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USE OF INELASTIC ANALYSIS TO DETERMINE THE RESPONSE OF PACKAGES TO PUNCTURE ACCIDENTS[*]

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ABSTRACT

The accurate analytical determination of the response of radioactive material transportation packages to the hypothetical puncture accident requires inelastic analysis techniques. Use of this improved analysis method reduces the reliance on empirical and approximate methods to determine the safety for puncture accidents. This paper will discuss how inelastic analysis techniques can be used to determine the stresses, strains, and deformations resulting from puncture accidents for thin skin materials with different backing materials. A method will be discussed to assure safety for all of these types of packages.

INTRODUCTION

The design basis accident (US NRC 1995) defined includes a free fall from 30 ft. onto an essentially unyielding target followed by a drop onto a 6-inch diameter punch from a height of 40 inches. Packages designed following the method and guidance of U.S. NRC Regulatory Guide 7.6 (US NRC 1978) must show that tearing of any portion of the package from the punch test will not lead to failure of the containment boundary. Because the punch test is followed by a pool fire burn test it is often desirable to keep the outer layers of a package intact to keep from exposing often flammable impact limiting material to open flames and oxygen. To keep the outer shell materials from tearing they are often designed with a large amount of conservatism resulting in heavier than otherwise required packages. To keep the package weight to a minimum without compromising the safety of the package, a greater understanding of the tearing mechanics of thin shells and methods to accurately predict the onset of tearing must be developed.

A common check for whether or not a material will tear is based on work done by Nelms (Nelms, 1968). His investigation into the tearing of thin shell materials was based on a series of tests with thin representative shell materials backed with lead. Most of the tests were performed with a prismatic test setup using flat plates backed by lead bricks impacting a small diameter punch. The resulting empirical equations from this work have been used to predict the onset of tearing for a given cask design. Some of the limitations of this work include using only lead as a backing material in the experiments and the small scale used in the experimental setup.

Because many cask designs use foam or honeycomb materials as energy adsorption material with a thin metallic skin to contain them, it is not well understood how this design versus lead as a backing material will resist tearing. This paper will compare the test data from Nelms paper to a finite element model to verify the analytical solution. The finite element model will be modified to help determine the effect of changing the backing materials from lead to softer foam materials.

NELMS EXPERIMENTAL RESULTS

Currently a common check for whether or not a material on a cask will tear from a 40 inch vertical drop onto a 6-inch diameter punch is through the use of the equations developed by Nelms. These equations were based on a series of small scale tests where lead backed plates of different materials and thicknesses were impacted onto hardened steel punches with varying amounts of energy. The plate being impacted was backed up by two lead bricks and a stiffening plate all aligned within a support frame. The frame provided the clamping

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force to keep the plates and lead bricks together. A diagram of the impact plate, lead bricks, stiffening plate and frame is shown in Fig. 1.

The entire frame was dropped in a test fixture that guided the fixture onto a 1/2" diameter hardened steel punch. The height of the drop was changed to vary the energy involved in the impact. The tests were repeated until the energy at which tearing occurs was bounded. The height difference between when tearing and no tearing occurred was based on visual inspection of the plates and was narrowed down to usually less than 1 inch difference in drop height.

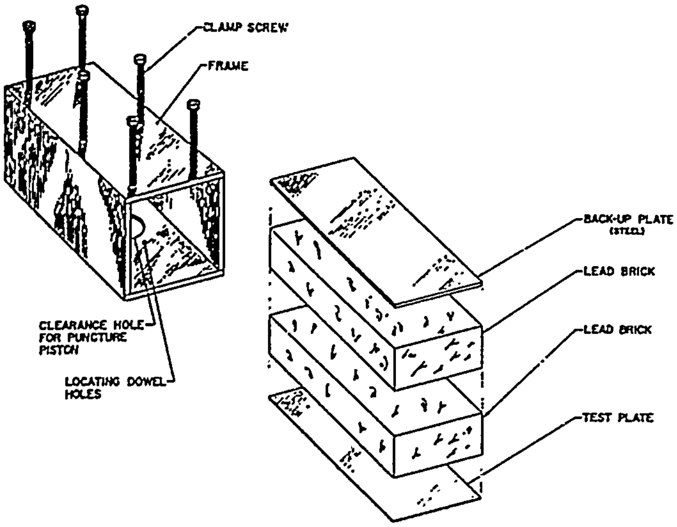

Figure 1. Test setup used in Nelms experimentation.

