

**AN EDUCATIONAL COMPUTER PROGRAM FOR NONLINEAR
RESPONSE HISTORY ANALYSIS, VISUALIZATION AND
ANIMATION OF RESPONSE OF SEISMICALLY ISOLATED
STRUCTURES**

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Abstract

A computer program, called DASISedu has been developed to perform advanced nonlinear response history analysis of seismically isolated structures for use in education. The program is an extension of program 3pleANI (MCEER report 13-0010). Key features of the program DASISedu include advanced models for friction pendulum, lead-rubber and elastomeric isolators with and without heating effects, added linear and nonlinear viscous dampers in the isolation system, added viscous or hysteretic dampers in the superstructure, quick generation and visualization of structural models, and interactive visualization and animation of computed response. Building and bridge models may be analyzed. The program includes a large database of ground motions for use in analysis. Also, the program can perform complex eigenvalue analysis to compute damping ratios for damped superstructure buildings based on linearization of behavior for dampers when they are not linear viscous. The program will be available free in the public domain together with a User Guide and Reference Manual and a Verification Manual.

Keywords: DASISedu, seismic base isolation, friction pendulum, elastomeric, lead-rubber.

1 INTRODUCTION

Proper use of seismic isolation systems and/or energy dissipation systems may achieve reliable performance of structures in earthquakes. ‘Proper’ utilization of these systems requires a thorough understanding of the behavior of structures utilizing these seismic protection systems [1,2].

Over the past few decades, effort has been put into the study of the mechanical behavior of various seismic isolation and energy dissipation devices subjected to a wide range of loadings, deformations and environmental conditions. This led to the development of validated theories [3,4,5] that could well describe the dynamic behavior of various seismic isolators (with the lead-rubber and friction pendulum isolators being amongst the most prominent types being used widely). These theories are very useful in analyzing the dynamic response of seismically isolated structures. The authors of this paper took these developed theories [3,4,5] as basis for developing a computer program, called DASISedu, to perform advanced nonlinear response history analysis of seismically isolated structures.

DASISedu program is an extension of program 3pleANI [3] and was primarily developed for use in education and research.

Key features of the program DASISedu include advanced models for friction pendulum, lead-rubber and elastomeric isolators with and without heating effects, added linear and nonlinear viscous dampers in the isolation system, added viscous or hysteretic dampers in the superstructure, quick generation and visualization of structural models, and interactive visualization and animation of computed response. Building and bridge models may be analyzed. DASISedu program includes a large database of ground motions for use in analysis. Also, the program can perform complex eigenvalue analysis to compute damping ratios for damped superstructure buildings based on linearization of behavior for dampers when they are not linear viscous. The program will be available free in the public domain together with a User Guide and Reference Manual and a Verification Manual.

The main objectives of this paper are:

- to demonstrate the new features of the DASISedu program (which extends the functionalities of its predecessor 3pleANI) and,
- to verify the correctness of calculations performed in DASISedu.

To achieve the first objective, this paper primarily focuses on the various analysis performed on building models with lead-rubber isolators.

To achieve the second objective, a characteristic planar frame model is chosen to be modelled and analyzed in two different environments, namely in DASISedu and SAP2000 computer programs. Obtaining the same results in both computer programs, as will be shown to be the case, implies that computations in DASISedu program are done correctly.

2 DESCRIPTION OF MODELS AND MODELLING CONSIDERATIONS

For the purposes in this paper, a planar representation of a characteristic four-story building is considered. All assigned properties of this planar frame model are shown in Figure 1. The vertical and horizontal masses at each node are assigned in units of kip-sec²/in and they are shown in Figure 1 as well.

Six variations of this frame model were considered and used for analysis. These model variations are listed in Table 1. They differ from each other based on the type of support conditions for the frame, consideration of supplemental dampers and consideration of heating effects for calculation of response for the lead-rubber isolation system.

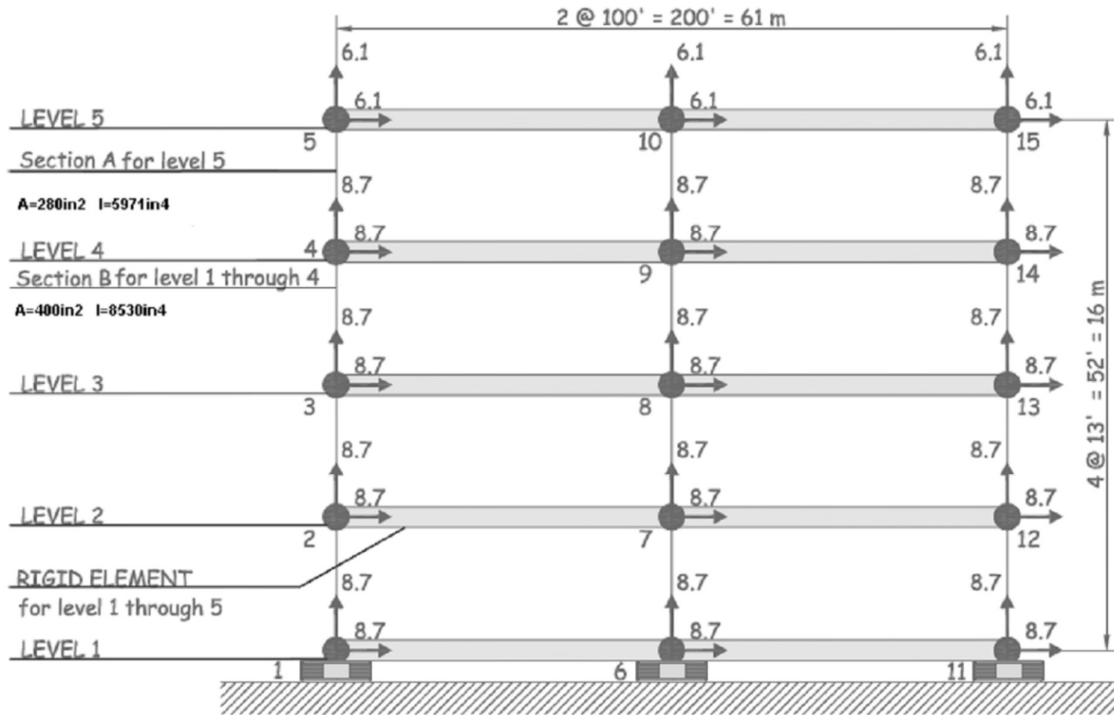


Figure 1: Geometric/physical/mechanical properties of the building model

Model Number	Model Name	Support	Supplemental Dampers	Heating Effects
1	Model1-FIX	Fixed	-	-
2	Model2-FIX		Yes	-
3	Model1-LR	Lead-Rubber Isolation System	-	-
4	Model2-LR		Yes	-
5	Model1-LR-H		-	Yes
6	Model2-LR-H		Yes	Yes

