Evaluation of the Impact Condition for a High Capacity Spent Nuclear Fuel System

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Abstract

Evaluations are performed for the structural component of a fuel basket in a sealed container which is used for maintaining the configuration of spent nuclear fuel during storage. Spent fuel assemblies are placed into a basket structure which is comprised of separate tubes whose positions are maintained by a series of pins and sockets and an exterior frame work of stiffeners. The canister is placed in a vertical storage cask. The controlling condition is associated with lateral impact of the tip over of the storage cask which results in deceleration being applied normal to the axis of the basket and spent fuel. It is necessary to investigate the potential geometric instability of the array of tubes as well as the potential for a pin-socket component to fail in shear. The angular orientation of the basket affects the development of potential instabilities as well as the level of shear developed in the basket tubes at the pin-socket. In this paper the impact analyses for a system to store 87 BWR fuel assemblies are presented.

Introduction

Systems used for storage of spent nuclear fuel must maintain containment and geometrical positioning of the fuel for a variety of accident conditions. Two components comprise such a system; a containment boundary, which prevents the release of fission gases to the environment and a basket structure which maintains the position of the fuel assemblies inside the containment boundary. For storage the containment boundary is comprised of a single stainless steel shell, but it is protected by an additional overpack. The cross section of the basket as contained inside a stainless steel canister and outer overpack is shown in Figure 1. As described above, the basket is a series of tubes with pins positioned at the tube corners (sockets) to prevent relative motion of the tubes during the accident. Attached to the outer tubes is a series of stiffened structural elements to assist in maintaining the configuration of the tubes. In the storage condition the overpack is a thick carbon steel liner inside a 26-inch thick concrete cylinder. Typically one approach would be to employ a sufficiently detailed model of the overpack with the basket model in a single combined model. It is observed that the ratio of the mass of the basket, fuel, and canister to the overpack is approximately 0.5 while a similar ratio of the natural frequencies of interest is 0.2. Based on the guidelines in Reference 1, the detailed basket evaluation can be decoupled from the overpack response during the accident conditions. A separate evaluation is performed to determine the deceleration of the canister for the tip over condition using detailed models of the overpack, while accounting for the mass of the canister, basket, and fuel. The results from the overpack model provide an acceleration time history to be used with a detailed basket model. This methodology reduces the model size for the accident evaluation. In this paper the focus is on the detailed basket response with a general description of the analyses of the overpack which provides the boundary condition for the basket tip over evaluation.

Impact Evaluation

Overpack Analysis

The controlling accident condition for the basket for storage is the tip over event of the concrete cask onto a concrete pad. This condition is typically evaluated for licensing of a storage cask, even though evaluations are performed to confirm that the cask remains upright during certain conditions such as seismic, tornados, explosions, and tornado missiles, automotive impacts. The initial step for the storage condition basket evaluation is the development of the half symmetry concrete cask model shown in Figure 2. The concrete is modeled using MAT_PSEUDO_TENSOR material to simulate crushing of the two concrete parts. The thickness of the concrete pad is 36 inches. The concrete overpack weighs approximately 220,000 pounds with a radial thickness of 26 inches with an outer diameter of 136 inches and a length of 218 inches. Since small strains are expected in the soil, a linear elastic material is used, and a modulus of elasticity is employed which is considered to bound the value at a storage site of interest. The edges of the soil elements not including the plane of symmetry can use either an infinite boundary condition or nodal restraints. The restraint of the exterior nodes is a conservative method to represent the presence of bed rock. In this analysis the nodes are restrained to eliminate uncertainty of the soil conditions outside the model. The canister and basket are not modeled but are represented by an additional mass along the lower surface of the steel liner of the cask as shown in Figure 2. The analysis is initiated with the specification of an initial angular velocity, which eliminates the need to solve for the rigid body motion of the system. The result of interest is the acceleration time history at an axial location corresponding to the top of the basket, which is shown in Figure 3. The filtering is performed using a Butterworth filter at 180 Hz, which corresponds to the natural frequency of the cask. Both the filtered and the unfiltered data are shown in Figure 3. While acceleration spikes do appear in the in the graph, the physical effect of the acceleration spikes on the large inertia is expected to be minimal.

