Dynamic Isolation Systems

Viscous Wall Dampers

Guidelines for Modeling

Dynamic Isolation Systems

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Introduction

This modeling guide provides protocols for including Dynamic Isolation Systems VWDs in structural models of buildings subjected to earthquakes or wind-induced vibration. This guide also provides the basis for the nominal properties of these dampers and recommended property modification factor associated with the first cycle effect (λ test).

The Viscous Wall Dampers discussed here are double vane dampers with a viscous fluid layer thickness of 5mm.

Schematic drawings for typical configurations of double vane VWDs are shown in Appendix C(page 4). Single vane and other configurations, are also available.

The material in this guide was prepared for Dynamic Isolation Systems by Button Engineering.

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Viscous Wall Dampers (VWDs)

VWDs reduce displacements and stresses in the superstructure by up to 50%, resulting in a better performing building and lower structural cost, which more than offsets the amount of the VWDs.

Ideal Structures for VWDs

- **Hospitals**
- **Flexible Medium to High-Rise Buildings**
- **Buildings With High Content Value**
- **Structures Requiring Continuous Operation**
- **Retrofits**

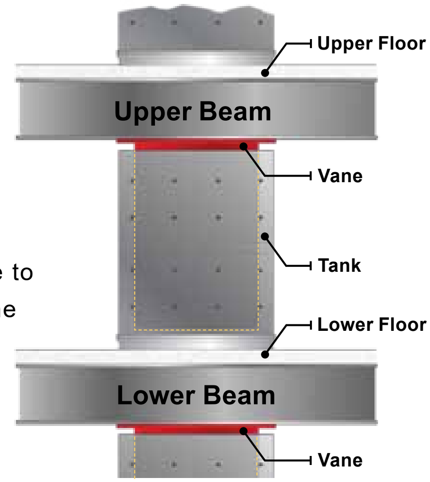
113 VWDs were installed in the $1.6 billion Geary Van Ness Medical Center project in San Francisco, California.

Benefits of Viscous Wall Dampers

- **Cost Savings.** VWDs reduce the weight of structural steel required and lower the total cost of the building.
- **Architectural Flexibility.** The compact, rectangular shape of the VWD is easier to incorporate and gives greater architectural freedom than diagonal braces or dampers.
- **Better Performance.** By reducing inter-story drift, VWDs provide superior seismic protection to the structure and its contents.
- **Maintenance Free.** VWDs have no moving parts or seals, are under no internal pressure and do not require maintenance.
- **Retrofits.** VWDs are ideal for retrofits; they are easy to install and may require less structural strengthening than hydraulic damper retrofits.

How Do Viscous Wall Dampers Work?

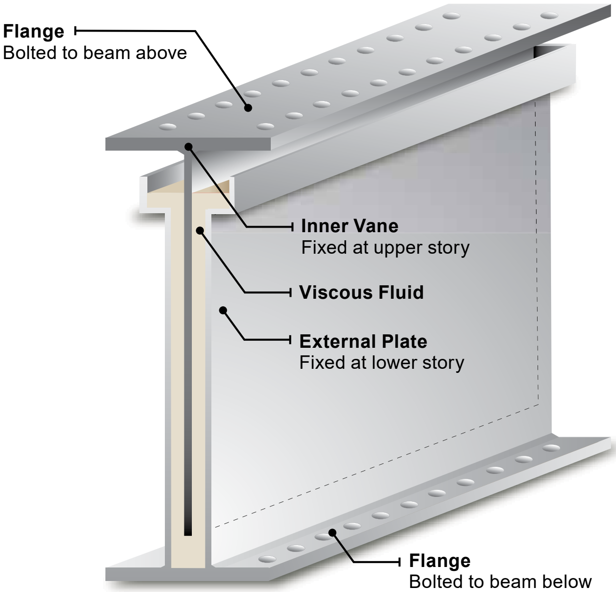
Each viscous wall damper consists of a narrow steel tank connected to the lower floor and containing a non-toxic, odorless, transparent fluid. Within the tank, and connected to the upper floor, is an inner steel plate, or vane.



During seismic excitation, or in strong winds, the relative floor movement causes the vane to move through the viscous fluid.

The damping force from the shearing action of the fluid is dependent on the displacement and velocity of the relative motion.

Viscous Wall Dampers may also be constructed with 2 vanes. A double-vane system provides twice the damping force with only a small increase in plan size.



Viscous Wall Dampers (VWDs)

Manufacturing

DIS maintains the highest production and performance standards in the industry. All key manufacturing processes are completed on-site at DIS’ 60,000 square foot, state-of-the-art, manufacturing facility near Reno, Nevada.

Testing of Wall Dampers is also conducted on-site, using the world’s largest purpose-built viscous wall damper test rig (below).

DIS engineers provide technical support and parameters for structural modeling and assist clients with feasibility studies, budget development and value engineering. Customers who have utilized DIS beginning in the design phase of their project have enjoyed overall cost reductions of up to thirty percent.

DIS Wall dampers are engineered, designed and manufactured in its Nevada plant, where they are they are also tested in the world’s largest, purpose-built VWD test rig.

Facility

Dynamic Isolation Systems is conveniently located in the Tahoe/Reno Industrial Center on I-80 just East of Reno, Nevada.

As the world leader in seismic protection, DIS has the experience, expertise and the equipment to complete any project.

DIS processes over 2,000 tons of steel each year and mills plates up to 132” long and turns parts up to 72” in diameter.

Welders at Dynamic Isolation Systems are AWS and OSHPD certified. For improved consistency and to reduce shrinkage in the assembly, parts are welded automatically, where practical.

DIS’ facility is serviced by nine overhead cranes with capacities up to 10 tons and forklifts with capacities up to 20,000 pounds.

Property tables for Standard VWD sizes

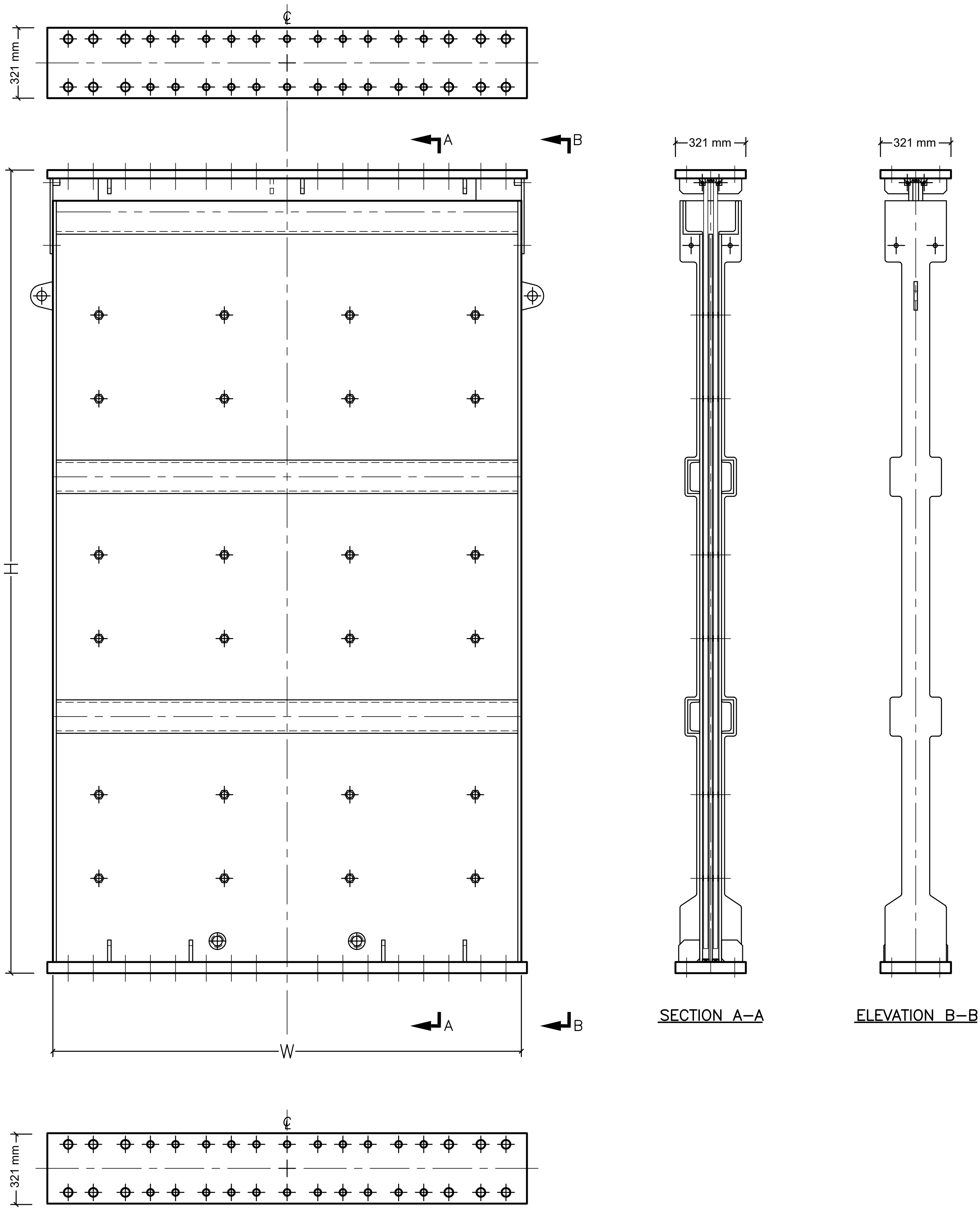
Standard Units

DIS VWD	Width (ft)	Height (ft)	Single Vane K [kip/in]	Single Vane C [kip-(sec/in)$^{\alpha}$]	Double Vane K [kip/in]	Double Vane C [k-(sec/in)$^{\alpha}$]	α (dimensionless)
6 x 8	6	8	155	40	310	80	0.5
7 x 8	7	8	185	45	370	90	0.5
8 x 8	8	8	225	55	450	110	0.5
9 x 8	9	8	260	65	520	130	0.5
6 x 9	6	9	170	45	340	90	0.5
7 x 9	7	9	205	55	410	110	0.5
8 x 9	8	9	245	65	490	130	0.5
9 x 9	9	9	285	75	570	150	0.5
6 x 10	6	10	180	50	360	100	0.5
7 x 10	7	10	210	60	420	120	0.5
8 x 10	8	10	255	70	510	140	0.5
6 x 11	6	11	185	55	370	110	0.5
7 x 11	7	11	220	70	440	140	0.5
8 x 11	8	11	265	80	530	160	0.5
6 x 12	6	12	190	65	380	130	0.5
7 x 12	7	12	225	75	450	150	0.5
8 x 12	8	12	270	90	540	180	0.5

Metric Units

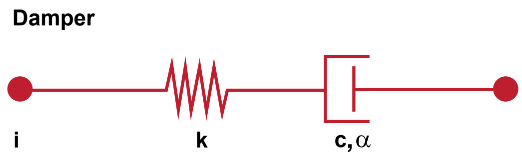
DIS VWD	Width (m)	Height (m)	Single Vane K [kN/m]	Single Vane C [kN-(sec/m)$^{\alpha}$]	Double Vane K [kN/m]	Double Vane C [kN-(sec/m)$^{\alpha}$]	α (dimensionless)
1.8 x 2.1	1.8	2.1	23500	800	47000	1600	0.5
2.1 x 2.1	2.1	2.1	28500	1025	57000	2050	0.5
2.4 x 2.1	2.4	2.1	32000	1225	64000	2450	0.5
1.8 x 2.4	1.8	2.4	27500	975	55000	1950	0.5
2.1 x 2.4	2.1	2.4	32000	1225	64000	2450	0.5
2.4 x 2.4	2.4	2.4	35500	1475	71000	2950	0.5