Table 1: List of all frame models used for analysis

All models in Table 1, containing the ‘Model1’ prefix in their name (Model1-FIX, Model1-LR, Model1-LR-H), represent the planar frame without any additional dampers, as illustrated in Figure 1. All other models in Table 1, containing the ‘Model2’ prefix in their name (Model2-FIX, Model2-LR, Model2-LR-H), represent the planar frame with supplemental energy dissipation devices (added dampers).

When considering the frame with supplemental dampers, dampers are added to the 1st, 2nd, 3rd and 4th stories with damping constants (effective in horizontal direction) of 500, 300, 200 and 100 kip-sec/in respectively.

The first two models in Table 1, containing the ‘FIX’ suffix in their name (Model1-FIX and Model2-FIX), represent the planar frame supported by a fixed foundation system.

The next two models in Table 1, containing the ‘LR’ suffix in their name (Model1-LR and Model2-LR), represent the planar frame supported by a lead-rubber isolation system under the base. For these two models, no heating effects for the lead-rubber isolation system are considered when computing the dynamic response of the frame model.

The last two models in Table 1, containing the ‘LR-H’ suffix in their name (Model1-LR-H and Model2-LR-H), represent the planar frame supported by a lead-rubber isolation system under the base. For these two models, heating effects on the lead-rubber isolation system are considered when computing the dynamic response of the frame model.

Regarding the modelling of the isolation system under the base of the frame model, in program SAP2000, three isolators are placed under the base of the frame model (one below each column), while in program DASISedu, all isolators are lumped into one isolator that carries the total vertical load. Thus, DASISedu does not consider the spatial distribution of the isolators and, accordingly, does not account for the vertical load variation due to the overturning moment effects.

Modelling of the nonlinear behavior of lead-rubber isolation system differs in DASISedu and SAP2000 environments.

The behavior of lead-rubber isolators in the DASISedu program is defined by the following driving parameters (without any heating effects):

- Shear strength/Weight $Q_d = Q/W$,
- Period T based on the post-elastic stiffness, and
- Yield displacement Y .

These are specified by the user in the DASISedu GUI. For the current generated models, these values were adopted as follows: $Q_d = 0.1$, $T = 5sec$, and $Y = 1in$. Based on these parameters, DASISedu internally calculates the effective and elastic stiffnesses, yield strength and other parameters needed for modelling the nonlinear behavior of isolators.

In modelling LRB isolators in SAP2000 program, however, the user specifies directly the effective stiffness K_{eff} , elastic stiffnesses K_{el} , yield strength F_y , an ‘alpha ratio’ α and some other parameters.

The relationship between these parameters with the driving parameters in DASISedu is set by the following expressions.

$$F_y = Q_d + K_d \cdot Y \quad (1)$$

$$K_{el} = \frac{F_y}{Y} \quad (2)$$

$$K_{eff} = K_d = \left(\frac{2\pi}{T}\right)^2 \cdot \frac{W}{g} \quad (3)$$

$$\alpha = K_d/K_{el} \quad (4)$$

where: F_y - Yield Strength
 Q_d - Normalized shear strength
 K_d - Post elastic stiffness
 Y - Yield displacement

The vertical stiffness of lead-rubber isolators in SAP2000 is assigned an arbitrary value. For the purposes of this study, the vertical stiffness of the Lead-Rubber isolator was adopted around 50000 kip/in.

Other properties needed in SAP2000 for modeling the lead-rubber isolators, such as the link element height, shear deformation location, isolator weight and mass, the Rotational/Torsional stiffnesses of the isolator and the rotational mass moment of inertia (as needed in the edit fields of ‘isolator property definition’ dialog box in SAP2000) are specified arbitrarily.

All these isolator properties and their values, as calculated for the models listed in Table 1, are presented in Table 2.

	In SAP2000	In DASISedu
Element Height	16.000	16.000
Shear Deformation Location	8.000	8.000
Link Element Mass	0.0050	0.0050
Supported Weight	15796.417	47389.252
Yield Strength	538.479	1615.438
Vertical Stiffness	48827.222	48827.222
Elastic Stiffness Kel	538.479	1615.438
Effective Stiffness Kd	64.587	193.760
Alpha Value Keff/Kel	0.120	0.120
Rotational/Torsional Stiffness	0	0
Rotational Mass Moment of Inertia	0.094	0.094

Table 2: Element properties for modeling the LR isolator in SAP2000

DASISedu can also consider the heating effects when modelling the behavior of lead-rubber isolators. In this case, the validated theory of Kalpakidis and Constantinou [5] and Kalpakidis et al [6] is used with a modification valid for large temperatures close to the melting temperature of lead introduced by Kim and Constantinou [7, 8].

Using this theory in DASISedu allows for the calculation of displacements and velocities at each time step of response history analysis, and consequently it also calculates the temperature increases and effective yield stress in the lead core of isolators. Changes in temperature result in changes in the yield strength of the lead core, and consequently on the normalized reference strength of the isolator.

The relationship between the yield strength and temperature is set by the following equation:

$$\sigma_{YL} = \begin{cases} \sigma_{YLO} \cdot e^{(-E_2 \cdot T_L)}, & T = T_L + T_o \leq 250^\circ\text{C} \\ \sigma_{YLO} \cdot e^{(-E_2 \cdot 250)} \cdot \left(\frac{327 - T_L}{327 - 250}\right), & 250^\circ\text{C} < T = T_L + T_o \leq 327^\circ\text{C} \\ 0, & T = T_L + T_o > 327^\circ\text{C} \end{cases} \quad (5)$$

This relationship is depicted in the graph of Figure 2.

More detailed explanations on calculating the changes of temperature and yield stresses on the lead core are found in Kalpakidis and Constantinou [5], Kalpakidis et al [6], and in the ‘DASISedu User Manual’.

