CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

USER GUIDE FOR AUTOCSM: AUTOMATED CAPACITY SPECTRUM METHOD OF ANALYSIS

BY

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REPORT NO. EERL 2004-05

PASADENA, CALIFORNIA

APRIL 2004

A REPORT ON RESEARCH SUPPORTED BY THE CALIFORNIA INSTITUTE OF TECHNOLOGY UNDER THE SUPERVISION OF PI NAME

User Guide for AutoCSM:

Automated Capacity Spectrum Method of Analysis

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AutoCSM

Earthquake Engineering Research Laboratory

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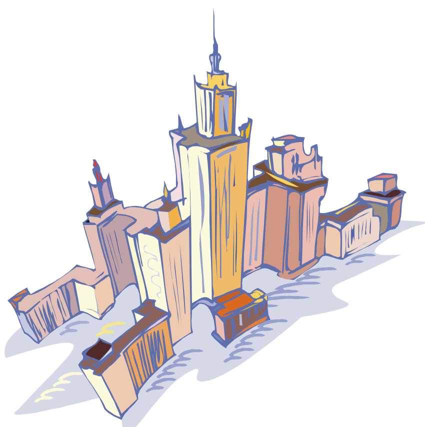


Version 1.1
April 2004
Caltech

Automated Capacity Spectrum Method of Analysis

California Institute of Technology
Pasadena, CA

April, 2004

Provisional Patent Filed
January 21, 2004
60/538,387

Contents

List of Figures

Chapter 1

Introduction

Within Performance-Based Engineering, four types of building analysis techniques are available: linear static, linear dynamic, nonlinear static and nonlinear dynamic. Nonlinear Static Procedures have become popular because of the appeal to structural engineers that displacement demands can be calculated which directly take into account the nonlinear load-deformation characteristics of both the structural elements and the entire structure without running a nonlinear time history analysis. The Capacity Spectrum Method is a Nonlinear Static Procedure that predicts a Performance Point displacement demand for a building subjected to earthquakes by combining structural capacity determined from a push-over analysis with seismic demand represented as response spectra.

AutoCSM implements a new graphical Performance Point solution procedure, developed by the authors, that both improves the accuracy of the Performance Point displacement prediction and gives insight into the sensitivity of the Performance Point. The solution procedure has been adopted for use in FEMA 440 [3]. It replaces the conventional CSM solution procedure as set forth in ATC-40 [4]. Determining the Performance Point for a given capacity spectrum and seismic demand has been fully automated by AutoCSM with minimal user inputs.

1.1 Capacity Spectrum Method of Analysis (CSM)

The Capacity Spectrum Method (CSM) combines structural capacity with seismic demand to predict a displacement demand on a structure. Linear response spectra with varying amounts of damping represent inelastic seismic demand. Each value of damping is associated with a corresponding value of ductility. Structural capacity is represented by a push-over curve of the building model. For different displacement values along the push-over curve, bilinear approximations are fit to the curve which define a yield displacement for the structure. When the demand and capacity ductilities are equal, the system is in a type of dynamic equilibrium.

The equilibrium point defines the expected performance of the structure, referred to as the *Performance Point*.

1.2 Modified Acceleration-Displacement Response Spectrum

The conventional Capacity Spectrum Method uses the secant period as the effective linear period in determining the Performance Point [4]. However, the improved effective linear periods developed by the authors have been found to be different from the secant period. Therefore, the conventional Capacity Spectrum Method will be modified in some fashion to enable the use of the effective parameters developed in this study. The solution is to modify the seismic demand. The seismic demand, in Acceleration-Displacement Response Spectrum (ADRS) format, will be reshaped by a *modification factor*. Every value of acceleration at every displacement will be multiplied by the ratio of the secant stiffness of the capacity spectrum to the effective stiffness. An ADRS and modified ADRS (MADRS) are shown in Figure 1.1.

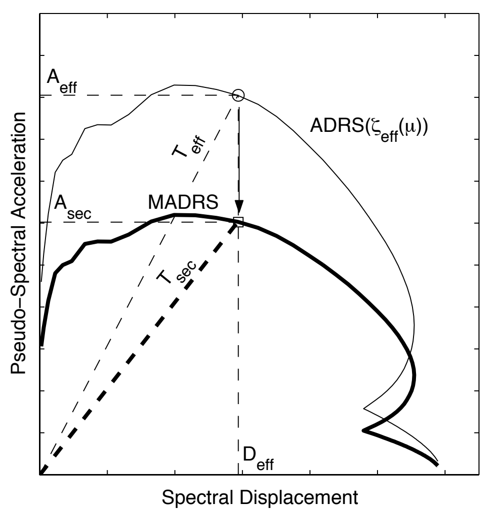


Figure 1.1: Modified Acceleration-Displacement Response Spectrum (MADRS).

The modification factor, M, is defined as:

$$M = A_{sec}/A_{eff} \tag{1.1}$$

A_{eff} is the acceleration obtained by the intersection of the ADRS and the radial line representing T_{eff}. A_{sec} is the value of acceleration corresponding to the intersection of the MADRS and the radial line representing the T_{sec}. A_{eff} and A_{sec} may be expressed as:

$$A_{eff} = D_{eff}(\frac{2\pi}{T_{eff}})^2 \tag{1.2}$$

$$A_{sec} = D_{eff}(\frac{2\pi}{T_{sec}})^2 \tag{1.3}$$

Substituting Equations 1.2 and 1.3 into Equation 1.1 yields:

$$M = (\frac{T_{eff}}{T_{sec}})^2 \tag{1.4}$$

The Modified Acceleration-Displacement Response Spectrum (MADRS) may now be used in combination with the capacity spectrum to determine the Performance Point as shown in Figure 1.2. Through the implementation of the modification factor, the Performance Point appears to occur at the secant period, when in fact it occurs at an effective period which is different from the secant period.

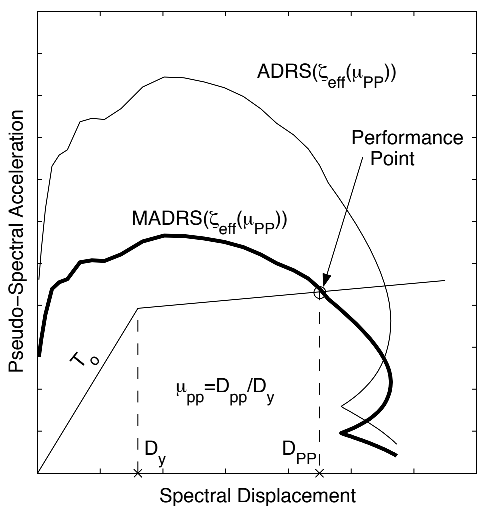


Figure 1.2: Determining the Performance Point using the Modified Acceleration-Displacement Response Spectrum (MADRS).

Additional insight can be gained into the Performance Point displacement prediction by creating a Locus of Performance Points. MADRS demand spectra may be calculated for a range of ductility values. The intersections of the MADRS and the corresponding secant period lines may be connected together to create a Locus of Performance Points. The Performance Point is located at the intersection of the Locus of Performance Points and the capacity spectrum as shown in Figure 1.3. The complete improved CSM is presented in References [3], [6] and [5].

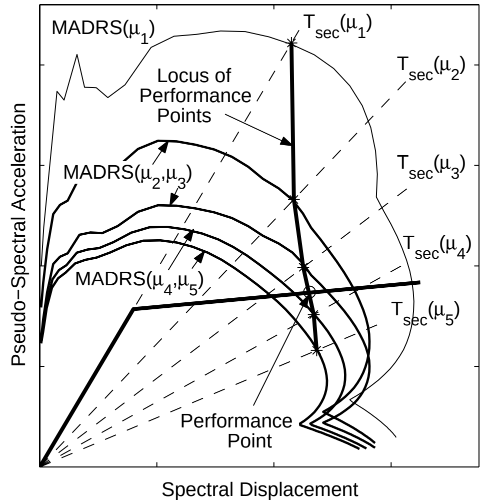
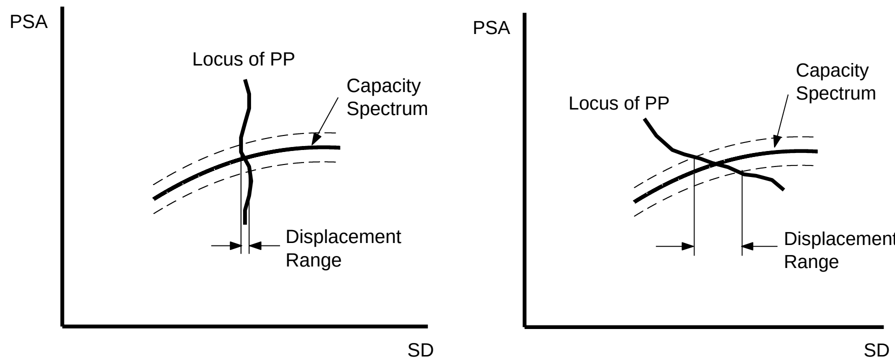


Figure 1.3: Determining the Performance Point using the Locus of Performance Points.

