Reliability of Acceptance Criteria in Nonlinear Response History Analysis of Tall Buildings

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SUMMARY:
The authors performed analytical evaluation of the reliability obtained using present demand definition and acceptance criteria for buildings designed using nonlinear response history analyses in accordance with ASCE 7-10 and ASCE 41-06. Design criteria in these standards present different means to determine design demands, depending on the number of ground motion records used in analysis. If 7 or more ground motion records are used, the most common approach presently adopted by structural engineers, the mean of the peak values for each demand parameter is evaluated against limiting acceptance criteria that include strength and nonlinear deformation capacities. The perception exists that a building designed according to the criteria will, on average, conform to the intended performance goals and that the probability of meeting the target performance in the design event is approximately 50%. The objective of this study is to explore the actual likelihood of meeting desired performance using these standard procedures and to propose a modification to these procedures to improve performance reliability.

Keywords: Reliability, Performance-based Design, Nonlinear Time History, Tall Buildings, Acceptance Criteria

1. INTRODUCTION

Nonlinear response history analysis is becoming increasingly popular in performance-based seismic design of buildings, especially tall buildings. It enables design of building with the intent and expectation that they will perform as anticipated by the building codes without adhering to their prescriptive requirements. Several US guidelines and standards have recently formalized the use of nonlinear response history in building design. Examples include ASCE 41-06 (2006), ASCE7-10 (2010), and PEER Tall Building Initiative (2010). One common feature of these first-generation standards is their reliance on comparison of individual mean response quantities for each demand parameter to a corresponding acceptance criterion. This approach ignores the role of correlation between demand parameters as well as inherent uncertainties in demands. This introduction revisits the effects of this simplification.

1.1. Joint Performance Evaluation of Demand Parameters

For the purpose of this study, we assume that a building will actually meet its intended performance only if all of the demands used to judge performance are less than or equal to the capacity or acceptance criteria for that demand. For multi degree of freedom structures, the demand parameters important to evaluating building performance are not independent. To project an extreme example, if for each earthquake event under consideration the demand for some performance measure (say story drift) exceeds the acceptance criteria at any story level, the building performance is unsatisfactory in some respects, even though the building may be analytically acceptable because the “mean” of the demands, computed at each story level independently of the others, does not exceed the acceptable capacity for any individual parameter. The probability of actually achieving acceptable performance is computed as a joint probability considering the performance of all elements not exceeding the target performance limit and not on a single demand parameter basis.

1.2. Effect of Demand Correlation

The element demand correlation structure is important. For the case when element demands are uncorrelated, the joint probability that the structure will have acceptable performance (all demand parameters having demand less than their capacities) may be obtained as the product of the individual probabilities of non exceedance for each element. For example, consider a simple 3-degree of freedom structure, with story drift at each level being the important performance parameter. If the analyses for a particular hazard level indicate that there is a 70% chance that in any ground motion the 1st story drift demand will be less than the acceptable value, a 70% chance that the 2nd story drift will be less than the acceptable value and an 80% chance that the 3rd story drift demand will be less than the acceptable value, if we assume there is no correlation in these demands, the probability for a given ground motion that all of the drifts will be less than the acceptable value is given by the product of these probabilities (0.7)(0.7)(0.8)=0.39. In this simple example, where demand correlation is ignored, even though the probability that any individual story drift will be acceptable is quite high (never less than 70% for any story), the probability that all of story drift demands will be less than the acceptable value is a much lower value of 39%. If correlation is ignored as in this example, the joint probability of acceptable performance (all demands less than their acceptance values) will always be less than the success probability for the parameter with the lowest acceptance rate. Further, as the number of demand parameters important to performance increases (e.g. more stories, or more elements), and the design becomes more efficient (the probability that demand on any element is less than the acceptable value approaches 50% for all elements) the probability of successful performance for any ground motion decrease notably. For example, in a structure with just 10 demand parameters of importance, and a 50% chance of capacity exceedance in any record for each demand, the probability of successful performance becomes $0.5^{10} = .1\%$. This latter example is an extreme adverse scenario, since typical designs do not result in such efficiency in meeting demand-to-capacity limits.