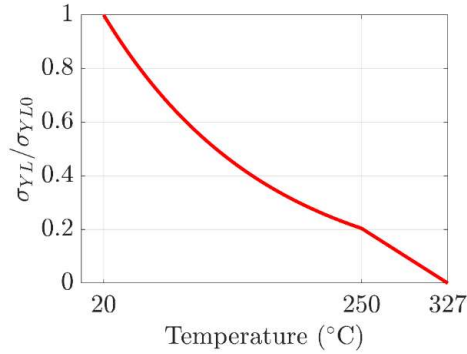


Figure 2: Relationship between effective yield stress of lead and temperature rise in the lead core valid up to the melting point of the lead (327°C)

When modeling the behavior of lead-rubber bearings using time-dependent properties (accounting for heating effects), the program DASISedu uses the following parameters as input:

- Reference value of the normalized shear strength, namely the ratio of strength Q to weight W , $(Q/W)_{ref}$ for the entire isolation system. This is the value of the ratio of strength to weight when the temperature is equal to T_0 , prior to the start of motion.
- Yield displacement, Y .
- Period, T_d , based on the post-elastic stiffness, which is used to compute the post-elastic stiffness of the isolation system
- Characteristic yield strength of lead at temperature T_0 , prior to the start of motion, σ_{YL0} .
- Radius of lead core for an individual lead rubber isolator, a .
- Ratio of radius to height of lead core, a/h_L for an individual isolator.
- Ratio of total steel shim thickness to height of lead core, t_s/h_L for an individual isolator.

For the current generated models, these values were adopted as follows: $(Q/W)_{ref} = 0.1$, $T = 5\text{sec}$, $Y = 1\text{in}$, $\sigma_{YL0} = 1.7\text{kip/in}^2$, $a = 6\text{in}$, $a/h_L = 0.45$ and $t_s/h_L = 0.35$. All these values are shown again later, in Figure 7, as they are specified inside the DASISedu graphical user interface (GUI). The program user needs to exercise care in specifying parameters Q/W , σ_{YL0} , a , a/h_L and t_s/h_L , so to properly represent the behavior of the system to be analyzed.

Based on this input data, the program DASISedu calculates changes in the temperature and yield stress of the lead core at every time step when performing response history analysis on structures with lead rubber isolation.

SAP2000 on the other hand, is not yet capable of considering the heating effects in describing the dynamic nonlinear behavior of lead-rubber isolators.

3 ANALYSIS CONSIDERATIONS

All models listed in Table 1 are analyzed both in program DASISedu v.2025 and in SAP2000 v.24.0.0 [9]. All analysis settings were kept identical for all models. The ground motion used for performing response history analysis is that of 1979 Montenegro earthquake scaled up by 200%. This ground motion record is shown in Figure 3 below.

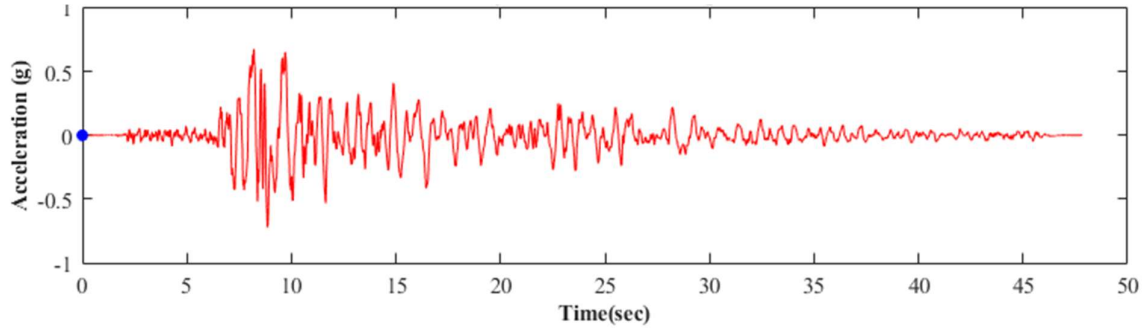


Figure 3: Ground motion used for all response history analysis

The time-step for all modal time-history analysis was set 0.02s.

4 GRAPHICAL USER INTERFACE OF DASISEDU

Upon starting the DASISedu program, the graphical user interface appears as shown in Figure 4. It is important to note that this entire window constitutes the GUI of the DASISedu program, and all work is done on this view beginning with the parametric modelling stage and moving forward with analysis tasks, simulation of dynamic response and up to visualization of analysis results through graphs. To this respect, this GUI is simplistic yet versatile for studying the dynamic response of seismically isolated structures.

