VISUALIZATION OF NONLINEAR SEISMIC BEHAVIOR OF THE INTERSTATE 5/14 NORTH CONNECTOR BRIDGE

Robert K. Dowell

Department of Civil and Environmental Engineering
San Diego State University

Abstract

This paper discusses modifications to the existing bridge visualization program, previously developed by the author, to properly include nonlinear behavior of the 5/14 North Connector bridge expected from future, severe, design-level earthquake motions. Such modifications recognize that nonlinear behavior will develop at predetermined column locations, based on current state-of-the-art seismic design practice. For single-column-bent bridges, plastic hinges are expected to develop at the base of the column in transverse bending and at both ends of the column under longitudinal loading. The bridge can now be viewed in full 3-D animation, developing plastic hinges at all critical locations and showing color-coded damage or ductility levels for transverse and longitudinal behavior for each bridge column. Spline functions were modified from cubic equations representing elastic member response to a combination of plastic and elastic responses.

Introduction

The existing bridge visualization program [1] has been modified to include the possibility of nonlinear response of the 5/14 North Connector Bridge from significant earthquake loading. This structure has been heavily instrumented as part of the California Strong Motion Instrumentation Program (CSMIP), with 42 sensors placed on and in the vicinity of the bridge. The author was the PI on 2 prior Lifeline Response Projects [1, 2], and is the PI for the project discussed in this paper. In the 1st project, detailed finite element analyses were conducted and compared to measured responses of the 5/14 North Connector, with excellent results. For the second project a bridge visualization computer program was developed that allows the animated measured response of 3 bridges to be viewed in 3-D, with any level of exaggeration to deformations and level of perspective. The three bridges included in the visualization program are the Golden Gate Bridge, Vincent Thomas Bridge and the 5/14 North Connector Bridge. As modifications to the visualization program for the on-going project only concern the 5/14 Connector, the other bridges will not be discussed further herein.

Of importance in the development of the original bridge visualization program is that it realistically displays the measured bridge motions without requiring detailed structural analyses. The reasons for this are that (1) real-time animation is possible while rotating the bridge with the mouse due to increased computing speed, (2) displacements are known at instrument locations for all time intervals by double integration and filtering of measured accelerations, (3) development and verification of detailed structural models takes considerable time and can be subjective and (4) a predictive analysis model, especially a nonlinear one, is complicated and results in skepticism opinions from decision makers, partly because different models often predict different behaviors. This is best demonstrated by comparing weather patterns predicted by the various computer models and reported on the nightly news. As with weather predictions, nonlinear response of bridge structures subjected to earthquakes is still considered to be a somewhat subjective practice. By avoiding structural modeling it can be argued the that the 3-D animated response represents the actual measured dynamic behavior of the structure, with all instrumented locations moving through the measured displacement time-histories and all other locations displayed by interpolation between measured data.

Modifications to the existing program includes (1) showing color-coded damage levels for the bridge columns that are designed to perform in the nonlinear range when subjected to a design-level earthquake and (2) changing the elastic spline functions to allow for plastic column displacements. Original cubic spline functions that are used to determine the bridge response between measured locations (based on elastic beam theory) are modified to properly display the nonlinear response of the structure that includes plastic and elastic displacement components. Both of these modifications require that the idealized yield displacement in the local transverse and longitudinal directions be known for each column of the 10-span structure. One possibility was to use moment-curvature analyses for each column in the transverse and longitudinal directions and then calculate the idealized yield displacements for the two local column directions. This idealized yield displacement represents displacement ductility 1 and all other displacement levels can be shown color-coded as a multiple of this yield displacement. The idealized yield displacement also provides the dividing line between measured elastic and plastic displacements, allowing realistic nonlinear splines to be displayed in the 3-D animation of the measured bridge response.

Running moment-curvature analyses for each column section requires that all of the column details be known, including the column shape, longitudinal and transverse reinforcement details and the axial load on the column. However, this goes against the original philosophy of the project to have a visualization tool that animates the measured bridge response with no dependency on a detailed structural analysis component. This dilemma is resolved in the following with the development of simple yield displacement expressions that are based only on the column geometry (aspect ratio and column height).

Idealized Yield Displacement

A series of moment-curvature analyses were conducted using ANDRIANNA [3] in order to compare the yield curvature for various sections. Since yield curvature has the dimensions of radians/inch, it was immediately clear that sections with different size, but with the same longitudinal and transverse steel ratios and the same axial load ratio would have yield curvatures in proportion to their gross section dimensions. In other words, the yield curvature multiplied by the gross section dimension (in the direction of loading) is identical for different size sections that are otherwise the same. It was of interest then to compare sections of the same size with varying levels of axial load and longitudinal steel ratios. The transverse steel ratios are modified accordingly so that all of the members have a displacement ductility capacity of 6, providing a realistic level of transverse confinement to the column.

Moment-curvature analyses were conducted for a 6 ft diameter column with longitudinal steel ratios ranging from 1 to 2% and axial load ratios ranging from 5 to 20%. This is the typical range for bridge columns. From this study it was found that the idealized yield curvature multiplied by the gross column dimension of 72 inches (6 ft) was, on average, equal to 0.0054 (with no result more than 10% outside of this value). As discussed above, the identical value is found from dimensional analysis for, say, a 1-foot diameter column and a 10-ft diameter column, so long as the longitudinal and transverse reinforcement ratios and the axial load ratio are kept the same. It was then required to determine if this ratio also works for different section shapes, and so moment-curvature analyses were also conducted for the bridge column sections of the 5/14 Connector. Separate moment-curvature analyses were conducted in the transverse (strong) and longitudinal (weak) directions for the 10.5'x7' and the 12'x8' columns. Since the axial loads vary along the connector a range of axial loads were included, representing axial load ratios of 5 to 10%.

Idealized yield curvatures are plotted against axial load ratio from moment-curvature analyses of the 6 ft column and the 5/14 Connector columns (10.5'x7' and 12'x8') in Figure 1. Here it is clear that there are significant differences between yield curvatures of the different sections. However, with yield curvature multiplied by the gross section dimension (in the loading direction) the comparisons are much closer, as shown in Figure 2. The normalized line in Figure 2 is placed at 0.0054, and a study of the data shows that all of the results are within 10% of the normalized line. So for standard bridge column ratios it appears that the idealized yield curvature multiplied by the gross section dimension (in the direction of interest) can be taken as the dimensionless constant of 0.0054.

For a cantilever column the idealized yield displacement is found in terms of the yield curvature and column length to be

$$\Delta_y = \frac{\phi_y L^2}{3}$$

However, the yield curvature may be expressed as the dimensionless constant of 0.0054 divided by the gross section dimension *D*, or

$$\phi_y = \frac{0.0054}{D}$$

permitting the cantilever yield displacement (representing transverse column response of the 5/14 Connector) to be written

$$\Delta_y = 0.0018\frac{L^2}{D}$$

The aspect ratio is given as the column length divided by the section dimension in the direction of interest

$$\eta = \frac{L}{D}$$

allowing the yield displacement in the transverse direction to be written in terms of the column aspect ratio and column length.

$$\Delta_y = 0.0018\eta L$$

In the longitudinal direction the column responds in double bending due to the continuity of the superstructure. However, the point-of-contraflexure is shifted somewhat and, based on typical ratios of superstructure-to-column stiffness, the point of inflection is found to be at 0.55 the column height. From the moment-area displacement method (recognizing that the M/EI diagram is the curvature) the idealized yield displacement is found as

$$\Delta_y = \frac{\phi_y L^2}{5}$$

and, as with the cantilever column, the yield curvature is given as

$$\phi_y = \frac{0.0054}{D}$$

The yield displacement for the longitudinal direction is

$$\Delta_y = 0.00108\frac{L^2}{D}$$

Or, in terms of the aspect ratio and column length

$$\Delta_y = 0.00108\eta L$$

With the 2 expressions given above for idealized yield displacements in the local transverse and longitudinal column directions, all ductility 1 displacement values can be found from the column aspect ratio η and the length L. The aspect ratio is the column length divided by the maximum column cross-section dimension in the direction of loading.

The cantilever yield displacement expression is further validated by comparisons against measured yield displacements reported from 7 reinforced concrete bridge column structural tests with varying aspect ratios, axial load ratios and longitudinal steel ratios. Axial load ratio ranged from 7 to 18%, longitudinal steel ratio ranged from 0.75 to 3% and the aspect ratio ranged from 4 to 10. For each of the 7 test units the simple expression given above is compared to reported, idealized yield displacements found directly from the measured experimental results (see Figure 3). These tests were conducted at UCSD and UCB under three different projects [4, 5 and 6].

