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Expansion of NGA-West2 Ground-Motion Database to Include Inelastic-Response Intensity Measures

Silvia Mazzoni, Yousef Bozorgnia, Mahdi Bahrampouri

Civil and Environmental Engineering Department and
Natural Hazards Risk and Resiliency Research Center,
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A report on research supported by the California Department of Transportation (Caltrans)

Report GIRS-2023-07

DOI: 10.34948/N3B88W

University of California, Los Angeles (headquarters)

Natural Hazards Risk & Resiliency Research Center

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September 2023

ABSTRACT

This report summarizes a comprehensive expansion of the NGA-West2 database to include inelastic-response intensity measures (IMs) for a set of single-degree-of-freedom inelastic systems. The primary IMs consist of maximum displacement, residual displacement, and hysteretic energy spectra. The maximum-displacement IMs were used to compute constant-strength and constant-ductility spectra, which are used to develop ground motion models for inelastic spectra. To be consistent with the original linear-elastic NGA-West2 database, these nonlinear-inelastic IMs were computed for as-recorded horizontal components as well as the resultant RotD00, RotD50, and RotD100 components. Two hysteretic models, two viscous damping values, 21 elastic oscillator periods, and five ductility levels are used in the computations of inelastic spectra. A total of 7,203 two-horizontal-component recordings of NGA-West2 were used to excite the model, resulting in a total of 1,225,230,300 nonlinear response history analyses.

ACKNOWLEDGMENTS

This study was supported by the California Department of Transportation (Caltrans) and coordinated by the Natural Hazards Risk and Resiliency Research Center headquartered at UCLA. The support is gratefully acknowledged.

The authors acknowledge the Texas Advanced Computing Center (TACC) at The University of Texas at Austin for providing HPC resources that have contributed to the research results reported within this paper. URL: http://www.tacc.utexas.edu

The opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the study sponsors, the Natural Hazards Risk and Resiliency Research Center, or the Regents of the University of California.

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1 Introduction

In this document we describe the process of extending the NGA-West2 database [Ancheta, 2013] with spectra of inelastic-response intensity measures (IMs) of a set of single-degree-of-freedom (SDOF) inelastic systems. These IMs are maximum inelastic displacement, maximum ductility, residual displacement, and hysteretic-energy spectra. Constant-ductility spectra, which give the yield strength corresponding to prescribed ductility levels, were also computed.

The necessary first step to develop ground motion models (GMMs) and probabilistic seismic hazard analysis (PSHA) for inelastic response spectra is the development of a database – the focus of this study and report. This report presents the details of the inelastic models used in the analysis as well as the IMs calculated based on the oscillator response. Past work on this topic has focused on the as-recorded components of response [Bozorgnia, 2010; Tothong, 2006], while in this work we have also computed the RotD00, RotD50 and RotD100 [Boore, 2010] of nonlinear response, thus making it consistent with previous NGA databases as well as implementation in building-code-compliant studies. Note, however, that vertical-direction response was not considered in this study. The wide range of SDOF models represented in this database is intended to cover a wide range of variables to investigate the sensitivity of the inelastic response to such variables.

An intensity-measures ground-motion database contains the response of parametrized damped SDOF systems to a set of input ground-motion accelerations, as shown in **Figure 1.1**. In this study, the ground-motion accelerations consisted of a subset of the NGA-West2 records. In addition to the elastic fundamental period and viscous damping, inelastic oscillators are also defined by their nonlinear properties, such as yield strength, post-yield stiffness, as well as by their inelastic properties such as the unloading and reloading hysteretic behavior. This study parametrized the yield-strength coefficient (ratio of yield strength to structure weight), post-yield stiffness ratio (ratio of post-yield tangent stiffness to initial elastic stiffness -- a single non-zero value was used), and hysteretic model (with and without stiffness degradation), as well as the parameters used in elastic response: fundamental elastic period and equivalent viscous damping ratio (2.5% and 5% or critical). These additional parameters of nonlinear inelastic systems increase the number of analysis parameters significantly; hence, the Open System for Earthquake Engineering Simulation (OpenSees) software framework was used to perform the analyses [Mazzoni, 2006] on the TACC High-Performance Computing (HPC) Resources [TACC].

This report presents a detailed summary of the nonlinear-inelastic model parameters and the inelastic-response intensity measures for a set of ground motions from the NGA-West2 database. Only ground motions recorded within 80km from the sources were used in the study because distant records are not expected to have high enough intensity to cause nonlinear response. Examples of the database will be shown in this report.

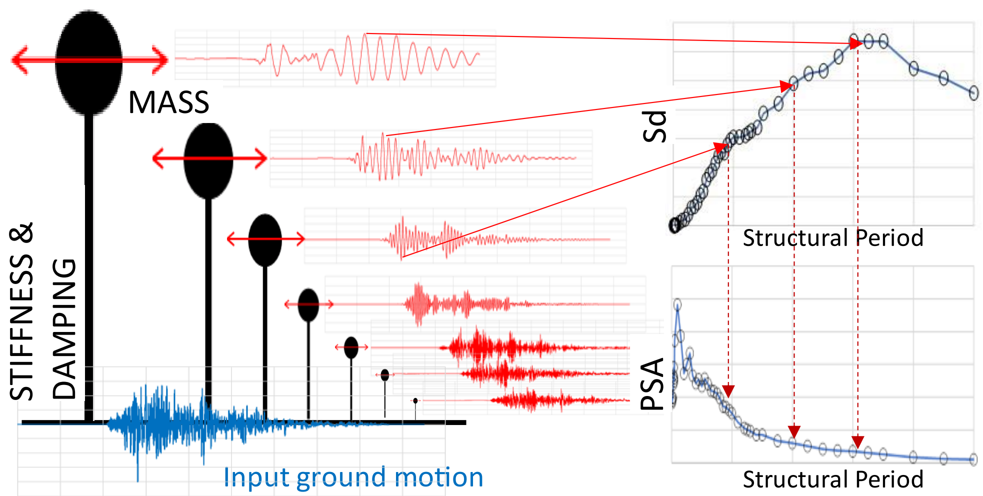


Figure 1.1. Graphical representation of computing traditional (elastic) Sd and PSA Intensity-measure response spectra.

2 NGA-West2 Database

The ground motions used in this study are a subset of the ground motions used by Campbell and Bozorgnia (CB14) [Campbell and Bozorgnia, 2014] in the development of their ground-motion model. The CB14 ground-motion set consists of carefully-selected recordings. The ground motions used in this study are all the CB14 recordings with a distance less than or equal to 80 km, as these are the ground motions that are expected to be large enough to cause some degree of inelastic system response. The total number of ground motions included in this study is 7203. **Figure 2.1** shows a plot of the magnitude and distance of the ground motions used in this study compared with the set of ground motions used by CB14.

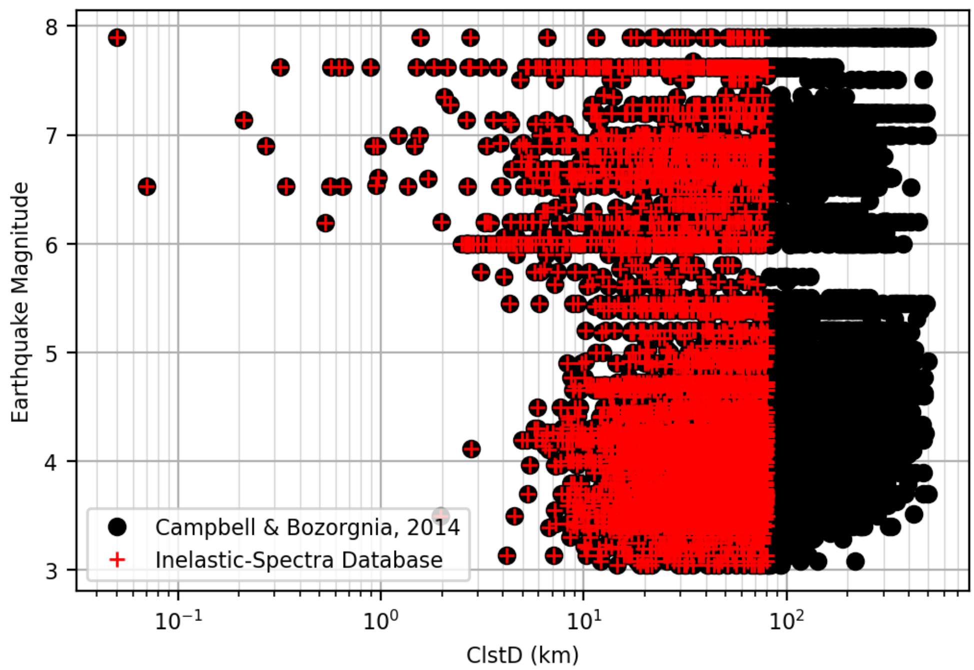


Figure 2.1. Magnitude and Distance of ground motions used in this study, compared to those used by CB14.

The Python script, which implements OpenSeesPy, used to compute the inelastic-response spectra was first validated for the special case of elastic response against the values published NGA-West2 Flatfile. The comparison of the RotD50-component of elastic PSA for 5% damping for a randomly selected set of 10 records is shown in **Figure 2.2**. The list of 10 RSN is: 5251, 13431, 9592, 5685, 6073, 1513, 171, 921, 13649, 1076.

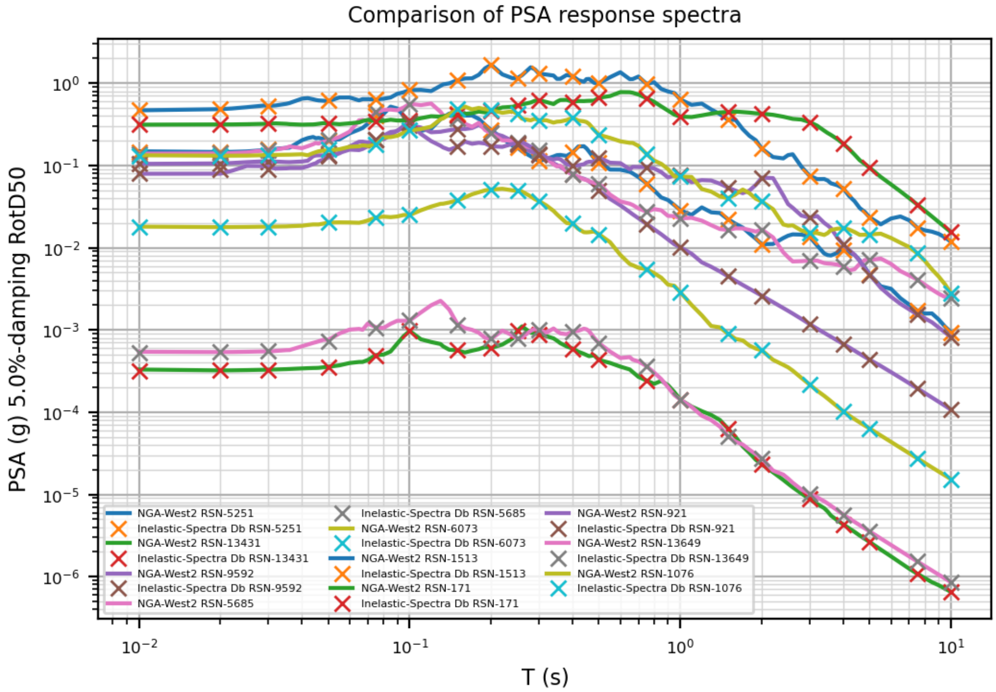


Figure 2.2. Comparison of Elastic PSA (RotD50, 5%-damping) response spectra for randomly selected records with NGA-West2 flatfile data.

