one designs the building. This is particularly true for assessing collapse performance, because the modeling assumptions and methods can become even more important when predicting strongly nonlinear structural response.

Developing such a codified collapse assessment method has been a recent focus of research for the authors and other collaborating researchers. This research is being carried out through the PEER Center and the Applied Technology Council (ATC) Project 63, and will soon be published by ATC.

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