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# PRACTICAL APPLICATION OF ADVANCED SEISMIC ANALYSIS OF STRUCTURES IN PRODUCTION PROJECT ENVIRONMENT

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## ABSTRACT

In the current state-of-practice of the performance-based design of structures, simplified procedures are often used to evaluate the deformation capacity of structural systems. One specific example is using the rotation limits for the deformation-controlled elements. This paper suggests the use of the strain limits, instead, and presents an efficient nonlinear analytical technique to compute the strain demand values for both steel and concrete structures. The beam finite element nonlinear properties are specified through “bending moment – curvature – axial force” relationships obtained from nonlinear section property calculations. Once the analysis is complete, this technique will use the time histories of result quantities to calculate the extreme fiber strain demands at each time step and quantify the structural element performance based directly on the material strains. This technique has been successfully employed in several projects. Due to its high efficiency, it has proven to be very well suited for the production environment without introducing unnecessary assumptions or sacrificing accuracy.

## Introduction

The state-of-practice in modeling of deformation-controlled action of beam and column elements is based on the nonlinear “bending moment - rotation” relationship and lumped plasticity concept. In this technique, the locations of the plastic hinges are predefined and hinge lengths are approximated. An alternative is a theoretically more rigorous approach which employs fiber elements and distributed plasticity concept. However, this type of modeling procedure is much more computationally resource consuming. This technique is still not practical to be used for project work where large structural systems are analyzed, and has mostly been used in academia for research applications. The analytical technique presented in this paper combines advantages of beam elements and distributed plasticity. The beam finite element nonlinear properties are specified through “bending moment – curvature – axial force” relationships obtained from nonlinear section property calculations. Once the analysis is complete, the time histories of bending moments, curvatures, and axial forces are used to

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calculate the extreme fiber strain demands at each time step. Then, the structural element performance is quantified by direct comparison of demand strains with those of the material standard tests. The significant advantage of this method, as oppose to the rotation capacity approach, is that the material strain limits are those obtained from material standard tests without any additional assumptions.

**Lumped Plasticity Elements**

Currently, the state-of-practice in nonlinear analysis in civil engineering is based on lumped plasticity beam elements (FEMA-356 2000). For each beam-column element of the model, the “bending moment – rotation” relation is to be specified. The rotation demands are computed and compared with the rotation limits. The technique is based on a set of simplifying assumptions.

1. Location of plastic deformation is predefined.
2. The effect of axial force on the stiffness and strength is ignored since “bending moment – rotation” relations are defined independent of axial force.
3. Rotation limits have been obtained from laboratory testing of cantilevers with single curvature deformed shape and extrapolated to a wide variety of loads and structures.
4. The axial stiffness is constant along the analysis.

The advantage of this technique is its computational efficiency. Therefore, it is applicable to practical analyses of complicated large scale structures.

**Fiber Elements**

A more rigorous approach employs fiber beam elements (for example, OpenSeas 2001). With the fiber elements, the stress is computed at each fiber and along the length of the element. Plasticity location is not predefined (distributed plasticity concept). Once analysis is done, the strain demand can be directly extracted. Although this is the most straight way to compute the strain demands, it is still considered to be an overwhelmingly computationally intensive procedure and therefore not practical. This approach is mostly suitable for modeling of sub-assemblages and local models.

The approach proposed in this paper is based on moment-curvature beam elements. The strain demands are computed from curvature demands using the “bending moment – curvature” relations that are dependent on the applied axial force. Plasticity might be encountered at any location along the beam-column element. This approach is much more computationally efficient than the fiber beam element technique and more rigorous than the lumped plasticity element technique. It can efficiently be employed for both static and dynamic nonlinear analyses of complicated large structures in production project environment.

## Moment-Curvature Elements

The moment-curvature rigidity is usually specified as a family of “bending moment – curvature” relations. Each “bending moment – curvature” relation corresponds to an axial force value (Figure 1). Calculation of the moment-curvature rigidity is a well established procedure (for example, Park and Paulay 1975). The computer code SCMC (SCMC 2006) is used in this study. A very important output data of this code are maximum tensile and compressive strains corresponding to each point of the “bending moment – curvature” diagram. In case of a reinforced concrete cross section, they are maximum tensile strain in the steel component and maximum compressive strain in the concrete component (see Figure 1).

