Concept Paper on Utilizing the FEMA P695 (ATC-63) Ground Motion Spectral Shape Guidelines to Adjust the Target Displacement in the ASCE/SEI 41 Nonlinear Static Procedure

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ABSTRACT

The FEMA P695 Methodology, developed through the recent ATC-63 Project, incorporates ground motion guidelines that include a so-called Spectral Shape Factor (SSF). This SSF adjusts the predicted collapse capacity of the building to account for the spectral shape of ground motions.

This paper explains how aspects of this new FEMA P695 Methodology could be adapted for use in refining the target displacement equation (i.e. inelastic displacement demand) in the ASCE/SEI 41 Nonlinear Static Method to account for spectral shape. The final result would be an additional coefficient (termed the "spectral shape coefficient") that would reduce the target displacement for sites where the ground motion is expected to have a less damaging spectral shape. This paper outlines how one would compute this spectral shape coefficient for any site and building of interest, and then explains the additional work needed to implement this new coefficient into ASCE/SEI 41.

An example is provided to illustrate the effect that the new coefficient has on the computed target displacement. For a 2% in 50 year motion at a San Francisco California site, application of the spectral shape coefficient results in a 40% reduction in the target displacement.

INTRODUCTION AND PURPOSE OF THIS PAPER

Recent research has found that rare earthquake ground motions (e.g. motions in 2% in 50 year exceedance) are less damaging to buildings than is typically expected (Baker and Cornell 2006, Haselton and Baker 2006, Zareian 2006). Rare ground motions typically have a unique spectral shape that results in less inelastic displacement demand being imposed on the building[1]. It is important to account for spectral shape because, for a given ground motion hazard level (e.g. 2% chance of exceedence in 50 years), the shape of the *uniform hazard spectrum (UHS)* can be quite different from the shape of the *mean (or "expected") response spectrum* of a real ground motion

[1] The reason for this is briefly explained later in this paper, but the full explanation for this effect is beyond the scope of this paper; interested readers are referred to Appendix B of FEMA P695 (FEMA 2009) and the Haselton et al. (2009).

having an equally high spectral amplitude at a single period (Baker 2005, Baker and Cornell 2006).

These research findings were utilized in the recent FEMA P695 (ATC-63) project (FEMA 2009), which was focused on the prediction of structural collapse. The FEMA P695 report includes detailed information regarding how this unique spectral shape affects structural collapse capacity, showing that neglecting to account for spectral shape can underestimate the collapse capacity by up to 60% in some cases.

However, this effect does not apply only to prediction of structural collapse, but applies more generally to the inelastic displacement demand a building undergoes when subjected to an earthquake. Even so, this effect has not yet been accounted when computing the target displacement in the current ASCE/SEI 41 (ASCE 2006) Nonlinear Static Procedure (NSP). In this procedure, the equation to predict the target roof displacement (ASCE/SEI 41 Equation 3-14) is follows. In the ASCE/SEI 41 NSP, the building is pushed to this target roof displacement, and the element force and deformation demands are recorded at this displacement. These element demands are then used to determine the performance level of the building.

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g \qquad (1)$$

The purpose of this paper is to conceptually explain how the above equation of the ASCE/SEI 41 NSP could be adapted to account for the spectral shape effects, and to outline what additional work would be needed to implement such a change. These proposed changes are based heavily on the advancements made in the ATC-63 project, and this paper draws heavily from Appendix B of FEMA P695 (FEMA 2009).

It should be noted that accounting for this spectral shape effect in determining the target displacement could be approached in other ways not discussed in this paper, such as (a) using the inelastic spectral displacement in equation 3-14 rather than spectral acceleration, or (b) using the capacity spectrum method with an appropriate spectral shape. This paper assumes that the framework of the ASCE/SEI 41 NSP and equation 3-14 will remain unchanged, and describes how the coefficients in this equation could be modified to account for the spectral shape effect.

INTRODUCTION TO THE FEMA P695 (ATC-63) METHODOLOGY, AND TREATMENT OF GROUND MOTIONS

The overall purpose of the FEMA P695 (ATC-63) Methodology is to provide a rationale basis for establishing the design provisions of a newly-proposed structural system (e.g. the R factor, etc.). The general approach taken in FEMA P695 is to predict the median collapse capacity of the newly-proposed structural system, and to ensure that this median capacity is large enough to provide adequate life safety. Collapse capacity is predicted through nonlinear dynamic analysis of representative structures of the proposed structural system, where simulation models are subjected to recorded ground motions.