When the demand parameters are positively correlated, they will tend to increase or decrease around their means concurrently. For this case, the joint probability of successful performance for the entire structure is higher than the product of the individual probabilities of success and may not be much different from the individual probability of the demand parameter with the lowest acceptance rate. When the demands are negatively correlated, they will tend to move in opposite directions – when one increases the other decreases. This behavior increases the likelihood that some demands will be higher than the acceptable value during any event, and hence the joint probability may be significantly lower than the product of individual probabilities, thus almost “ensuring” that. If a design is such that several, negatively correlated demands have high usage ratio (ratio of mean demand to performance limit), negative correlation will almost surely lead to joint probabilities of successful performance for the structure (all demands) approaching zero.

1.3. Calculation of Joint Probability

For the purpose of calculating the joint probability, we assume that demands have a jointly lognormal distribution. The lognormal distribution parameters can be computed from the demand parameter statistics, as follows.

$$\beta_i = [\ \ln(1 + \delta_i^2)\ ]^{0.5} \tag{1}$$

$$\lambda_i = \ln(\mu_i) - 0.5\ \beta_i^2 \tag{2}$$

$$\rho_{o,ij} = \beta_i^{-1}\ \beta_j^{-1}\ [\ \ln(1 + \rho_{ij}\ \delta_i\ \delta_j)\ ] \tag{3}$$

where μ_i is the estimated mean for each parameter obtained from the suite of analyses, δ_i is the estimated coefficient of variation for demand i, and ρ_{ij} is the estimated correlation coefficient between demands i and j. β_i is the logarithmic standard deviation, and λ_i is the logarithmic mean for demand i, which corresponds to the logarithm of the median demand. Equation 3 is derived by Liu and Der Kiureghian (1986) under the assumptions of the so-called “Nataf” distribution.

We used the open-source computer package R, described in Venables and Smith (2012) to explore this. R has an external library "mvtnorm" which can compute multi-variate normal probability values using numerical integration, and can generate jointly normal random variables. The implementation of closed-form multi-normal probability calculation in R has a limit of 20-variables. Hence, we used Monte-Carlo simulation. We used the natural logarithms of the demands as input to R, since the natural logarithm of the values of a lognormally distributed population is normally distributed. The mean vector is composed of the logarithmic means λ_i, and the variance-covariance matrix's element [i,j] is defined as $\rho_{o,ij}\ \beta_i\ \beta_j$ of jointly normal logarithms of demand values.

2. DESCRIPTION OF ANALYTICAL CASE STUDY

We considered as a case-study structure a 40-story steel building designed by Simpson Gumpertz & Heger Inc. (SGH). The structure has first-mode periods of 5.0 and 6.5 seconds in the X and Y directions, respectively. The seismic force resisting system is buckling-restrained braced frames (BRBF). We used the structural simulation software Perform-3D developed by Computers and Structures (2011) to perform nonlinear response history analysis. The ground motion suite consisted of 40 horizontal acceleration record pairs, with the Fault Normal (FN) component aligned with the building's X-direction, and the Fault Parallel (FP) component aligned with the Y-direction. We judged that this number of records is sufficient to estimate a robust correlation structure for the response parameters. We selected the 40 ground motion records using the Digital Ground Motion Library (DGML) database developed by AMEC Geomatrix (2011). Figure 1 shows the design spectrum for horizontal ground motion and the fitted spectra for the selected acceleration records after scaling. For demand parameters, we considered the X and Y story drift ratios above ground, and the brace strain demands. There are a total of 2 directions x 40 stories = 80 story drift demands and 1056 braces. There are 4 basement stories in addition to the 40 stories above ground. However, given that the drift demands on these stories were typically low due to shear walls in the basement, they were ignored in the reliability study as this did not constitute a controlling design parameter.

