# SIMPLIFIED APPLICATION OF THE FEMA 351 PROBABILISTIC SEISMIC PERFORMANCE EVALUATION GUIDELINES TO A WOODFRAME BUILDING

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## Abstract

The FEMA 351 guidelines for seismic evaluation (and upgrade) of existing welded steel moment-frame buildings represent a major step towards practical implementations of probabilistic performance-based assessments. Even so, a present-day structural engineer may find the guidelines to be rather complicated, and hence difficult to generalize. In this paper, a simplified step-by-step procedure derived from the same basis as the FEMA 351 guidelines is demonstrated for a building model borrowed from the CUREE-Caltech Woodframe Project. Like in FEMA 351, the performance objective considered consists of the specification of one or more performance levels (e.g., incipient damage and incipient collapse) and an acceptably low probability of exceeding each (within a specified period of time). Unlike FEMA 351, though, the level of confidence that each of these exceedance probabilities does not surpass its tolerable limit is not evaluated, and this check is not recast into a demand and resistance factor design format. Instead, the goal of the evaluation procedure outlined here is relatively transparent – i.e., to compare the mean probability of exceeding each performance level with its tolerable limit, similar to DOE 1020. Incremental Dynamic Analyses of the example woodframe building provides much of the data needed to carry out the procedure.


## Introduction

This paper outlines a step-by-step procedure for evaluating the seismic performance capability of a given building, and demonstrates it for a retrofitted small house designed by Reitherman & Cobeen (2003) and modeled by Isoda *et al.* (2001) as part of the CUREE-Caltech Woodframe Project. The house is hypothetically located at a site in Berkeley, California, near the Hayward Fault. The procedure is derived from the same basis as the FEMA 351 (2000) guidelines for steel moment-resisting frame buildings (i.e., Cornell *et al.* 2002), but is intended to be simpler and thereby more general.

## Performance Definitions

### *Performance Objective*

Like FEMA 351, the evaluation procedure outlined in this paper considers a probabilistic performance objective. Such a performance objective consists of the specification of one or more performance levels and a tolerable probability of exceeding each (i.e., experiencing poorer performance) within a specified period of time. Unlike FEMA 351, however, the level of confidence that the probability of exceeding each performance level does not surpass the tolerable limit is not evaluated in this paper. Instead, the mean probability of exceeding each performance level is considered, like in DOE 1020 (1994).

An advantage of the latter is that it is relatively simple but still accounts for the same (epistemic) uncertainties and (aleatory) randomness as the FEMA 351 approach.

*Performance Levels*

Two performance levels are considered in this paper, namely Incipient Damage and Incipient Collapse. The Incipient Damage performance level is not defined as first yield, but rather the point at which up to roughly half of the hinge elements of the system yield mechanism have reached yield while the maximum hinge deformation does not exceed 150% yield (from Appendix I of the SEAOC Blue Book, 1999). As in FEMA 351, the Incipient Collapse performance level is defined as the point at which the local stiffness of the Incremental Dynamic Analysis curve (structural demand versus ground motion severity, as demonstrated later in this paper) is less than one-fifth of its initial elastic stiffness. Other performance levels could also be incorporated into the general step-by-step procedure outlined below.

In order to quantify the point at which each of the performance levels is exceeded, a pertinent structural demand measure is used. In FEMA 351, for example, the maximum (over all stories) peak (over time) story drift ratio (i.e., inter-story drift normalized by story height) is used. For the woodframe house considered in this paper, the maximum (of four) peak cripple-wall drift ratio is used, since almost all of the deformation is concentrated at the cripple wall level.

## Evaluation Procedure

*Overview*

Since the type of performance objective considered in this paper limits the (mean) probability of exceeding each performance level to an acceptably low level (for a specified period of time), the goal of the step-by-step evaluation procedure outlined here is to compute this exceedance probability for each performance level and compare it with its tolerable limit. Note that in FEMA 351 (but not here) this exceedance probability check is recast into a demand and resistance factor design format. The format adopted here is thought to be more transparent.