Schematic for Viscous Wall Damper



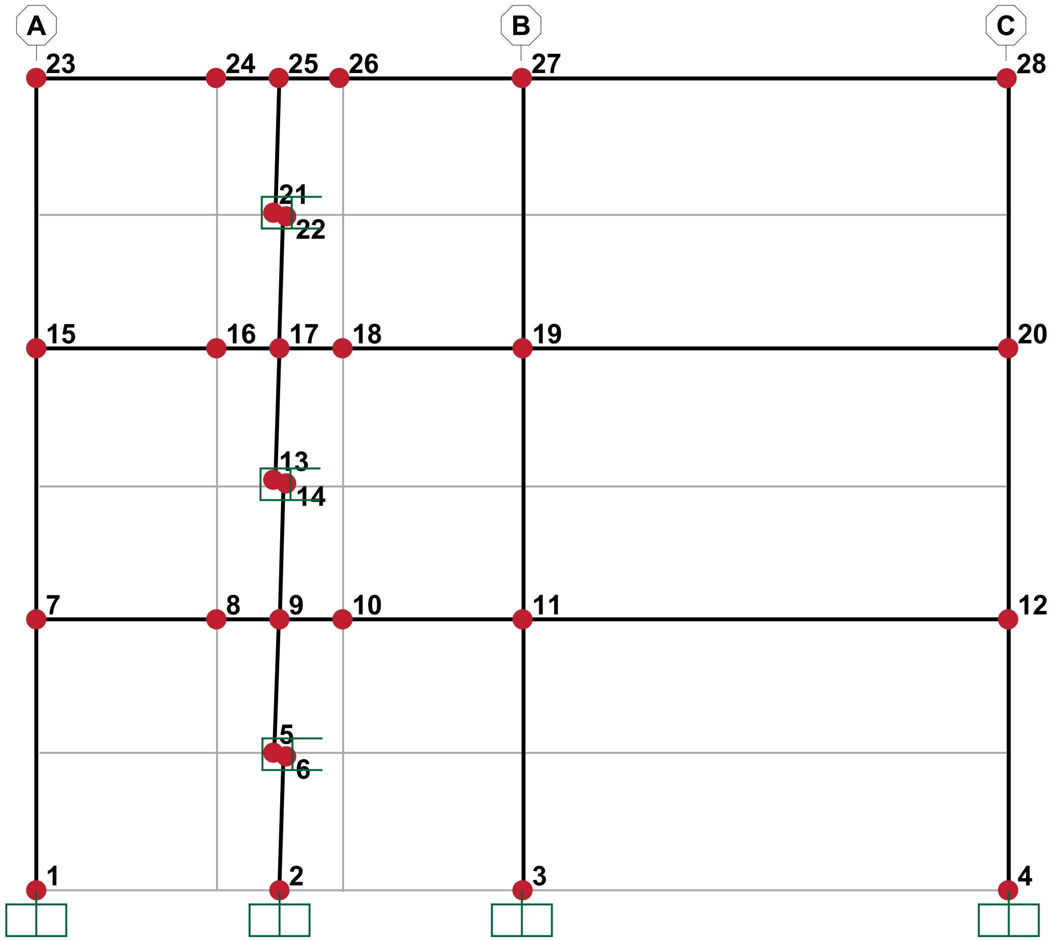
Modeling of DIS Viscous Wall Dampers in SAP2000, ETABS

The seismic response of DIS VWDs can be readily modeled using existing nonlinear elements in SAP2000, ETABS or PERFORM-3D. This section is written in the context of SAP2000 and assumes that nonlinear response history analysis is performed. For VWD modeling, ETABS has identical capabilities to SAP2000. Modeling of VWDs in PERFORM-3D is discussed beginning on page 12.



DIS VWDs are best represented by an Exponential Maxwell Damper model, as shown in the figure above (from the CSI Analysis Reference Manual). The SAP2000 element type is NLLINK. The model consists of a linear spring, K, in series with an exponential damper characterized by C and α, such that the force in the damper is related to the velocity across the damper through the force-velocity relationship $F = CV^{\alpha}$.

Unlike piston dampers, DIS VWDs connect to beams above and below. Therefore, to use the above 2-node element, a typical frame containing VWDs can be modeled as follows:



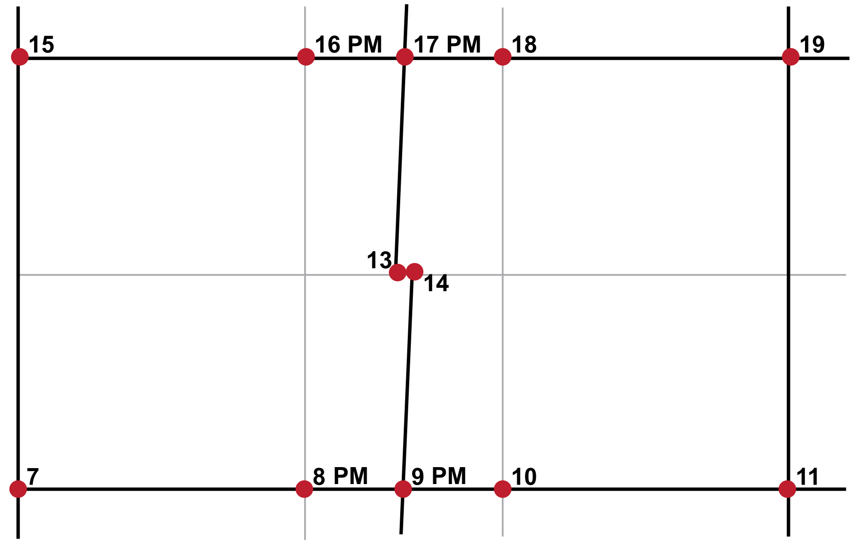
Adding VWD Elements to an Existing Frame Model

The frame in this example is a two-bay, three story moment frame with 7-foot wide by 12-foot tall VWDs centered in the bay between grid lines A and B. The story height is 15 feet and the bay width is 27 feet. The following modeling steps are required after typical modeling of the moment frame members:

1. In the damper bay(s), divide the beams into three elements such that the length of the center element (for example, between nodes 8 and 10) is the same as the width of the VWD, i.e., 7 feet in this case, and located to reflect the position of the VWD in the bay – centered in this example.

2. Divide the center elements into two equal elements (for example, creating nodes 9 and 17).

3. Since the VWD properties provided by DIS include the stiffness of the tank and vanes and their effect on the beams above and below the VWD, beam elements within the width of the VWD can be modeled as very stiff. Assign Property Modifiers to the beam sections within the width of each VWD so that their moment of inertia, I33, is increased by a factor of (say) 100 relative to the actual beam section (see members with "PM" designation in figure below).



4. At the mid-height of each bay and story containing a VWD, create a pair of nodes (for example nodes 13 and 14) a small distance (for example 6 inches) apart. This pair of nodes should be centered within the width of the VWD.

5. With a stiff frame element connect the center of the beam below to one of these nodes (in this case node 14), and the center of the beam above to the other (in this case node 13). The in-plane bending stiffness of these stiff elements should be comparable to that of the stiffened mid-section of the beam below (nodes 8-9-10) and the beam above (nodes 16-17-18), including the effect of the Property Modification factors, as discussed in 3, above. The stiffness of these elements should be such that when the bay deforms in shear, including the forces generated in the VWD element (see page 8, step 6), close to 100% of the total shear deformation is concentrated in the damper element. This can be easily checked by comparing the in-plane drift between (say) nodes 7 and 15 with the deformation in the VWD element between (say) nodes 13 and 14.

Adding VWD Elements to an Existing Frame Model, cont.

6. Connect the VWD NLLINK element (see details below for properties) horizontally between the two nodes at the mid-height of the story and bay containing the VWD (for example, nodes 13 and 14). Use the "Draw 2 Joint Link" command from the SAP2000 Draw menu.

In a large model, VWD bay modeling can easily be duplicated using the Replicate features in SAP2000 or ETABS.

VWD Nominal Properties

Based on extensive dynamic wind, sinusoidal cyclic and earthquake tests on two VWD sizes at UCSD in 2010, the following nominal properties are recommended at 70°F. The technical basis for these values is presented in Appendix B.

Damper Size	Source	K (k/in)	C [k-(sec/in)$^{\alpha}$]	α (dimensionless)
7 x 9	UCSD Tests	410	108	0.5
7 x 10	Interpolation	425	120	0.5
7 x 12	UCSD Tests	450	150	0.5

VWD Maximum and Minimum Properties

In accordance with the requirements of Chapter 18 of ASCE 7-16, seismic analysis is typically performed with maximum and minimum properties for the VWDs. These properties are derived from the nominal properties through use of property modification factors, as defined by equations 18.2-3a and 18.2-3b of ASCE 7-16. The following table provides suitable values of the various components that make up these property modification factors. The ambient temperature factors are taken from information presented in Appendix A. The actual ambient temperature range on a project may vary from the range assumed here (68°F to 74°F).

Source of Variation	λ_{max}	λ_{min}
1. Testing, including first cycle effects, λ_{test}	**1.55**	**1.00**
Aging, λ_a	*1.05*	*0.95*
Ambient Temperature (assumed 68° to 74°F, actual may vary) λ_{temp}	*1.055*	*0.898*
2. Aging and Environment, $\lambda_{ae}(\lambda_a.\lambda_{temp}$, including 75% reduction)	**1.08**	**0.89**
3. Specification, all VWDs, λ_{spec} (used for analyis properties)	**1.10**	**0.90**
Specification, individual VWDs, λ_{spec} (used for design connections)	*1.15*	*0.85*
Total Variation for Analysis (1 x 2 x 3)	**1.84**	**0.80**

The maximum property modification factor (1.84) for analysis is dominated by first cycle effects. The minimum property modification factor (0.80) is dominated by temperature effects.

For this example, for a 7x12 VWD, the maximum properties for analysis are therefore:

K = 1.84 x 450 = 828 k/in

C = 1.84 x 150 = 276 k-(sec/in)$^{0.5}$

α = 0.5

and the minimum properties for analysis are:

