Dynamic Impact Analyses and Tests of Concrete Overpacks – 13638

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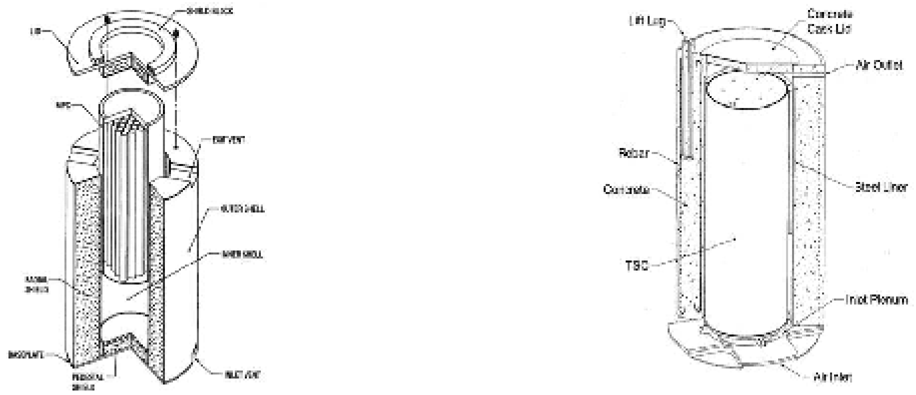
ABSTRACT

Concrete cask is an option for spent nuclear fuel interim storage which is prevailingly used in US. A concrete cask usually consists of metallic canister which confines the spent nuclear fuel and concrete overpack. When the overpack undergoes a severe missile impact which might be caused by a tornado or an aircraft crash, it should sustain acceptable level of structural integrity so that its radiation shielding capability and the retrievability of canister are maintained. Missile impact against a concrete overpack involves two damage modes, local damage and global damage. Local damage of concrete is usually evaluated by empirical formulas while the global damage is evaluated by finite element analysis. In many cases, those two damage modes are evaluated separately. In this research, a series of numerical simulations are performed using finite element analysis to evaluate the global damage of concrete overpack as well as its local damage under high speed missile impact. We consider two types of concrete overpack, one with steel incased concrete without reinforcement and the other with partially-confined reinforced concrete. The numerical simulation results are compared with test results and it is shown that appropriate modeling of material failure is crucial in this analysis and the results are highly dependent on the choice of failure parameters.

INTRODUCTION

The concrete storage cask of spent nuclear fuel is widely used in US as a method of interim storage of spent nuclear fuel before its final disposition. The storage cask usually consists of metallic canister which confines the spent nuclear fuel with welded closure and the concrete overpack which provides radiation shielding and structural protection of canister. In the safety assessment of the concrete cask, the impact resistance of the concrete overpack against external shock such as a missile impact should be evaluated together with a probable accident scenario. It is important that the structural integrity of the concrete overpack is maintained under the missile impact accident so that its radiation shielding capability and the retrievability of the canister are not lost. The procedure of structural evaluation under high speed missile impact caused by an aircraft crash is well summarized in [1]. The structural evaluation of concrete overpack involves the evaluation of local damage of concrete [2] such as penetration, spalling, scabbing as well as the 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 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 annular cylindrical shape and a steel liner is attached to the inside of the concrete annulus as a structural support. Some commercially available storage casks have steel liners attached outside the concrete annulus as well. (Fig. 1) Thus, the applicability of the empirical formulas to the local damage evaluation of concrete overpack is suspicious. And the decoupling of local damage with the global response may lead to too conservative estimation of the damage.