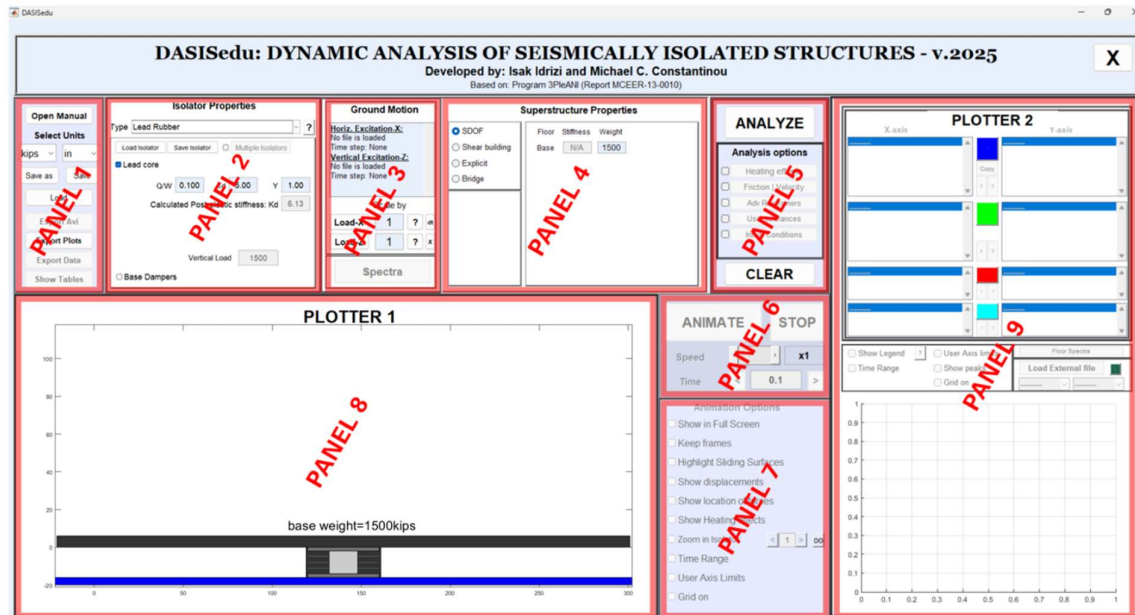


Figure 4: Panels constituting the DASISedu GUI

This DASISedu GUI window consists of a group of 9 panels, each having specialized roles and functions. Panel 1 is used for configuring the global settings such as adoption of working units. Panel 2 through Panel 5 contain all input parameters necessary for modelling the structure, isolator properties, ground motion records and various analysis settings. Panel 5 has two distinguished big buttons, namely ‘ANALYZE’ (used for running the Analysis computations) and ‘CLEAR’ (used for clearing the analysis results).

When ‘ANALYZE’ button is pressed and computations are completed, GUI components residing in Panels 1 through 5 are locked while GUI components residing in panels 6 through 9 are enabled, thus switching the program into simulation mode. When ‘CLEAR’ button is pushed, GUI components residing in Panels 1 through 5 are enabled back while GUI components residing in Panels 6 through 9 are locked, thus switching the program back into modelling mode.

Panels 6 and 7 are used for controlling the visualization of the structural model and its simulation in the graphical region of Panel 8.

Panel 9 is used for the presentation of analysis results through graphs using various response quantities.

Since the focus of this paper is primarily set in demonstrating the DASISedu analysis capabilities and correctness of computations, we will not provide further details on using the DASISedu GUI for modelling of representative frame models. Instead, the reader is advised to check the ‘Users Guide and Reference manual’ for detailed explanations on how to use the DASISedu program. This document is a PDF file, which is opened when clicking on the top-right button inside ‘Panel 1’ of the DASISedu GUI.

Using the DASISedu GUI for generation of all models listed in Table 1, is very straightforward and easy. As you specify the input parameters in Panels 1 through 5, the model is simultaneously plotted in the graphical region of Panel 8 (named Plotter 1).

Figure 5 shows a characteristic view of the DASISedu GUI when working on Model1-LR frame model. When supplemental dampers are added as explained in the ‘modeling considerations’ section (section 2 of this paper) Model2-LR is generated and DASISedu GUI takes the view as shown in Figure 6. Finally, when checking the ‘Heating Effects’ checkbox in the Analysis Panel (Panel 5 in figure 4), Model1-LR-H is generated and DASISedu GUI takes the view as shown in figure 7. Note in Figure 7 how additional parameters appear in the ‘Isolator Properties’ Panel (Panel 2 in Figure 4).

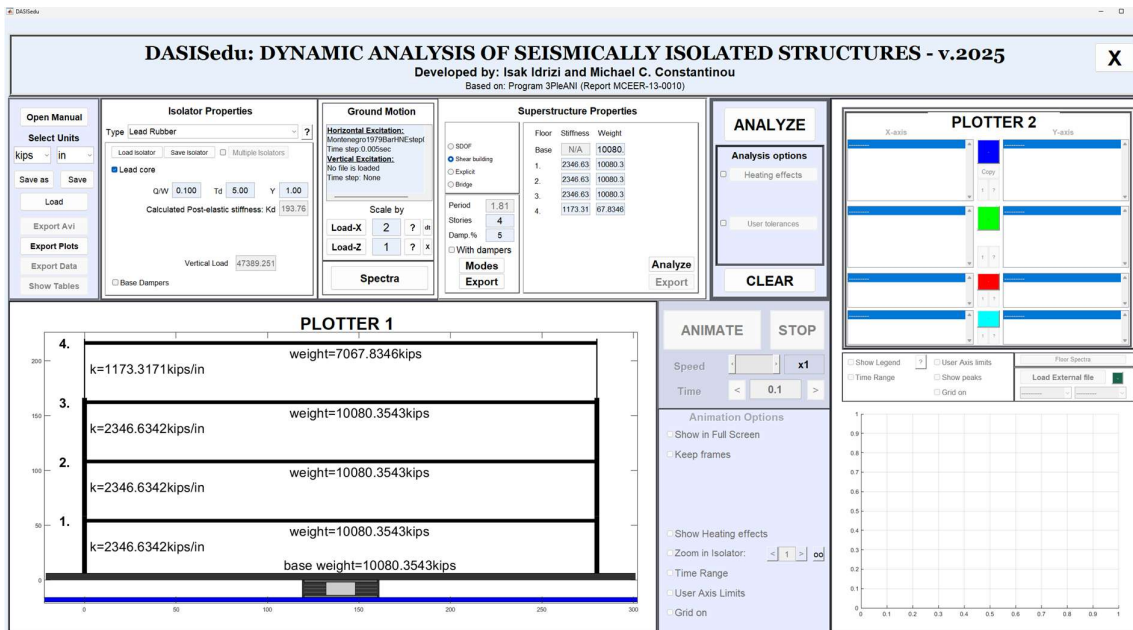


Figure 5: State of DASISedu graphical user interface when preparing the Model1-LR frame model

