Accident Impact Analysis of a Spent-Fuel Storage Transportation Package

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INTRODUCTION

Packages used for the storage and transportation of radioactive spent fuel must demonstrate the ability to withstand severe impact scenarios such as those established by the Atomic Energy Control Board (AECB 1983) in Canada and the International Atomic Energy Agency (IAEA). One such package is the Dry Storage Container (DSC) for transporting and storing used fuel. Structural assessments of the package design subject to postulated impact scenarios included a 9-metre centre of gravity over corner drop, a 1-metre pin drop over the welded flange and a 1-metre lid pin drop on the lid region. Impact simulations were carried out on full scale analytical models using an in-house non-linear finite element code (Sauvé 1993). The simulations were supported by validation experiments conducted on a half scale DSC

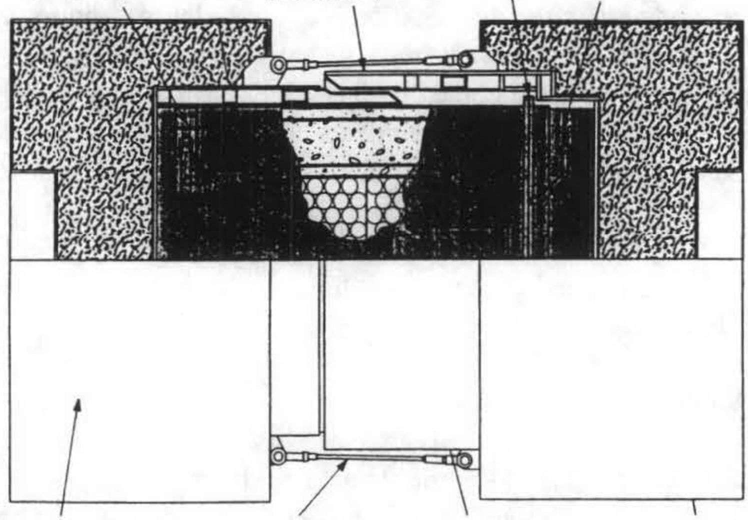

Figure 1: DSC Assembly With Outer Packaging

The package shown in Figure 1 consists of the DSC and outer packaging having two integrated impact limiters. The impact limiters are constructed from 304L stainless steel shells encasing high density polyurethane foam. The side armour is constructed from welded 304L stainless steel plates of various thickness. The DSC consists of 300WT steel inner and outer liners which surround the high-density concrete shielding. The two impact limiters which surround the DSC are held together using a series of six high strength wire ropes. The inner containment houses four modules which hold a total of 384 used CANDU nuclear reactor fuel bundles and is sealed using a welded lid flange assembly.

ANALYTICAL MODELS

9m Centre of Gravity Over Corner Drop Impact Model

The overpack/impact limiter assembly consists of a steel shell encasing high density polyurethane foam. The outer steel shell is fabricated using 6.35mm 304L stainless steel plates. The steel inner shell and armour plate arrangement is made of 304L stainless steel plates of varying thickness with double plates surrounding the lid, welded lid flange, and side of the container. The steel casing and overpack assembly are modeled using four-node shell elements and the polyurethane foam is modeled using eight-node three-dimensional continuum elements (solids). The top impact limiter in proximity to the impact point has a refined mesh due to the localized impact zone for the drop orientation. The bottom impact limiter remote from the impact is modeled using a coarser mesh. The attachment lugs which house the wire ropes are modeled using shell elements while the wire ropes are modeled using tension only analog elements.

Hydrodynamic material formulations are used to characterize the foam and concrete, while finite strain elastic-plastic hardening material models are used for steel models.

The DSC container is modeled, with a less refined mesh in order to capture the rigid body effect. The inner and outer 300WT liners were modeled with shell elements while the welded lid flange and concrete were modeled with solid elements. The model consisted of 28545 nodes, 5 beam elements, 13174 shell elements, and 16723 continuum elements. Figure 2 shows the components of the DSC and their respective finite element meshes.

