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PRELIMINARY DROP TESTING RESULTS TO VALIDATE AN ANALYSIS METHODOLOGY FOR ACCIDENTAL DROP EVENTS OF CONTAINERS FOR RADIOACTIVE MATERIALS[1]

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ABSTRACT

The National Spent Nuclear Fuel Program, operating from the Idaho National Engineering and Environmental Laboratory (INEEL), developed the standardized Department of Energy (DOE) spent nuclear fuel (SNF) canister. During the development of this canister, more than twenty drop tests were completed, evaluating high strain behavior, puncture resistance, maintenance of containment, and other canister responses. Computer analyses of these drop-test specimens/canisters employed the ABAQUS/Explicit software. A pre-drop analysis was performed for each test specimen to predict the deformed shape and resulting material straining. Typically, a post-drop analysis was also performed to better match actual test specifics (actual impact angle, test specimen material properties, etc.). The purpose for this analysis effort was to determine the capability of current analysis techniques to accurately predict the deformed shape of a standardized DOE SNF canister subjected to a defined drop event, without actually having to perform a drop test for every drop event of interest.

Those analytical efforts yielded very accurate predictions for nearly all of the drop tests. However, it was noted, during one small-scale test, that the calculated deformed shape of the test specimen depended on the modeled frictional behavior as it impacted the essentially unyielding flat surface. In order to calculate the correct deformed shape, the modeled frictional behavior had to be changed to an unanticipated value.

This paper will report the results of a preliminary investigation that determined the appropriate frictional modeling for a variety of impact angles. That investigation included drop testing performed at the INEEL from September 2000 to January 2001.

BACKGROUND

The Department of Energy's (DOE) National Spent Nuclear Fuel Program (NSNFP) has been working with the Department's Office of Civilian Radioactive Waste Management (OCRWM), the Idaho National Engineering and Environmental Laboratory (INEEL), the Hanford Site, Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), and the Savannah River Site (SRS) to develop a set of standard canisters for the handling, interim storage, transportation, and disposal in the national repository of DOE SNF. Through these efforts, the NSNFP has produced a design for such canisters, referred to as the "standardized DOE SNF canisters," that are 18 inches (457 mm) and 24 inches (610 mm) in outer diameter, and approximately 10 feet (3.0 m) and 15 feet (4.57 m) long (Morton, 1999). The standardized DOE SNF canister construction has been specified to meet the criteria of the ASME B&PV Code, Section III, Division 3, Subsections WA and WB (ASME 1997). Note that limited Code changes are necessary before the standardized canister can be N-stamped.

The NSNFP validated the standardized DOE SNF canister design by: (1) building a number of test canisters to verify the constructability of the design and verifying the ease of loading internals; (2) employing current volumetric weld inspection methods on the test canisters to assure their viability - especially on the final closure weld; (3) performing drop tests on the test canisters to simulate accidental drops during handling, with follow-up pressure tests and limited helium leak testing to demonstrate containment; (4) evaluating the deformations of the test canisters with regard to future over-packaging of a damaged canister; and (5) demonstrating the capability of finite element (FE) methods to accurately predict canister response during

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accidental drop events. A summary of validation efforts (3) and (5) to date is available (Snow, 2000).

PROBLEM DEFINITION

During the initial development (1998) of the standardized DOE SNF canister, the NSNFP drop-tested six 5-inch (127 mm) diameter test specimens, one short 18-inch (457 mm) diameter test specimen, and two full-sized [18-inch (457 mm) and 24-inch (610 mm) diameter, both 15-foot (4.57 m) long] preliminary test canisters. Drop heights varied from 40 inches (1 m) to 30 feet (9 m). Details on these drop tests, including the flat steel impact surface and puncture bar, are available (Snow, 1999). All of these tests oriented the test specimen/canister at impact in a near vertical or horizontal position, except for the short 18-inch (457 mm) diameter specimen, which impacted at 32 degrees off vertical.

All pre-drop and post-drop FE evaluations employed the ABAQUS/Explicit software (ABAQUS, 1999). The frictional behavior between the test specimen/canister and the impact surface was simply modeled using one coefficient of friction for static and dynamic conditions. A brief evaluation of the analysis models for the two full-sized test canisters indicated that some range of values for the coefficient of friction would likely produce similar deformations in the near vertical and horizontal drops. However, a small change in the coefficient of friction value caused significant changes in the deformed shape in the short 18-inch (457 mm) diameter specimen. A coefficient of friction value of 0.1 gave the best match between the calculated deformed shape and the actual post-drop shape, while a value of 0.5 resulted in a significantly different calculated shape.