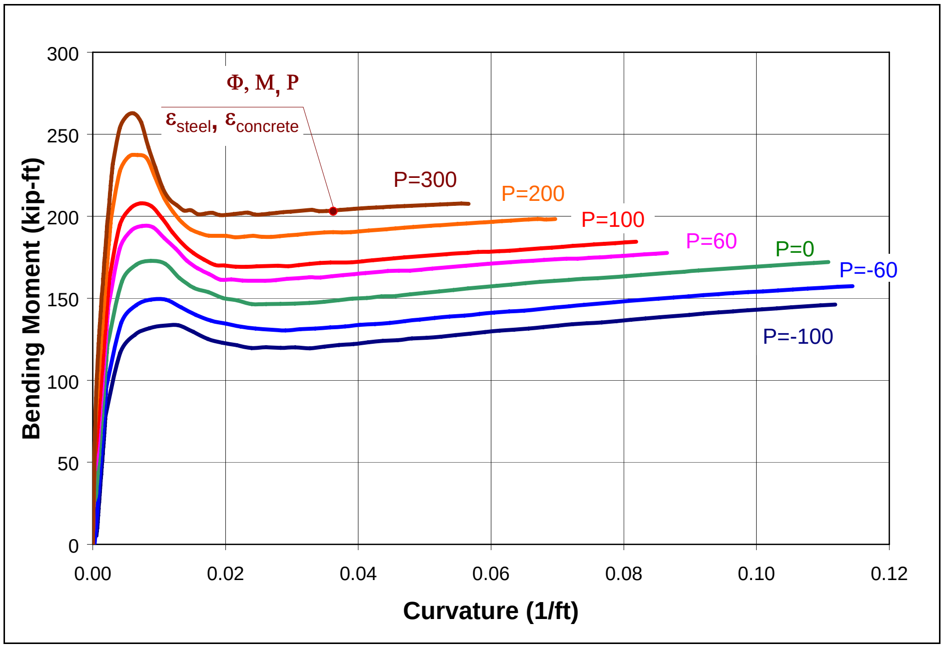


Figure 1. Bending moment – curvature relation.

While using SCMC, the cross section is subdivided into fibers and for each fiber (concrete and steel) the "stress – strain" relations are defined as shown in Figure 2. The confined and unconfined concrete can be easily separated from each other by defining proper concrete material properties.