K = 0.80 x 450 = 360 k/in

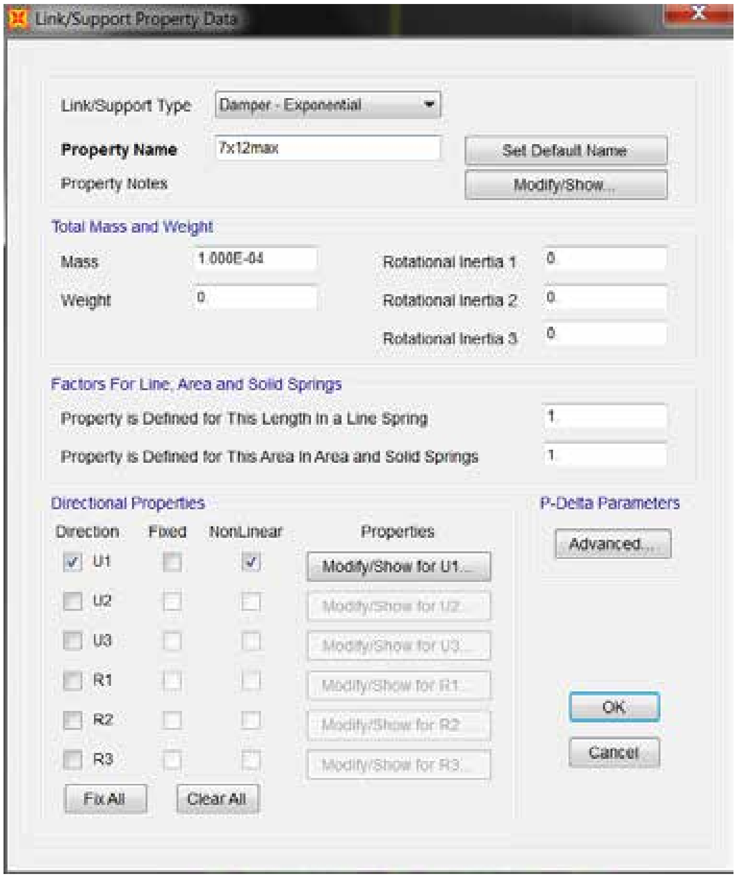
C = 0.80 x 150 = 120 k-(sec/in)$^{0.5}$

α = 0.5

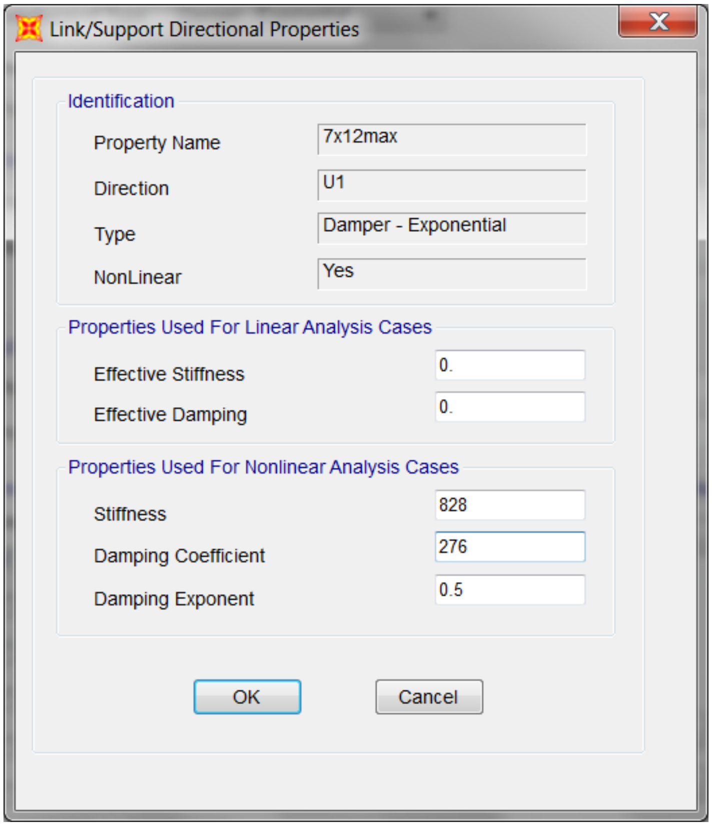
Maximum VWD properties will typically result in maximum forces throughout the structure, and will usually control the design of members and connections. Minimum VWD properties will typically result in maximum displacements and will control drifts and other displacement-related response.

Specification of VWD Properties using NLLINK Elements

The VWD properties are specified using the Define → Section Properties → Link/Support Properties → Add New Property menu. For the Link/Support Type, choose “Damper – Exponential” from the pull-down menu. For the maximum property case, the GUI screen looks as follows:



It is always good modeling practice to assign a small mass to the NLLINK element. This should not be confused with the mass associated with the weight of the VWD itself, approximately half of which is tributary to the beam above, and half to the beam below. The VWD is active and nonlinear for the U1 direction only, so check the U1 box and the corresponding Nonlinear box. On pressing the “Modify/Show for U1” button, the following GUI screen appears:



It is recommended that only Nonlinear Response History Analysis be used for structures containing VWDs. Leave the “Properties Used For Linear Analysis Cases” section blank (zeros), and under the “Properties Used For Nonlinear Analysis Cases” section, enter the appropriate values of Stiffness (K = 828 k/in in this example), Damping Coefficient (C = 276 k-(sec/in)$^{0.5}$ in this example) and Damping Exponent (α = 0.5 for DIS VWDs). Once the appropriate values are entered, click the “OK” button on two successive screens to exit the definition of this property.

This process is repeated to define the minimum damper properties.

Modeling of DIS Viscous Wall Dampers in SAP2000, ETABS

Assigning VWD Properties to NLLINK Elements

Once the VWD properties are defined, either the maximum or minimum VWD property can be assigned to the various NLLINK elements previously drawn in the model (see page 8, step 6) in the usual way within SAP2000 or ETABS.

Out-of-Plane Stiffness of VWDs

The out-of-plane stiffness of VWDs is small and can be ignored in seismic analysis. The in-plane behavior of VWDs is insensitive to out-of-plane deformation.

Running NLRH Analyses in SAP2000 or ETABS

Once the model is complete, NLRHA can be performed in the usual way using either FNA with Ritz vectors or Direct Integration. Guidelines for performing these types of nonlinear analyses successfully are beyond the scope of this document. Refer to the CSI Analysis Reference Manual for recommendations.

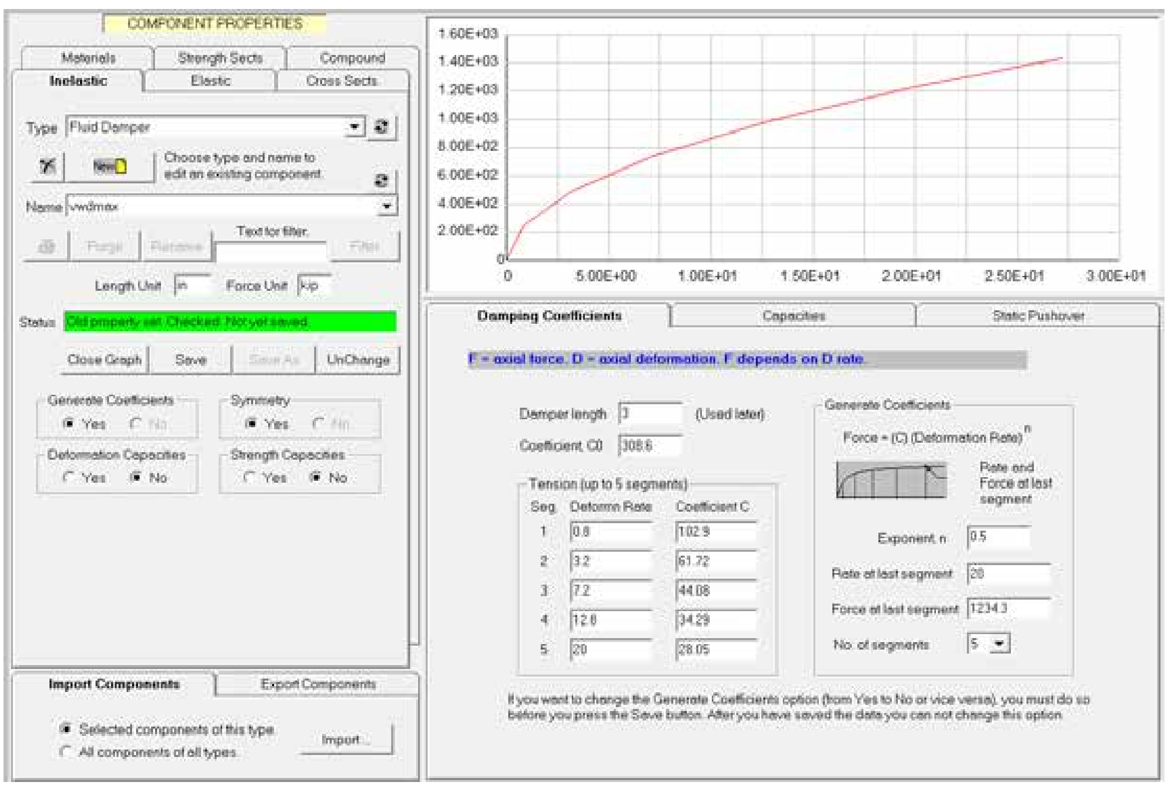
Potential Beam Hinge Locations in VWD Bays

It must be recognized that beam hinges in VWD bays have the potential to form immediately adjacent to the ends of the VWDs if the beams in those bays do not have sufficient moment capacity. This behavior is undesirable, and should be avoided through careful selection of VWD bay beam sections.

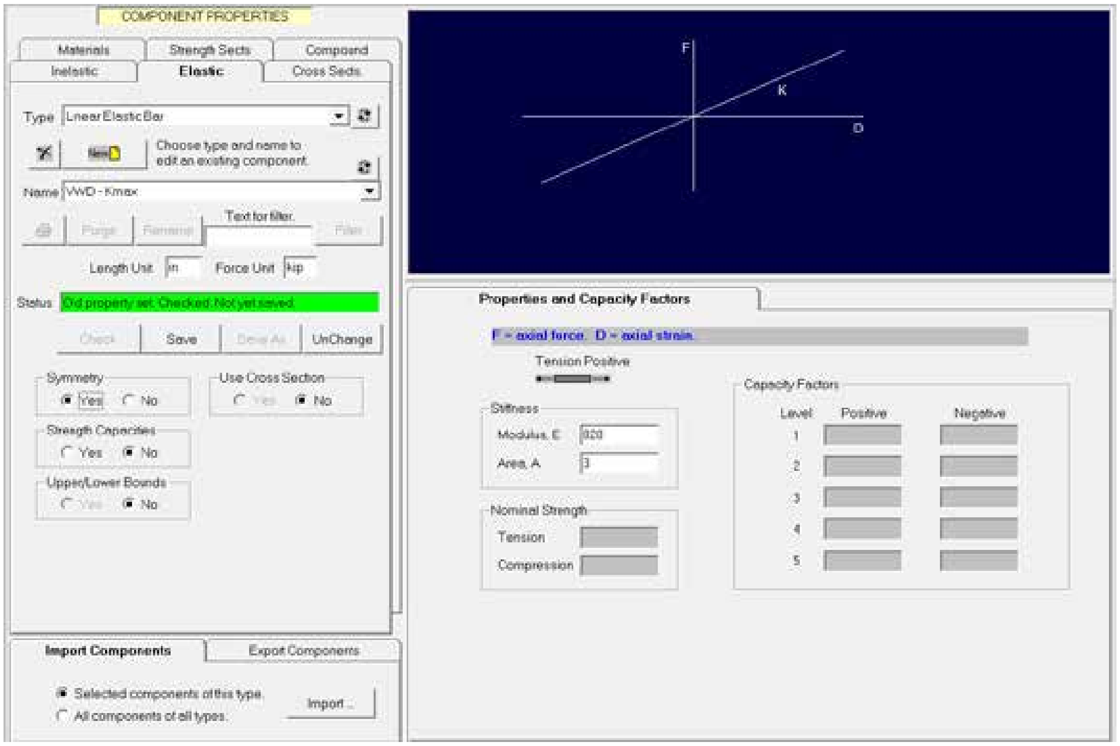
Modeling of DIS VWDs in PERFORM-3D

The basic approach for modeling structures incorporating VWDs through frame geometry and member properties and connectivity is the same in PERFORM-3D as previously described for SAP2000 / ETABS. The essential difference is the definition of the element representing the VWD itself. Whereas SAP2000 and ETABS use a single "Exponential Damper" NLLINK element which defines K, C and α in a single GUI form, PERFORM-3D requires the use of a "Compound Component" consisting of a Linear Elastic Bar and an Inelastic Fluid Damper. The Linear Elastic Bar provides the stiffness, K, of the Maxwell Model, while the Inelastic Fluid Damper defines the damper, C and α, of the Maxwell Model.