All of the column tests reported in [6] and the reference column tests reported in [4] and [5] are included in the comparison. Figure 3 show reasonably close results between the simple expression and measured yield displacements. It is interesting to plot these results against column height for all 7 structural tests (Figure 4). Here points are plotted from the 7 tests as well as the corresponding points from the simple expression. A best-fit exponential curve is drawn through the two sets of points, demonstrating a very similar trend between the simple expression and the measured results. Indeed, more variation is seen between competing methods for calculating theoretical yield displacement than between the simple expression and the measured results.

The two validated yield displacement expressions are used for this project in determining displacement ductility one in the local transverse and longitudinal directions. The expressions are included directly in the visualization program, requiring only the column height and overall column cross-section dimensions (width and depth) to determine the ductility one displacement for both local directions. With this it is possible for the program to determine and display in changing colors, and in real time, the displacement ductility demand for each column in both local directions. This is an excellent indicator of the damage level sustained. Ductility demand is the relative displacement between the top and bottom of the column (measured) divided by the idealized yield displacement found from the new and simple expressions. Ductility one assessment also allows the program to more accurately display the column behavior under dynamic loading, as the measured column displacements can be separated into elastic and plastic components. Elastic displacements follow cubic spline shape functions while plastic displacements follow straight shape functions between plastic hinges. Combining these gives realistic deformation patterns for nonlinear response in single and double bending.

Visualization Program

The initial panel for the modified bridge visualization program is shown in Figure 5. Here all 3 bridges that were included in the original program are given and can be used. However, nonlinear behavior has been included only for the 5/14 North Connector. This is a 10-span, single-column-bent, cast-in-place, prestressed concrete box-girder bridge. Several pictures of the structure are given in the 5/14 Connector tab (Figure 6). From this panel the Model tab is clicked and from the Views box, near the bottom of the screen, the Isometric tab is clicked, showing the model from an angle with a level of perspective of 2000 (Figure 7). This perspective number represents a viewpoint that is positioned 2000 ft from the center of the bridge. Other standard views can be selected or the bridge can be rotated about any axis with the mouse.

By clicking on the Select EQ tab, a menu appears and the EQDatabase is clicked followed by selecting the 514 directory (Figure 8). In this directory there are 3 data files that the visualization program can read, developed from past, recorded earthquakes measured at the bridge site. Of these three the most interesting is the Hector Mine Earthquake record (HMine.txt), as it resulted in 50 times more structure displacement than the other 2 earthquakes listed. Even so, the maximum relative column displacements were still very small compared to yield displacement of the columns indicating that the bridge has not yet performed in the nonlinear range as expected from a major earthquake. Elevation and plan views of the model are given in Figures 9 and 10, selected from the Views box.

Longitudinal and transverse column yield displacements are automatically computed by the program and can be viewed by clicking the Yield Displacement button (Figure 11). Displacement ductility demand is color-coded from Magenta at ductility 1 to deep red at ductility 6 (Figure 12). In order to test the behavior of the modified model the displacement demands from an earthquake must be larger than the yield displacements. With this in mind, is was decided to use the existing measured data from the Hector Mine Earthquake and scale up the results to represent large measured motions. This will test the color changing capabilities in the animation that graphically show damage levels developing in the columns and provide visual validation of the modified splinning techniques where elastic and plastic components are initially separated and then added back together again after using different spline techniques. Prior to exceeding yield displacement the columns behave in single bending in the transverse direction and double bending with a shifted point-of-contraflexure at 0.55 up the height of the column in the longitudinal direction.

Prior to column plastic hinging, at the base of the column there should be no absolute rotations and there should be no relative rotations between the top of the column and the superstructure. However, as ductility demand increases the plastic hinge formation will be visible by the more straightened appearance of the column (plastic displacement component of total measured relative displacement is larger than the elastic displacement) and the concentrated relative rotation between the superstructure and top-of-column, as well as the concentrated rotation at the column base. The superstructure rotation at the top of the column will be less than the total top-of-column rotation, but it will be the rotation associated with column yield displacement. In Figure 13 the column at Bent 10 is at a displacement ductility of 3 in the longitudinal direction. In order to really see the behavior, longitudinal deformations have been magnified by a factor of 25. It is clear that the column shape is a combination of elastic and plastic displacements, with concentrated plastic rotation at the base of the column and a definite relative rotation between the top of the column and the superstructure. Note that the superstructure is rotating at the top of column, but not as much as the column is. To view the displacement ductility colors legend the Ductility check box under Display is chosen. Within the ductility color legend, Transverse or Longitudinal behavior can be chosen. If both are selected then it will show the maximum ductility demand from either local direction.

Prior to forming plastic hinges, the columns respond in single bending in the transverse direction (Figure 14). Longitudinal and transverse ground motions are shown near the top of the screen, indicating small input in Figure 14 at 16 seconds and much larger ground motions by the time Figure 13 was captured at about 45 seconds. Transverse plastic hinging is seen in Figures 15 and 16 with maximum displacement ductility demands of 3 and 4, respectively. A few seconds later the end columns reach displacement ductility 6, with an exaggerated displaced shape that resembles a straight line (Figure 17). From initial loading the columns respond in double bending in the longitudinal direction, with no rotation at the base of the columns and no relative rotation at the column/superstructure joint (Figure 18). In Figure 19, plastic and elastic longitudinal column behaviors are seen in the same picture, with the column at Bent 9 exceeding ductility 3 and the adjacent Bent 8 column responding with less demand.

Conclusions

The existing bridge visualization program has been modified to include nonlinear behavior of the bridge columns for the 5/14 North Connector subjected to future large ground shaking from a design-level earthquake. The program allows measured responses of the bridge to be viewed in 3-D animation, with any level of deformation exaggeration, level of perspective and time-scale. Different deformation scales can be applied to the longitudinal and transverse directions. While animated the bridge model can be rotated about different axes, translated in any direction and zoomed in or out with the computer mouse, and different components of the model can be turned on and off. The animation can be slowed down or sped up, and the model can be paused at any time. While paused, the bridge can be rotated and the deformation scales can be changed, as can the distortion associated with level of perspective. In fact, all of the functions that apply to the bridge model while being animated also apply to it when frozen in time. This is interesting because very different appearances and viewpoints are possible while the model data remains the same.

Modifications to the bridge visualization program that have been implemented as part of this on-going project include color-coded damage indicators that display different colors for each level of displacement ductility that the columns are subjected to, based on measured relative displacements between the top and bottom of the columns in the two principal directions. Displacement ductility demand is defined as the displacement demand of the column divided by the idealized yield displacement. As the column acts in single bending in the transverse direction and double bending in the longitudinal direction, the yield displacements are different in the local longitudinal and transverse directions.

To avoid detailed calculations in keeping with the visualization tool philosophy, simple expressions were developed to determine the yield displacement of a column based only on its aspect ratio in the direction of loading and on the column height. Different expressions were developed for the longitudinal and transverse column directions. This approach was validated both analytically and experimentally, by comparing the simple expression and measured yield displacements from 7 cantilever column experiments. The only additional input required for the modified program is the overall section dimensions (width and depth, independent of section geometry), as the column lengths were already included in the original version of the program.

With realistic yield displacements determined, column ductility levels are displayed with changing colors of the columns as the bridge moves through measured motions collected by the Strong Motion Instrumentation Program. An important aspect of including column plastic hinging in the bridge visualization program is to modify the cubic spline functions that work well for animating linear-elastic column response, but do not capture the dynamic behavior of bridge columns subjected to a significant earthquake. For bridges the columns are designed to respond to a major earthquake in the nonlinear range and are detailed to allow significant ductility demands (the cost is prohibitive to design bridge columns to remain elastic in high seismic areas). Significant displacement ductility capacity of well-confined reinforced concrete bridge columns has been verified by large-scale and full-scale cyclic experiments at many institutions. In the modified visualization program measured deformations are separated into their elastic and plastic components and the elastic part is splined with a cubic function, while the plastic term is represented by a straight line between plastic hinges.

The simple yield displacement expression allows the modified program to determine transverse and longitudinal yield displacements for each column, which in turn permits realistic splines to be displayed for the columns and bridge superstructure. It also allows damage levels to be quickly assessed based on the displacement ductility demand. Local transverse and longitudinal displacement ductility demands can be viewed separately or together in the animation program.