3 Inelastic Model

3.1 Model Characteristics

The fundamental characteristic of the inelastic model is that it is a Single-Degree-of-Freedom (SDOF) system. The inelastic SDOF system is not intended to be a model of a specific structural system; however, it is one step closer to the real seismic performance than the traditional elastic SDOF. OpenSees was selected as the platform to perform the analyses because of its vast library of hysteretic models as well as its ability to be run parametrically within Python, thus, making it the efficient solution for the large number of computations and processing necessary to build the database. The OpenSees model consists of a mass-spring system, which defines the fundamental period, with viscous damping. The nonlinear-inelastic characteristics of the model were assumed to be symmetric and uncoupled in both positive and negative direction, as well as in the two horizontal directions of lateral loading.

The nonlinear behavior of the SDOF model used in the study is shown in **Figure 3.1**. The parametrization of the fundamental period was performed by keeping the mass constant for all cases and varying the elastic-stiffness value (represented by index i in **Figure 3.1**). In the study, the yield strength was defined as a factor of the weight, Fy=Cy*W. The yield-strength coefficient, Cy, was parametrized with values ranging from 0.01 to 3 (represented by the index j in **Figure 3.1**). Systems with high values of Cy are expected to remain elastic. We also included a second set of record-and-period-specific Cy values to ensure yielding for all earthquake records in the dataset. This second set was achieved by applying a ground-motion and period-specific factor to the original set of coefficients, equal to the elastic RotD50 PSA obtained from the NGA-West2 flatfile, normalized by g. While these factors may result in unrealistic structures, they were necessary for the numerical validity of ground-motion model development.

The post-yield behavior was defined using the strain-hardening ratio, β_{sh}, shown in **Figure 3.1**. A value of 2% for the strain-hardening ratio was used in all models. Further studies can be performed to evaluate the effect of this factor and compare it to elasto-plastic systems where this factor equals zero.

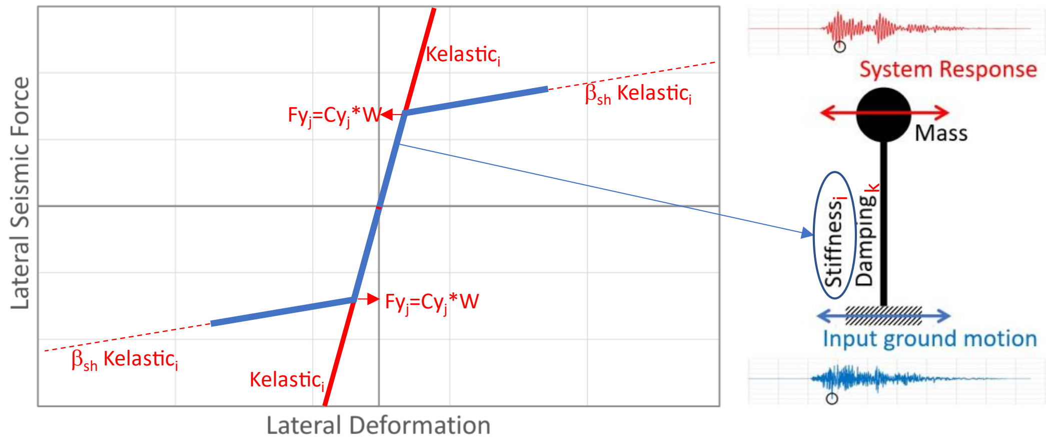


Figure 3.1. Nonlinear-Response Analysis Model.

The viscous damping ratio was also parametrized to two values: 5% for consistency with elastic response spectra, and 2.5% for consistency with inelastic-response analyses where hysteretic energy dissipation is modeled explicitly (index k in **Figure 3.1**).

Two hysteretic models were used in the analyses: an isotropic-hardening model (Bilinear) and a stiffness-degrading Takeda-type model (Takeda). The main difference between these models lies in the reloading stiffness during load reversals, as shown in **Figure 3.2**. The "Bilinear" model unloads and reloads with a constant stiffness equal to the initial elastic stiffness. The unloading stiffness in the "Takeda" model used in this study was also set equal to the elastic stiffness, as is the case for the "Bilinear' model. The reloading stiffness of the "Takeda" model, however, degrades with the level of nonlinearity. As we will show in this report, the differences in hysteretic-energy dissipated by these two models are not significant, but are, indeed, measurable.

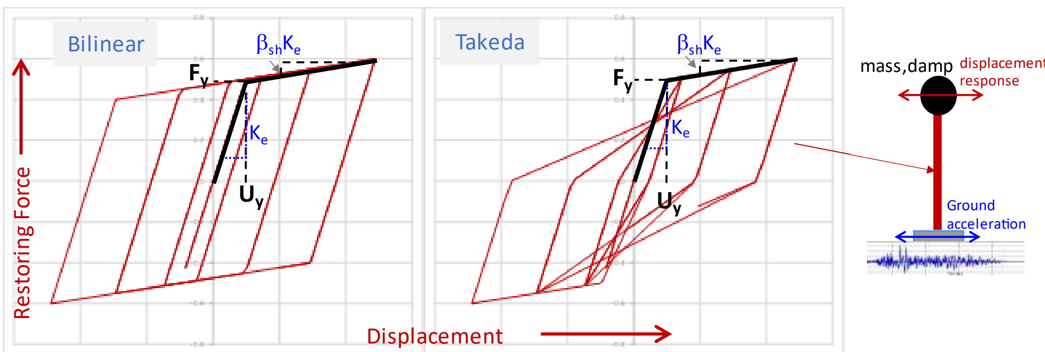


Figure 3.2. Inelastic-Response Analysis Model.

The 2D horizontal-component considerations for the inelastic-response IMs were handled in a manner consistent with the NGA-West2 elastic response spectra. The RotD00, RotD50, RotD100, and as-recorded H1 and H2 components of each inelastic-response IM were computed by rotating the two horizontal components of the ground motion through 180-degrees. The strength of the model in one direction was uncoupled from that of the other – a behavior qualitatively consistent with rectangular structures instead of axisymmetric ones.

An example of the response of the inelastic SDOF system at each analysis step is shown in **Figure 3.3**, **Figure 3.4**, and **Figure 3.5**. These figures show the response of a 1-second period 5%-damped oscillator to the NGA-West2 record RSN=864. The nonlinear model has a strength coefficient, Cy, of 0.5. In both figures, the plots correspond to the response in the horizontal H1 direction, while the bottom plots correspond to the response in the orthogonal H2 direction. The plots in **Figure 3.3** show the displacement response versus time, while the plots in **Figure 3.4** show the hysteretic loops which are the restoring force as a function of displacement. The displacement plots compare the response of the elastic model and the two inelastic models, as well as the yield displacement, which is the same in all directions. These plots show that the displacement response for all three cases is the same until the yield displacement is exceeded in either the positive or negative direction. After yielding, the three systems respond differently. The plots in **Figure 3.4** show that even though the two inelastic systems have the same nonlinear properties: initial stiffness, strength, and yield displacement, their hysteretic behaviors differ significantly and this difference is expected to affect response. In addition, the 2D displacement path shown in **Figure 3.5** indicate that, while the three systems do behave differently, the maximum-displacement amplitudes are in the same order of magnitude.

The inelastic-response figures bring to evidence that the system response is affected by both the yield strength, and the hysteretic behavior.

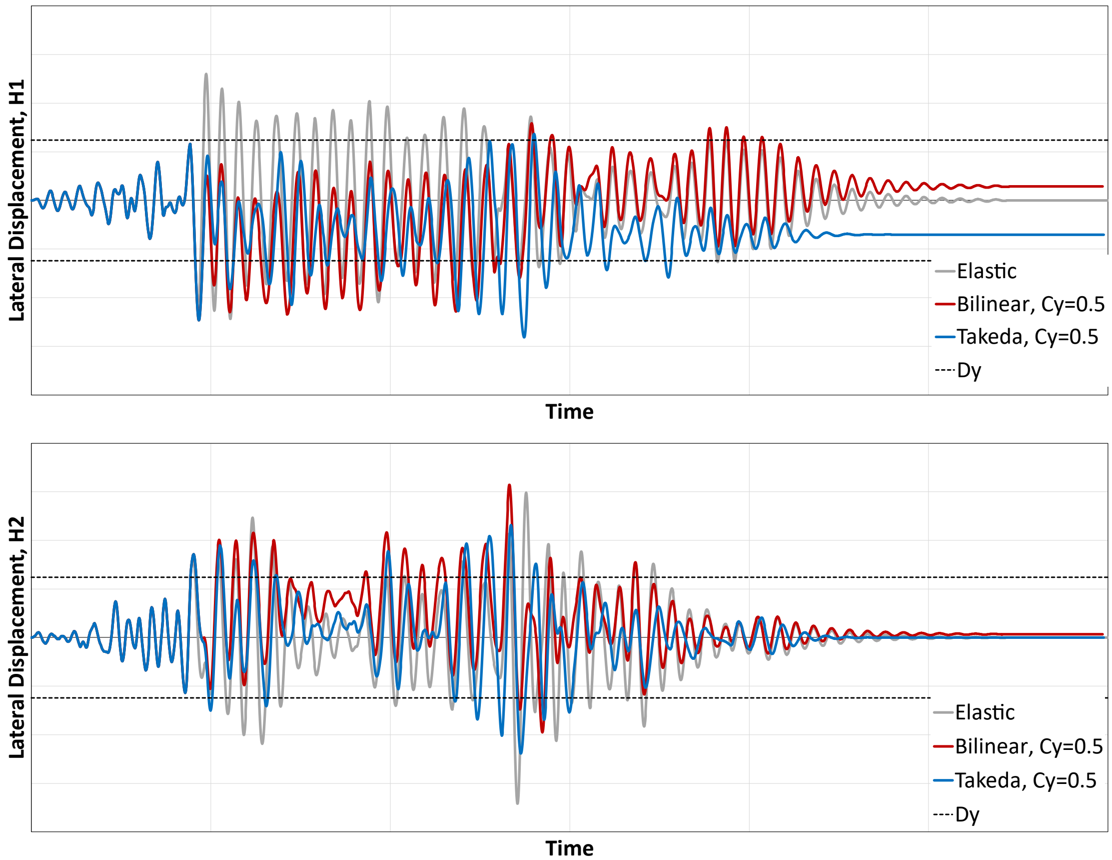


Figure 3.3. Inelastic response to RSN864, T=1.0s, 5% damping.

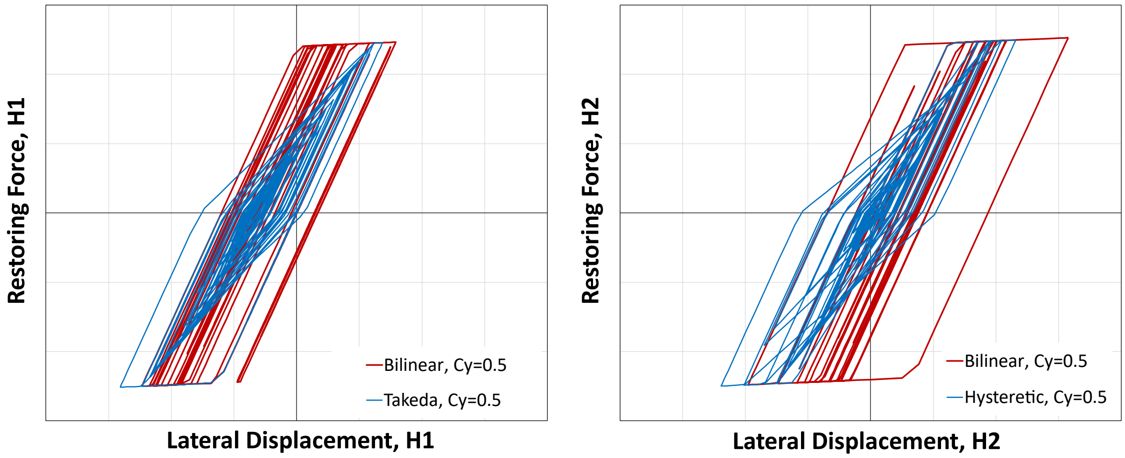


Figure 3.4. Inelastic response to RSN864, T=1.0s, 5% damping.