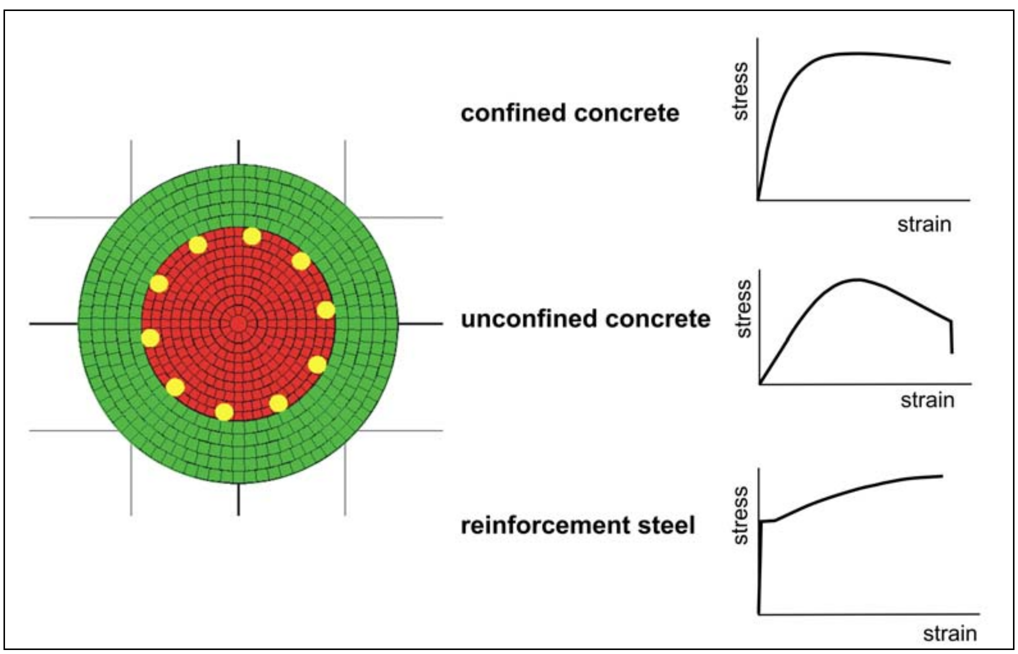


Figure 2. Cross section property calculation.

## Strain Demand Computation

The moment-curvature might be employed for beam-column finite elements within available commercial codes. In this study, a powerful finite element commercial code ADINA (ADINA 2006) is used. As result of a static or dynamic nonlinear analysis, time histories of demand values of axial forces, bending moments and curvatures are obtained for all beam-column finite elements. In course of post processing, in every integration point of all beam-column finite elements at each time step the demand strain value is calculated using correspondence between the strains and curvatures found with SCMC when the moment-curvature rigidities were calculated (Figure 3).

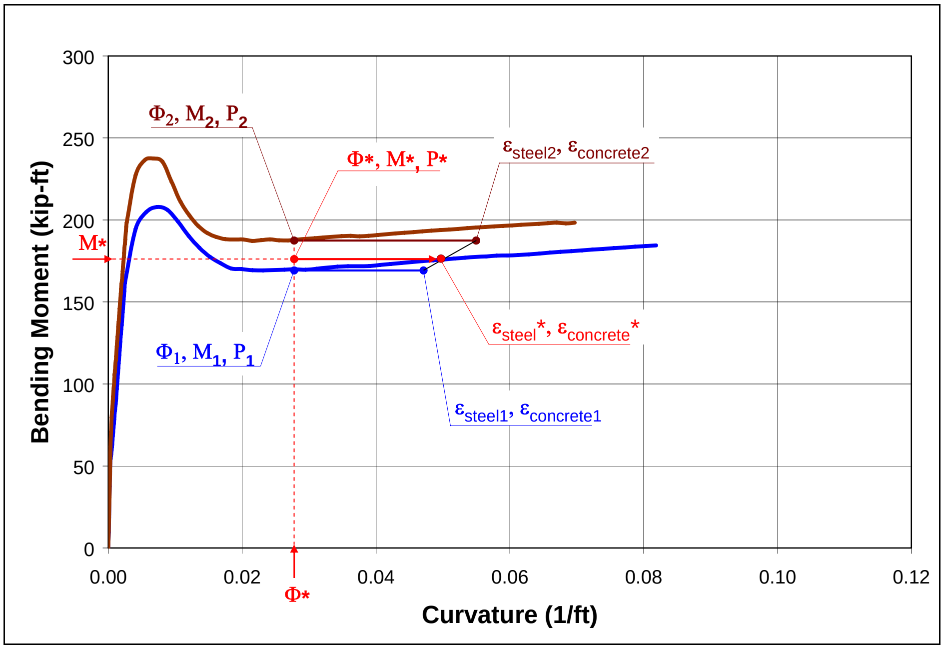


Figure 3. Strain interpolation.

## Case Studies

The above technique has been implemented to a wide variety of structural types such as: port structures, long-span cable bridges, buildings

### Port Structures

In the Wharf and Embankment Strengthening Program of Berth 60 to Berth 63 Port of Oakland Project, 3D models of Berth 60-61, 62, and 63 were developed with soil-structure interaction presented by spring components (Oyenuga et al 2001). A set of 3D nonlinear dynamic analyses under multi-support excitation was performed. Ground motion displacements were applied at each soil spring component. Figure 4 shows Berth 60-61 with 1098 concrete piles. All piles were modeled with nonlinear properties using ADINA moment-curvature beam finite element. The analyses demonstrated occurrence of plastic zones in the piles which location was not predefined but rather resulted from the specific combination of the pile geometry and strength, soil resistance and ground motion at each pile location. After a seismic analysis was complete, the demand moments, curvatures, and axial forces were extracted and used in the post processing procedure described earlier to compute concrete and reinforcement strains. These analyses were checked for three design performance levels with three strain limits for steel and concrete.