Still to be added to the bridge visualization program, as the project continues, is the display of complete section geometries including the multi-cell box-girder superstructure with overhangs and the column sections to add more reality to the 3-D animation of the bridge. The ground line will also be added. It is not yet clear, however, if animation speed can continue to be real-time with the complete sections and ground surface displayed, and this is anticipated to be a challenge due to the increased amount of graphics and computations. Based on the plane sections hypothesis of beam bending, all section locations can be determined based on the location of the member centroid, the section curvature (from the splines) and distance to the section edge from the section centroid. The existing visualization model represents superstructure and column members with lines that follow the section centroids.

Nonlinear time-history analyses using SAP2000 [7] will also be conducted of the 5/14 Connector subjected to measured ground motions from other sites or scaled up measured motions from the bridge site. Displacement time-history results from the time-history analysis at instrumented locations will be saved to a data file and will represent virtual measured bridge motions. The bridge visualization program will then be loaded with these “measured” motions and side-by-side animated views from both programs will be compared from various angles and perspectives. Elastic and nonlinear comparisons will be conducted. Note that this step is required since the 5/14 Connector has not yet been subjected to an earthquake large enough to cause plastic hinges to develop at the column ends.

Supported by the California Department of Conservation, California Geological Survey, Strong Motion Instrumentation Program, Contract 1004-795.

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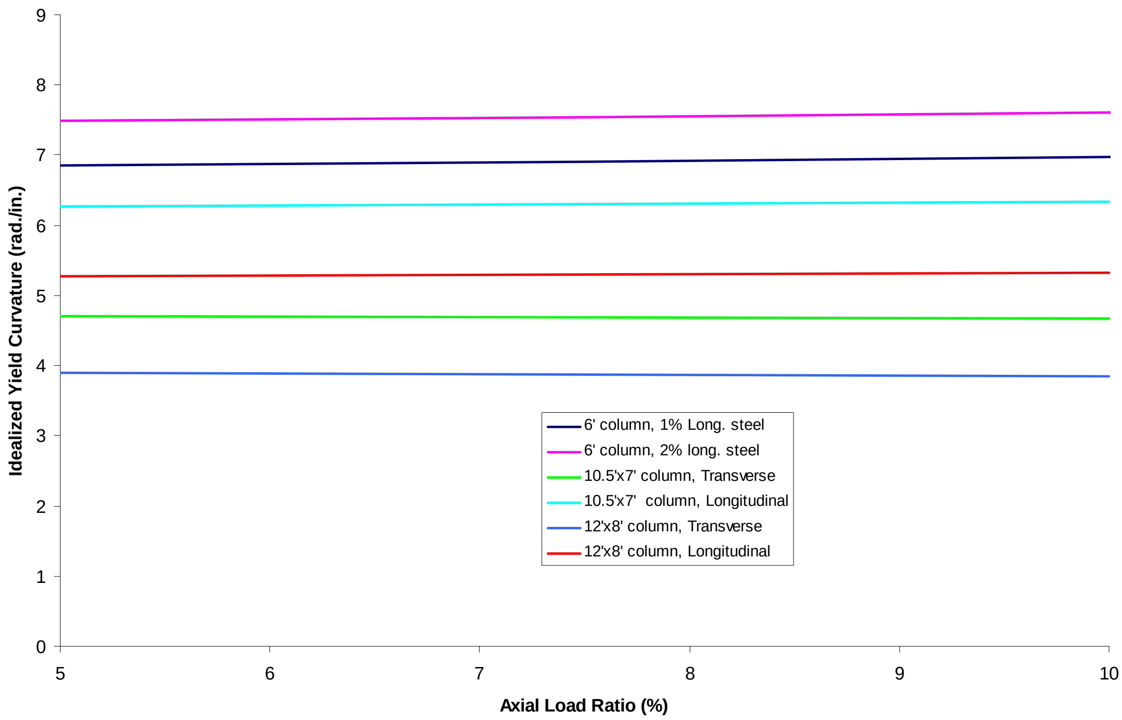

Figure 1. Idealized yield curvature from moment-curvature analyses

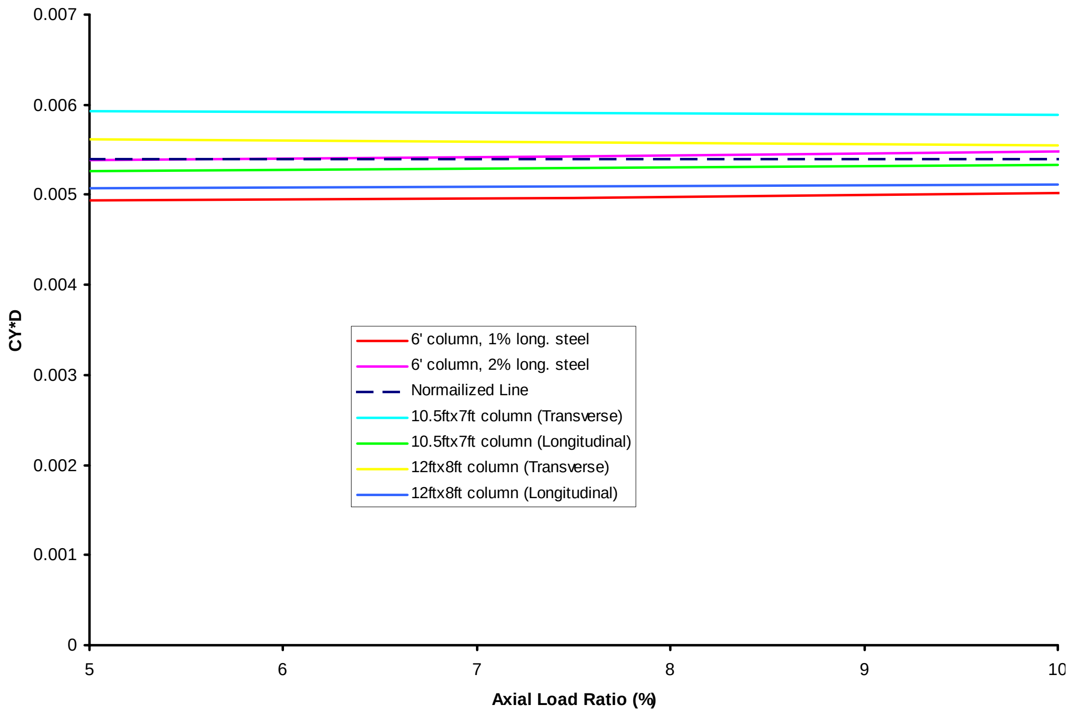

Figure 2. Idealized yield curvature multiplied by gross section dimension (in loaded direction)