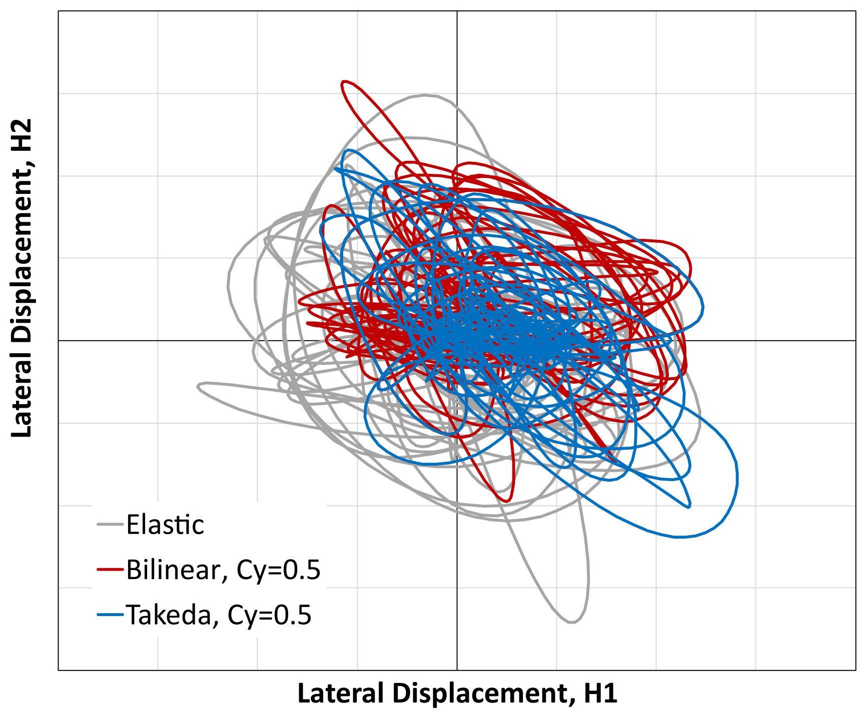


Figure 3.5. Inelastic response to RSN864, T=1.0s, 5% damping.

3.2 Parameterization

Table 3.1 lists the parameter values used in this study. The 21 periods typically used by the NGA ground-motion modelers were chosen.

A wide range of yield-strength coefficients was used to represent a wide range of structural systems as well as to ensure that the responses to a ground motion had a range from yielding to elastic. The two yield-strength models represent (a) the case where a single unmodified value was used for all ground motions and periods, Unity, and (b) the case where the coefficient was modified for each ground-motion and period: Mod. Even though both hysteretic models used in this study are bilinear, the isotropic-hardening model was labelled “Bilinear” and a stiffness-degrading model was labelled “Takeda”.

Table 3.1 Study Parameters

Parameter	**Values**
Period	0.01,0.02,0.03,0.05,0.075,0.1,0.15,0.2,0.25,0.3,0.4,0.5,0.75,1.0,1.5,2.0,3.0,4.0,5.0,7.5,10.0
Damping Ratio	0.05, 0.025
Model Type	Elastic, Inelastic
Strain-Hardening Ratio	0.02
Yield-Strength Coefficient	0.01,0.025,0.05,0.075,0.1,0.25,0.5,0.75,1.0,1.5,3.0
Yield-Strength Coeff. Model	Unity, Mod
Hysteretic Model	Bilinear, Takeda

To compute the RotD00, RotD50, and RotD100 values of response, each record was rotated incrementally through 180 degrees. Because the two horizontal components are orthogonal to each other, and because each OpenSees analysis was run with both components simultaneously (2D analysis) on a symmetric system, the rotations only span 90 degrees, with 1-degree interval.

The above parameters require 170,000 analyses per record. Thus, running all of the above parameters for all 7,203 ground-motion records resulted in 1,225,230,300 OpenSees analyses, requiring the use of a supercomputer. The analyses were thus run on the TACC Supercomputer (Texas Advanced Computing Center, https://www.tacc.utexas.edu/).

3.3 OpenSees Script

A sample python code to compute inelastic-response spectra is shown in

Table 3.2. This code uses a python package, eSEESminiPy, developed by the first author of this report and made accessible via pip install. This package uses OpenSeesPy (OpenSees integrated in a Python environment) to compute the inelastic response. This sample code is provided herein to help users get started on computing inelastic responses. Additional scripting is required to compute RotDXX components and to compute additional response metrics, such as residual displacement and hysteretic energy. It is worth noting that the script requires no knowledge of OpenSees, as the OpenSees model and analyses are performed by the eSEESminiPy python package, which can be pip installed from https://pypi.org/project/eSEESminiPy/.

Table 3.2 Sample Python code to compute Inelastic-Response Spectra

```
##########################################################################################################
########################## INELASTIC RESPONSE SPECTRA ####################################################
##########################################################################################################
### Inelastic-Response Spectra Script
##    Copyright by Silvia Mazzoni, 2023
###########################################################################################################
##########################################################################################################

### step 0:
pip install eSEESminiPy
from eSEESminiPy import runOpenSees_SDOF_Transient
from eSEESminiPy import ReadSMDFileToList
import glob
###########################################################################################################
##########################################################################################################
# USER INPUT: MODEL PARAMETERS
AllModelList = ['BilinearTakeda']
ScaleFactor = 1.0;
iBsh = [0.02]
iDampingRatio = [0.025]
iCy = [0.01,0.025,0.05,0.075,0.1,0.25,0.5,0.75,1.0,1.5,3.0]
iTperiod = [0.01,0.02,0.03,0.05,0.075,0.1,0.15,0.2,0.25,0.3,0.4,0.5,0.75,1.0,1.5,2.0,3.0,4.0,5.0,7.5,10.0]

iOmega = [2*pi/Tperiod for Tperiod in iTperiod]
###########################################################################################################
# USER INPUT: FILEPATHS
RecordFilesPath = 'D:\\Tools\\NGAWest2records\\NGAWest2CollapsedBASE4.ACA_\\AT2'
FilePathList = sorted(glob.glob(f'{RecordFilesPath}/RSN84*.AT2'))
outputFolder = 'C:\\workingPath\\tmp'
###########################################################################################################
def makeMaterialInput(ModelLabel,Bsh,Cy,Omega,Weight,Mass):
   K = Omega*Omega*Mass
   # "BilinearTakeda":
   f1p = Cy*Weight
   eps1p = f1p/K
   K2 = Bsh*K
   eps2p = 10*eps1p
   f2p = f1p+K2*(eps2p-1*eps1p)
   [pinchX,pinchY, DuctilityDamage, EnergyDamage, BetaUnload] = [1.0,1.0,0,0,0]
   OpsMatLabel =  'Hysteretic'
   OpsMatInput =  [f1p,eps1p,f2p,eps2p,,-f1p,-eps1p,-f2p,-eps2p,pinchX,pinchY,DuctilityDamage,EnergyDamage,BetaUnload]
   return OpsMatLabel,OpsMatInput
##########################################################################################################
# define units -- output will be in these units.
sec = 1.0
cm = 1
meter = 100*cm
g = 9.806649999787735*meter/sec/sec
pi = 3.141592653589793
Mass = 1.0
Weight = Mass*g
##########################################################################################################
Nfiles = len(FilePathList)
for ModelLabel in AllModelList:
   if ModelLabel == 'Elastic':
```

```
    iCyModelHere = [-888]
    iBshHere = [-888]
    Q = "PSA_g"
  else:
    iCyModelHere = iCy
    iBshHere = iBsh
    Q = "Umax_cm"

  OutFilePath = f'{outputFolder}/InelasticResponseSpectra_{ModelLabel}_{Q}.csv'
  fileOutID = open(OutFilePath,"w")
  fileOutID.write(f'ModelLabel,Filepath,DampingRatio,Bsh,Cy,{str(iTperiod)[1:-1]}\n')

  for iFile in range(Nfiles):
    FileHpath = FilePathList[iFile]
    # read record and scale value by g, so you have units of acceleration
    dtH,accH = ReadSMDFileToList(FileHpath,g)
    for DampingRatio in iDampingRatio:
      for Bsh in iBshHere:
        for Cy in iCyModelHere:
          print('model:',ModelLabel,'file:',FileHpath,'damp:',DampingRatio,'Bsh:',Bsh,'Cy:',Cy)
          OutArray = [ModelLabel,FileHpath,DampingRatio,Bsh,Cy]
          if plotSwitch:
            Tlist = []
            ResponseList = []
          for Tperiod,Omega in zip(iTperiod,iOmega):
            OpsMatLabel,OpsMatInput = makeMaterialInput(ModelLabel,Bsh,Cy,Omega,Weight,Mass)
            DtAnalysis  = min(min(Tperiod/5.,0.005),dtH/2) #  Analysis time step
            # run the analysis for 1.1 times the input-motion time (TmaxAnalysis = EQtime*TmaxAnalysisFactor)
            TmaxAnalysisFactor = 1.1;
            timeSwitch = True; # Boolean on whether to also return time (will be first element in output, after ok)
            eleForceSwitch = True; # Boolean on whether to also return element force (will be last element in output, after ok)
            dampOut = True; # Boolean on whether to run additional analysis at almost-critical damping for 2 period cycles
            AnalysisResults = runOpenSees_SDOF_Transient(Mass,Omega,DampingRatio,DtAnalysis,accH,dtH,ScaleFactor,OpsMatLabel,
                                      OpsMatInput,TmaxAnalysisFactor,timeSwitch,eleForceSwitch,dampOut)
            # returned values: <timeOut>,nodeDispOut,<forceOut>: ok=OpenSees-Analysis return code (want 0 for convergence),
            #    arrays of time (optional), array of nodal displacement, array of element force (optional)
            ok = AnalysisResults[0]
            Time = AnalysisResults[1]
            NodalDispResponse = AnalysisResults[2]
            ForceResponse = AnalysisResults[3]
            if ok == 0:  # the analysis converged
              OutValue = max(abs(max(NodalDispResponse)),abs(min(NodalDispResponse)))
            else:
              print("did not converge")
              OutValue = -999

            if ModelLabel=='Elastic':
              # convert to psa
              OutValue = OutValue*Omega*Omega/g
                        OutArray.append(OutValue)
          fileOutID.write(f'{str(OutArray)[1:-1]}\n')
  fileOutID.close()
#################################################################################################################
```

4 Inelastic-Response Intensity Measures

Three classes of inelastic-response intensity measures (IMs) were computed in this study: maximum-displacement metrics, residual displacement, and energy dissipation. The displacement response in one horizontal direction to a single ground motion of a single case of the elastic and inelastic models is shown in **Figure 4.1**. Two intensity measures are shown in this figure: the maximum-displacement demand and the residual displacement. The figure shows that the maximum displacement occurs at different times for the different systems.

Unrecoverable plastic deformations in yielding systems lead to permanent deformation, shown in the residual displacements once the system comes to rest, as shown in the figure. This inelastic-response IM is important in the evaluation of a structure for its stability and ability to withstand aftershocks. Extra critically-damped analysis steps were taken to ensure that the system had come to rest. The figure shows the two hysteretic models have different residual displacements, which are consistent with the direction of the maximum displacement.