Basket Analysis

Figure 1 shows the half symmetry periodic model of the basket for the 0º orientation. Periodic conditions are applied to each end face of the model and symmetry conditions are applied to the plane of symmetry of the model. The basket is constructed of ASTM 537 Class 1 material. The inelastic behavior of the material is represented using a piece wise linear stress strain curve. Since the impact occurs over a relatively short duration and the peak accelerations can occur in the range of milliseconds, it is expected that the material strength is affected by the strain rate. To determine the strain rate sensitivity, factors for the stress strain curve were obtained from Reference 2 for similar carbon steels. The elements for the fuel are modeled using a material with minimal elastic modulus and yield strength.

In the 0 º basket orientation the inertial weight of basket and fuel is transferred towards the bottom of the model via the pin-socket connections at tube corners and a component along the common interface (flats) between tubes. Since friction contains a significant level of uncertainty, the load is assumed to be transferred normal to the surface along the common interface of the tubes outside of the pin-socket portion of the tubes (see Figure 1). If a 45º basket orientation is considered, the flats between the tubes are reoriented to be either in the horizontal or vertical position. The flats in the horizontal position permit the vertical inertial load to be transmitted though the flats instead of being concentrated in the region of the pin. Whereas in the 0º orientation the tube side walls are subjected to primarily compressive stresses with minimal bending stresses, the 45 º orientation induces more bending stresses in the side walls of the tubes.

The 0º orientation therefore results in the maximum shear load at the pin, which may result in geometric instability of the basket. The impact analyses of both these orientations can be performed using a one-half symmetry model. For other basket orientations, a full model as shown in Figure 4 must be used. In this detailed model of the basket, the concrete storage overpack is represented by a stiff elastic shell. Configuration of the tube array is maintained by the pin-socket at the tube corners during the impact. Analyses are performed to determine if the pin could be removed from the socket due to the motion of the tube during the impact. Since the impact can produce a vibratory motion in the basket, the concern is that a pin could potentially be removed due to large relative motion of the tubes. To bound the tolerance occurring during construction, the outer dimension of all tubes not attached to the exterior stiffeners was artificially reduced by 0.069 inch. This would generate a total gap (due to all the tubes being reduced in size) larger than a single pin diameter, which during construction is a physical impossibility. If vibratory conditions existed during the impact for tubes not attached to the stiffeners, the pin could be removed from the socket. The tubes attached to the exterior stiffeners are expected to remain connected to the stiffeners during the impact. This implies that at the end of the impact, a large gap will appear between the tubes at the top of the basket not attached to the stiffeners and those tubes attached to the stiffeners. These gaps are not considered as significant since they are not physically possible. To perform an analysis of the tip over condition, the acceleration time history shown in Figure 3 is applied to the nodes on the thick outer shell. The initial condition consists of specifying an initial velocity in the downward direction which is primarily used to simulate the actual physical condition. The initial positions of the pins are unchanged when the tube size was artificially reduced. This permits the pins to be suspended between the tubes without any contact prior to the initiation of the impact.

Figure 5 shows the response of the pin at the time of maximum acceleration and near the end of the impact. Other frames show similar behavior which is the absence of motion which would lead to the removal of the pin from the socket. Figure 5 also shows the effectiveness of the interface simulated between the two parts. The overlap is observed to be insignificant. The results for the full model shown in Figure 4 showed similar results. This evaluation, however, does not address the possibility of the pin being extracted from the socket due to deformation between the pin and the socket (i.e., the pin being sheared out of the socket). The mesh used in the initial evaluation required refinement and the position corresponding to the maximum shear load was remeshed as shown in Figure 6. Load transfer at the interface of the two dissimilar meshes was analytically performed using constraints. The 0º basket orientation analysis was repeated using the same conditions as for the initial basket analysis. The maximum plastic strains shown in Figure 7 are significantly less than a typical ultimate strain of approximately 20% for this type of carbon steel. The time history of the maximum plastic strains is shown in Figure 8, showing that maximum strain is induced between the first and second acceleration spikes.

