IMPACT ANALYSES AND TESTS OF CONCRETE OVERPACKS OF SPENT NUCLEAR FUEL STORAGE CASKS

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A concrete cask is an option for spent nuclear fuel interim storage. A concrete cask usually consists of a metallic canister which confines the spent nuclear fuel assemblies and a concrete overpack. When the overpack undergoes a missile impact, which might be caused by a tornado or an aircraft crash, it should sustain an acceptable level of structural integrity so that its radiation shielding capability and the retrievability of the canister are maintained. A missile impact against a concrete overpack produces two damage modes, local damage and global damage. In conventional approaches [1], those two damage modes are decoupled and evaluated separately. The local damage of concrete is usually evaluated by empirical formulas, while the global damage is evaluated by finite element analysis. However, this decoupled approach may lead to a very conservative estimation of both damages. In this research, finite element analysis with material failure models and element erosion is applied to the evaluation of local and global damage of concrete overpacks under high speed missile impacts. Two types of concrete overpacks with different configurations are considered. The numerical simulation results are compared with test results, and it is shown that the finite element analysis predicts both local and global damage qualitatively well, but the quantitative accuracy of the results are highly dependent on the fine-tuning of material and failure parameters.

KEYWORDS : Spent Nuclear Fuel, Concrete Cask, Concrete Overpack, Missile Impact, Safety Evaluation

1. INTRODUCTION

The concrete storage cask of spent nuclear fuel is widely used in the U.S. as a method of interim storage of spent nuclear fuel before its final disposition. The storage cask usually consists of a metallic canister, which confines the spent nuclear fuel with welded closure, and the concrete overpack, which provides radiation shielding and structural protection of the canister. In the safety assessment of the concrete cask, the resistance of the concrete overpack against external shock should be evaluated together with a probable accident scenario. It is important that the structural integrity of the concrete overpack is maintained under a missile impact accident so that its radiation shielding capability and the retrievability of the canister are not lost. The procedure of structural evaluation under a high speed missile impact caused by an aircraft crash is well summarized in [1]. The structural evaluation of concrete overpacks involves the evaluation of local damage of concrete [2] such as penetration, spalling, scabbing as well as global responses such as deformation, vibration and so on. As summarized in [1], the conventional approach is to decouple the evaluation of local damage from the global response

evaluation, and the local damage is then evaluated by empirical formulas. However, those empirical formulas are mostly developed for reinforced concrete slabs, which are different from the concrete overpacks of storage casks. The concrete overpack has an annular cylindrical shape and a steel liner is attached inside the concrete annulus as a structural support. Some commercially available storage casks have steel liners outside the concrete annulus as well (Fig. 1). Thus the applicability of the empirical formulas to the local damage evaluation of concrete overpack is in doubt and the decoupling of local damage with the global response may lead to a too conservative estimation of both damages.

In this research, we apply finite element analysis with material failure and element erosion to the structural evaluation of concrete overpacks under high speed missile impacts. The local and global damage are evaluated simultaneously in a simulation. Two types of concrete overpacks with different configurations are considered. An impact scenario based on an aircraft engine crash is devised for this purpose, and the simulation results are verified by a comparison with test results.

2. CONCRETE OVERPACK SEGMENT MODEL

The overpack configurations considered in this research are based on the design of commercially available storage casks shown in Fig. 1 [3, 4]. For the ease of simulation and tests, segment models are designed for both types of concrete overpacks as shown in Fig. 2. The segment models are plane rectangular sections of the overpacks with the size of 2 m× 2 m. Important features and dimensions are determined from the original design of each cask as summarized in Table 1.

The Type 1 segment model has steel liners on all six surfaces while the Type 2 segment model does not have a steel liner in front. Only the Type II segment model has a reinforcement bar inside the concrete, which is made of A706 carbon steel. Rebars are placed in two layers, and the spacing of the rebar grid in the front and rear layer is 182 mm and 201 mm, respectively. The same cement and same size of aggregates are used for both models.

Two important responses of concrete overpacks under missile impacts are the penetration depth and the deformation of the rear liner. The penetration depth of an impacting missile into the concrete is related to the shielding capability of overpack and the deformation of the rear liner is related to the retrievability of the canister. The first is a local damage while the latter is a global structural response. Smaller values for both measures are preferred in a given impact condition.