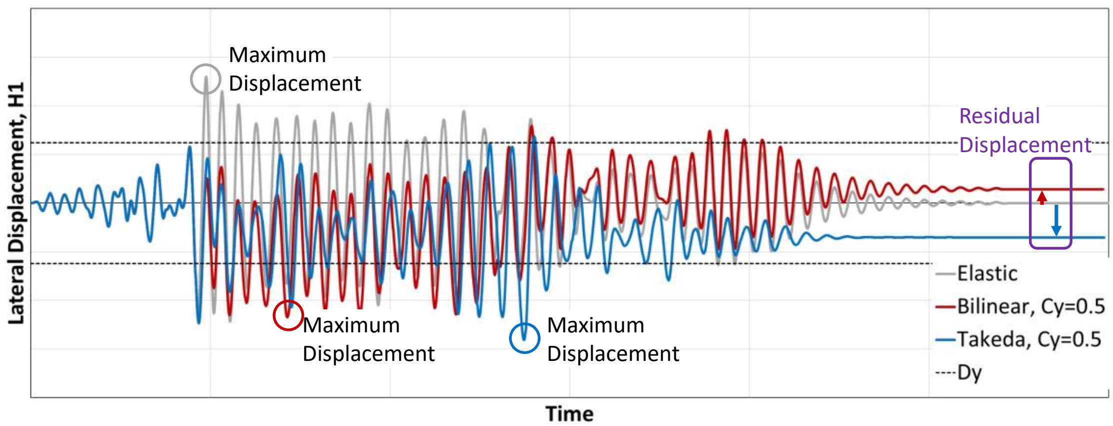


Figure 4.1. Response to a single ground motion: displacement versus time for both Elastic and Inelastic models (RSN=864, T=1.0sec, Cy=0.5, Orientation=H1, Damping=5%).

Because energy dissipation is defined as the area inside a force-deformation response, the two hysteretic models considered in this study are expected to dissipate energy differently. **Figure 4.2**a shows the general shape of the dissipated energy by the inelastic models in their force-deformation response, while **Figure 4.2**b shows the cumulative energy dissipated during the analysis as a function of time. This second plot shows that the elastic system recovers all its energy by unloading and reloading along the same elastic path. **Figure 4.2** shows an interesting phenomenon: while the overall-hysteresis loops of the Bilinear model looks ”fatter” than those of the Takeda model, the cumulative energy dissipated by this model is less than that dissipated by the Takeda model. This behavior can be attributed to the difference in loading/reloading paths.

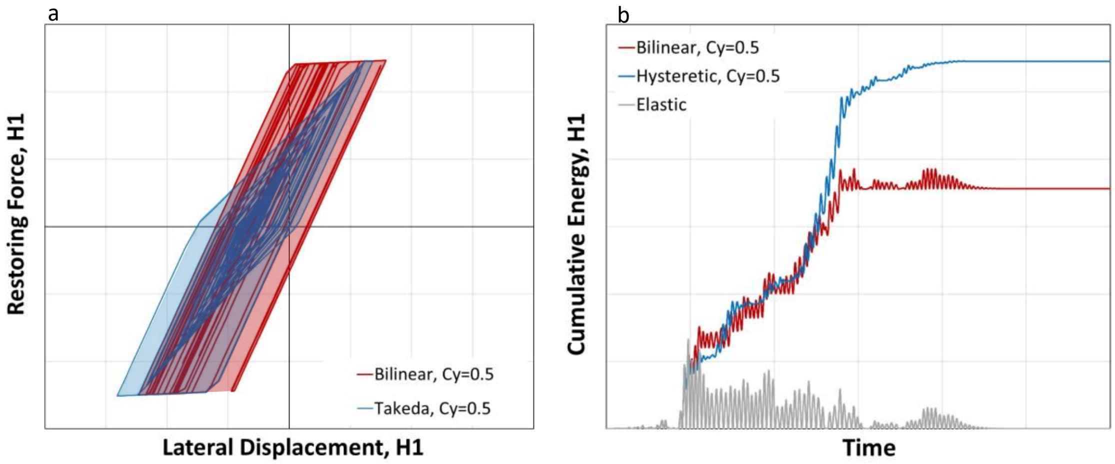


Figure 4.2. Response to a single ground motion: (a) Hysteretic Behavior of Inelastic Models; (b) Cumulative Energy time series (RSN=864, T=1.0sec, Cy=0.5, Orientation=H1, Damping=5%).

The inelastic-response IMs -- the maximum-displacement demand, the residual displacement, and the hysteretic energy – were computed for all records, study parameters, and components presented in the previous section: RotD00, RotD50, and RotD100 components, as well as the as-recorded components H1 and H2 were tabulated into a database format. Plots of each quantity for each record were also generated.

5 Inelastic-Response IM Spectra

All the intensity measures (IMs) indicated previously were assembled into inelastic-response spectra, where the IM is grouped for each ground motion and analysis parameter at each elastic period. The parametrized IMs were processed and grouped and stored into tables in spectra format: IM versus elastic period, for all records with one table per IM, parameter (elastic/inelastic model, damping ratio, strength characteristic, strain-hardening ratio), and component. Each row of each table corresponds to a different inelastic-strength parameter, such as Cy, and each column corresponds to a different period. The data in these tables were plotted for each record (RSN) and will be made available with the database tables.

5.1 Maximum-Displacement Demand Spectra

Figure 5.1 show the maximum-displacement response spectra for an individual record, one plot per nonlinear model, and for the RotD50 component. Lines with a Cy value at or above 1.0 are dashed to distinguish the high values of Cy from the lower values. A value of Cy=1.0 corresponds to a structure that is expected to remain elastic. The figures show that (a) there is a measurable, but not significant difference between the responses of the two inelastic models, and (b) there is a significant difference in behavior between the short and long-period ranges. The systems with lower-strength have relatively higher demands in the shorter-period range, while the higher-strength systems have somewhat higher demands in the longer-period range. This behavior needs to be compared to other records to determine a pattern, a task beyond the scope of this study. If a system does not yield, it converges to the same elastic response as the response computed from the NGA-West2 flatfile spectra, which is also shown in the plots. While **Figure 5.1** was computed for 5% damping, the same spectrum for 2.5% damping is shown in **Figure 5.2**.

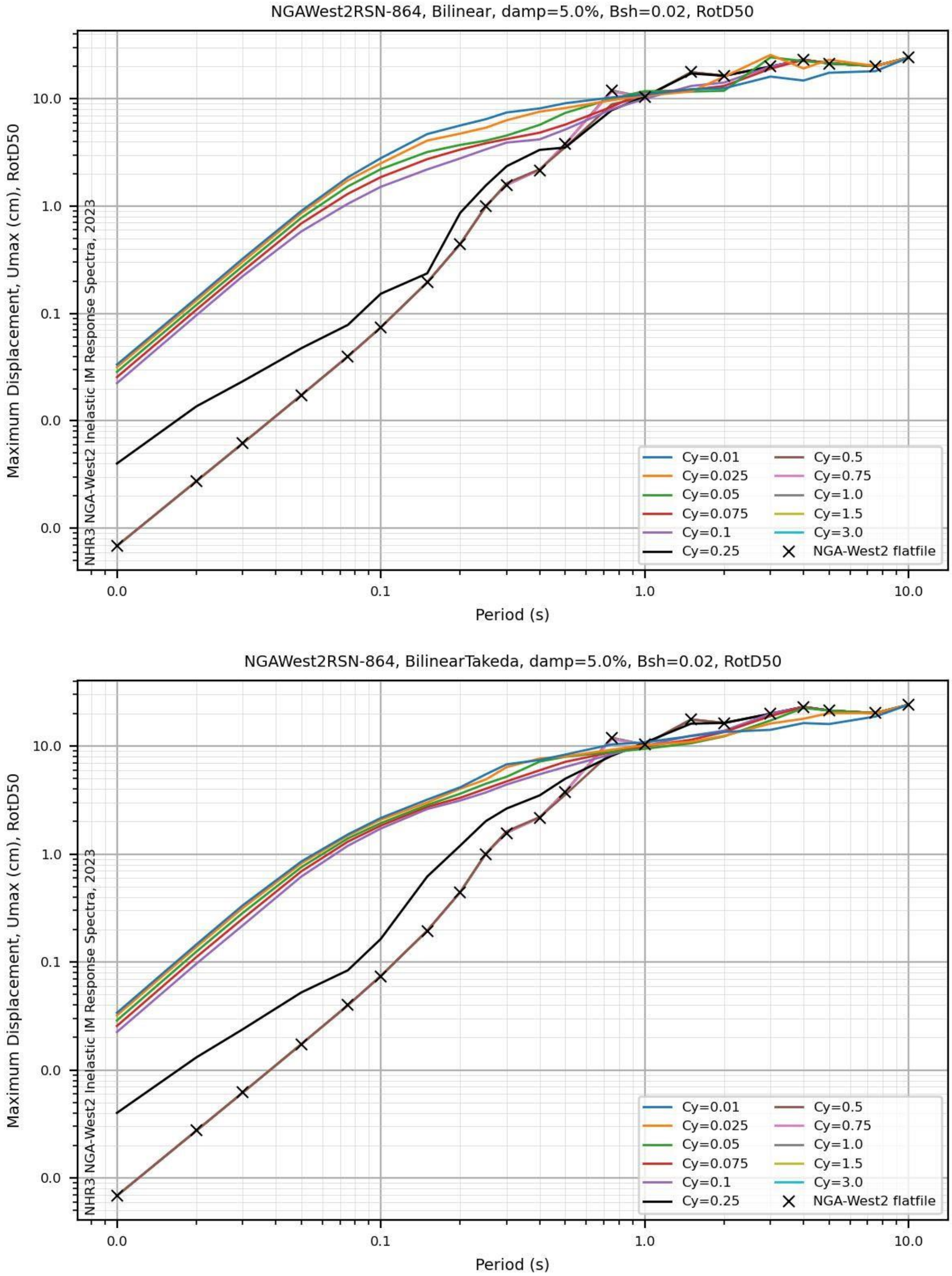


Figure 5.1. Maximum-displacement response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=**5%**).