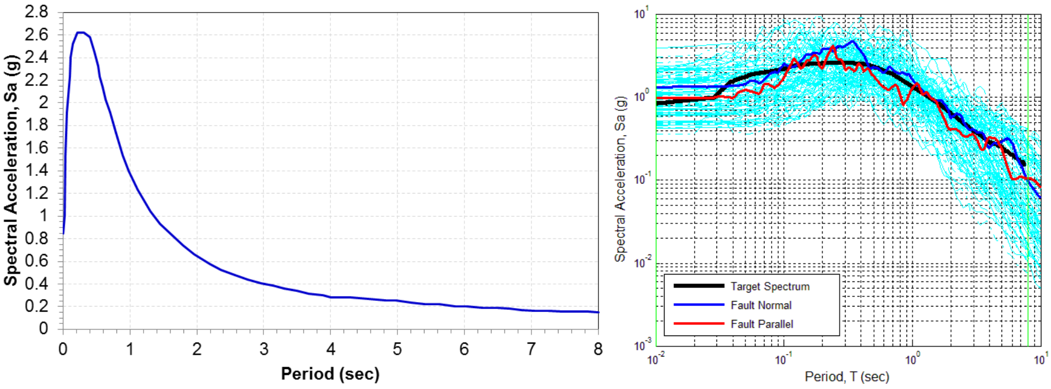

Figure 1. Case Study Design Spectrum and Fitted Spectra from Ground Motion Suite

Figure 2 shows the building's lateral force resisting system and drift ratios for the 40 records in the original orientation. The average drift is highlighted by a thick dark line. The plots show that there is a larger contribution of higher mode effects in the Y direction than the X direction. Thus, drift demands in the Y-direction have higher negative correlation than the X-direction. The plots also show that the highest mean drift ratio is in the X-direction (8^{th} story). However, the highest mean drift ratio in the Y-direction (31^{st} story) is of similar magnitude. These characteristics suggest that the effects of correlation as discussed earlier will not be severe yet are not negligible (since X-direction drift ratio drives the design without dominating it). We judged that these are suitable characteristics for a typical case study to minimize bias.

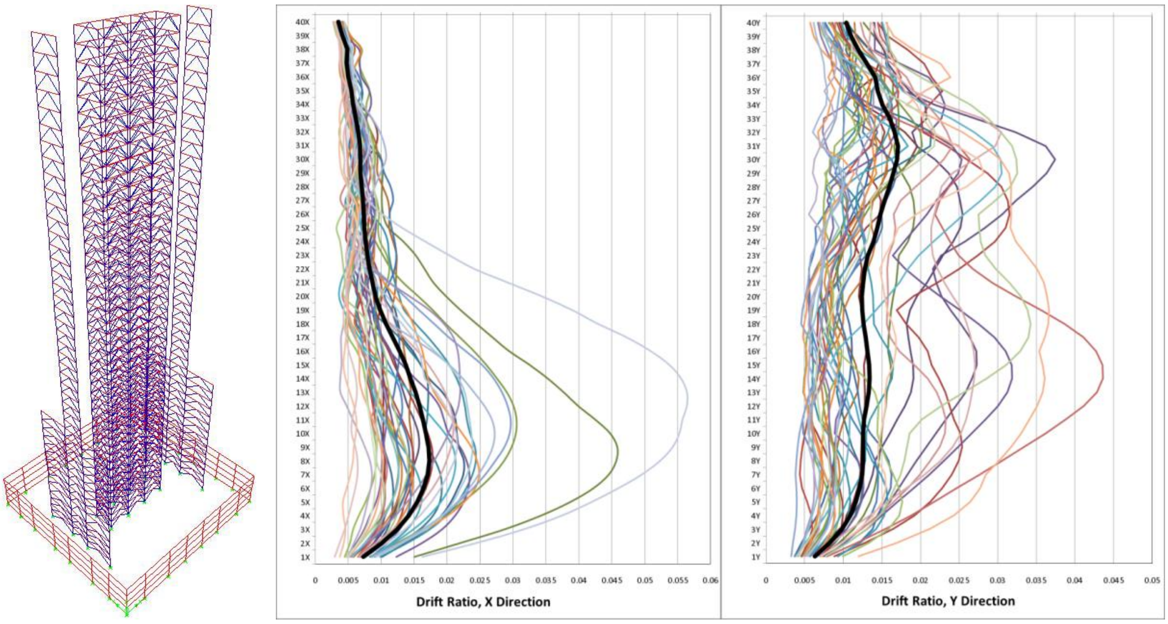

Figure 2. Case Study Lateral System and Story Drift Ratios for the Original Record Set (Average Drift in Bold)

3. MONTE CARLO SIMULATION

We considered the demands in two groups: story drift ratios, and brace strains. The demands were obtained from the output of 40 nonlinear response history analyses for amplitude-scaled ground motion records at the MCE level. The amplitude scaling considered the range of 1/5 times the lower first-mode period to 1.5 times the higher first-mode period. The analyses were repeated with the ground motions rotated 90 degrees. We computed the probabilities by grouping the response in 3 alternative datasets: from the 40 motions in their original orientation, from 90°-rotated motions, and from the combined 80 motions. For each analysis, we estimated the average value and variance for each demand parameter, and the correlation structure between demand parameters. Table 1 summarizes these demand parameters for story drift ratios and Table 2 for brace strains (compression positive).