The target is conservatively modeled as an unyielding surface. This is achieved by defining the nodes of the outer shell of the impact limiter adjacent to the target as slave nodes to a rigid wall boundary.

lm Pin Drop Slab Model

The slab impact model was developed in order to accurately assess the integrity of the concrete wall and overpack shell in the case of the 1m centre of gravity pin drop on the lid. In this case the impact of the target pin on the overpack generates strong interaction between the concrete, DSC liner, and overpack.

The finite element mesh of the slab model representing the DSC lid is shown in Figure 3. The mesh consists of concrete slab sandwiched between two steel liners (12.7mm) plus the two protective 304L stainless steel liners (19 and 25.4mm). The foam effect was taken into account using the simplified calculations described in (Morandin et al. 1993). Symmetry was exploited so that only a quarter of the lid was modeled with the appropriate boundary conditions. Fully fixed boundary conditions were applied to the last layer of nodes on the pin to simulate the anchoring of the pin. The density of the bottom steel liner was adjusted to represent the remaining mass of the model. Due to the highly localized nature of this drop scenario, only a portion of the overpack shell was modeled.

1m Pin Drop Welded Lid Flange Model

The welded flange model was used to assess the overpack shell structural integrity in the area of the DSC welded lid flange. The finite element mesh used for the 1m pin drop over welded lid flange analysis is shown in Figure 4. The mesh consists of three separate components: the DSC, the pin and the overpack. To simplify the analysis, it was assumed that the pin strikes the outer protection channel directly. As mentioned earlier, the foam effect was taken into account using the simplified calculations described in (Morandin et al. 1993). It was not necessary to model the welded flange, as the established acceptance criteria permitted no contact between the flange and the overpack. Acceptance was dictated by a residual clearance. The correct DSC mass was incorporated using a coarse block with an equivalent material density. Symmetry was exploited requiring only half of the DSC, overpack and pin assembly to be modeled.

