

Experiences Acquired through Nonlinear Modeling and Analyzing three-Dimensional Structure Models for Collapse Safety Assessment



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SUMMARY:

The present paper discusses some important issues in seismic collapse modeling and analyzing 3-D structures (especially irregular ones) encountered in a comprehensive study conducted by the authors. The study is an effort to investigate the seismic collapse behavior of three-dimensional buildings, incorporating the recently-developed nonlinear degrading models of reinforced concrete members. All models have been built and analyzed using the OpenSees simulation platform. Various issues such as mass irregularities modeling techniques, lumped plasticity model definitions, elements connectivity, bi-directional seismic loading effects, advanced frontal solution method of solving equilibrium equations, and efficient post-processing with emphasis on incremental dynamic analysis (IDA) will be dealt with in this paper. A new graphical and powerful post-processor for collapse safety assessment, developed by the authors, will also be introduced.

Keywords: irregular structures, collapse assessment, nonlinear modeling, OpenSees, post-processor

1. INTRODUCTION

The subject of inelastic analysis and exploring the post-yield behavior of structures has gained a wide attention in earthquake engineering community during the past four decades. Such efforts, indeed, have intended to elaborate seismic resistance capacity of different types of structures. The followings, however, should be considered as obstacles in the path, many of which have been overcome in recent years: limitations of programming techniques and languages, hardware limitations (especially CPU computational capacity), enormous volume of data generated in a nonlinear time-history analysis, limitations on existing algorithms for solving large sparse systems of equilibrium equations, etc. It is believed that enhancements occurred in the field have been quite considerable, leading to the development of robust analytical platforms for nonlinear seismic response of structures. Enhancements in mathematical solution techniques, nonlinear finite element methods, software and hardware engineering, and even network engineering are believed to occur interactively and reflected in both commercial and non-commercial software platforms. The past four decades have been the era of developing complicated and powerful nonlinear structural analysis programs.

It is thought that OpenSees (available online at www.opensees.berkeley.edu) as one of the most powerful and robust analytical platforms, has gained much attention in both structural and geotechnical earthquake engineering community during the past decade. The Software, developed by Pacific Earthquake Engineering Research Center (PEER), reflects the latest achievements in the above-mentioned interacting fields. The program has been developed as an object-oriented and open-source simulation platform and uses the capabilities of C++ and Tcl/Tk programming languages. The program has facilitated the exchange of cutting-edge research ideas among researchers, students and engineers engaged in the subject.

The authors are currently involved in a comprehensive research on evaluating the seismic inelastic response and collapse assessment of reinforced concrete (RC) three-dimensional low and medium-rise structures with mass irregularities in plan. Modeling and analyzing three-dimensional nonlinear structures have certain characteristics stated in the next section of this paper. These characteristics on

one hand, and the capabilities of OpenSees on the other, encouraged the authors to conduct their research based on this software.

This paper, generally, tries to: **a)** share the experiences acquired by the authors through modeling and analyzing three-dimensional RC structures for collapse safety assessment of irregular structures, **b)** explore capabilities and limitations of OpenSees in performing such assessment, and **c)** to introduce a new efficient and graphical post-processor developed by the authors for interpreting modal, nonlinear static (pushover) and nonlinear incremental dynamic (IDA) analyses outputs generated by OpenSees for collapse assessment.

2. NONLINEAR MODELING CONSIDERATIONS FOR COLLAPSE ASSESSMENT

In general, two known methods are used for inelastic modeling of structures; namely Concentrated Plasticity (Fig. 1-a) and Distributed Plasticity (fiber element model) (Fig. 1-b). Due to the limitations of latter, mainly regarding the models calibration and element formulation in post-peak (negative stiffness) response range, it is generally recommended to use the former as the right method for capturing inelastic effects, which are considered to be quite severe prior to the total collapse of the structure (FEMA P-695,2009). A zero-length spring model with appropriate initial (linear) and post-yield specifications should generally work well as a concentrated plasticity model.