The tearing or incipient puncture energy was assumed to be the average of the bounding energy values. The incipient puncture energy divided by the ultimate tensile strength of the materials typically used in cask design were plotted against the thickness of the test plate.

The test data for prismatic models for each size punch used appear to fall along a straight line when plotted in a log-log graph, as shown in Figure 2.

The good correlation of data with a straight line shown in the figure suggests that for a given punch size, the data might be represented by an equation of the form,

$$\frac{E_F}{S} = At^n \qquad (1)$$

where

E_F = the incipient puncture energy of a prismatic cask jacket, in-lbs,

S = the ultimate tensile strength of the jacket material, pounds per square inch,

A = a constant,

t = the thickness of the jacket material in inches, and

n = a constant.

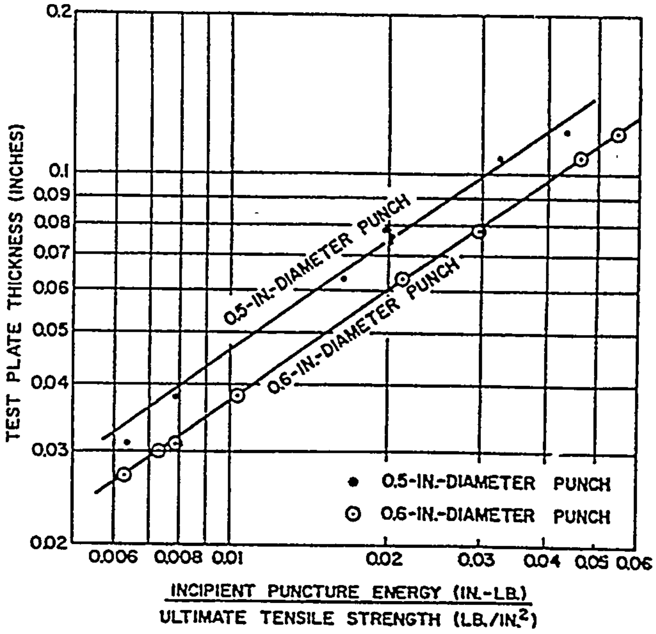

Figure 2. Relationship between plate thickness, incipient puncture energy and the ultimate tensile strength of the candidate material.

Using the method of least squares to fit the data plotted in Fig. 2, and generalizing the equations to account for different punch sizes and plate thicknesses results in the following empirical equation that was developed by Nelms.

$$\frac{E_F}{S} = 2.14d^{1.6}t^{1.4} \qquad (2)$$

where

d = punch diameter in inches.

Equation 2 appears to adequately represent the data for the prismatic models. Of the thirty-eight data points used by Nelms in his report, thirty are predicted by Equation 2 with a difference of only 10 percent or less, and only two of the data points differ by more than 15 percent.

CORRELATION OF ANALYSIS WITH NELMS EXPERIMENTAL RESULTS

Two of Nelms drop test experiments were modeled in the explicitly integrated finite element code PRONTO2D (Taylor and Flanagan, 1987, Attaway, 1992) to compare analytical results with experimental results. Because the prismatic tests contained loads that were axisymmetric and a response near the punch that was essentially axisymmetric, the problem was modeled using a 2D axisymmetric model. Figure 3 shows the mesh of the test fixture and the punch. Contained in the model are the external load frame, the lead backing material, the plate to be punctured, the clamping plate to hold the lead in place and a ring to model the clamping bolts. The diameter of the model was chosen so the cross sectional area of the lead matched the area of lead bricks used in the testing. This also insured that the calculated weight in the finite element analysis was close to the actual experiment.