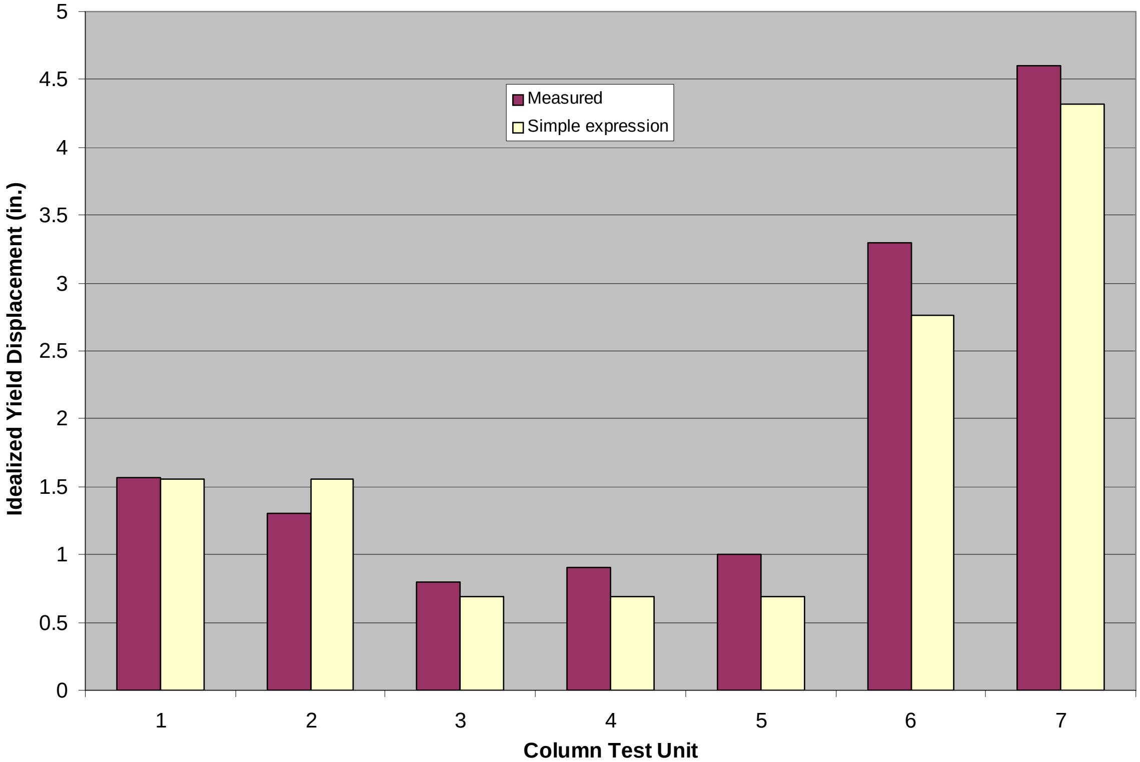

Figure 3. Measured versus simple expression yield displacements

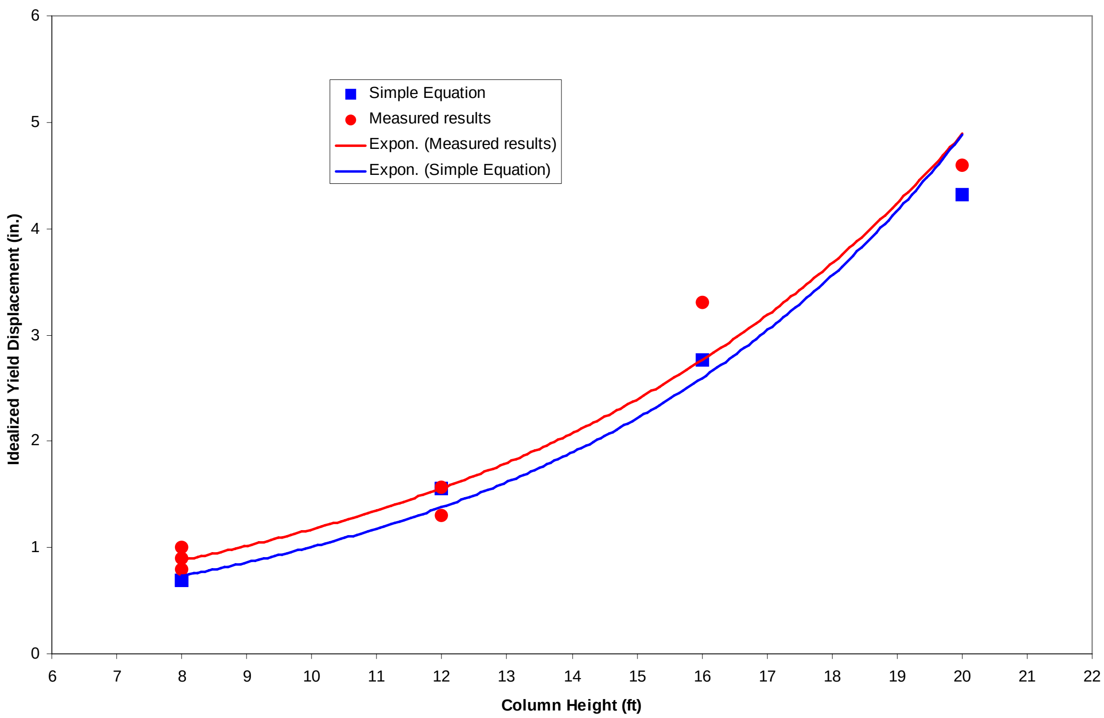

Figure 4. Measured and simple expression yield displacements versus column height