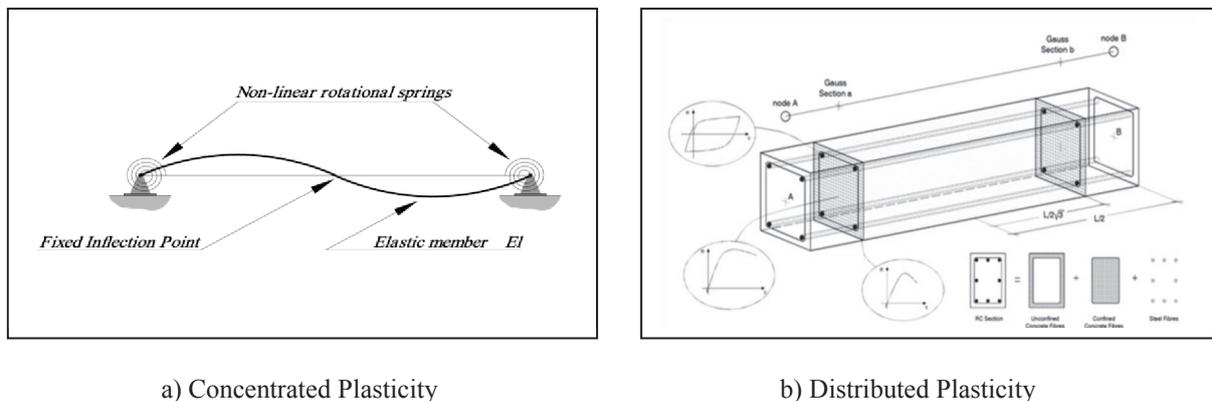


Figure 1. Methods for modeling inelastic behavior in structural elements (Bozorgnia, Y. and Bertero, V., 2004)

A nonlinear analysis for collapse safety assessment of structures has the following characteristics:

- 1) The materials (elements) models shall be capable of monitoring the response from elastic range to the peak point and eventually to the post-peak range of behavior appropriately.
- 2) The model shall be capable of capturing different modes of degradation such as peak strength degradation, unloading and reloading stiffness degradations and cyclic deterioration.
- 3) In three-dimensional assessment, the interacting effects among different modes of behavior such as moment, shear and axial modes have to be captured by the model.
- 4) Degrading effects due to P- Δ shall be captured by the model, especially for tall (flexible) structures.
- 5) There shall be a possibility for establishing simple relationships between structural design parameters and corresponding nonlinear modeling properties of concentrated springs.
- 6) Covering a rational range of design parameters such as (P_u/P_o) - the ratio of design axial force to the axial force capacity of elements- is preferable in the models.
- 7) Modeling the beam-to-column joint is preferable for increasing accuracy of the model.

Currently, researchers involved in collapse safety assessment of reinforced concrete structures take benefit from inelastic models adopted in (FEMA P-695, 2009) for both columns and beams. Generally, these models-which are based heavily on a comprehensive test database- cover items 1, 2, 5 and to some extent item 7. Item (4) is intended to be covered in the analytical model input. The inability of the adopted models in capturing items 3 and 6 is a major limitation, especially in assessing

collapse safety margin of three-dimensional irregular (coupled response) structures. Enhanced and more comprehensive calibrated models are therefore needed for modeling such structures.

The adopted model for RC structures in FEMA P-695, which is generally developed for two-dimensional structures, has been implemented in OpenSees by Altoontash (2004). It is the latest version of element collapse models developed by Ibarra et. al. (2008) for inelastic and collapse modeling of RC structures. The model has been implemented as the Clough model. There are, however, some limitations with the implemented model as below:

- 1) As with other material models, there is a lack of information on the model in the manual of the software. Documentation is imperfect and the model arguments are not clearly defined. Inexperienced users may face great difficulty in using the model. The new online Wiki of the software may overcome this problem, as it could be updated more easily than the printed version of the manual.
- 2) There is a very important and undocumented bug in the model implementation regarding the unloading stiffness degradation rules. It is a very important bug and has not been fixed since the first implementation of the model.
- 3) No interaction effects are considered in the model. This is due to the limitations of the calibrated test data.

The lack of appropriate post-processor for interpreting the output data should also be added to the above list of limitations. This is, indeed, a main source of complications about the software made by new users. It seems that, the two post-processors coded by the OpenSees developers (i.e. the Navigator and Tcl graphical post-processor) are not being updated currently. Since developers implement new codes to the software, it is believed that the gap between the above-mentioned post-processors and the new implementations is getting larger day by day. Due to this major limitation, advanced users try to develop their own post-processors to overcome this problem, especially for extracting enormous nonlinear time-history analysis outputs. In authors' opinion, with no appropriate post-processor, nonlinear collapse assessment of three-dimensional structures would become quite time-consuming and difficult, if not impractical. This is the reason that the authors have developed their own graphical post-processor which is very efficient in evaluating the nonlinear inelastic static and dynamic response of structures. The developed program will be introduced later in this paper and is accessible via a request sent to any of the authors.