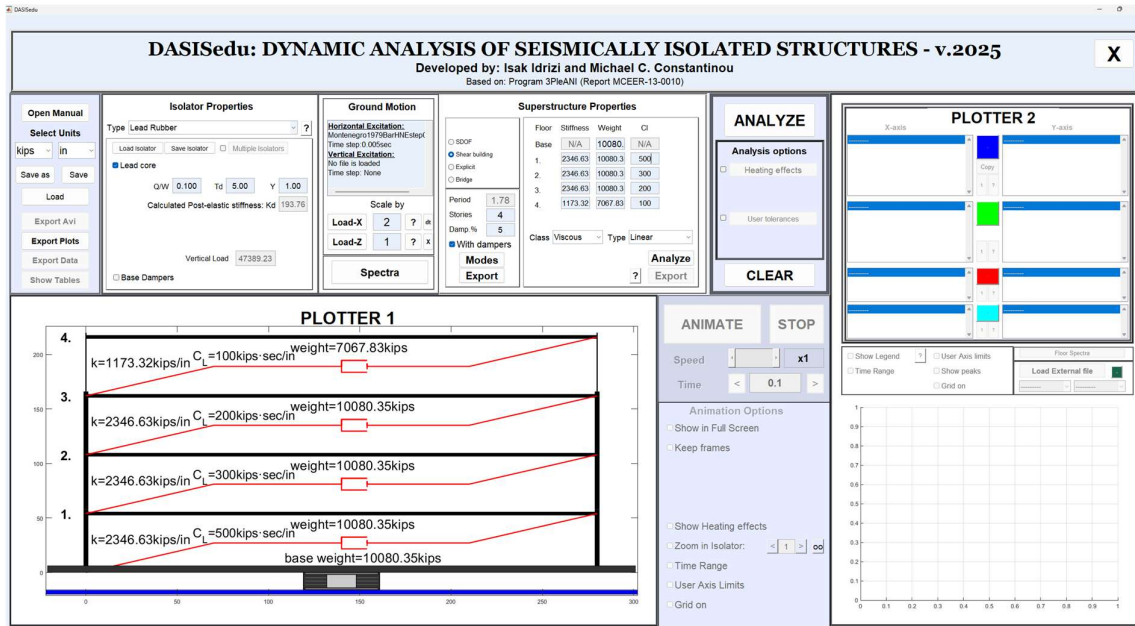


Figure 6: State of DASISedu graphical user interface when preparing the Model2-LR frame model

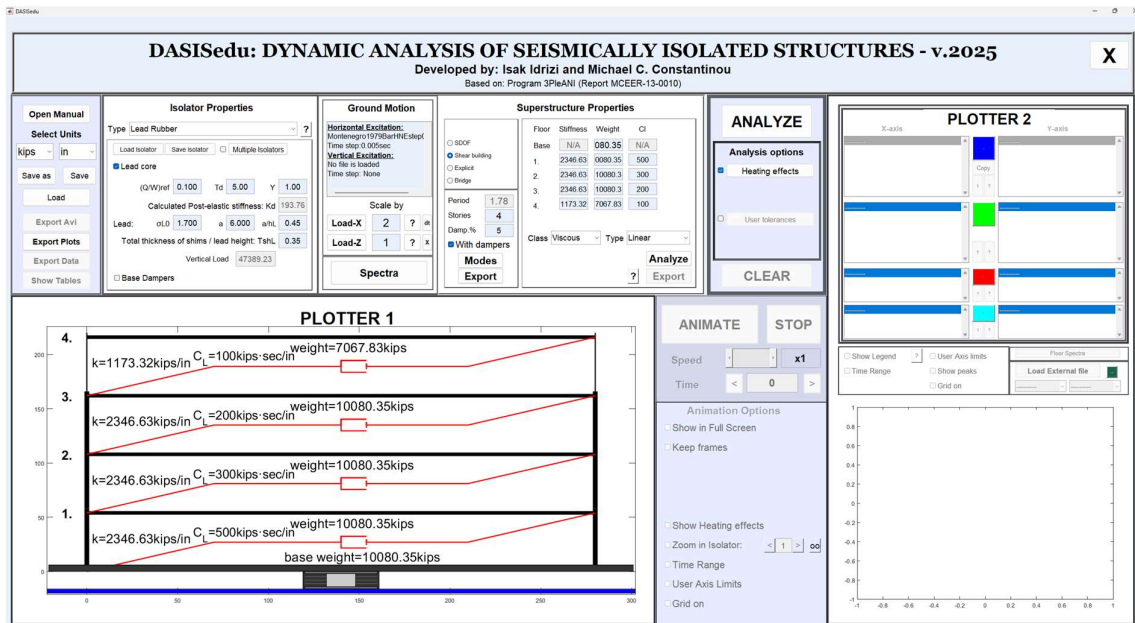


Figure 7: State of DASISedu graphical user interface when preparing the Model2-LR-H frame model

These additional parameters (are also shown in Figure 8 – left) are important as they govern the behavior of lead-rubber isolators when heating effects are considered in analysis. Additionally, when ‘heating effects’ checkbox is checked, a dialog box appears with heating properties that are equally important for modelling the behavior of Lead-Rubber isolators. This dialog box is shown in figure 8-right.

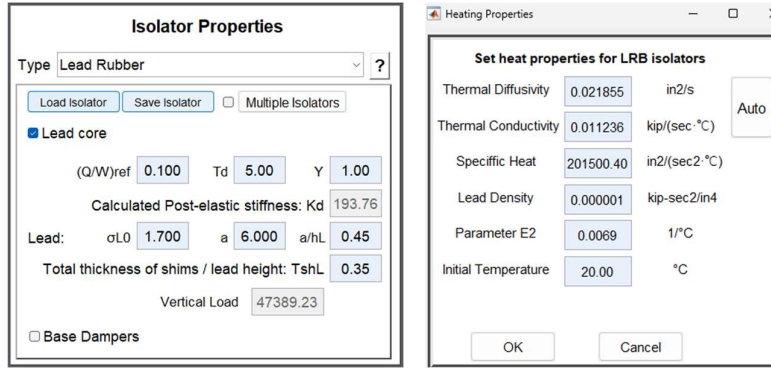


Figure 8: Specified parameters in program DASISedu for dynamic analysis of the structure with Lead-Rubber isolation system and with heating effects

5 ANALYSIS RESULTS

Having described the modelling, analysis settings and the DASISedu environment, it is time to present some of the most characteristic results obtained from analyzing the models listed in Table 1, both in DASISedu and SAP2000 environments. These results are compactly presented in the following subsections.

5.1 Eigen-analysis for the fixed frame (Model1-FIX)

The eigenvalues and eigenvectors of the fixed frame model (Model1-FIX) as obtained from the two programs are shown in table 3 and figure 9. The program DASISedu conducts complex eigenvalue analysis that includes the superstructure damping in the modal calculations, while SAP2000 conducts real eigenvalue analysis. Hence, for this analysis case only, the inherent damping in DASISedu was set to zero to eliminate the effect of damping in the calculated modal properties. Results from both programs are identical.