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

Fig. 1 Two types of concrete overpacks

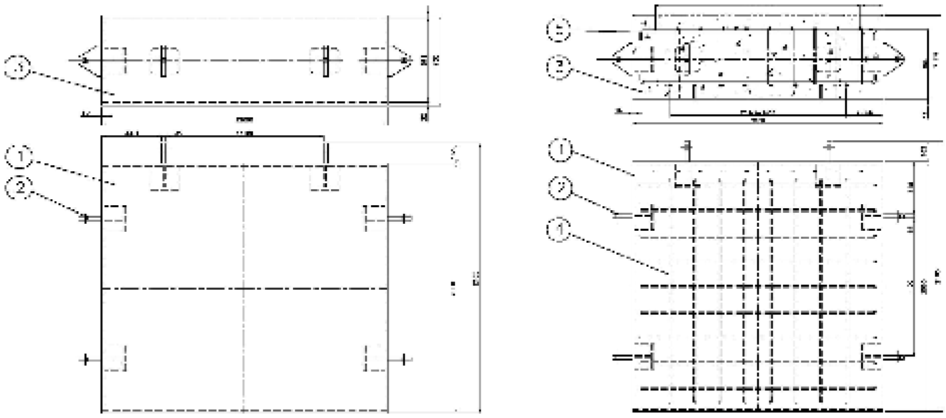
In this research, we evaluate the structural behavior of two types of concrete overpacks shown in Fig. 1 with a simplification using dynamic finite element analysis considering a scenario of aircraft engine crash. The local damage and global structural responses are evaluated at the same time and the accuracy of the simulation is assessed by a comparison with test results.

CONCRETE OVERPACK SEGMENT MODEL

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 section of the overpacks with the size of 2 m × 2 m and have the same configuration with the original overapacks such as the thickness of outer, inner steel liners, concrete properties and reinforcements. The Type 1 segment model has steel liners in all the six surfaces while the Type 2 segment model does not have steel liner in the front face exposing the bare concrete. The thickness of steel liners, concrete properties and the construction of reinforcements are determined based on literature about the commercially available concrete storage casks. They are designed with the same scale with the reference cask models considered.

The steel liners and lifting lugs are made of A516 Gr.70. The compressive strength of concrete of

Type 1 segment model is 23 MPa and that of Type 2 segment model is 28 MPa. The density of concrete in Type 1 model is 2300 kg/m3 while that of concrete in Type 2 model is 2315 kg/m3. Both are made from the type II Portland cement. In Type 2 segment model, the reinforcing bars are made of A706.



(a) Type 1 segment model (b) Type 2 segment model

Fig. 2. Concrete overpack segment models

Two measures will be carefully monitored in an impact accident. One is the penetration depth of impacting missile into the concrete which is related with the shielding capability of overpack. The other is the deformation of the backside liner which corresponds to the inner liner of real annular concrete overpack. It is related with the retrievability of the canister and the displacement of the center point of backside liner in the direction of impact will be monitored. The first one is a local damage while the latter is a global structural response. Smaller values for both measures are preferred in a given impact condition.

IMPACT CONDITIONS

Missile Design

A rigid missile is designed considering the compatibility with the 155 mm cannon which is used to fire the missile with a designated velocity in the verification tests. The missile has a 155 mm diameter with 50 kg weight and the shape is shown in Fig. 3. The material used is high strength steel SCM440 with yield strength 950 MPa and ultimate tensile strength of 1.1 GPa.