3- PREPARING INPUTS FOR OPENSEES AND PERFORMING NONLINEAR ANALYSIS

The OpenSees takes the structure input data from text file written in Tcl/Tk programming language format. All needed data such as materials specifications, elastic elements data, nonlinear elements data, masses, loads, support conditions, records, and static and dynamic load patterns should be defined appropriately in the text input file. While it may be rather convenient to define two-dimensional structures via a line-by-line written input text file, it seems that preparation of such input data file for three-dimensional structure is quite time-consuming. The problem would be overcome by either using an appropriate graphical user interface (GUI) or using Loop commands in the Tcl/Tk input file. The authors have taken benefits from the second technique by defining all the needed input data in Lists and then calling these lists (via the *lindex* command in Tcl/Tk) in loop commands to make the complete input file. In this way, the time needed to model even large structures would be reduced quite effectively.

Modeling mass properties of the model is another issue of importance. In general, mass can be defined either by defining the total mass at each floor at the calculated center of mass or by defining the nodal masses separately. It seems that for modeling structures with mass irregularities in plan, it would be better to define masses via the latter approach; since the former needs defining polar mass moment of inertia, which again depends on the distribution of nodal masses in the plan. Unbalancing nodal masses for introducing mass eccentricity in plan should be based on a rational distribution. An interesting subject which needs more study, is investigating the effects of nodal mass distribution on nonlinear response of structures. At best, this can be a sensitivity analysis.

4. NONLINEAR ANALYSIS OF LARGE THREE-DIMENSIONAL MODELS

As we know, performing nonlinear analyses, especially time-history procedures, are quite time-consuming. This, mainly, comes from iterations needed in solving the equilibrium equations and updating the state of the structure in the current step. It is obvious that the speed of the analysis – a major concern in nonlinear three-dimensional structures- depends on various parameters such as numbers of active degrees of freedom in the structure, hysteretic rules adopted for a specific material or element model, computer hardware specifications and capabilities of the solution algorithms and the computer program used as the analysis engine.

Analysis engine of OpenSees is quite robust and powerful. It takes benefits from various algorithms for solving large equilibrium systems of equations, various convergence tests (based on energy, displacement, etc), various integrators and constraints.

In a collapse safety assessment, due to the need for monitoring the structure behavior from initial elastic state to yielding to peak and finally to a residual state via a descending branch under large number of records scaled to different intensities (IDA analysis), speed is a major concern. Without a robust and fast analysis program, it would be quite tedious and difficult –if not impractical- to assess collapse safety of three-dimensional structures efficiently.

Fortunately, OpenSees is able to solve large systems of equations in a Parallel Mode. As we know, parallel solution is a very efficient technique for solving large sparse algebraic systems of equations commonly encountered in nonlinear finite element analysis of structures. It is believed that implementing parallel capabilities in earthquake engineering simulation platform is a great achievement. With this powerful capability, one can engage all his/her own computer CPUs powers for solving a large model. It is therefore argued that taking the benefits from multi-core CPU technologies is essential for assessing collapse safety margin of three-dimensional structures on personal computers (PCs). Performing approximately 150 nonlinear three-dimensional incremental dynamic analyses (IDA) by considering bi-directional seismic loading, is now possible with parallel capabilities of OpenSees in an overnight for a typical 6-story 3-span (with about 100 nodes) in each direction with a Core-i7® or similar CPU. It is therefore possible to define smaller analyses intensity steps in IDA analyses for increasing accuracy.

It is also possible to perform the analyses in the parallel mode on a cluster of computers. In this case, a Message Passing Interface (MPI) module passes the segmented equation systems to different computers on the network and collects the results upon completion of the jobs (tasks) from each computer.

4- NEW GRAPHICAL POST-PROCESSOR FOR NONLINEAR RESPONSE AND COLLAPSE SAFETY ASSESSMENT OF 3-D STRUCTURES

As stated in the previous sections, a major problem in using OpenSees is the lack of suitable post-processor, which due to the enormous amount of numerical outputs generated by OpenSees is quite essential in assessing seismic collapse safety of buildings. In assessing the collapse behavior, one needs to examine both the nonlinear static (pushover) curve and nonlinear time-history analysis results (IDA results). Moreover, the user should be confident with the elastic analysis results, mainly modal analysis and internal forces in the elements.

