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A Technique for Dynamic Analyses of Containers with Locking-Ring Closures

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ABSTRACT

The explicit method of the finite-element analysis is capable of analyzing the dynamic responses of a complex structure with complicated contact conditions. The method has been widely used in evaluating the dynamic responses of shipping package for radioactive materials. However, the previous analyses focused on the stresses and deformations of the structure components subjected impact loads and the possibility of the locking-ring closure separating from the drum body is not accounted for. The major difficulty for applying the explicit method to a container with a locking-ring closure is that the phenomenon of pre-loading a locking-ring closure is a static process; whereas, the explicit method involves the propagation of stress waves in the structure and thus is only applicable to dynamic analyses.

The purpose of the present paper is to propose a technique that extends the application of the explicit finite-element method to the dynamic analysis of the container pre-loaded by a lock-ring. Unlike the conventional dynamic analysis by the explicit method that only needs one load step, the proposed technique requires three sequential procedure steps (not load steps) to complete an entire analysis. Furthermore, one procedure step may consist of two load steps.

The paper discusses the procedures of the proposed technique in details. The application of the technique is illustrated by an example problem. The adequacy of the technique is also verified.

1.0 INTRODUCTION

The drum type packages have been used to transport radioactive materials. The top closure of a drum type package typically consists of a formed drum lid and a raised rim. A gasket is installed between the contact surfaces of the lid and the drum rim. The lid is retained to the drum by a locking ring, which is pulled tight in the circumference direction by a bolt. The bolt passes through the lugs located on either side of the gap in the locking ring. Figure 1 shows a typical locking-ring closure.

The packages used by the Department of Energy (DOE) for the transport of radioactive materials are required to pass the HAC 30-foot drop test. The explicit method of the finite-element analysis has been widely used to simulate the drop tests of the radioactive material shipping packages for the Hypothetical Accident Condition (HAC). However, all the previous analyses published in the open literature were performed under the assumption that the locking-ring closures were integral parts of the packages.
The possibility of the locking-ring closure separating from the drum due to an impact load has not been evaluated in details analytically due to the mathematical difficulties.

The previous test results, Blanton 1997 and Smith 1998 and 1999, show that the impact load of a 30-foot drop may cause closure failure. Therefore, it is important to study the effectiveness of the pre-loaded locking-ring closure during impact. The present paper proposes an analytical method that is more economic and may provide more comprehensive results than the experiment method.

2.0 DESCRIPTION OF TECHNIQUE

The proposed technique consists of the following three procedure steps:

<u>First Procedure Step: Quasi-Static Analysis for Pre-load</u>

The analysis to simulate the process of locking-ring tightening pre-load is performed under the assumption that the bottom of the package is fixed. In addition, the package is assumed to be located at a certain small distance above the target rigid floor but is already oriented at the desired inclined angle with respect to the floor.

The pre-load is physically a body load instead of a surface load and thus is self-limited; namely, the magnitude of the load will be adjusted by structural deformations. In the conventional static method, the pre-load can be treated as a thermal load through an equivalent temperature difference. On the other hand, in the proposed technique, the pre-load is applied dynamically at a reasonably slow rate. Its selflimiting characteristics will be preserved, if the pre-load is applied in one of the following two ways.

(1). For Model without Symmetrical Plane Passing through Middle of Bolt

The initial gap between the nut and the lug is equal to the combined elongation of the bolt and locking-ring after the pre-load torque is applied. The appropriate pre-load can be generated analytically by closing this gap as follows.

During the first load step, the nut is displaced to close the gap and then continue to be displaced by a small distance to ensure that the contact surface of the nut passes the contact surface of the lug. The displacement of the nut is accomplished by specifying the boundary conditions of the nodes in the finite-element model of the nut.

In the subsequent load step, the contact surfaces of the nut and lug are defined as a contact pair to establish the separation/contact relationship of the two contact surfaces. In the mean time, the boundary conditions of the nut are completely removed so that the nut will spring back but be stopped by the lug. At this point, the package is only subjected to the body force caused by the pre-load of the tightened locking ring.