Similar modeling technique was employed for Port of Oakland Berth 22 Reconstruction Project. An important issue in the analysis of these facilities was to properly capture three-dimensional effects of the soil-structure interaction. A thorough analytical effort involved considering these important effects, so that the entire system might be designed for the desired performance level under various seismic events was conducted. In course of this project, employment of the advanced analytical procedures (including the moment-curvature technique) and application of the performance based MOTEMS Criteria provided designers all the necessary information to address many key performance issues (Sedarat, Ballard and Krimotat 2004). These issues included:

a) Determination of the wharf performance for 10%-50year and 50%-50year events.
b) Investigation of various pile head design solutions.
c) Investigation of the dike geometry effects.
d) Explicit consideration of the dike movement.

Strain values in both concrete and reinforcements were computed and compared with the strain limits defined in the design criteria.

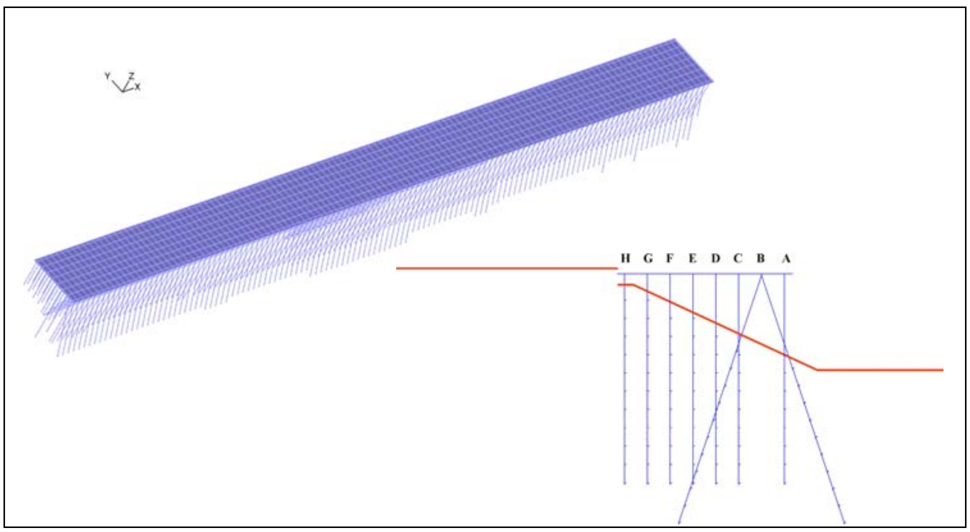


Figure 4. Berth 60-61

**Long-Span Bridge Structures**

The moment-curvature beam elements were extensively used in modeling of the new cable-stay Cooper River Bridge, located in South Carolina, in course of its designing (Figure 5). Multi-support time history analyses included evaluation of the soil-structure interaction effects on the response of the bridge through the drill shafts that were modeled explicitly. The bridge has a 1546 ft (451 m) main span, two 650 ft (198 m) side spans and two 225 ft (69 m) anchor spans, with a total suspended span length of 3296 ft (1005 m). The two 572.5 ft (174 m) high diamond shaped towers support a 126 ft (38 m) wide deck carrying 8 traffic lanes and a 12 ft (4 m) pedestrian walkway/bikeway on the south side. The main span utilizes a composite concrete deck with I-shaped steel edge girders. The pedestrian walkway/bikeway is cantilevered outside of the south edge girder. The high level approaches also utilize composite steel construction with steel girders spaced 12 ft (4 m) on centers. Both high approaches are jointless over their full length, 4350 ft on the Charleston side and 2090 ft on the Mount Pleasant side. A final check of the seismic performance of the main span was made using nonlinear time history analysis of the main span unit and the west and east high level approach structures combined in a single model. This global model represented 9737 linear feet (1.84 miles) of structure, and had 55,350 degrees of freedom, 23,853 nodes, 14,316 elastic elements, 2382 nonlinear moment-curvature elements, 2078 nonlinear plasticity based (hysteretic) horizontal soil springs (p-y springs), 799 nonlinear vertical soil springs (t-z and q-z springs) and 563 sets of spatially varying ground motion time-histories.