An important part of the ATC-63 Methodology is the treatment of ground motions. As indicated earlier, recent research has shown that rare earthquake ground motions are typically less damaging that once thought, due to the unique spectral shape of such motions. Figure 1 begins to explain the reason for this. Figure 1 shows the acceleration spectrum of a Loma Prieta ground motion[2] (PEER 2008), which has a 2% in 50 year intensity of 0.9g at a period of 1.0 second. This figure also shows the intensity predicted by the Boore et al. (1997) attenuation prediction, consistent with the event and site associated with this ground motion. These predicted spectra include the median spectrum and the plus/minus one and two standard deviation spectra, assuming that S_a values are lognormally distributed.

Figure 1 shows that this 2% in 50 year motion has an unusual spectral shape with a "peak" from 0.6 to 1.8 seconds that is much different from the shape of a uniform hazard spectrum. This peak occurs around the period for which the motion is said to have an 2% in 50 year intensity, and at this period the observed S_a(1s) is much higher (0.9g) than the mean expected S_a(1s) from the attenuation function (0.3g). This peaked shape makes intuitive sense because it is unlikely that a ground motion with a much larger than expected spectral acceleration (much higher than the mean) at one period would have similarly large spectral accelerations at all other periods.

Referring to Figure 1, epsilon (ε) is defined as the number of logarithmic standard deviations between the observed spectral value and the median prediction from an attenuation function. At a period of 1.0 second, the spectral value is 1.9 logarithmic standard deviations above the predicted mean spectral value, so this record is said to have "ε = 1.9 at 1.0 second." Similarly, this record has ε = 1.1 at 1.8 seconds. Thus, the ε value is a function of the ground motion record, the period of interest, and the attenuation function used for ground motion prediction.

Positive ε values are expected for rare ground motions (e.g. 2% in 50 year motions), so these rare motions tend to have the peaked spectral shape shown in Figure 1. This peaked shape makes the ground motion less damaging to the structure because the acceleration demands reduce as the structural softens and the period elongates and the higher mode demands being lower. This reduced demand is evident by observing the Loma Prieta motion with the mean + 2σ attenuation prediction at T = 1 sec, but is significant less at other periods. This positive ε effect occurs for sites across the United States (U.S.), but is more pronounced for western U.S. sites where the earthquake events occur more frequently.

[2] This motion is from the Saratoga station and is owned by the California Department of Mines and Geology. For this illustration, this spectrum was scaled by a factor of +1.4, in order to make the S_a(1s) demand the same as the MCE demand. For the purposes of this example, please consider this spectrum to be *unscaled*, since later values (e.g. ε) are computed using unscaled spectra.