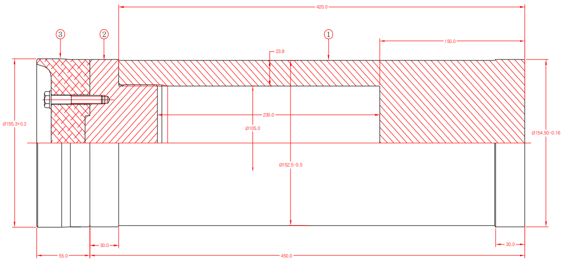


Fig. 3. Design of rigid missile

Impact Scenario

The impact scenario considered in this research is an aircraft engine crash with impact velocity of 150 m/s. This scenario considers a targeted aircraft crash like 9.11 terrorist attacks. The impact velocity 150 m/s is the measured velocity from the aircraft that struck Pentagon during the 9.11 terrorist attack [3] and it is the only available data for impact velocity of targeted aircraft crash into a low profile building. Since the size of concrete cask is smaller than the Pentagon building, setting the impact velocity at 150 m/s renders the current approach to be on the conservative side. The engine is the hardest part of an aircraft and the perpendicular impact by an aircraft engine is the most severe impact condition. Thus, the perpendicular impact of a large size commercial aircraft (B747) engine with the impact velocity 150 m/s is considered 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 the two impacting projectiles, the aircraft engine and the rigid missile described in the previous section. We take an approach to match the penetration depth by the two projectiles when they hit reinforced concrete slab with the velocity of 150 m/s. The penetration depth is calculated by the modified NDRC formula [1] which predicts the penetration depth of an equivalent solid circular cylindrical missile. It is given as follows:

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

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

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). A more detailed explanation about this formula can be found in [1, 2]. The engine of B747 has effective diameter of 1.5 m and weight of 4.5 ton [4]. The modified NDRC formula estimates the penetration depth of a rigid missile with 4.5 ton weight and 1.5 m effective diameter into a reinforced concrete wall as 33 inch (83.8 cm). However, Sugano et al. [5] showed that the aircraft engine is a deformable missile rather than a rigid one and the correction factor for the penetration depth calculation is 0.5. Thus, the penetration depth by the aircraft engine is reduced to 16.5 inch (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. In this calculation, the correction factor is not applied because the missile is very close to a rigid missile.

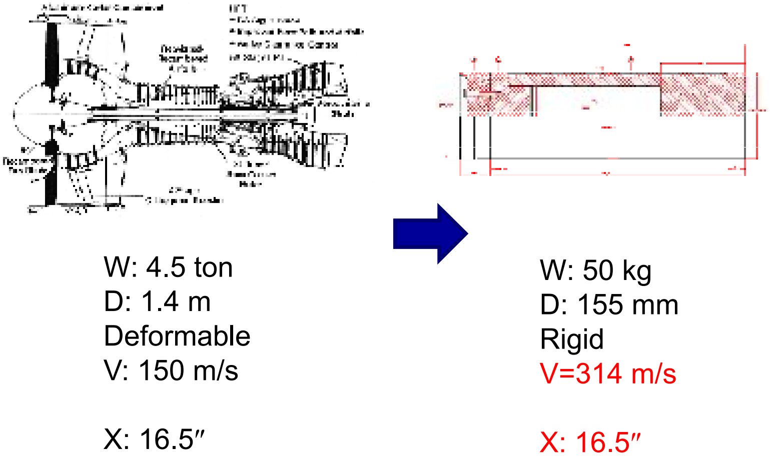


Fig. 4 Calculation of impact velocity

Because the modified NDRC formula has limited applicability and the overpack segment model considered in this work is different from the reinforced concrete slab, we do not expect that exactly same penetration occurs in our problem with the calculation. Rather, we intend to pose a similar level of severity to our problem with a very severe aircraft engine crash. Limitations of the modified NDRC formula can be found in [1].

NUMERICAL SIMULATION

Modeling

Finite element (FE) models of the concrete overpack segment model, impacting missiles and the supporting structure are built mainly using 8 node hexahedron elements. For efficiency, half of real structures are modeled with 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 1. The rebars are modeled using second order beam elements connected with nodes in the concrete. The missile and impacting area in the overpack segment models are modeled with relatively dense mesh for better accuracy.