Periods of vibration				
	1st Mode	2nd Mode	3rd Mode	4th Mode
SAP2000	1.8141	0.7219	0.4807	0.3628
DASISedu	1.8140	0.7220	0.4810	0.3630

Table 3: comparison of eigenvalues obtained from DASISedu and SAP2000

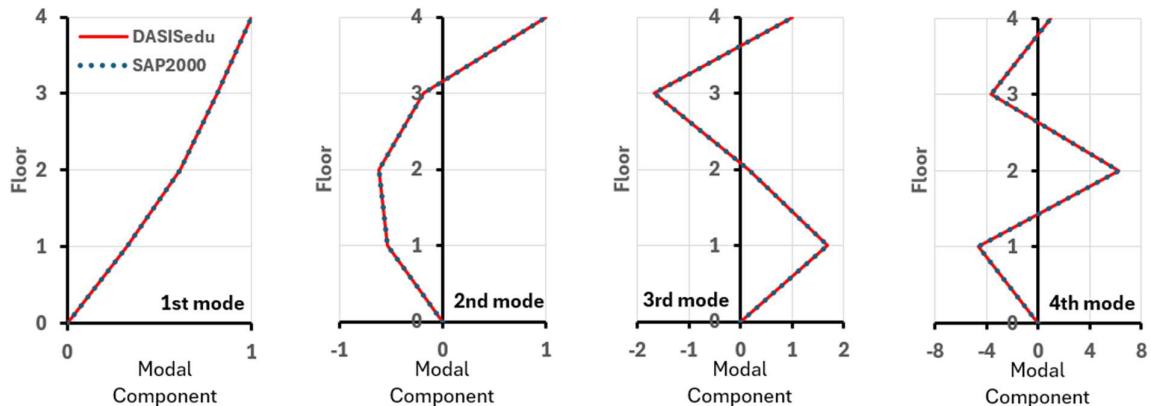


Figure 9: Eigen-modes for Model1-FIX (comparison of results obtained between DASISedu and SAP2000)

5.2 Response history analysis for fixed (non-isolated) frames (Model1-FIX vs. Model2-FIX)

Two characteristic results (2nd story drift and the 4th floor acceleration histories) obtained from the response history analysis of both models with fixed superstructure (as run in both DASISedu and SAP2000 programs) are shown below in Figures 10 and 11.

The results of story drifts from the two programs are essentially identical. Results for floor acceleration response are slightly different, though. This is particularly evident in the ‘spikes’ of acceleration history. These differences likely reflect the ways numerical integration methods and tolerances are implemented in the two programs, and acceleration histories are more susceptible to these differences.

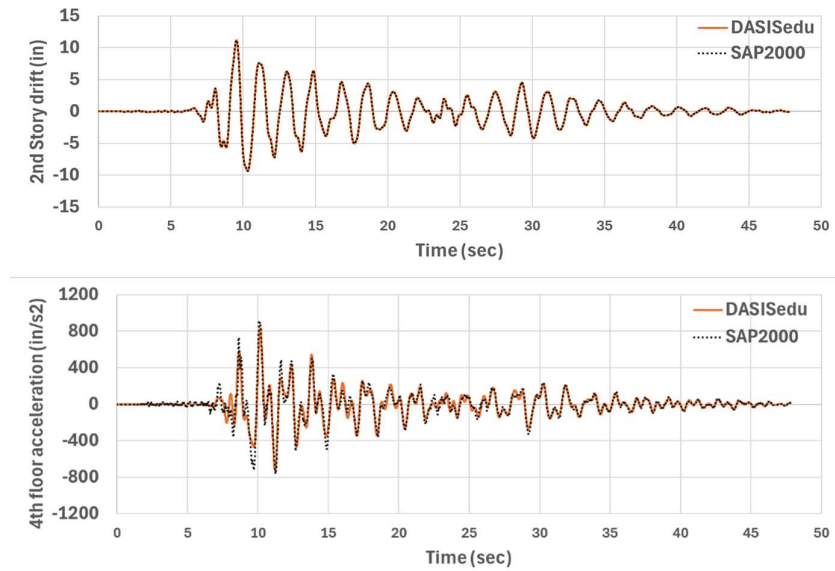


Figure 10: 2nd story drift history and 4th floor acceleration history for Model1-FIX (comparison of results obtained between DASISedu and SAP2000)

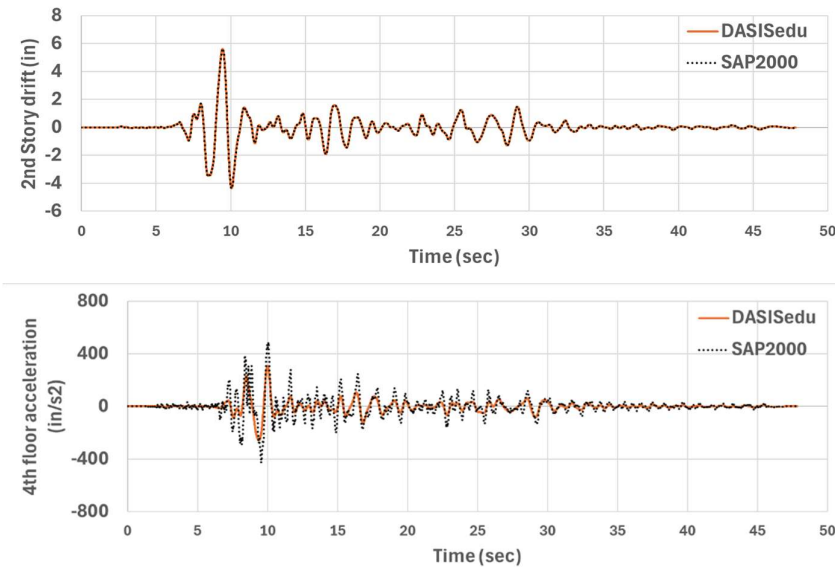


Figure 11: 2nd story drift history and 4th floor acceleration history for Model2-FIX (comparison of results obtained between DASISedu and SAP2000)

5.3 Response history analysis for Model1-LR (bare frame with Lead-Rubber isolation)

Figure 12 and Figure 13 compare various response quantities obtained by programs DASISedu and SAP2000 for the models with lead-rubber isolators without heating effects. There is very good agreement between the results obtained by the two programs although the peak floor accelerations and peak story drifts are systematically slightly larger in the SAP2000 analysis. This result is as expected, and the reasons for any discrepancy are the same as the were for the previous case when Triple FP isolators were used for isolating the frame structure.