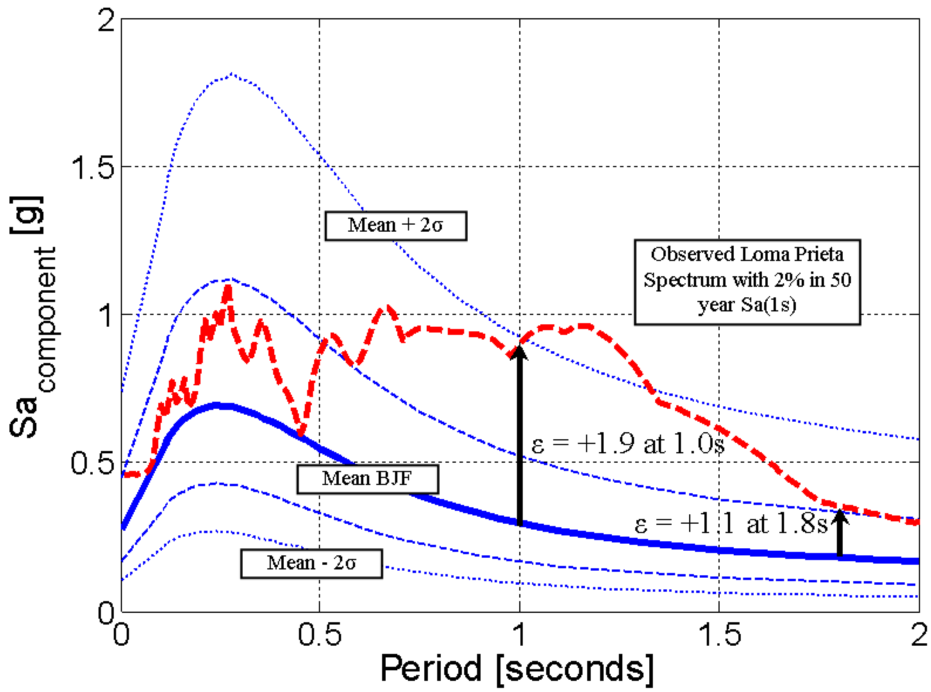

Figure 1. Comparison of an observed spectrum with spectra predicted by Boore, Joyner, and Fumal (1997); after Haselton and Baker (2006).

The ATC-63 project looked in detail at the collapse capacities of 118 buildings, and used the results to develop empirical equations that account for the distinctive spectral shape of rare ground motions (ε) on the median collapse capacity of a building. The basic approach of ATC-63 is as follows:

- Predict the median collapse capacity using nonlinear dynamic time-history analyses with a general set of 22 far-field ground motions.
- Compute the Spectral Shape Factor (SSF).
- Multiple the median collapse capacity by the SSF to predict the adjusted median collapse capacity.

The SSF shows how much the spectral shape (ε) effect changes the median collapse capacity, so this is the parameter of interest when we are looking at the implication for the ASCE/SEI 41 NSP. Accounting for this spectral shape (ε) effect has been shown to increase the collapse capacity by up to 60% in some cases.

The following equations[3] show how the SSF would be computed in FEMA P695.

$$SSF = \exp[\beta_1(\bar{\varepsilon}_o(T_1))] \quad (2)$$

$$\beta_1 = (0.14)(\mu_T - 1)^{0.42} \quad \text{where } \mu_T \leq 8.0 \quad (3)$$

[3] To simplify the discussion of the SSF, we assume here that the ground motions are ε-neutral (i.e. have average ε of zero for all periods). This is not assumed in FEMA P695, but this would be assumed for any changes in the ASCE/SEI 41 NSP, so this is assumed in equation 2.

where β_1 is a parameter that indicates how sensitive the median collapse capacity is to changes in the ε value, $\bar{\varepsilon}_o(T_1)$ is the expected ε value for the site and hazard level of interest, and μ_T is the ductility demand of the building.

Using the above two equations, the user can compute the SSF based on the expected ε value ($\bar{\varepsilon}_o(T_1)$) and the ductility of the building (μ_T). This SSF shows how much the median collapse capacity is increased by the spectral shape (ε) effect.

The ductility of the building (μ_T) is computed in accordance with the guidelines of FEMA P695. Since FEMA P695 is focused on collapse prediction, this value is computed as an estimate of the near-collapse ductility demand of the building.

For establishing the $\bar{\varepsilon}_o(T_1)$ value in FEMA P695, the goal is that the assessment process be relatively general and not specific to a single site. Accordingly, the FEMA P695 estimates of $\bar{\varepsilon}_o(T_1)$ are based on the Seismic Design Category (SDC) of the site rather than site-specific information. This approach is not discussed in detail here because the ASCE/SEI 41 NSP is a site-specific procedure, which would necessitate a more precise approach. This more precise approach is discussed in the next section.

IMPLICATIONS OF FEMA P695 FOR THE ASCE 41 NONLINEAR STATIC PROCEDURE

The last section showed that the spectral shape (ε) effect is important to structural response and outlined how it is accounted for in FEMA P695. In FEMA P695, the SSF is applied to adjust the median collapse and a similar adjustment should be made to the inelastic displacement demand (i.e. the target displacement) used in the ASCE/SEI 41 NSP. This adjustment to the ASCE/SEI 41 NSP would affect the C_1 coefficient of the procedure.