Table 1 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

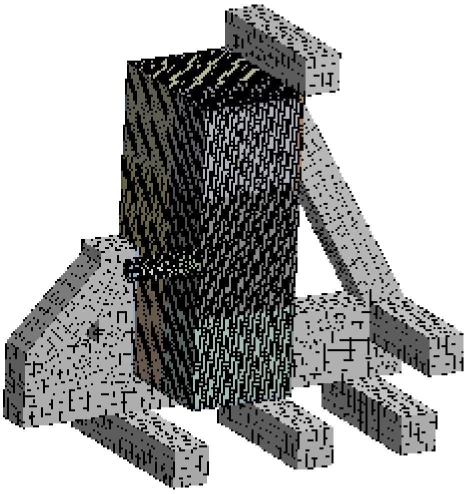


Fig. 5 FE model of concrete overpack segment model

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 with piecewise linear plasticity model and the rebar material is modeled as elastic-perfectly plastic as can be seen in Fig. 6. For numerical stability, the softening behavior is ignored in the material modeling. For the concrete, the RHT concrete model [6] is utilized which is provided by the ANSYS AUTODYN material library [7]. It is well noted that the proper tuning of damage parameters of RHT concrete model is a challenging task and in our work we tuned parameters for compressive strength, failure and erosion control while the other parameters are set to default values provided by ANSYS AUTODYN. Aggressive investigation into the RHT concrete model and its parameter tuning can be found in literature such as [8, 9]. The failure criteria and erosion criteria in those references are adopted in our simulation as summarized in Table 2. For simplicity, the supporting structure is modeled as a rigid body.

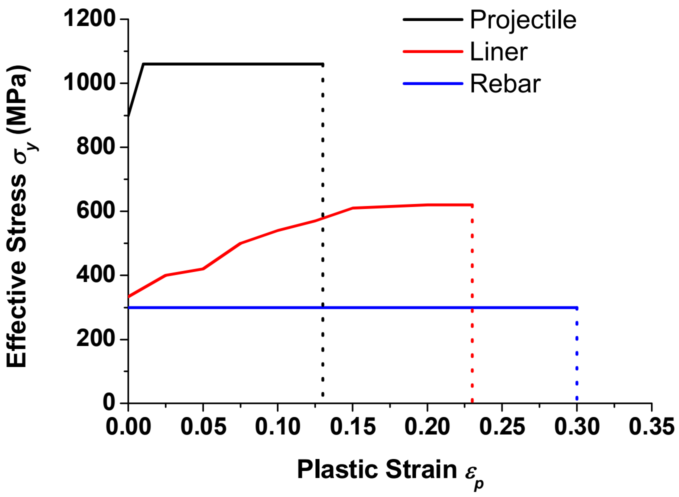


Fig. 6 Material properties for metals in the simulation

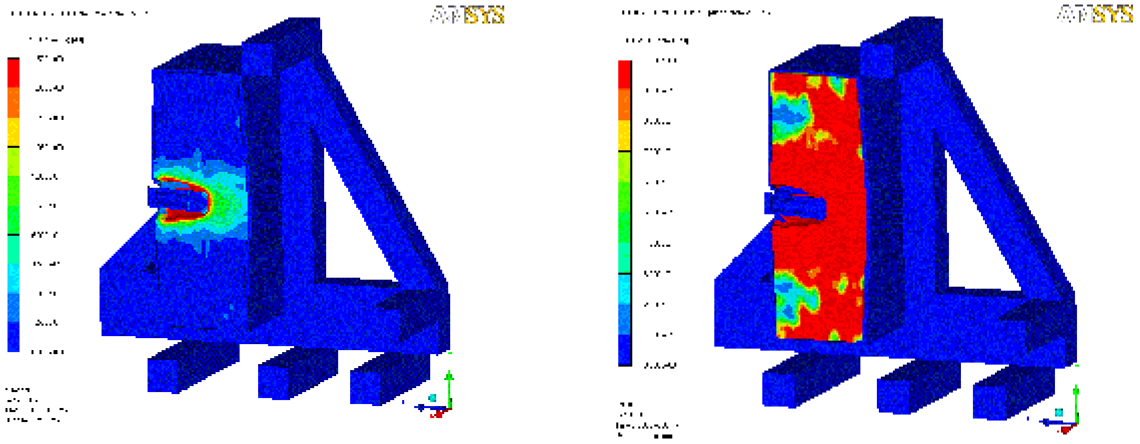
Table 2 Failure and erosion criteria

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

The boundary condition is given such that the bottom surfaces of the supporting structure are fixed and support structure contacts the vertical edges at left and right sides of overpack segment model. As mentioned earlier, symmetry boundary condition is imposed on the plane of symmetry. The impact velocity is applied to the missile as initial condition.