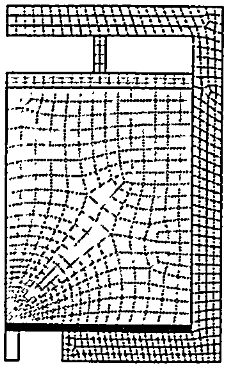

Figure 3. Axisymmetric finite element mesh of the tearing experiment.

In the analysis the bottom of the punch was fixed and the remainder of the model was given an initial velocity in the vertical direction toward the punch. The plate impacted the punch at time zero in the analysis. The impact event was assumed to be completed when the total kinetic energy in the model reaches a minimum value.

The first impact plate material modeled a mild carbon steel material with a plate thickness of 0.12 inches. The yield strength was about 22 ksi and the ultimate strength was about 46.5 ksi. The percent elongation for the material was 49% at failure in a tensile test. These impact plate material properties were modeled with a power law material model in the analysis that reflect the yield strength and plasticity of the material (Stone et al., 1990). The lead was also modeled with a power law model with a yield strength of 800 psi and a very flat hardening curve. The lead material model was taken from some previous analyses that were verified against experimental data (Ludwigsen and Ammerman, 1995). The load frame, pressure plate and punch were modeled with an elastic material model because no yielding was expected in these components.

The incipient energy value for the materials reported by Nelms was used to determine the initial impact velocity of 128 in/sec which corresponds to a drop height of 21.2 inches. The impact reached minimum kinetic energy and maximum deflection at 0.004 seconds after initial contact. Figure 4 shows the strains in the plate near the punch. The maximum strain of 48.9% occurs on the bottom side of the plate at a location adjacent to the edge of the punch. The strain at failure for the material was not reported and cannot be calculated directly. However, the 49% elongation over 1 inch for the material that was reported by Nelms agrees well with the maximum strain predicted in the analysis.

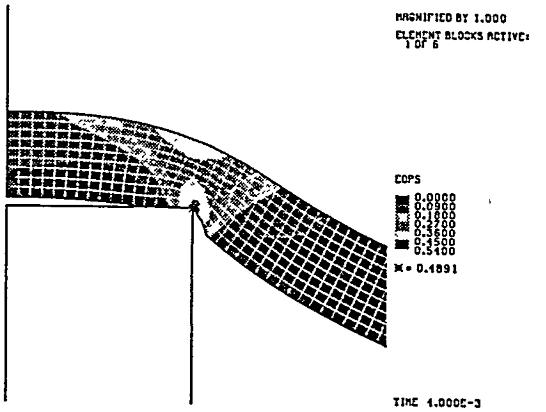

Figure 4. Equivalent plastic strains in the impact plate.

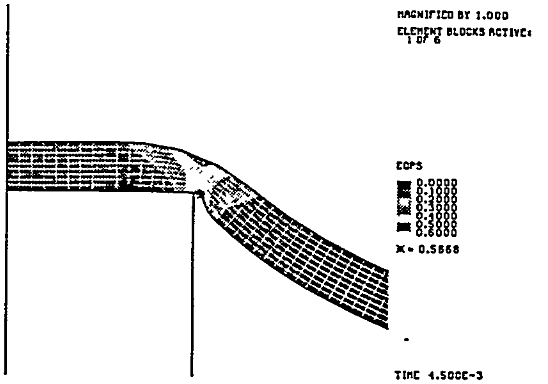

Figure 5. Strains in the plate with lead backing.

Another similar analysis was performed on a 316 stainless steel material with a yield of 47.14 ksi and an elongation at failure over 1 inch of 54%. The thickness of this plate was 0.074 inches with the rest of the test dimensions remaining the same as the previous analysis. The impact velocity was 120 in/s which corresponds to a drop height of 18.6 inches. Figure 5 shows the strains in the deformed plate at the end of the impact event. The maximum strain of 56.7% matches very well with the with the reported 54% elongation.

did both have lead backing?

