Appendix A. Verification of *Perform*

A.1 Introduction

This study is using *Ram Perform 2D* because it has the combined capabilities of nonlinear inelastic time history analysis and use of nonlinear damper elements. Before the study was started it was important to check that *Perform* was accurate. Several different models were used to verify the accuracy of *Perform*. All of these models were run in *Perform*, and compared to models run in *SAP2000* (Computer and Structures, Inc. 1998) or *Drain-2DX* (Prakash et al., 1993). *Perform* can run several types of analyses, and for this study the following needed to be verified: linear inelastic time history analysis without added viscous damping, linear time history analysis with added linear and nonlinear viscous damping, nonlinear pushover analysis, and nonlinear time history analysis. *SAP2000* was selected to perform the linear time history analyses with the different types of added damping, while *Drain-2DX* was used to perform the nonlinear analyses. In comparing these programs, it is assumed that if both programs yield similar results then both programs are valid, and if the results are different beyond some tolerance then one of the programs is not valid.

A.2 Linear Time History without Added Damping

A simple frame, consisting of two columns and one girder, was used to validate a linear time history analysis without added damping. The properties of the girders and columns of the frame are presented in Table A.1. This frame was subjected to a “pulse” acceleration time history that is shown in Figure A.1. This history is 10 seconds long with a two-second impulse that has a period of a second and amplitude of 1 g. In addition, for the analysis a value of 5% of critical damping was selected for the frame’s inherent natural damping.

Table A.1: Section Properties for SDOF Frame

Member	A (in^2)	I (in^4)
Girder	27.7	3270
Column	59.2	5310

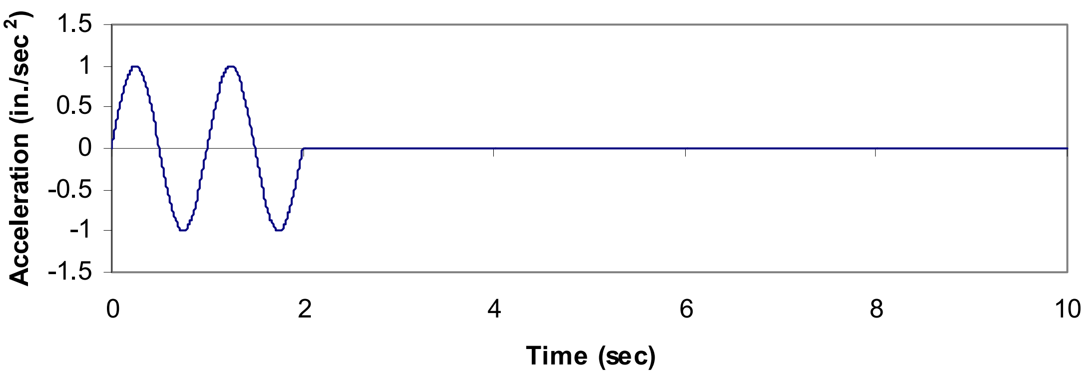

Figure A.1: Pulse Time History

The results for the linear elastic time history run in *SAP2000* and *Perform* are shown in Figure A.2, which is a plot of time versus the displacement of the top of the frame. The figure shows that the outputs from the two programs are identical. In order to get similar results, a step-size of 0.005 sec had to be used in the analysis. The original step-size was equal to 0.01 sec and therefore needed to be cut in half. From these results it can be concluded that the linear time-history analysis of *Perform* is accurate. Also, it must be noted that users of *Perform* need to be careful when selecting a step-size.