Table 1. Summary of story drift demands

Statistic	Database		
	Original records	**Rotated records**	**Combined**
Maximum average demand	1.73%	1.77%	1.74%
Mean C.O.V.	0.45	0.42	0.44
Minimum correlation coefficient	-0.11	-0.32	-0.06

Table 2. Summary of brace strain demands

Statistic	Database		
	Original records	**Rotated records**	**Combined**
Maximum average demand	0.0112	0.0086	0.0098
Mean C.O.V.	0.54	0.55	0.55
Minimum correlation coefficient	-0.67	-0.63	-0.53

The dispersion in the results represents record-to-record variability, and is approximately equal to the coefficient of variations (C.O.V.). We augmented this dispersion to account for uncertainty due to modeling and construction quality assurance. We assumed a value $\beta_U = 0.25$ each for modeling and quality assurance, and defined the total dispersion as the square root of the sum of squares (SRSS), where the resultant variability is expressed as $\beta_T^2 = \beta_R^2 + \beta_U^2 + \beta_U^2$, where β_R^2 is the record-to-record variability from the analysis.

We observed that the correlation coefficients for the brace strain can be highly negative, which is unlikely for jointly lognormal random variables and borderline consistent with the limits established in Liu and Der Kiureghian (1986) for validity of Equation 3. We note that this correlation structure may result in artificial behavior, especially near the distribution tails, and interpret such results with some caution. We attribute this negative correlation to the behavior of brace pairs which alternate in compression and tension for any drift ratio, since the drift response history for any acceleration record is typically asymmetric due to localization and accumulation of nonlinearity.

An efficient building design would result in a maximum value for the average demand parameter equal to the limit imposed by the performance criteria. However, a conservative design can be acceptable where the maximum average demand is lower than the limit. In order to eliminate the sensitivity of the reliability study to extra conservatism in the specific building design, we evaluated the reliability based on the joint probabilities of exceeding the maximum average demand level by any demand parameter. In other words, we redefined the acceptance criteria to set it at the maximum encountered average demand, so that there is no conservatism in the building design.

Thus, for each demand parameter we established a deterministic performance limit. For example, for story drifts in the original record database, the deterministic performance limit is 1.73% (Table 1). This deterministic limit considers that demand exceedance of an acceptable value will *certainly* result in failure to satisfy the performance objectives, while non-exceedance will *certainly* not.

For each demand parameter, we also established a family of probabilistic performance limits. These probabilistic limits consider that demand exceedance of an acceptable value will *likely* result in failure to satisfy the performance objectives (i.e. unacceptable damage), while non-exceedance will *likely* not. The probabilistic limit is defined using a fragility curve, i.e. a lognormal probability distribution which has a median value equal to the deterministic limit and a measure of uncertainty, β. We investigated a range of β values of 0.2, 0.4 and 0.6. During the Monte-Carlo simulation, a performance limit is generated independently for each demand parameter from the associated fragility function and compared to the simulated demand.

4. PERFORMANCE EVALUATION BASED ON INTER-STORY DRIFT RATIO

We performed the following evaluations to assess the reliability:

1. We evaluated the joint probability of achieving variable performance goals. The performance goals correspond to exceeding the deterministic performance limit by the following percentages of demands: None, ≤5%, ≤10%, ≤25%, and ≤50%.
2. We evaluated the probability of achieving the same performance goals using the probabilistic performance limits.
3. We evaluated the expected percentage of demand parameters exceeding the following threshold values of the deterministic performance limit: 100%, 110%, 125%, and 150%. We also evaluated the joint probabilities of not exceeding these thresholds.

Figures 1 through 4 display the results generated from Monte Carlo simulation. Figure 3 presents the joint probabilities of achieving the performance goals using the original record set. The performance goal is defined as allowing up to none, 5%, 10%, 25% or 50% of the demand parameters to exceed the performance criteria. The performance criteria are evaluated using both a deterministic limit and a family of probabilistic limits parameterized by the variability, β, in the limit-state fragility function. We observe the following:

1. At the performance goal of having no story drift ratio exceed the deterministic drift criterion, the joint probability of achieving the performance goal is 31%. This value is smaller than the 50% assumed by many engineers.
2. The joint probability for achieving the same performance goal is lower for the probabilistic performance criteria, and decreases with increased variability in the limit state. The lowest

probability, for β = 0.6, is close to zero.