During 1999, nine standardized DOE SNF test canisters were constructed and pre-drop evaluated at the INEEL, drop-tested at Sandia National Laboratories, and then post-drop evaluated back at the INEEL (Snow, 2000). Eight of the nine canisters were dropped in a near vertical (0 to 6 degrees off vertical) or near horizontal (80 to 90 degrees off vertical) orientation, while one impacted at 45 degrees. As found in the previous drop-testing efforts, the calculated deformed shape of the near vertical and near horizontal impacting canisters appeared to be independent from the coefficient of friction. However, the 45 degree-impacting canister shape varied significantly with different coefficient of friction values. The best match between the calculated and the actual deformed shape required a coefficient value of 0.3. [Based on the evaluation results for the 1998 short 18-inch (457 mm) diameter specimen, a much lower coefficient value was expected.]

Again, one of the objectives of the standardized DOE SNF canister program was to show that FE methods could be employed to accurately predict the deformed shape of a canister subjected to an accidental drop. Therefore, it was necessary to determine the appropriate friction parameter for all canister impact angles.

Due to project objectives and limited funding, this friction phenomenon was not pursued during 1999. However, a preliminary investigation with the goal of determining a more appropriate frictional modeling parameter for a given angle of impact was initiated in 2000. That investigation included drop testing performed at the INEEL, from September 2000 to January 2001, on eleven existing standardized DOE SNF canister ends.

FRICTIONAL MODELING

ABAQUS/Explicit has a variety of capabilities available for modeling friction. These include: friction coefficient to be defined in terms of slip rate and contact pressure; static and kinetic friction coefficient with a smooth transition zone; friction with a shear stress limit; general frictional surface conditions; and etc. A number of these analysis options were tried early on, but none produced the correct canister response for varying impact orientations. In the case of accidental drop events, a frictional modeling method still had to be justified. (An accidental drop event is certainly a nonlinear, dynamic, and very fast-occurring event.)

It was also recognized that this friction modeling could be representing more than just frictional forces (e.g., energy loss from heat in the impact area, localized material property variations, etc.), in its influence on the analytical model of a canister during a drop event. Considering these issues and others, it was determined that the simplest approach would be the best. Therefore, a single coefficient of friction would be used to represent the frictional influence for a drop event.

That coefficient of friction will be referred to in this paper as the “friction parameter”. Note that static and dynamic coefficients of friction for drop events are not being redefined herein. This friction parameter is only being used in the analytical models to achieve a better match between the calculated and actual deformed geometry of a specimen after a drop event.

FRICTION TEST CANISTER DESIGN

The test canisters are referred to as preliminary because they were not built from new materials. Instead, they were constructed from the 18-inch diameter test canisters of the 1999 test program. Many of those test canister ends were undamaged or slightly damaged as a result of the previous testing. For example, one 1999 test canister was dropped (vertically oriented) onto the impact surface – but did not tip over (that end was completely undamaged). Another 1999 test canister was dropped (horizontally oriented) onto a puncture post, and its ends experienced only the 24-inch (610 mm) drop off the post onto the flat impact surface (both ends being only slightly flattened as a result). (It was recognized that plastic analysis is history-dependent, and that slightly damaged test canister ends could respond differently than undamaged ends.) These test canister ends were employed in this preliminary evaluation of the friction parameter because they were readily available and would provide relatively good preliminary results. They would also provide insights for future testing.

In summary, the friction test specimens were made from the 1999 18-inch (457-mm) diameter standardized DOE SNF canister end pieces (Snow, 2000) cut at 4-foot 9-inches (1448 mm) in length with a flat plate welded on the cut end. The test canisters included:

- Body made of longitudinally-welded SA-312 pipe, 3/8-inch (9.5-mm) nominally thick, 316L stainless steel,
- Lower heads are ASME flanged and dished, 3/8-inch (9.5-mm) nominal thickness, SA-240 316L stainless steel,
- Skirts made of longitudinally welded pipe to match the body material, 8 inches (203 mm) long,
- Lifting rings made of SA-240 plate, 316L stainless steel, 1-inch (25-mm) wide by ½-inch (12-mm) thick, located just within the outer end of each skirt,
- Interior impact plates made of 2-inch (51-mm) thick plate, A-36 carbon steel, flat on one side for the contents to bear on and contoured on the other side to match the inside surface of the head.
- Contents included a spoked-wheel divider and rebar (steel reinforcing bar) to simulate an internal structure and SNF loading.