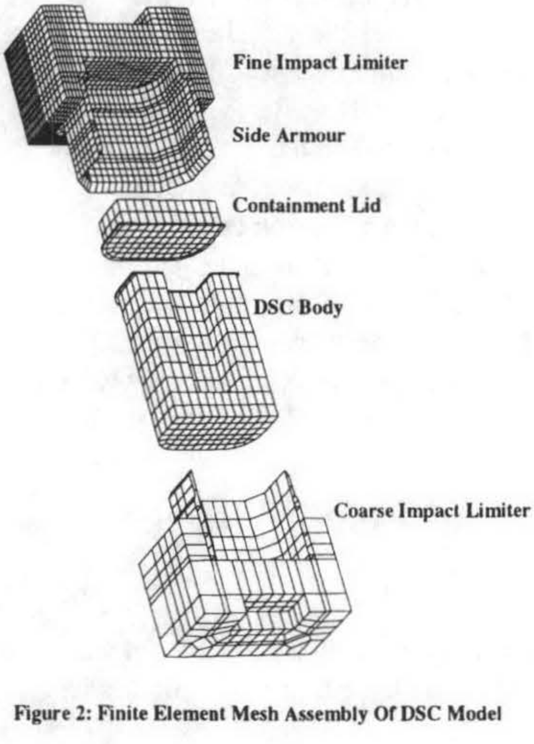

Figure 2: Finite Element Mesh Assembly Of DSC Model

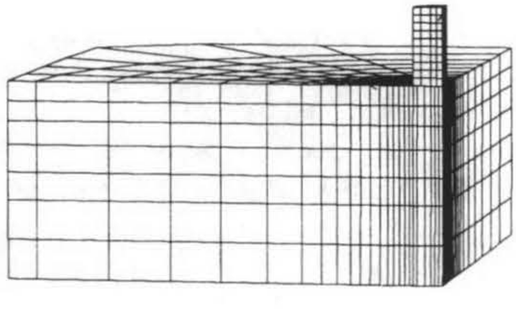

Figure 3: 1m Pin Drop Slab Model

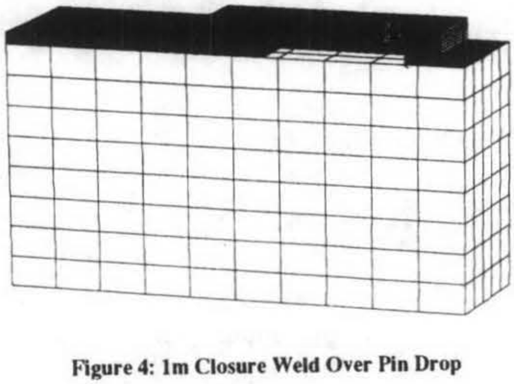

Figure 4: 1m Closure Weld Over Pin Drop

In addition, boundaries were imposed to simulate the rigidity provided by the overpack structure that was not included in the model. Without this reinforcement structure the overpack plate would bend across the entire section which does not physically characterize the overpack response during impact.

Interface Surfaces

To allow for independent motion of several components which form the DSC and overpack protection assembly, a contact algorithm, developed at OHT, which makes use of the master/slave surfaces concept, is used. Contact surfaces are defined between the overpack assembly and the container body to allow for sliding of the two surfaces during impact as well as between the top and bottom overpack assemblies. A contact surface also exists between the two plates making up the welded lid flange to allow for any possible separation. The only tie between the two impact limiters are the wire ropes that are modeled as tension-only elements with each end of the rope tied to a node on either attachment lug.

The pin drop welded flange model has contact surfaces defined between the pin and overpack, between the liners of the overpack, and between the overpack and the DSC. The slab model had multiple interface surfaces between the two overpack liners and between the overpack liner and the DSC liner.

INSTRUMENTATION

The container was instrumented with both electronic and mechanical accelerometers during the tests (Figure 5). All electronic instrumentation was subjected to a rigorous quality assurance program to ensure transducer traceability, repeatability, and system accuracy. It should be noted that each accelerometer measures the actual response of the container at a specific location. In this regard, transducer output is a result of not only the impact force, but also the combination of material deformation behavior, vibrational response, and component interaction effects (i.e., impacts between the limiters, container body, and rigging). To obtain actual container impact deceleration, filtering techniques have been employed in an attempt to remove effects from the accelerometer signals unrelated to impact. The level of filtering was determined by measuring the natural frequency of the DSC Transportation Package at various stages of assembly which ranged from 2000 to 3000 Hz (Boag 1993). The reported container decelerations are the maximum values obtained after filtering the individual signals to remove frequencies above 1000 Hz.

DESCRIPTION OF DROP TESTS

9m Centre of Gravity Over Corner Drop

The DSC model was oriented so that the centre of gravity of the half-scale model was directly above the impact point (Figure 6). The model struck the target plate in the intended orientation with no visible in-flight rotation. On impact, the corner of the top impact limiter progressively deformed. The package rebounded and rotated causing a corner of the bottom impact limiter to hit the target plate. The package rebounded a second time and the top limiter impacted the target plate a second time before coming to rest. The maximum deceleration during impact was measured at 53 g by averaging four accelerometer traces.