From this new graphical solution procedure, information is available far beyond just a Performance Point coordinate. The new Performance Point solution procedure gives insight into the sensitivity of the displacement prediction. The procedure clearly reveals how variations in both the capacity or demand will effect the prediction. If the strength of the capacity spectrum were increased or decreased, the Performance Point changes, but by how much? The answer depends on the slope of the Locus of Performance Points near the Performance Point which is directly observable in this procedure.

Examples of different Loci of Performance Points are shown in Figure 1.4. Figure 1.4(a) shows a case where Locus is is nearly 90 degrees. In this case, raising or lowering the capacity spectrum has very little effect on the Performance Point displacement. The displacement range is very small. However, Figure 1.4(b) shows a case where the slope of the Locus is between vertical and horizontal. In this case, raising or lowering the capacity spectrum has a very large effect on the Performance Point displacement and the corresponding displacement range is large.

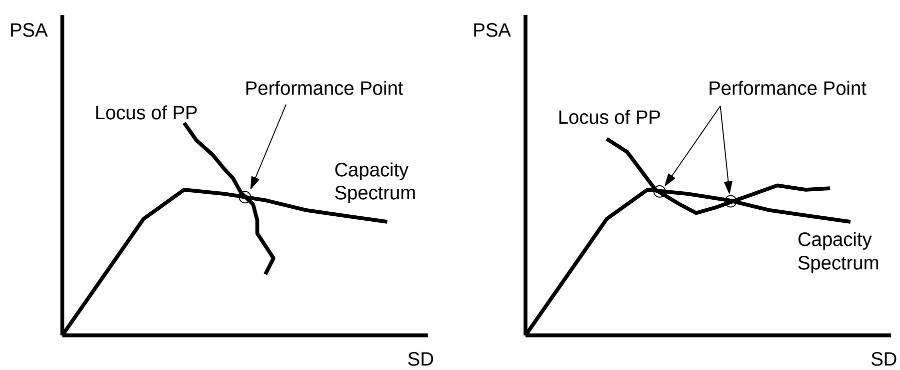
While the solution procedures in ATC-40 make no mention of it, the possibility of multiple Performance Point solutions can clearly be seen in the new procedure. There may be one, several or zero intersections of the Locus of Performance Points and the capacity spectrum. Extending the Locus to ductilities beyond the first intersection will reveal if multiple intersection points exist as seen in Figure 1.5. Multiple Performance Points require serious attention. A conservative approach is to use the Performance Point at the largest displacement.



(a) Nearly vertical Locus of Performance Points.

(b) Locus with a slope between vertical and horizontal.

Figure 1.4: Sensitivity of the Performance Point displacement prediction to changes in the capacity spectrum.



(a) A single Performance Point.

(b) Multiple Performance Points.

Figure 1.5: Extending the Locus of Performance Points to large values of ductility clearly reveals multiple Performance Points.

Chapter 2

AutoCSM

AutoCSM is an automated Excel sheet that requires user inputs for both structural capacity and seismic demand and calculates the Locus of Performance Points. The intersection of the Locus of Performance Points and the capacity spectrum is the Performance Point for the structure. The Performance Point is determined in a completely graphical procedure performed by AutoCSM. Three options exist for specifying the seismic demand. One option is to obtain a site specific design spectrum for 5% damping. Spectra for different values of damping are thereby calculated by applying the ASCE 7-02 spectral reduction rules. The second option is to obtain a family of design spectra for 5%, 10%, 20%, 30% and 40% damping. These would most likely be obtained from a qualified ground motion consultant. Linear interpolation will be employed for the necessary damping values needed in the analysis. The third approach is to use the NEHRP design spectrum as set forth in FEMA 356 [2].

AutoCSM consists of four worksheets: *Inputs - Capacity*, *Inputs - Demand*, *Calculations* and *Solution*. No cells on the worksheet *Calculations* are input cells. Those cells contain the calculations performed by AutoCSM and may only be observed. The worksheet *Solution* contains the graphical solution for the Performance Point.

2.1 Using AutoCSM

1. Open AutoCSM and click on the worksheet labeled *Inputs - Capacity*. Run the macro *calc_Teff* by clicking on the appropriate button at the top of the worksheet. A graphical user interface will pop-up and begin asking for several input items. The first item is the capacity spectrum coordinates (step 1a). The second item is the bilinear approximations to the capacity spectrum for different maximum displacements (step 1b). The third item is the seismic demand spectrum (step 1c). If at any step, a mistake has been made in

the inputs, the user will be alerted. The program will not proceed until all mistakes have been properly corrected.

1a. Capacity spectrum: For a building designed on a specific site, a computer model of the structure is constructed and a push-over analysis is performed using the first mode shape load profile. A load-deflection curve is obtained from the push-over analysis. Convert the push-over curve into a capacity spectrum using the following equations

$$\text{Pseudo-Spectral Acceleration} = \text{Force } \tilde{\mathbf{a}}^T\mathbf{M}\tilde{\mathbf{a}}/(\tilde{\mathbf{a}}^T\mathbf{M}\tilde{\mathbf{I}})^2 \tag{2.1}$$

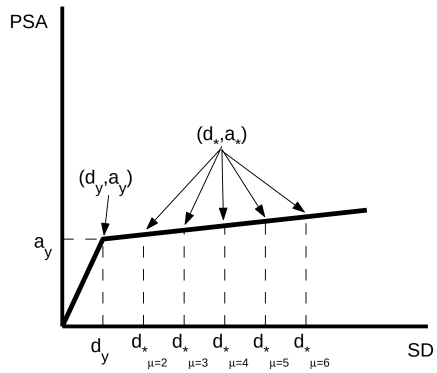
$$\text{Spectral Displacement} = \text{Displacement } \tilde{\mathbf{a}}^T\mathbf{M}\tilde{\mathbf{a}}/(\tilde{\mathbf{a}}^T\mathbf{M}\tilde{\mathbf{I}}) \tag{2.2}$$

where $\tilde{\mathbf{a}}$ is a column vector of the fundamental lateral mode shape, $\mathbf{M}$ is the square mass matrix for the horizontal degrees of freedom and $\tilde{\mathbf{I}}$ is the identity column vector. **Leave no cells blank except the cell after the last input coordinate**.

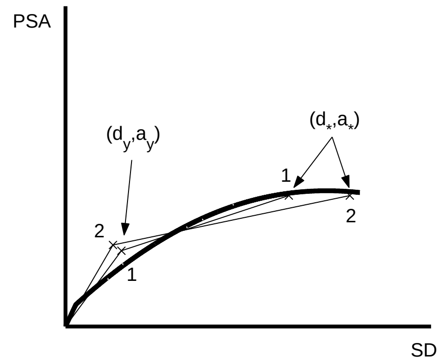
Pseudo-spectral acceleration and spectral displacement must have consistent displacement units throughout the entire analysis. One may also use the spectral conversion equations in ATC-40, Section 8, to convert from a push-over curve to a capacity spectrum. The capacity spectrum coordinates must be input into columns C and D. The program will accomodate up to 275 pairs of capacity spectrum coordinates.

1b. Bilinear approximations to the capacity spectrum: Along the capacity spectrum, bilinear approximations must be fit for several values of maximum displacement, d_*. Guidelines for bilinear approximations are given in ATC-40, Section 8.2.2.1.1. Each bilinear approximation requires the determination of a yield point (d_y, a_y) and an end point (d_*, a_*). The first bilinear approximation must be for a ductility greater than 1.0 and the values of ductilities must increase for each subsequent bilinear approximation. The bilinear approximation coordinates must be input into columns E thru H. The program will accomodate to input up to 275 bilinear approximations.

