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A USER-FRIENDLY ENVIRONMENT FOR NONLINEAR-STRUCTURAL ANALYSIS

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SUMMARY

Nonlinear analysis of structures has become increasingly important in the study of structural response to hazardous loads such as earthquake and blast. Currently available tools for such analysis are research programs lacking convenient user-interfaces, or are general purpose Finite Element programs that require very fine-grained modeling that is often impractical to the engineer. This paper describes the outcome of a collaborative effort between the University at Buffalo and Larsa, Inc. in developing a user-friendly environment for such analyses, aimed at overcoming the above-mentioned shortcomings. The environment provides the ability to perform modeling at the necessary level, yet not requiring the engineer to have to deal with the fine-grained details. Both theoretical and implementation aspects are discussed. Firstly inelastic material models as well as uni-axial and coupled "spring" elements based on these models and the user-interfaces related to them are discussed. Next, two inelastic beam-column elements, one with concentrated uncoupled flexural plasticity and the other with distributed plasticity with three-dimensional interaction are described along with the various numerical as well graphical outputs representing to the inelastic response of such elements. Nonlinear static as well as dynamic analysis procedures utilizing automatic step size control algorithms are discussed next. Analysis features are described for the equivalent static procedure (pushover analysis) used in seismic design and in the load redistribution analysis under element loss such as under blast loading. Since both these load conditions involve constant load profiles with only a scalar parameter, an automatic stepping algorithm combined with an arc-length control strategy is utilized. Several illustrative examples of all these features are presented.

INTRODUCTION

Nonlinear analysis of structures has become increasingly important in the study of structural response to hazardous loads such as earthquake and blast. Currently available tools for such analysis are research programs lacking convenient user-interfaces, or are general purpose Finite Element programs that require

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very fine-grained modeling that is often impractical to the engineer. This paper describes the outcome of a collaborative effort between the University at Buffalo and Larsa, Inc. (LARSA [1]) in developing a user-friendly environment for such analyses, aimed at overcoming the above-mentioned shortcomings. The environment provides the ability to perform modeling at the necessary level, yet not requiring the engineer to have to deal with the fine-grained details.

REPRESENTATIONS OF CONSTITUTIVE BEHAVIOR

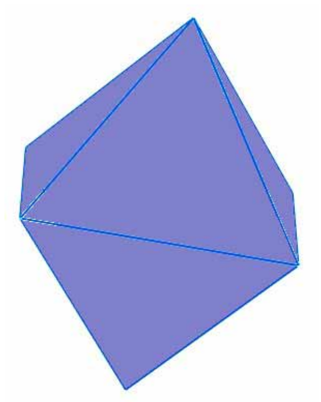


Figure 1. Octahedral Yield Surface

In addition to conventional material and section property definitions, it is possible to specify nonlinear and inelastic constitutive behavior in two other fashions: (i) Nonlinear Curve and (ii) Yield Surface.

Spring Curve

The spring curve is the definition of a force-displacement or a moment rotation relationship by specifying points along the curve as shown in Figure 6. It is used in the modeling of nonlinear and hysteretic springs and of end springs in connection beams as discussed later.

Yield Surface

The yield surface is a surface comprising a patchwork of planes. It is defined to be the bounding surface of a closed volume enclosed by intersecting planes. The planes are defined in the form:

$$ax + by + cz = d \tag{1}$$

where x, y and z are various stress resultants such as forces and moments. Notice that equation (1) is related to design code equations such as:

$$\left|\frac{P}{P^y}\right| + \left|\frac{M_y}{M_y^y}\right| + \left|\frac{M_z}{M_z^y}\right| = 1 \tag{2}$$

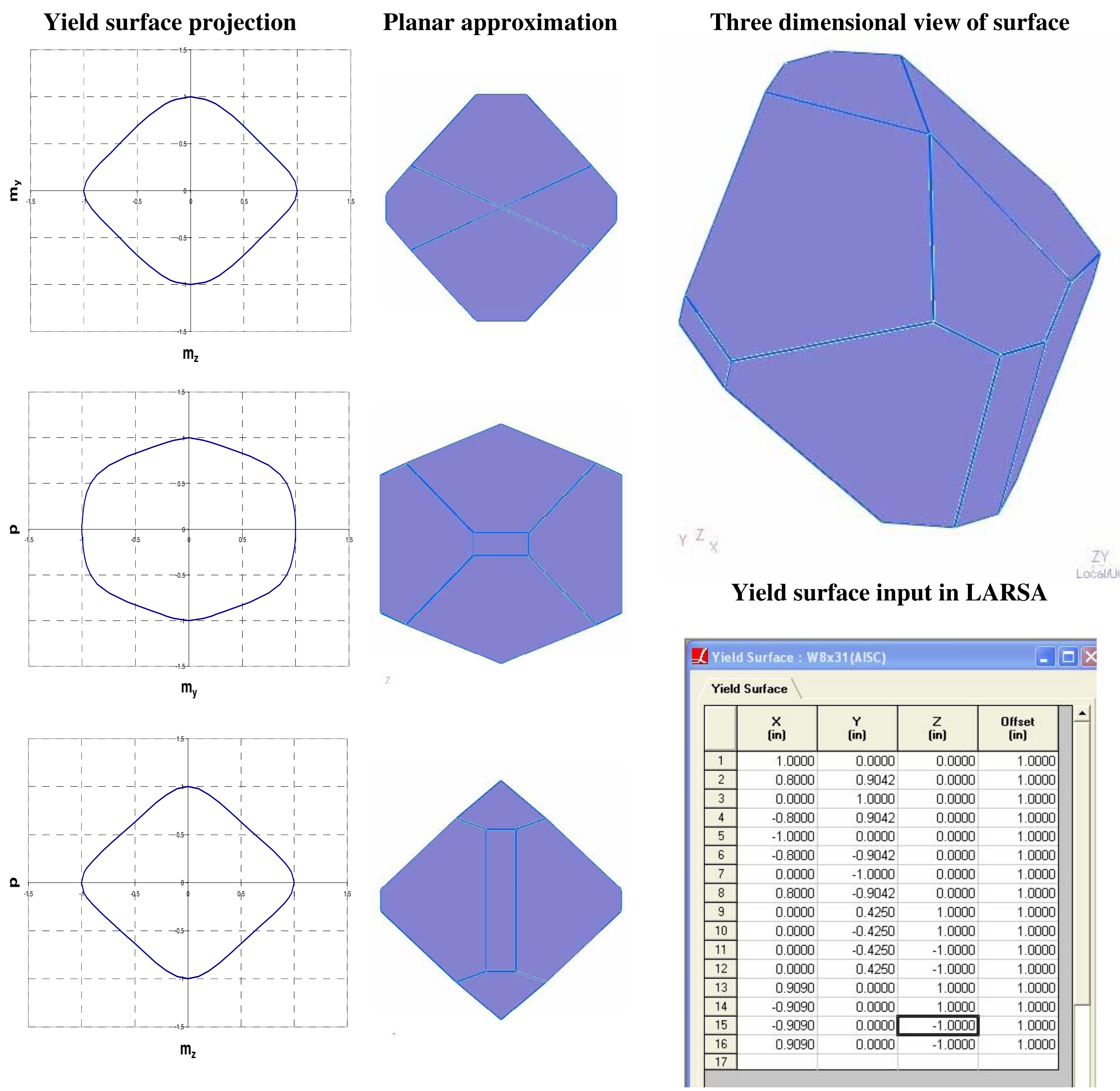
where P = axial force, M_y = bending moment about the weak axis and M_z = bending moment about the strong axis and P^y, M_y^y and M_z^y are their respective factored capacities. Equation (2) could be represented using eight planes of the form (1) as shown below resulting in an octahedral yield surface:

$$\begin{gathered}
(i)\frac{P}{P^y}+\frac{M_y}{M_y^y}+\frac{M_z}{M_z^y}=1 \quad \left(a = {}^{1}\!/\!_{P^y}, b = {}^{1}\!/\!_{M_y^y}, c = {}^{1}\!/\!_{M_z^y}, d = 1\right) \\
(ii)\frac{P}{P^y}-\frac{M_y}{M_y^y}+\frac{M_z}{M_z^y}=1, \quad (iii)\frac{P}{P^y}+\frac{M_y}{M_y^y}-\frac{M_z}{M_z^y}=1, \quad (iv)\frac{P}{P^y}-\frac{M_y}{M_y^y}-\frac{M_z}{M_z^y}=1 \\
(v)-\frac{P}{P^y}+\frac{M_y}{M_y^y}+\frac{M_z}{M_z^y}=1, \quad (vi)-\frac{P}{P^y}-\frac{M_y}{M_y^y}+\frac{M_z}{M_z^y}=1, \\
(vii)-\frac{P}{P^y}+\frac{M_y}{M_y^y}-\frac{M_z}{M_z^y}=1, \quad (vii)-\frac{P}{P^y}-\frac{M_y}{M_y^y}-\frac{M_z}{M_z^y}=1
\end{gathered} \tag{3}$$

Such as yield surface is shown in Figure 1. Surfaces that are not as simple can be approximated to any desired accuracy by a patchwork of planes, thus providing for a general way of representing any yield surface. For instance McGuire [2] presents a yield surface suitable for steel I-sections:

$$p^2 + m_z^2 + m_y^2 + 3.5p^2m_z^2 + 3p^6m_y^2 + 4.5m_z^2m_y^2 = 1 \qquad (4)$$

where $p = P/P^y$, $m_y = M_y/M_y^y$ and $m_z = M_z/M_z^y$. The piecewise planar approximation of this surface is shown in Figure 2. The yield surface is used in the triaxial-interaction spring and the hystertic beam element.