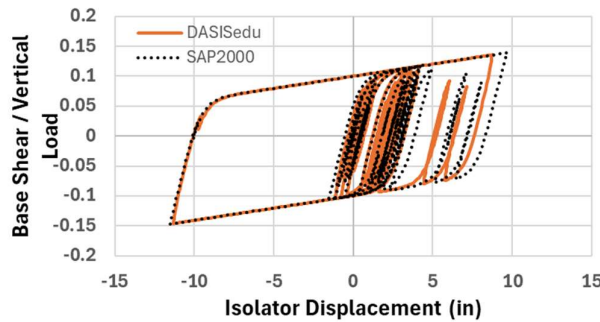


Figure 12: Cyclic loops of normalized base shear (base shear/vertical load) vs. isolator displacements for Model1-LR, (comparison of results obtained between DASISedu and SAP2000)

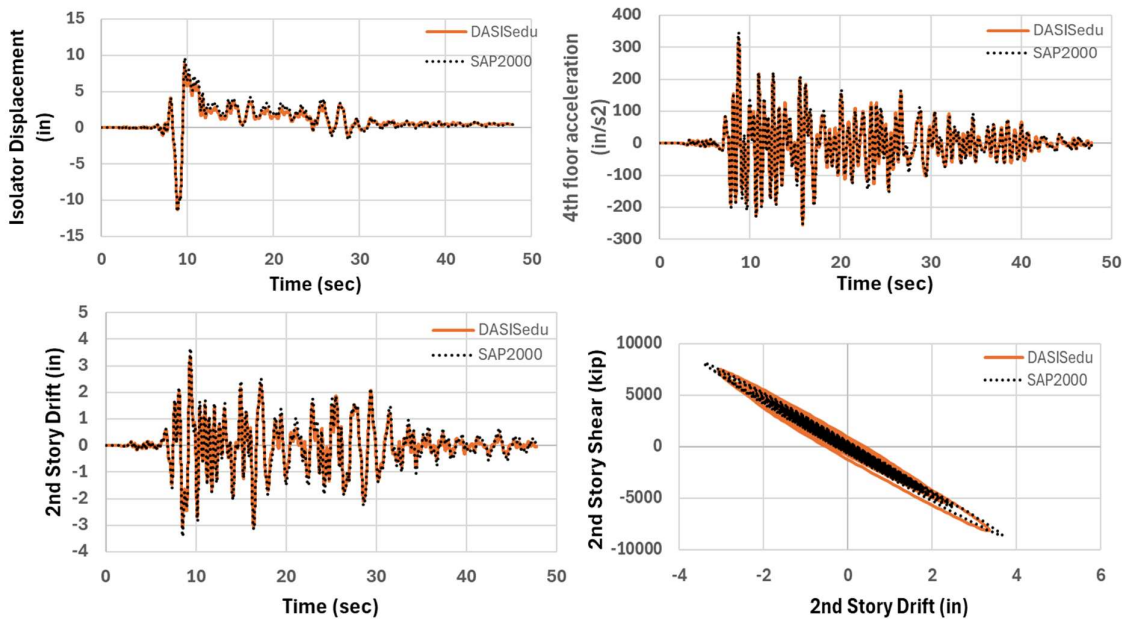


Figure 13: Characteristic responses for Model1-LR (comparison of results obtained between DASISedu and SAP2000)

5.4 Response history analysis for Model2-LR (frame with Lead-Rubber isolation and with added dampers)

Figures 14 and 15 compare various response quantities obtained by programs DASISedu and SAP2000 from the analysis of the frame structure with lead-rubber isolators and supplemental linear viscous dampers in the stories of the frame structure (Model2-LR). There is very good agreement between the results obtained by the two programs, including the peak values of acceleration and drift.

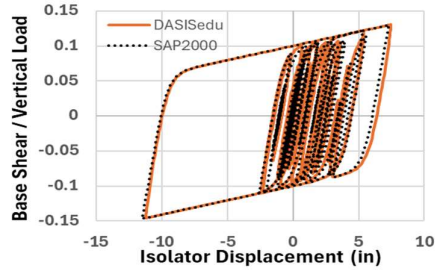


Figure 14: Cyclic loops of normalized base shear (base shear/vertical load) vs. isolator displacements for Model2-LR, (comparison of results obtained between DASISedu and SAP2000)

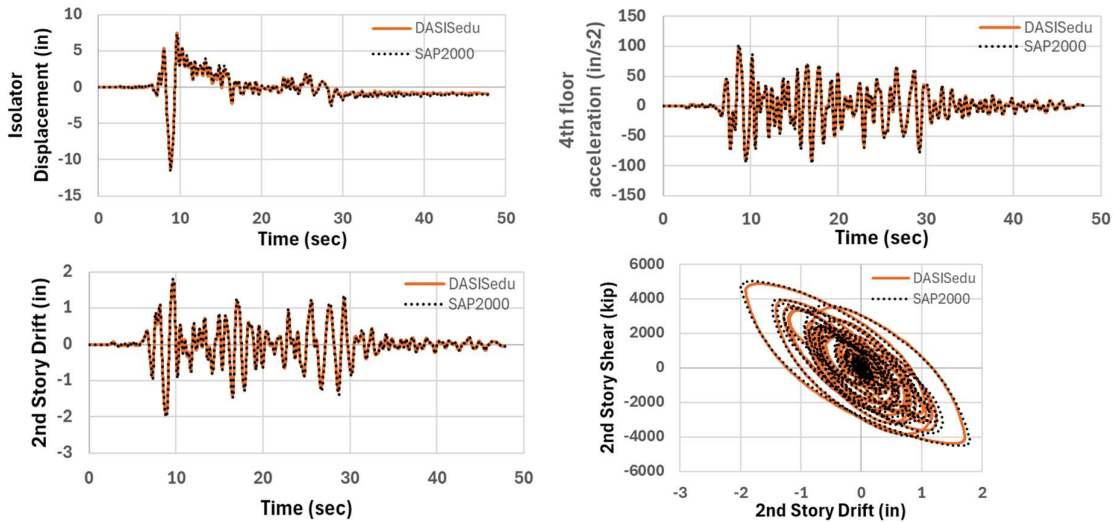


Figure 15: Characteristic responses for Model2-LR (comparison of results obtained between DASISedu and SAP2000)

5.5 Response history analysis for Model1-LR-H and Model2-LR-H (frames with Lead-Rubber isolators and consideration of heating effects)

As mentioned earlier in section 2, SAP2000 cannot account for heating effects in the behavior of lead-rubber isolators. The results of Model1-LR-H and Model2-LR-H (shown in Figures 16 and 17) will only be compared to their corresponding models without heating effects, namely Model1-LR and Model2-LR.