1c. Design spectrum: Three options exist for specifying the seismic demand. One option is to obtain a 5% damped design spectrum and accept the ASCE 7-02 spectral reduction rules for different levels of damping as set forth in Section 9.13.3.3. In this case, the nominal amount of damping in the structure (ζ_o) must be defined as greater than or equal to 2% and less than or equal to 10% ($2\% \leq \zeta_o \leq 10\%$). The ASCE 7-02 spectral reduction rules are reproduced in Table 2.1. For example, if you are given the spectral displacement for 5% damping and you want to calculate the spectral displacement for 30% damping, you divide the 5%



(a) Bilinear capacity spectrum



(b) Curved capacity spectrum

Figure 2.1: Examples of capacity spectrum shapes.

damped spectral displacement by 1.7. For damping values between the ones given in Table 2.1, linear interpolation is employed. The program will accomodate up to 300 combinations of spectral displacement and pseudo-spectral acceleration for the 5% damped design spectrum.

Damping value (%)	Reduction coefficient
2	0.8
5	1.0
10	1.2
20	1.5
30	1.7
40	1.9
50	2.0

Table 2.1: Spectral reduction rules as set forth in ASCE 7-02, Table 9.13.3.3.1.

A second option is to obtain a family of design spectra for 5%, 10%, 20%, 30% and 40% damping. Linear interpolation will be used for damping values between these spectra. In this case, ζ_o must be defined as greater than or equal to 5% but less than or equal to 10% ($5\% \leq \zeta_o \leq 10\%$). The program will accomodate up to 300 combinations of spectral displacement and pseudo-spectral acceleration for each spectrum. Each spectrum must contain the same number of combinations.

The third option is to use the NEHRP design spectrum as presented in FEMA 356. The program will prompt you to select a site classification as described in Section 1.6.1.4 of FEMA 356. The mapped BSE-2 short-period response acceleration parameter, S_s, and the modified mapped response acceleration parameter at a one-second period, S_1, are also input at this time. These parameters are described in Section 1.6.1.3 of FEMA 356. The coordinates of the design spectrum and subsequent demand spectra are automatically calculated by AutoCSM.

Note: If selecting the first or second design spectrum input option, the following relationship between period (T), pseudo-spectral acceleration (PSA) and spectral displacement (SD) may be useful: $T = 2\pi\sqrt{\mathrm{SD}/\mathrm{PSA}}$ where PSA in units of either cm/sec^2 or in/sec^2. The values of the periods associated with the 5% damped demand spectrum coordinates are shown on the worksheet *Inputs - Demand* with a grey font under the heading *PerADRS*. Often ADRS coordinates are not properly distinguished between spectral acceleration (SA) and pseudo-spectral acceleration. When damping is equal to zero, SA and PSA are identical. However, when damping is not zero, the two are not equal. If the ADRS is spectral acceleration, not pseudo-spectral acceleration, then a radial line may not represent a constant value of period for all levels of damping.

Two examples of capacity curves are shown in Figure 2.1. Figure 2.1(a) shows a bilinear capacity spectrum in which the yield point coordinate, (d_y, a_y), will not change for different maximum displacement points, (d_*, a_*). Figure 2.1(b) shows a rounded capacity spectrum which requires separate yield points for different maximum displacement points. Bilinear approximations are necessary because the equivalent parameter equations have been developed from models with bilinear hysteretic backbone shapes.

AutoCSM will next ask for the model type of the building. Click on the appropriate model type. Hysteretic classification of a building is discussed in Section 2.2. The options are bilinear (BLH), stiffness degrading/strength degrading (STDG) or pinching (PIN1 or PIN2).

Next, AutoCSM will ask for the percentage of nominal viscous damping in the building. Use 5% unless information is available that reveals a different nominal viscous damping value.

All user inputs are summarized on the worksheet *Inputs - Capacity*.

2. Run the macro *calc_Disp* by clicking on the appropriate button at the top of the *Inputs - Capacity* worksheet. The *Solution* worksheet will now pop-up onto the screen. Plotted there is the design spectrum for the nominal damping value (ζ_o), the capacity spectrum and the Locus of Performance Points. The Performance Point is the intersection of the capacity spectrum

and the Locus of Performance Points. Directly observable is the sensitivity of the Performance Point displacement prediction to slight changes in either the demand or capacity as discussed in Section 1.1.

3. At any time go back to *Inputs - Capacity* and add more bilinear approximations to the capacity spectrum. Choosing d_* to be the smallest or largest displacement will increase the length of Locus of Performance Points. Adding a d_* value near the Performance Point displacement will decrease the ductility gradation along the Locus of Performance Points. Both macros must be re-run to update the *Solution* worksheet.

2.2 Structural Models

The capacity spectrum the a structural surrogate for the building model. The capacity spectrum is meant to represent the expected hysteretic backbone curve to cyclic response. What happens to the hysteresis loops during the cycles of response is unknown. Different hysteretic models are available to categorize the building model. Effective linear parameters have been calculated for several hysteretic models. The hysteretic response of the inelastic single-degree-of-freedom systems subjected to a sinusoidal acceleration history are shown in Figures 2.2 and 2.3.

2.2.1 Hysteretic Classification

Once a push-over curve has been obtained for a given building model, there still exists the question as to how the building will behave during the inelastic cycles of response. Answering this question is left to the judgment of the engineer by examination of the structural plans and, in the case of a retrofit, an inspection of the existing building [1].

The capacity spectrum is fit with several bilinear approximations as discussed in Section 2.1, Step 1. AutoCSM automatically calculates the second slope ratio for each approximation. When the building is categorized as a hysteretic model type, there are restrictions on the second slope ratio (α) values for each model type. The bilinear model (BLH) works for $\alpha \geq 0\%$, the strength and stiffness degrading (STDG) model for $\alpha \geq -5\%$ and the pinching models (PIN1 and PIN2) for $\alpha \geq 2\%$. Discrete values of α have been calculated for each hysteretic model and linear interpolation is used for any values between the discrete values. Therefore, if a negative alpha value is present, the STDG categorization must be used.

Most new construction with a well designed lateral force resisting system should be categorized as a bilinear hysteretic system (BLH). The lateral resisting system should be free from any non-structural elements that may effect its performance.

Hysteretic Model	Range of values for α
BLH	$\geq$0%
STDG	$\geq$-5%
PIN1	$\geq$0%
PIN2	$\geq$0%

Table 2.2: Allowable α values for each hysteretic model type.

For example, non-structural elements should not be constructed such that they will effect the stiffness of the building upon their failure.

Any existing construction that has a well designed lateral load resisting system with structural elements that are well detailed and constructed properly should probably be categorized as stiffness degrading (STDG). The condition of the lateral load resisting system must be determined through investigation of the structural plans and if applicable, inspection of the building. The year in which the building was constructed and the material of construction will have an impact on this categorization. Older buildings, particularly those built before 1970, should be examined very carefully since it was the 1971 San Fernando Earthquake that motivated many changes in structural design and building code requirements. Existing concrete buildings must be extremely well detailed to fit in this category. Design and detailing of concrete buildings changed significantly after the structural failures experienced at such buildings as the Olive View Hospital in Sylmar due to the 1971 earthquake. New construction with slightly questionable lateral load resisting elements may conservatively be categorized as stiffness degrading.

Buildings with poor existing lateral force systems should be categorized as a pinching hysteretic model. The components making up the lateral resisting system may be poorly detailed or are expected to have very poor hysteretic response properties. The two pinching models (PIN1 and PIN2) reflect different amounts of dissipated hysteretic energy. For a building that is poorly designed but containing a large amount of redundancy, perhaps the PIN2 model with less degradation is best. Any other poorly designed existing building should be categorized as PIN1. Conservatively, all poorly designed existing buildings may be categorized as PIN1 for the analysis.

Bilinear Hysteretic Model (BLH)

The bilinear hysteretic model (BLH) is shown in Figure 2.2. The force versus displacement diagram has two slopes: the initial linear stiffness, k_o, and the post-yield stiffness, αk_o. The point where the slope changes from the initial linear stiffness to the post-yield stiffness is the yield point of the structure. The hysteresis loops do not deteriorate in any manner with an increasing number of response cycles.

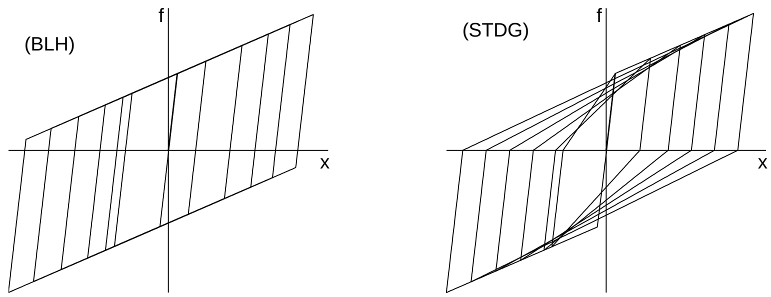


Figure 2.2: Force (f) versus displacement (x) for bilinear (BLH) and stiffness and strength degrading models (STDG).

