INCENTIVES FOR USE OF INELASTIC ANALYSIS IN RAM TRANSPORT CONTAINER DESIGN[*]

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ABSTRACT

There is much interest within the radioactive material transportation container design community in the use of inelastic analysis. In other industries where inelastic analysis is used in design there is typically an improved knowledge of the capacity of the structure and a more efficient us of material. This paper describes the results of a program in which the incentives for inelastic analysis for radioactive material transport container design were investigated to determine if there are similar benefits. Detailed are the elastic and inelastic analyses of two containers subjected to impacts onto a rigid target following a nine-meter free fall in a center-of-gravity-over-corner orientation.

INTRODUCTION

The use of inelastic analysis methods instead of the traditional elastic analysis methods in the design of radioactive material (RAM) transport packagings leads to a better understanding of the response of the package to mechanical loadings. Thus, better assessment of the containment, thermal protection, and shielding integrity of the package after a structural accident event can be made. A more accurate prediction of the package response can lead to enhanced safety and also allow for a more efficient use of materials, possibly leading to a package with higher capacity and/or lower weight. This paper discusses the incentives for using inelastic analysis in the design of RAM shipping packages.

Inelastic analysis provides an improved knowledge of the package behavior. This allows for incorporation of a more uniform margin of safety, which can result in weight savings and a higher level of confidence in the post-accident configuration of the package. It must be demonstrated that the use of inelastic analysis provides a better design to overcome the difficulties associated with this type of analysis. In this paper, comparisons between elastic and inelastic analyses are made to illustrate the differences in the two analysis techniques for two different types of packages. One is a package to transport a large quantity of RAM by rail (rail cask) with lead gamma shielding, and the other is a package to transport RAM by truck (truck cask) with depleted uranium (DU) gamma shielding. Analyses of the center-of-gravity-over-corner impacts will be compared for each package.

The comparisons indicate that a package designed to just meet the elastic design criteria will actually undergo some yielding in the locations of highest stress. This results in two consequences in the predicted behavior of the cask. First, the overprediction of the stiffness of these yielded regions by the elastic analysis technique results in an underestimation of the stresses in other portions of the structure. This is demonstrated in the analyses of the rail cask impact. The elastic analysis predicts a maximum stress near the impact limiter in the outer shell, and the inelastic analysis predicts a redistribution of this stress resulting in higher stresses at other locations. The highest stress in the inelastic analyses occurred in the inner shell near the impact end. Secondly, in an inelastic analysis, the yielding of a portion of a structure causes the force in that region to rise less rapidly than forces in adjacent regions. This behavior tends to cause the stresses throughout the structure to be more uniform, allowing a more efficient use of material and therefore a lighter overall package. This is demonstrated in both analyses. Details of these analyses are described below.

ANALYSES OF RAIL AND TRUCK CASKS SUBJECTED TO A NINE-METER CORNER DROP

The problems and benefits of using elastic and inelastic analysis in the design of RAM transportation packages are explored via two designs (a rail cask and a truck cask) for shipping a bulk quantity of high level RAM waste. The waste is assumed to have very little strength but high volumetric stiffness and a specific weight of 1.7. The shielding requirements for the package are assumed to be similar to those for spent fuel. The rail cask utilizes lead for its gamma shielding, 304 stainless steel shells on the inside and outside of the gamma shielding, and solid stainless steel ends as shown in Fig. 1. In addition, the package is encased in neutron shielding, a 304 stainless steel neutron shielding shell and polyurethane foam impact limiters. The truck cask is of similar construction except it utilizes depleted uranium instead of lead for its gamma shielding. The dimensions and material properties for the casks can be found in prior work by the authors (1). This reference has detailed analyses for the two casks subjected to nine meter end, side, and corner impacts.

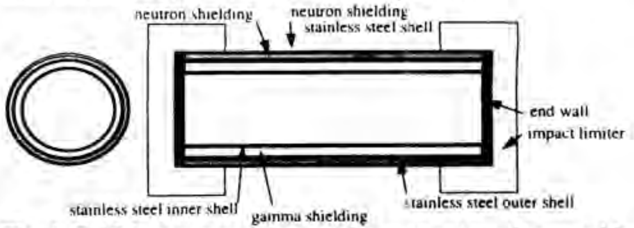

Fig. 1. RAM transportation package construction used in these analyses.