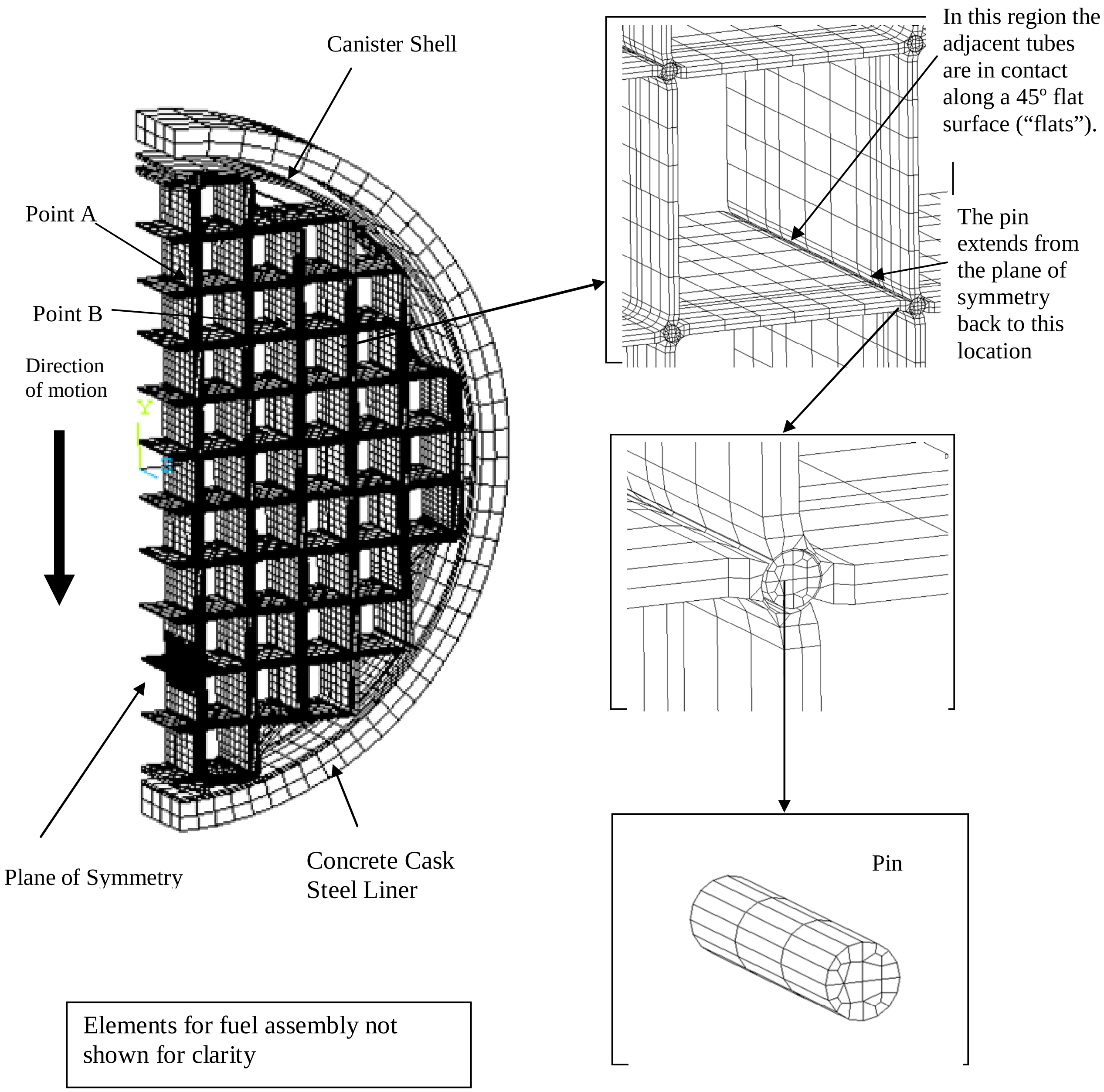
Conclusion

An evaluation of a basket design for storing 87 BWR spent fuel assemblies has been performed. The analyses confirm that the tubes do not disengage and become geometrically unstable during accident conditions. A detailed evaluation of the pin-socket experiencing the maximum shear does not exceed the ultimate strength of the basket material, confirming that the pins remain in the tube socket and that the basket maintains the fuel configuration during accident conditions.