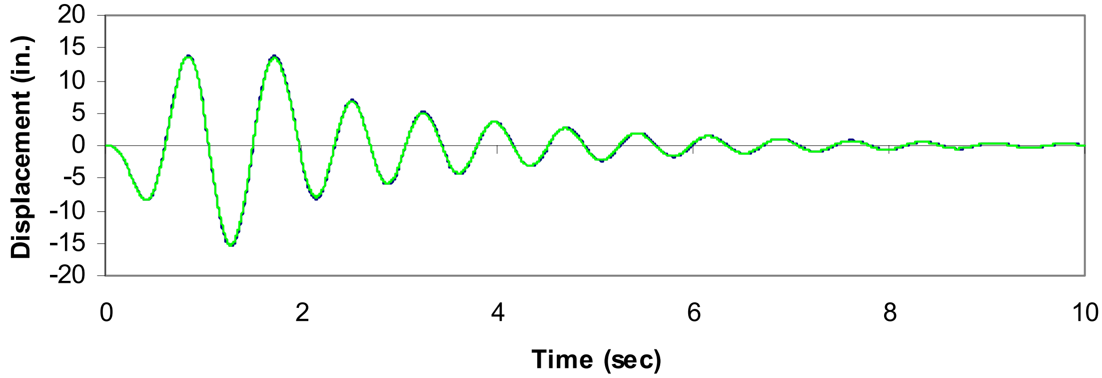

Figure A.2: Results of a Linear Elastic Time History Analysis

A.3 Linear Time History with Added Damping

The SDOF frame, as shown in Figure A.3, was used to validate linear time history analyses with added linear and nonlinear viscous damping. The structure is similar to the previous one used for the linear time history check without added damping, except it has chevron braces with a viscous damper and the properties of all the members are changed. These new properties are shown in Table A.2.

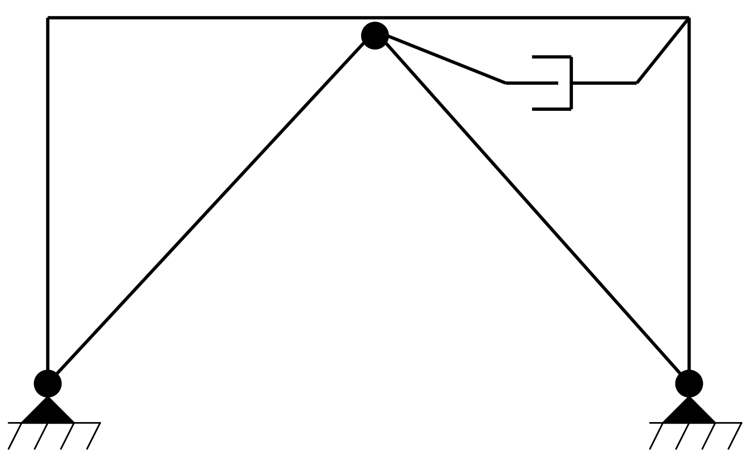

Figure A.3: Linear SDOF Frame w/ Fluid Viscous Damper

Table A.2: Properties for SDOF Frame w/ Fluid Viscous Damper

Member	A (in^2)	I (in^4)
Girder	1000	20000
Column	1000	4320
Brace	10	10

Several analyses were run in order to confirm that *Perform* is accurate regardless of the parameters used to define the dampers. Seven linear time histories were run in both *Perform* and *SAP2000* with dampers that had a damping coefficient $C_0 = 10$ k-sec/in. and a damping exponent $\alpha = 0.5, 0.7, 0.9, 1.0, 1.1, 1.3$, and 1.5. The damping coefficient and exponent are the parameters for the force-velocity relationship of a viscous damper as represented in

$$P(t) = C_0 \left| \frac{du}{dt} \right|^{\alpha} \operatorname{sgn}\left[\frac{du}{dt} \right] \qquad \text{A.1}$$

where α is a real positive exponent that ranges from 0.1 to 2, and sgn is the signum function.

These analyses used the same acceleration history as before and a value of 0% critical damping was selected for the frame. The results are shown in the displacement time history plots in Figure A.4-Figure A.10. These plots demonstrate that the two different programs give similar results for the seven different α values. However, these values did not match until the spring stiffness of the damper and the time step of the analysis were adjusted. In *SAP2000* a viscous damper is modeled using a dashpot in series with a spring. Analysis requires a damping coefficient C_0 and a spring stiffness k. It may seem reasonable to enter in a very large number for the spring stiffness, but this will lead to convergence problems. Therefore, the stiffness selected needs to be large enough that it does not influence the results, but small enough so the analysis is able to converge.