3. At the performance goal of having no more than 5% of the story drift ratios exceed the drift criteria, the joint probability ranges from 40% (deterministic) to 10% (β = 0.6). The sensitivity to variability in the limit-state definition decreases.
4. At the performance goal of having no more than 10% of the story drift ratios exceed the drift criteria, the joint probability ranges from about 50% (deterministic) to 20% (β = 0.6).
5. The sensitivity to variability in the limit-state definition decreases for higher joint probabilities.
6. At the performance goals of having no more than 50% story drift ratios exceed the drift criteria, the sensitivity to variability in the limit-state becomes insignificant (and slightly reversed). The probabilities range from 86% (deterministic) to 89% (β = 0.6).
7. The main effect of considering the probabilistic nature of performance criteria is that the joint probability values decrease significantly for the more demanding performance goals (e.g. no demand parameters allowed to violate). The variability in the independently simulated performance limits makes it more likely that any drift demand will exceed the performance limit.

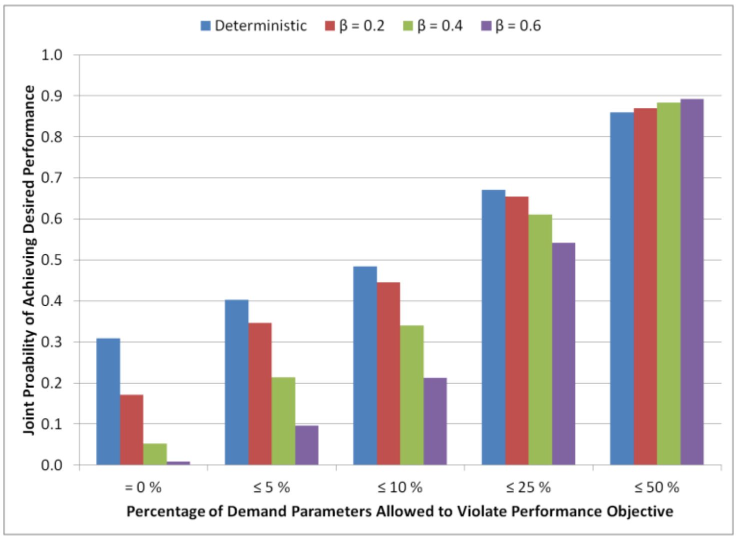

Figure 3. Probabilities of Meeting Variable Drift Performance Goals Using Original Record Set

Figure 4 presents the joint probabilities of achieving the aforementioned performance goals using the rotated record set, and using both a deterministic limit and a family of probabilistic limits. We observe the following:

1. The probabilities for the more stringent performance goals are slightly lower than those of the original record set (Figure 3), while those for the least stringent performance goals are slightly higher. This is attributed to the higher negative correlations between drifts from the rotated record set (Table 1).
2. The sensitivity to the variability in the limit-state for the range of performance goals is similar to that observed in the original record set (Figure 3).

Figure 5 presents the joint probabilities of achieving the aforementioned performance goals using the combined record set, and using both a deterministic limit and a family of probabilistic limits. We observe the following:

1. The probabilities roughly fall in between those of the original and rotated record sets and are bounded by them for all performance goals (Figures 3 and 4).
2. The sensitivity to the variability in the limit-state for the range of performance goals is similar to that observed in the original and rotated record sets (Figures 3 and 4).

From Figures 3 through 5, we infer that the performance goal having a joint probability of occurrence of 50%, which the implicit design targets, corresponds to the exceedance of the deterministic performance limit by just above 10% of the individual demands.

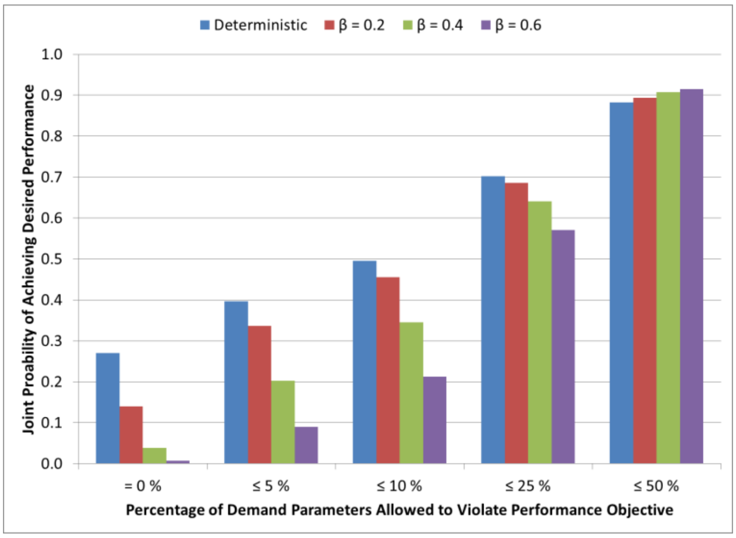

Figure 4. Probabilities of Meeting Variable Drift Performance Goals Using Rotated Record Set