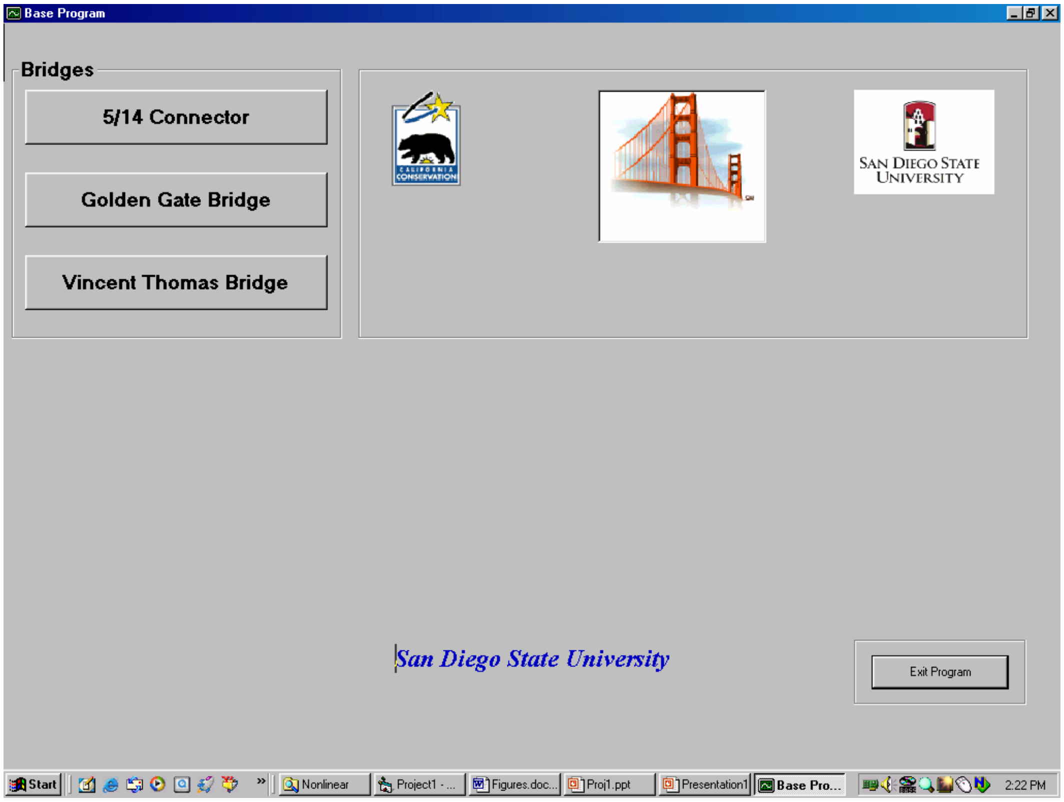

Figure 5. Graphical user interface, initial panel

Figure 6. 5/14 Connector tab

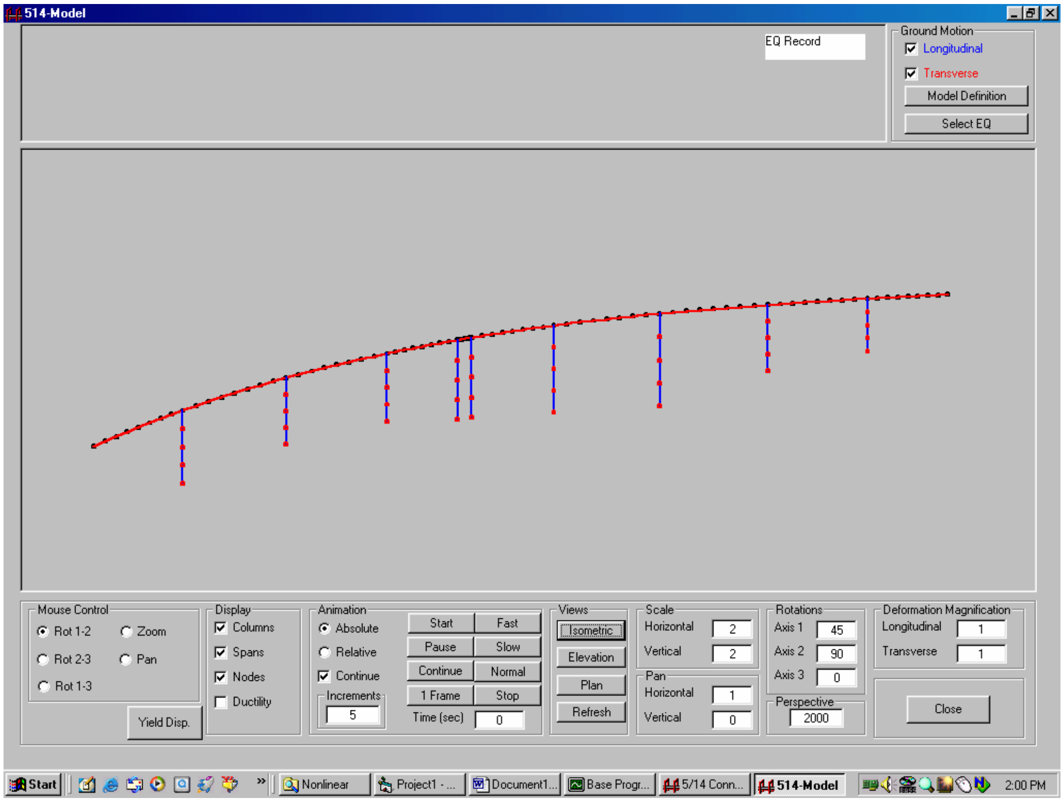

Figure 7. Model tab, isometric view of 5/14 Connector

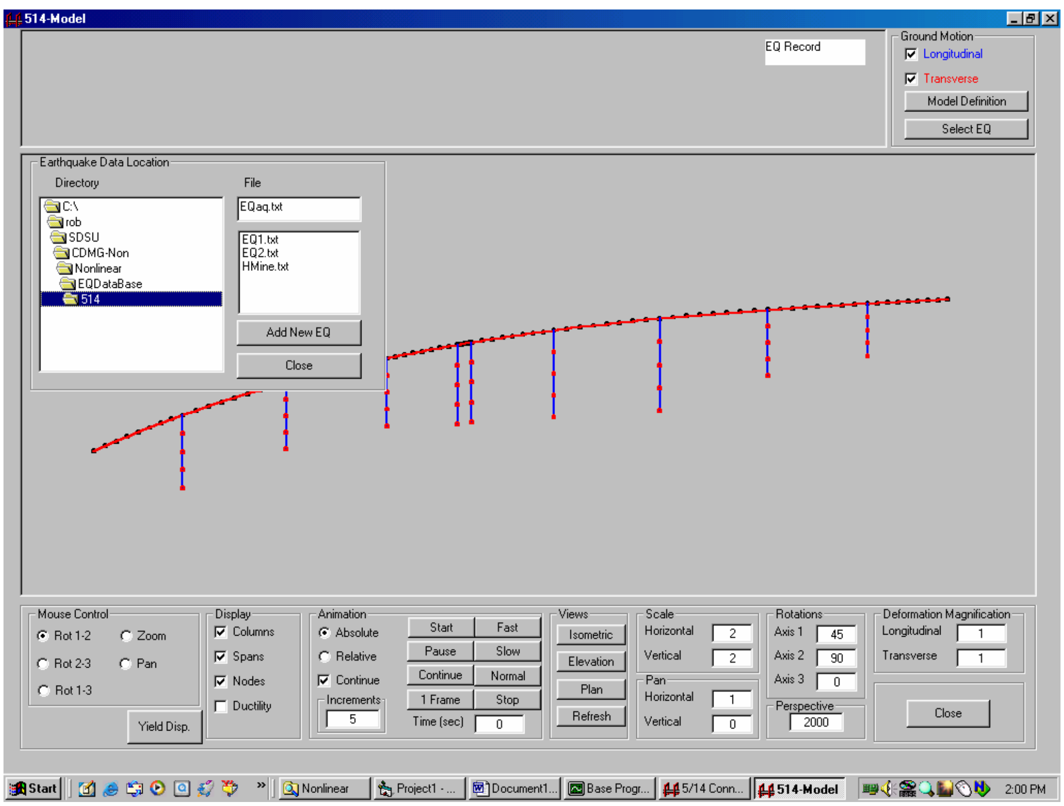

Figure 8. Selection of earthquake file from database directory