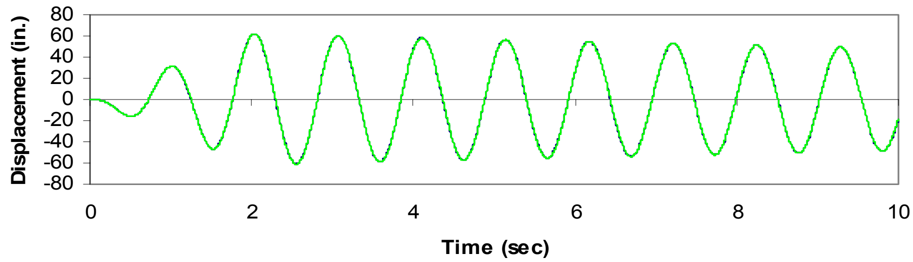

Figure A.4: Displacement Time History for SDOF Frame w/ Damper α=0.5

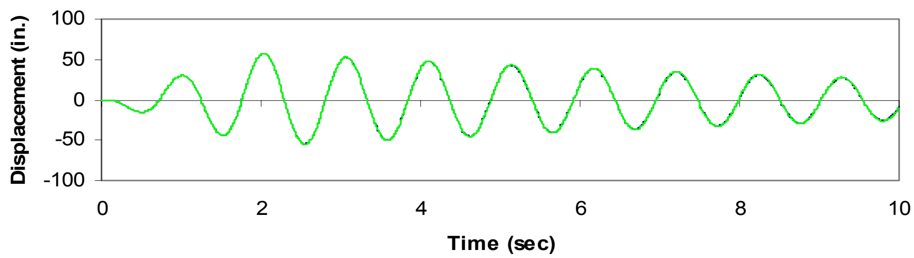

Figure A.5: Displacement Time History for SDOF Frame w/ Damper α=0.7

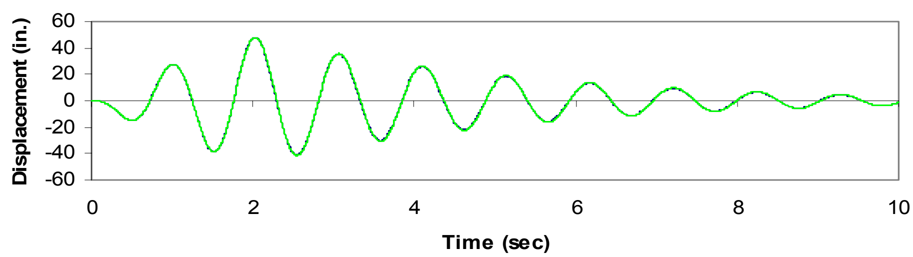

Figure A.6: Displacement Time History for SDOF Frame w/ Damper α=0.9

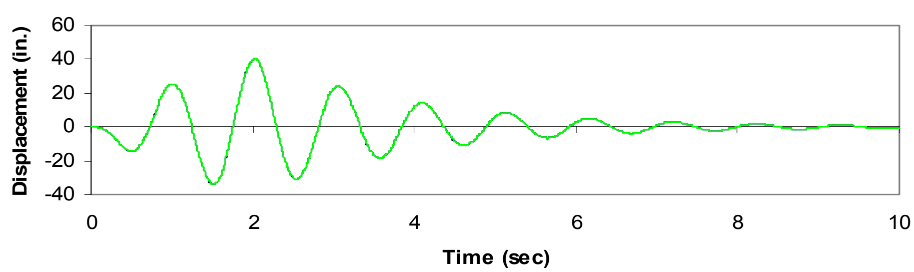

Figure A.7: Displacement Time History for SDOF Frame w/ Damper α=1.0

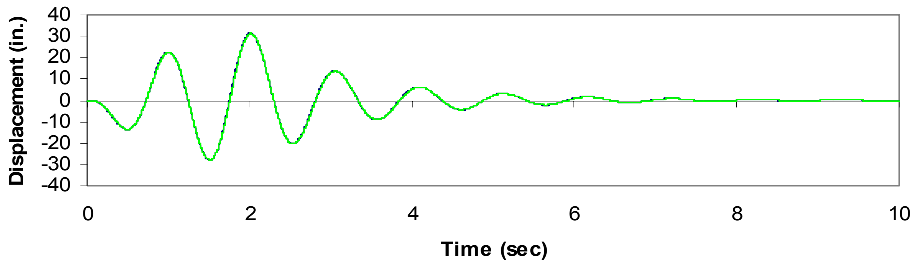

Figure A.8: Displacement Time History for SDOF Frame w/ Damper α=1.1

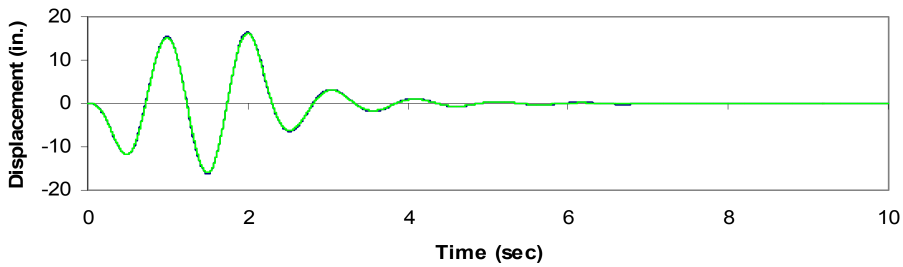

Figure A.9: Displacement Time History for SDOF Frame w/ Damper α=1.3

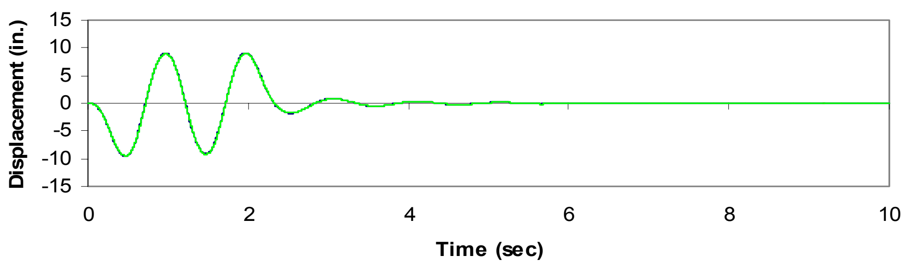

Figure A.10: Displacement Time History for SDOF Frame w/ Damper a=1.5

For this part of the verification, a sensitivity analysis was run by performing several time histories with a value of C_0=10 k-sec/in., values of k that ranged from 10,000 to 1,000,000 k/in., and values of α that ranged from 0.5 to 1.5. The results of the sensitivity analysis are presented in Table A.3. The runs where the analysis fails to converge are denoted by NR.

Table A.3: Results for Spring Stiffness Sensitivity Analysis

