Impact Characteristics of Energy Absorbing Materials for Radioactive Material Transport Packages*

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INTRODUCTION

Energy-absorbing materials such as wood, grout, and polyurethane foams have been used as impact limiters in radioactive-materials transport packages to absorb kinetic energy in the event of an accidental impact. However, the dynamic behaviors of most of these materials are not well characterized or understood, especially at high impact velocities (V > 122 m/s).

As part of a current program at Lawrence Livermore National Laboratory (LLNL) to evaluate package response during high-velocity impacts, a study to characterize several candidate energy-absorbing materials is being conducted. The impact study focuses on surfaces of two different hardnesses—unyielding and yielding. A soft-rock-type surface was chosen as a representative yielding surface in the study. Scaled package impact tests at velocities around 137 m/s on unyielding surface and close to 275 m/s on yielding surface were conducted. The particular point of interest is the dynamic behavior of materials having isotropic or nearly isotropic properties, such as grout (a mixture of sand and cement), high-density foam, and resin. This study excludes any anisotropic energy-absorbing materials such as wood, for even though wood is generally considered to be a good energy-absorbing material and is widely used as an impact limiter, its dynamic response at high impact velocities is difficult to predict using analytical means because of its inherent anisotropic structural properties.

The current study is limited to the grout material. The grout material was adapted from LLNL's previous involvement with the Shippingport Project [Fischer, 1988]. In that project, the grout was found to be a good energy-absorbing material for transport packages.

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The objective of the study is to characterize the dynamic behavior of the grout for high-velocity impact conditions when it is used as an energy-absorbing material in a transport package. The approach is to conduct a number of tests with grout-filled package models and then use these test results to correlate and benchmark analytical models. The resulting analytical models can be used to better achieve predictions on package responses to high-velocity impact. This study is useful in designing package impact limiters using grout as an energy-absorbing material.

A simple three-layer package model is employed to represent a typical transport package. The model contains an outer structural shell, a layer of energy-absorbing material inside the shell, and a structure in the center representing a container used for transporting the radioactive contents.

PACKAGE MODEL TESTING

Based on LLNL's considerable experience with the particular grout mix used to fill the decommissioned Shippingport reactor pressure vessel and neutron-shield tank package, the same grout mix was adapted and used as the baseline in the current study. This particular grout mix required a 28-day cure time to reach the proper grout strength in the test package.

The same grout mix was used for the package impacting a target surface simulating the condition of soft rock, but with a cure time of 14 days to yield a strength similar to that of soft rock.

Laboratory Measurements of Grout Properties

Nine grout test specimens, 10.16 cm long and 5.08 cm in diameter, were tested to measure their unconfined and confined compressive properties. Three samples having a cure time of 14, 21, and 28 days respectively were tested for unconfined compressive strength. Table I lists the test results for the three samples.

Table 1. Measured unconfined compressive strength on grout samples

Grout sample # (cure time-days)	Compressive strength (MPa)
1 (14)	23.99
4 (21)	25.95
7 (28)	30.58

The remaining six grout samples were tested to measure their properties under different amount of confining pressures. Tests were carried out at a strain rate of 10^{-5}/sec.

Package Test Model Construction

The outer shell of the test package models was fabricated from commercially available 15.24-cm diameter and 0.2769-cm-wall stainless steel tubes cut to 11.5062 cm in length. The front of the model was a welded stainless-steel cap having a radius of curvature of 13.7617 cm and a depth of 5.08 cm. The shell was then annealed to a fully soft state. The containment vessel was simulated by placing a hardened maraging 300 steel tube (7.3660 cm in length by 3.5560 cm in diameter.) at the center of the package. The whole assembly was then filled with pre-mixed grout and left to cure 28 days prior to the test. A 0.6350-cm-thick stainless plate was then welded on the back after cure and back-filled with a hard epoxy.