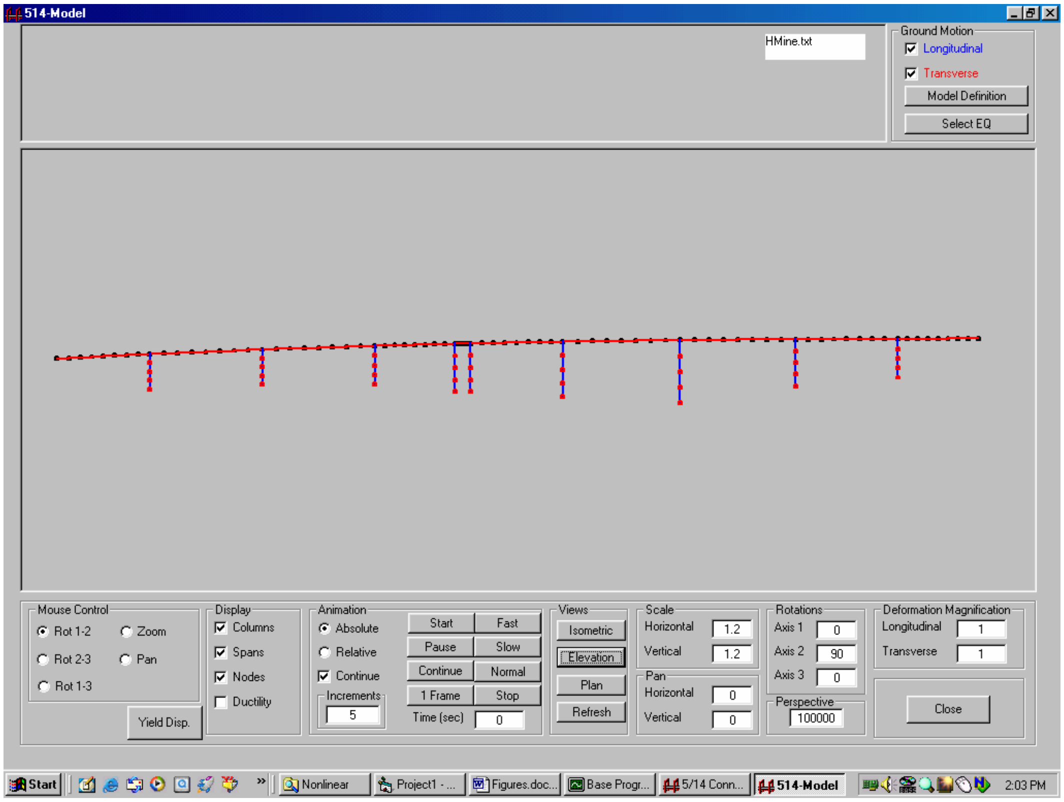

Figure 9. Elevation view of model

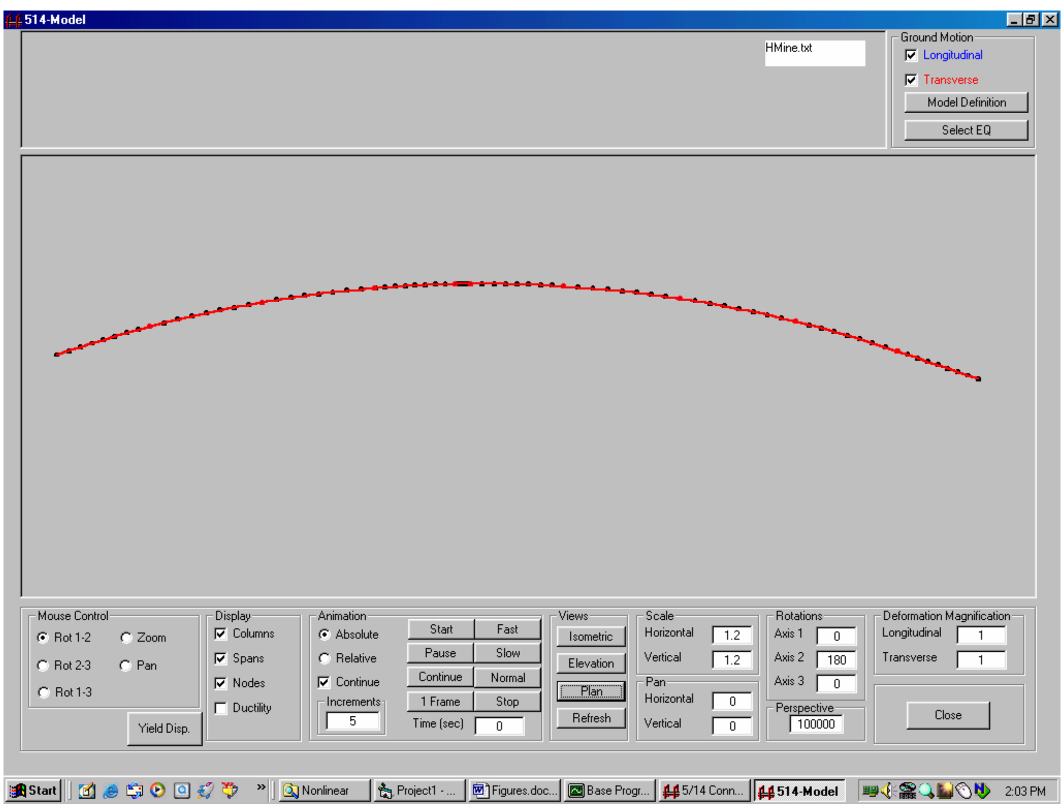

Figure 10. Plan view of model

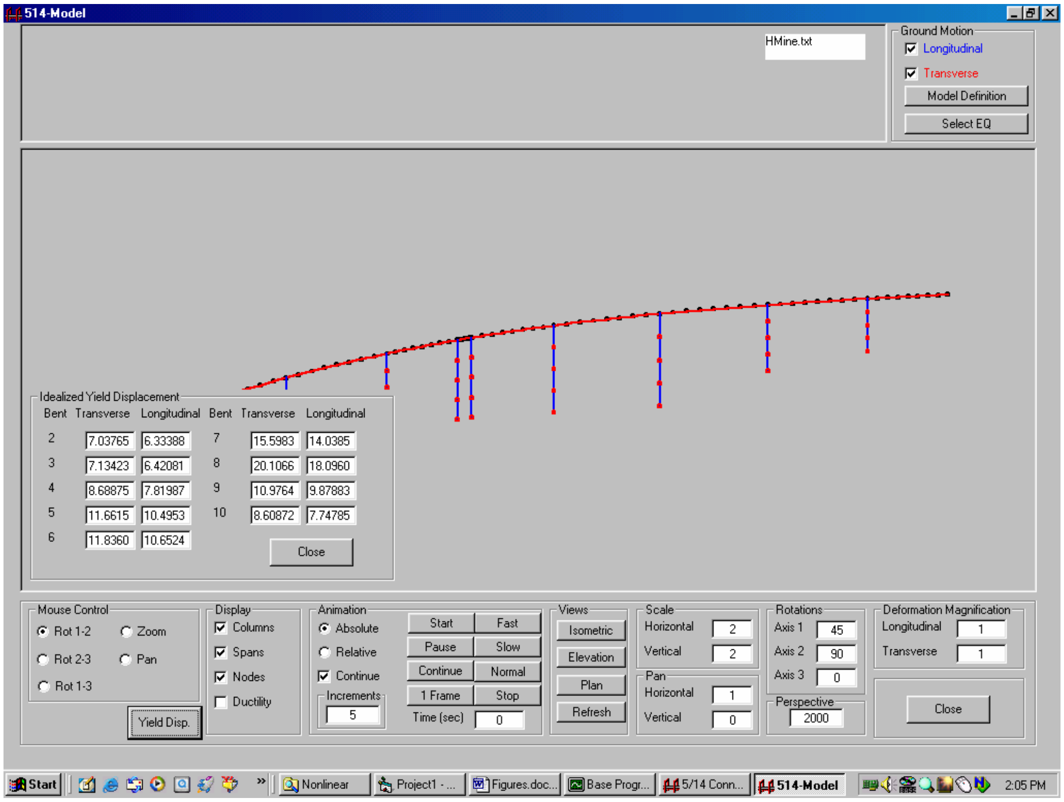

Figure 11. Longitudinal and transverse yield displacements for each column