Damping Exponent	Results	Spring Stiffness, k (kips/in.) 1000	10000	100000	1000000	10000000
α=0.5	Max. Disp (in.)	61.78	61.77	61.77	NR	NR
	Iterations	6347	7423	29623	large	large
α=0.7	Max. Disp (in.)	57.72	57.70	57.69	NR	NR
	Iterations	9989	13123	14564	large	large
α=0.9	Max. Disp (in.)	48.04	47.95	47.94	47.94	NR
	Iterations	13895	50695	46678	51233	large
α=1.0	Max. Disp (in.)	40.43	40.21	40.19	40.19	NR
	Iterations	15661	46059	72538	78532	large
α=1.1	Max. Disp (in.)	31.80	31.34	31.31	31.31	NR
	Iterations	19110	58560	162405	116884	large
α=1.3	Max. Disp (in.)	17.78	16.51	16.44	16.44	16.43
	Iterations	22344	61565	163375	205580	209602
α=1.5	Max. Disp (in.)	11.41	9.36	9.24	9.23	9.23
	Iterations	23465	63247	147164	277967	347339

From the results of the analysis shown in Table A.3, it can be observed that the stiffness required for the spring is related to the value of α. The *SAP2000* manual suggests that Equation A.2 be used to select the value of k

$$\mathrm{k} = \frac{10^m c}{\Delta \mathrm{t}_{\mathrm{LOAD}}} \qquad \text{A.2}$$

where *m* is an integer from 2 to 4, and Δt_{Load} is the time step of the loading history. This equation does not account for α, therefore it is important that the equation is used carefully in analysis.