A 1100-O aluminum ball was placed inside the hardened maraging 300 steel tube and was held in place by a screw-type aluminum plug. This assembly was designed to be a passive-type accelerometer. In model impact tests, a flat spot formed on the ball due to the differential deceleration of the ball and the steel in contact with it. After each test, the spot diameter was measured and a corresponding force was estimated from prior calibration tests on samples of the ball. The calibration measurements were spot diameter versus force. The maximum acceleration value experienced by the steel container was derived from the estimated force. Figure 1 shows the test package assembly.

Testing Method

The package impact tests were carried out using a 155-mm cannon facility at LLNL. The cannon was used to propel the package model at different pre-calibrated velocities by varying the amount of powder loading. The package velocity was measured immediately before impact, using a contact-pin-type timing system. Two high-speed movie cameras were installed to record the impact event.

The "unyielding target surface" was simulated in the test by a 5.08-cm-thick steel plate welded onto a steel frame and backed by a concrete-filled steel block weighing about 9 tons.

The "soft rock target surface" was simulated by a 122 cm^3 grout block having a cure time of 14 days. The grout block was also backed by the 9-ton block.

Testing Results

A total of six package-impact tests were conducted—four on the "unyielding surface" target and two on the "soft rock" target. Figure 2 shows the deformed shape of the test package after it impacted the steel plate at 144 m/s. Figure 3 shows the deformed shape of the test package after it impacted on the grout block target at 288 m/s. Both figures were overlayed with the package original shape to make easy comparisons. The aluminum balls in all the test packages were retrieved after the test, and spot diameter was measured to determined the maximum deceleration of the container. The maximum decelerations were estimated to be about 66,000 g for package impact on the steel plate and about 80,000 g for package impact on the grout target.

ANALYTICAL METHOD

A three-layer finite element package model was constructed for the analytical correlation of the test results. The model takes advantage of the axisymmetric property of the package. The unyielding foundation is modeled as an unpenetrable rigid wall in the finite element analysis. The corresponding finite element model for a package impacting on the soft rock was also constructed.

A finite element computer code capable of simulating package high-velocity impacts where both large material and geometric nonlinearities occur is required for accurate simulation. The finite element codes employed in this study to simulate the dynamic event of package impact are DYNA2D [Hallquist, 1988] and DYNA3D [Whirley, 1991]. DYNA is an explicit finite element code for analyzing the transient dynamic response of solids and structures. Many material models are available to represent a wide range of material behaviors. DYNA also has a sophisticated contact interface capability to handle arbitrary mechanical interactions between independent bodies or between two portions of one body. During the last ten years, DYNA has been used extensively at LLNL and in industry, having been applied to a wide spectrum of problems, many involving large inelastic deformations and contact. The code has been benchmarked against many textbook problems [Lovejoy and Whirley, 1990], as well as different dynamic applications, with excellent results.

Grout Representation in the DYNA Code

Currently, there are several material models available in the DYNA code that are suitable for the modeling of the geological material behaviors such as grout. A material type used to model concrete/geological materials in the code was selected for the modeling of grout material in this current study. This model was developed to incorporate more features and offers more versatility in the modeling of geological and concrete materials. It has the capabilities of modeling strain-rate effect for the yield strength via the use of a load curve multiplier. Material damage and failure phenomenon in materials such as grout can also be modeled through the use of a two-curve concept. The two yield-versus-pressure curves are defined as the upper, or undamaged, curve, represented by

$$\sigma_{max} = a_0 + \frac{P}{a_1 + a_2 P}$$

where σ_{max} = the material yield stress at the undamaged state,
P = pressure, and
a_0, a_1, a_2 = material constants that characterize the yield-versus-pressure relationship at undamaged state

and the lower, or failed (damaged), curve, which is represented by

$$\sigma_{failed} = a_{0f} + \frac{P}{a_{1f} + a_2 P}$$

where σ_{failed} = the material yield stress at the damaged state, and
a_{0f}, a_{1f}, a_2 = material constants that characterize the yield-versus-pressure relationship at damaged state.