Start by defining the Inelastic Fluid Damper properties. This component is found under Component Properties → Inelastic → Fluid Damper. Check "New" and provide a name for this component and define its length, which may be taken as half the length between the two damper nodes (nodes 13 and 14, 6 inches apart in the earlier SAP2000 example). The PERFORM-3D Inelastic Fluid damper element defines the force-velocity as piecewise linear, although the program will calculate the properties of and transitions between linear segments of the relationship. For maximum properties of a 7x12 VWD, C = 276 k-(sec/in)$^{0.5}$ and α = 0.5. Under the Damping Coefficients tab, go to the Generate Coefficients box, select 5 segments, specify the exponent as 0.5, chose a velocity (rate) for the last segment that is close to but less than the maximum expected velocity, say 20 in/sec, and finally specify the corresponding force, F = 276 v$^{0.5}$ = 276 x 20 $^{0.5}$ = 1,234.5 kips. Hit the "Check" button. PERFORM-3D will generate the piecewise linear damper coefficients and transitions and plot the generated force-velocity relationship as shown below. If everything looks right, hit the "Save" button.



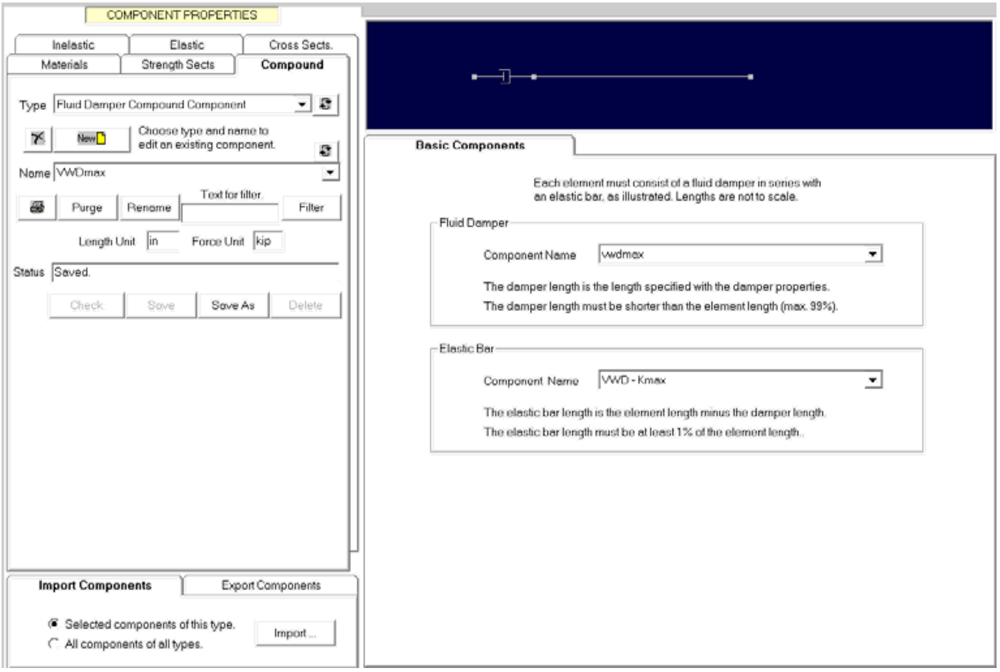
Next, define the Linear Elastic Bar representing the stiffness portion of the Maxwell model, K = 810 k/in for the maximum property for a 7x12 VWD. This component is found under Component Properties → Elastic → Linear Elastic Bar. Hit "New" and define the name for the elastic bar. Set the area, A, to the length of the elastic bar (6 inches minus 3 inches for the damper length in this example) and set the modulus, E, to the desired stiffness, K. The GUI forms looks as follows:



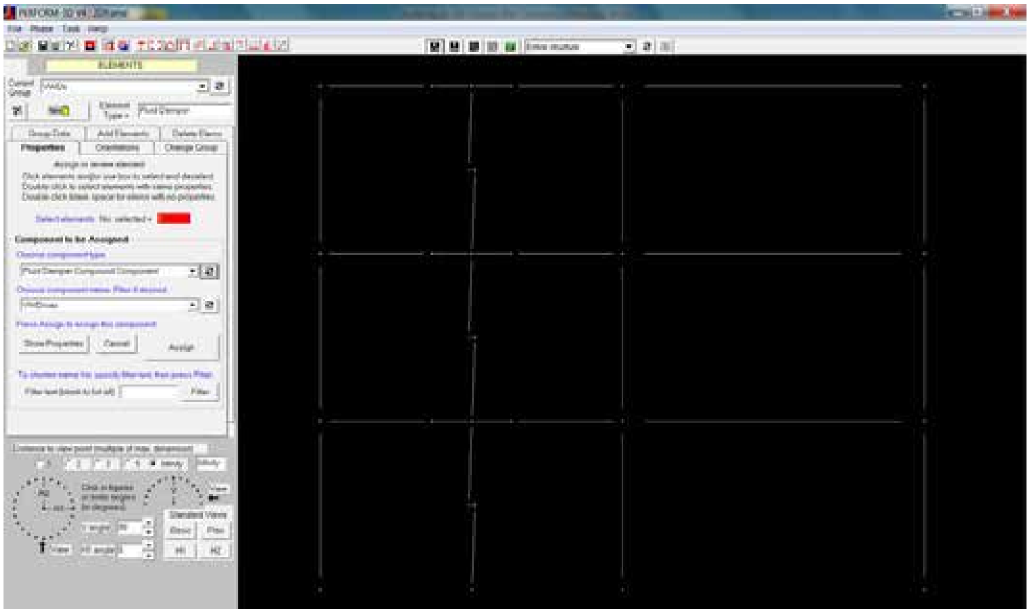
Note that the stiffness of the bar is K = EA / L = 828 x 3 / 3 = 828 k/in as required, although the length of the bar is not defined until the last step below. Hit the "Save" button.

Finally, define the Compound Component for the nonlinear Maxwell model. This is an assembly of the Fluid Damper component and the Linear Elastic Bar component. This component is found under Component Properties → Compound → Fluid Damper Compound Component. Hit "New" and define the name for the VWD element.

Under "Basic Components" select the component names for both the Fluid Damper and the Elastic Bar making up the Fluid Damper Compound Component. Notice the text in both selection boxes regarding the length of the contributing components.



The final length of the Compound Damper element is not defined until Fluid Damper elements are added to the model and the component properties are assigned to each VWD element under Elements → Add Elements and Elements → Properties. A PERFORM-3D model consistent with the earlier SAP2000 model is shown below from the GUI form where the Fluid Damper properties are assigned to the Fluid Damper elements below.



Running NLRH Analyses in PERFORM-3D

Once the model is complete, NLRHA can be performed in the usual way within PERFORM-3D, which uses a direct integration solution scheme. Guidelines for performing nonlinear analyses successfully within PERFORM-3D are beyond the scope of this document. Refer to the CSI Analysis Reference Manual for recommendations.

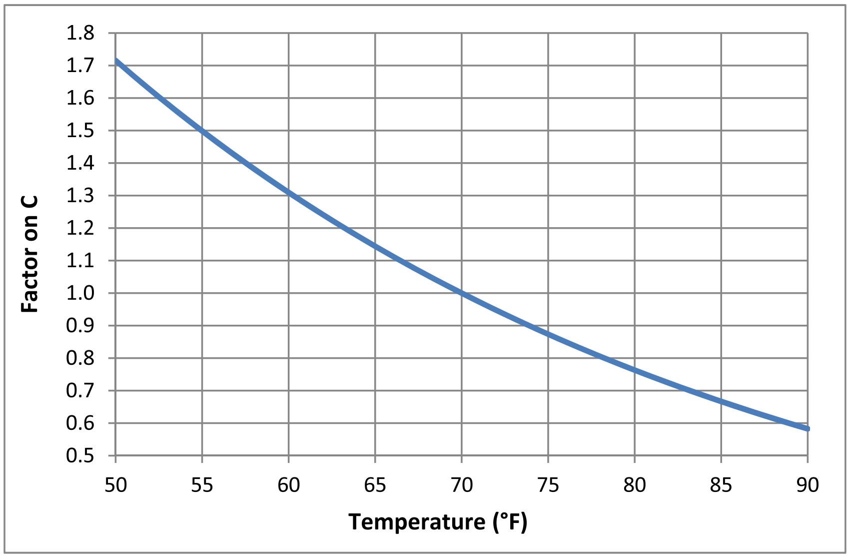
Appendix A: Temperature Dependency

DIS Viscous Wall Dampers

Ambient Temperature Variation Factors

Temperature Equation $C(T) = C(70)e^{-0.027\,(T-70)}$ where T is in °F

Temperature (°F)	Factor on K and C
50	1.716
51	1.670
52	1.626
53	1.582
54	1.540
55	1.499
56	1.459
57	1.420
58	1.383
59	1.346
60	1.310
61	1.275
62	1.241
63	1.208
64	1.176
65	1.145
66	1.114
67	1.084
68	1.055
69	1.027
70	1.000
71	0.973
72	0.947
73	0.922
74	0.898
75	0.874
76	0.850
77	0.828
78	0.806
79	0.784
80	0.763
81	0.743
82	0.723
83	0.704
84	0.685
85	0.667
86	0.649
87	0.632
88	0.615
89	0.599
90	0.583



Appendix B: Basis for Nominal VWD Properties (at 70°F) and First Cycle Factor, λ_{test}

Nominal VWD Properties

In January 2010 DIS conducted extensive dynamic testing on two DIS viscous wall dampers at UCSD. The first VWD was nominally 7'x9' (test specimen named 7x9-2) and the second was nominally 7'x12' (test specimen named 7x12-3). The following dynamic tests were performed on the two specimens, and this data set provides the basis for the VWD nominal properties.

7 x 9 Test Matrix

Test ID	Test Type	N cycles	Max. Displ. (inches)	Period, T (seconds)	Target Velocity (in/sec)	Test Velocity (in/sec)
5	wind	> 4 hours	0.20, 0.10	35.0, 3.5	0.2	0.2
7	EQ - DE	-	2.10	-	6.3	6.3
8	multi-velocity	2, 2, 2, 2	0.50	3.2, 1.6, 0.8, 0.4	1.0, 2.0, 3.9, 7.9	7.2
9	multi-velocity	2, 2, 2, 2	1.00	3.2, 1.6, 0.8, 0.4	2.0, 3.9, 7.9, 15.7	14.0
10	multi-velocity	2, 2, 2	1.75	2.7, 1.3, 0.7	4.1, 8.2, 16.4	17.0
11	EQ - MCE 1	-	3.80	-	11.3	11.3
12	EQ - MCE 2	-	3.70	-	17.4	17.4
13	MCE sinusoidal	5	3.80	5.1	4.3	4.8
14	MCE sinusoidal	5	3.80	3.2	6.9	7.6
15	MCE sinusoidal	6	3.90	1.3	17.2	19.0

7 x 12-3 Test Matrix

Test ID	Test Type	N cycles	Max. Displ. (inches)	Period, T (seconds)	Target Velocity (in/sec)	Test Velocity (in/sec)
5	wind	> 4 hours	0.27, 0.03	35.0, 3.5	0.1	0.1
6	EQ - DE	-	2.50	-	7.7	7.7
8	multi-velocity	2, 2, 2, 2	0.50	3.2, 1.6, 0.8, 0.4	1.0, 2.0, 3.9, 7.9	7.2
9	multi-velocity	2, 2, 2, 2	1.00	3.2, 1.6, 0.8, 0.4	2.0, 3.9, 7.9, 15.7	12.9
10	multi-velocity	2, 2, 2	2.05	3.2, 1.6, 0.8	4.1, 8.2, 16.4	19.0
11	EQ - MCE 1	-	4.10	-	11.5	11.5
12	EQ - MCE 2	-	3.90	-	18.6	18.6
13	MCE sinusoidal	5	4.10	5.1	5.1	5.1
14	MCE sinusoidal	5	4.10	3.2	8.1	8.1
15	MCE sinusoidal	6	4.10	1.3	20.1	20.1

A nonlinear Maxwell model, constant for each VWD size across all tests, was fitted to each of the above tests. The following pages provide a comparison of the force-displacement data from the UCSD test program, temperature-adjusted to 70°F, and the corresponding force-displacement data from an analytical model of that VWD. All analysis was conducted using a VWD component model in SAP2000 v17 with direct integration. The recorded test displacement histories were fed through the analytical model (at node 2 below) and the model force was recorded.