The confinement of concrete tower was taken into account and various design iterations were analyzed to obtain the proper level of confinement that could satisfy the design criteria on strain limits in both concrete and reinforcements (Bryson et al 2003, Sedarat, Kozak et al 2004).

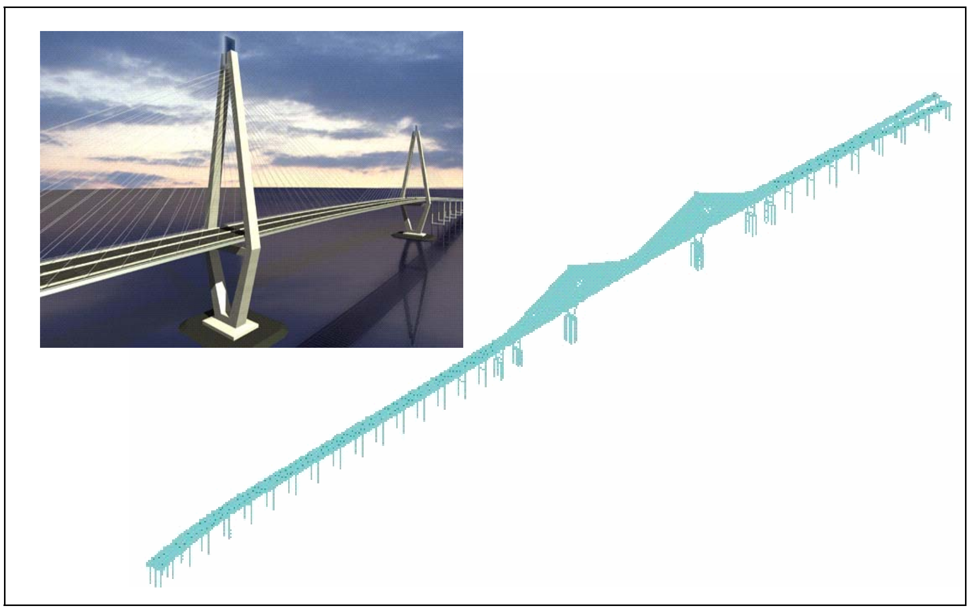

Figure 5. Cooper River Bridge.

In course of the Auburn Foresthill Bridge retrofit design project, a bridge that is located in Sacramento, (Figure 6 and Figure 7), the moment-curvature beam employment was quite crucial since possibility of buckling of the steel truss members was studied (Reno 2009). The bridge steel superstructure and concrete towers were both represented with moment-curvature elements. In order to capture buckling, the nonlinear moment-curvature rigidities and large displacements were taken into account. The strains in the extreme fibers of each truss element of the superstructure as well as those of the concrete and reinforcements of the towers were computed. A retrofit design was developed to meet the strain limit requirements.

Figure 6: Auburn Foresthill Bridge.