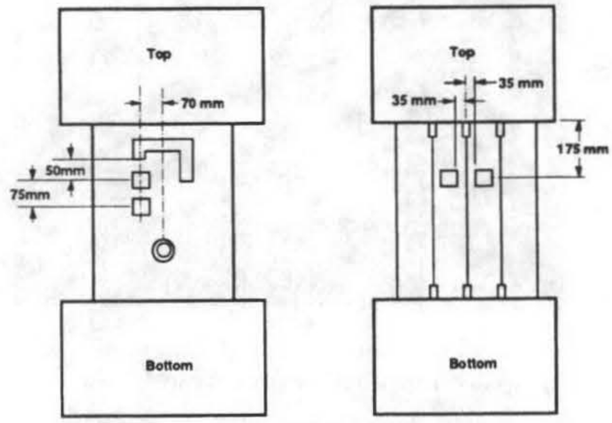

Figure 5: 1/2 Scale DSC Accelerometer Locations

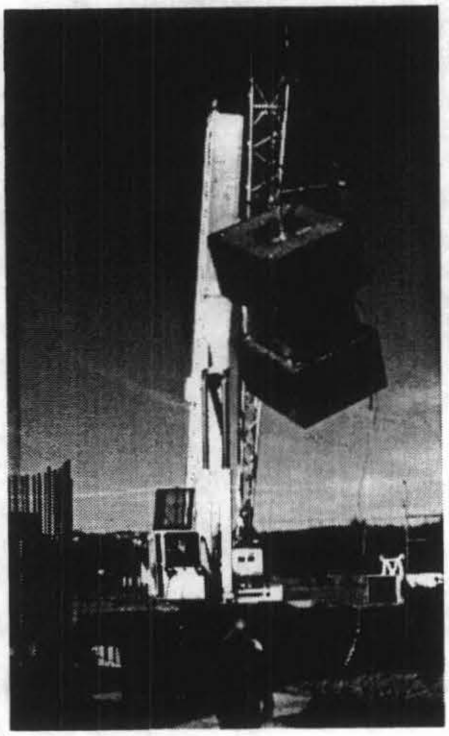

Figure 6: 9 Metre C. of G. Over Corner Drop

1m Centre of Gravity Over Lid Pin Drop

Following the 9m drop, the DSC model was dropped, top down, onto a steel pin from a height of 1 m (Figure 7). The height of the drop was measured from the top of the pin to the point of impact inside the impact limiter recess. On impact the pin penetrated through the outer shell of the top impact limiter and squarely struck the armour plates at the desired location. The pin buckled and the armour plates deformed inwards leaving a localized circular indentation in the DSC containment lid. No tearing of the armour plates or the DSC outer shell was observed. The maximum deceleration measured on impact with four electronic accelerometers ranged from 27 g to 33 g.

1m Pin Drop Over Welded Lid Flange

The DSC model was dropped from 1m onto a steel pin at the welded lid flange along one of the long sides of the package (Figure 8). On impact, the pin penetrated the impact limiter and impacted the armour plates directly in line with the DSC welded lid flange. The armour plates deformed inward contacting one another resulting in some localized deformation on the inside of the outer packaging but did not contact the flange. The maximum deceleration measured on impact with four accelerometers averaged 24 g.