Based on the above mentioned requirements for a typical post-processor, the authors have developed a new graphical user interface (GUI) which reads the OpenSees-generated numerical results and convert them to quite useful graphical representations. Figure (2) shows a print screen of the software.

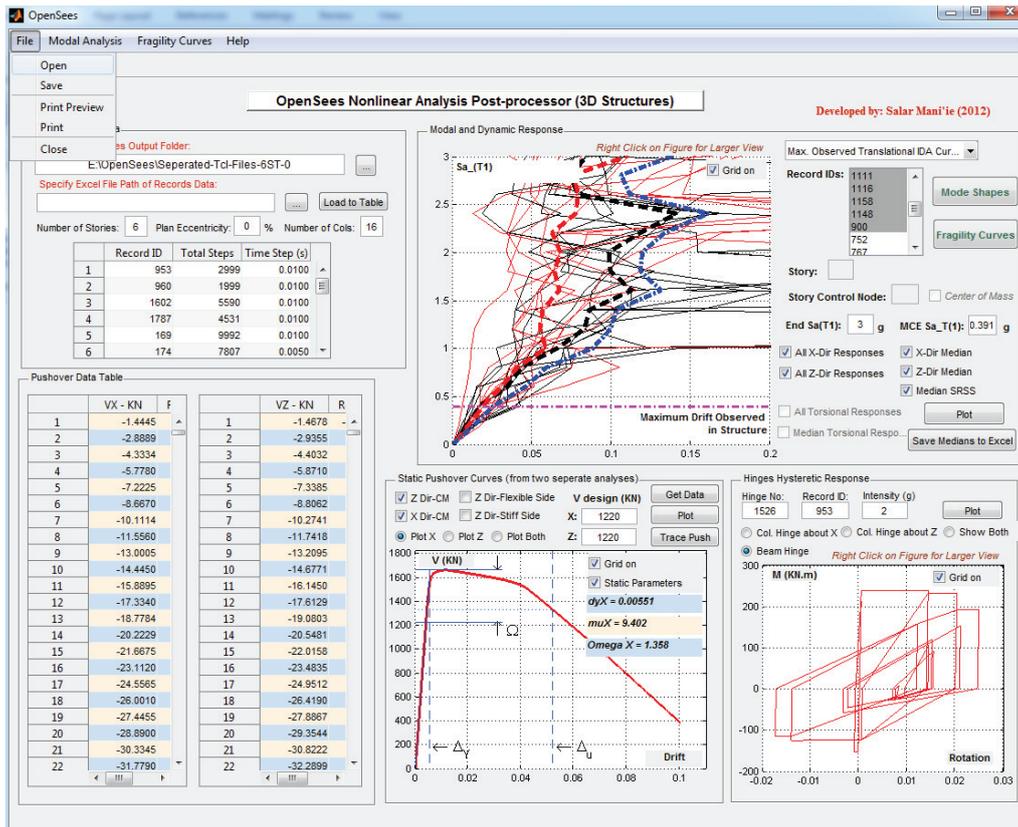


Figure 2. A screen of the software environment

At the upper left of the software window, general model data are introduced to the software. This includes the output folder path for the results, number of stories, plan eccentricity (in 3-d models), number of columns and records general data which can be imported from an existing excel file. The generated results and figures on the screen can be saved using the Save item in the File Menu also can be reopened via the Open item in the menu. Print Preview and Printing capabilities are, also, provided for the software in the File Menu.

The other four panels relate to different processing modules; namely modal and dynamic responses, pushover data table (base shear vs. roof drift in both directions), pushover curves with related performance parameters (i.e. δ_y , μ and Ω) and Hinges hysteretic response modules.