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Depending on whether an elastic design criteria or an inelastic design criteria was used, a different material model was used for the 304 stainless steel inner shell, outer shell, and end walls. A linear elastic material model was used for these components with the elastic design criteria, whereas an elastic-plastic material model with linear hardening was used with the inelastic design criteria.The energy absorbing impact limiter was a 0.32 g/cm^3 polyurethane foam, and its model included the effects of volumetric crush and lock-up (2). When a change in the wall thickness was required, a replacement ratio of 1/1.75 lead to stainless steel and 1/3 DU to stainless steel was used such that the shielding effectiveness was unchanged.

The maximum allowable stresses are computed by the formulas specified in the NRC Regulatory Guide 7.6 (3) for the elastic analysis and in the ASME Boiler and Pressure Vessel Code, Section III, Appendix F (4) for the inelastic analysis. For the stainless steel material, the maximum allowable membrane plus bending stress was 482 MPa for the elastic analysis and 465 MPa for the inelastic analysis.

The finite element model for each RAM transportation package consisted of a total of 31,960 elements with two elements through the thickness of the inner shell and two elements through the thickness of the outer shell. All analyses were performed with a transient dynamic analysis code PRONTO3D (5).

ANALYSIS OF A RAIL CASK WITH LEAD GAMMA SHIELDING

The nine-meter center-of-gravity-over-corner drop impact was modelled as a dynamic event with initial velocity of 13.4m/s. Figure 2 shows the deformed shape of the rail cask for the inelastic analysis.

In the inelastic analysis, the von Mises stress exceeds yield in the outer shell at approximately 8.8 milliseconds. Because the stainless steel is allowed to yield, part of the load is transferred to the shielding and inner wall. The stresses continue to increase until the maximum g-loading is reached at 57.6 milliseconds when the maximum vonMises stress is 297 MPa (engineering stress of 308 MPa). The location of this maximum stress, as shown in Fig. 3, is in the inner shell. For the inelastic analysis, a maximum plastic strain of 0.063 for the 304 stainless steel is observed in the inner shell of the cask. This amount of plastic strain does not result in severe permanent deformation. Figures 2 and 3 show the deformed cask with no visible signs of deformation in the stainless steel shells.

In the elastic analysis, the von Mises stress increases to 851 MPa and does not redistribute to the shielding and inner shell. Figure 4 shows a series of deformed shapes (with displacements magnified by 5x) of the outer shell (for a cask design with outer shell thickness 1.52 cm) at 40 msec, 48 msec, *and 56* msec. The high stresses are due to a combination of the endwall bending the shell and the impact limiter pushing inward on the outer shell. The outer shell thickness of 1.52 cm is the same as that used in the inelastic analysis. The outer shell thickness was significantly increased in the redesigns (to 8.89 cm), yet the maximum stress still exceeded the allowable stress. With the outer shell thickness of 8.89 cm, the maximum von Mises stress was 598 MPa (engineering stress of 599 MPa) at 59.2 milliseconds which corresponds to the maximum g-loading on the cask. The location of this maximum stress was in the outer shell as shown in Fig. 5. Because of the relatively small stiffness of the lead shielding, practically none of the load on the outer shell is transferred to the inner shell. The maximum von Mises stress of 598 MPa *exceeds* the maximum allowable membrane plus bending stress of 482 MPa specified by the NRC Regulatory Guide 7.6. The outer shell wall thickness was increased from an initial thickness of 1.52 cm to a point where it was felt that the design was no longer realistic (8.89 cm) and, therefore, no further redesign was attempted.

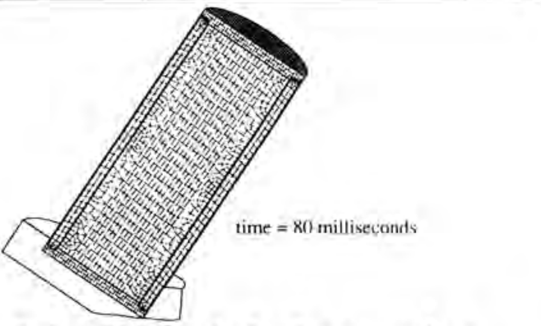


Fig. 2. Deformed rail cask after 9 m corner drop.