(2). For Model with Symmetrical Plane Passing Middle of the Bolt

If the symmetrical plane of the model passes through the middle of the bolt, the displacement component of the bolt middle point perpendicular to the symmetrical plane is always equal to zero. Therefore, the contact surfaces of the nut and the lug can be defined as a contact pair initially. In the mean time, the boundary condition of the bolt middle point is specified to displace this point by one half of the combined elongation of the nut and locking-ring. This boundary condition will remain effective during the rest of the analysis. In this case, only one load step is needed to accomplish the pre-load analysis.

The analytical procedures describe above are carried out dynamically. The validity of the method can be justified by comparing the kinetic energy with the total energy consumption including elastic energy and plastic energy together with energy dissipation through friction on the contact surfaces between the locking ring and the closure or drum rim. If the kinetic energy is only a small portion of the consumed energy, the inertia effect on the structure deformations by applying the pre-load dynamically rather than statically is negligible and thus the analysis can be considered valid.

<u>Second Procedure Step: Rigid-Body Motion of Assembly Model</u>

In a conventional dynamic analysis, the initial velocity must be defined in the beginning of the analysis. However, in the present case, the first load step is devoted to the analysis of the locking-ring pre-load. During the duration of applying the pre-load, the model is basically stationary by fixing the nodes at the bottom of the model. Therefore, the velocity of a free-falling package at the instant when it is about to strike the target floor can not be defined as an initial velocity.

To work around the inability of defining the initial velocity, the model is forced to move as a rigid body in accordance with a specified time history of velocities. The analytical procedures are as follows.

(1). The boundary conditions applied at the bottom of the package are completely released so that the stationary model is free to move.

(2). In the mean time, the velocity of the entire model is defined by specifying the nodal displacements of the entire model in accordance with a smooth time-history function. The first and second derivatives of the specified function are both smooth, and thus the resulting velocity of the model will not have any oscillation.

During this step of the analysis, all the nodes are made to move in unison, and the model, in effect, undergoes a rigid body motion to reach the desired velocity. Therefore, there are no deformations introduced after the application of the pre-load.

<u>Third Procedure Step: Impact Analysis</u>

In this step, the boundary conditions specified as the nodal velocity during the second step are all released. As a result, the model will travel at the velocity obtained after a free fall until it impacts the target floor. In addition, the gravitational force is imposed onto the package by specifying the gravitational value as the body load for all the elements of the package model.

3.0 ANALYSIS OF EXAMPLE PROBLEM

To illustrate the procedures of the proposed technique and also verify its validity, the analytical results of an example problem are presented.

<u>Description of Example Problem</u>

The example model consists of the stainless steel 304L components; namely, an outer container, a closure of the outer container, a locking ring, a closed inner container (mainly to simulate the content weight), a lug, a bolt and a nut. In addition, there is a rubber gasket between the lid and the drum rim. To reduce the impact load, there exists a pad of foam between the lid of the outer can and the top of the inner container. The finite-element computer code, ABAQUS, HKS 1998, is used to perform the analysis. The outer and inner containers and the locking ring are modeled by 3D shell elements. The gasket, foam, lug, bolt and nut are modeled by brick elements. In addition, the target floor is represented by a 3D rigid shell element.

The package is dropped from a 30-foot height and its axis is oriented at 30-degree inclined angle with the target floor. The package also travels with its lug and bolt pointing toward the floor in such a way that a half model with its symmetrical plane passing through the mid-point of the bolt. Figure 2 shows the solid section of the model; whereas, Figure 3 displays the finite-element model.

Structural Analysis for Pre-load

Since the model is symmetric, the second method of pre-load discussed in Section 2.0 for the first procedure step analysis is applicable. The purpose of the example problem is merely to illustrate the application of the technique, and thus the input data of the pre-load analysis is estimated by a simple hand calculation as follows.

The elongation of the locking ring due to the pre-load by tightening the bolt is approximately:

$$\delta = \frac{\sigma \times (2\pi R)}{E} \qquad (1)$$

where $\delta =$ elongation of locking ring
$\sigma =$ stress applied at locking ring
$R =$ radius of drum rim
$E =$ Young's modulus of locking ring

Let the bolt to be tightened in such a way that the stress in the locking ring along the drum circumference is 20000 psi. Then, for the material of stainless steel 304L and the drum rim radius of 3.14 inches, the elongation of the locking ring calculated from Equation (1) is equal to 0.014 inches. The elongation of the bolt or lug can be estimated from the following equation based on force balance.

$$\delta_b = \left(\frac{l_b}{l}\right)\left(\frac{A}{A_b}\right)\left(\frac{E}{E_b}\right)\delta \qquad (2)$$

where δ_b, l_b, and E_b designate the elongation, length and Young's modulus of the bolt or the lug. The combined value of elongation estimated using Equations (1) and (2) for the present model is 0.0176 inches. Therefore, the gap between the mid-point of bolt and its final anchor point is estimated to be 0.0176 inches. The mid-point of the bolt is then displaced toward the symmetric plane to close this gap in order to produce an adequate pre-load.