The Spectral Shape Factor (SSF) approach taken in FEMA P695 is almost directly applicable to the ASCE/SEI 41 NSP. The primary differences are as follows:

- The β_1 predictive equation in FEMA P695 was specifically developed for prediction of collapse capacity, where the β_1 indicates the sensitivity of the median collapse capacity to changes in the ε values of the ground motions. A new β_1 predictive equation would need to be developed to predict the effects that changes to the ε values have on the inelastic displacement demand (roof displacement of the building) rather than the median collapse capacity. Such an equation for β_1 could be created using the nonlinear dynamic time history results for the same 118 buildings used in FEMA P695. This equation could be created using the same form shown in equation 3 (based on building ductility demand, μ) or could be created based on the R value of the building, for consistency with the current C_1 coefficient equation in ASCE/SEI 41.
- The definition of building ductility demand (μ_T) is based on the collapse limit state in FEMA P695. For the ASCE/SEI 41 NSP, the building ductility demand (μ) will be based on the demand imposed during the pushover to the target displacement. This change would be made as part of developing the new β_1 predictive equation above.

- The $\bar{\varepsilon}_o(T_1)$ value would be computed using deaggregation for the specific site where the building resides, rather than using the more general approach of FEMA P695. Figure 2 shows an example of this for a 2% in 50 year Sa(2.0 second) motion in San Francisco California (with NEHRP soil class D and 30m shear wave velocity of 275 m/s). For this example, the expected ε value ($\bar{\varepsilon}_o(T_1)$) is 1.39.

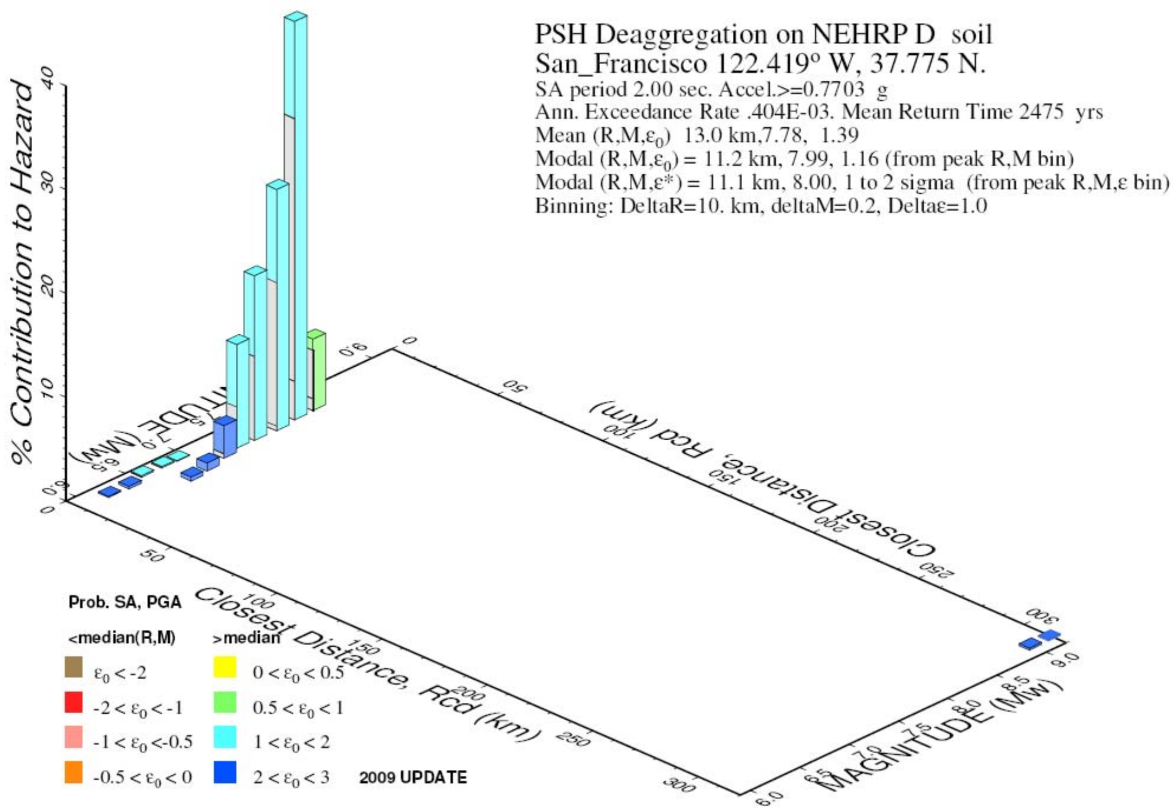

Figure 2. Deaggregation of the seismic hazard for an 2% in 50 year Sa(2.0s) in San Francisco California (USGS 2009).