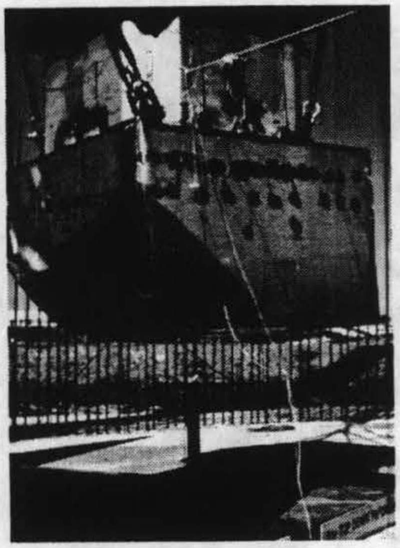

Figure 7: 1 Metre C. of G. Over Lid Pin Drop

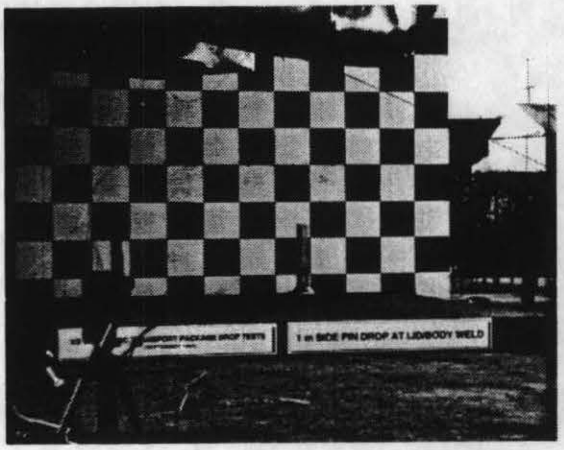

Figure 8: 1 Metre Pin Drop Over Welded Lid Flange

COMPARISON OF RESULTS

9m Centre of Gravity Over Corner Drop

The accelerometer trace and the predicted deceleration time history are compared in Figure 9. The magnitude and time of occurrence of the peak load compare very well. The experimental curve shows a secondary peak due to slap down. This explains the time difference during unloading. Slap down was not considered in the analysis which was terminated once the initial drop energy was dissipated. The general shapes of the two curves also compare very closely. Figure 10 shows a comparison of analytical and experimental impact limiter. It is evident that the analysis captured the creasing in the outer impact limiter liner. A comparison of the deformation in the top impact limiter is presented in Figure 11. The predicted deformations are within 5% of the measured damage. The analysis also predicted some localized tearing of the outer shell of the impact limiter in the vicinity of the impact, which was confirmed in the test.

1m Centre of Gravity Over Lid Pin Drop

The indentation on the inside plate of the overpack next to the container lid was measured to be approximately 12 mm deep. This converts to 24 mm in full scale which compares to

33 mm predicted by analysis (Figure 12). The predicted deformation is higher due to the conservative concrete material properties used for the yield condition. The analysis predicted no ductile tearing of the armour plates or the lid plate, which was confirmed in the test.