In the following, each panel (module) will be briefly introduced with its capabilities:

a) Modal and Dynamic Response Panel

Dynamic response evaluation is essential in assessing seismic collapse safety. The main data required are the results of incremental dynamic analyses (IDAs) which should be performed under different records with appropriate intensities ranging from low to high. Figures (3) and (4) show a larger view of this panel with the output options included in the drop-down menu on the right. These include:

- Nodal Translational IDA curves along axis
- Maximum observed translational IDA curves along axis
- Absolute torsional IDA curves about Y-axis (vertical axis)
- Maximum observed absolute torsional IDA curves about Y-axis (vertical axis)
- Structure hysteretic response
- Stories CM/Roof Drift SRSS IDA curve
- Maximum observed CMs translational IDA curves along axis

- Nodal time-history drift response
- Beam-hinge time-history response
- Column-hinge time-history response

The user selects the desired output in the drop-down menu, sets the required data in the text fields on the panel and finally clicks Plot button to generate the results.

IDA results:

Since generating IDA curves is quite time-consuming when large numbers of records are selected, the progress of generating is shown to the user. Outputs can be generated for center of mass of stories (CM) or at another controlling node in the plan. Also, the user can specify the End intensity (in terms of $S_{a(T1)}$ – spectral intensity at the fundamental period of the structure on the Median Response Spectrum of the record set) for plotting. After generating the IDA curves in both directions (for 3-d models), median curves at each intensity for both directions as well as the SRSS combination of them will be plotted in different colors. The user can limit the displaying curves using the checkboxes on the panel.

After generating the IDA curves, median curve data can be written to an Excel file via pressing the Save Medians to Excel button on the panel. This is useful while the user intends to do more with his/her numerical data.

The user, also, has the possibility to peak up the collapse level for each record graphically, upon which the software can automatically calculate collapse margin ratio and the fragility curves for the two directions separately based on the collapse data taken by the user.

Torsional IDA (TIDA) curves, a new measure introduced by the authors for collapse safety assessment of three-dimensional buildings, which show absolute story torsion angle or inter-story torsion drift vs. spectral intensity can also be plotted. This measure is useful in assessing collapse behavior of 3-D torsionally-stiff or torsionally-flexible structures.

Structures hysteretic response:

Structure hysteretic response, defined as base shear vs. story-1 drift is accessible through an item in the drop-down list. The software generates the curves for the two directions separately. Figure (5) shows a typical hysteretic response for a structure under record ID. No. 1787 at spectral intensity equals to 1g.