By defining those two curves and defining an appropriate scale factor, η, versus the effective plastic strain in this material model, as used in the following fashion

$$\sigma_{yield} = \sigma_{failed} + \eta \ (\sigma_{max} - \sigma_{failed}) ,$$

one is able to describe either a hardening or a softening phenomenon as commonly observed in the grout or concrete material according to the amount of plastic strain levels produced in the material.

The pressure-volumetric strain relationship of the material is treated independent of its deviatoric behavior and can be described by using either the equation-of-state type 8 (tabulated with compaction), 9 (saturated), or 11 (air-filled porosity).

FINITE ELEMENT PACKAGE MODEL CORRELATION WITH THE TEST — RESULTS AND DISCUSSION

The finite element package model with a non-moving rigid wall representing the unyielding surface was given an initial velocity of 144 m/s to simulate the package impact onto a steel plate. The grout material was simulated using the material model described above with an undamaged σ_y - P curve having parameters $a_0 = 1,606$, $a_1 = 0.6$, and $a_2 = 0.0000835$, and no damage curve. The grout pressure-volumetric strain relationship was defined using the actual laboratory measurement. The result of the simulation is shown in Figure 4. The deformed shape of the package model correlated very well with the actual test result. The predicted maximum deceleration is 58,930 g, which is approximately 12% lower than the measured maximum deceleration from the passive-accelerometer measurement.

Next the simulation was performed on the finite element package model impacting on "soft rock." The package was given an initial velocity of 288 m/s. However, while keeping the package grout undamaged σ_y - P curve the same, the damage curve of the grout inside the package as well as the grout simulating the soft rock had to be activated in order to obtain a reasonable match of package deformation pattern and the penetration depth into the soft-rock target. The parameters used in the soft-rock undamaged σ_y - P curve were $a_0 = 1160$, $a_1 = 0.238$, and $a_2 = 0.0000835$. The parameters invoked for the damaged σ_y - P curve were $a_{0f} = 0$ and 0, $a_{1f} = 2.55$ and 1.385, and $a_2 = 0.0000835$ and 0.0000835 for the package grout and the grout simulating soft rock, respectively. Again, the laboratory-measured pressure-volumetric strain relationship was used for the grout simulation of soft rock. The result of the simulation is shown in Figure 5. The maximum calculated deceleration was 133,462 g. This value is about 40% higher than the maximum containment vessel acceleration measured with the passive accelerometer.

The need to activate the grout damage curves at higher impact velocity in the analysis can be explained thus: the grout mix undergoes a transition from a complete bonding and thus a full-strength state at the relatively low impact velocity to a progressively debonding and pulverization state with a gradually diminished strength as the impact velocity increases. The degree of damage or failure of the grout can be adequately represented by the prescribed damage curve.

CONCLUSION

A series of high-velocity impact tests using grout as the package energy-absorbing material was successfully carried out. The purpose of these tests was to characterize the dynamic behavior of grout material when used as an energy-absorbing material for packages. These package-impact tests were simulated accurately with the dynamic finite element code DYNA, using appropriate grout material properties. The need to invoke the grout damage curve illustrates the fact that the grout mix under study undergoes a transition where the grout retains its full strength at relatively low impact velocity to a diminished strength where progressive debonding and pulverization takes place as the impact velocity increases. The transitional velocity range is a function of a particular grout mix as well as impact conditions. Laboratory tests of the grout mix that include the failure region and different failure modes should be an integral part of the investigation process to accurately correlate package benchmark tests with analytical models.