To begin the discussion of possible modifications to the target displacement in the ASCE/SEI 41 NSP, equation 4 shows the C_1 coefficient in the current version of ASCE/SEI 41. This coefficient represents the ratio of inelastic displacement demand to elastic displacement demand, so this would be adjusted to account for the spectral shape (ε) effect.

$$C_1 = 1 + \frac{R-1}{aT_e^{\,2}} \tag{4}$$

Based on using a similar approach to FEMA P695, the adjustment to the C_1 coefficient would be accomplished through applying a Spectral Shape Coefficient (*SSC*) as follows in equations 5 through 7.

$$C_1 = \left[1 + \frac{R-1}{aT_e^{\ 2}}\right] \cdot SSC \tag{5}$$

$$SSC = \exp\left[\beta_1\left(\bar{\varepsilon}_o(T_1)\right)\right] \tag{6}$$

$$\beta_1 = (a)(\mu - 1)^b \qquad \text{where } \mu \leq c \tag{7}$$

In order to use the above three equations in the ASCE/SEI 41 NSP, the regression parameters a, b, and c would be calibrated for prediction of the inelastic displacement demands, rather than prediction of the collapse capacity, as was mentioned previously. As mentioned previously, equation 7 could alternatively be based on R rather than μ, for consistency with the current ASCE/SEI 41 equation for C_1.

ILLUSTRATIVE EXAMPLE

This section briefly illustrates the possible modification to the ASCE/SEI 41 NSP, by applying the current procedure and a modified procedure to a 12-story (158' tall) reinforced concrete (RC) special moment frame (SMF) building. This 12-story structure is a perimeter frame building with 20' bay widths, and the simplified structural model consisting of a two-dimensional three-bay frame. The first-mode period of this building is 2.01 seconds, based on eigenvalue analysis. This model has been used in FEMA P695 (FEMA 2009) as well as the recent Pacific Earthquake Engineering Research (PEER) Center Ground Motion Selection and Modification (GMSM) study (PEER GMSM 2009). The most complete documentation of this design and model (ID 1013) is available in Haselton and Deierlein (2007) and at http://myweb.csuchico.edu/~chaselton/.

Figure 3 shows the static pushover curve for this building.

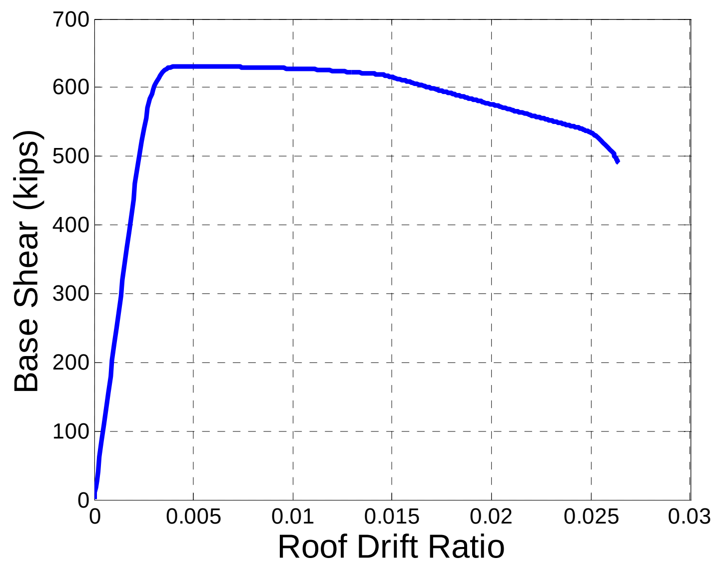

Figure 3. Static pushover curve for 12-story RC SMF perimeter frame building (ID 1013). This is based on the lateral load distribution from ASCE 7-05.