The test specimen design is shown in Figures 1 and 2. All preliminary friction test specimens weighed about 1950 lbs. (886 kg).

DROP TEST DETAILS

The test specimens were labeled as follows: FPC-XX-YY, where FPC is abbreviated for "friction preliminary canister", XX represents the intended impact angle, and YY is the specimen number. For example, specimen FPC-10-01 was intended to impact at 10° and is numbered specimen 01. The eleven test specimens were intended to be dropped at the following angles (measured from vertical): 10°, 20° and so on through 70°, 35°, 24° and 7°. (Actual angles at impact were measured from videotape taken during the testing.)

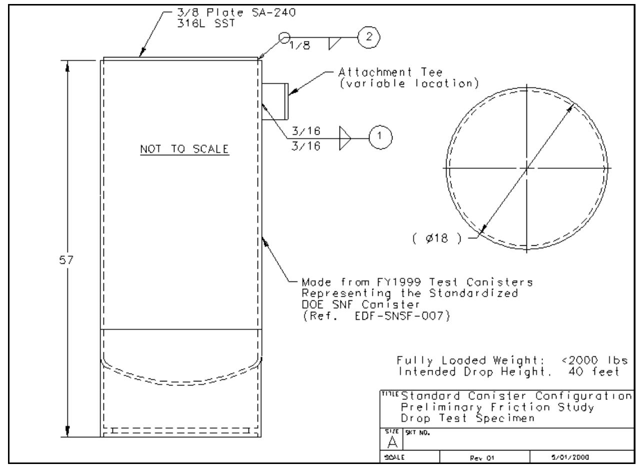

Figure 1. Friction Test Specimen Design

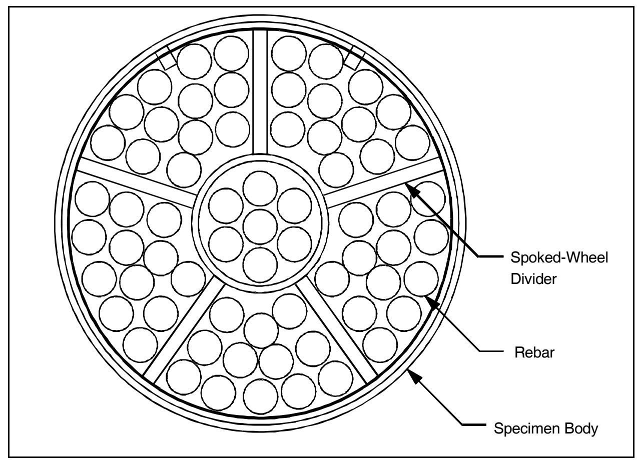

Figure 2. Friction Test Specimen Internals

All testing was performed in the drop pit at the Water Reactor Research Test Facility (WRRTF) at the INEEL site. The target at the drop test facility consisted of a 6-foot (1.8 m) wide by 8-foot (2.4 m) long by 2-inch (51 mm) thick carbon steel plate bolted to the concrete floor. The reinforced concrete floor was 16 inches (406 mm) thick, poured onto bedrock (lava). The design of the facility provided the desired "essentially unyielding surface", especially for test specimens weighing less than 2000 pounds (909 kg). All test specimens were dropped onto this flat surface from 40 feet (12 m).

ANALYTICAL MODELING

Figure 3 shows the FE model employed in the evaluation of the test specimens for the drop events. As can be seen, there is significant detail in the model.