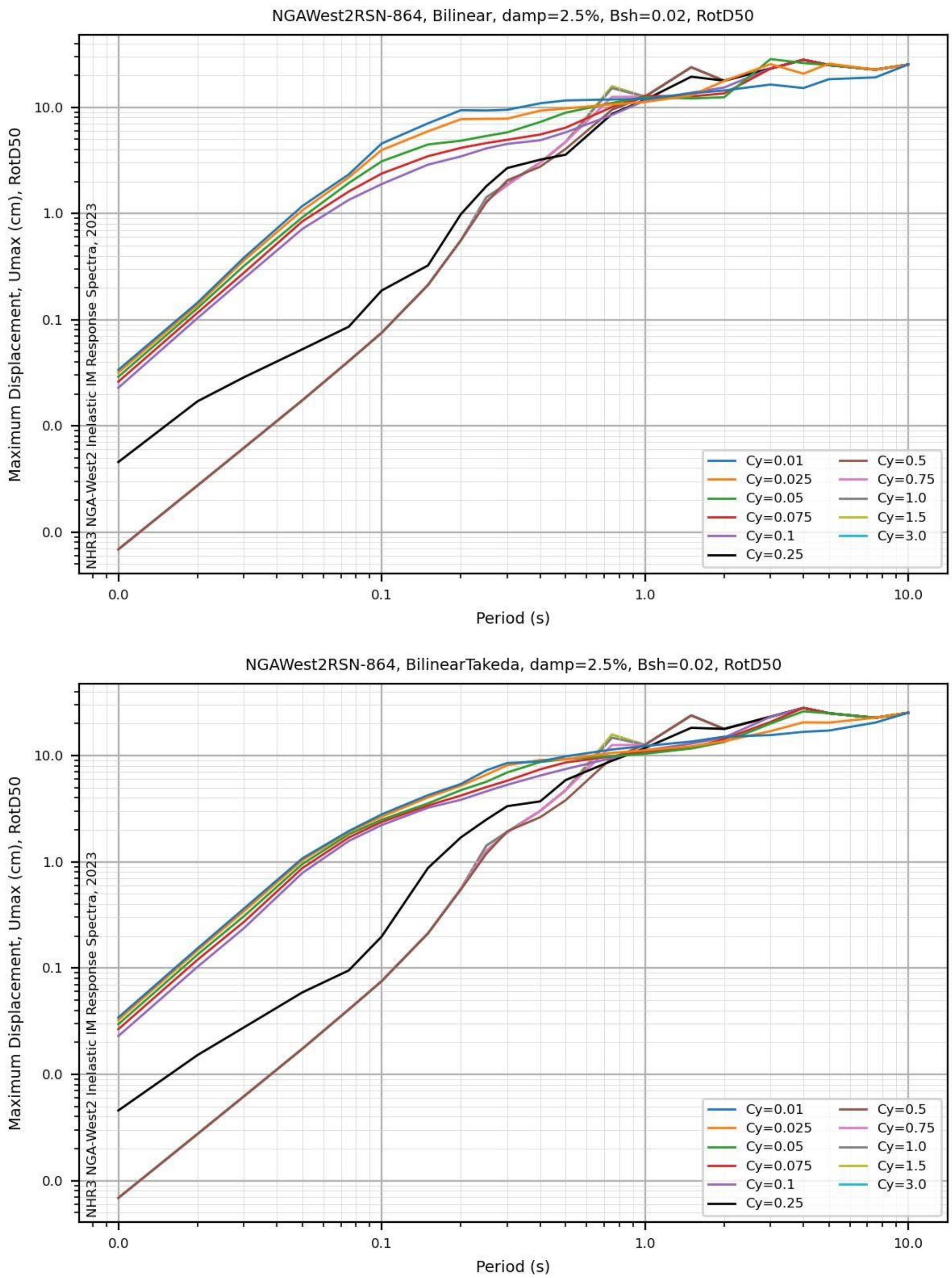
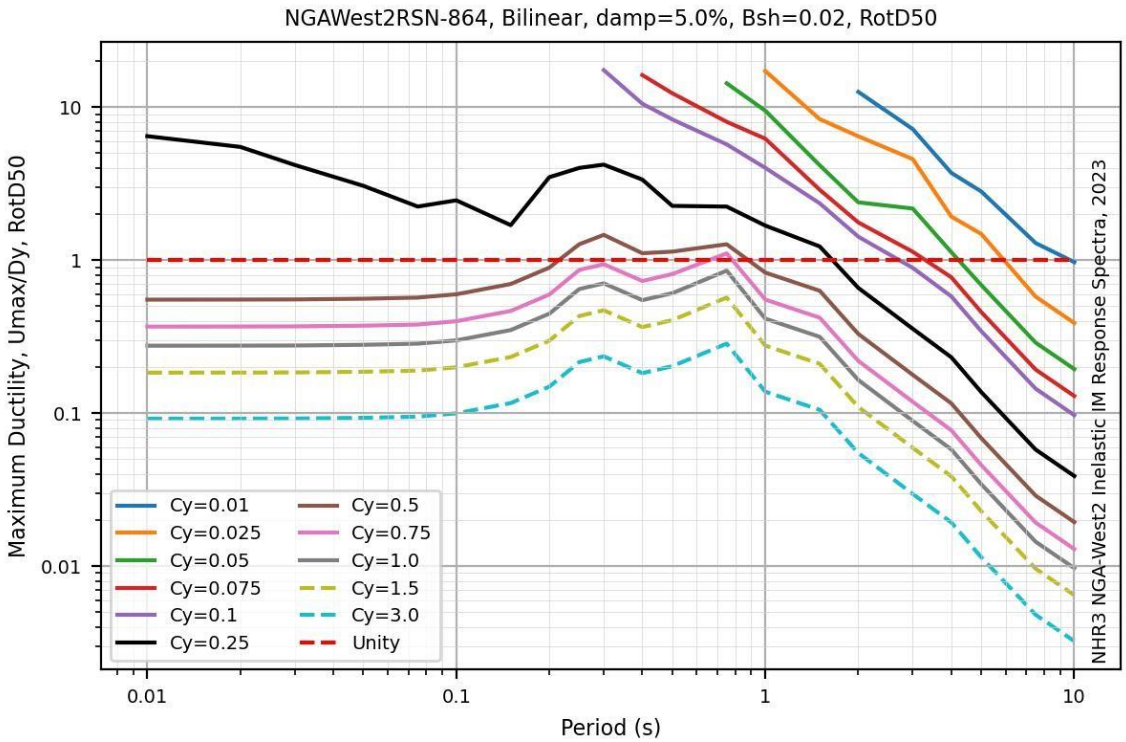


Figure 5.2. Maximum-displacement response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=**2.5%**).

5.2 Constant-Strength Spectra

The maximum-displacement demands were normalized by the yield displacement (a function of the yield-strength coefficient) to compute maximum displacement ductility demands. A ductility demand value at or above 1 indicates that the system has yielded, below 1 it has remained elastic.

A ductility-demand spectrum, known as a constant-strength spectrum, for a range of yield-strength coefficients and the two inelastic-response models is shown in **Figure 5.3** and **Figure 5.4** for the two damping ratios. These ductility demands quantify the expected performance level given a structural system yield strength and ground-motion record. When the ductility demand exceeds a value of 1.0 (delimited by the red dashed line in the plots), the system performs inelastically, as expected. Higher ductility demands results in higher damage and higher likelihood of collapse. As shown in the figure, the type of hysteretic response does not have a significant impact on this metric, as shown when comparing the two plots. The plots in this figure only show values between 1/20 and 20 to improve interpretation in this range.



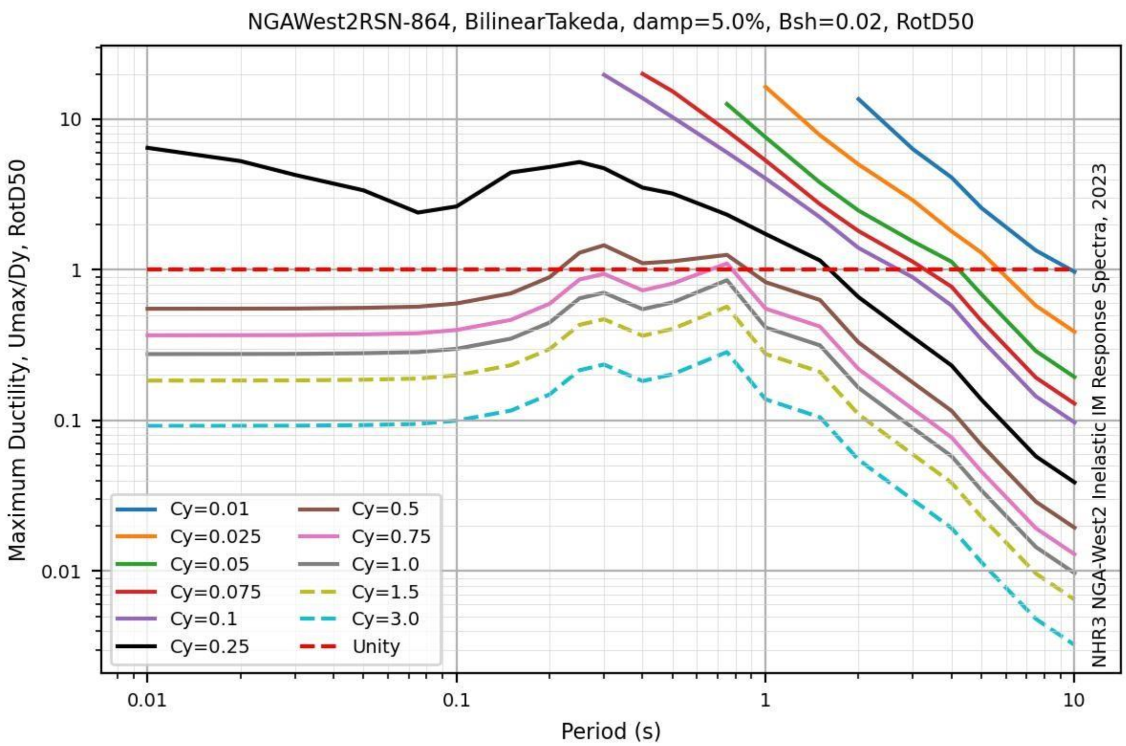


Figure 5.3. Maximum-displacement ductility (Constant-Strength) response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=5%)