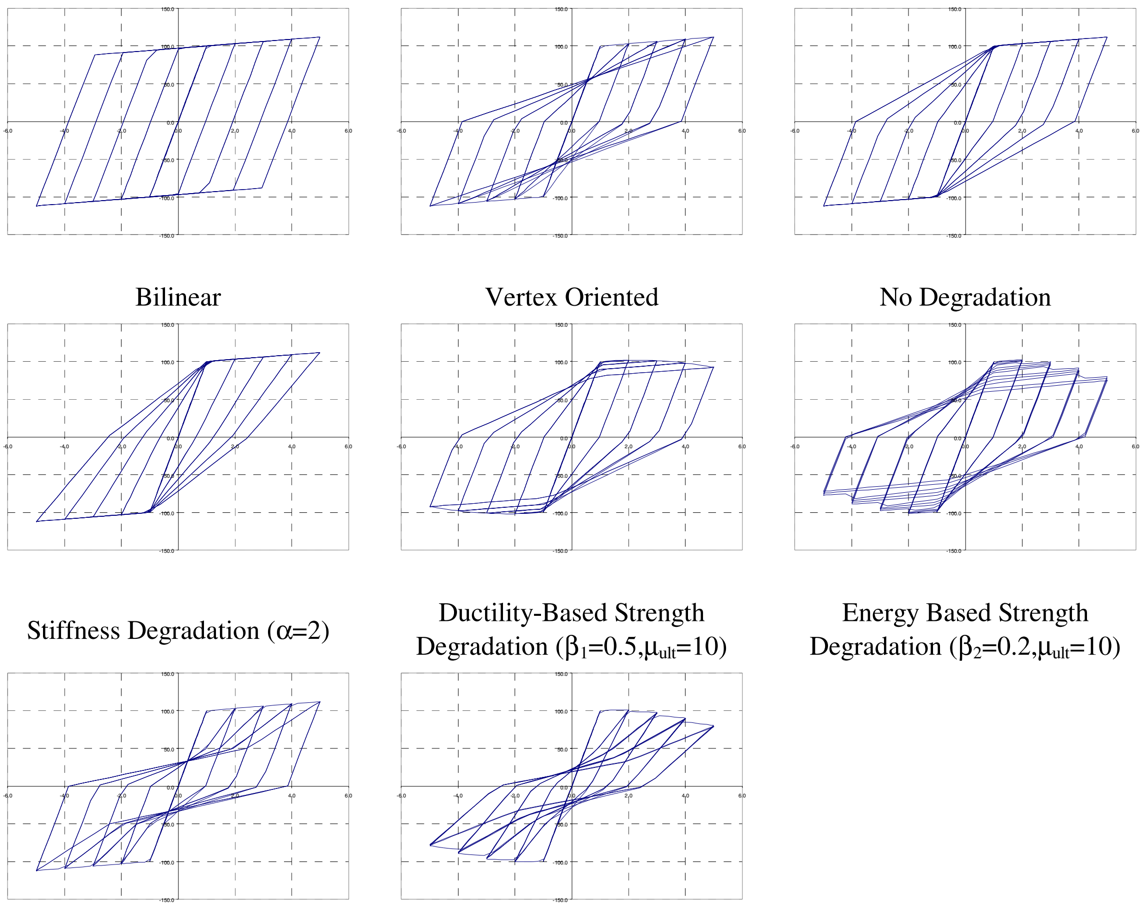
	X (in)	Y (in)	Z (in)	Offset (in)
1	1.0000	0.0000	0.0000	1.0000
2	0.8000	0.9042	0.0000	1.0000
3	0.0000	1.0000	0.0000	1.0000
4	-0.8000	0.9042	0.0000	1.0000
5	-1.0000	0.0000	0.0000	1.0000
6	-0.8000	-0.9042	0.0000	1.0000
7	0.0000	-1.0000	0.0000	1.0000
8	0.8000	-0.9042	0.0000	1.0000
9	0.0000	0.4250	1.0000	1.0000
10	0.0000	-0.4250	1.0000	1.0000
11	0.0000	-0.4250	-1.0000	1.0000
12	0.0000	0.4250	-1.0000	1.0000
13	0.9090	0.0000	1.0000	1.0000
14	-0.9090	0.0000	1.0000	1.0000
15	-0.9090	0.0000	-1.0000	1.0000
16	0.9090	0.0000	-1.0000	1.0000
17				

Figure 2. Three dimensional yield surface

INELASTIC ELEMENTS

Spring Elements

Five types of spring models are available: (i) Linear elastic spring, (ii) Nonlinear elastic spring (iii) Uniaxial Hysteretic Spring and (iv) Triaxial Hysteretic Spring. The first three springs work in translation and rotation in the global axis or as axial or torsional springs. The triaxial hysteretic spring is used to couple the local axial force and bending moments by means of a yield surface as discussed above. The linear spring can either be specified using a spring constant or by a 6x6 stiffness matrix. The nonlinear spring and the envelop of the hysteretic spring are specifies using a spring curve such as shown in Figure 6. The hysteretic spring uses a polygonal hysteretic model (PHM) introduced by Sivaselvan [3]. This is the same model used in the computer program IDARC2D (Valles [4]) and in the FEMA program NONLIN [5]. This model has strength and stiffness degradation capabilities as shown in Figure 3.



Bilinear | Vertex Oriented | No Degradation

Stiffness Degradation (α=2) | Ductility-Based Strength Degradation (β_1=0.5,μ_{ult}=10) | Energy Based Strength Degradation (β_2=0.2,μ_{ult}=10)

Slip (γ = 0.5) | Combined Degradation (α=5,β_1=0.5,β_2=0.2,γ=0.5, μ_{ult}=10)

Figure 3. Capabilities of the polygonal hysteretic model

Beam Elements

Besides the elastic beam element in LARSA 2000, three types of inelastic beam elements with inelastic material behavior have been implemented – (i) the "connection" beam element, (ii) the "hysteretic" beam element and (iii) the "yield-surface-based" beam element. The connection beam does not consider either axial interaction between force and moment components (uncoupled plasticity) or spread of plasticity along the length of the member (concentrated yielding model). while the latter includes both axial force-moment-moment interaction (3D coupled plasticity) and the spread of yielding along the length of the member due to hardening (distributed yield model). This section describes the connection beam element.

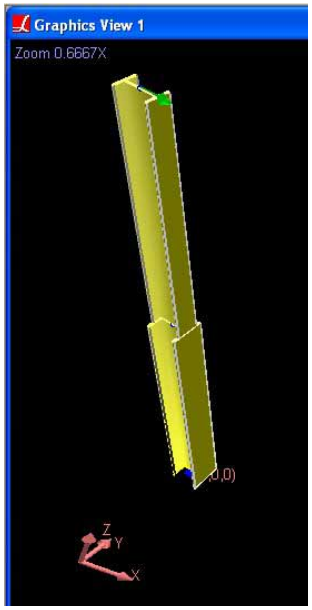
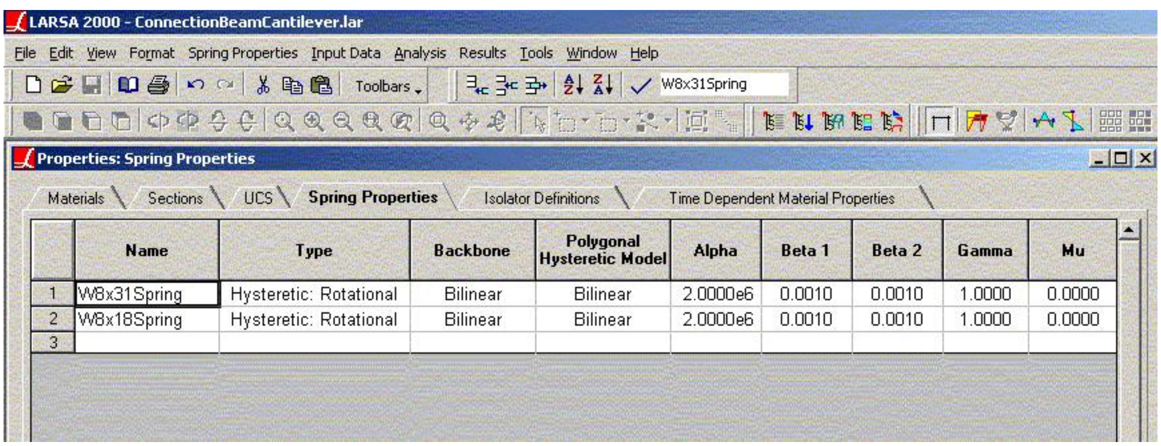