The *SAP2000* data, presented earlier in Figure A.4-Figure A.10, were produced using this sensitivity analysis. For each value of α an appropriate value of k was selected so that the results are not dependent on this value.

Some other parameters of the analysis in *SAP2000* were also investigated. These parameters are relative force tolerance, relative energy tolerance, maximum iteration limit, and minimum sub-step size. These are all parameters that are used for the time history analysis of the nonlinear damper. Each time step of the analysis needs to be broken down into sub-steps in order to solve for the force in the damper. The relative force and energy tolerance determine the amount of error allowed in an equilibrium check at the end of each time step. The maximum iteration limit is a limit on the number of iterations that can be made for each step. The minimum sub-step size is a limit on the allowable step-size. The results of the investigation, as shown in Table A.4 and Table A.5, show that the analysis is not sensitive to any of these parameters for the ranges in which they are used.

Table A.4: Results from Max. Iteration Limit and Min. Sub-step Size Sensitivity Analysis

Damping Exponent	Results	Max. Iteration Limit		Min. Sub-step Size (sec)	
		100	1000	1.00E-05	1.00E-06
α=0.5	Max. Disp (in.)	61.77	61.77	61.77	61.77
k=10000 (k/in)	Iterations	7423	10841	7640	7423
α=0.7	Max. Disp (in.)	57.70	57.70	57.70	57.70
k=10000 (k/in)	Iterations	13123	18942	13519	13123
α=0.9	Max. Disp (in.)	47.94	47.94	47.94	47.94
k=100000 (k/in)	Iterations	46678	89530	48145	46678
α=1.0	Max. Disp (in.)	40.19	40.19	40.19	40.19
k=100000 (k/in)	Iterations	72538	226445	80902	72538
α=1.1	Max. Disp (in.)	31.31	31.31	31.31	31.31
k=100000 (k/in)	Iterations	162405	697389	192979	162405
α=1.3	Max. Disp (in.)	16.44	16.44	16.44	16.44
k=1000000 (k/in)	Iterations	205580	1003684	251066	205580
α=1.5	Max. Disp (in.)	9.23	9.23	9.23	9.23
k=1000000 (k/in)	Iterations	277967	1543832	369765	277967

Table A.5: Results from Relative Force and Energy Tolerances Sensitivity Analysis

Damping Exponent	Results	Relative Force and Energy Tolerances		
		1.00E-04	1.00E-05	1.00E-06
α=0.5	Max. Disp (in.)	61.77	61.77	61.77
k=10000	Iterations	4097	7423	18386
α=1.1	Max. Disp (in.)	31.31	31.31	31.31
k=100000	Iterations	97440	162405	260240
α=1.5	Max. Disp (in.)	9.23	9.23	9.23
k=1000000	Iterations	217273	277967	363012

Once the appropriate parameter values were selected in *SAP2000*, a sensitivity analysis was run in *Perform* in order to choose the correct time step size for each value of α. The damper is modeled in this program as it is modeled in *SAP2000,* with a spring in series with a dashpot. However, a different approach is used for obtaining the damper's force-velocity relationship for the different values of α. *SAP2000* uses an exact continuous relationship, but *Perform* requires the user to enter a piecewise linear relationship. As a result, this may be the cause of any small differences between the two sets of solutions.

The sensitivity analysis was run with the same acceleration data as before and with a value of k=100,000 k/in. The results are presented in Table A.6. It can be concluded from these results that for greater values of α, a smaller step size is required for convergence. An exception occurs when α=1.5; for this damper type the step size must equal 0.005 sec in order for the solution to converge to the *SAP2000* solution. A possible cause for this could be that *Perform* is also sensitive to the value selected for k.