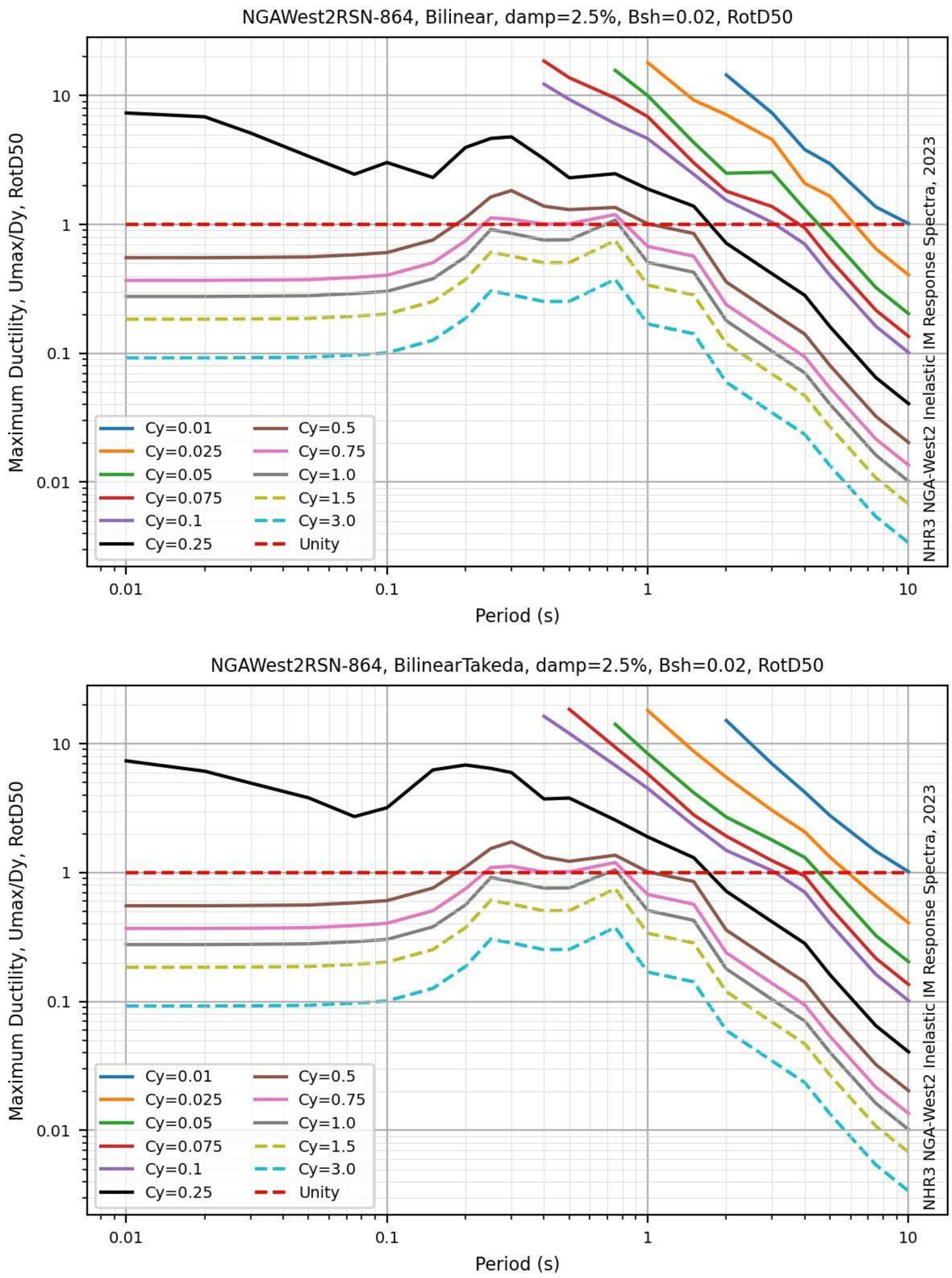


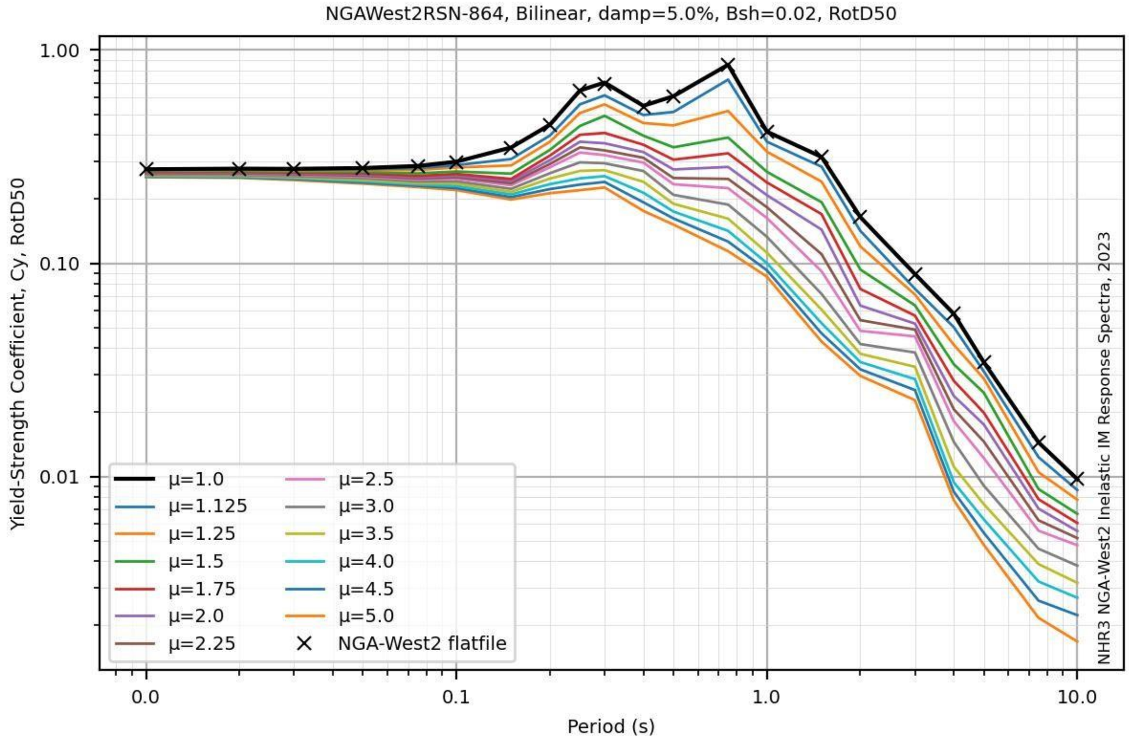
Figure 5.4. Maximum-displacement ductility (Constant-Strength) response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=2.5%)

5.3 Constant-Ductility Spectra

The constant-strength spectra were interpolated to compute constant-ductility spectra for each individual record. There are two types of constant-ductility spectra. The most common type is the Yield-Strength Coefficient ductility spectrum, shown in **Figure 5.5** and **Figure 5.6** for the two damping ratios. This spectrum quantifies the yield strength required to achieve a certain level of ductility demand for each period. The other type is the Maximum-Displacement constant-ductility spectrum, shown in **Figure 5.7** and **Figure 5.8** for the two damping ratios. This spectrum quantifies the maximum-displacement demand at each ductility level.

The maximum displacement at each ductility level can further be normalized by the maximum displacement of the elastic system, which corresponds to ductility=1. This ratio is shown in **Error! Reference source not found.** and **Error! Reference source not found.** for the tw o hysteretic models and two damping levels. The data in the figures show that the ratio depends on the oscillator period. For short-period systems, the ratio is proportionate to the ductility level. In this case the maximum inelastic displacement demand could be estimated to be equal to the ductility times the maximum elastic demand. In the longer-period range, starting at approximately 1 second, however, the ratio approaches unity, indicating that the displacement demands of the elastic oscillator are the same as the inelastic one. The response in the moderate periods, between 0.1 and 1.0 seconds is record-dependent.

Error! Reference source not found. and **Error! Reference source not found.** were de veloped by comparing the response of the elastic and inelastic systems with the same damping. However, because the hysteretic behavior of an inelastic system models some of the energy dissipation explicitly, viscous-damping ratios for inelastic modeling are typically set between 2% and 3%, depending on the structural system. Therefore, for consistency, the inelastic modeling was done at 2.5% and is compared to the elastic model with 5% damping, as shown in **Error! R eference source not found.** for the two hysteretic models. As expected, the ratio is no longer unity for the case of ductility=1. These figures show that the response in the short-period range is independent of damping. However, in the long-period range and ductility above 1, the response of the elastic system with 5% damping is closer to that of the inelastic system with 2.5% damping than it is for the cases where the two systems have the same damping ratio.



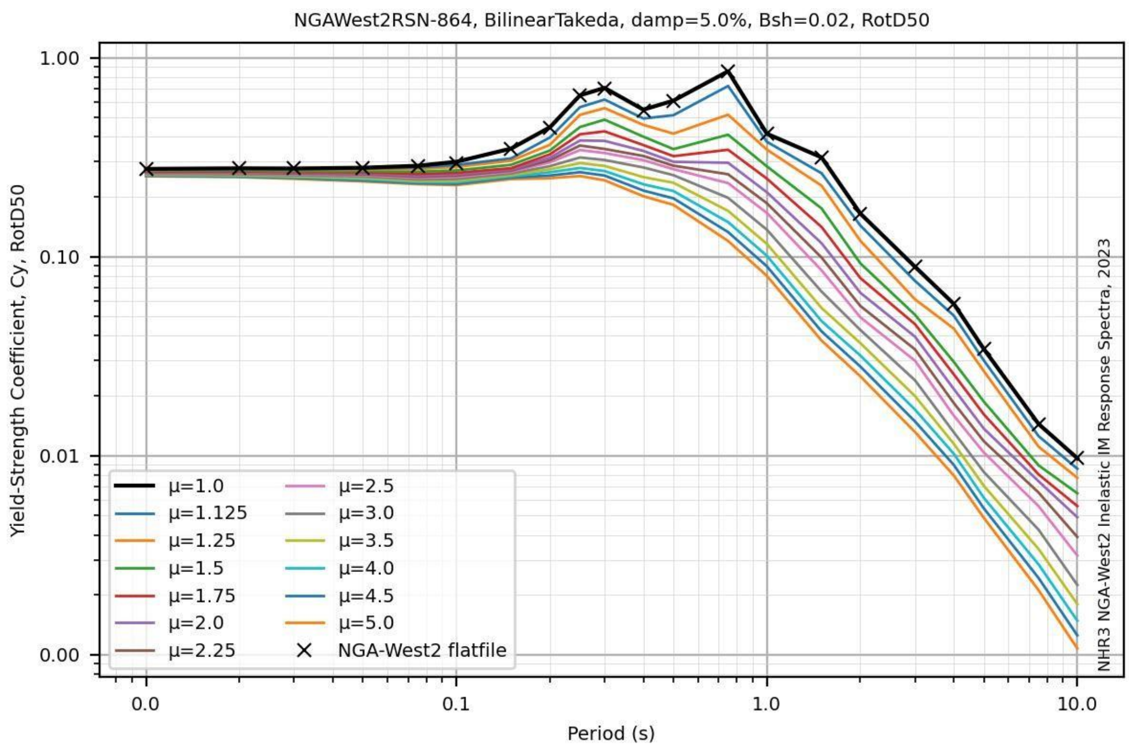
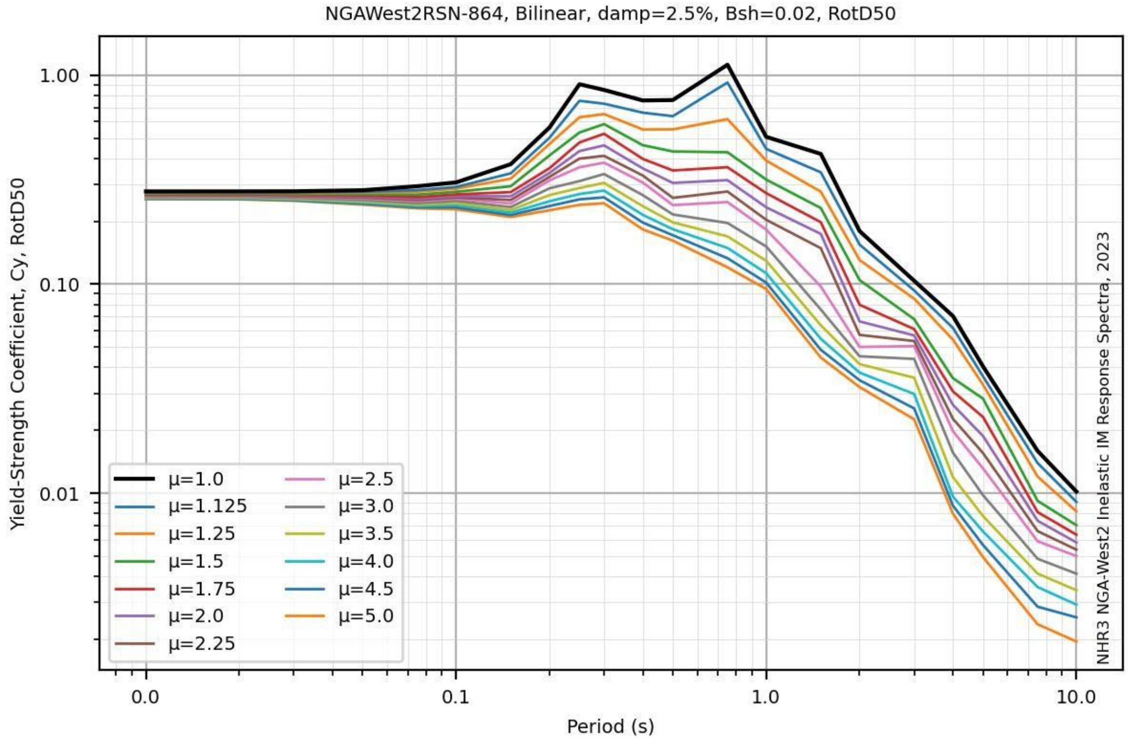


Figure 5.5. Yield-Strength Constant-ductility response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=5%)



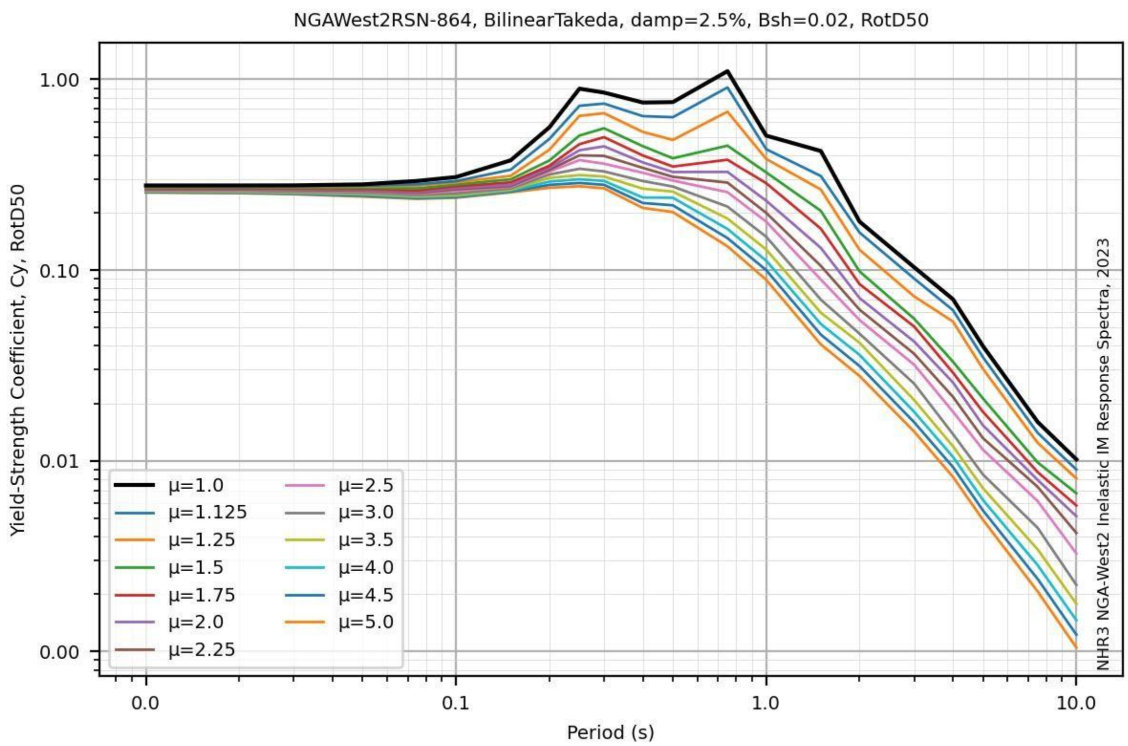


Figure 5.6. Yield-Strength Constant-ductility response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=2.5%)