Table 1. Comparison of Overpack Segment Model I and II

	Type I	Type II
Front (outer) liner	19 mm	None
Rear (inner) liner	32 mm	45 mm
Rebar	None	A706 ϕ19 mm
Thickness of concrete	679 mm	673 mm
Compressive strength of concrete	23 MPa	28 MPa
Density of concrete	2300 kg/m^3	2315 kg/m^3

(a) Concrete cask of Holtec Int'l   (b) Concrete cask of NAC Int'l

Fig. 1. Two Types of Concrete Overpacks
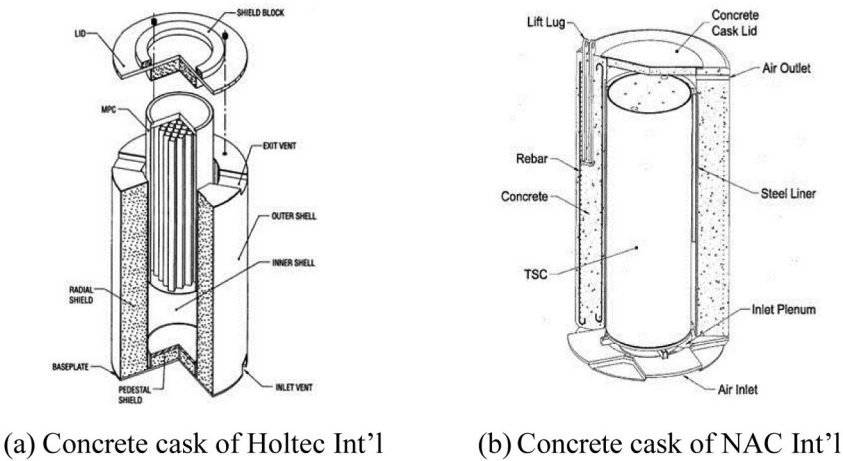
(a) Type 1 segment model   (b) Type 2 segment model
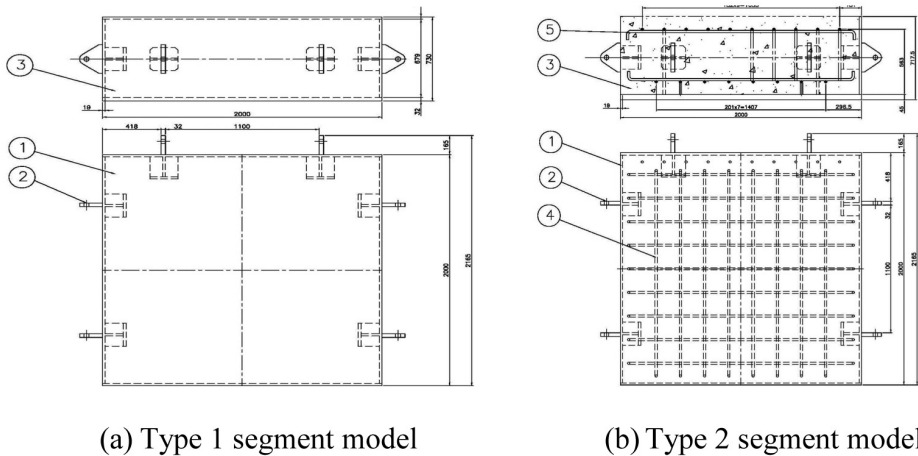
Fig. 2. Concrete Overpack Segment Models

3. IMPACT CONDITIONS

3.1 Missile Design

A rigid missile is designed considering the compatibility with a 155 mm cannon, which is used to fire the missile in the verification tests (Fig. 3). The diameter of the missile is 155 mm and the weight is 50 kg. A high strength steel SCM440 with yield strength of 950 MPa and ultimate tensile strength of 1.1 GPa was chosen for the material of the missile.

3.2 Impact Scenario

The accident scenario referred to in this research is the crash of an aircraft engine into the storage cask. Impact conditions are determined based on the information in reference [5], which deals with a safety assessment of nuclear facilities against a targeted aircraft crash. The perpendicular impact of a large size commercial aircraft (B747) engine with an impact velocity of 150 m/s was chosen in this work.