Figure 4. Cantilever modelled with two connection-beams

Connection Beam Element

The connection beam element consists of an elastic beam with built-in yielding springs at the ends. There can be up to four such end-springs – two springs at each end, one for each direction of bending. The properties of these springs can be assigned so as to model the elastic-plastic behavior of the beam itself and/or to model the flexibility and inelastic behavior of the end connections. The spring properties are assigned in LARSA 2000 using spring curves representing the moment-rotation behavior and by selecting the appropriate parameters that determine hysteretic behavior. When one or more spring properties are assigned to a member of "Beam" type in the "Member End Nonlinear Springs" tab of the member geometry spreadsheet, LARSA 2000 automatically uses a connection beam element for that member. The following example illustrates the use of the connection beam element. The example consists of a two-segment cantilever (Figure 4). A screenshot of the spring properties for the two beam elements is shown in Figure 5. The spring curves are created to reflect the inelastic properties of the beam cross-sections. In this example, the moment rotation curve is specified to be rigid-plastic by using an artificially large initial elastic slope and a post-yield slope of α*6EI/L, where E is the material modulus of elasticity, I is the moment of inertia of the cross-section, L is the length of the beam and α is the hardening ratio, taken as 3% in this case. One of the two spring property curves is shown in Figure 6.



	Name	Type	Backbone	Polygonal Hysteretic Model	Alpha	Beta 1	Beta 2	Gamma	Mu
1	W8x31Spring	Hysteretic: Rotational	Bilinear	Bilinear	2.0000e6	0.0010	0.0010	1.0000	0.0000
2	W8x18Spring	Hysteretic: Rotational	Bilinear	Bilinear	2.0000e6	0.0010	0.0010	1.0000	0.0000
3									

Figure 5. Spring properties for connection-beam elements

The association of the spring properties with the ends of the beam elements is shown in Figure 7. Notice that since only the behavior in the XZ plane is of interest in this case, the no springs are associated for bending about the local Y axis. By default, the element will behave elastically in this direction. The force-displacement plot when the cantilever is subjected to cyclic support displacement at the top is shown in Figure 8. In many occasions such as in bolted connections and reinforced concrete elements, the hysteretic behavior cannot be adequately represented by a simple bilinear model as done above. In such cases, LARSA 2000 provides parameters that can be modified to obtain different types of hysteretic behavior. For example, the pinching parameter, gamma(γ) is assigned a value of 0.5 in Figure 10 and the resulting pinched hysteretic loops are shown in Figure 9.