Shortly put, the (mean) probability of exceeding each performance level is computed by convolving (i) a spectral acceleration ground motion (mean) hazard curve for the designated site (e.g., from the U.S. Geological Survey) with (ii) the probability of exceeding the performance level given the spectral acceleration of the ground motion (or its "fragility"). The latter accounts for the earthquake record-to-record variability in structural demand given spectral acceleration, the variability in structural capacity for each performance level, and the uncertainty in estimating both (median) demand and capacity via nonlinear dynamic analysis. The steps involved in the computation of the exceedance probability are detailed below and concurrently demonstrated for the Berkeley site and woodframe house considered as an example.

*Step 1: Establish the performance objective to be evaluated by specifying the tolerable probability of exceeding each performance level,* $P_o$ .

As described above, the performance objective consists of the specification of one or more performance levels and an acceptably low probability of exceeding each within a specific period of time, denoted $P_o$ . For the woodframe example considered here, tolerable probabilities of exceeding the Incipient Damage (ID) and Incipient Collapse (IC) performance levels are arbitrarily set at $P_o^{ID}$ = 5x10$^{-2}$/year and $P_o^{IC}$ = 5x10$^{-3}$/year.

*Step 2: Obtain or compute a mean spectral acceleration hazard curve for the site,* $\bar{H}(S_a)$ *, and estimate its log-log slope,* $k$ *, in the vicinity of each* $P_o$ .

A mean spectral acceleration hazard curve (i.e., mean exceedance probability as a function of spectral acceleration) for the designated site, denoted $\bar{H}(S_a)$, can be (i) obtained from the U.S.G.S. for 5%-damped spectral acceleration at a period of 0.1, 0.2, 0.3, 0.5, 1.0, or 2.0 seconds (Frankel & Leyendecker, 2001), or (ii) computed via Probabilistic Seismic Hazard Analysis (PSHA) using any one of a number of available computer codes. The period considered for $S_a$ should be as close as possible to the fundamental period of the given structure. The log-log slope, $k$ , of $\bar{H}(S_a)$, which will typically vary with the exceedance probability (or $S_a$ ), should be estimated at or near the tolerable exceedance probability ( $P_o$ ) for each performance level.

For the Berkeley site considered as an example, $\bar{H}(S_a)$ from the U.S.G.S. for a period of 0.2 seconds is illustrated in Figure 1a. The values of $k$ at the tolerable exceedance probabilities specified in Step 1 are noted in the figure (i.e., $k^{ID}$ =1.13 and $k^{IC}$ =1.80).

*Step 3: Estimate the median and the variability of structural "capacity,"* $\hat{C}$ *and* $\beta_{CR}$ *, for each performance level.*

The structural "capacity," $C$ , for each performance level is defined as the largest value of the pertinent structural demand measure (e.g., cripple-wall drift) for which the performance level (e.g., Incipient Collapse) is not exceeded. Typically this structural capacity will be a random quantity, at least to the extent that it will vary from ground motion to ground motion. In order to compute a sample of such capacity values, Incremental Dynamic Analysis (IDA) can be employed for a suite of ground motion records. A step-by-step description of the IDA procedure, which involves nonlinear dynamic analyses of the structure for an incrementally scaled ground motion record, is available in Section A.6 of FEMA 351. A more detailed discussion is provided by Vamvatsikos & Cornell (2004).

Computed via IDA for ten ground motions assembled by Somerville (2001) for the U.C. Berkeley Science Building as part of the PEER Testbed Program, ten structural capacity values (per performance level) for the woodframe house considered as an example are shown in Figure 1b. The median (computed as geometric mean) and variability (computed as standard deviation of natural logarithms of data) of these structural capacity values are $\hat{C}^{ID}$ = 0.0032 and $\beta_{CR}^{ID}$ = 0.01, and $\hat{C}^{IC}$ = 0.0174 and $\beta_{CR}^{IC}$ = 0.42.

*Step 4: Estimate the median and the variability of structural "demand," $\hat{D}$ and $\beta_{DR}$, as a function of ground motion spectral acceleration ($S_a$).*

For each of several values of spectral acceleration ($S_a$), the median and variability of structural demand, $\hat{D}$ and $\beta_{DR}$, can be calculated from a sample of structural demand values interpolated from the IDA curves established in Step 3. For each performance level, at least the following two values of $S_a$ should be considered: (i) the value of $S_a$ corresponding to the tolerable exceedance probability ($P_o$) on the spectral acceleration hazard curve [$\bar{H}(S_a)$], and (ii) the median of the $S_a$ values associated with the capacity points found in Step3. Note that some of the IDA curves established in Step 3 may need to be extrapolated or extended by performing additional nonlinear dynamic analyses.