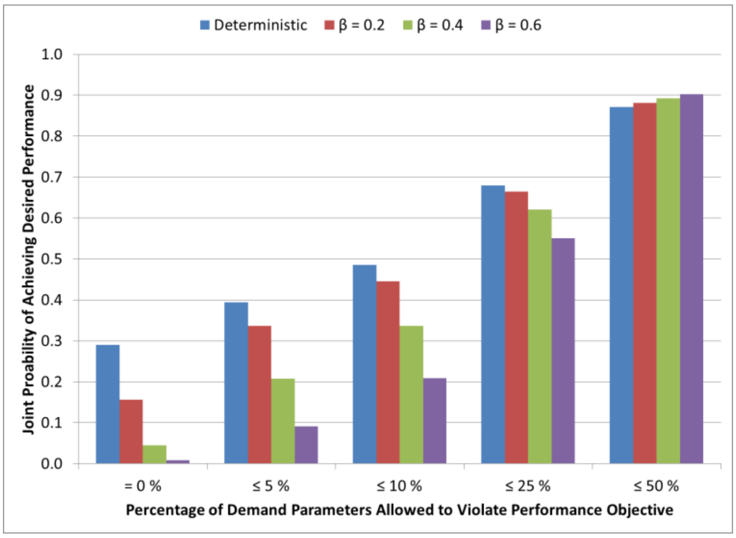

Figure 5. Probabilities of Meeting Variable Drift Performance Goals Using Full Record Set

Figure 6 presents the expected percentage of demand parameters exceeding the deterministic performance criterion by a specified threshold. We observe the following:

1. The expected percentage of story drifts just exceeding the deterministic limit is between 19 and 20%, depending on the record set being used for the analysis.
2. The expected percentage of story drifts exceeding 150% of the deterministic limit is between 6 and 7%.
3. The use of the rotated record set consistently results in slightly better predicted performance. However, the performance for all three records sets is effectively similar.
4. The sensitivity to the record set selection does not diminish for higher threshold values.

The joint probability of not exceeding the deterministic performance goal at any story level is shown to always fall below the target of 50% (Figure 3). As discussed earlier, this assessment is based on a design where the calculated maximum average demand is set equal to the deterministic performance limit. Often, due to the iterative nature of the nonlinear response history analysis procedure, there will be some difference between these two quantities, which provide a conservative buffer. Recognizing this, we evaluated the exceedance threshold for which the joint probability of non-exceedance meets the 50% target. This threshold can be used in design application as a minimum buffer size between the calculated maximum average demand and the deterministic performance limit in order to guarantee a 50% probability of non-exceedance. Figure 7 presents the results of this investigation. We observe that the 50% probability of non-exceedance limit is at approximately 125% (or slightly higher) of the deterministic drift limit for all three record sets.

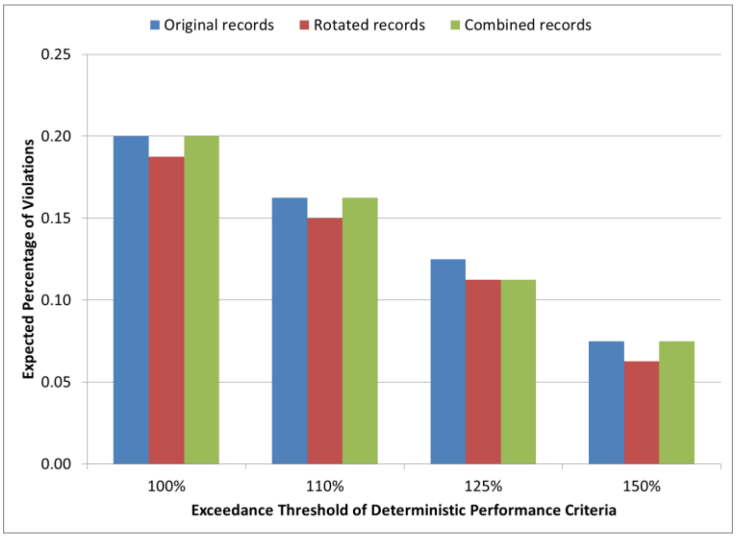

Figure 6. Expected Percentage* of Drift Performance Violations for Multiple Exceedance Thresholds
* Percentages are calculated from rounded mathematical expectation divided by the total number.