For purposes of illustration, this building is assumed to be at the San Francisco site used in Figure 2. This site has a 2% in 50 year Sa(2.0s) value of 0.77g and $\bar{\varepsilon}_o(T_1)$ = 1.39 (from Figure 2).

Application of the Current ASCE/SEI 41 Nonlinear Static Procedure

Using the current NSP, the target displacement is computed according to equation 3-14 of ASCE/SEI 41 (ASCE 2006), as follows:

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g \quad (8)$$

$$\delta_t = (1.3)(1.0)(1.0)(0.77g)\frac{(2.0s)^2}{4\pi^2}(386.4 in/s/s) = 39.2 \text{ inches} \quad (9)$$

The target displacement of 39.2 inches corresponds to a roof drift ratio of 2.07%, and Figure 3 shows that this displacement is on the negative slope of the static pushover curve. This is undesirable because this occurs near the point when several elements in the structure have exceeded the Collapse Prevention limit state.

Effects of the Possible Change to the ASCE/SEI 41 Nonlinear Static Procedure

The proposed change to the ASCE/SEI 41 NSP would be to modify the C_1 coefficient as shown previously in equations 5-7. To do this, we must first compute the building ductility demand (μ) as shown in equation 10; in this equation, the yield roof drift ratio is computed according to the approach from FEMA P695 (FEMA 2009).

$$\mu = RDR / RDR_{yield} = 0.0207 / 0.0023 = 11.7 \tag{10}$$

Once the building ductility demand (μ) is computed, it can be used to estimate the value of β_1. Equation 11 shows the generic form of the equation, where the parameters (a, b, and c) would need to be calibrated as explained previously.

$$\beta_1 = (a)(\mu - 1)^b \quad \text{where } \mu \le c \tag{11}$$

For this specific building, analyses have been done to show that the β_1 value is approximately -0.25 (PEER GMSM 2009). Therefore, we will use this β_1 = -0.25 value for this example.

$$\text{Assumed for illustration:} \qquad \beta_1 = \text{-0.25} \tag{12}$$

The Spectral Shape Coefficient (SSC) can now be computed according to equation 6, and the resulting C_1 coefficient can be computed according to equation 5.

$$SSC = \exp\left[\beta_1 (\bar{\varepsilon}_o (T_1))\right] = \exp\left[-0.25 \cdot (1.39)\right] = 0.71 \tag{13}$$

$$C_1 = \left[1 + \frac{R-1}{aT_e^{\,2}}\right] \cdot SSC = [1.0] \cdot 0.71 = 0.71 \tag{14}$$

Based on this updated estimate of C_1, the target displacement can be recomputed as follows:

$$\delta_t = (1.3)(0.71)(1.0)(0.77g)\frac{(2.0s)^2}{4\pi^2}(386.4in/s/s) = 27.8 \text{ inches} \tag{15}$$

This target displacement of 27.8 inches relates to a roof drift ratio of 1.47%, so Figure 3 shows that this displacement is just at the start of the negative slope on the static pushover curve.

Since the target displacement was reduced by the reduction in the C_1 coefficient, the building ductility demand (μ) is also affected. Since the SSC is dependent on the building ductility demand (μ), this technically becomes an iterative calculation. Even so, this is not included in this example, because this is unwarranted complication for an approximate method. If it is decided that the ASCE/SEI 41 NSP will be updated based on the concept of this paper, then an approach will be developed to estimate the correct answer without requiring that the user to iterate.

Summary of the Impacts of the Possible Change to the ASCE/SEI 41 Nonlinear Static Procedure

For this example site in San Francisco, the target roof drift is 2.1% (39.2”) based on the current ASCE/SEI 41 NSP, and this target roof drift would be reduced to 1.5% (27.8”) if the C_1 coefficient were adjusted to account for the effects of spectral shape (ε). For this example site and building, this change to the NSP would cause the displacement demand to decrease by 40%.

Figure 4 shows these target displacements on the static pushover curve, showing that the 2.1% roof displacement demand would clearly lead to a negative stiffness, but that the 1.5% roof drift demand would only push the building to the verge of a negative stiffness. This comparison clearly shows that this possible modification to the ASCE/SEI 41 NSP could have a large impact on the building performance level that is predicted by the procedure.