Appendix B: Basis for Nominal VWD Properties (at 70°F) and First Cycle Factor, λ_{test}

The parameters of the nominal Maxwell model (K, C and α) for each of the VWD types are as follows:

Damper Size	K (k/in)	C [k-(sec/in)$^{\alpha}$]	α (dimensionless)
7 x 9	410	108	0.5
7 x 12	450	150	0.5

In the following plots, the tests are grouped together as follows so that there are 4 pages of plots for each VWD size:

- Wind test (1 total, Test 5)
- Multi-velocity sinusoidal tests at 3 increasing displacements (3 total, Tests 8, 9 and 10)
- MCE sinusoidal tests at 3 increasing frequencies (3 total, Tests 13, 14 and 15)
- Earthquake tests (3 total, one at DE and 2 at MCE, Tests 6/7, 11 and 12)

These plots demonstrate that a nonlinear Maxwell model can reproduce the recorded hysteresis behavior of the VWDs over a wide range of dynamic test conditions.

VWD Properties including First Cycle Effects

However, the nominal model does not capture the "first cycle" effect that is apparent in the earthquake tests 6/7, 11 and 12, and in the MCE sinusoidal tests 13, 14 and 15. A first cycle factor, λ_{test}, of 1.55 is applied to the nominal K and C values to give a second set of VWD properties.

Damper Size	K (k/in)	C [k-(sec/in)$^{\alpha}$]	α (dimensionless)
7 x 9	636	167	0.5
7 x 12	698	233	0.5

These properties, shown in the table above, were run through the SAP2000 VWD component model for the three earthquake cases. Plots present the resulting model hysteresis loops compared with tested loops for the three earthquake cases with λ_{test} equal to 1.55. The maximum forces from the tests and the models are compared in the table below. This table demonstrates that the forces generated by the VWD model including a λ_{test} factor of 1.55 equal or exceed the recorded first cycle forces from the earthquake tests at both DE and MCE levels. Therefore, the use of a first cycle factor, λ_{test}, equal to 1.55 is justified regardless of VWD damper size or earthquake level.

Test	EQ Level	Test F_{max} (k)	Model F_{max} (k)	Ratio Model/Test
7 x 9-2 Test 7	DE	348	348	1.00
7 x 9-2 Test 11	MCE	516	505	0.98
7 x 9-2 Test 12	MCE	537	665	1.24
7 x 12-3 Test 6	DE	508	510	1.00
7 x 12-3 Test 11	MCE	656	679	1.04
7 x 12-3 Test 12	MCE	747	890	1.19

Finally, it should be noted that no first-cycle correction is required for wind-level VWD properties.

Test and SAP2000 Hysteresis Loops for 7' x 9' Viscous Wall Damper

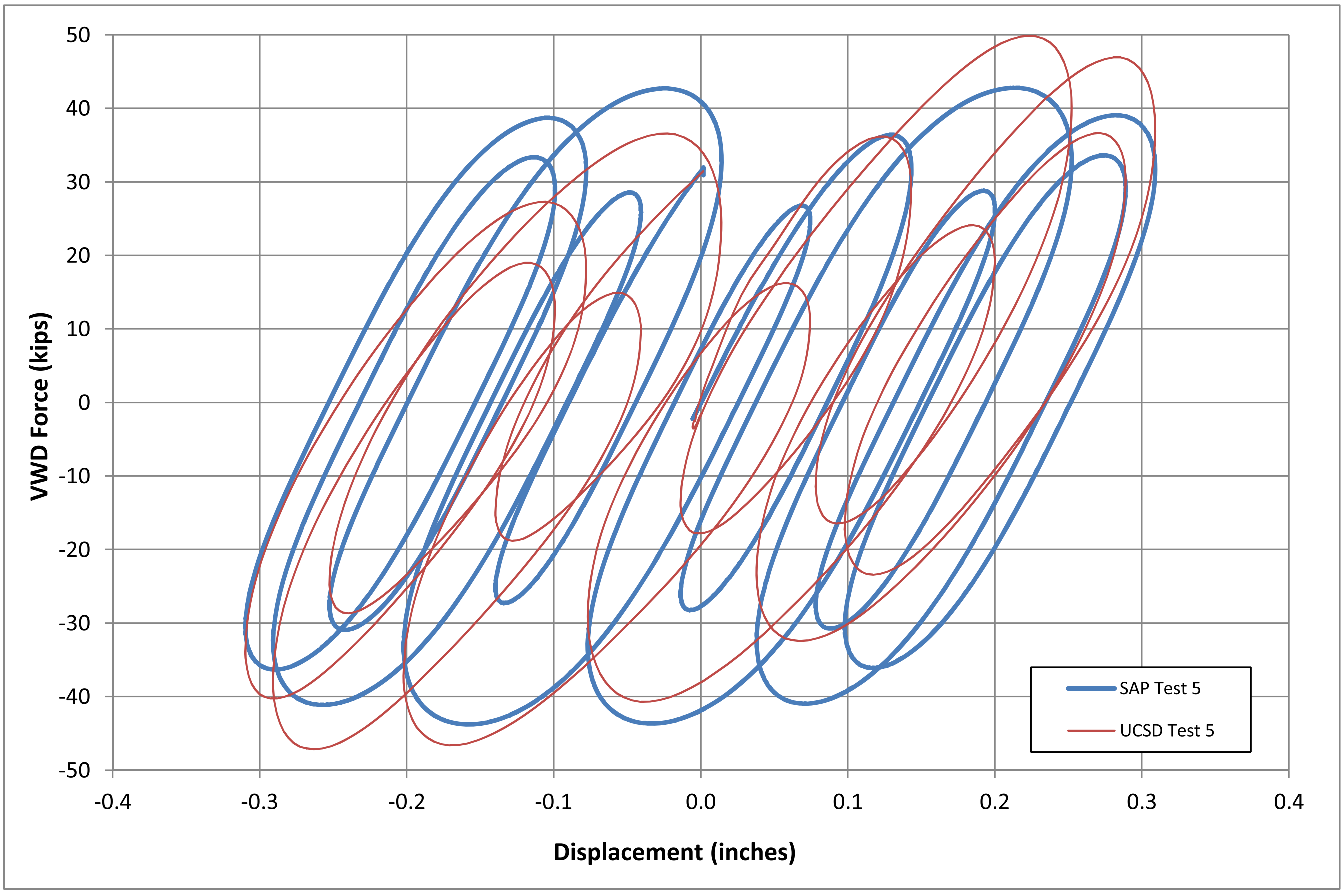
<u>**Simulated VWD Loops compared to UCSD Test Data**</u>

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x9	17.1.1	direct integration
Wind Test - First 35 second cycle ONLY		**Nominal VWD Properties**	

Test 5

Maximum Velocity	0.2 in/sec	
Hysteresis Area	**70** k-in	*UCSD Test*
	65 k-in	*SAP2000*



Test and SAP2000 Hysteresis Loops for 7' x 9' Viscous Wall Damper

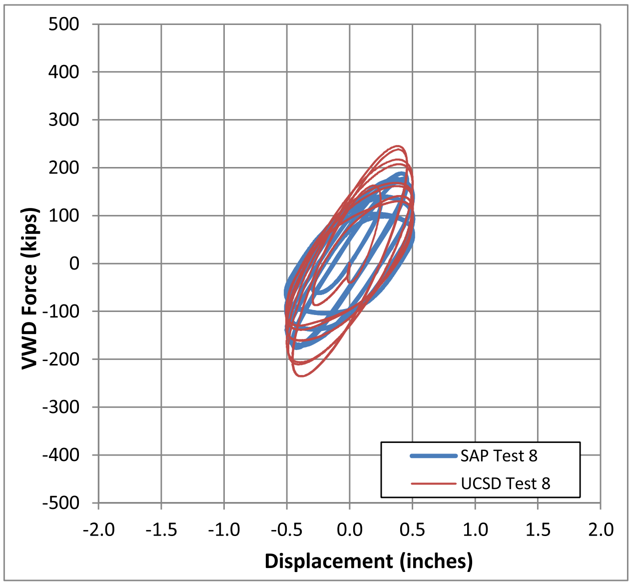
Simulated VWD Loops compared to UCSD Test Data

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x9	17.1.1	direct integration
Multi-Velocity Sinusoidal Test		**Nominal VWD Properties**	

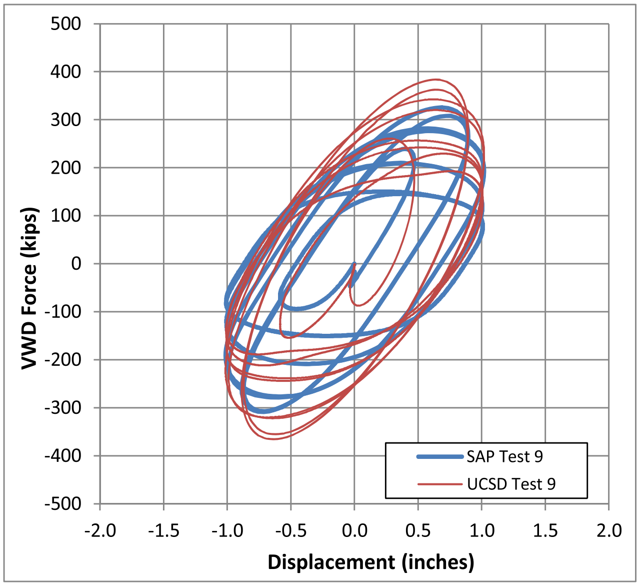
Test 8

Maximum Velocity	7.2 in/sec	
Hysteresis Area	**1,500** k-in	*UCSD Test*
	1,066 k-in	*SAP2000*



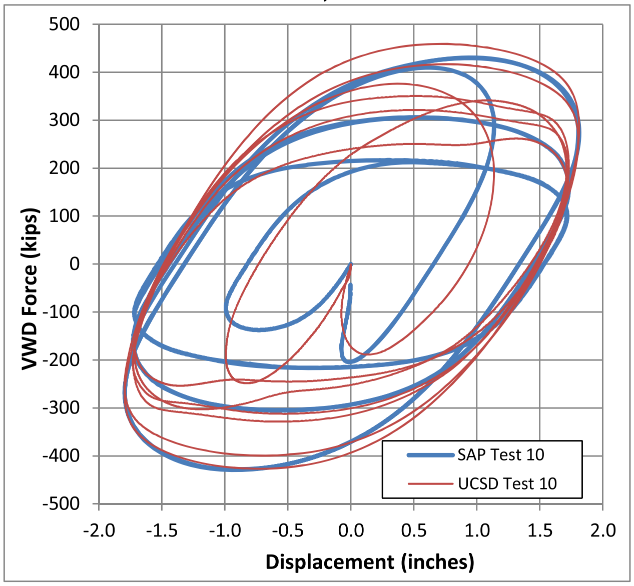
Test 9

Maximum Velocity	14.0 in/sec	
Hysteresis Area	**5,584** k-in	*UCSD Test*
	4,257 k-in	*SAP2000*