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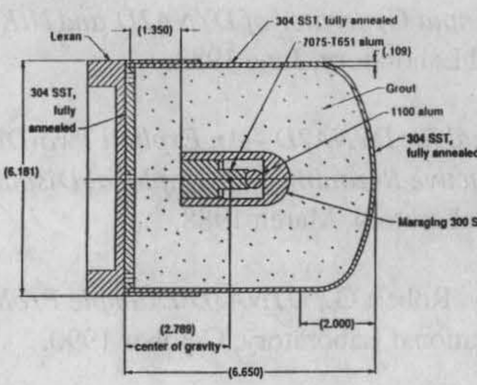
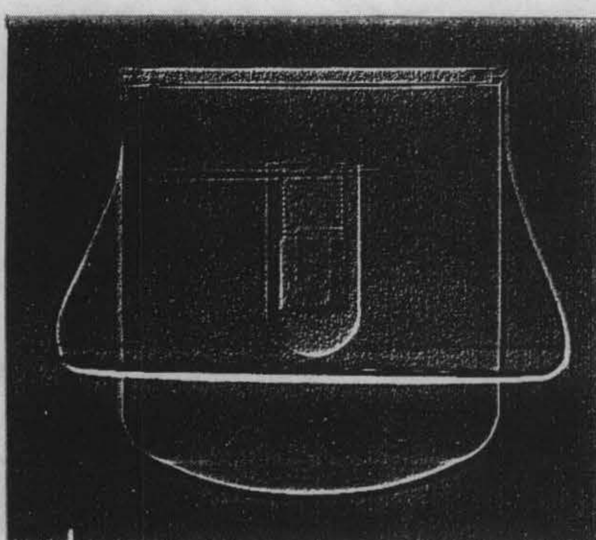


Figure 1 Test package assembly.



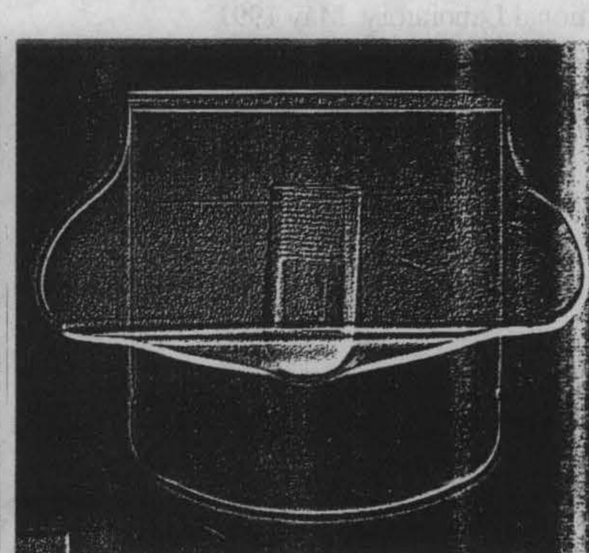
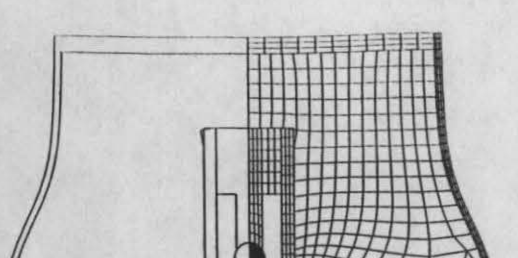


Figure 2 Deformed shape of test package after impact on steel plate at 144m/s.

Figure 3 Deformed shape of test package after impact on grout block target at 288m/s.



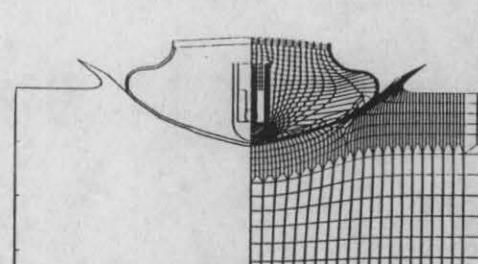


Figure 4 Finite element simulation result of test package impact on steel plate.

Figure 5 Finite element simulation result of test package impact on grout.