References

1) ASCE 4-86, “Seismic Analysis of Safety-related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety-related Nuclear Structures,” American Society of Civil Engineers, New York, NY, 1986.
2) Atlas of Stress-Strain Curve, H. E. Boyer, ASM International, 1987

Figure 1 Basket Finite Element Model



Elements for fuel assembly not shown for clarity

Figure 2 Finite Element Models for Tip-Over Evaluation

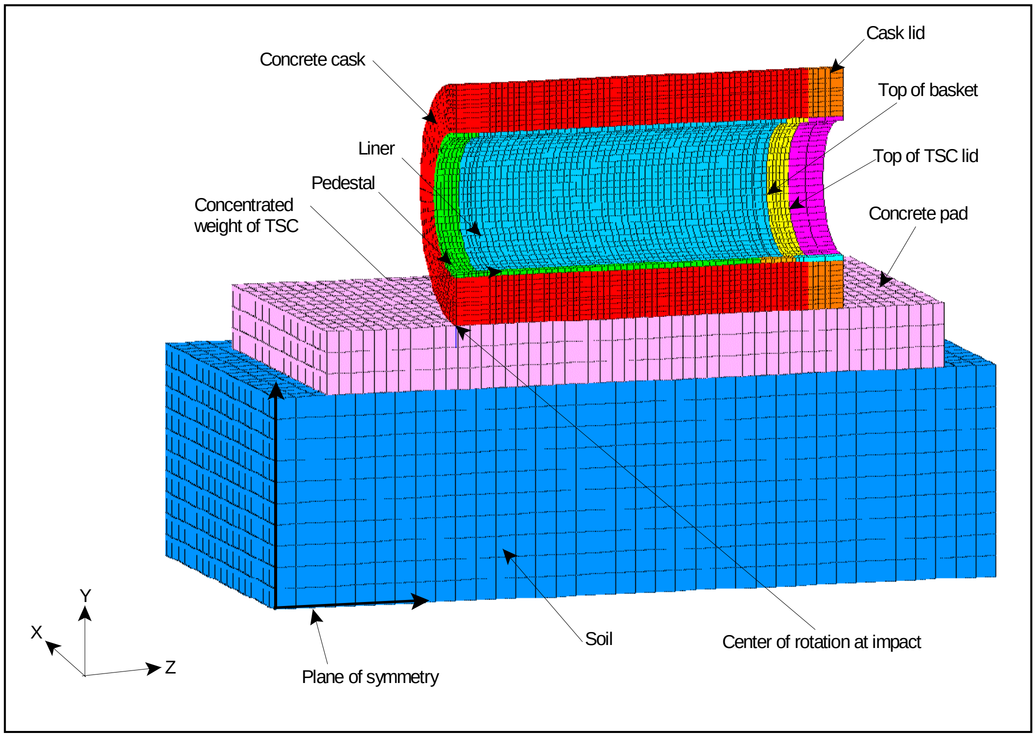


Figure 3 Acceleration Time History for the Tip Over Accident