Test 10

Maximum Velocity	17.0 in/sec	
Hysteresis Area	**11,150** k-in	*UCSD Test*
	9,964 k-in	*SAP2000*



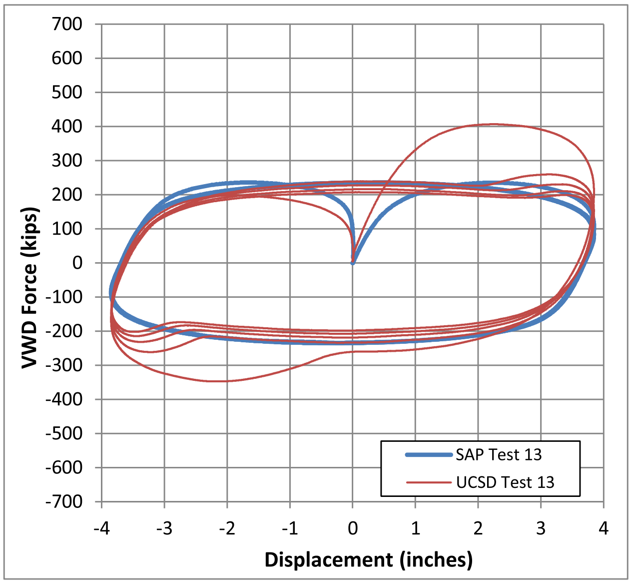
Simulated VWD Loops compared to UCSD Test Data

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x9	17.1.1	direct integration
MCE Sinusoidal Tests		**Nominal VWD Properties**	

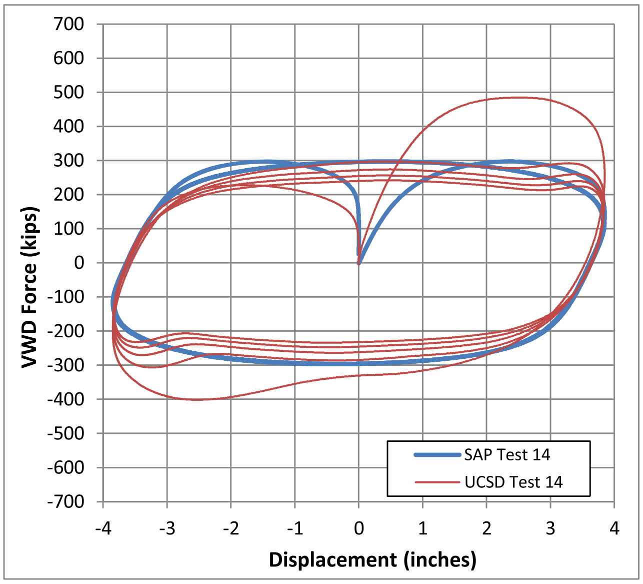
Test 13

Maximum Velocity	4.8 in/sec	
Hysteresis Area	**15,361** k-in	*UCSD Test*
	15,164 k-in	*SAP2000*



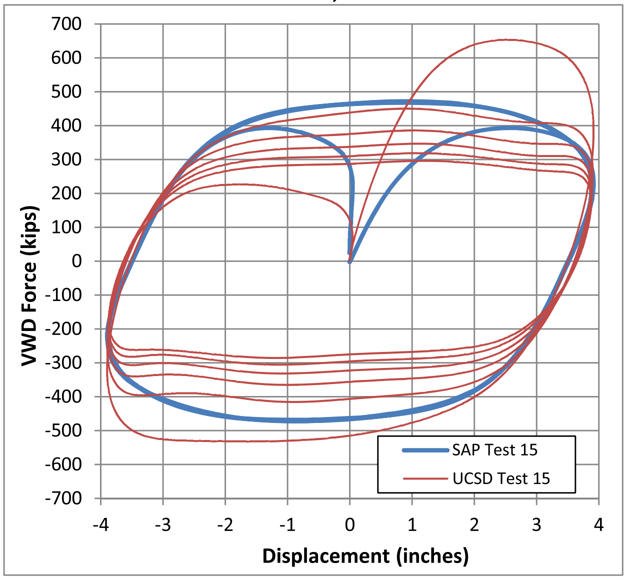
Test 14

Maximum Velocity	7.6 in/sec	
Hysteresis Area	**18,140** k-in	*UCSD Test*
	18,820 k-in	*SAP2000*



Test 15

Maximum Velocity	19.0 in/sec	
Hysteresis Area	**28,530** k-in	*UCSD Test*
	33,967 k-in	*SAP2000*



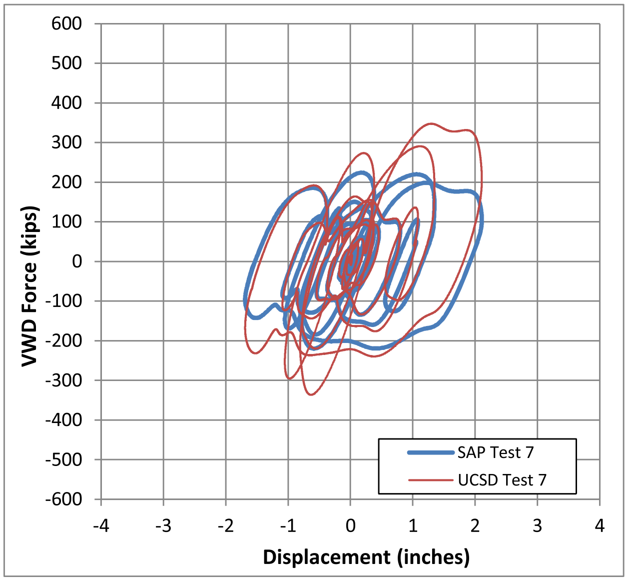
Simulated VWD Loops compared to UCSD Test Data

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x9	17.1.1	direct integration
Earthquake Tests		**Nominal VWD Properties**	

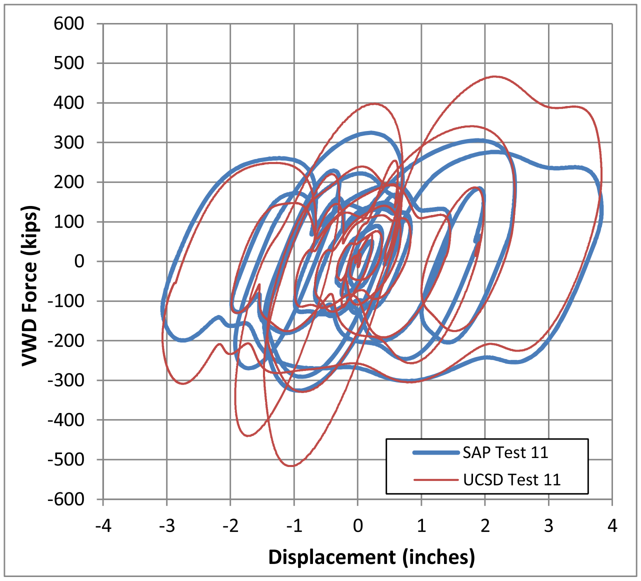
Test 7 DE

Maximum Velocity	6.3 in/sec	
Hysteresis Area	**3,232** k-in	*UCSD Test*
	2,660 k-in	*SAP2000*



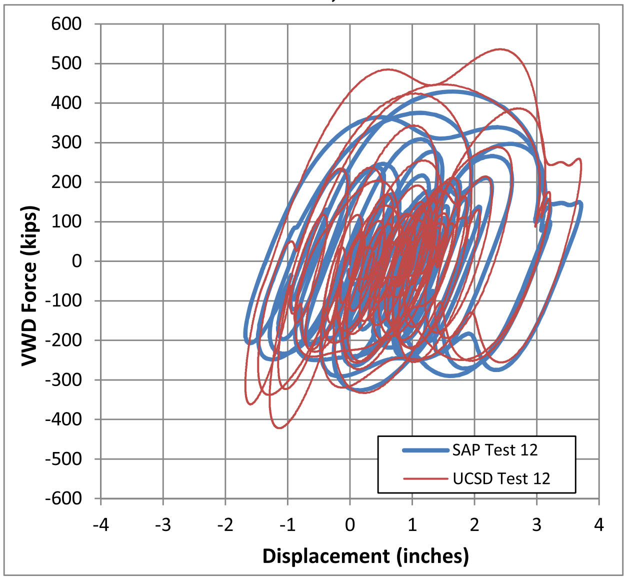
Test 11 MCE

Maximum Velocity	11.3 in/sec	
Hysteresis Area	**8,649** k-in	*UCSD Test*
	7,579 k-in	*SAP2000*



Test 12 MCE

Maximum Velocity	17.4 in/sec	
Hysteresis Area	**13,900** k-in	*UCSD Test*
	11,293 k-in	*SAP2000*



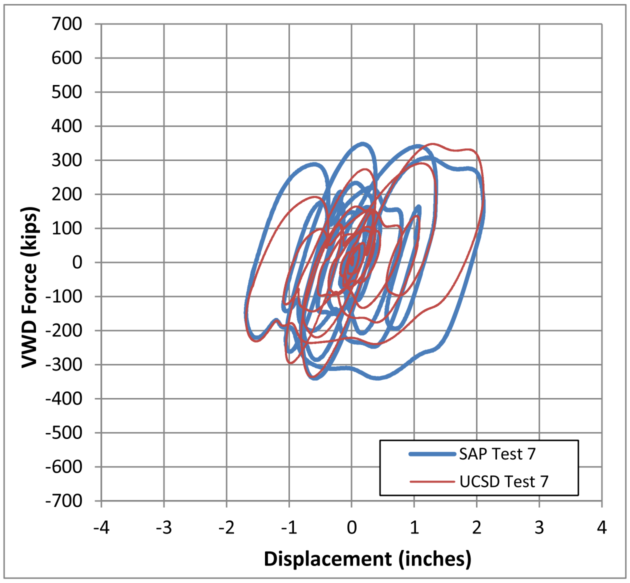
Simulated VWD Loops compared to UCSD Test Data

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x9	17.1.1	direct integration
Earthquake Tests		**VWD Properties with λ_{test} =1.55**	

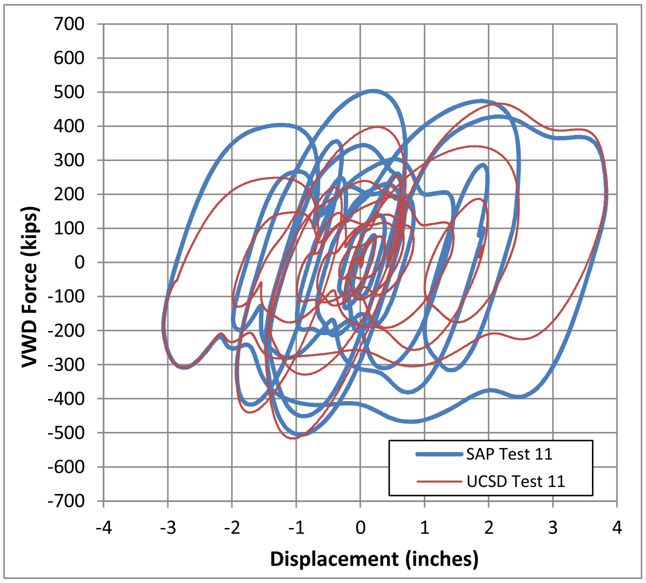
Test 7 DE

Maximum Velocity	6.3 in/sec	
Hysteresis Area	**3,232** k-in	*UCSD Test*
	4,122 k-in	*SAP2000*