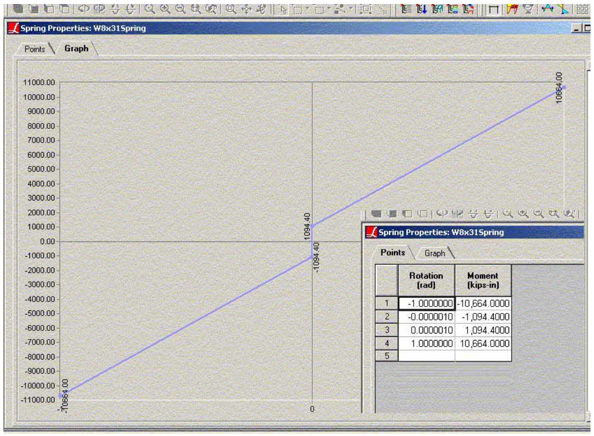


Figure 6. Spring curve for connection-beam end spring

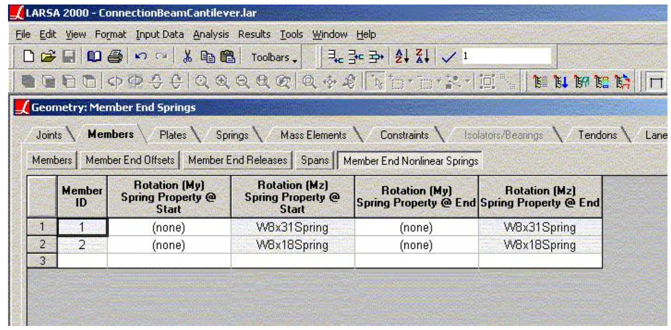


Figure 7. Association of springs with member ends

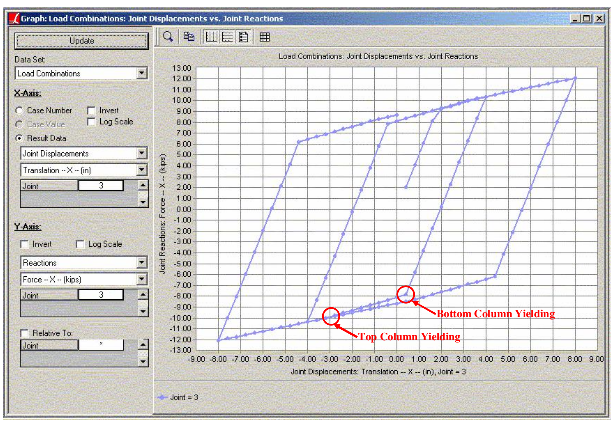


Figure 8. Force-displacement plot under cyclic loading

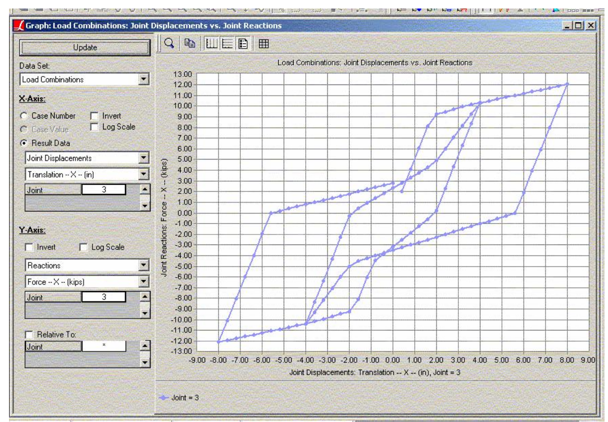


Figure 9. Force-displacement plot with slip behavior

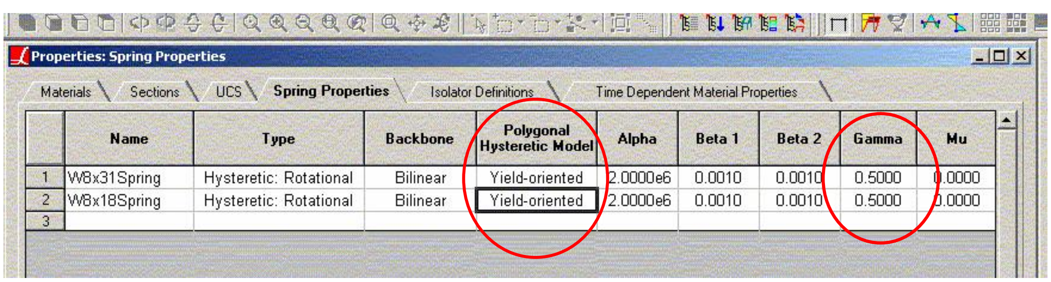


Figure 10. Hysteretic parameters for slip behavior

Hysteretic Beam Element

The hysteretic beam element models the continuous spread of plasticity along the length of a member and represents the interaction between axial force and strong and weak-axes bending moments using the smooth yields surface of equation (4) at a specified number of Gauss points along the length of the member. The formulation of the element is discussed in Simeonov [6] and Sivaselvan [7]. This element is used in the analysis examples presented in the next major section.

Yield Surface-based Element

In contrast to the hysteretic beam element the yield surface-based element accounts for interaction at the Gauss integration points using the piecewise planar yield surface discussed above. The formulation of this element is the subject of another article (Sivaselvan [8]). The element is used to model the 3D frame shown in Figure 11. The frame is subject to the non-proportional cyclic displacement profile shown in Figure 12. The x and y-displacement are on the respective axes in this plot. The resulting force-displacement plots in the x and y directions are shown in Figure 13 and Figure 14 respectively. The distortion of the hysteresis loops due to the interaction between the two moments can be seen.