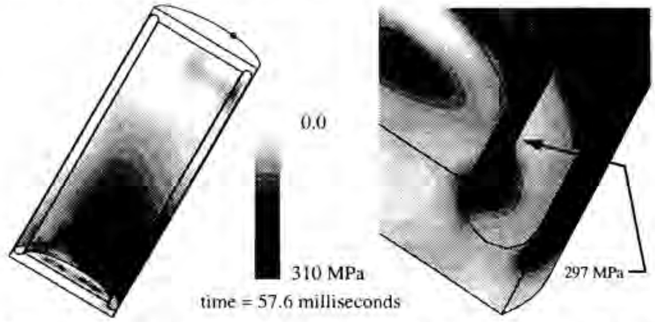
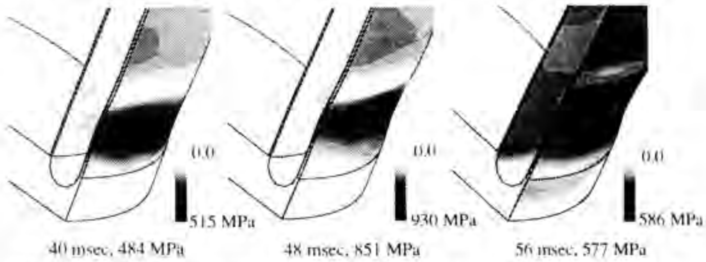


Fig. 3. Maximum von Mises stress during the 9 m corner drop of inelastic rail cask.



40 msec, 484 MPa 48 msec, 851 MPa 56 msec, 577 MPa

Fig. 4. Von Mises stress history in the outer shell (for 1.52 cm thickness) of the elastic rail cask. Displacements are magnified by 5 sx.

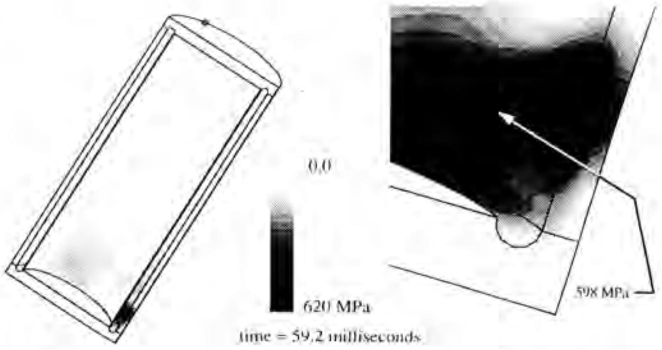


Fig. 5. Maximum von Mises stress during the 9 m corner drop of elastic rail cask (for 8.89 cm outer shell thickness).

ANALYSIS OF A TRUCK CASK WITH DU GAMMA SHIELDING

The nine-meter center-of-gravity-over-corner drop impact was modelled as a dynamic event with initial velocity of 13.4m/s. Figure 6 shows the deformed shape of the truck cask for the inelastic analysis. The von Mises stress exceeds yield in the outer shell as the cask is loaded to the maximum g-load. At approximately 11.2 milliseconds, an instability forms in the outer shell at its mid-length resulting in a von Mises stress of 226 MPa (engineering stress of 227 MPa), as shown in Fig. 7. At a later time (12.8 milliseconds), the inner shell also reaches a stress slightly above yield. This is caused by redistribution of the relative stiffness of the inner and outer shell due to the permanent deformation in the outer shell. A plastic strain of 0.0337 was observed in the outer shell of the cask and a plastic strain of 0.00744 was observed in the inner shell of the cask. This small amount of plasticity does not result in noticeable deformations, yet it is sufficient to allow redistribution of forces.

Fig. 6. Deformed truck cask after 9 m corner drop.