When the parameters related to ultimate strength and elongation at failure are known for a given material, analysis techniques appear to accurately match the experimental plate tearing results. These experiments were very limited in their scope due to having lead as the only backing material.

FOAM-BACKED PLATE TEARING ANALYSES

The same two analyses were repeated with the lead replaced with a low density 10 lbs/ft^3 500 psi crush strength foam. The weight difference between the lead and the foam was added to the weight of the upper pressure plate so that the model weight was constant. The same initial velocities as the lead backed models were used.

The plate made out of the mild steel is predicted to have a deformed shape and strain contours as shown in Figure 6. The maximum strain of 29.4% in the top of the plate over the edge of the punch. This compares to the predicted strain of 49% with the lead backing.

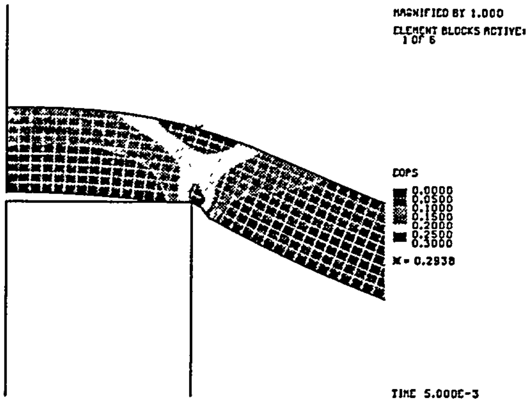

Figure 6. 0.12 inch thick plate backed by foam maximum plastic strains

Figure 7 shows the results for the thinner plate made out of the 316 stainless steel material with foam backing. The maximum strain of 39.8% occurs at the top of the plate just over the edge of the punch. This compares with a predicted strain of 56.7% with the lead backing.

Note the differences in the shape of the plates. The lead backed plate punctures have much sharper bends near the punch resulting in higher strains with a large shear component. This is very much like the failure that occurs when plates are punched in a die to make holes. The shape of the plates with the foam backing exhibit more in-plane membrane stresses with less shearing deformation near the punch.

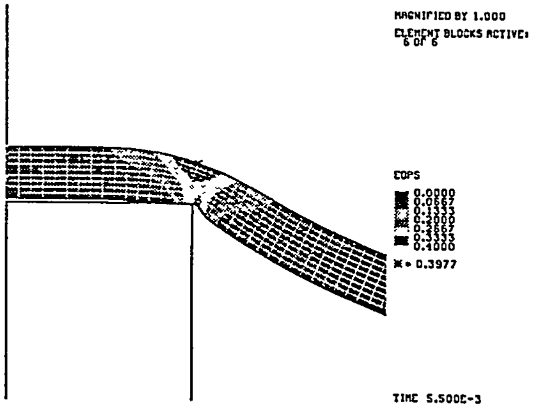

Figure 7. 0.074 inch thick plate backed by foam maximum plastic strains.

The large changes in maximum strains and the different behavior at maximum strain indicates that the properties of the backing material does make a significant difference in both the failure energies and the failure mechanism. It should be noted that this observation has been made only for punch loads that are perpendicular to flat plates being punched. Other orientations and shapes of plates will be studied in both further analyses and experimentation in the near future.

Conclusions

A current method of predicting tearing in thin plates from punch loads is to use the equations developed by Nelms. His work used a series of drop tests with thin plates backed by lead bricks impacting a small hardened steel punch. The empirical equations developed by him are often used in cask design to insure that outer shell materials do not fail in a punch drop test. It is clear the type of material used behind the plates can significantly influence both the failure loads and failure behavior. Two tests from Nelms' report were simulated in a finite element model with predicted strain results matching well with the reported strain limit for each material. When the same analyses were run with the lead brick replaced with crushable foam, the plates experienced different behavior at maximum deformation and a significant reduction in maximum strain.

Based upon these analyses of two examples it appears that the equations developed by Nelms do not adequately address the prediction of tearing failure for plates with backing material other than lead. Additional work using other materials and punch angles is needed to determine both the effect of backing material and punch orientation on the tearing failure of thin plates.

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