This procedure step is performed as a quasi-static analysis; namely, the y component of the displacements at the mid-point of the bolt is increased by 0.0176 inches during the duration of 0.001 seconds. In other words, the pre-load due to locking ring tightening is applied at the speed of 17.6 inches per second. The effect of the inertia force on the resulting stresses will be discussed in Section 4.0.

Figures 4 and 5 show the vertical components of the displacements in the lid edge and the drum rim, respectively. The distribution of these displacements is axially symmetric, which is an indication that the pre-load is appropriately applied.

Determination of Impact Threshold Velocity

The velocity at the instant when the package is about to strike the target floor is obtained by forcing the package to move as a rigid body from stationary to the desired velocity. To minimize the inertia effect, the velocity of the package is increased following a function of time with its first and second derivatives both smooth.

After a 30-foot free fall, the package will travel at the velocity of 527.454 inches per second. The present sample model is initially located 0.5 inches above the target floor so that there is time to apply the pre-load before it impact the floor. If the package is forced to travel as a rigid body following the time history shown in Figure 6, then after 0.000852 seconds, the package will travel approximately 0.45 inches. Thus, there will still be a clearance of 0.05 inches between the package and the floor to avoid any over-closure.

The analysis of this procedure step is accomplished by specifying the velocity of the overall package model as the nodal boundary conditions and also following the function of velocity variation shown in Figure 6. The specified nodal velocity components of the entire model are 456.789 in/sec in the X-direction and 263.727 in/sec in the Z-direction because of the 30-degree inclined angle.

In the mean time, the boundary conditions to fix the bottom of the drum must be completely released in order to free the package for the subsequent motion.

The history of the velocity at a certain node of the lug is plotted in Figure 7. The result shows that the velocity is not exactly equal to zero in the beginning but oscillates slightly. The application of the locking-ring pre-load apparently causes this oscillation, although the drum is fixed at the bottom. However, the velocity quickly becomes smooth and reaches the desired value.

The adequacy of this procedure step will be discussed in Section 4.0.

Impact Analysis

After applying the pre-load and also establishing the travelling velocity, the model has all the appropriate initial conditions and is ready to impact the target.

Since the velocity established in the previous procedure step is the initial velocity of the model before impact, this boundary condition must be released during this procedure step. The appropriate velocity will then be calculated. In addition, the gravitational load is added as a distributed load to simulate the gravitational force.

Figures 8 and 9 show the deformed shapes of the model.

4.0 VERIFICATION OF TECHNIQUE

Analysis for Pr-load

As discussed in Section 2.0, the adequacy of quasi-static method for the pre-load analysis can be verified by examining the energy results. Figure 10 shows the plots of various energies caused by the locking ring pre-load for the example problem discussed in Section 3.0. The kinetic energy is only a small portion of the total energy consumed during the quasi-static pre-load process. This implies that the inertia effect on the structural response is negligible. Thus, it is concluded that the quasi-static approach of pre-load analysis is acceptable as long as the pre-load is applied smoothly and at an appropriate rate.

Determination of Initial Velocity at Impact Threshold

Since the first load step is devoted to the analysis of the pre-load, the velocity of the package at the impact threshold can not be directly defined as an initial velocity. As a result, the threshold velocity is achieved by forcing the model to move as a rigid body through specifying appropriate boundary conditions until it reaches the desired impact threshold velocity. To justify the validity of this approach, a box of 12 inches in width, 12 inches in length and 6 inches in height is analyzed by using both the conventional method and the proposed technique. The box consists of six stainless steel 304L plates with 0.8-inch thickness. It is dropped from a 30-foot height to a rigid surface. The energy results obtained from the analyses by the conventional method and by the proposed technique, displayed in Figures 11 and 12, respectively, are identical. The deformed shapes and the stress results, which are not shown in the present paper, are also identical. Therefore, it can be concluded that the proposed technique to achieve the threshold impact velocity is valid.