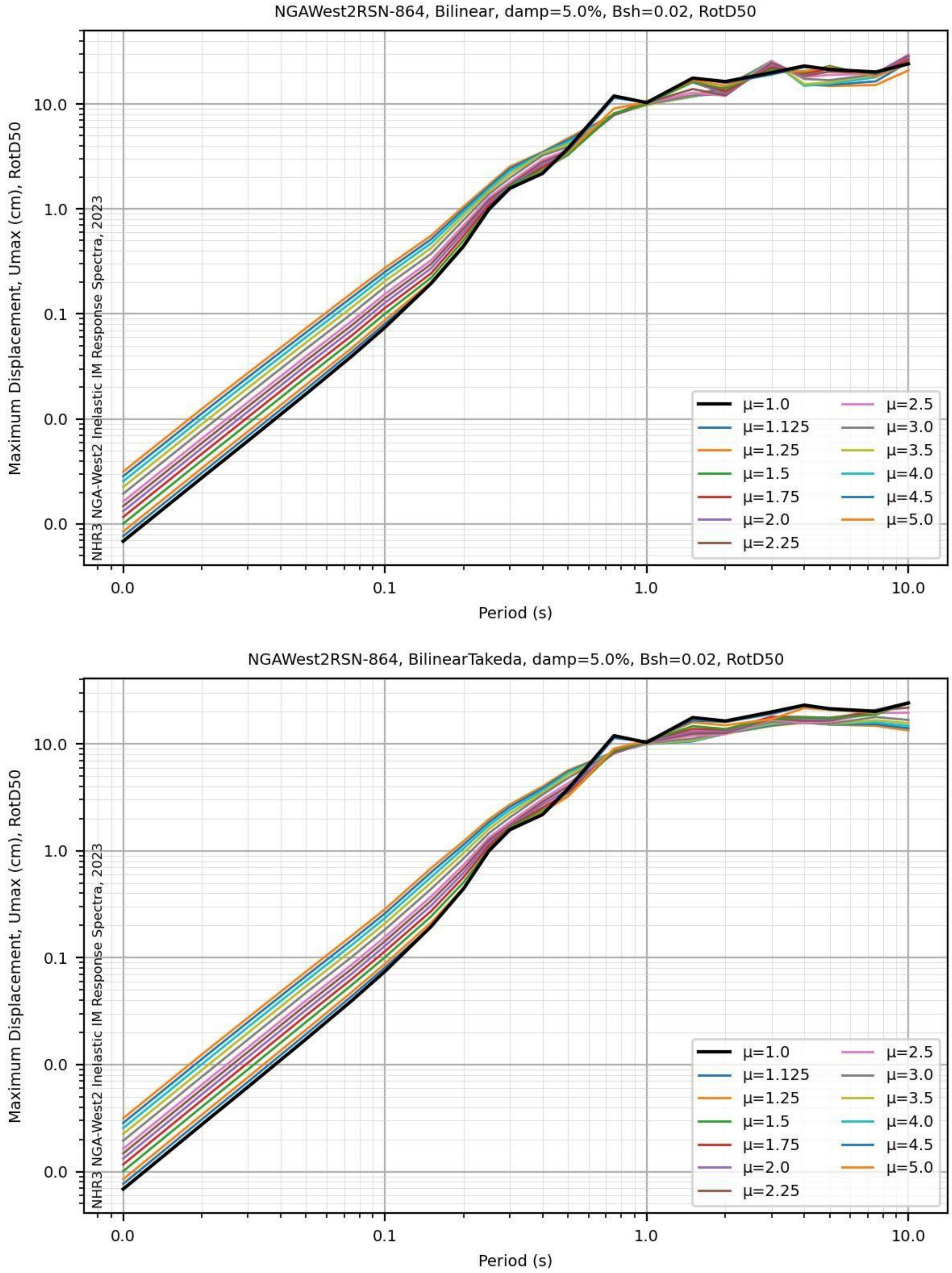


Figure 5.7. Maximum-Displacement Constant-ductility response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=5%)

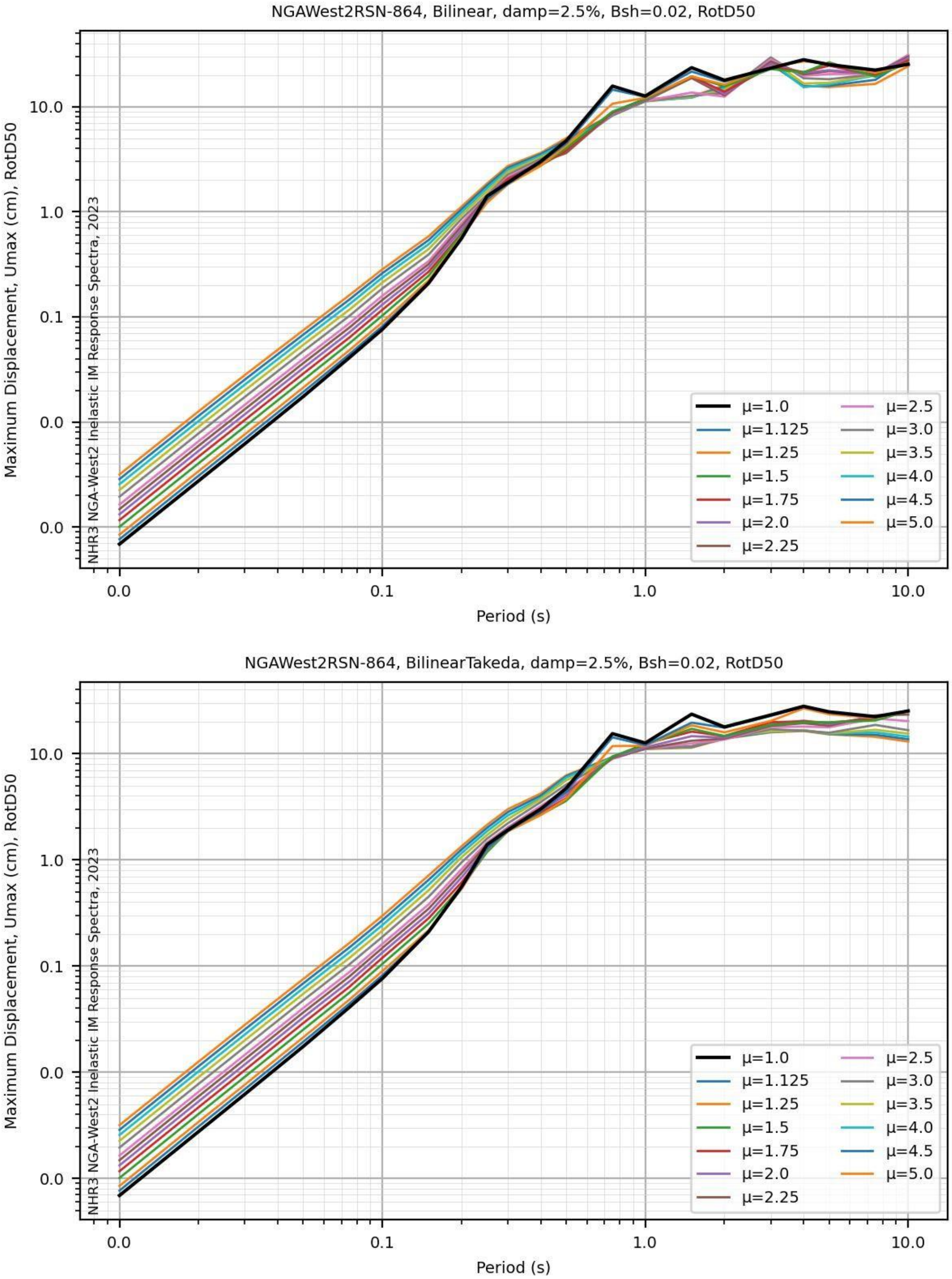
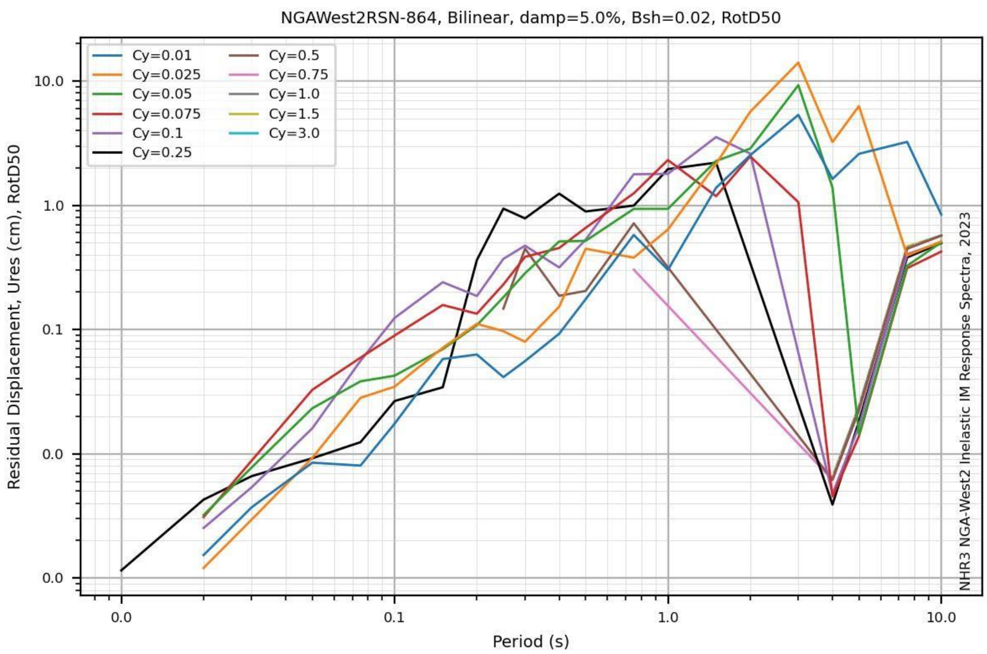


Figure 5.8. Maximum-Displacement Constant-ductility response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=2.5%)

5.4 Residual-Displacement Spectra

The residual-displacement spectra for an individual record and the two hysteretic models are shown in **Figure 5.9**. The residual displacements increase with increasing period (flexibility), as expected. Residual-displacement data was collected and will be processed in a future project.