Table A.6: Perform Time Step Sensitivity Analysis

Damping Exponent	Results	Step Size, ΔT (sec) 0.010	0.005	0.0025	0.001	SAP2000 Results
α=0.5	Max. Disp (in.)	61.77	61.81	61.81	61.81	61.77
α=0.7	Max. Disp (in.)	57.76	57.76	57.76	57.76	57.69
α=0.9	Max. Disp (in.)	48.76	48.10	48.02	47.99	47.94
α=1.0	Max. Disp (in.)	40.43	40.43	40.44	40.44	40.19
α=1.1	Max. Disp (in.)	33.45	32.86	31.32	31.23	31.31
α=1.3	Max. Disp (in.)	16.75	16.59	16.24	16.17	16.44
α=1.5	Max. Disp (in.)	10.02	9.05	8.84	8.59	9.24

To investigate *Perform's* sensitivity to spring stiffness, the analyses were run again for k=10,000 kip/in. and for 1,000,000 kip/in. The results of these analyses are displayed in Table A.7 and Table A.8. From the tables it can be observed that models with α<1 are not affected by the change in stiffness, while models with α ≥ 1 do not give good results when k=10,000 kip/in. The models will not even converge when k=10,000 kip/in. and α=1.3 and 1.5. Therefore, from these analyses it is concluded that a large value of k should be selected when analyzing structures that include dampers with values of α>1.

Table A.7: Perform Time Step Sensitivity Analysis, k=10000 (k/in.)

Damping Exponent	Results	Step Size, ΔT (sec) k=10000 (k/in.) 0.010	0.005	0.0025	0.001	SAP2000 Results
α=0.5	Max. Disp (in.)	61.78	61.81	61.48	61.81	61.77
α=0.7	Max. Disp (in.)	57.91	57.98	58.00	58.01	57.7
α=0.9	Max. Disp (in.)	48.22	48.03	48.00	48.00	47.95
α=1.0	Max. Disp (in.)	46.61	46.62	46.63	46.63	40.21
α=1.1	Max. Disp (in.)	31.51	31.23	31.04	31.29	31.34
α=1.3	Max. Disp (in.)	15.06	F.T.C.	F.T.C.	15.10	16.51
α=1.5	Max. Disp (in.)	F.T.C.	F.T.C.	F.T.C.	F.T.C.	9.357

Table A.8: Perform Time Step Sensitivity Analysis, k=1000000 (k/in.)

Damping Exponent	Results	Step Size, ΔT (sec) k=1000000 (k/in.) 0.010	0.005	0.0025	0.001	SAP2000 Results
α=0.5	Max. Disp (in.)	61.77	61.81	61.81	61.81	NR
α=0.7	Max. Disp (in.)	58.01	57.75	57.75	57.74	NR
α=0.9	Max. Disp (in.)	48.62	48.20	48.03	47.98	47.94
α=1.0	Max. Disp (in.)	40.18	40.19	40.20	40.20	40.19
α=1.1	Max. Disp (in.)	35.95	33.76	32.84	31.39	31.31
α=1.3	Max. Disp (in.)	20.12	20.02	16.99	17.04	16.44
α=1.5	Max. Disp (in.)	14.14	13.70	11.50	9.17	9.23

The last analysis that was done in *Perform* for this section was to find the sensitivity of the program to the damping coefficient, C_0. Originally all of the previous analyses were done with C_0=10 k-sec/in.; two additional sets of analyses were performed for all the values of α and the previous range of time-steps when k=100,000 and C_0=5 and 15 k-sec/in. The analyses were also run in SAP2000 for a time-step of 0.01 sec and with k=100,000. The results of these analyses are presented in Table A.9 and Table A.10.

Table A.9: Perform Time Step Sensitivity Analysis, k=100000 (k/in.) C_0=5 (k-sec/in.)

Damping Exponent	Results	Step Size, ΔT (sec) 0.010	0.005	0.0025	0.001	SAP2000 Results
α=0.5	Max. Disp (in.)	62.96	63.01	63.01	63.01	62.99
α=0.7	Max. Disp (in.)	60.91	60.90	60.90	60.90	60.86
α=0.9	Max. Disp (in.)	55.86	55.41	55.36	55.34	55.32
α=1.0	Max. Disp (in.)	50.26	50.28	50.29	50.29	50.23
α=1.1	Max. Disp (in.)	43.80	43.84	43.28	43.17	43.23
α=1.3	Max. Disp (in.)	31.22	27.03	26.38	26.25	26.47
α=1.5	Max. Disp (in.)	13.67	13.62	13.57	13.55	14.46

Table A.10: Perform Time Step Sensitivity Analysis, k=100000 (k/in.) C_0=15 (k-sec/in.)