5.0 CONCLUSION

A technique has been proposed to analyze the problem of a container with a locking-ring closure subjected to an impact load. The basic principles of the technique are that the phenomenon of locking-ring tightening is treated as a quasi-static process and the impact threshold velocity is obtained through a rigid-body motion by specifying the boundary conditions. As a result, the problem can be solved by using the explicit finite-element method that is more suitable than the implicit finite-element method in analyzing the dynamic response of a complex structure with complicated contact conditions.

The application of the technique is illustrated by an example problem. The two principles that the technique is based on are also justified.

6.0 REFERENCES

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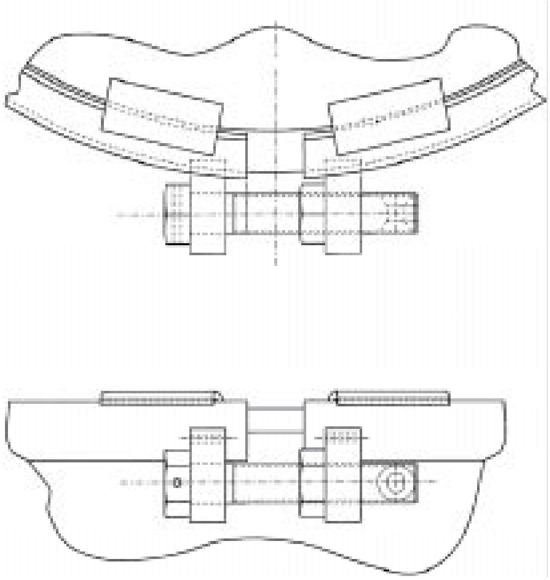