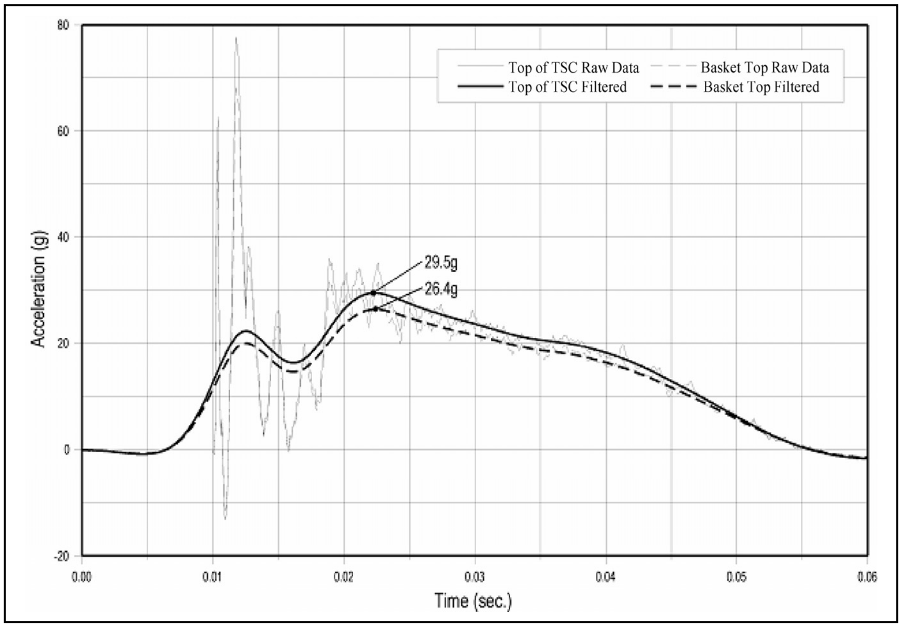


Figure 4 Finite Element Model for the 22.5º Orientation of the Basket

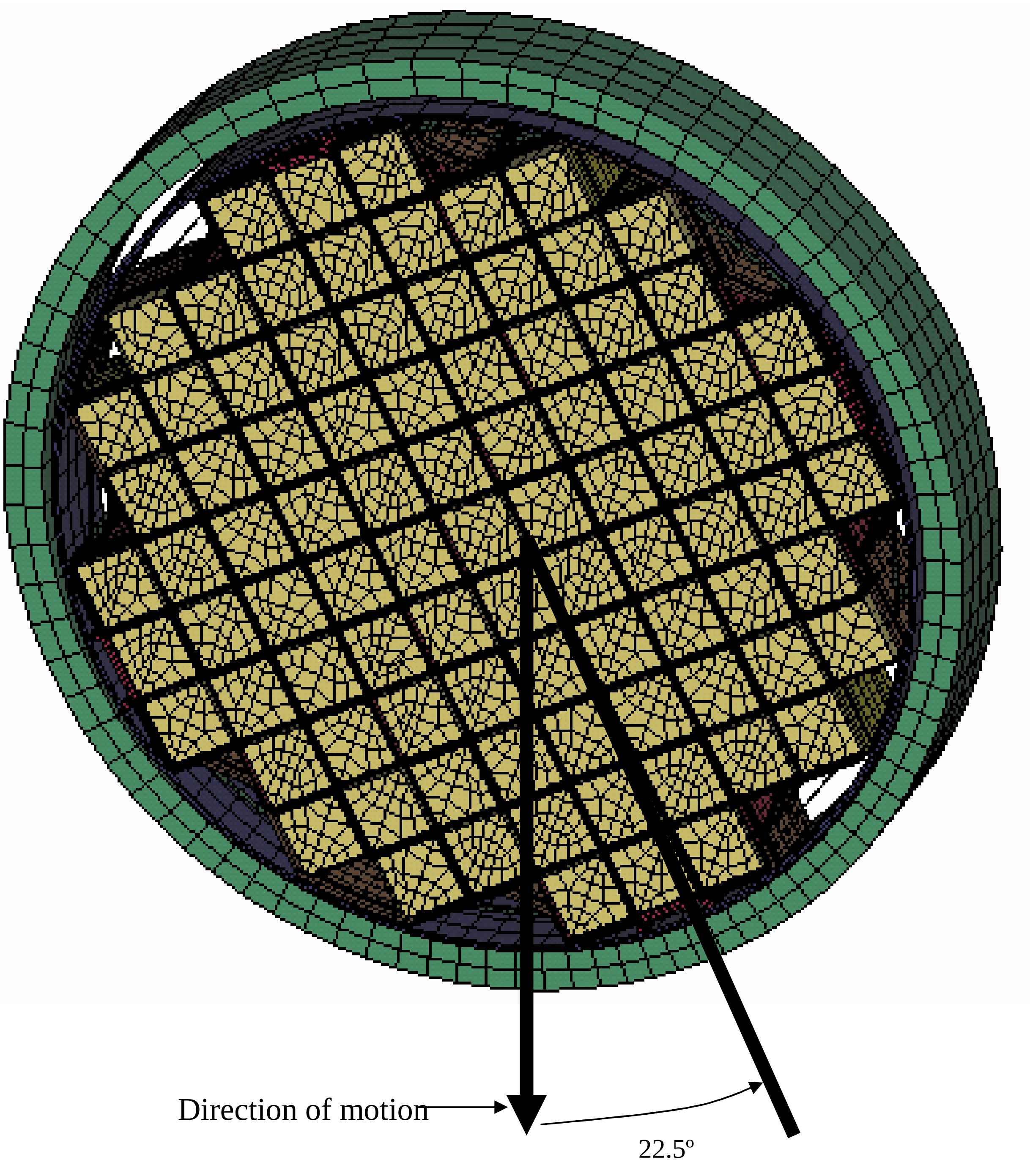
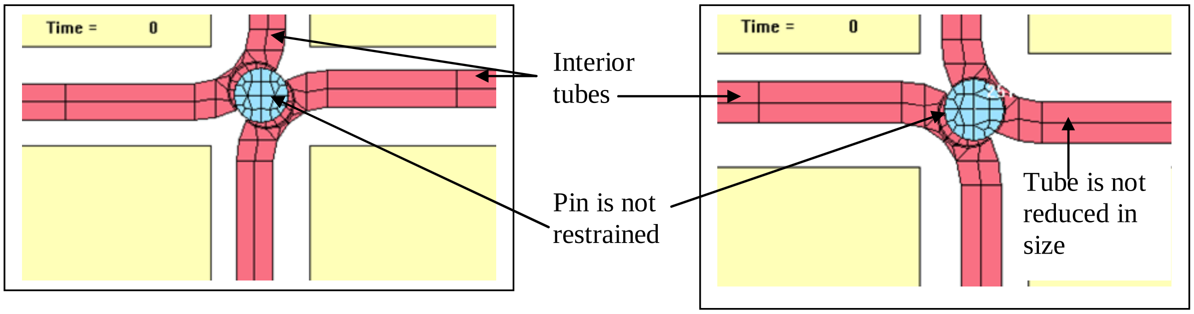
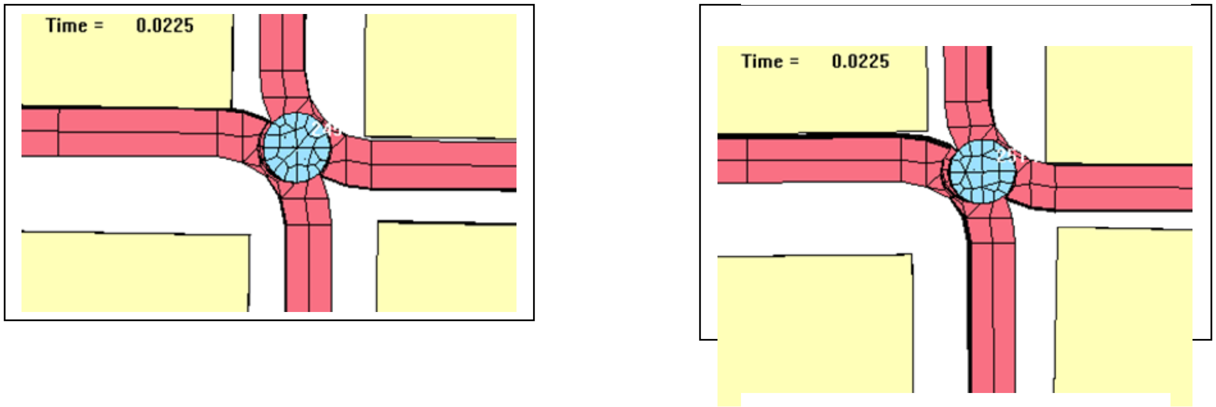