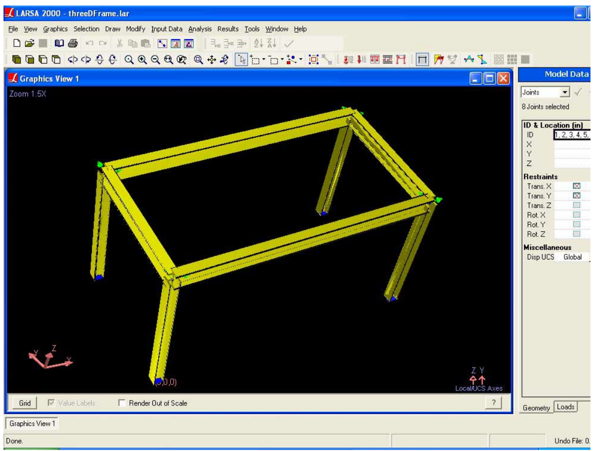


Figure 11. 3D Frame model

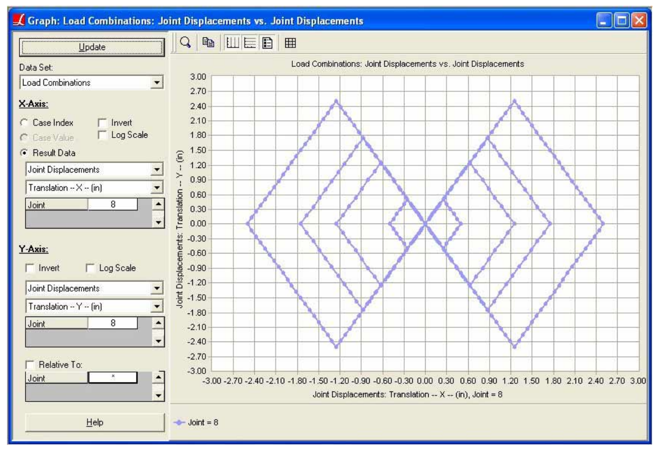


Figure 12. Non-proportional displacement history

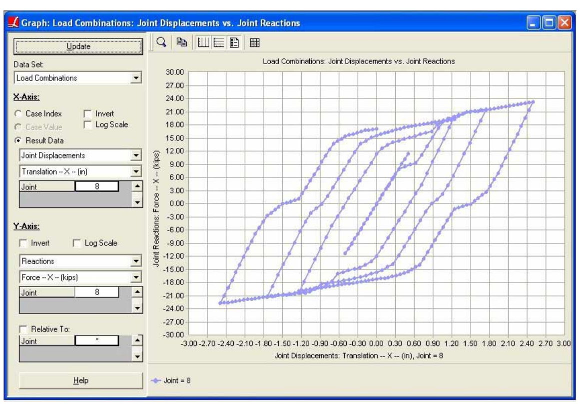


Figure 13. Force-displacement plot in the x-direction

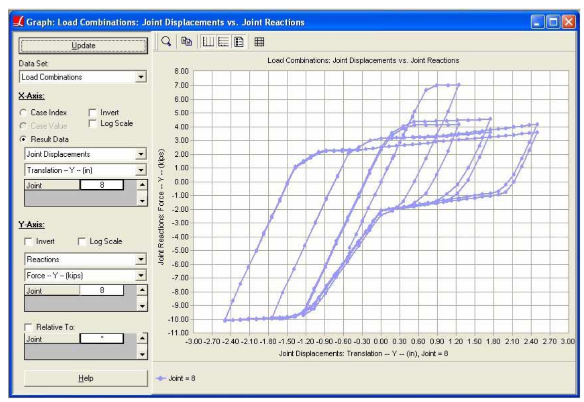


Figure 14. Force-displacement plot in the y-direction

Figure 15 shows a plot of the strong and weak-axis moments at the end-section of one of the elements. The plot shows the initial yield surface and the translation of the yield surface due to kinematic hardening. Figure 16 shows a plot of the displaced shape, while Figure 17 shows a plot of the variation of the yield fuction along the length of the hysteretic elements. Figure 18 through Figure 20 show the axial force and weax and strong axis bending moment diagrams.

SPECIAL ANALYSIS PROCEDURES

Besides the regular static and dynamic analysis procedures, it is possible to perform several special analyses suitable for seismic and collapse applications. These are discussed below.

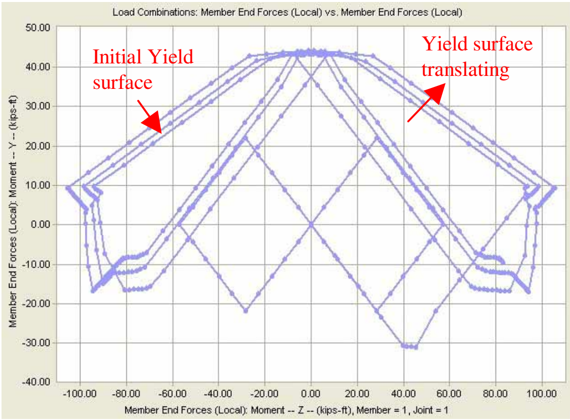


Figure 15. Weak and Strong-axis moments in the bottom cross-section of element 1

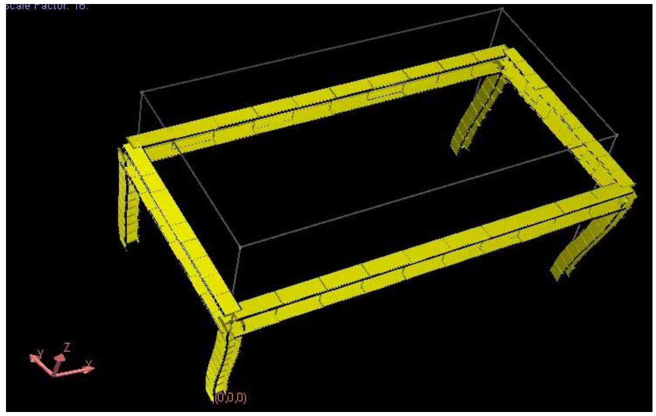


Figure 16. Displaced shape

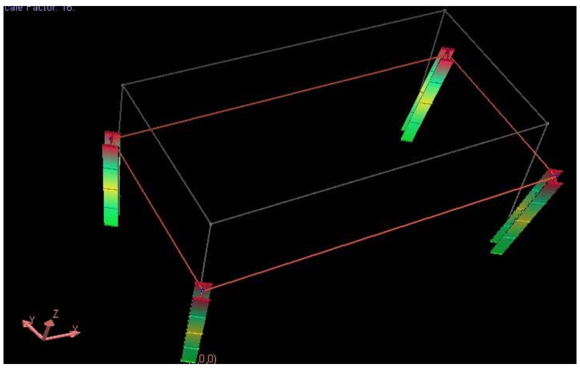


Figure 17. Yield Function Plot

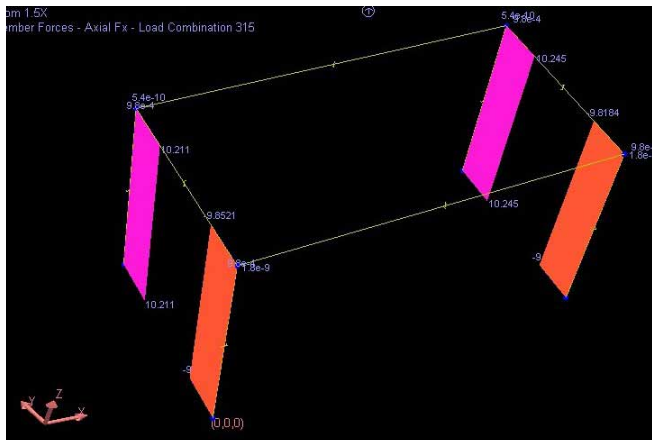


Figure 18. Axial force diagram

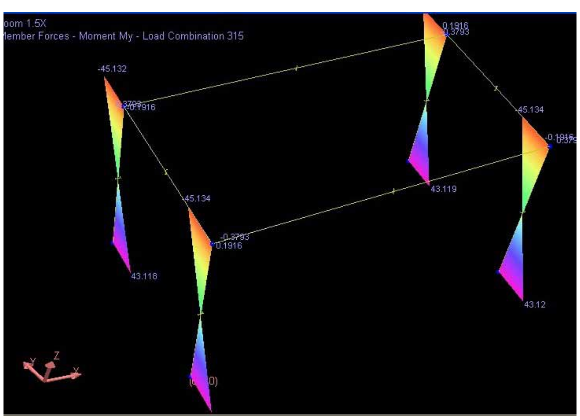


Figure 19. Weak axis moment diagram

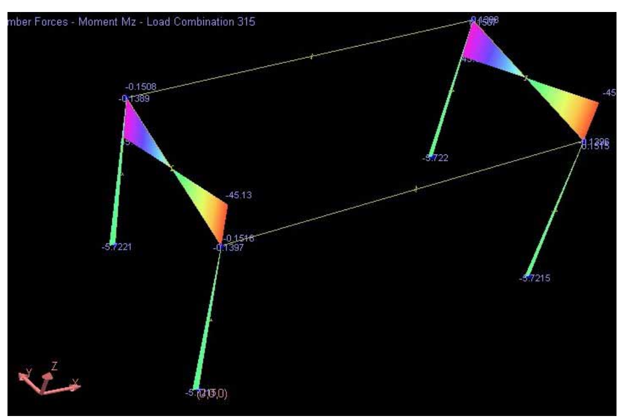


Figure 20. Strong axis moment diagram

Pushover Analysis (Equivalent Static Procedure)