Figure 1.Configuration of Typical Locking-Ring Closure

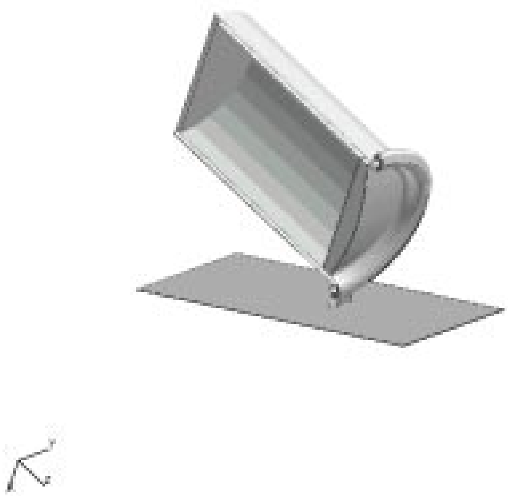

Figure 2. Solid Sections of Sample Problem

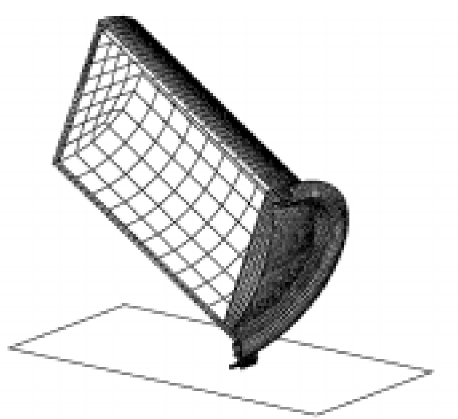

Figure 3. Finite-Element Model of Sample Problem

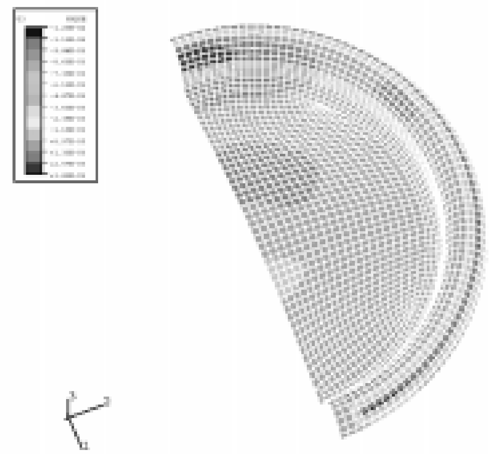

Figure 4. Vertical Displacements of Lid Closure due to Pre-load

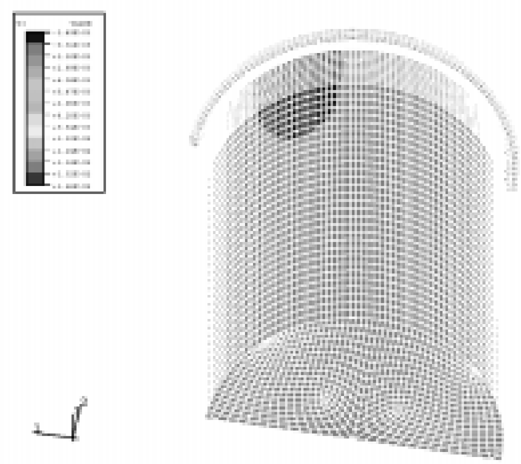

Figure 5. Vertical Displacements of Drum Rim due to pre-load

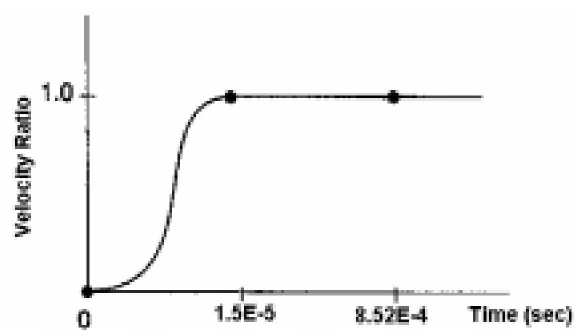

Figure 6. Profile of Input Velocity Function

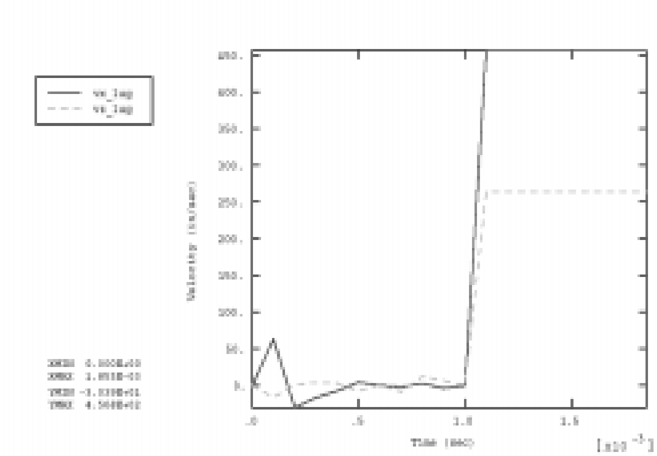

Figure 7. Time-History of Model Velocity before Impact

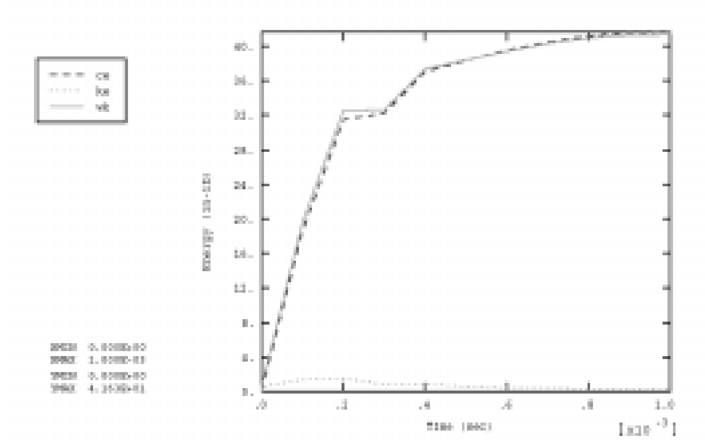

Figure 10. Consumed Energy (ce), Kinetic Energy (ke) and External Work (wk) Caused by Pre-load