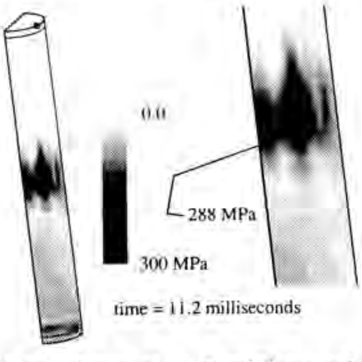


Fig. 7. Von Mises stress at 11.2 milliseconds into the 9 m corner drop of inelastic truck cask.

Figure 8 shows the maximum von Mises stress during the elastic analysis. Because the inner and outer shells are modelled as elastic materials, the von Mises stress is significantly higher than that predicted by the inelastic analysis, and since the outer shell is not allowed to permanently deform, there is no redistribution of stiffness, and therefore the inner shell is not loaded as much as in the case of the inelastic analysis. At approximately 8.81 milliseconds, the von Mises stress increases past the 207 MPa yield stress and reaches a value of 350 to 400 MPa. At 9.04 milliseconds, an instability forms in the outer shell (in the same manner as it did in the inelastic analysis). This results in a maximum von Mises stress of 1048 MPa occurring at 9.045 milliseconds, as shown in Fig. 8. This level of stress is much higher than the allowable stress of 482 MPa, and a significantly thicker outer shell would be required as was the case with the rail cask. No attempt was made to redesign the cask.

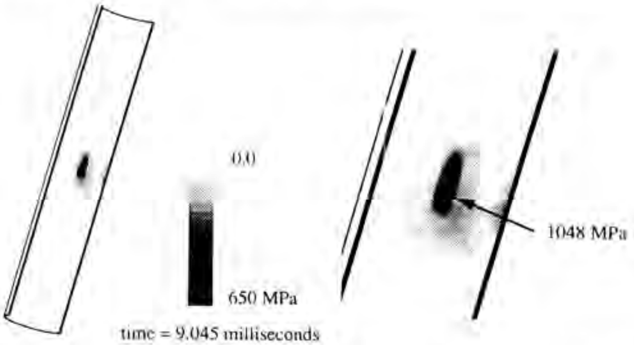


Fig. 8. Maximum von Mises stress during the 9 m corner drop of elastic truck cask.

COMPARISON OF RESULTS

The center-of-gravity-over-corner impact scenario modelled above with a transient dynamic analysis technique provided a foundation for comparing elastic and inelastic design methodologies. The elastic analyses in this study using a transient dynamic technique with nonlinear behavior of all elements except the stainless steel model the impact event in the most accurate way possible while retaining the requirement for elastic behavior of the stainless steel. Generally elastic analysis are performed in a quasi-static fashion ignoring all sources of nonlinear behavior such as shielding response. This commonly utilized technique was not used in this study so that the comparisons would be based entirely on differences in the stainless steel shell response instead of modelling technique. A few issues, to be discussed later, have not been resolved and require further study. However, even with these limitations, the use of inelastic analysis technique for radioactive material transportation container design seems to have an advantage over elastic analysis. Based on the impact scenarios of a rail and truck RAM package studied in (1) and summarized here, an improved knowledge of the behavior of the cask is obtained by using the inelastic analysis. This can lead to a better overall design in the following ways.

First, elastic analysis may underpredict maximum stress at a particular location, resulting in inappropriately sized wall sections. Elastic analysis does not properly account for the decrease in stiffness resulting from yielding in part of the structure and does not show the redistribution of load caused by this yielding. For the rail cask, the elastic analysis underpredicted the stress in the inner shell. This was a result of the outer shell yielding and redistributing the load to the gamma shielding and inner shell. It was also observed in the inelastic analysis that significant plastic straining can occur through the thickness in several areas. This may indicate that the elastic analysis is neglecting significant physical features of the impact scenario.

Second, elastic analysis may overpredict the maximum stress. The inelastic shells can yield and redistribute the loading to other less loaded parts of the structure, whereas the elastic shells cannot predict this behavior. This was shown in both of the nine-meter center-of-gravity-over-corner drop analyses. For the rail cask, the elastic analysis of the impact event would require an outer shell thickness of over 8.89 cm to meet the design criteria. With the same impact limiter, the inelastic analysis suggested that the loading on the outer shell causes it to yield and redistribute the load to the gamma shielding and inner shell requiring an outer shell thickness of only 1.52 cm. Therefore, the inelastic analysis may also allow for a better distribution of structural material, which can lead to weight savings. The weight savings can increase the capacity of the package, thereby decreasing the number of shipments required to transport a given quantity of material, which increases the overall shipping program safety. The use of inelastic analysis may also decrease the overall cost of a transportation package, especially for designs where multiple packages will be constructed.