Covering the range of $S_a$ values called for above (over both the ID and IC performance levels), the corresponding values of $\hat{D}$ for the woodframe house considered are shown in Figure 1b (labeled as the "Median IDA"). Although indirectly, the values of $\beta_{DR}$ are also shown in the figure via the "1-Sigma IDA's," which are given by $\hat{D} \div e^{\beta_{DR}}$ and $\hat{D} \times e^{\beta_{DR}}$.

*Step 5: Estimate the $S_a$ at which the median structural demand ($\hat{D}$) equals the median structural capacity ($\hat{C}$), denoted $s_a^{\hat{C}}$, for each performance level.*

For each performance level, $s_a^{\hat{C}}$ can be interpolated (or extrapolated) from the ($S_a$, $\hat{D}$) pairs calculated in Step 4. As illustrated in Figure 1b, the $s_a^{\hat{C}}$ values for the woodframe house example are $(s_a^{\hat{C}})^{ID} = 0.51g$ and $(s_a^{\hat{C}})^{IC} = 1.07g$.

*Step 6: Estimate the variability of structural demand given spectral acceleration ($\beta_{DR}$ given $S_a$), and the log-log slope of the median structural demand ($\hat{D}$) versus $S_a$, denoted $b$, in the vicinity of $s_a^{\hat{C}}$ for each performance level.*

Both $\beta_{DR}$ (the variability of structural demand given $S_a$) and $b$ (the natural log-log slope of the median structural demand versus $S_a$) can be estimated from the ($S_a$, $\beta_{DR}$) and

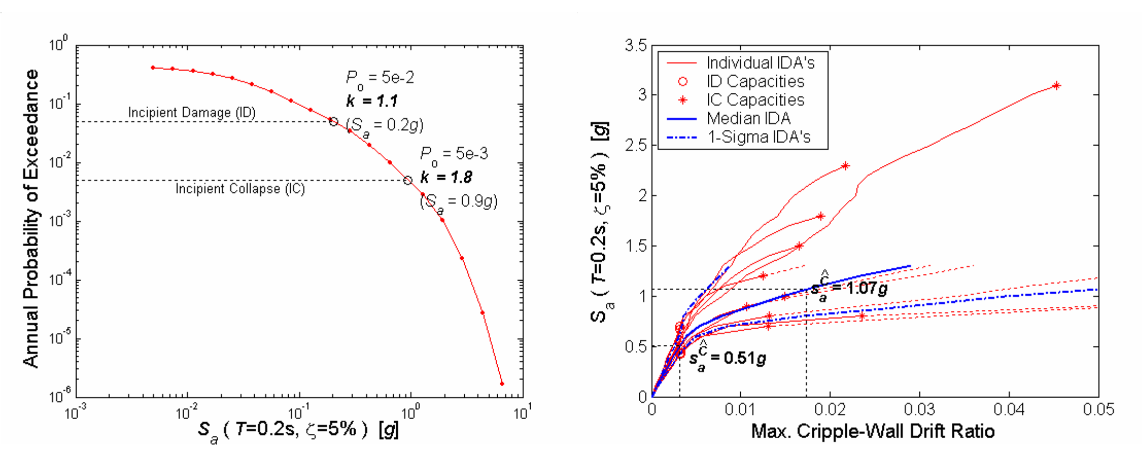


**Figure 1. Mean spectral acceleration hazard curve for the Berkeley site and Incremental Dynamic Analysis (IDA) results for the woodframe building example.**

$(S_a, \hat{D})$ pairs calculated in Step 4. For each performance level, the value of $S_a$ at which $\beta_{DR}$ and $b$ should be estimated is $s_a^{\hat{C}}$. In other words, $\beta_{DR}$ shall be interpolated (or extrapolated) at $S_a = s_a^{\hat{C}}$, and $b$ shall be estimated in the vicinity of $S_a = s_a^{\hat{C}}$.