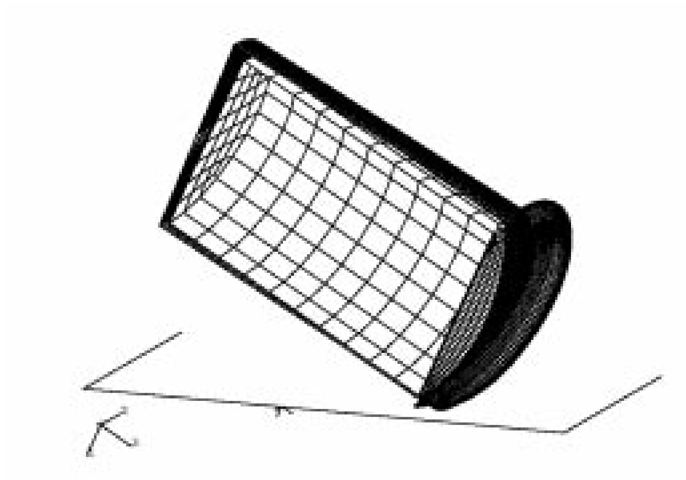

Figure 8. Deformed Shape of Sample Problem Model

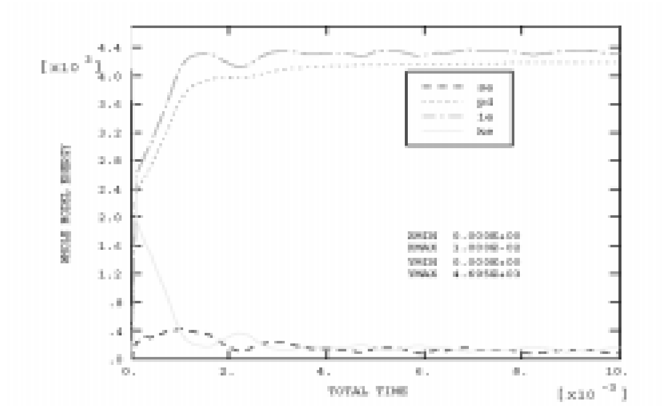

Figure 11. Energy Results of Verification Model By Conventional Explicit Method (se=elastic strain energy; pd=plastic strain energy; ie=total internal strain energy; ke=kinetic energy)

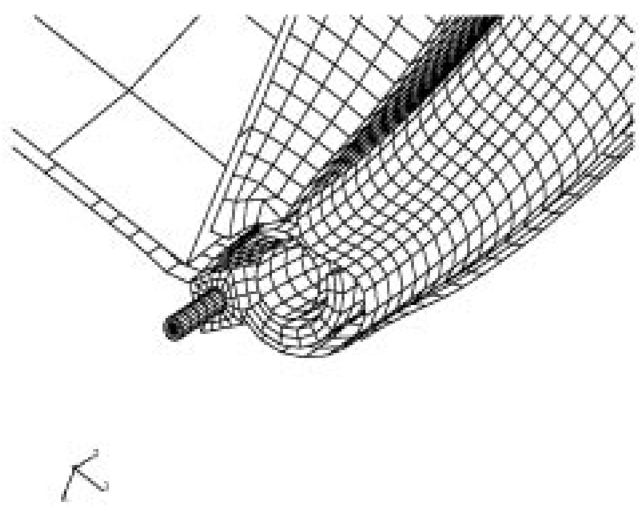

Figure 9. Blow-Up View of Deformed Shape in Lug Region

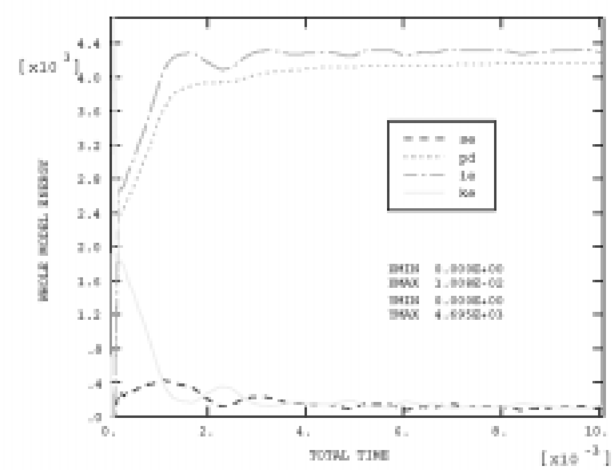

Figure 12. Energy Results of Verification Model By Proposed Technique