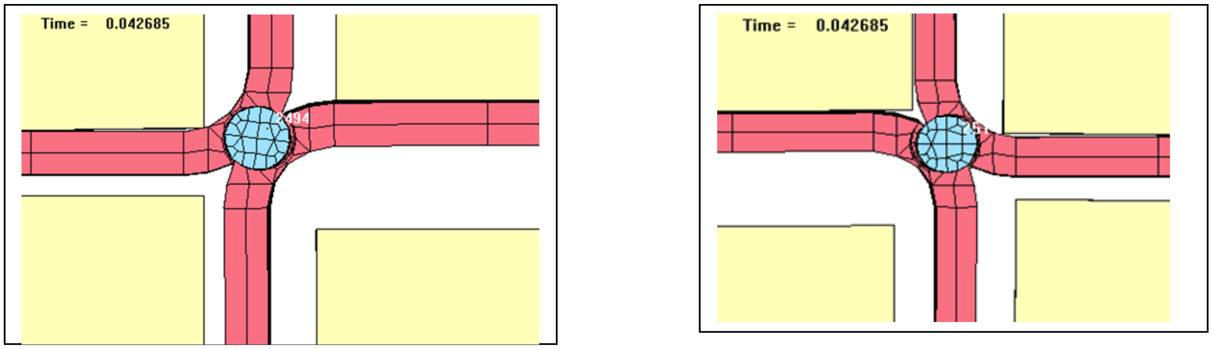
Figure 5 Motion of Basket Tubes for the 0º Basket Orientation


Point A at Time: 0 second

Point B at Time: 0 second


Point A at Time: 0.0225 second

Point B at Time: 0.0225 second


Point A at Time: 0.043 second

Point B at Time: 0.043 second

Note: Point A and Point B are defined in Figure 1

Figure 6 Refined Mesh for a Single Pin-Socket Position for the 0º Basket Orientation