Since the missile used in this work is different from the actual aircraft engine, the impact velocity needs to be adjusted considering the difference between those two impacting projectiles. The approach taken in this research

is to match the penetration depth by those two projectiles when they hit a reinforced concrete slab with a velocity of 150 m/s. The penetration depth is calculated by the modified NDRC formula [1], which is given as follows:

$$x = \sqrt{4KNWD\left(\frac{V}{1000D}\right)^{1.8}} \quad for \ \frac{x}{D} \leq 2.0$$

$$x = \left[KNW\left(\frac{V}{1000D}\right)^{1.8}\right] + D \quad for \ \frac{x}{D} > 2.0$$

(1)

where x is the penetration depth into the concrete (inch), K is the concrete penetrability factor defined as $180/(f_c')^{1/2}$ where f_c' is the ultimate compressive strength of concrete (lb/in^2), N is the missile shape factor, W is the missile weight (lb), D is the missile effective diameter (inch) and V is the missile velocity (ft/sec). For the missile shape factor N, 0.72 is assigned for flat-nosed bodies, 0.84 for blunt-nosed bodies, 1.00 for average bullet-nosed (spherical end) bodies, and 1.14 for very sharp-nosed bodies. A more detailed explanation about this formula can be found in [1, 2]. The engine of the B747 has an effective diameter of 1.5 m and a weight of 4.5 ton [6]. The modified NDRC formula estimates the penetration depth of a rigid missile with a 4.5 ton weight and a 1.5 m effective diameter into
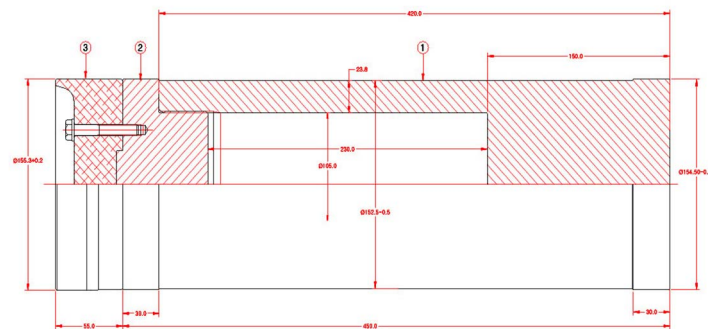

Fig. 3. Design of Rigid Missile

W: 4.5 ton
D: 1.4 m
Deformable
V: 150 m/s

X: 16.5″

W: 50 kg
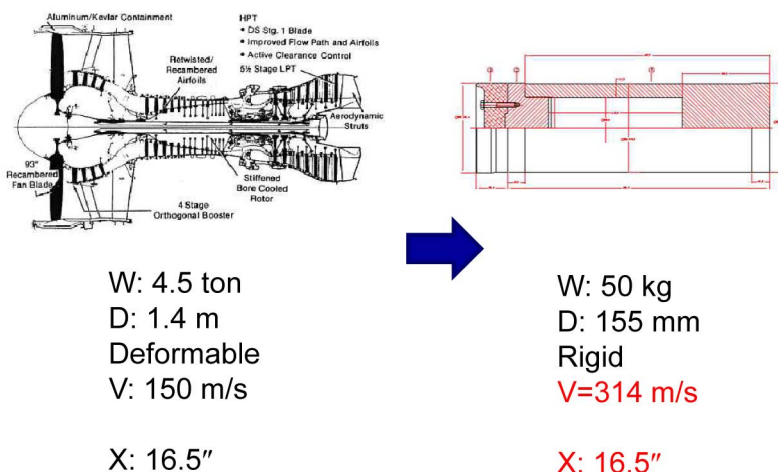D: 155 mm
Rigid
V=314 m/s

X: 16.5″

Fig. 4. Calculation of Impact Velocity

a reinforced concrete wall as 33 inches (83.8 cm). However, Sugano et al. [7] showed that the aircraft engine is a deformable missile rather than a rigid one, and suggested a correction factor 0.5 for the penetration depth calculation. Thus, the penetration depth by the aircraft engine is reduced to 16.5 inches (41.9 cm). To produce the same penetration depth with the rigid missile described in the previous section, the impact velocity should be 314 m/s from the modified NDRC formula.

Because the modified NDRC formula has limited applicability and the overpack segment model considered in this work is different from the reinforced concrete slab, it is not expected that exactly the same depth of penetration occurs in our problem. Rather, it is intended that a similar level of severity is posed to the problem with that of a sever aircraft engine crash. Limitations of the modified NDRC formula can be found in [1].