Stiffness and Strength Degrading Model (STDG)

The stiffness and strength degrading model (STDG) is shown in Figures 2.2. This model is based on one developed by Riddell and Newmark [9]. The force versus displacement diagram has a decreasing stiffness as ductility increases. Once nonlinear response has occurred, a zero-force crossing will always change slope and head directly to the previous maximum displacement. Translation of the positive yield point has no effect on the location of the negative yield point and vice verse. Figure 2.2 shows the system response to a harmonic forcing function. For alpha values greater than zero, the model is stiffness degrading and for alpha values less than zero, the model degrades in both stiffness and strength. In general, strength degradation can occur in two ways: in-cycle or out-of-cycle. An in-cycle degradation model has been used here because it was desired to have a hysteretic model push-over curve that matches the building push-over curve. This would not be true for an out-of-cycle degradation model. Building and hysteretic model push-over curves already match for any non-negative second slope ratio model. To be consistent, it was decided to have it also occur for the negative second slope ratios.

Pinching Hysteretic Models (PIN)

Pinching hysteretic models (PIN) are shown in Figure 2.3. Models PIN1 and PIN2 were developed by Iwan and Gates [7], [8]. The models consist of a combination of linear and Coulomb slip elements. The Coloumb slip elements determine the energy dissipated in a cycle of response which is the area enclosed by the hysteresis loops. The hysteretic energy dissipated by PIN1 is less than the hysteretic energy dissipated by PIN2. The resulting hysteresis loops show a pinching shape common in reinforced concrete component tests.

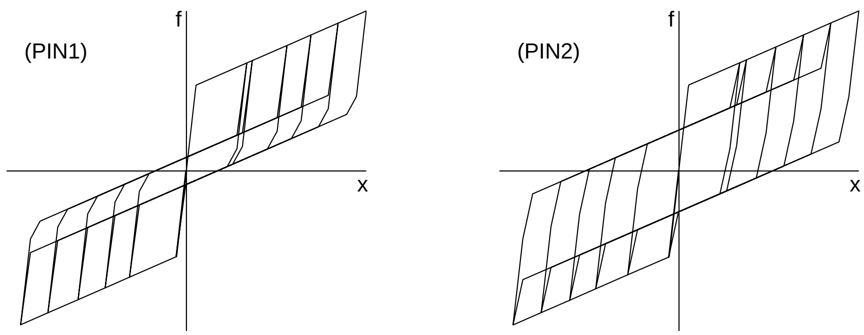


Figure 2.3: Force (f) versus displacement (x) for pinching models (PIN1 and PIN2).

Chapter 3

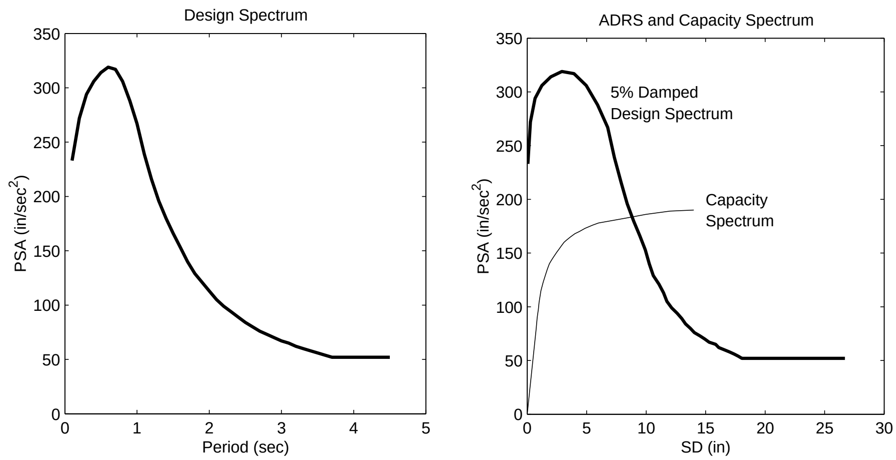
AutoCSM Examples

3.1 Example 1

In this example, a site-specific design spectrum is used in conjunction with the ASCE 7-02 spectral reduction rules. Discrete data for the 5% damped site-specific design spectrum and the capacity spectrum is given in Table 3.1. The capacity spectrum is obtained from the push-over curve which is multiplied by the appropriate matrices and vectors as in Equations 2.1 and 2.2. The design spectrum is given as pseudo-spectral acceleration values at discrete period values. From the design spectrum information, spectral displacement (SD) must be calculated by using the relationship $T = 2\pi\sqrt{\mathrm{SD/PSA}}$. The design spectrum and capacity spectrum are plotted in Figure 3.1.

The capacity spectrum must be fit with several bilinear approximations. The bilinear approximations are established for several values of maximum displacement, d_* as seen in Figure 3.2. For each bilinear fit, coordinates for d_y, a_y, d_* and a_* must be defined. The guidelines for bilinear approximations are given in ATC-40, Section 8.2.2.1.1. The bilinear approximations must be input in ascending ductility order and the first bilinear approximation must have a ductility value greater than 1.0.

Run the macro *calc_Teff* by clicking on the button at the top of the *Inputs - Capacity* worksheet. A graphical user interface will appear and begin asking you a series of questions about input information. Carefully read each pop-up and click on the correct button. The third pop-up entitled, *Input: Seismic Demand*, defines the demand options. Select the first option which reads *5% Design Spectrum reduced by the ASCE 7-02 reduction rules*. Additionally, the structure has been determined to be classified as stiffness degrading (STDG) Select STDG for model type. The nominal damping value for the structure has been determined to be 5% which must also be selected on the appropriate pop-up. Issues pertaining to the hysteretic classification of a structure are discussed in Section 2.2. Figure 3.3 shows the *Inputs - Capacity* worksheet and Figure 3.4 shows the *Inputs - Demand* worksheet with



(a) Design spectrum in acceleration versus period format

(b) Acceleration versus displacement design spectrum and the capacity spectrum

Figure 3.1: Capacity spectrum and design spectrum for Example 1.

all input values. Note that the ductility values must be in ascending order. Also, the PerADRS column confirms that the transformation from PSA and period to SD and PSA was done correctly. After double-checking all the input data, run the macro *calc_Disp*. The worksheet *Solution* will immediately pop-up. The worksheet *Solution* for this example is shown in Figure 3.5. As discussed in Section 1.1, the Performance Point is located at the intersection of the Locus of Performance Points and the capacity spectrum.