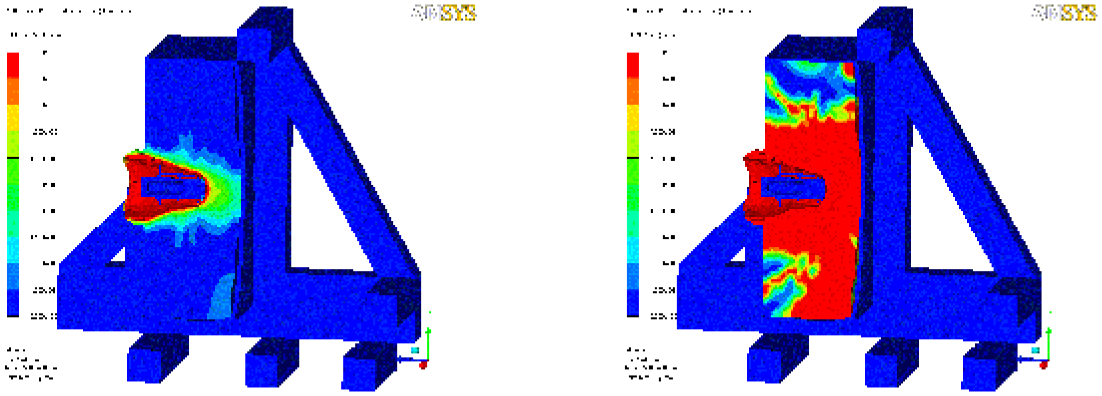
Analysis Results

Implicit dynamic analyses are performed using ANSYS AUTODYN [7]. The analysis results for Type 1 segment model is summarized in Fig. 7. The penetration depth and displacement of center point of backside liner are calculated as 450 mm and 53 mm, respectively. The analysis results for Type 2 segment model is summarized in Fig. 8. The penetration depth and the deformation of backside 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 the high speed missile impact. Comparing the damage contour plots, it is seen that damage is propagated into wider volume of concrete in Type 1 segment model and it is due to the confining effect of steel liners which in turn increases the resistance against the penetration. In Type 2 segment model, the damage is concentrated in the vicinity of impacting area and bigger volume of concrete is eroded around the missile path than the case of Type 1. Significant volume of concrete is pushed out from the front face of overpack segment model due to the impact shock. In Type 1 segment model, escape of concrete from the front face is not observed but the front liner is also deformed making the model look potbellied.



(a) Effective plastic strain (b) Damage

Fig. 7 Analysis results of Type I segment model



(a) Effective plastic strain (b) Damage

Fig. 8 Analysis results for Type 2 segment mode

VERIFICATION BY TESTS

The verification tests were performed in the testing site of 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 314 m/s and the actual velocity was considered in the numerical simulation. Fig. 10 shows the moment of impact of 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 impact but much deeper penetration was observed in the concrete, which means that the missile was rebounded after it reached the deepest point in the concrete. The penetration depth is measured as 504 mm and the displacement of center point of backside liner is 43 mm. When comparing these results with those by numerical simulation, it is observed that the numerical simulation slightly underestimates the penetration depth while overestimating the displacement of backside liner. As predicted by numerical simulation, the front liner is also deformed making the model potbellied.