4. NUMERICAL SIMULATION

4.1 Modeling

Finite element (FE) models of the concrete overpack segment models, impacting missiles and the supporting structure are built mainly using 8 node hexahedron elements. For numerical efficiency, half of the real structures are modeled with a symmetry boundary condition on the plane of symmetry as in Fig. 5. The number of nodes and elements used in the FE models are summarized in Table 2. The rebars are modeled using second order beam elements connected to the nodes of concrete. The missile and impact area in the overpack segment models are modeled with a higher mesh density for better accuracy.

The material properties are given based on the actual tensile test data of the materials that constitute the overpack segment models and missile. The materials for the steel liner and missile are modeled by the piecewise linear
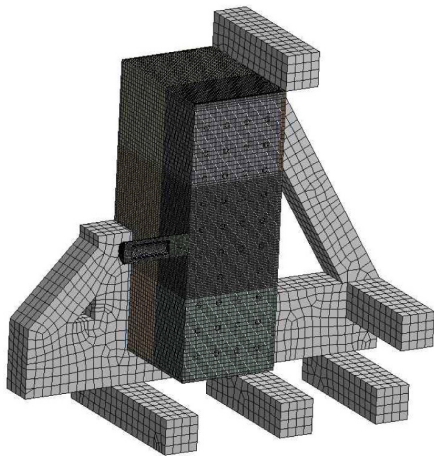
plasticity model and the rebar material is modeled as elastic-perfectly plastic as in Fig. 6. For numerical stability, the softening behavior is ignored in the material models. For the concrete, the RHT concrete model [8] is used, which is provided by the ANSYS AUTODYN material library [9]. It is well noted that the proper tuning of damage parameters of the RHT concrete model is a challenging task, and in our work only those parameters for compressive strength, failure and erosion control are calibrated, while the other parameters are set to default values provided by ANSYS AUTODYN. Intensive investigations into the RHT concrete model and the tuning of its parameters can be found in literature such as [10, 11]. The failure criteria and erosion criteria in those references are adopted in our simulation as summarized in Table 3. For simplicity, the supporting structure is modeled as a rigid body.

Table 2. Number of Nodes and Elements in FE Model

		Number of nodes	Number of elements
Supporting structure		4828	3068
Missile		1380	1062
Concrete		91474	80850
Steel liners	Type I	26030	13068
	Type II	12784	5631
Rebar (only for Type II)		35990	18140

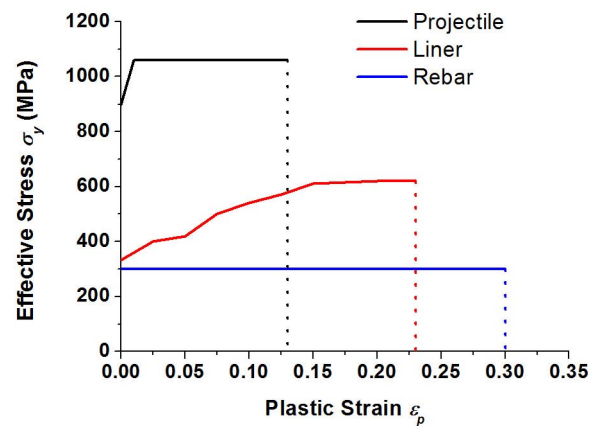
Fig. 6. Material Properties for Metals in the Simulation

Table 3. Failure and Erosion Criteria

Parts	Failure criteria	Erosion criteria
Liner	Plastic strain ≥ 0.22	Plastic strain ≥ 0.23
Missile	Plastic strain ≥ 0.13	Not applied
Rebar	Plastic strain ≥ 0.3	Plastic strain ≥ 1.00
Concrete	RHT failure model	Geometric strain ≥ 2.00

Fig. 5. FE Model of Concrete Overpack Segment Model
(Half Model)

The boundary condition is given such that the bottom surfaces of the supporting structure are fixed in all directions and the vertical column of the support structure supports the overpack with a contact condition. As mentioned earlier, a symmetry boundary condition is imposed on the plane of symmetry. The impact velocity is applied to the missile as an initial condition.