Based on the curves labeled "Median IDA" and "1-Sigma IDA's" in Figure 1b, the values of $\beta_{DR}$ for the woodframe house considered are $\beta_{DR}^{ID}$= 0.19 and $\beta_{DR}^{IC}$= 1.06, and the values of $b$ are $b^{ID}$= 1.19 and $b^{IC}$= 2.65. For $b$, note that the dependent (or "*y*") variable is $\hat{D}$, even though it is plotted as the ordinate in Figure 1b like conventional force-deformation plots.

*Step 7: Estimate the uncertainty in computing the median structural demand ($\hat{D}$) given spectral acceleration ($S_a$), denoted $\beta_{DU}$, and the uncertainty in computing the median structural capacity ($\hat{C}$), denoted $\beta_{CU}$, for each performance level.*

Uncertainty enters the estimation of the median structural demand given spectral acceleration ($\hat{D}$ given $S_a$) and of the median structural capacity ($\hat{C}$) through uncertainties in modeling, for example, the damping, the live load, the material properties, as well as the number of ground motion records used to estimate $\hat{D}$ and $\hat{C}$. Ideally, both $\beta_{DU}$ and $\beta_{CU}$ would be estimated via sensitivity studies of the effect of variations in uncertain modeling parameters on structural demand and capacity (e.g., Yun *et al.* 2002 for steel moment frames). In lieu of this, default estimates of $\beta_{DU}$ for nonlinear dynamic analysis can be obtained from Table A-3 of FEMA 351 (assuming here that "Immediate Occupancy" in FEMA 351 maps to Incipient Damage). FEMA 351 also suggests values for $\beta_{CU}$ in Equations A-12 and A-14.

Based mostly on the default estimates from FEMA 351, for the example woodframe house it is assumed that $\beta_{DU}^{ID}$ and $\beta_{CU}^{ID}$ = 0.10, and that $\beta_{DU}^{IC}$ = 0.34 and $\beta_{CU}^{IC}$ = 0.15. Note that the estimate of $\beta_{DU}^{IC}$ is actually based on the standard error in estimating $\hat{D}$ using only 10 ground motions (i.e., $\beta_{DR}^{IC} / \sqrt{10}$), since it is larger than the default value (0.15) suggested in FEMA 351.

*Step 8: Calculate the mean probability of exceeding each performance level, $\bar{P}$, and compare it with the tolerable exceedance probability ($P_o$) specified in Step 1.*

Using the results of Steps 2-7, the mean probability of exceeding each performance level can be calculated via Equation 1 (Cornell *et al.*, 2002).

$$\bar{P} = \bar{H}(s_a^{\hat{C}}) \cdot \exp\left[\frac{1}{2}\frac{k^2}{b^2}(\beta_{DR}^2 + \beta_{DU}^2 + \beta_{CR}^2 + \beta_{CU}^2)\right] \qquad (1)$$

If $\bar{P} \le P_o$ for all of the performance levels considered, the performance objective established in Step 1 is achieved.

For the Berkeley site and woodframe house example, the mean probabilities of exceeding the Incipient Damage and the Incipient Collapse performance levels, calculated according to Equation 1, are $\bar{P}^{ID} = 1.5\text{x}10^{-2}$/year and $\bar{P}^{IC} = 5.6\text{x}10^{-3}$/year. While $\bar{P}^{ID}$ is less than the tolerable exceedance probability $P_o^{ID}$ specified in Step 1, $\bar{P}^{IC}$ is greater than $P_o^{IC}$, so the overall performance objective is not achieved in this example.

## Summary

As demonstrated for a small retrofitted house borrowed from the CUREE-Caltech Woodframe Project, a relatively simple and transparent step-by-step procedure derived from the same basis as the FEMA 351 guidelines can be used to probabilistically evaluate the seismic performance of a given building at a designated site. The procedure makes use of a mean ground motion hazard curve for the site and the results of incremental (nonlinear) dynamic analyses of the building in order to compute the mean (annual) probability of exceeding each of the performance levels that are specified as part of an overall performance objective. Such exceedance probabilities could also serve as quantitative bases for "rating" different buildings or alternative designs.

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