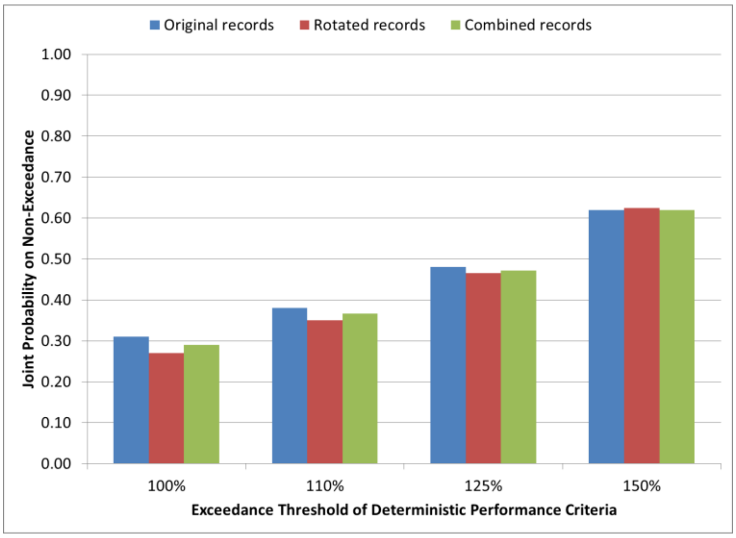

Figure 7. Joint Probability of Non-Exceedance for Multiple Drift Performance Thresholds

5. PERFORMANCE EVALUATION BASED ON BRACE COMPRESSIVE STRAINS

We performed the following evaluations to assess the reliability:

1. We evaluated the joint probability of achieving variable performance goals. The performance goals correspond to exceeding the deterministic performance limit by the following percentages of demands: None, ≤1%, ≤2%, ≤5%, and ≤10%.
2. We evaluated the probability of achieving the same performance goals using the probabilistic performance limits.
3. We evaluated the expected percentage of demand parameters exceeding the following threshold values of the deterministic performance limit: 100%, 110%, 125%, and 150%.

Figure 8 presents the joint probabilities of exceeding the selected performance goals. Only the deterministic performance limits is shown for clarity. The sensitivity to uncertainty in the performance limit is similar to that observed in the drift ratio performance and is not shown. The relatively large number of braces compared to story drifts results in two distinct differences from the story drift performance probabilities, especially, that groups of braces are adjacent and thus subject to similar demands:

1. It is almost certain that some braces will exceed the average demand of the most stressed brace. This probability ranges from 0 to 10% depending on the record set. We believe that this observation is due mainly to the high negative correlation between the demand parameters. Thus, the accuracy of the computed probability values may be affected by tail sensitivity. We can only be certain that they are generally low.
2. It is likely that only a small percentage (10% or less) of the braces will exceed the performance limit, while the majority of the braces are subjected to demand levels well below it.

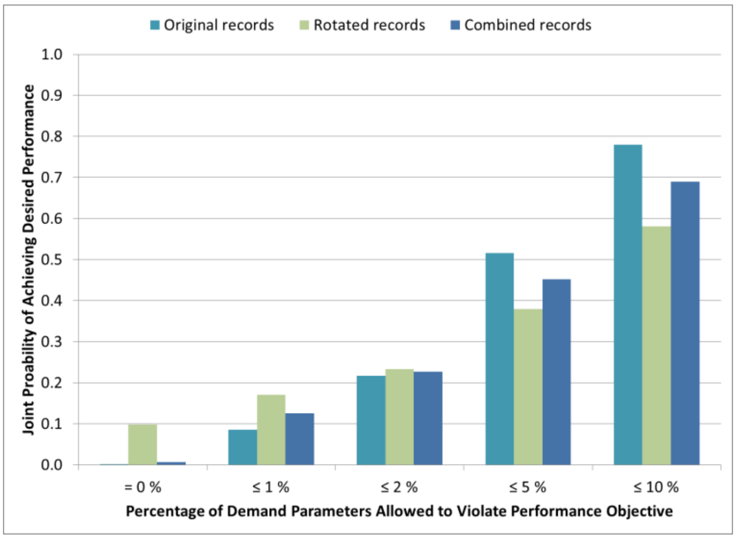

Figure 8. Probabilities of Meeting Variable Deterministic Brace Strain Performance Goals