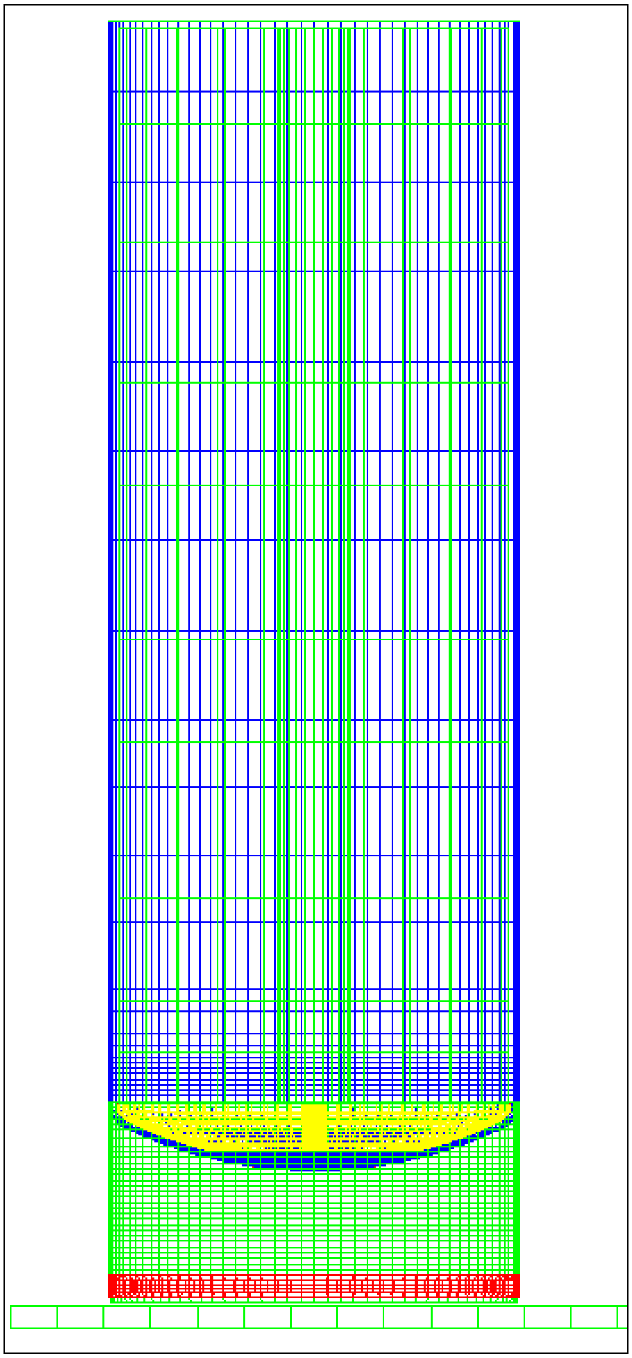

Figure 3. Finite Element Model of Test Specimen

The test specimens were modeled using linear quadrilateral shell elements (ABAQUS element type S4R) for the test specimen body, lower head, skirt, and flat top plate. Shell elements were located at the geometry midplane. The internal impact plate was simulated using solid linear brick elements (ABAQUS element type C3D8R), as was the lifting ring. The head-to-body joint and the lifting ring-to-skirt connection all consisted of full penetration welds and were represented by using common nodes. The skirt-to-head weld was also full penetration, but was modeled using common nodes and multipoint constraints (ABAQUS option MPC BEAM).

The internal components were also modeled with finite elements. The spoked-wheel divider was modeled using linear quadrilateral shell elements, while the rebar was modeled with solid linear brick and wedge elements (Snow, 2000).

The impact surface was modeled with solid elements on a fixed base. Material modeling is detailed in Snow, 2000.

Placing the specimen just above the impact surface and applying an initial velocity reflecting the drop height and a gravitational acceleration simulated the drop event.

ANALYTICAL VS. ACTUAL DEFORMATION RESULTS

The results from test specimen FPC-20-02 will be used as an example of how this friction parameter was estimated. Figure 4 shows test specimen FPC-20-02 which was dropped from 40 feet (12 m) onto the steel plate at an actual impact orientation of 21° off vertical. Note that the right side of the specimen body, passing through the straight flange of the head and into the skirt, is straight. At about 3 inches (76 mm) from the bottom, the skirt is bent inward to match the impact surface.

Prior to the preliminary 1998 testing (Snow, 1998), a typical friction parameter value (to simulate the contact between the test canister and the impacted steel surface) between 0.45 to 0.60 would have been chosen for inclusion into the computer analyses. Figure 5 shows the results of the FE model (in cross-section) of the test specimen which used a friction parameter value of 0.45. The right side of the skirt has buckled in a clear "S" pattern. This pattern is also seen in Figure 6 where a friction parameter value of 0.35 was employed. Figures 7 and 8 show that "S" pattern fading out with the lowering of the friction parameter value to 0.25 and 0.15. In fact, the significant deformation pattern has changed from inward to outward. Figure 9 shows the deformed shape of the test specimen with a friction parameter value of 0.05, which better matches the actual deformation shape shown in Figure 4, as does Figure 10 with a value of 0.025.