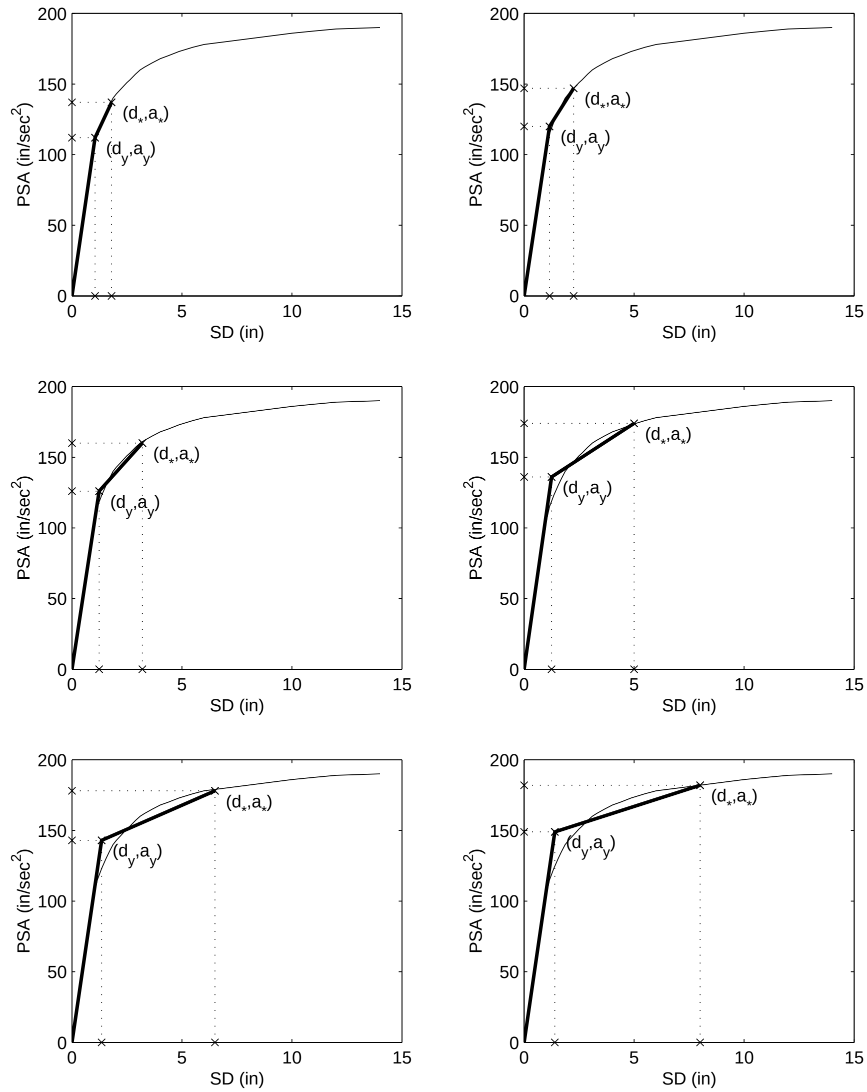


Figure 3.2: Bilinear approximations to the capacity spectrum for Example 1. The bilinear approximations determine the values of d_y, a_y, d_* and a_*.

Capacity Spectrum		Design Spectrum			
Accel (in/sec^2)	Disp (in)	Period (sec)	PSA (in/sec^2)	Period (sec)	PSA (in/sec^2)
0	0	0.1	233	3.3	60
26	.25	0.2	272	3.4	58
52	.50	0.3	294	3.5	56
78	.74	0.4	306	3.6	54
90	.85	0.5	314	3.7	52
98	.95	0.6	319	3.8	52
104	1.00	0.7	317	3.9	52
115	1.16	0.8	306	4.0	52
123	1.35	0.9	288	4.1	52
130	1.55	1.0	267	4.2	52
135	1.70	1.1	239	4.3	52
140	1.87	1.2	216	4.4	52
143	2.02	1.3	196	4.5	52
146	2.20	1.4	180		
151	2.50	1.5	166		
153	2.65	1.6	153		
157	2.89	1.7	140		
160	3.10	1.8	129		
162	3.30	1.9	121		
165	3.65	2.0	113		
168	4.02	2.1	105		
170	4.38	2.2	99		
173	4.87	2.3	94		
176	5.50	2.4	89		
178	6.00	2.5	84		
180	7.00	2.6	80		
183	8.5	2.7	76		
186	10.00	2.8	73		
187.5	11.00	2.9	70		
189	12.00	3.0	67		
189.5	13.00	3.1	65		
190	14.00	3.2	62		

Table 3.1: Capacity spectrum coordinates and design spectrum data for Example 1.

1. Click here for macro: calc_Teff **2. Click here for macro: calc_Disp**

Model	Nominal	Capacity Spectrum		Bilinear approximations to Cap Spec						
Type	Damping (%)	disp	accel	dy	ay	d*	a*	T_o	alpha (%)	ductility
STDG	5	0	0	1.05	112	1.8	137	0.60837	31.25	1.71429
		0.25	26	1.16	120	2.25	147	0.61776	23.945	1.93966
		0.5	52	1.24	126	3.2	160	0.62331	17.0716	2.58065
		0.74	78	1.25	136	5	174	0.60237	9.31373	4
		0.85	90	1.35	143	6.5	178	0.61049	6.41591	4.81481
		0.95	98	1.4	149	8	182	0.60905	4.69799	5.71429
		1	104					#DIV/0!	#DIV/0!	#DIV/0!
		1.16	115					#DIV/0!	#DIV/0!	#DIV/0!
		1.35	123					#DIV/0!	#DIV/0!	#DIV/0!
		1.55	130					#DIV/0!	#DIV/0!	#DIV/0!
		1.7	135					#DIV/0!	#DIV/0!	#DIV/0!
		1.87	140					#DIV/0!	#DIV/0!	#DIV/0!
		2.02	143					#DIV/0!	#DIV/0!	#DIV/0!
		2.2	146					#DIV/0!	#DIV/0!	#DIV/0!
		2.5	151					#DIV/0!	#DIV/0!	#DIV/0!
		2.64	153					#DIV/0!	#DIV/0!	#DIV/0!
		2.89	157					#DIV/0!	#DIV/0!	#DIV/0!
		3.1	160					#DIV/0!	#DIV/0!	#DIV/0!
		3.3	162					#DIV/0!	#DIV/0!	#DIV/0!
		3.65	165					#DIV/0!	#DIV/0!	#DIV/0!
		4.02	168					#DIV/0!	#DIV/0!	#DIV/0!
		4.38	170					#DIV/0!	#DIV/0!	#DIV/0!
		4.87	173					#DIV/0!	#DIV/0!	#DIV/0!
		5.5	176					#DIV/0!	#DIV/0!	#DIV/0!
		6	178					#DIV/0!	#DIV/0!	#DIV/0!
		7	180					#DIV/0!	#DIV/0!	#DIV/0!
		8.5	183					#DIV/0!	#DIV/0!	#DIV/0!
		10	186					#DIV/0!	#DIV/0!	#DIV/0!
		11	187.5					#DIV/0!	#DIV/0!	#DIV/0!
		12	189					#DIV/0!	#DIV/0!	#DIV/0!
		13	189.5					#DIV/0!	#DIV/0!	#DIV/0!
		14	190					#DIV/0!	#DIV/0!	#DIV/0!

Figure 3.3: *Inputs - Capacity* worksheet for Example 1.

Design Spectrum 5%		Design Spectrum 10%		Design Spectrum 20%		Design Spectrum 30%		Design Spectrum 40%	
disp	accel	disp	accel	disp	accel	disp	accel	disp	accel
0.06	233								
0.28	272								
0.67	294								
1.24	306								
1.99	314								
2.91	319								
3.93	317								
4.96	306								
5.91	288								
6.76	267								
7.33	239								
7.88	216								
8.39	196								
8.94	180								
9.46	166								
9.92	153								
10.25	140								
10.59	129								
11.06	121								
11.45	113								
11.73	105								
12.14	99								
12.60	94								
12.99	89								
13.30	84								
13.70	80								
14.03	76								
14.50	73								
14.91	70								
15.27	67								
15.82	65								
16.08	62								
16.55	60								
16.98	58								
17.38	56								
17.73	54								
18.03	52								
19.02	52								
20.03	52								
21.07	52								
22.14	52								
23.23	52								
24.35	52								
25.50	52								
26.67	52								

Periods for ADRS				
5%	10%	20%	30%	40%
0.1000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.2000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.3000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.4000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.5000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.6000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.7000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.8000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
0.9000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.0000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.1000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.2000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.3000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.4000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.5000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.6000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.7000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.8000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.9000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.0000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.1000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.2000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.3000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.4000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.5000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.6000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.7000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.8000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2.9000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.0000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.1000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.2000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.3000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.4000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.5000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.6000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.7000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.8000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3.9000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.0000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.1000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.2000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.3000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.4000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.5000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Figure 3.4: *Inputs - Demand* worksheet for Example 1.

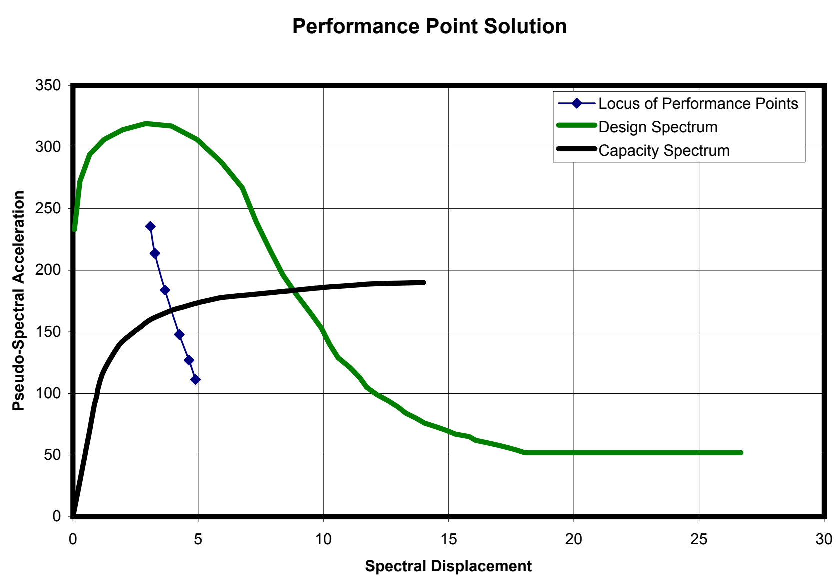


Figure 3.5: *Solution* worksheet for Example 1.