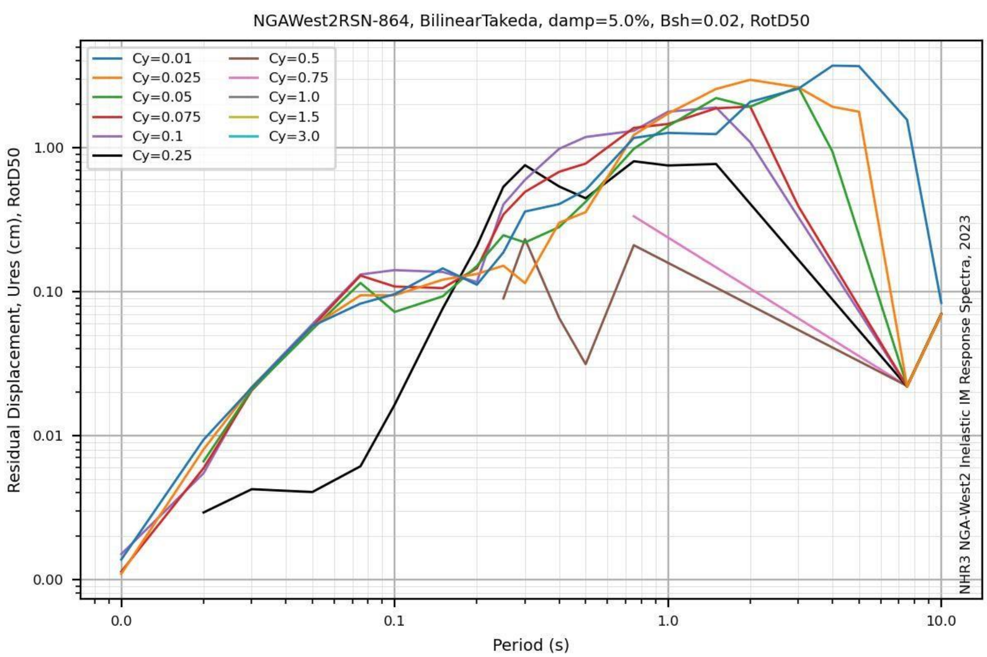


Figure 5.9. Residual-Displacement response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=5%) (only non-zero values are plotted)

5.5 Hysteretic-Energy Spectra

The normalized hysteretic-energy response spectra are shown in **Figure 5.10**. The figure shows that once a system yields, the energy dissipation is sensitive to the strength ratio only for longer-period systems. Hysteretic-energy data was collected and will be processed in a future project.

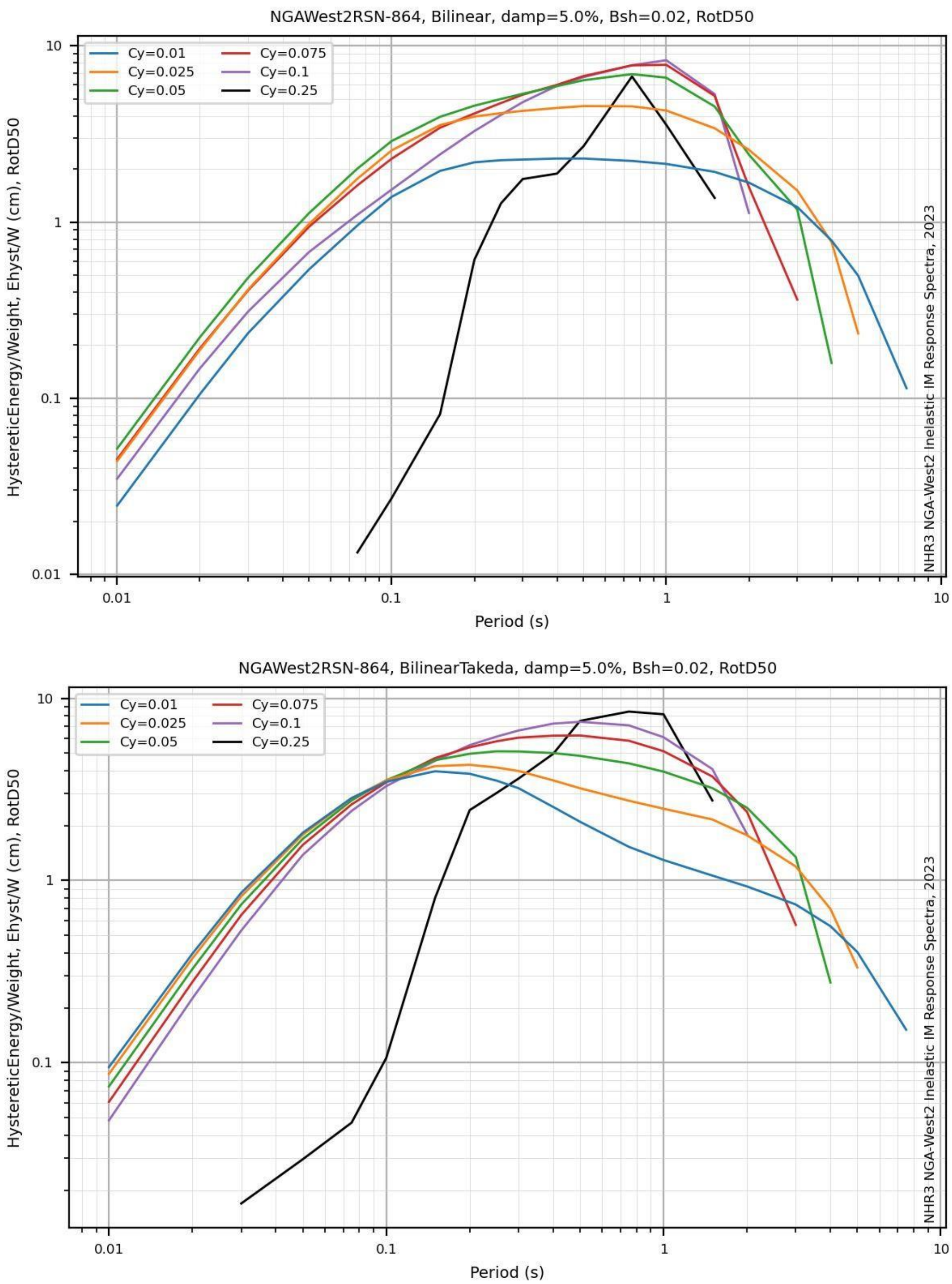


Figure 5.10. Hysteretic-Energy response spectra for Bilinear and Takeda Inelastic Models (RSN=864, Orientation=RotD50, Damping=5%)

6 Data Access

Digital download is available for the datasets of inelastic-response metrics associated with the maximum-displacement response which are used in a separate study to develop ground motion models for inelastic spectra (Bahrampouri, et al., 2022). The datasets were grouped by intensity measure and by component (H1, H2, RotD00, RotD50, RotD100), each in a separate table, resulting in 5 table per intensity measure. Each dataset table contains the data for all elastic and inelastic models. The database tables listed below can be accessed from the following web page: https://www.risksciences.ucla.edu/nhr3/inelastic-response-spectra-data, which will have updated links, if necessary.

6.1 Maximum Displacement and Ductility Demand Dataset

The maximum displacement and ductility demands were assembled into a single table for each horizontal-direction component. For each maximum displacement data, we also computed the corresponding maximum ductility, MU. For the case of the elastic model, a value of -888 was assigned to the ductility value, indicating that this intensity measure does not apply in this case. The files may be downloaded from the links provided in Table 6.1.

The following values are tabulated in each file: RunFilename0, Database, RSN, DampingRatio, ModelClass, ModelLabel, Cy, CyModel, Bsh, Period, CyModFactor, CyValue, okeyRunSumWantZero, K, Dy, Umax_XX, MU_XX. The first three columns (RunFilename0, Database, RSN) identify the ground-motion record and file corresponding to this case. ModelCalss specifies whether the model is Elastic or Inelastic, ModelLabel specifies which elastic/inelastic model was used. The columns for Cy, CyModel, CyModFactor, CyValue describe information about the yield-strength coefficient, CyValue is the actual value for the specific row. Bsh, Period, DampingRatio identify the model characteristics, as well as the computed values K – the elastic stiffness – and Dy, the yield displacement. Umax_XX and MU_XX, where XX represents the horizontal component (H1,H2,etc..) represent the maximum displacement demand (in cm) and the maximum-ductility demand.

Table 6.1 Maximum-Displacement and Ductility Demand Dataset – Download Link

File	Google-Drive Link
InelasticIMSpectraDb_UmaxAndMU_AllData_H1	https://drive.google.com/file/d/1U22qOIWpGHCz1rtsYoUasR5abJVCzCI6/view?usp=sharing
InelasticIMSpectraDb_UmaxAndMU_AllData_H2	https://drive.google.com/file/d/12bid3ljSxg-Wo48pcRvVYNBb8U38Dl4t/view?usp=sharing
InelasticIMSpectraDb_UmaxAndMU_AllData_RotD00	https://drive.google.com/file/d/1sZqmoxMU-7Ed8XATQJy0Ccno4cFBEWO9/view?usp=sharing
InelasticIMSpectraDb_UmaxAndMU_AllData_RotD50	https://drive.google.com/file/d/1mX4RLDKSVIdZ2E6C0Mpjw0dQAmW6IVaG/view?usp=sharing
InelasticIMSpectraDb_UmaxAndMU_AllData_RotD100	https://drive.google.com/file/d/1z53ufKSrIzfV9M1C1rh2q_byWy-Jtg6U/view?usp=sharing

6.2 Constant-Ductility Spectra Dataset

Two constant-ductility datasets were produced: yield-strength coefficients, Cy, and maximum-displacements, Umax. These datasets, whose links are given in Table 6.2 and Table 6.3, are formatted and grouped in a manner that is consistent with that of the maximum-displacement and ductility demand dataset.

Table 6.2 Constant-Ductility Spectra, Cy Dataset – Download Link

File	Google-Drive Link
InelasticIMSpectraDb_ConstDuctility _Cy_AllData _H1	https://drive.google.com/file/d/14TKjZZJN103A_2_cIk5OVIrznVOwf QRr/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility _Cy_AllData _H2	https://drive.google.com/file/d/1ImicXSb6xN5bDd_bNS8dV51SQLOJb XpO/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility _Cy_AllData _RotD00	https://drive.google.com/file/d/1O0c3ylgHttlD75013izO1Rccprfrm561/ view?usp=sharing
InelasticIMSpectraDb_ConstDuctility _Cy_AllData _RotD50	https://drive.google.com/file/d/1AuSeX3LmLxNYpGBywBj-BfpK_HmU1MdL/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility _Cy_AllData _RotD100	https://drive.google.com/file/d/1PzftcF51WVakYKGgdh-C9lumv9Dsdv5-/view?usp=sharing

Table 6.3 Constant-Ductility Spectra, Umax Dataset -- Download Link

File	Google-Drive Link
InelasticIMSpectraDb_ConstDuctility_Uma x_AllData_H1	https://drive.google.com/file/d/1IFxaBMOsdZ8zGPsWJvM7VFY mJO9tZ4lA/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility_Uma x_AllData_H2	https://drive.google.com/file/d/1et7iEHBVor-GkaiC85J40MotH8cgO9X5/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility_Uma x_AllData_RotD00	https://drive.google.com/file/d/1-hGel8a7c19XP9sClX8QPSzMArwCjWf-/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility_Uma x_AllData_RotD50	https://drive.google.com/file/d/1yjrJltdjyIITQZZzHPX0yV0IPK2 PTDXZ/view?usp=sharing
InelasticIMSpectraDb_ConstDuctility_Uma x_AllData_RotD100	https://drive.google.com/file/d/1JB0mBXVMRwcIq73sXNdut9v MwWt_BeJp/view?usp=sharing

7 Concluding Remarks

This document summarizes a major extension of NGA-West2 database by developing a database of inelastic-response IMs – maximum displacement, yield strength, residual displacement, and hysteretic energy. Through a parametrized study, the following response spectra were developed and tabulated:

- Maximum-Displacement Spectra
- Maximum-Ductility Spectra (Constant-Strength Spectra)
- Constant-Ductility Spectra
- Residual-Displacement Spectra
- Dissipated-Energy Spectra

These spectra were computed for a range of fundamental periods, ranging from 0.01-10 seconds, yield strength, viscous damping ratio, and inelastic-response model. In a manner consistent with the original linear NGA databases, we computed these metrics for both horizontal as-recorded components and RotD00, RotD50 and RotD100 resultants.

A sample python script has been included in this report.

8 References

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