These results show that the friction parameter value incorporated in the analyses does indeed play an important role in determining the calculated deformation of a test specimen for an accidental drop event.

Figure 4. Side View of Deformed Test Specimen (21° Impact Angle)

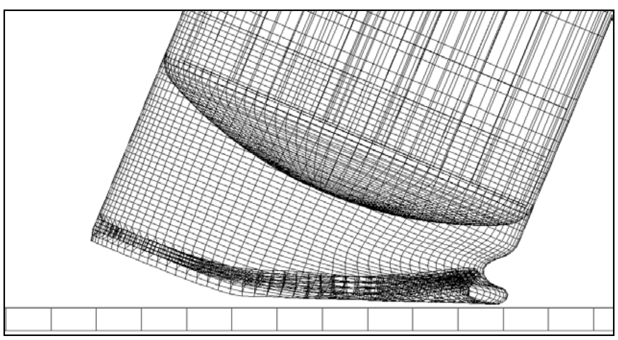

Figure 5. Model Side View, Friction Parameter Value of 0.45

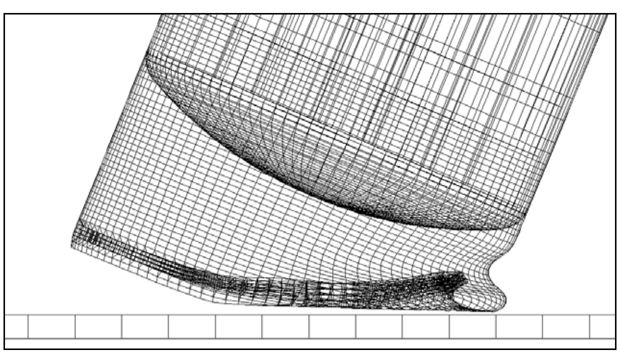

Figure 6. Model Side View, Friction Parameter Value of 0.35

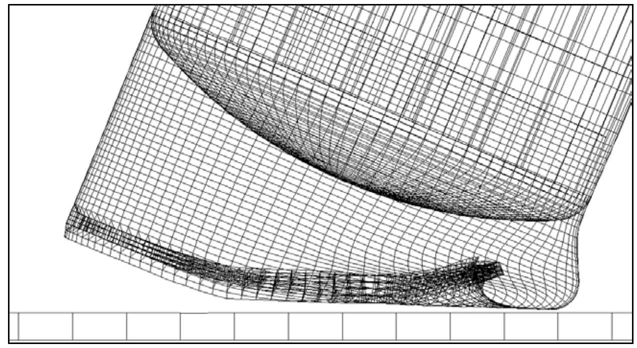

Figure 7. Model Side View, Friction Parameter Value of 0.25

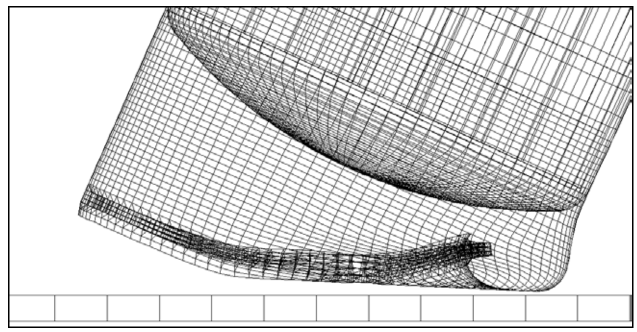

Figure 8. Model Side View, Friction Parameter Value of 0.15

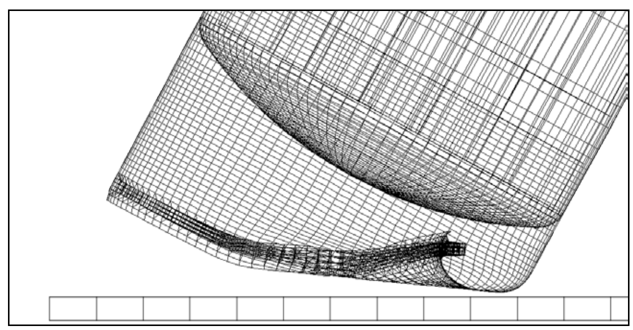

Figure 9. Model Side View, Friction Parameter Value of 0.05

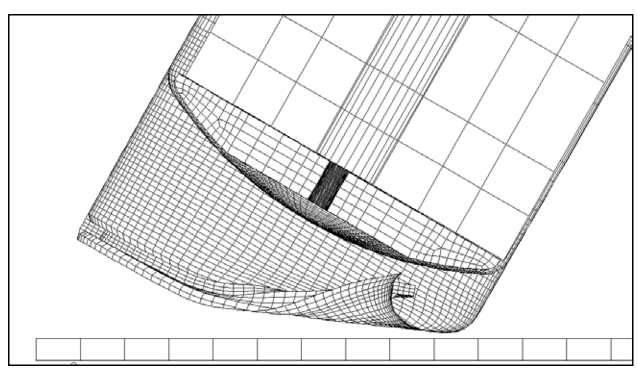

Figure 10. Model Side View, Friction Parameter Value of 0.025

Results for other drop angles showed a range of friction parameter values that gave the best match of shape and deformation magnitudes. This is shown in Figure 11.

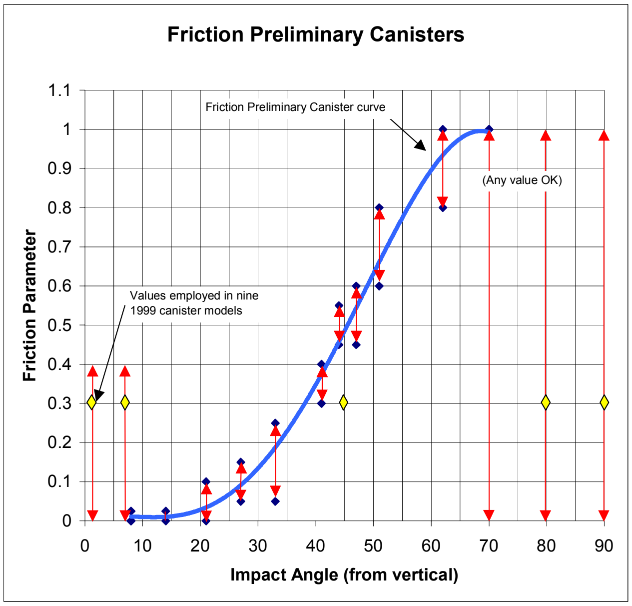

Figure 11. Friction Parameter vs. Impact Angle

In Figure 11, above, the double-arrow lines for ½ degree, 6 degrees, and 70 through 90 degrees indicate that the deformed shape of a specimen was acceptable for those wide ranges of friction parameter values. The double-arrow lines between 14 degrees and 62 degrees show smaller ranges of friction parameter values that gave acceptable analytical results for the test specimens. The curve is a fourth order polynomial fit of the test data. The value of the friction parameter increases as the impact angle (from vertical) increases over this range.

Again, the friction parameter on the vertical axis of Figure 11 is not redefining the static or dynamic coefficient of friction values for drop events. It is only using that parameter in the analytical models to achieve a better match between the calculated and actual deformed geometry of a test specimen after a drop event.

Because these friction test specimens were not new (made from the 1999 test canisters dropped once), the results shown in Figure 11 are considered preliminary.

CONCLUSIONS

The deformed shape of a test specimen after an accidental drop event can be accurately predicted using FE methods in ABAQUS/Explicit. However, it appears that the contact between the test specimen and the impacted surface ("unyielding, flat surface") must be defined to include friction parameter values that vary with the impact angle. This paper gives preliminary friction parameter values for use within the analytical model. This investigation has only obtained preliminary results for a single specimen geometry and material. However, the results obtained to date provide a surprising set of analysis guidelines unanticipated prior to these tests.

Regardless of model geometry, structural analysts should be aware that the manner in which friction is simulated within an analytical model may influence the resulting calculation of deformed shape.

PROPOSED FY2001 & 2002 TASKS

Drop testing scheduled for 2001 and 2002 includes new construction of friction test specimens, with varying geometries, that will be used to further investigate the dependence of deformed specimen shape on frictional modeling parameters.

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NOTICE