The structure is subjected to a load of fixed profile but progressively increasing scale. The progressive increase in load scale is performed using auto-stepping combined with ar-length control (see for example, Crisfield [9]). This is available as a special analysis option Figure 21. A load case that is selected for pushover analysis as shown in Figure 22 is only used for profile information. The scaling is done automatically by the analysis engine. An example is shown in Figure 23. Hysteric beam elements are used in the modeling. The results are shown in Figure 24 and Figure 25.

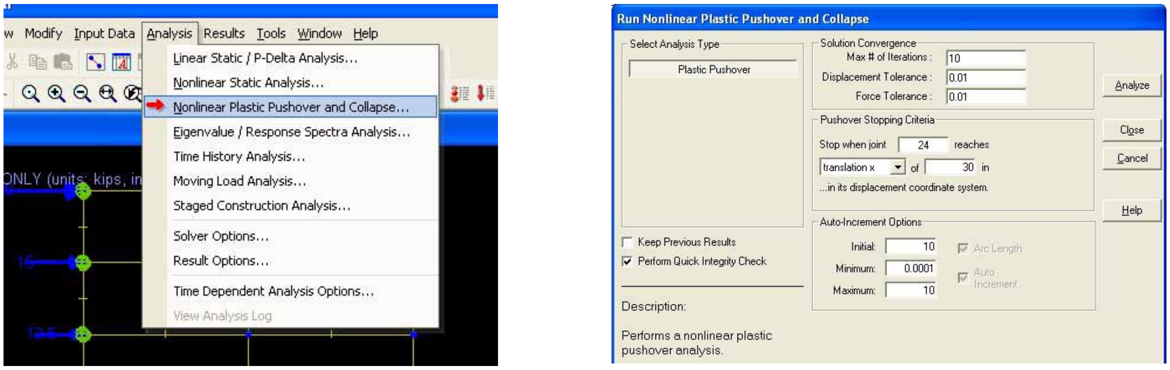


Figure 21. Pushover analysis configuration

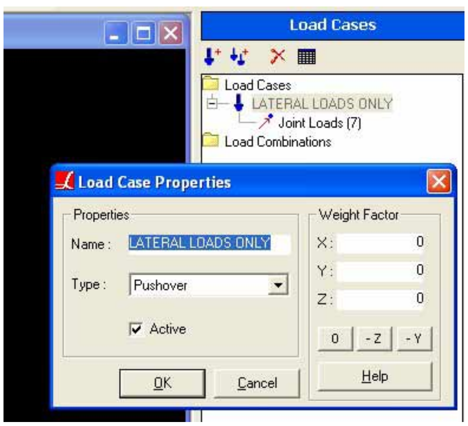


Figure 22. Pushover load-case configuration

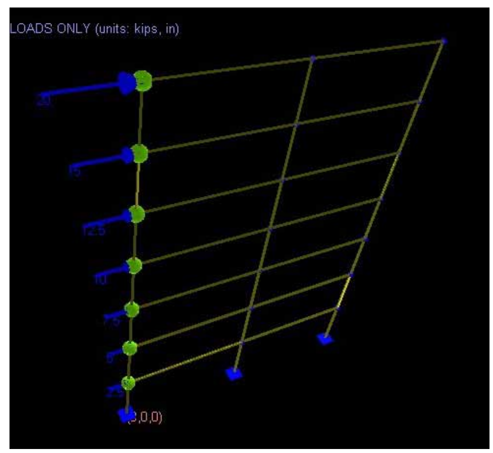


Figure 23. Example structure and load profile for pushover anlysis

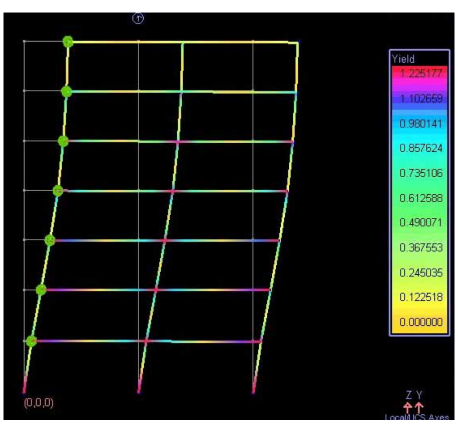


Figure 24. Displaced shape and yield function plot

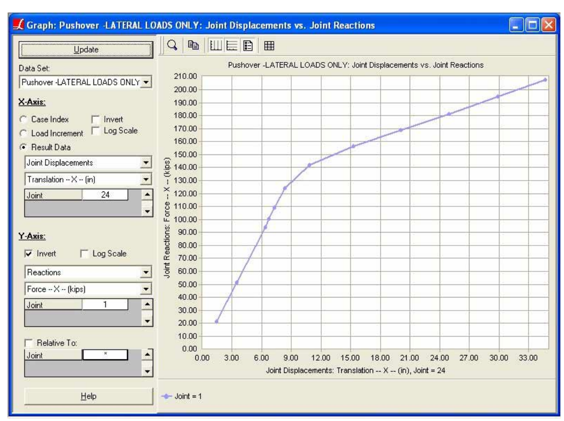


Figure 25. Base shear-roof displacement plot

Collapse Analysis

It is possible to analyze the inelastic load redistribution that occurs as a result of the loss of one of more members from a structure. When one more members are lost, the resulting unbalanced forces are first applied artificially to equilibrate the structure. The same load profile is then applied gradually in the opposite direction using the automatic stepping and arc-length control procedure. A load factor may be applied on these reapplied loads to represent dynamic conditions. The analysis is performed using the stage analysis capability of LARSA 2000 (Figure 26). The member removal stage is setup as a deconstruction stage and is specified as an inelastic collapse stage.