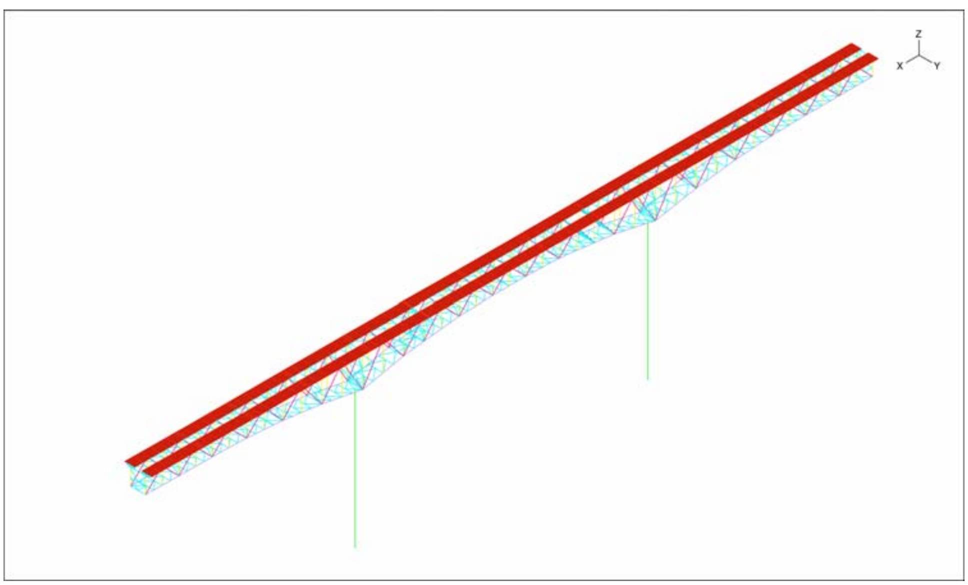


Figure 7: Finite element model of Auburn Foresthill Bridge.

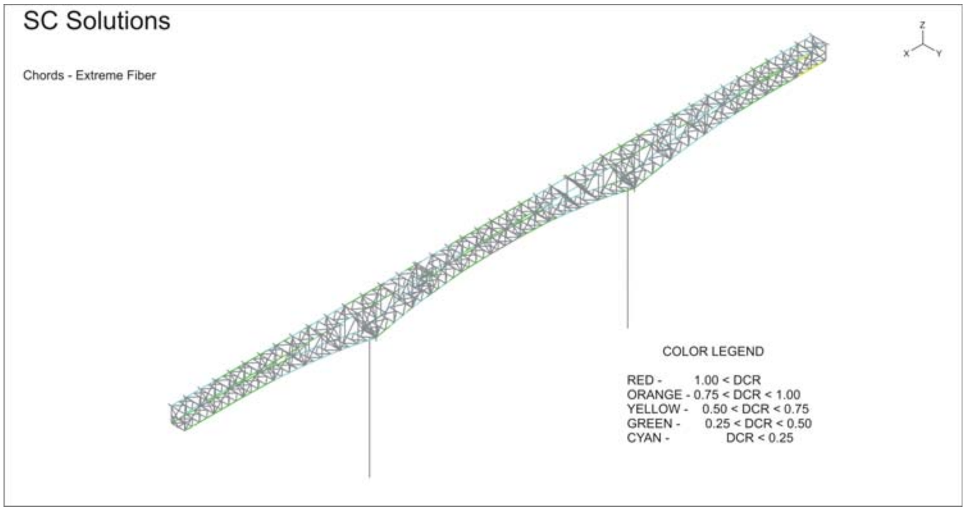


Figure 8: Strain demand-to-capacity ratio.

**Building Structures**

Dynamic ground motion analysis of a 54-story concrete building located in a high seismicity zone, Tehran, Iran, represents another application of the moment-curvature beam technique. The concrete shear walls and columns were modeled in a way that their nonlinear behavior both in shear and flexure could be taken into account. The strain values in concrete and reinforcement were extracted and compared with the design strain limits. The non-ductile actions such as shear forces were compared directly with the force capacities of the structural elements. The final element model of this structure contained 165,814 degrees of freedom with 8922 elastic elements and 7279 inelastic elements.