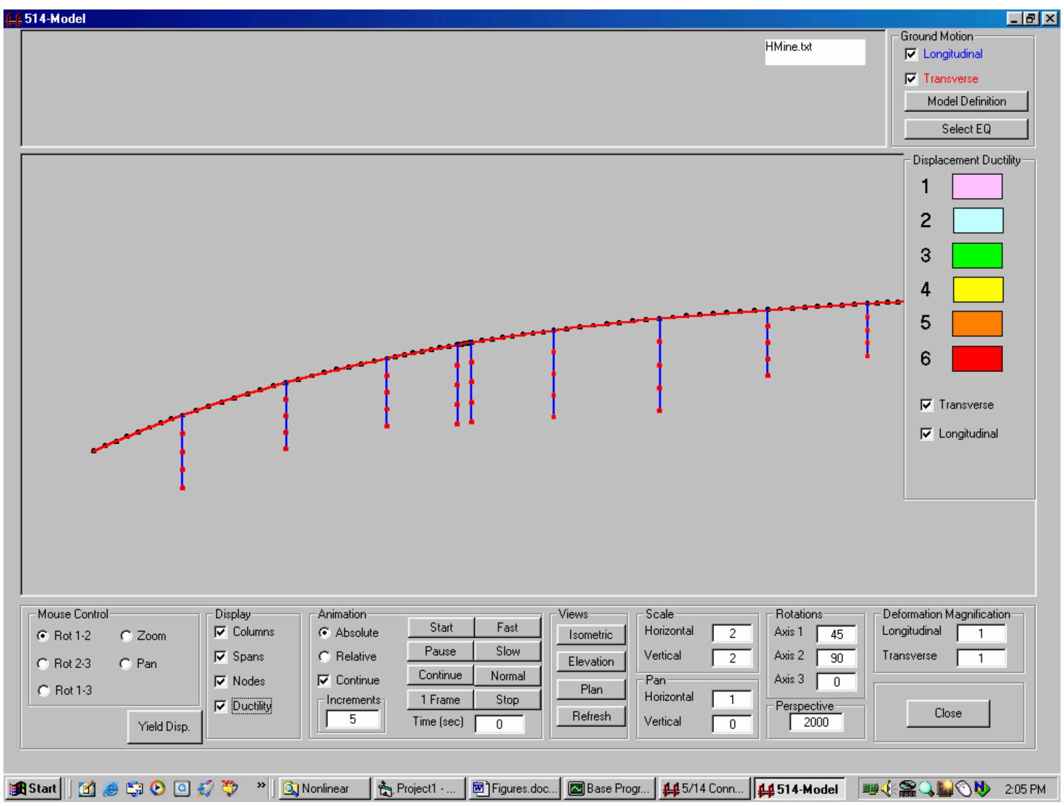

Figure 12. Displacement ductility levels

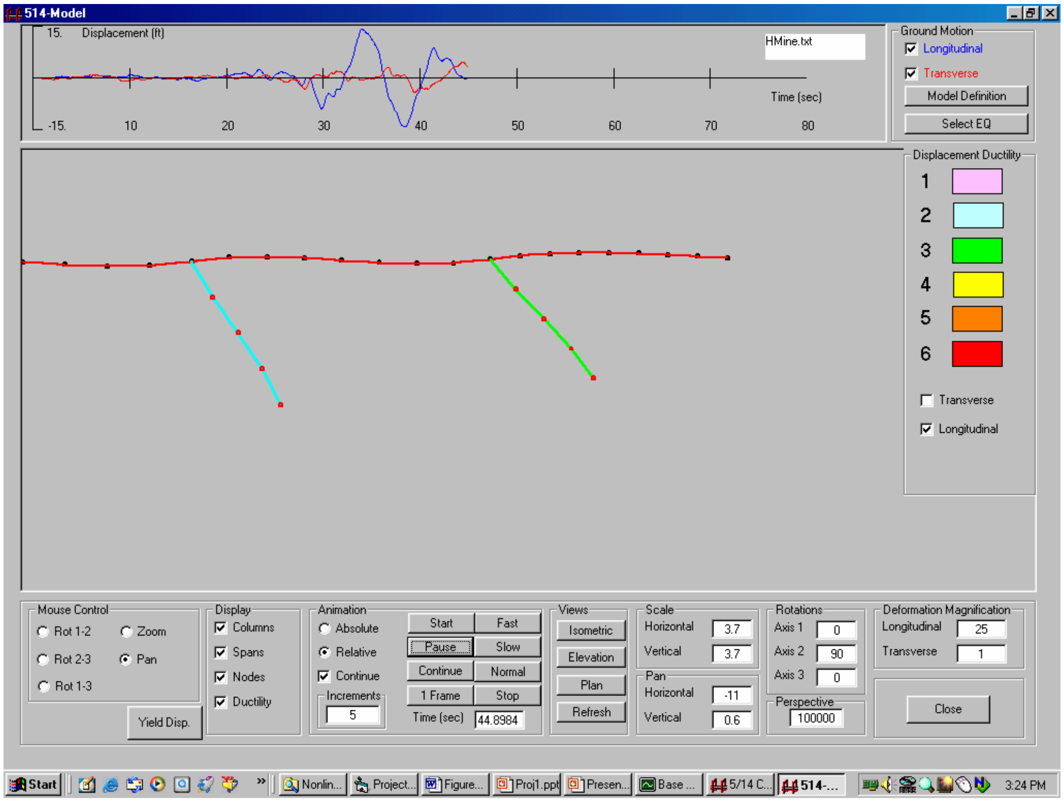

Figure 13. Column at Bent 10 at displacement ductility 3

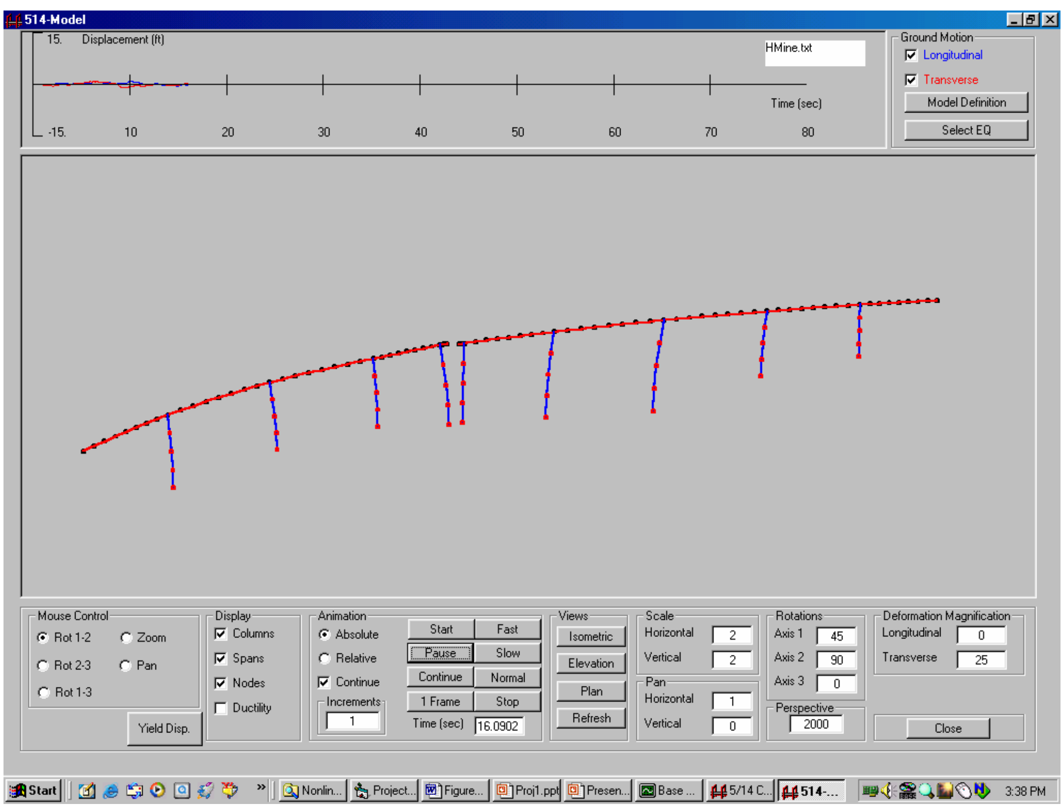

Figure 14. Transverse response prior to plastic column hinging.