Fig. 9 Test settings

Fig. 10 Moment of impact for Type 1 segment model

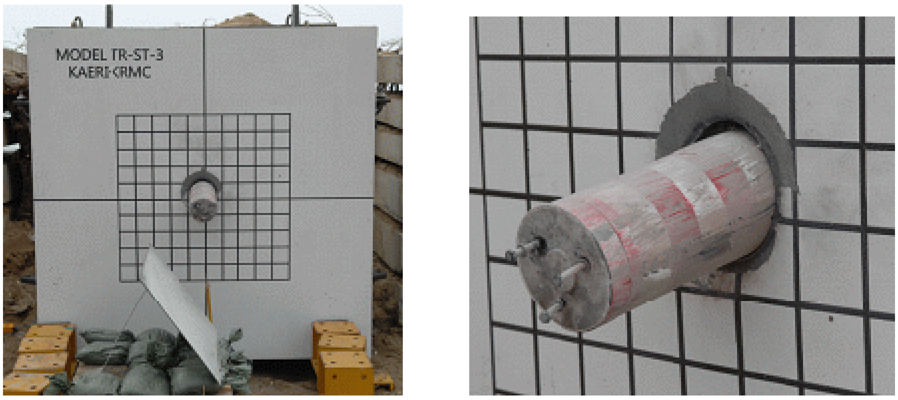


Fig. 11 After impact (Type 1)

Figs. 12 and 13 show the moment of impact of Type 2 segment model and the shape after the impact, respectively. Different from the case of Type 1 model of which concrete is fully confined by steel liners, a significant spalling and radial cracking [2] were observed in the case of Type 2 segment model. The spalling diameter was measured as about 1.1 m. The whole body of missile became imbedded in the concrete after the impact and actually the missile perforated the whole depth of concrete and hit the backside liner. The penetration depth and displacement of center point of backside liner are measured as 672 mm and 52 mm, respectively. The simulation overestimates the deformation of backside liner while underestimating the penetration depth with bigger discrepancy than the case of Type 1 segment model. The spalling phenomena is not very accurately predicted by the simulation but the diameter of fully damaged area in Fig. 8 in the concrete matches very well with the spalling diameter.

Fig. 12 Moment of impact for Type 2 segment model

Fig. 13 After impact (Type 2)

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

DISCUSSION AND CONCLUSION

Through a series of numerical simulations and tests, the accuracy of finite element analysis for concrete overpack of SF storage cask under high speed missile impact has been assessed. It is demonstrated that the numerical simulation predicts the qualitative response and tendencies of 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 concrete overpack at the same time instead of using 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 front steel liner increases the resistance to impact significantly in both measures considered, the penetration depth and deformation of backside liner. The numerical simulation results show reasonable agreement with the test results. However, it is noted that this work is more focused on the verification of the numerical simulation rather than actual performance assessment of existing concrete overpacks. There are many factors neglected in this research such as the effect of overpack shape, size effect of impacting missile, 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.

REFERENCES

[1] US DOE, *Accident analysis for aircraft crash into hazardous facilities*, DOE-STD-3014-2006, 2006.

[2] Q.M. Li et al., “Local impact effects of hard missiles on concrete targets”, *International Journal of Impact Engineering*. Vol. 32, pp. 224-284, 2005

[3] NEI, "Deterring terrorism: Aircraft crash impact analyses demonstrate nuclear power plant's structural strength," NEI, 2002.

[4] K Shirai et al. “Safety analysis of dual purpose metal cask subject to impulsive load due to aircraft engine crash,” *Journal of Power and Energy Systems*, Vol. 3, pp. 72-82, 2009

[5] T Sugano et al. "Local damage to reinforced concrete structures caused by impact of aircraft engine missiles: Part 2 Evaluation of test results," *Nuclear Engineering Design*, Vol. 140, pp. 407-423, 1993.

[6] M Rebecca et al. “*Survey of four damage models for concrete*,” SAND2009-5544, Sandia National Laboratory, 2009

[7] Century Dynamics Ltd., Horsham. *AUTODYN: Theory Manual*, 4.3 edition, 2000.

[8] Z Tu and Y Lu, “Modifications of RHT material model for improved numerical simulation of dynamic response of concrete,” *International Journal of Impact Engineering*. Vol. 37, pp. 1072-1082, 2010

[9] T. Elshenawy, Q.M. Li, "Influences of target strength and confinement on the penetration depth of an oil well perforator", *International Journal of Impact Engineering*, Vol 54, pp.130-137, 2013