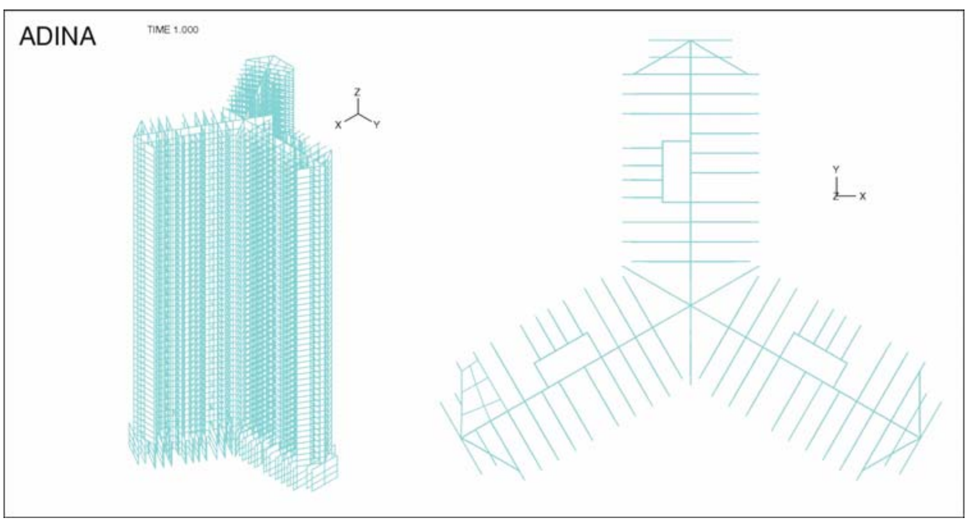


Figure 9: 54-Story reinforced concrete building finite element model.

**Tunnel Structures**

Within the Silicon Valley Rapid Transportation Project, the moment-curvature beam technique was employed in seismic response study of the precast tunnel linings (Figure 10). The 4.3 mile segment of BART extension from Fremont to San Jose will be constructed with twin circular tunnels using a closed face tunnel boring machine (TBM) to interconnect the stations and portals. The internal diameter of the 10 inch thick precast reinforced concrete lining is about 18 feet and the nominal ring length is 5 feet. The lining and soil were modeled with three dimensional solid finite elements. A wide range of soil properties were examined. The sand and clay soil materials were modeled with Mohr-Coulomb formulation. All the segments were connected by contact surfaces. Strains in concrete and reinforcements were obtained with the moment-curvature beams that were embedded into the solid elements and followed deformation of the lining (Kramer, Sedarat and Kozak 2007).

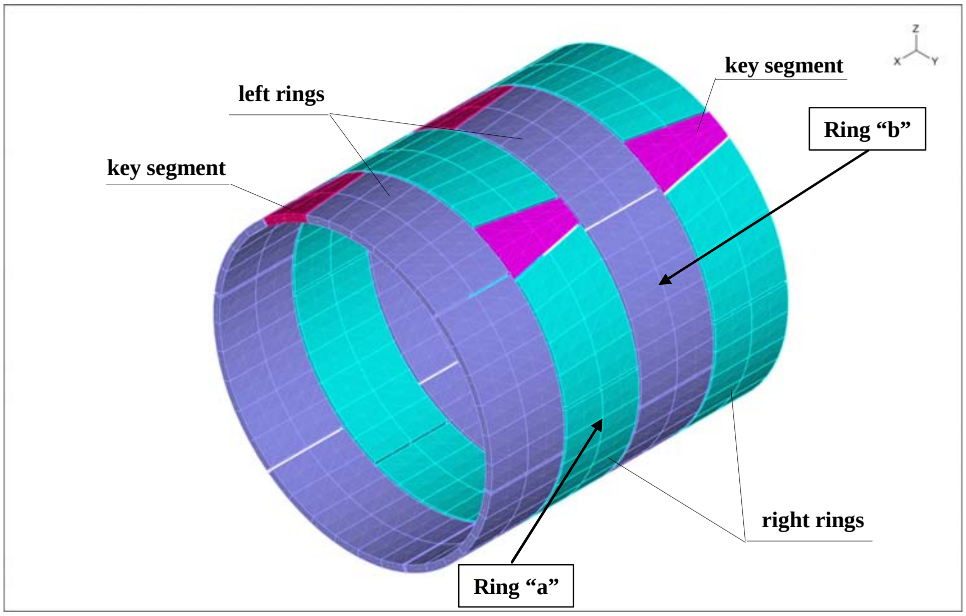


Figure 10: Tunnel segment finite element model.

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