4.2 Analysis Results

Implicit dynamic analyses are performed using ANSYS AUTODYN [9]. The analysis results for the Type 1 segment model is summarized in Fig. 7. The penetration depth and displacement of the center point of the rear liner are calculated as 450 mm and 53 mm, respectively. The analysis results for the Type 2 segment model is summarized in Fig. 8.
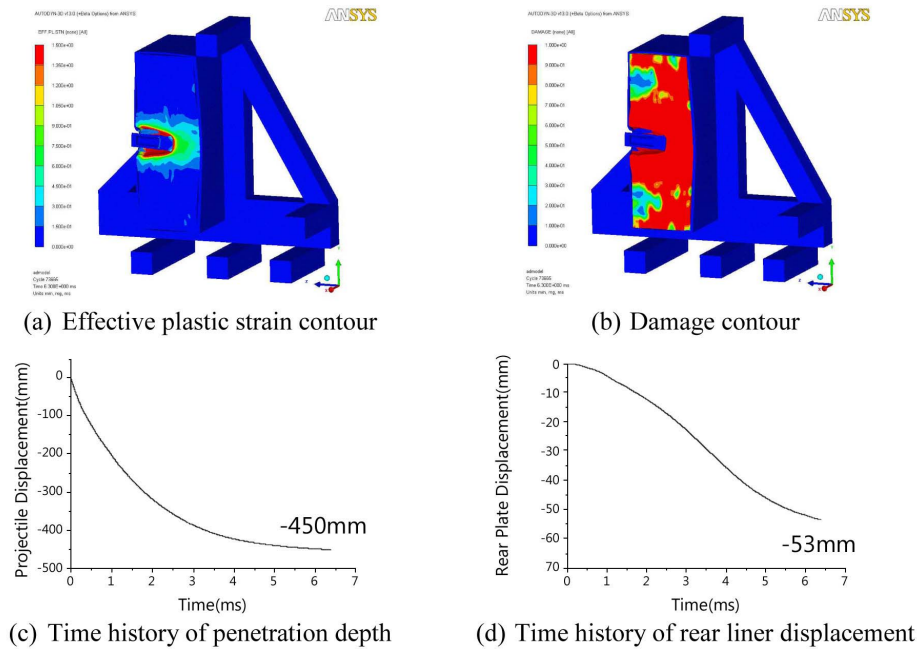
(a) Effective plastic strain contour

(b) Damage contour

(c) Time history of penetration depth

(d) Time history of rear liner displacement

Fig. 7. Analysis Results of Type I Segment Model

(a) Effective plastic strain contour

(b) Damage contour

(c) Time history of penetration depth

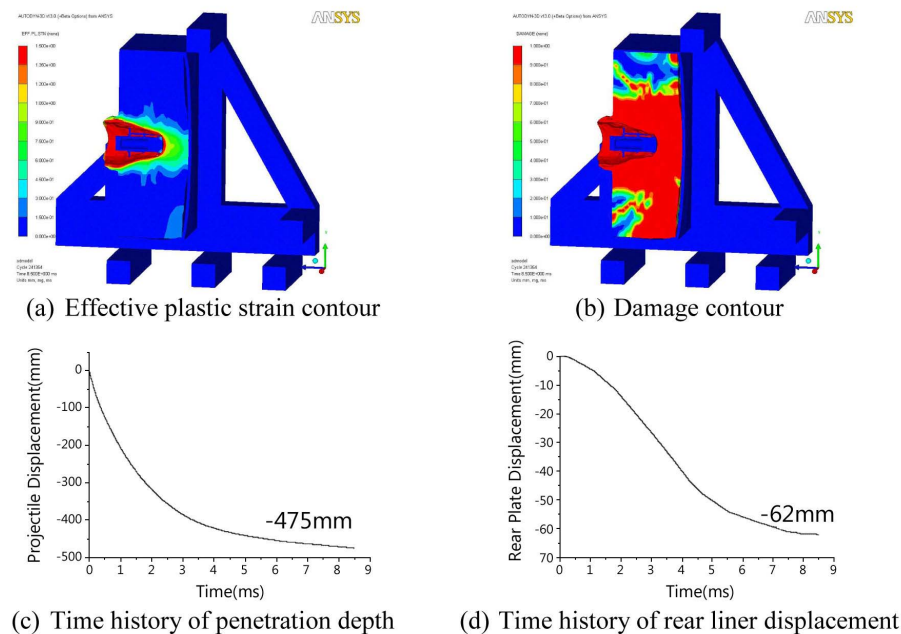(d) Time history of rear liner displacement

Fig. 8. Analysis Results for Type 2 Segment Model

The penetration depth and the deformation of the rear liner are calculated as 475 mm and 62 mm, respectively. It is observed that the Type 1 segment model is more resistant than the Type 2 segment model in both measures against a high speed missile impact. Comparing the damage contour plots, it is seen that damage is propagated into a wider volume of concrete in the Type 1 segment model, due to the confining effect of the steel liners, which increases the resistance against the penetration. In the Type 2 segment model, the damage is concentrated in the vicinity of the area of impact and a bigger volume of concrete is eroded around the missile path compared to the case of Type 1 segment model. A significant volume of concrete is extruded from the front face of the overpack segment model due to the impact shock. In the Type 1 segment model, extrusion of concrete from the front face is not observed, but the front liner is deformed.