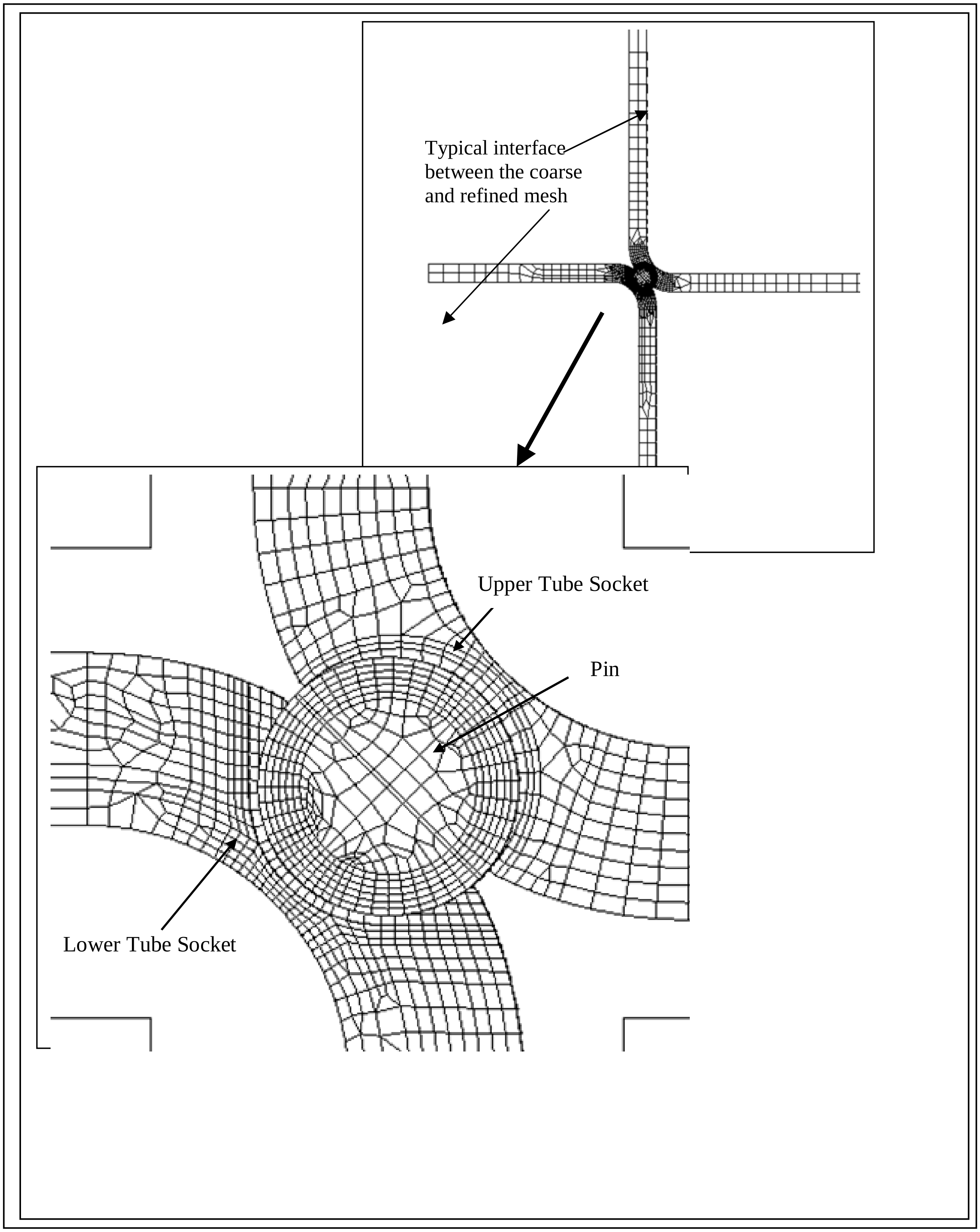
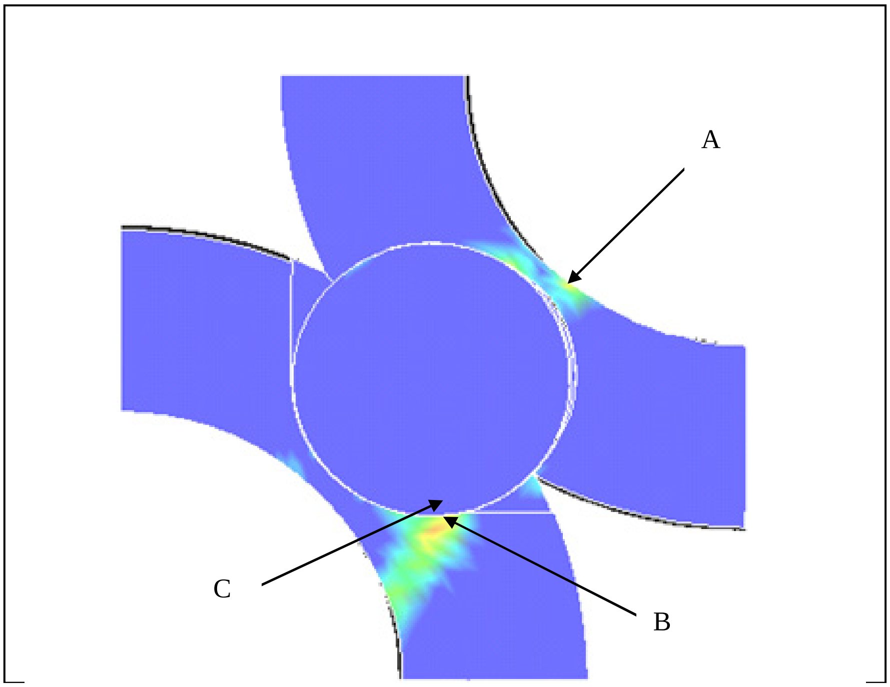


Figure 7 Maximum Plastic Strains for the 0° Basket Orientation



Maximum Plastic Strain		
Upper Tube Socket (Location A)	Lower Tube Socket (Location B)	Pin (Location C)
7.1%	9.0%	6.2%

Figure 8 Plastic Strain Time History for the Maximum Strain