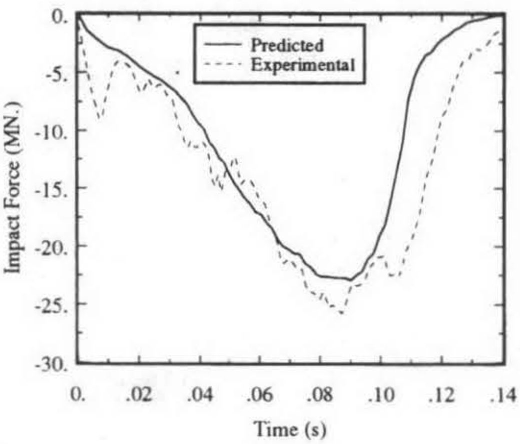

Figure 9: Impact Force Time History - DSC Package

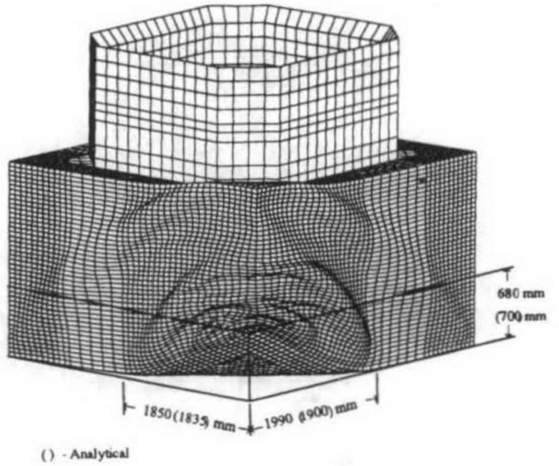

Figure 10: Impact Limiter Deformation Comparison

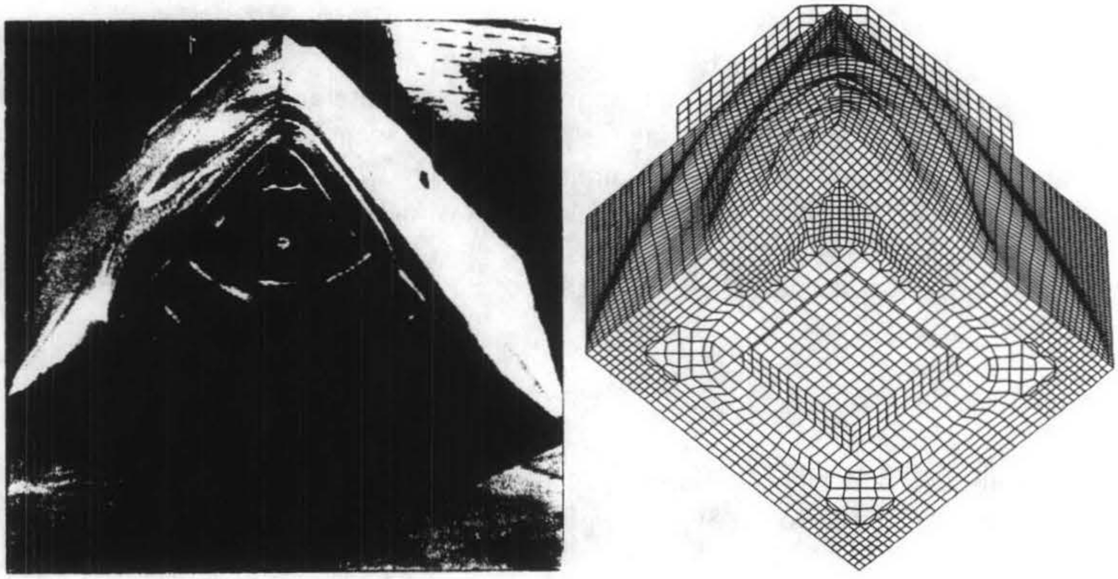

Figure 11: Top Impact Limiter Damage Comparison

Im Pin Drop Over Welded Lid Flange

The overpack plate damage was measured to be approximately 35 mm which corresponds to 70 mm full scale. The predicted deformation in the overpack plate is 74 mm which is in excellent agreement with the test (Figure 13). The analysis predicted no contact of the overpack with the welded flange, which was confirmed by the test.

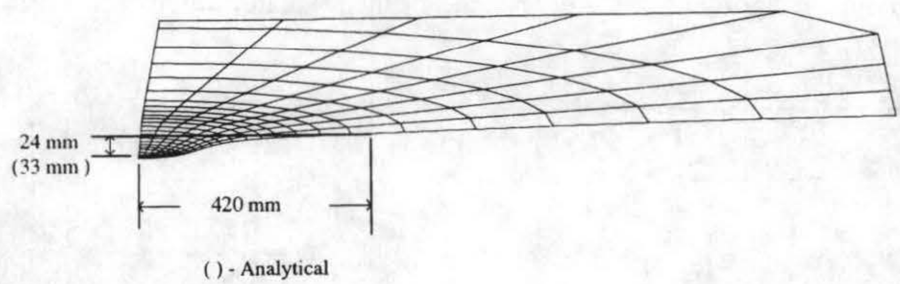

Figure 12: Deformation Comparison for Slab Pin Drop

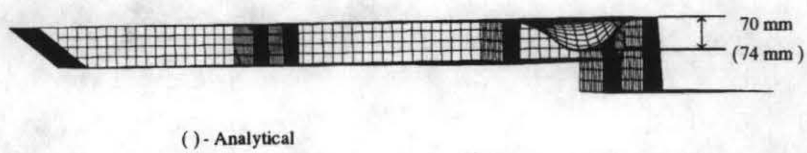

Figure 13: Deformation Comparison for Welded Flange Pin Drop

CONCLUSION

The analytical and experimental results show that the structural integrity of the Dry Storage Container is maintained during the postulated accident scenarios. There is excellent agreement between tests and computer code predictions. The original design was based on analysis and confirmed through testing, which makes design by analysis a feasible method. This work was in support of design and licensing of a combined transportation and storage container. The DSC recently has been licensed by the regulatory body.

REFERENCES

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