3.2 Example 2

In this example, the capacity spectrum and bilinear approximations are exactly the same as Example 1. The seismic demand is the NEHRP design spectrum. Run the macro *calc_Teff* by clicking on the button at the top of the *Inputs - Capacity* worksheet. On the pop-up window entitled, *Input: Seismic Demand*, select the third option which reads *NEHRP Deisgn Spectrum (as set forth in FEMA 356)*. The site classification is *C* and the values of S_s and S_1 are 1.5 and 0.6, respectively. These parameters are discussed in FEMA 356, Sections 1.6.1.3 and 1.6.1.4. Additionally, the units are designated as *inches*. Run the macro *calc_Disp*. The worksheet *Solution* for this example is shown in Figure 3.6.

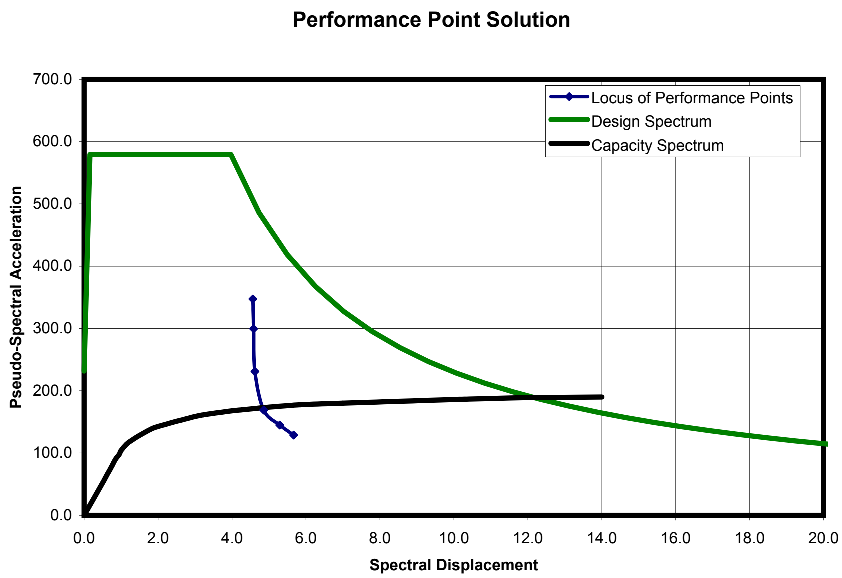


Figure 3.6: *Solution* worksheet for Example 2.

3.3 Example 3

This example will use a family of ADRS for the seismic demand. A picture of the family of ADRS and the capacity spectrum is shown in Figure 3.7. The capacity spectrum data and the bilinear approximations are given in Figure 3.8. On the pop-up window entitled, *Input: Seismic Demand*, select the second option which reads *5%, 10%, 20%, 30% and 40% damped spectra input by the user*. The family of ADRS is obtained from a ground-motion specialist for the building site. Some of the spectra coordinates are displayed in Figure 3.9. The hysteretic model type is bilinear (BLH) and the nominal damping is set at 5%.

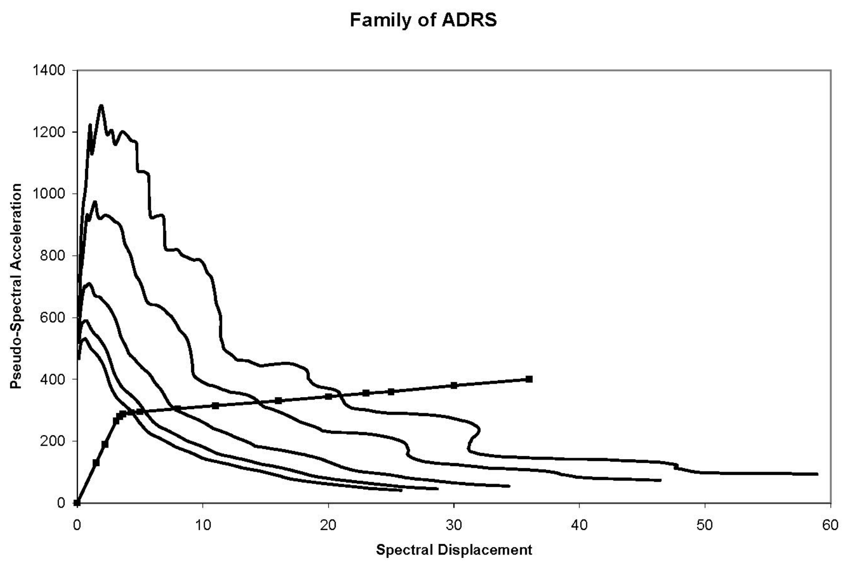


Figure 3.7: Family of ADRS and capacity spectrum for Example 3.

1. Click here for macro: calc_Teff **2. Click here for macro: calc_Disp**

Model Type	Nominal Damping (%)	Capacity Spectrum disp	Capacity Spectrum accel	Bilinear approximations to Cap Spec dy	ay	d*	a*	T_o	alpha (%)	ductility
BLH	5	0	0	3.6	288	4	291	0.7025	9.38	1.11
		1.5	130	3.6	288	6	296	0.7025	4.17	1.67
		2.2	190	3.6	288	8	305	0.7025	4.83	2.22
		3.1	265	3.6	288	10	312	0.7025	4.69	2.78
		3.35	280	3.6	288	12	318	0.7025	4.46	3.33
		3.6	288	3.6	288	14	325	0.7025	4.45	3.89
		4.3	293	3.6	288	16	330	0.7025	4.23	4.44
		5	295					#DIV/0!	#DIV/0!	#DIV/0!
		8	305					#DIV/0!	#DIV/0!	#DIV/0!
		11	315					#DIV/0!	#DIV/0!	#DIV/0!
		16	330					#DIV/0!	#DIV/0!	#DIV/0!
		20	344					#DIV/0!	#DIV/0!	#DIV/0!
		23	355					#DIV/0!	#DIV/0!	#DIV/0!
		25	360					#DIV/0!	#DIV/0!	#DIV/0!
		30	380					#DIV/0!	#DIV/0!	#DIV/0!
		36	400					#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!

Figure 3.8: *Inputs* - *Capacity* worksheet for Example 3.