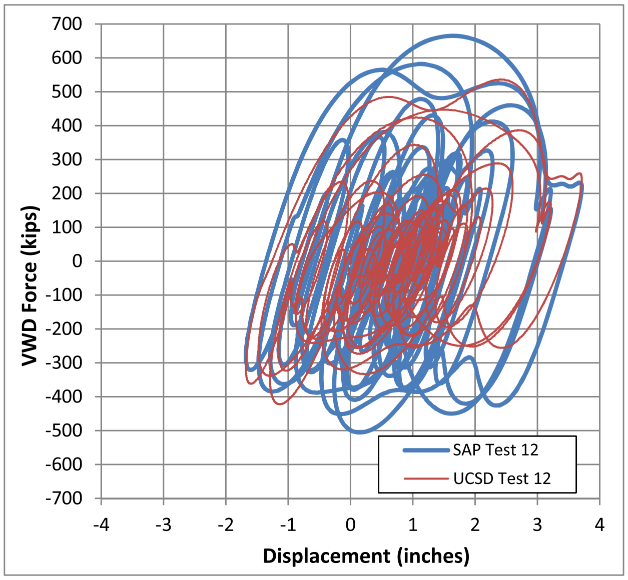
Test 11 MCE

Maximum Velocity	11.3 in/sec	
Hysteresis Area	**8,649** k-in	*UCSD Test*
	11,748 k-in	*SAP2000*



Test 12 MCE

Maximum Velocity	17.4 in/sec	
Hysteresis Area	**13,900** k-in	*UCSD Test*
	17,504 k-in	*SAP2000*



Test and SAP2000 Hysteresis Loops for 7' x 12' Viscous Wall Damper

Simulated VWD Loops compared to UCSD Test Data

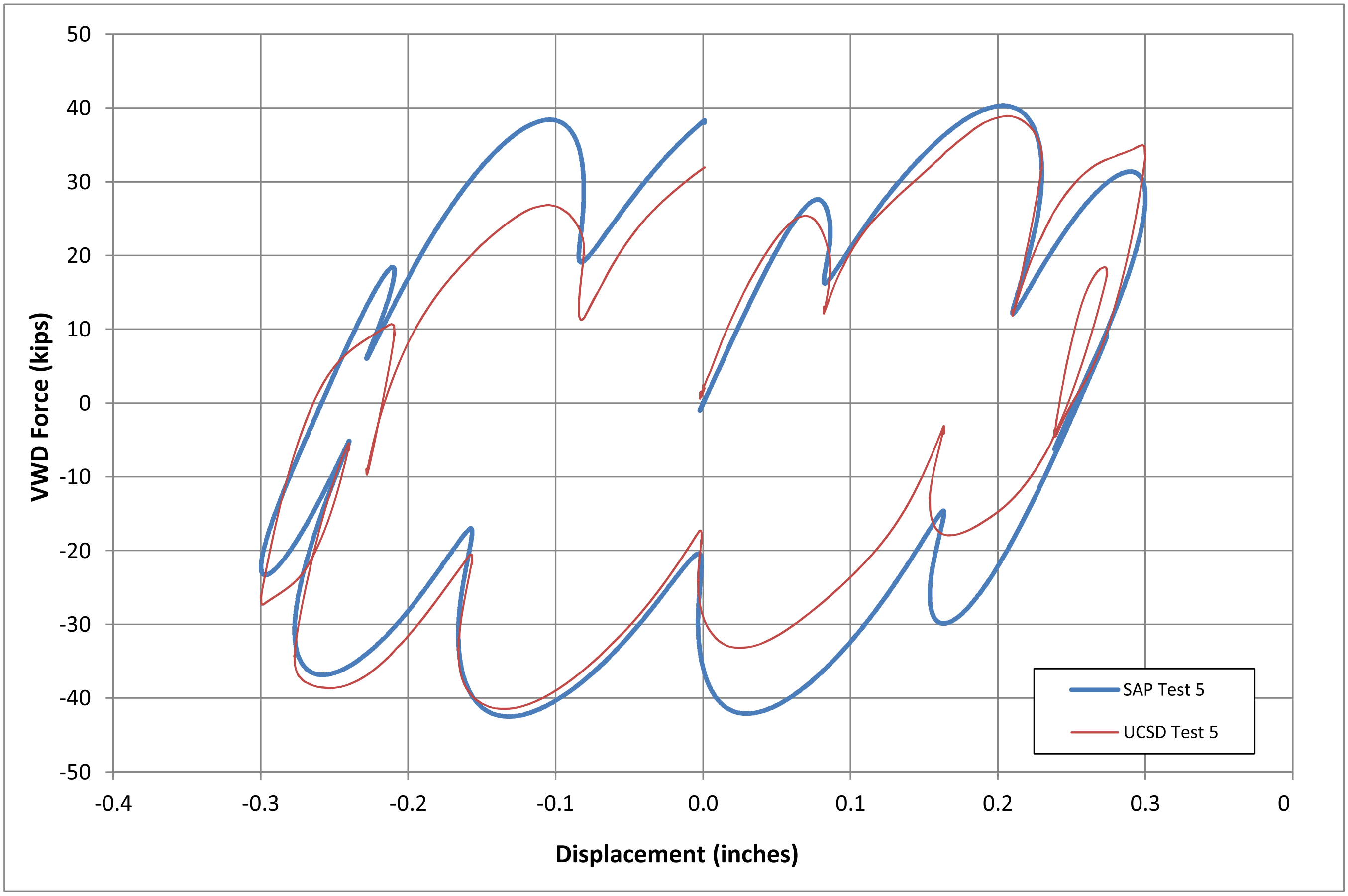
Test Forces Corrected to 70° F

SAP2000 Model VWD-rev1-7x12 17.1.1 direct integration

Wind Test - First 35 second cycle ONLY **Nominal VWD Properties**

Test 5

Maximum Velocity	0.1 in/sec	
Hysteresis Area	**27** k-in	*UCSD Test*
	31 k-in	*SAP2000*



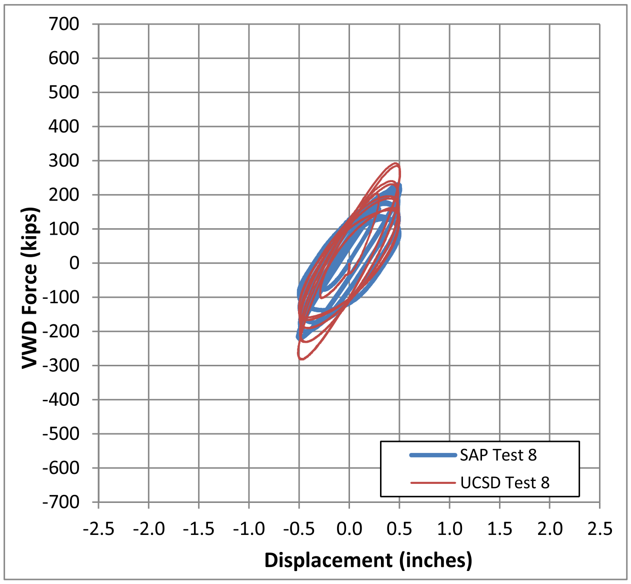
Simulated VWD Loops compared to UCSD Test Data

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x12	17.1.1	direct integration
Multi-Velocity Sinusoidal Tests		**Nominal VWD Properties**	

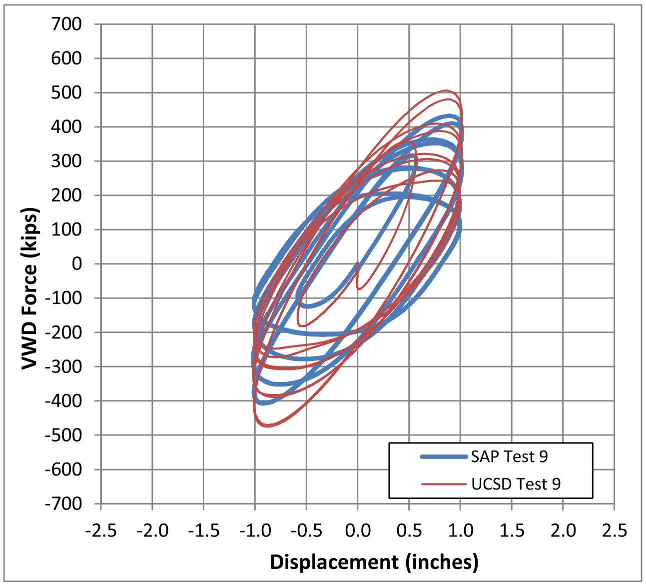
Test 8

Maximum Velocity	7.2 in/sec	
Hysteresis Area	**1,426** k-in	*UCSD Test*
	1,067 k-in	*SAP2000*



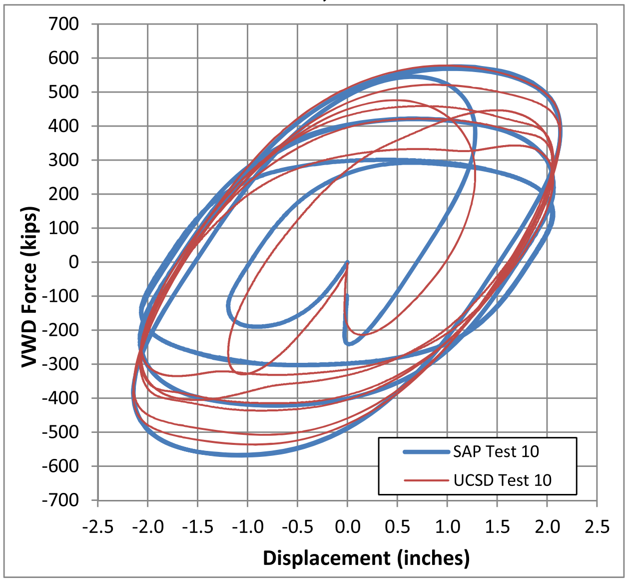
Test 9

Maximum Velocity	12.9 in/sec	
Hysteresis Area	**5,875** k-in	*UCSD Test*
	4,967 k-in	*SAP2000*



Test 10

Maximum Velocity	19.0 in/sec	
Hysteresis Area	**16,200** k-in	*UCSD Test*
	15,835 k-in	*SAP2000*



Test and SAP2000 Hysteresis Loops for 7’ x 12’ Viscous Wall Damper

Simulated VWD Loops compared to UCSD Test Data

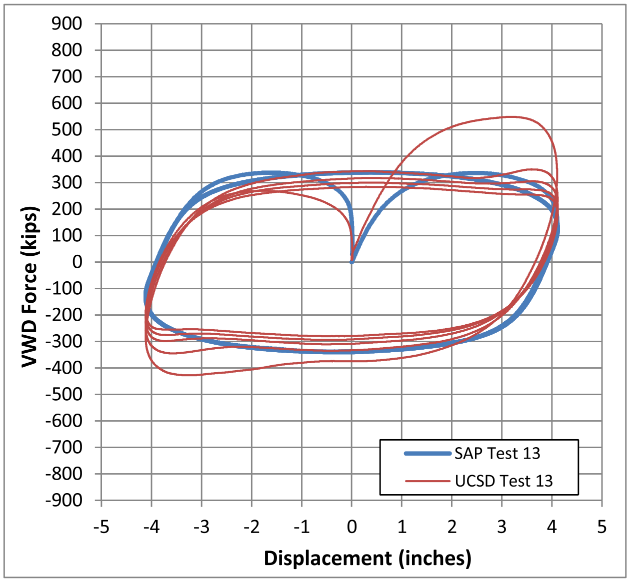
Test Forces Corrected to 70° F

SAP2000 Model　　VWD-rev1-7x12　　17.1.1　　direct integration

MCE Sinusoidal Tests	**Nominal VWD Properties**

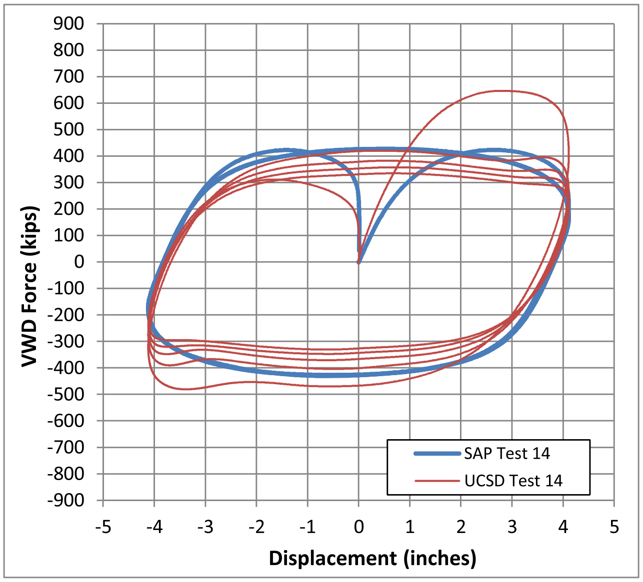
Test 13

Maximum Velocity	5.1 in/sec	
Hysteresis Area	**22,061** k-in	*UCSD Test*
	23,019 k-in	*SAP2000*