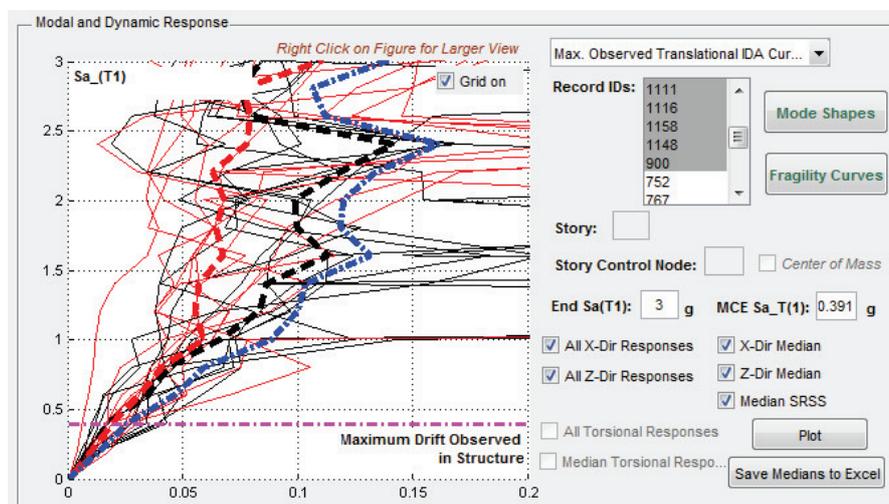


Figure 3. Modal and Dynamic Response Panel

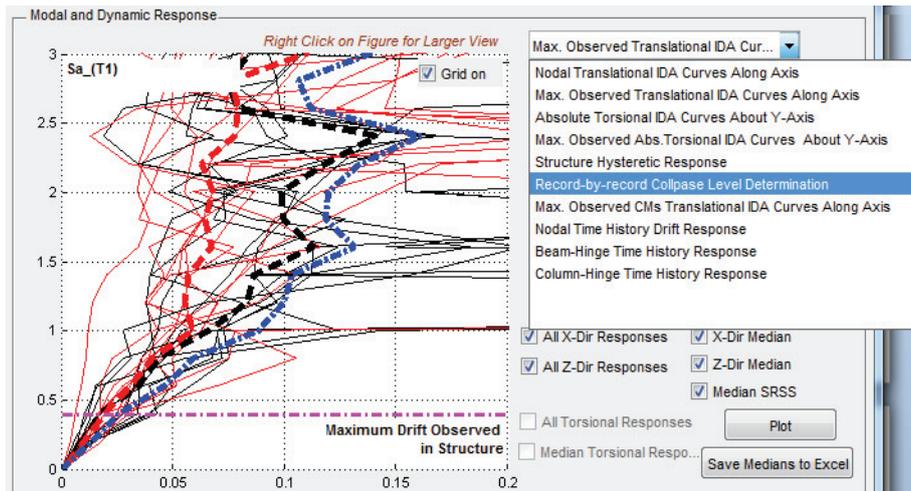


Figure 4. Modal and Dynamic Response Panel

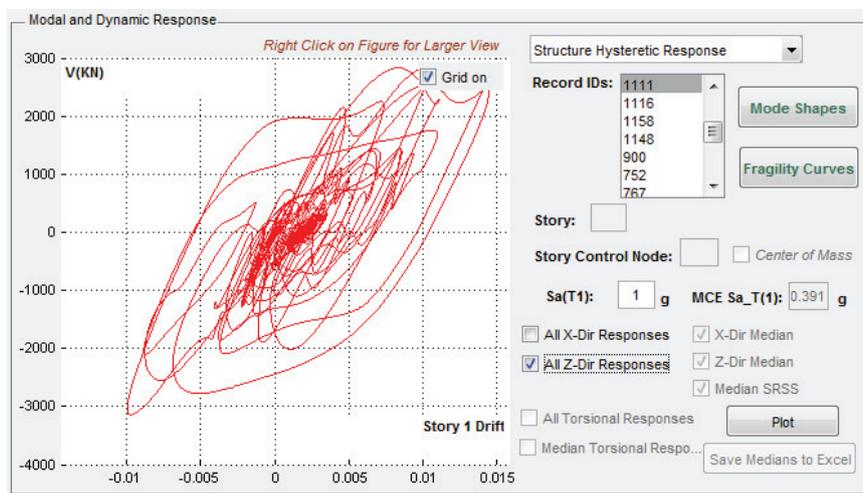


Figure 5. A typical hysteretic response for $S_{a(T_1)}=1g$ under record ID. No. 1787

Nodal time-history response

Nodal time-history response can be plotted via specifying the node ID at the desired story under a specific record ID and intensity. The plot will be generated for both directions in plan with different colors (red and black). Figure (6) shows a typical nodal history response at CM of story 6 of a typical model under record ID. No. 1787 and spectral intensity equal to 0.4g. Note that, as seen in Figure (2), a toolbar is provided at the top of the screen to enable the user to do Zoom in/Zoom out, pan and point-by-point data tracing (see Figure 6) in the generated plots. The user can also turn on/off response along any direction in plan using the Checkboxes on the panel.

Beam-hinge or Column-hinge time-history response

Beam-hinge or column-hinge time-history response can be plotted for a specific hinge ID in the model under a specific record and specific spectral intensity. This option plots the hinges rotation (in radian) vs. time. Figure (7) shows a typical beam-hinge plot for a hinge with ID. 1526, under record ID. No. 1787 and spectral intensity equal to 1.0g.

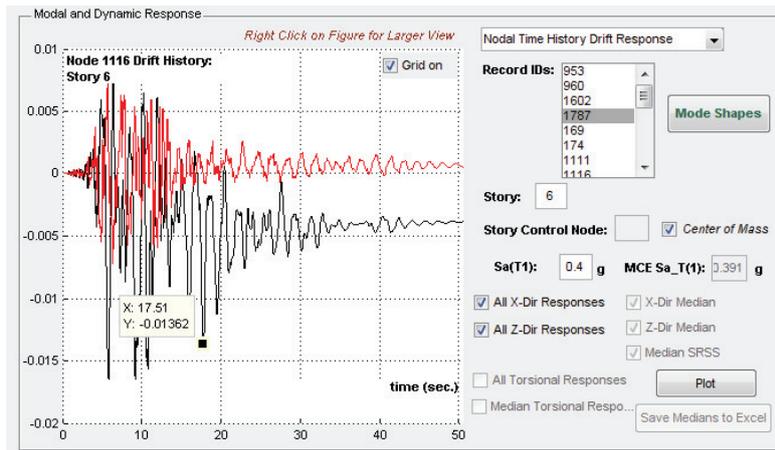


Figure 6. A typical nodal time-history response (data cursor is seen on the plot)