Design Spectrum 5%		Design Spectrum 10%		Design Spectrum 20%		Design Spectrum 30%		Design Spectrum 40%		Periods for ADRS				
disp	accel	disp	accel	disp	accel	disp	accel	disp	accel	5%	10%	20%	30%	40%
0.1812	715.348927	0.15384	607.3359764	0.14004	552.8557601	0.1314	518.7464073	0.1314	518.7464073	0.1000	0.1000	0.1000	0.1000	0.1000
0.3186	873.4599895	0.27012	740.5493169	0.22104	605.9937102	0.19872	544.8021629	0.19872	544.8021629	0.1200	0.1200	0.1200	0.1200	0.1200
0.4812	969.2354363	0.387	779.4973272	0.31896	642.4508204	0.2814	566.7972813	0.2814	566.7972813	0.1400	0.1400	0.1400	0.1400	0.1400
0.6636	1023.354606	0.54732	844.0362314	0.43848	676.1912715	0.37656	580.7028489	0.37656	580.7028489	0.1600	0.1600	0.1600	0.1600	0.1600
1.00236	1221.345268	0.76416	931.10579	0.57456	700.0839389	0.48036	585.3040951	0.48036	585.3040951	0.1800	0.1800	0.1800	0.1800	0.1800
1.14408	1129.1617	0.92628	914.2017165	0.70956	700.3076499	0.59652	588.7416417	0.59652	588.7416417	0.2000	0.2000	0.2000	0.2000	0.2000
1.47324	1201.677354	1.1586	945.0350131	0.86892	708.7517898	0.72288	589.6313743	0.72288	589.6313743	0.2200	0.2200	0.2200	0.2200	0.2200
1.87512	1285.186986	1.42212	974.7056813	1.0308	706.4991817	0.84948	582.224413	0.84948	582.224413	0.2400	0.2400	0.2400	0.2400	0.2400
2.1324	1245.322155	1.59792	933.1856961	1.18776	693.6521493	0.97824	571.2924148	0.97824	571.2924148	0.2600	0.2600	0.2600	0.2600	0.2600
2.36784	1192.32878	1.82664	919.8068461	1.341	675.2622195	1.1148	561.3589279	1.1148	561.3589279	0.2800	0.2800	0.2800	0.2800	0.2800
2.74956	1206.091977	2.11968	929.7956914	1.52316	668.1327395	1.2588	552.1714676	1.2588	552.1714676	0.3000	0.3000	0.3000	0.3000	0.3000
3.00948	1160.249104	2.40984	929.0690418	1.73052	667.1698363	1.4148	545.4498557	1.4148	545.4498557	0.3200	0.3200	0.3200	0.3200	0.3200
3.51252	1199.5565	2.69928	921.8278812	1.9326	659.9999123	1.57932	539.3516824	1.57932	539.3516824	0.3400	0.3400	0.3400	0.3400	0.3400
3.91248	1191.809563	2.98872	910.4161749	2.13552	650.5165923	1.74576	531.7889068	1.74576	531.7889068	0.3600	0.3600	0.3600	0.3600	0.3600
4.29096	1173.132346	3.30336	903.1262159	2.34852	642.0765465	1.91028	522.2633766	1.91028	522.2633766	0.3800	0.3800	0.3800	0.3800	0.3800
4.7148	1163.330271	3.57204	881.3655426	2.55684	630.8749829	2.07612	512.2620772	2.07612	512.2620772	0.4000	0.4000	0.4000	0.4000	0.4000
4.81152	1076.820838	3.76188	841.9108255	2.75904	617.4746786	2.2368	500.5970776	2.2368	500.5970776	0.4200	0.4200	0.4200	0.4200	0.4200
5.25804	1072.206089	4.02372	820.506707	2.95392	602.355823	2.38584	486.5144001	2.38584	486.5144001	0.4400	0.4400	0.4400	0.4400	0.4400
5.67528	1058.842504	4.27716	797.9938972	3.12708	583.4223541	2.5248	471.0543893	2.5248	471.0543893	0.4600	0.4600	0.4600	0.4600	0.4600
5.73192	982.149008	4.46688	765.3878213	3.28824	563.4310412	2.65428	454.8037078	2.65428	454.8037078	0.4800	0.4800	0.4800	0.4800	0.4800
5.85648	924.8182525	4.6656	736.7620207	3.43008	541.6565226	2.7744	438.1156872	2.7744	438.1156872	0.5000	0.5000	0.5000	0.5000	0.5000
6.35964	928.507854	4.93296	720.2124812	3.60492	526.3185547	2.9022	423.7213889	2.9022	423.7213889	0.5200	0.5200	0.5200	0.5200	0.5200
6.8418	926.2806501	5.1624	698.914208	3.78672	512.6670559	3.03264	410.5755431	3.03264	410.5755431	0.5400	0.5400	0.5400	0.5400	0.5400
6.94176	873.8829725	5.3472	673.1473043	3.9564	498.0625364	3.17508	399.7038717	3.17508	399.7038717	0.5600	0.5600	0.5600	0.5600	0.5600
7.0224	824.1178353	5.553	651.6755439	4.1148	482.8947466	3.32232	389.8927954	3.32232	389.8927954	0.5800	0.5800	0.5800	0.5800	0.5800
7.4586	817.9270154	5.85864	642.4717681	4.32588	474.3858254	3.46212	379.6639421	3.46212	379.6639421	0.6000	0.6000	0.6000	0.6000	0.6000
7.97628	819.1751113	6.24048	640.9060237	4.53984	466.2479172	3.62316	372.1035992	3.62316	372.1035992	0.6200	0.6200	0.6200	0.6200	0.6200
8.32668	802.5491951	6.58548	634.7273671	4.73376	456.253306	3.78816	365.1136778	3.78816	365.1136778	0.6400	0.6400	0.6400	0.6400	0.6400
8.76588	794.4514952	6.90408	625.7166056	4.93968	447.6830805	3.96324	359.1883466	3.96324	359.1883466	0.6600	0.6600	0.6600	0.6600	0.6600
9.2172	786.9387343	7.18584	613.5069039	5.13912	438.7636797	4.13904	353.3796488	4.13904	353.3796488	0.6800	0.6800	0.6800	0.6800	0.6800
9.75768	786.1587059	7.488	603.2946756	5.3466	430.7659338	4.30632	346.9524475	4.30632	346.9524475	0.7000	0.7000	0.7000	0.7000	0.7000
10.10244	769.3448016	7.7358	589.114859	5.56668	423.9269246	4.48032	341.1958796	4.48032	341.1958796	0.7200	0.7200	0.7200	0.7200	0.7200
10.34064	745.4932509	7.96152	573.9740893	5.76468	415.5961366	4.64376	334.7850558	4.64376	334.7850558	0.7400	0.7400	0.7400	0.7400	0.7400
10.674	729.5578766	8.16828	558.2942676	5.93724	405.8047786	4.79772	327.9196567	4.79772	327.9196567	0.7600	0.7600	0.7600	0.7600	0.7600
10.84128	703.478927	8.442	547.7922443	6.08736	395.0022028	4.94268	320.7251564	4.94268	320.7251564	0.7800	0.7800	0.7800	0.7800	0.7800
10.95876	675.991412	8.6736	535.0312546	6.25032	385.5511611	5.07876	313.2834503	5.07876	313.2834503	0.8000	0.8000	0.8000	0.8000	0.8000
11.05296	648.9490938	8.84088	519.0719105	6.432	377.6400685	5.20848	305.8039092	5.20848	305.8039092	0.8200	0.8200	0.8200	0.8200	0.8200
11.22948	628.2909594	8.9622	501.4363297	6.60132	369.3447671	5.33052	298.2433314	5.33052	298.2433314	0.8400	0.8400	0.8400	0.8400	0.8400
11.39004	607.9783067	9.05064	483.1056591	6.75276	360.4492689	5.45448	291.1495934	5.45448	291.1495934	0.8600	0.8600	0.8600	0.8600	0.8600
11.43696	583.0489192	9.12252	465.0602456	6.89268	351.3844259	5.58804	284.8747117	5.58804	284.8747117	0.8800	0.8800	0.8800	0.8800	0.8800
11.40744	555.9847903	9.16308	446.5974059	7.02072	342.1813778	5.71548	278.5655633	5.71548	278.5655633	0.9000	0.9000	0.9000	0.9000	0.9000
11.43708	533.4567822	9.18984	428.6393446	7.14456	333.2418753	5.83836	272.3171245	5.83836	272.3171245	0.9200	0.9200	0.9200	0.9200	0.9200
11.56872	516.8795375	9.25884	413.6762699	7.2624	324.4772069	5.96244	266.3962158	5.96244	266.3962158	0.9400	0.9400	0.9400	0.9400	0.9400
11.6706	499.9314458	9.45312	404.9416439	7.40376	317.1535689	6.09396	261.045896	6.09396	261.045896	0.9600	0.9600	0.9600	0.9600	0.9600
11.90976	489.5652633	9.69252	398.422899	7.56552	310.9899604	6.22692	255.9651688	6.22692	255.9651688	0.9800	0.9800	0.9800	0.9800	0.9800

Figure 3.9: *Inputs* - *Demand* worksheet for Example 3.

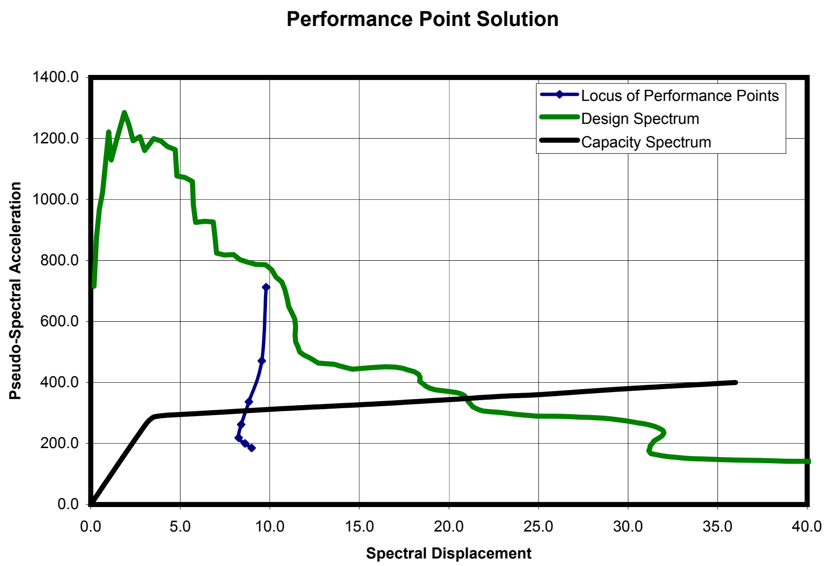


Figure 3.10: *Solution* worksheet for Example 3.