Damping Exponent	Results	Step Size, ΔT (sec) 0.010	0.005	0.0025	0.001	SAP2000 Results
α=0.5	Max. Disp (in.)	60.98	60.64	60.63	60.63	60.59
α=0.7	Max. Disp (in.)	54.79	54.79	54.79	54.80	54.70
α=0.9	Max. Disp (in.)	42.61	42.23	41.98	41.87	41.79
α=1.0	Max. Disp (in.)	33.34	33.34	33.34	33.34	32.86
α=1.1	Max. Disp (in.)	24.13	24.10	23.96	23.93	24.02
α=1.3	Max. Disp (in.)	13.59	11.99	11.99	11.99	12.16
α=1.5	Max. Disp (in.)	6.94	6.95	6.96	6.94	7.16

From the results it can be observed that the *Perform* output is very similar to the *SAP2000* output for almost all values of α. When the results of these analyses are compared to the analyses that are summarized in Table A.6, it can be concluded that the program is working as expected. These tables show that, as the values of C_0 are increased, the maximum displacement decreases. This is expected because a greater value of C_0 means that the damper will produce a greater force at a certain velocity, which in turn will decrease the response. The difference between the maximum displacement for α=1.5 for the two programs may be larger than acceptable. However, this can most likely be corrected by increasing the spring stiffness of the damper in *Perform*.

Once the correct values were selected for the parameters of the dampers and the time history analysis in both *SAP2000* and *Perform*, it can be seen that both programs give similar answers. Therefore, it can be concluded that *Perform* is accurate in calculating linear time history analyses of frame structures with added linear and nonlinear damping. However, in order to get the correct results, a modeler may need to run his or her own sensitivity analysis to determine the correct properties that match the demands of their problem.

A.6 Nonlinear Pushover and Nonlinear Inelastic Time History Analysis

The LA 9-story building described in Chapter 3 was used to verify the accuracy of nonlinear pushover and nonlinear inelastic time history analysis in *Perform.* The purpose of using the LA 9-story was that there was access to a *Drain-2DX* version provided by the Gupta and Krawinkler (1999) study. This allowed for the verification of nonlinear analysis in *Perform* and provided a comparison to check the validity of the LA 9-story model used in this study.

A.6.1 Nonlinear Pushover

The results of the nonlinear pushover analysis are illustrated in Figure A.11. The figure plots the base shear normalized by the weight of the structure versus the displacement of the roof normalized by the height. An important note about the pushover analysis is that the p-delta effect was included using the approach described in Chapter 3. From the figure it is observed that the results from the two different programs are similar until the first significant yield. After yield the plot displays a slight variation, which remains almost constant, between the two curves.

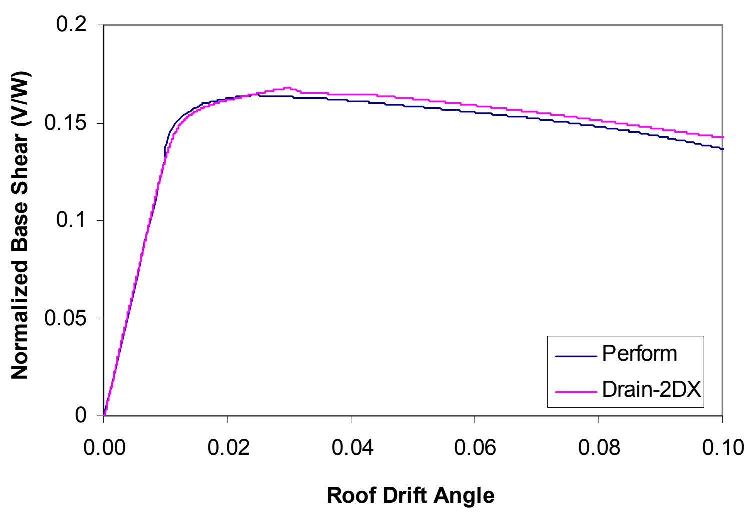

Figure A.11: Nonlinear Pushover Curves

The error between the two curves exhibited in Figure A.11 is about 3%. This is insignificant for this study for two reasons. The first is that the curves are offset by 3%, but the behavior of the modeled structures is similar. The second is that the beam and column are modeled differently for the two different programs. *Drain-2DX* uses a "Type 2" element and Perform uses the model described in Chapter 3. These models differ enough that the difference between the curves in Figure A.11 is acceptable. Therefore, it is concluded that nonlinear pushover analysis run in *Perform* is valid and accurate.