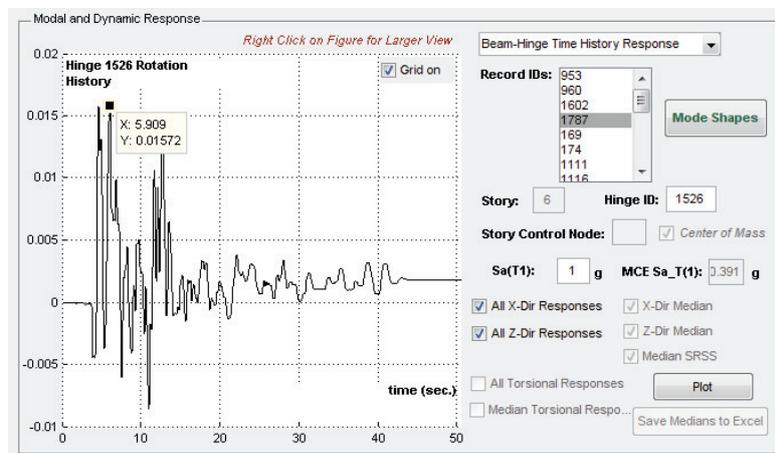


Figure 7. A typical beam-hinge time-history response (data cursor is seen on the plot)

Mode Shapes

Another useful capability of the software is extracting eigen-value analysis results generated by OpenSees and draw and animate the mode shapes. The user should specify the required number of modes in the Recorders of his/her model. By clicking on the green-text Mode Shapes button of the right upper side of Modal and Dynamic Response panel or from the Modal Analysis menu, a new figure as shown in figure (8) will open.

The user only needs to specify Mode No. in the drop-down menu and click the Start-Refresh Button on the Animation Control panel. An animation starts; its speed and scale can be controlled using the two sliders placed at the bottom of the Animation Control panel. Mode period and frequency will be shown in the text boxes. Undeformed shape and grid lines can be removed from the figure using a Checkbox at the bottom of the figure.

b) Static nonlinear response (pushover) curves

The next panel to introduce is the nonlinear static response panel. On this panel, the user should specify the desired node on plan for generating the pushover curve, which can be the center of mass (CM) or the nearest and farthest node (stiff and flexible side, respectively) and design base shears in both directions for a 3-D model. By pushing the Get data button, the pushover curve will be plotted with automatically calculated performance parameters, (i.e. δ_y , μ and Ω), all based on FEMA P-695

recommendations. (Figure 9) Simultaneous plotting pushover curves in both directions is also possible

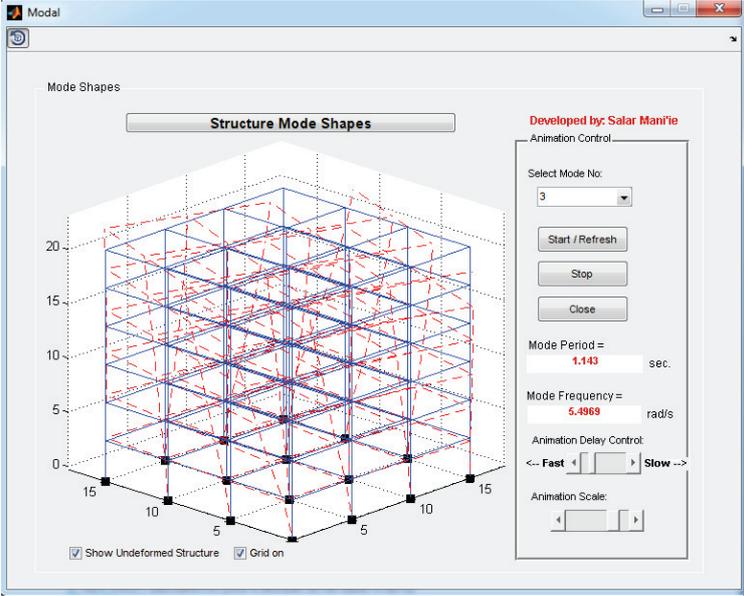


Figure 8. Mode shapes and periods (a typical torsional mode is shown)