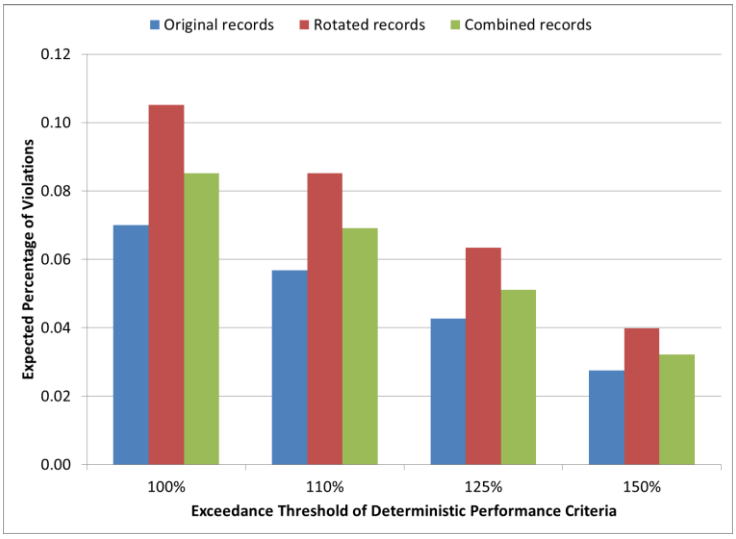

Figure 9. Expected Percentage* of Brace Strain Performance Violations for Multiple Exceedance Thresholds
* Percentages are calculated from rounded mathematical expectation divided by the total number.

Figure 9 presents the expected percentage of brace strain demands exceeding the deterministic performance criterion by a specified threshold. We observe the following:

1. The expected percentage of braces just exceeding the deterministic limit is between 6 and 11%, depending on the record set being used for the analysis. This percentage is significantly lower

than the corresponding values for story drift performance.
2. The expected percentage of braces exceeding 150% of the deterministic limit is between 2 and 4%.
3. The sensitivity of the results to the record set selection is similar to that of the story drift performance.

Due to the highly negative brace strains correlation structure discussed earlier, it is not possible to calculate accurate joint probabilities of non-exceedance for multiple exceedance thresholds (similar to Figure 7 for drift ratios). This probability is highly tail-sensitive, since the Monte Carlo process is often biased to generate at least 1 out of 1056 braces with artificially high strain in an unrealistically large percentage of simulated runs. Thus, they are not a reliable basis for judgment in this case study.

6. CONCLUSIONS

We evaluated the reliability of nonlinear response history analysis acceptance criteria based on comparing the average maximum value of each demand parameter to a deterministic limit, as required by common US design guidelines. Our case study represented a 40-story BRBF steel building which comprised 1056 braces. The design ground motion suite consisted of 40 horizontal ground motion pairs to estimate the mean and correlation structure of the demands. We evaluated the performance for the record set in the original orientation, 90°-rotated, and the combination thereof. We based our performance measures on the joint probability of not exceeding the acceptance criteria by the demand parameters of interest, namely the story drift ratios and brace compressive strains. We computed the joint probabilities and expected number of acceptance criteria violations using Monte Carlo simulation of joint lognormal distributions. We investigated the use of both deterministic and fragility-based probabilistic acceptance criteria, where the former is typically suitable for design applications and the latter is more appropriate for loss estimation. Our findings for the case study are the following:

1. The joint probability of not exceeding the deterministic drift limit at any story level is approximately 30%, compared to the 50% assumed by many engineers. The corresponding probability for the brace strains is close to zero.
2. For both story drifts and brace strains, a 50% joint probability of achieving the performance objective can be achieved if the latter is relaxed to allow 5-10% of the demand parameters to exceed the deterministic acceptable value.
3. A 50% joint probability of achieving the drift performance objective can be achieved if the deterministic acceptable value includes a 25% buffer (i.e. 80% reduction from the target limit). Alternately, it can be achieved if the performance objective is redefined to allow for reaching approximately 125% of the deterministic acceptable value in any individual story.
4. For ductile limit states, we expect that a tall building can sustain the additional demands described in conclusions 2-3 without compromising its structural integrity experiencing collapse.
5. For joint probabilities less than or equal to 50%, realistic consideration of uncertainty in the acceptance criteria -characterized by the associated probability of damage- consistently results in even lower joint probabilities of achieving the performance objectives.
6. The sensitivity to the ground motion suite orientation was largely minor.

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