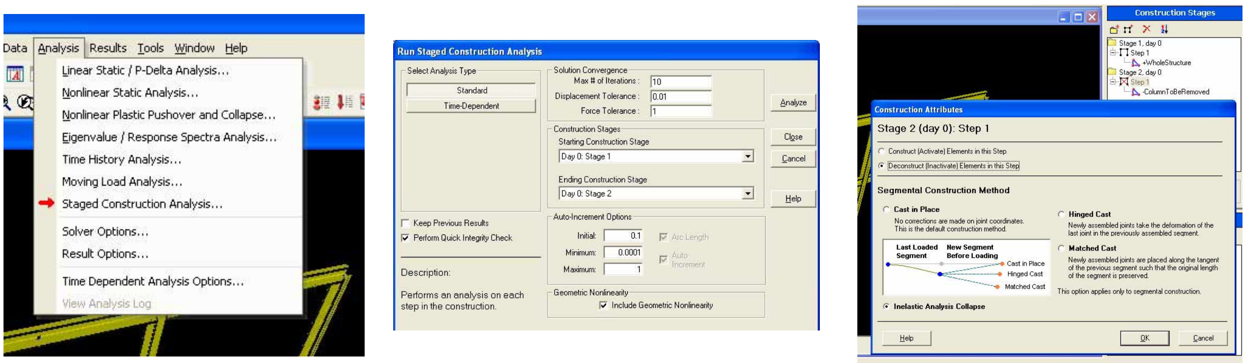


Figure 26. Collapse analysis configuration

A two-story two-bay frame is used as an example. The middle column in the lower story is removed. Figure 27 and Figure 28 show the bending moment diagrams before and after the removal of the column are shown respectively. The yield diagram is shown in Figure 29. The tension stiffening behavior is influenced by geometric nonlinearity as well as by axial force-moment interaction. These are both considered in the analysis.

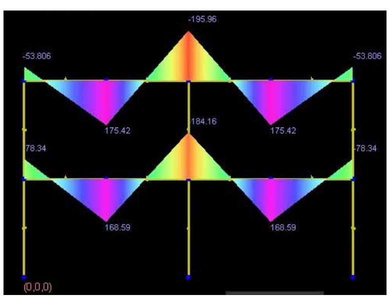


Figure 27. Moment diagram before column removal

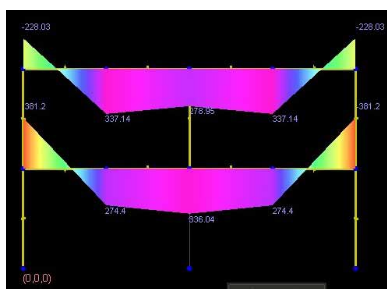


Figure 28. Moment diagram after member removal

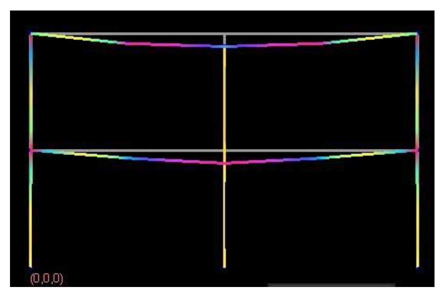


Figure 29. Yield diagram after member removal

Nonlinear dynamic time-history analysis

Figure 30 shows the result of a nonlinear time-history analysis of a portal frame. The program has the ability for automatic time-stepping in nonlinear dynamic analysis.

CONCLUDING REMARKS

Inelastic analysis tools have been presented for static and dynamic analyses of structures for seismic and collapse applications. The examples presented in this paper are available for download from http://www.larsausa.com.

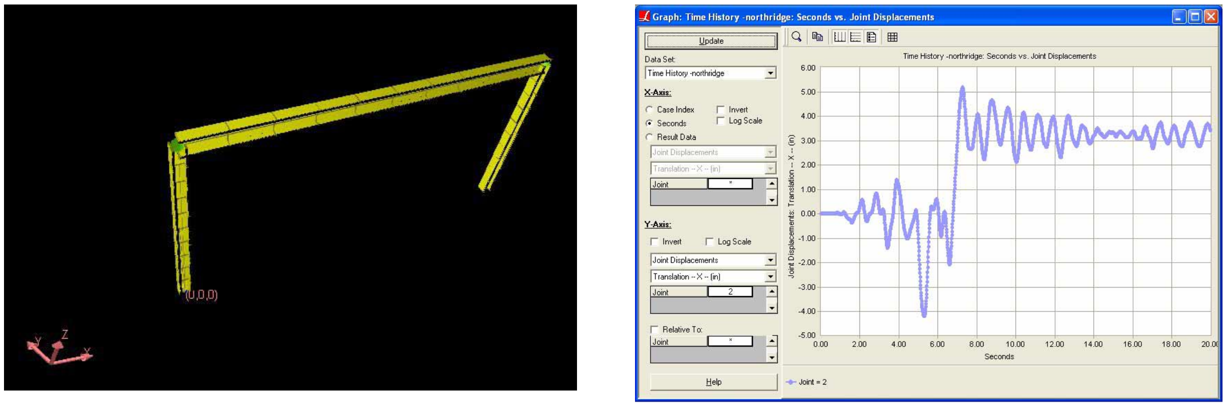


Figure 30. Nonlinear time-history analysis of a portal frame subject to Northrdge earthquake (Displacement time-history of top node)

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