During the initial modeling phase an interesting observation was made about the effect of shear deformations on overall building deformation. The model developed in *Perform* was careful to include shear deformations, but they were ignored in the *Drain-2DX* model provided by Gupta and Krawinkler (1999). When the two models were compared, one with shear deformations and one without, the initial stiffness of the two structures differed by more than 5%. This error could result in significant differences in the dynamic behavior of a structure. This observation strengthens the notion that for taller structures shear deformation significantly contributes to overall structural deformation and must be considered.

A.6.2 Nonlinear Inelastic Time History Analysis

The final step in the verification of *Perform* was to validate the accuracy of the nonlinear inelastic time history analysis. The LA 9-story structure was subjected to the pulse time history that was previously used and is illustrated in Figure A.1. The peak acceleration of the loading history was scaled to 0.3g in order to obtain an inelastic response from the structure. It was difficult to model inherent natural damping exactly the same in both programs; therefore it was set to 0%. P-delta effect was also included in this analysis according to the approach described in Chapter 3.

The results of the analyses for the two programs are superimposed on one plot of the roof displacement versus time shown in Figure A.12. This figure demonstrates that the two responses are almost identical for most of the time history. The differences displayed in the plot have been attributed to errors caused by different approaches to modeling the beam and column elements. Therefore, it is concluded that nonlinear inelastic time history analysis run in *Perform* is valid and accurate.

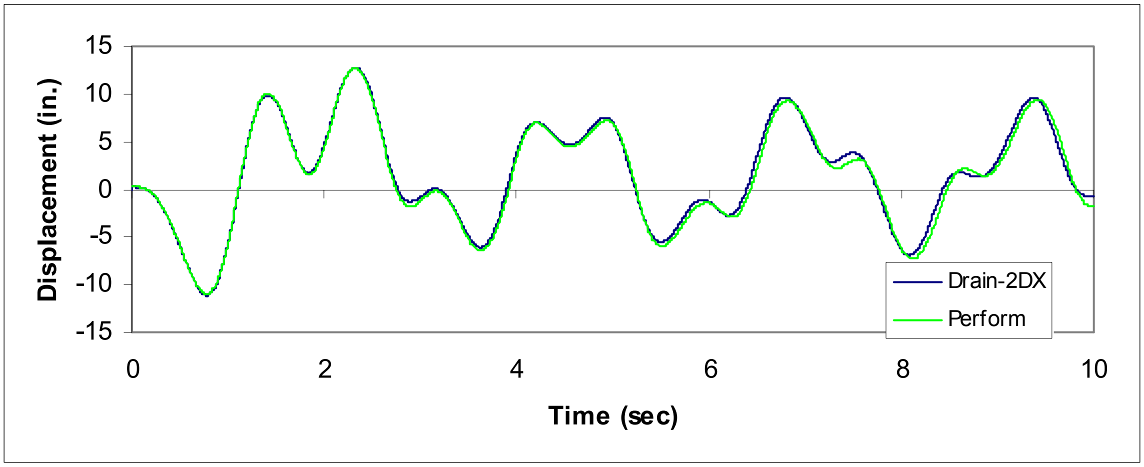

Figure A.12: Roof Displacement vs. Time from Nonlinear Inelastic Time History Analysis

A.7 Conclusions

The objective of this smaller study was to verify that *Perform*, a relatively new computer program, was valid in analysis of structures important to the larger study. *Perform* was compared to *SAP2000* to prove the validity of a nonlinear damper element. This comparison proved that when the damping parameters are chosen carefully, the results would match for the two programs. *Perform* was compared to *Drain-2DX* in order to check the validity of nonlinear pushover and inelastic time history analysis. The results of these comparisons showed that nonlinear analysis run in *Perform* is valid and accurate. Therefore, it can be concluded that *Perform* is an acceptable program to study nonlinear dampers used in structures that behave inelastically.