5. VERIFICATION BY TESTS

Verification tests were performed at the testing site of the Agency for Defense Development (ADD) using a 155 mm cannon as in Fig. 9. The actual impact velocity was measured as 329 m/s, which is higher than the target velocity of 314 m/s, and the actual velocity was considered in the numerical simulation. Fig. 10 shows the moment of impact of the Type I segment model and Fig. 11 shows

the deformed shape after the impact together with the missile. About half of the missile body (~250 mm) is protruding from the front liner after the impact, but when the missile was removed from the overpack, much deeper penetration was observed in the concrete. This means that the missile was rebounded after it reached the deepest point inside the concrete. The penetration depth is measured as 504 mm and the displacement of the center point of the rear liner is 43 mm. When comparing these results with those of the numerical simulation, it is observed that the numerical simulation slightly underestimates the penetration depth while overestimating the displacement of the rear liner. As predicted by the numerical simulation, the front liner is deformed, making the model look potbellied.

Figs. 12 and 13 show the moment of impact of the Type 2 segment model and the shape after the impact, respectively. Different from the case of the Type 1 model, in which concrete is fully confined by steel liners, a significant spalling and radial cracking [2] were observed. The spalling diameter was measured at about 1.1 m. The whole body of the missile became imbedded in the concrete after the impact and the missile actually perforated the whole depth of the concrete and hit the rear liner. The penetration depth and displacement of the center point of the rear liner are measured as 672 mm and 52 mm, respectively. The simulation overestimates the deformation of the rear liner while underestimating the penetration depth with a bigger discrepancy than in the case of the Type 1 segment model. The spalling phenomena is not accurately

Fig. 9. Test Settings

Fig. 11. After Impact (Type 1)

Fig. 10. Moment of Impact for Type 1 Segment Model

Fig. 12. Moment of Impact for Type 2 Segment Model

Fig. 13. After Impact (Type 2)

simulated by analyses, but the diameter of the fully damaged area in Fig. 8 in the concrete matches very well with the spalling diameter measured in the test.

It is expected that the discrepancy of the numerical simulation and test can be minimized by a sophisticated calibration of material parameters and the eroding parameter of the concrete. It was observed that the penetration depth is very sensitive to the eroding parameter and a smaller eroding parameter produces a bigger penetration depth while reducing the deformation of the rear liner. It is due to the fact that an earlier erosion of elements involves a bigger loss of mechanical energy while making the progress of the missile easier. Thus, it is expected that a smaller eroding parameter could produce closer results to the test results in our problem, but finding the exact parameter value is not straightforward.

6. DISCUSSION AND CONCLUSION

Through a series of numerical simulations and tests, the accuracy of finite element analysis for the concrete overpack of the SF storage cask under a high speed missile impact has been assessed. It is demonstrated that the numerical simulation predicts the qualitative response and tendencies of the concrete overpack well, but the quantitative accuracy of the solution is dependent on the proper tuning of material and eroding parameters. Although the tuning of parameters might be a demanding work, the

numerical simulation scheme adopted in this work can be used to evaluate the local damage and global response of the concrete overpack simultaneously instead of using a decoupled approach with empirical formulas developed for reinforced concrete slabs.

In our work two types of concrete overpacks are considered in the form of segmented models. It was observed that the existence of a front steel liner increases the resistance to an impact significantly in both measures considered, those being the penetration depth and deformation of the rear liner. The numerical simulation results show reasonable agreement with the test results. However, it is noted that this work is focused on the verification of the numerical simulation rather than the actual performance assessment of existing concrete overpacks. Only part of the design features of existing casks are reflected in the design of segment models. There are many factors neglected in this research, such as the effect of overpack shape, the size effect of the impacting missile, the effect of reinforcement allocation and so on. These are very important factors in the evaluation of structural response of actual concrete overpacks, and they will be considered in our future research.

ACKNOWLEDGEMENT

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