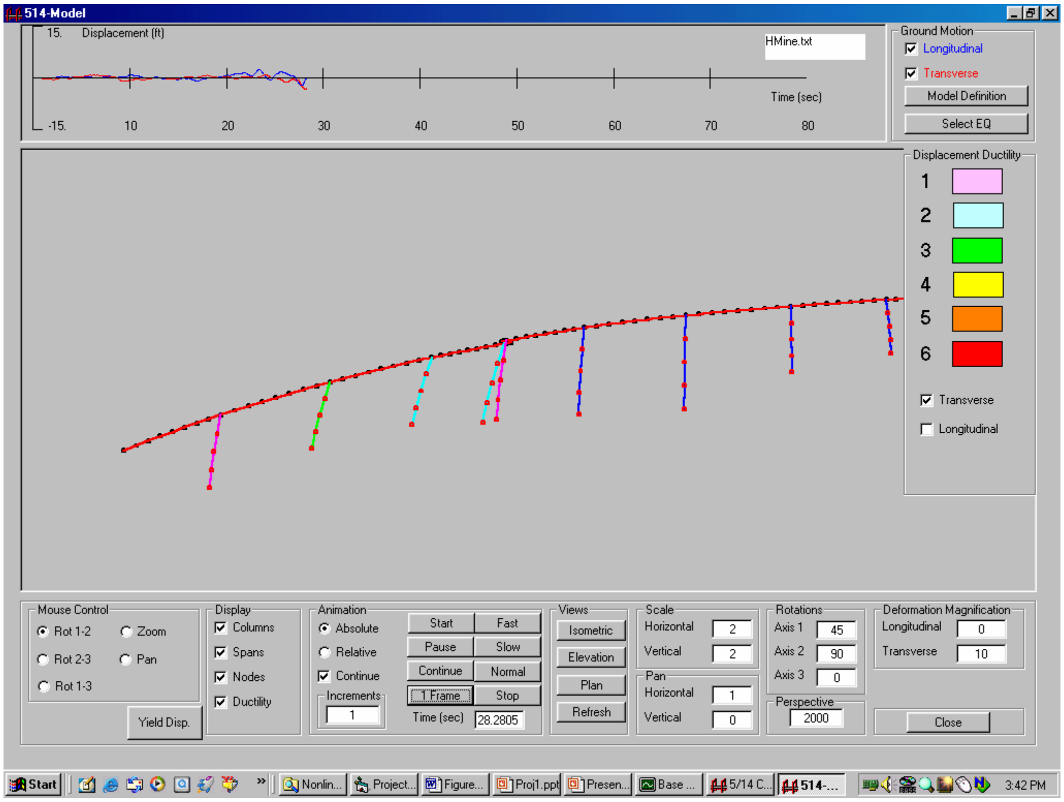

Figure 15. Transverse response with the Bent 2 column exceeding ductility 3

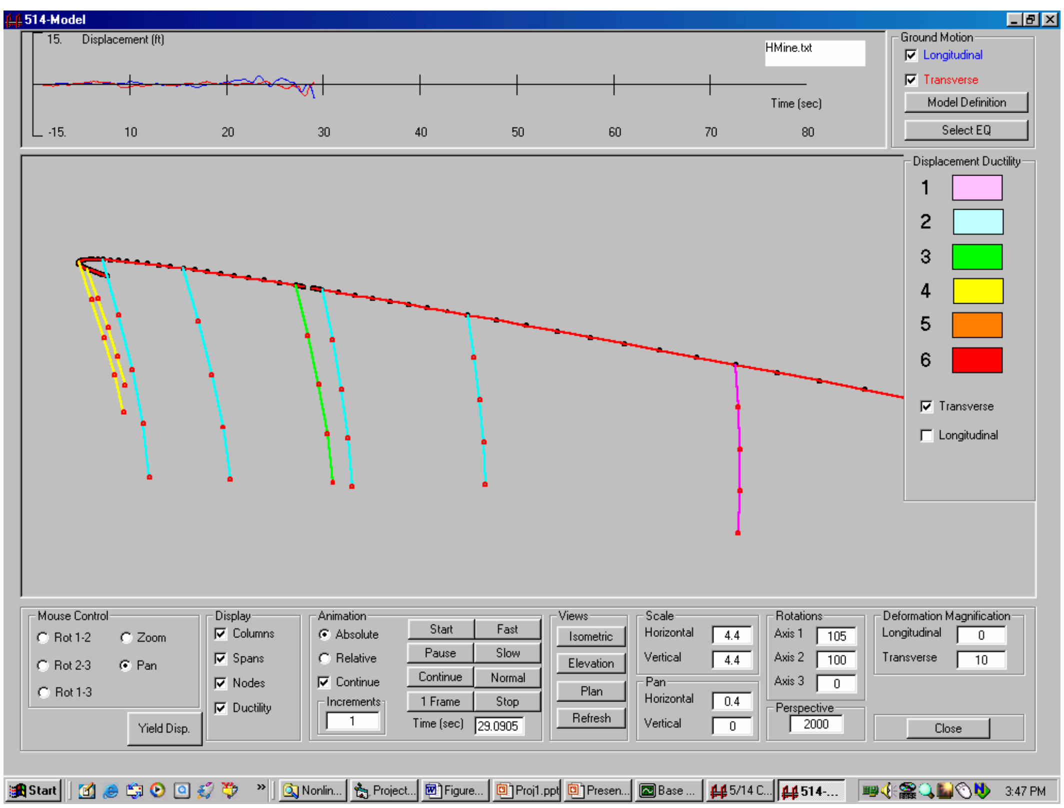

Figure 16. Transverse response with columns at Bents 9 and 10 beyond ductility 4

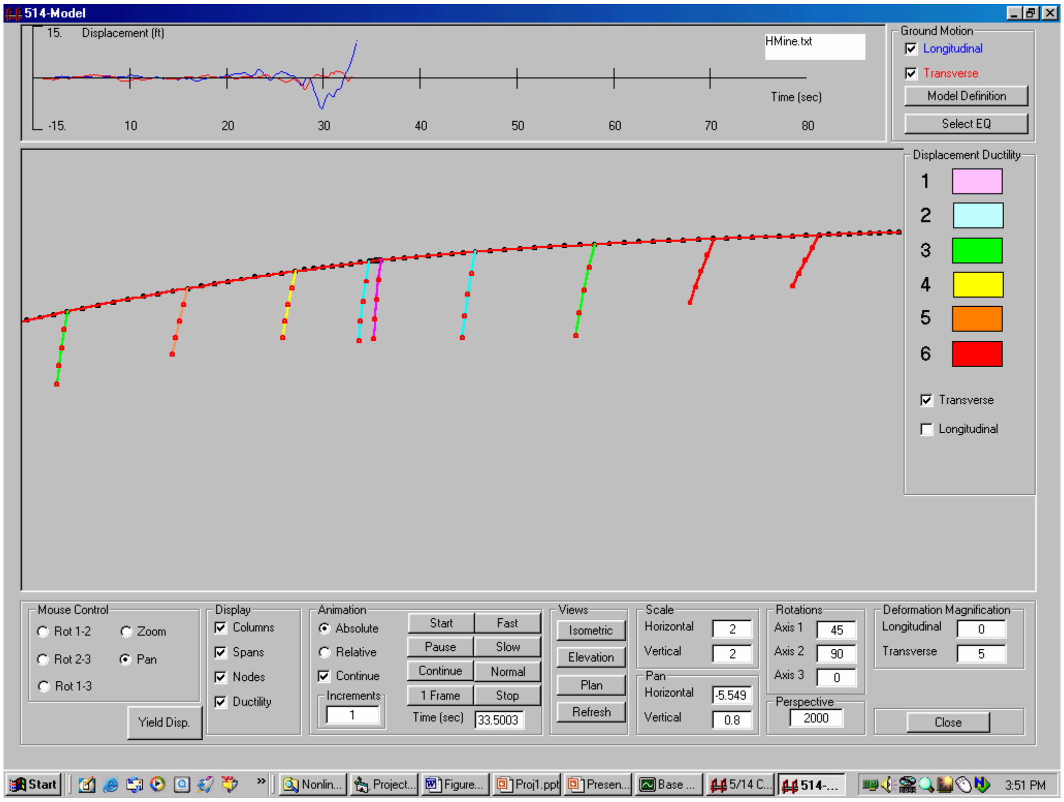

Figure 17. Transverse response with Bent 9 and Bent 10 columns exceeding ductility 6

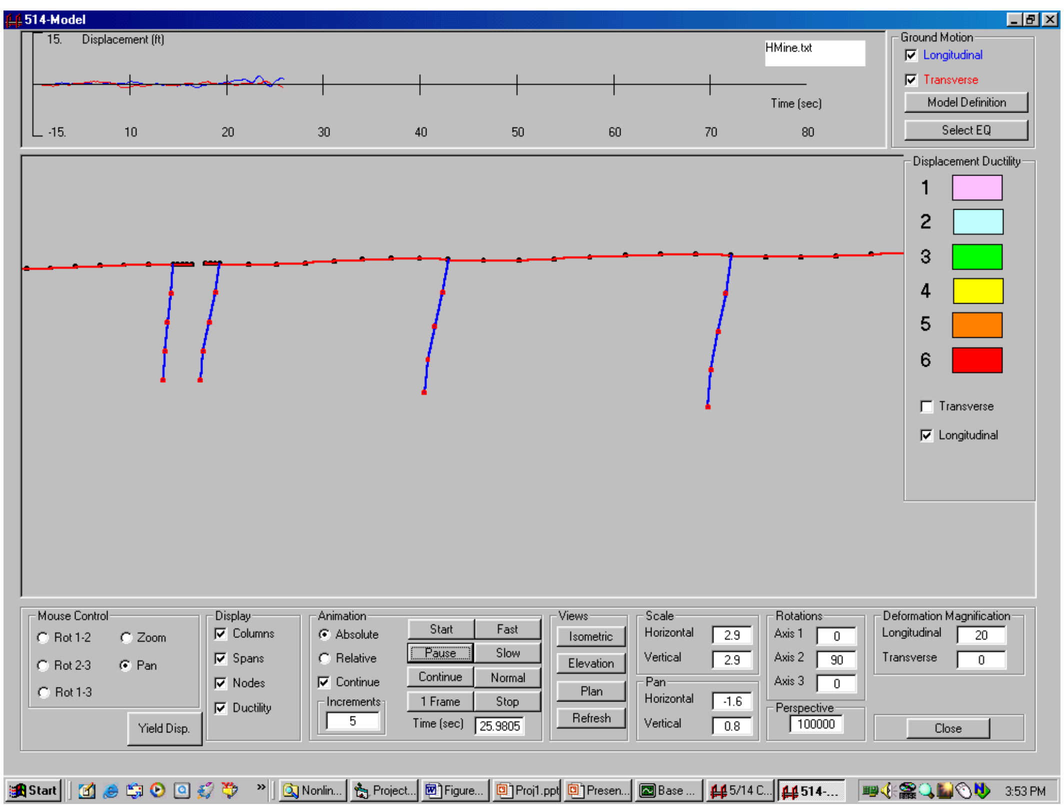

Figure 18. Longitudinal response prior to plastic hinging

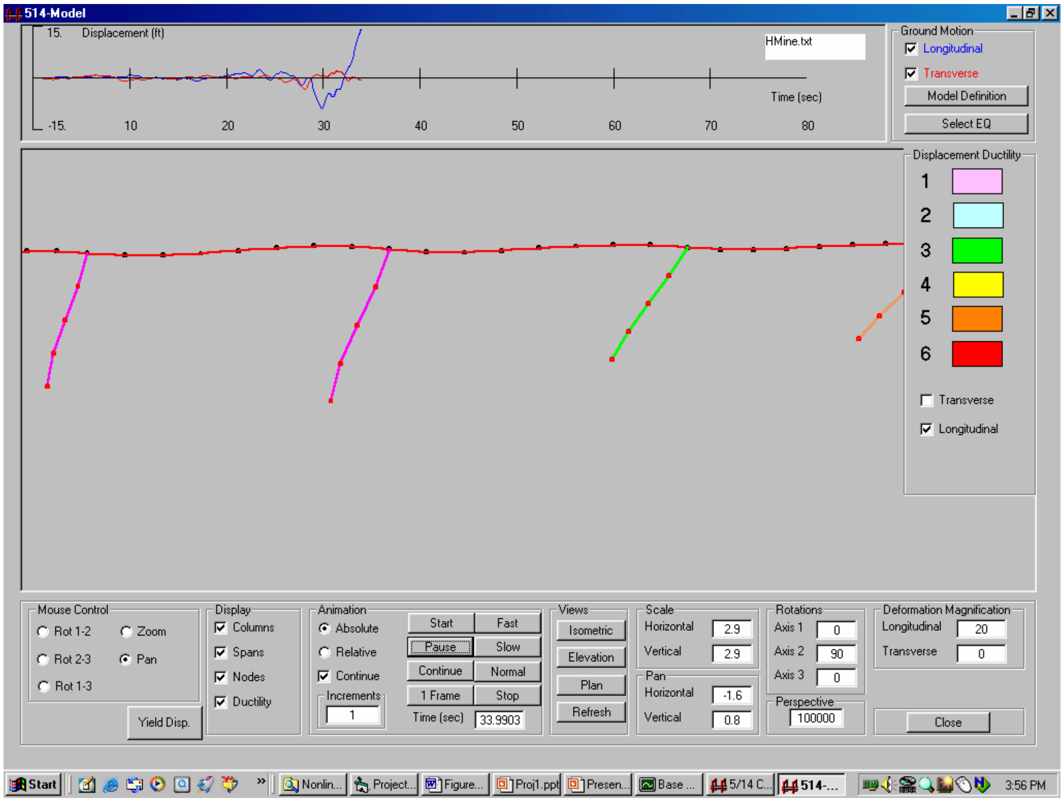

Figure 19. Longitudinal plastic response of Bent 9 column at ductility 3