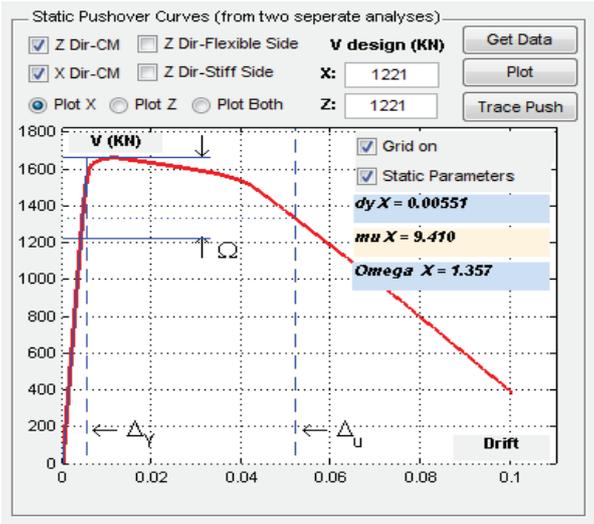


Figure 9. Pushover curve and automatically calculated performance parameters

using the Plot Both Radio button on the panel. Another interesting capability of the software, is tracing the hinges response from initial state to collapse state by clicking the Trace Push button on the panel. A window as in figure (10) will open. In this window, the user specifies the roof drift in a text field in the Data Control panel and then clicks ‘Go to Step’ button. All hinges rotations will be shown graphically in the figure on the left with red (for x-direction hinges) and green (for z-direction hinges) circles, radii of which are scaled based on the relative rotation value compared to the maximum observed rotation in the structure. The maximum rotation value and the hinge in which such rotation has occurred are shown on the Data Control panel in two separate text fields for beams and columns separately. Also the current status of the structure will be shown on the pushover curve at the lower right side of the window with the red circle. Rotation values can be viewed using the checkboxes in the View Options panel. The user can view his/her structure in 3-D or in different planes by clicking the appropriate buttons on the mentioned panel in the window.

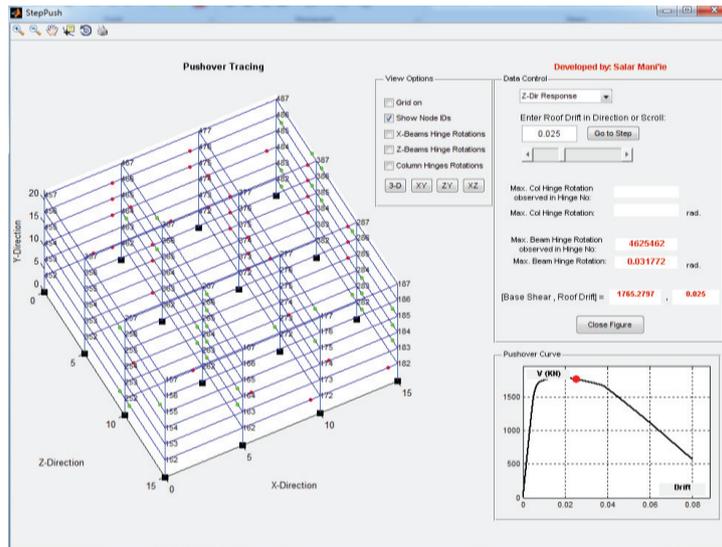


Figure 10. Step-by-step pushover tracing window

c) Hinges hysteretic response and fragility curves

This panel on the main window of the software plots the hysteretic response of beam and column hinges under a specific record and spectral intensity. Due to space limitations, this figure will not be shown again here (refer to figure (1) for a screen shot of this panel). It is quite useful for checking the general behavior of hinges that the user intended to simulate.

CONCLUDING REMARKS

This paper identified major problems in collapse safety assessment of 3-D structures such as defects in existing nonlinear models for capturing bi-lateral seismic loading effects on these structures. It is argued that some of these defects can be resolved by creating suitable analytical models, while some other need more study, such as the necessity for developing bi-axial hinges models specifically applicable to collapse assessment of 3D structural systems. Also, the lack of an appropriate post-processor in using OpenSees analysis software as a good modeling and analysis engine option for collapse safety assessment of RC structural systems was recognized. The paper introduced a new graphical user interface (GUI) specifically developed by the authors for post-processing the analysis results generated by OpenSees for collapse behavior assessment of 3D structures.

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