ISSUES INVOLVED IN CONDUCTING ACCURATE ANALYSES

The use of inelastic analysis for RAM transportation containers potentially has several advantages over the currently used elastic analysis. The most prominent of these is that the analysis method models the behavior of the package more accurately, which leads to a better understanding of the response of the container to the loads applied to it. The transient dynamic analysis technique utilized in this study provides improved knowledge of the structural integrity of the cask, but with additional cost. The computer cost for one center-of-gravity-over-corner impact scenario summarized here involved approximately 25 cpu-hours on a Cray Y-MP^{TM}. This cost should be added to the time spent by an experienced user in constructing the finite element model. Such a model typically includes a variety of material models and nonlinear material behavior. For many materials the nonlinear material properties are not readily available or are not accepted by a standards group.

Some additional material properties required include strain rate and temperature dependent stress-strain curves. In the examples considered in (1) and summarized here, the strain rates can typically range from $10^{-1}s^{-1}$ to $10^{3}\,s^{-1}$. The fact that the contents will have a temperature higher than the outside ambient means there will be a temperature gradient through the wall of the cask. For certain materials, especially the lead shielding used in the cask, the effects of temperature and strain rate on the material behavior can be significant and should be considered in the analysis. For elastic analysis the effects of strain rate and temperature on yield stress are well known. For an inelastic analysis it is necessary to consider the entire material response (often much past the strain corresponding to yield) where the effects of temperature and strain rate are not well known for a wide selection of materials.

An improved understanding of the response of the container depends on how accurately the loading history is predicted. The transient dynamic analysis technique can more *accurately* predict the load history if all sources of nonlinearity are considered. That includes the nonlinear thermo-mechanical behavior of the cask materials, i.e. shielding, contents, and impact limiters, and the nonlinearities arising from fabrication, i.e. initial stresses, geometric imperfections, and fastener details. In elastic analysis the stresses from these sources are typically superimposed on the results of the elastic impact analysis. If any nonlinear behavior is considered in a transient dynamic analysis, it is no longer appropriate to superimpose these as they may influence the load history.

There are also several modelling issues that have not been resolved and require further study. During some impact scenarios stress waves in the shell walls may result in localized instabilities in the shells. These events occur over a few microseconds and, to some degree, will depend on the finite element model, i.e. finite element size, solution time step and material model. The analyses were conducted using a finite element model with only two elements through the thickness of the inner and outer stainless steel shells. This may not be sufficient to accurately model the bending behavior of these shells. A more robust model requires three or more elements through the thickness of shells in bending. The extent to which the results presented here are influenced by modelling issues have not yet been investigated.

SUMMARY

The design criteria currently used in the design of RAM transportation containers are taken from the ASME Boiler and Pressure Vessel Code. These load based criteria are ideally suited for pressure vessels where the loading is quasistatic and all stresses are in equilibrium with externally applied loads. For impact events, the use of load based criteria is less supportable. Impact events tend to be energy controlled, and thus, energy based criteria would appear to be more appropriate. Determination of an ideal design criteria depends on what behavior is desired. If the intent is that there will be no yielding in the package, an elastic analysis with an allowable stress less than the yield point stress is sufficient. This type of acceptance criteria will lead designers to using materials with the highest possible yield stress, and perhaps a lower margin of safety against gross rupture. However, if the goal is to prevent release of radioactive material, some amount of inelastic deformation is acceptable. In this case, the acceptance criteria should limit through-wall tearing and keep deformations to an acceptably small amount. An elastic analysis cannot predict the margin of safety against through-wall tearing and the deformations associated with an impact event nearly as well as an inelastic analysis. The overwhelming advantage of nonlinear dynamic analysis techniques is a better understanding of the response of the structure to the imposed environment. A better understanding of package behavior during impact events should lead to a safer package.

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