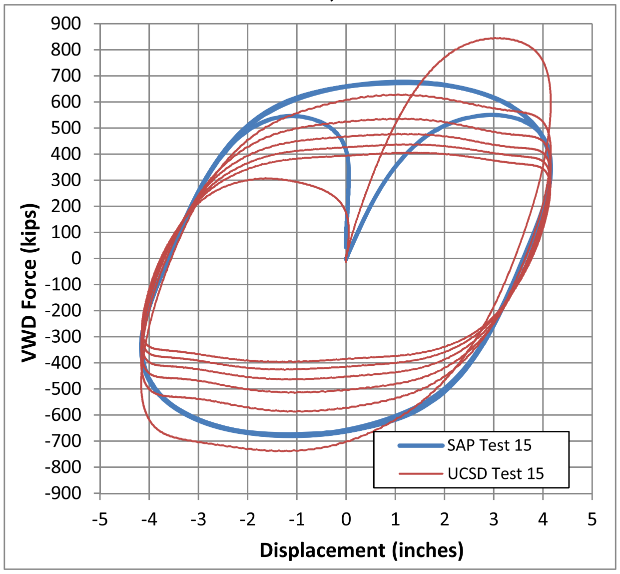
Test 14

Maximum Velocity	8.1 in/sec	
Hysteresis Area	**25,825** k-in	*UCSD Test*
	28,375 k-in	*SAP2000*



Test 15

Maximum Velocity	20.1 in/sec	
Hysteresis Area	**39,664** k-in	*UCSD Test*
	49,728 k-in	*SAP2000*



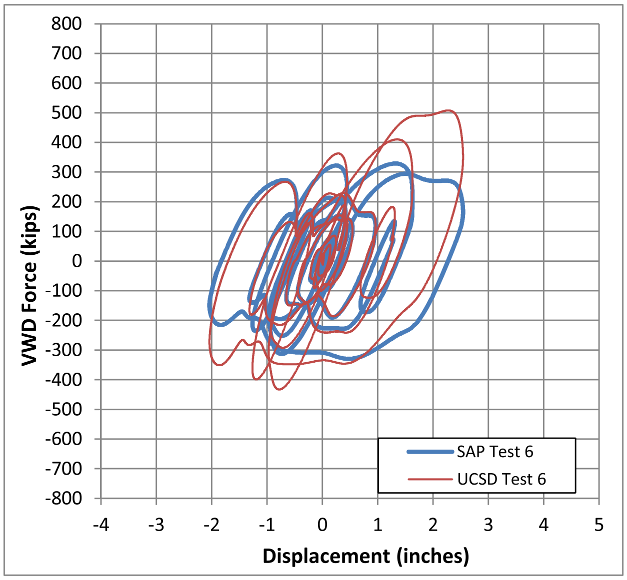
Simulated VWD Loops compared to UCSD Test Data

Test Forces Corrected to 70° F

SAP2000 Model	VWD-rev1-7x12	17.1.1	direct integration
Earthquake Tests		**Nominal VWD Properties**	

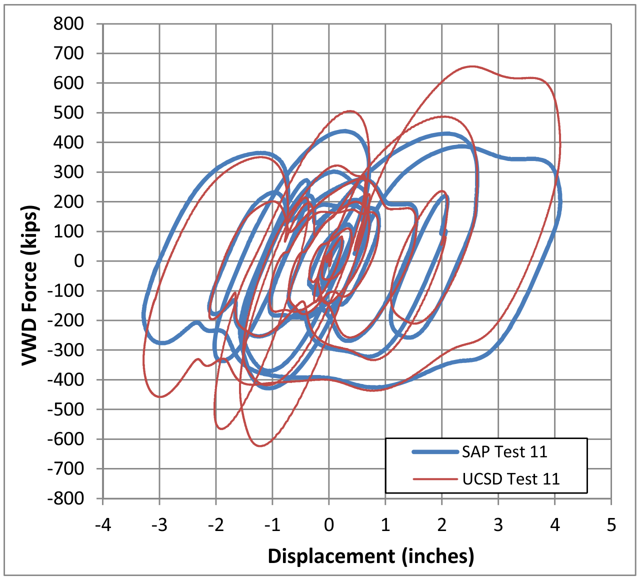
Test 6 DE

Maximum Velocity	7.7 in/sec	
Hysteresis Area	**5,242** k-in	*UCSD Test*
	4,499 k-in	*SAP2000*



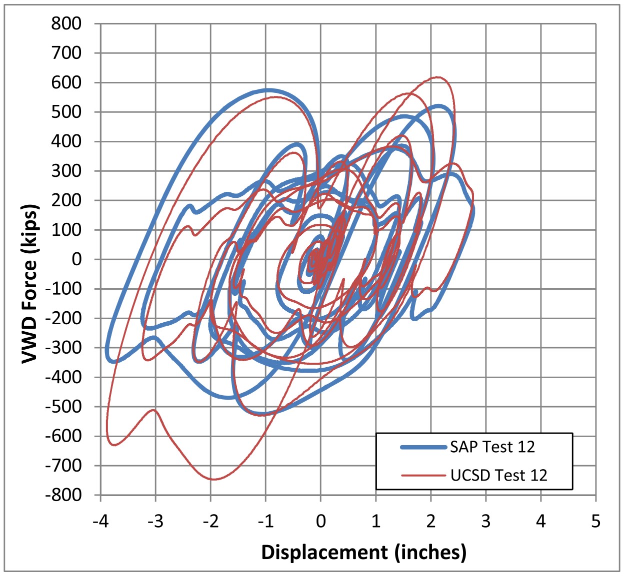
Test 11 MCE

Maximum Velocity	11.5 in/sec	
Hysteresis Area	**11,693** k-in	*UCSD Test*
	10,436 k-in	*SAP2000*



Test 12 MCE

Maximum Velocity	18.6 in/sec	
Hysteresis Area	**14,230** k-in	*UCSD Test*
	3,803 k-in	*SAP2000*



Test and SAP2000 Hysteresis Loops for 7' x 12' Viscous Wall Damper

Simulated VWD Loops compared to UCSD Test Data

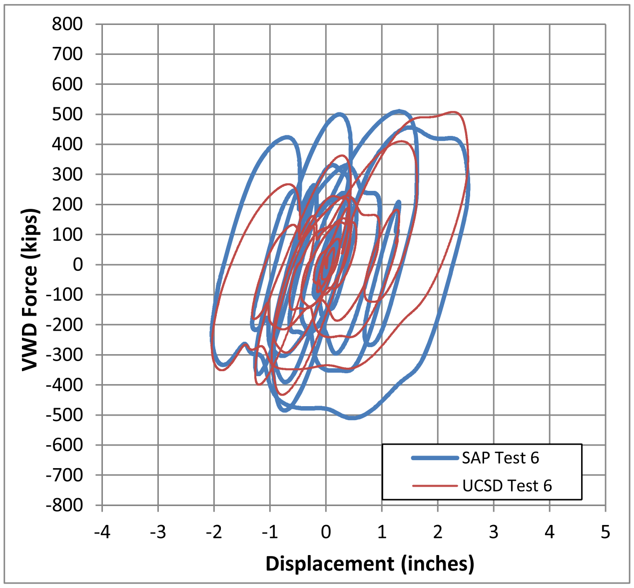
Test Forces Corrected to 70° F

SAP2000 Model VWD-rev1-7x12 17.1.1 direct integration

Earthquake Tests	**VWD Properties with λ_{test} =1.55**

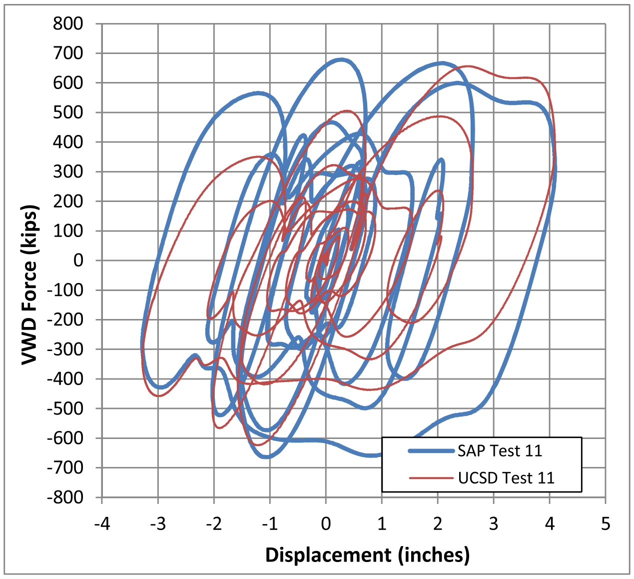
Test 6 DE

Maximum Velocity	7.7 in/sec	
Hysteresis Area	**5,242** k-in	*UCSD Test*
	6,973 k-in	*SAP2000*



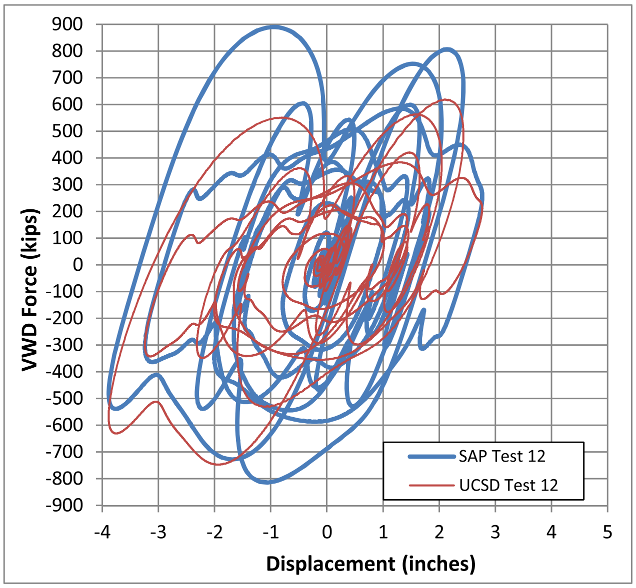
Test 11 MCE

Maximum Velocity	11.5 in/sec	
Hysteresis Area	**11,693** k-in	*UCSD Test*
	16,176 k-in	*SAP2000*



Test 12 MCE

Maximum Velocity	18.6 in/sec	
Hysteresis Area	**14,230** k-in	*UCSD Test*
	21,395 k-in	*SAP2000*



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