Results are presented in Figures 16 and 17, where it may be observed that heating of the isolators results in a small increase in temperature (up to 60 degrees) so that the heating effects are not important. While for this study case no notable difference is observed on the isolator displacements with heating effects considered, it must be noticed that heating effects generally have notable effects on the isolator’s displacements when high intensity ground motions with prolonged time durations occur.

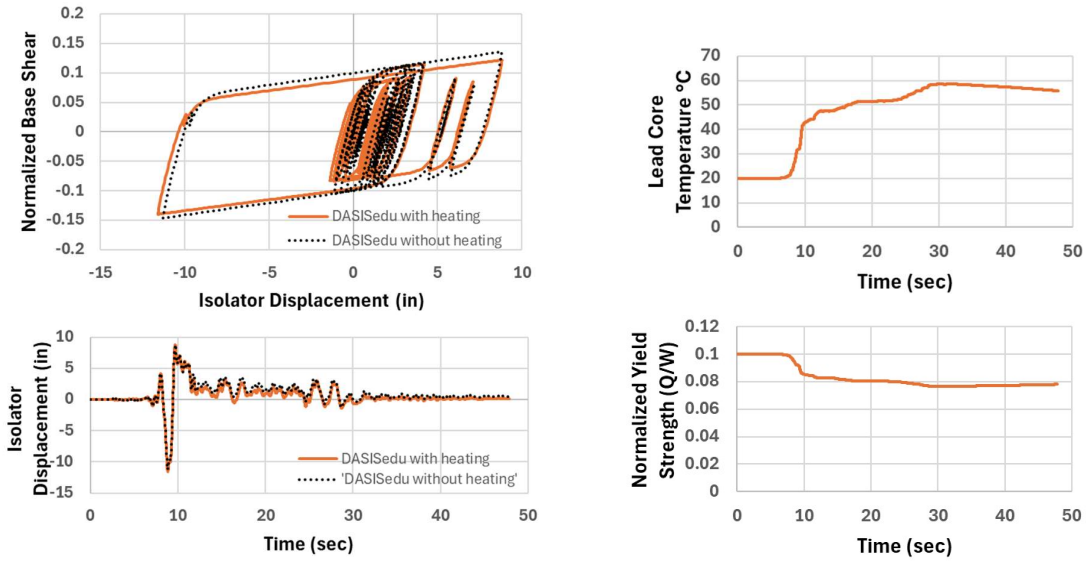


Figure 16: Characteristic responses for Model1-LR-H obtained in DASISedu program (comparison of results obtained between Model1-LR-H and Model1-LR)

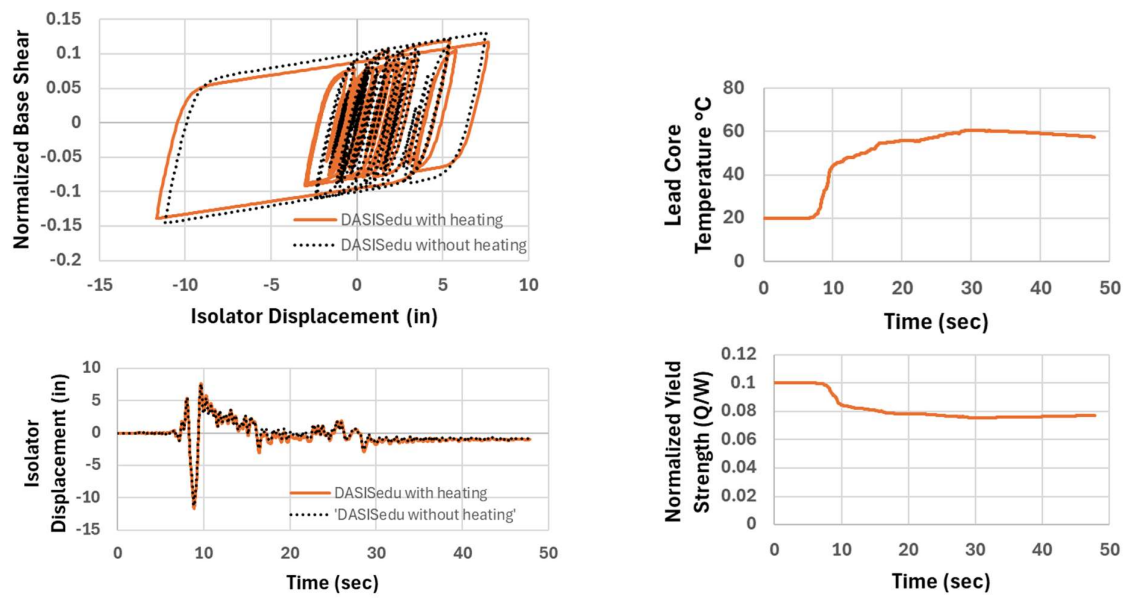


Figure 17: Characteristic responses for Model2-LR-H obtained in DASISedu program (comparison of results obtained between Model2-LR-H and Model2-LR)

6 CLOSING REMARKS

The results presented in Figures 9 to 17, show that programs DASISedu and SAP2000 programs generate nearly identical results.

Program DASISedu has features for considering the effect of heating on the dynamic behavior of lead-rubber and friction pendulum isolators.

DASISedu program was developed as a tool for studying the non-linear dynamic response of simple two-dimensional frames of typical buildings and bridges utilized with various seismic isolation systems and energy dissipation devices. To this respect, the most distinguishing feature of the DASISedu program is the parametric approach for fast modelling and analysis setups.

These features make the DASISedu program a highly versatile program and very desirable for educational purposes. DASISedu is not a commercial program and is meant to be used for free by educational institutions.

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