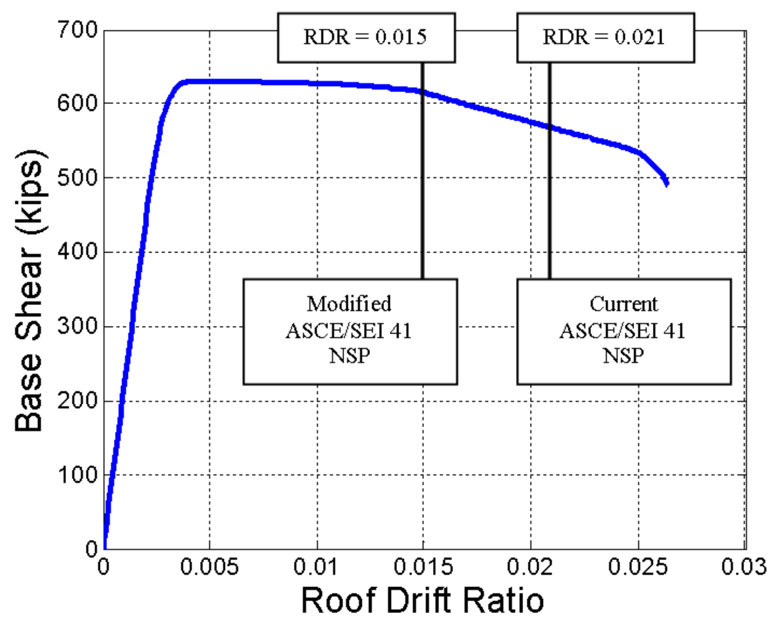

Figure 4. Static pushover curve for 12-story RC SMF perimeter frame building, showing the target displacements for both the current ASCE/SEI 41 NSP and the possibly modified procedure.

The above results are only for a single example building and example site. This is compared with other possible sites, buildings, and ground motion levels, as follows:

- The impacts would be even larger for sites and ground motion levels with higher values of $\bar{\varepsilon}_o(T_1)$. Higher $\bar{\varepsilon}_o(T_1)$ values can occur for rare motions at other western U.S. sites (typical up to about 2.0 for a 2% in 50 year motion).
- Accordingly, the impacts would be smaller for smaller values of $\bar{\varepsilon}_o(T_1)$.
- The impacts would be smaller if the building ductility level were smaller (e.g. for smaller ground motion levels, for a building with less nonlinearity, for non-ductile structures, etc.).

SUMMARY AND POSSIBLE NEXT STEPS

This paper has shown that spectral shape (ε) is an important consideration when predicting the inelastic displacement demand of a building, and this is not accounted for in the current version of the ASCE/SEI 41 Nonlinear Static Procedure (NSP). This paper outlines how the ASCE/SEI 41 NSP could be modified to account for this effect, and illustrates this modification would lead to a 40% decrease in target displacement for a 2% in 50 year motion at an example site in San Francisco, California. Such a large decrease in target displacement would undoubtedly have a large impact on the building performance level that is concluded from the NSP.

At this point, the decision of whether to pursue this modification to the ASCE/SEI 41 NSP is really a decision regarding the balance of accuracy versus simplicity of the procedure. The target displacement could be more accurately predicted with the inclusion of the Spectral Shape Coefficient (*SSC*), but the basis for this *SSC* is admittedly conceptually difficult, and it would be difficult to make this transparent for most users of the NSP. The following lists the possible paths forward:

a) Use the concept presented in this paper to develop the *SSC* and add it to the ASCE/SEI 41 NSP. This would be the most accurate approach.

b) Develop the *SSC* and add it to ASCE/SEI 41 NSP, but leave an option for the user to elect to use *SSC* = 1.0. This would allow more advanced users to account for the spectral shape affect, but would still allow a simpler (and typically conservative) application of the procedure using *SSC* = 1.0. This is the most desirable option in the opinion of the authors.

c) Make no modification to the ASCE/SEI 41 NSP, but instead modify the Nonlinear Dynamic Procedure (NDP) to account for this spectral shape (ε) effect. This would require modification to section 1.6.2.2 of ASCE/SEI 41, and the possible approaches to this are not addressed in this paper.

d) Make no modification to either the ASCE/SEI 41 NSP or the NDP. This would be the simplest approach.

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