3.4 Example 4

This example uses a capacity spectrum with a negative post-yield stiffness. The capacity spectrum and the bilinear approximations are shown in Figure 3.11. The coordinates of both the capacity spectrum and the bilinear approximations are displayed in Figure 3.12. The hysteretic model type is set as strength/stiffness degrading (STDG). The nominal damping value is set at 5%. The seismic demand is the NEHRP design spectrum for site class C with values S_s and S_1 as 1.5 and 0.6, respectively. The units are specified as inches. The solution is shown in Figure 3.13.

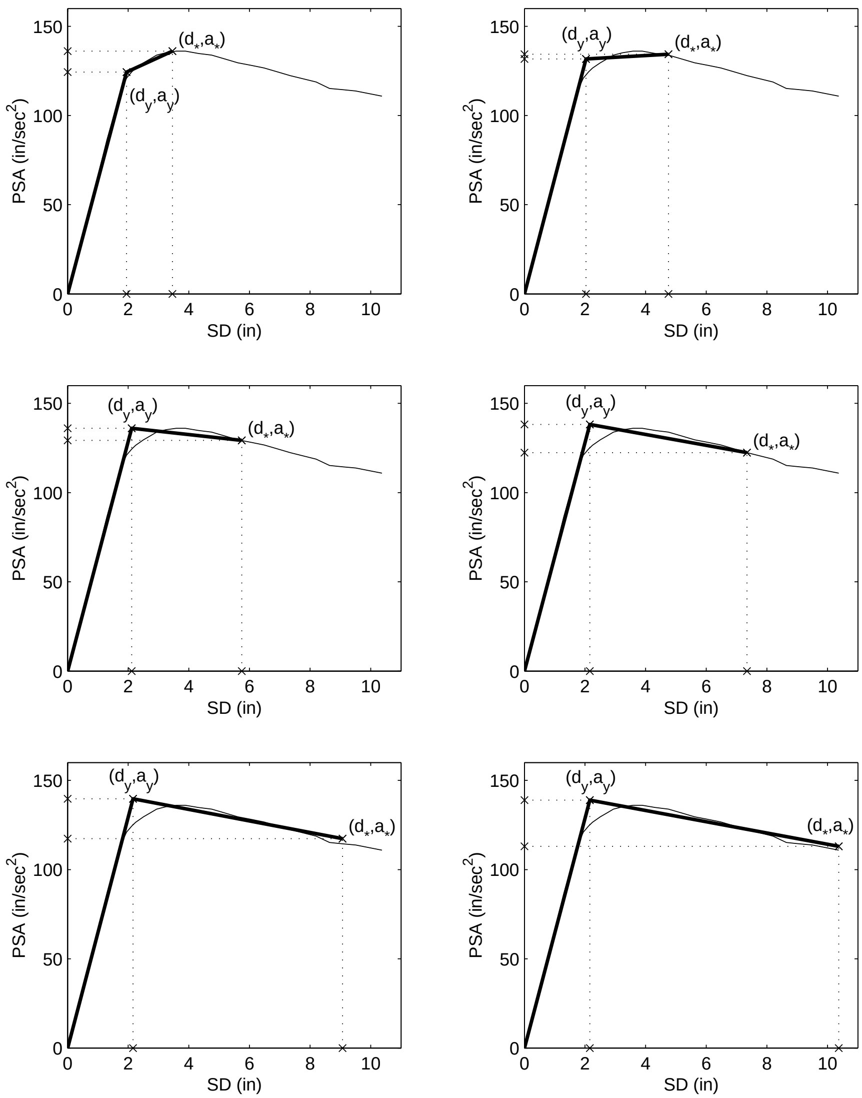


Figure 3.11: Bilinear approximations to the capacity spectrum for Example 4. The bilinear approximations determine the values of d_y, a_y, d_* and a_*.

1. Click here for macro: calc_Teff　　2. Click here for macro: calc_Disp

Model Type	Nominal Damping (%)	Capacity Spectrum disp	accel	Bilinear approximations to Cap Spec dy	ay	d*	a*	T_o	alpha (%)	ductility
STDG	5	0	0	1.8144	118.8	2.4624	129.6	0.7765	25.45	1.36
	Site Class	0.9504	62.64	1.944	124.416	3.456	136.08	0.7854	12.05	1.78
	C	1.296	86.4	2.0304	131.76	4.752	134.352	0.7800	1.47	2.34
	Ss	1.7712	114.48	2.1168	136.08	5.7456	129.24	0.7837	-2.93	2.71
	1.5	1.944	120.96	2.16	138.24	7.344	122.4	0.7854	-4.77	3.40
	S1	2.1168	124.416	2.16	139.68	9.072	117.36	0.7813	-4.99	4.20
	0.6	2.2464	126.576	2.16	138.96	10.368	113.04	0.7834	-4.91	4.80
	units	2.5056	129.6					#DIV/0!	#DIV/0!	#DIV/0!
	in	2.7216	131.76					#DIV/0!	#DIV/0!	#DIV/0!
		2.9376	133.92					#DIV/0!	#DIV/0!	#DIV/0!
		3.24	135.216					#DIV/0!	#DIV/0!	#DIV/0!
		3.5856	136.08					#DIV/0!	#DIV/0!	#DIV/0!
		3.888	136.08					#DIV/0!	#DIV/0!	#DIV/0!
		4.32	134.784					#DIV/0!	#DIV/0!	#DIV/0!
		4.752	133.92					#DIV/0!	#DIV/0!	#DIV/0!
		5.184	131.76					#DIV/0!	#DIV/0!	#DIV/0!
		5.616	129.6					#DIV/0!	#DIV/0!	#DIV/0!
		6.048	128.16					#DIV/0!	#DIV/0!	#DIV/0!
		6.48	126.72					#DIV/0!	#DIV/0!	#DIV/0!
		6.912	124.56					#DIV/0!	#DIV/0!	#DIV/0!
		7.344	122.4					#DIV/0!	#DIV/0!	#DIV/0!
		8.208	118.8					#DIV/0!	#DIV/0!	#DIV/0!
		8.64	115.2					#DIV/0!	#DIV/0!	#DIV/0!
		9.072	114.48					#DIV/0!	#DIV/0!	#DIV/0!
		9.504	113.76					#DIV/0!	#DIV/0!	#DIV/0!
		10.368	110.88					#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!
								#DIV/0!	#DIV/0!	#DIV/0!

Figure 3.12: *Inputs* - *Capacity* worksheet for Example 4.

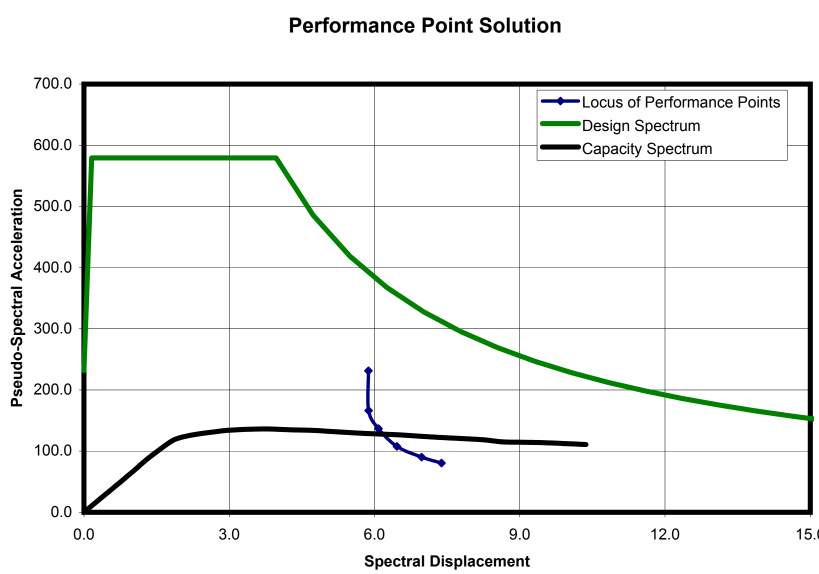


Figure 3.13: *Solution* worksheet for Example 4.

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