Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division III Applied Computation

NUMERICAL SIMULATION OF A HARD AND A SOFT MISSILE IMPACT INTO A STEEL REINFORCED CONCRETE TARGET: OVERVIEW OF WORK PERFORMED BY SNL FOR THE US NRC IN SUPPORT OF THE IRIS 2012 EXERCISE

SAND2013-2600C

John L. Bignell[1], Jonathan S. Rath[2], Syed A. Ali[3], and Richard F. Rivera-Lugo[4]

[1]Principal Member of the Technical Staff, Sandia National Laboratories, Albuquerque, NM (jbignel@sandia.gov)
[2]Senior Member of the Technical Staff, Sandia National Laboratories, Albuquerque, NM
[3]Project Manager (Retired), U.S. Nuclear Regulatory Commission, Washington, DC
[4]Project Manager, U.S. Nuclear Regulatory Commission, Washington, DC

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

ABSTRACT

The assessment of nuclear power plant containment structures for the impact of missile type projectiles has in recent times increasingly come to involve the use of analytical models employing the finite element method. Recognizing a need to identify effective means for performing these missile impact assessments, a round-robin study in 2010 entitled "Improving the Robustness Assessment Methodologies for Structures Impacted by Missiles" (IRIS) was launched with the intent being to investigate the effectiveness of today's analytical methods for modeling missile impacts on steel-reinforced concrete structures. As part of its participation in the second phase of the IRIS round robin exercise, Sandia National Laboratories, for the United States Nuclear Regulatory Commission constructed two finite element models used to simulate (with the commercially available code LS-DYNA) two separate tests involving the impact of either a soft (flexural test) or a hard (punching test) missile into a steel reinforced concrete panel target. Results from these analyses are presented and a comparison made between the model response and test observed behavior. In general, the numerical models were able to match the test data with reasonable accuracy; however, in many instances, detailed response parameters were not precisely reproduced by either model. Despite this, it is clear that numerical methods are capable of producing results reasonable enough to make accurate and useful predictions in extreme situations involving missile impacts into steel reinforced concrete structures.

INTRODUCTION

The assessment of nuclear power plant containment structures for the impact of missile type projectiles has been a long standing practice in the nuclear industry (Bangashi, 1982; Kennedy, 1975). Early assessments of missile impacts on nuclear facilities largely made use of empirically based methods for determining the robustness of those structures against such impacts (Adeli and Amin, 1985; Bignon and Riera, 1980; Riera, 1979). With the growth in the availability of low-cost high-performance computational resources and the continued improvement in advanced simulation techniques, the use of analytical models employing the finite element method in missile impact assessments has become more attractive and prevalent. Recognizing a need to identify effective means for performing these missile impact assessments, the Committee on the Safety of Nuclear Installations (CSNI) in conjunction with the Committee on Nuclear Regulatory Activities (CNRA), both part of the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), launched a round-robin study in 2010 entitled "Improving the Robustness Assessment Methodologies for Structures Impacted by Missiles" (IRIS) (NEA/CSNI, 2011). The intent of IRIS was to investigate the effectiveness of today's analytical methods for modeling missile impacts on steel-reinforced concrete structures. Phase I involved the blind prediction of the response of two missile impact tests. Phase II, which was recently completed, involved the re-simulation of the blind missile impact tests; however, participants were asked to improve upon their phase I models making use of newly provided concrete material test data and any lessons learned from the phase I work. The results presented here pertain to the analyses performed by Sandia National Laboratories for the United States (US) Nuclear Regulatory Commission (NRC) in support of the second phase of the IRIS round-robin study.

TEST DESCRIPTION

Two tests involving the impact of a missile into a steel reinforced concrete panel were conducted at the VTT Technical Research Center of Finland in 2010 for the IRIS round-robin study (NEA/CSNI 2011). These tests are referred to as the VTT Flexural and VTT Punching tests.

VTT Flexural Test

The VTT Flexural test made use of a deformable thin-walled 50.5 kg EN 1.4432 stainless steel pipe missile with a 0.254 m outer diameter and total length of 2.11 m. The pipe's wall thickness was constant along its length at 2 mm except over a length of 0.244 m at its trailing end where it was reinforced with a S355J2H carbon steel doubler pipe with a wall thickness of 12.5 mm.

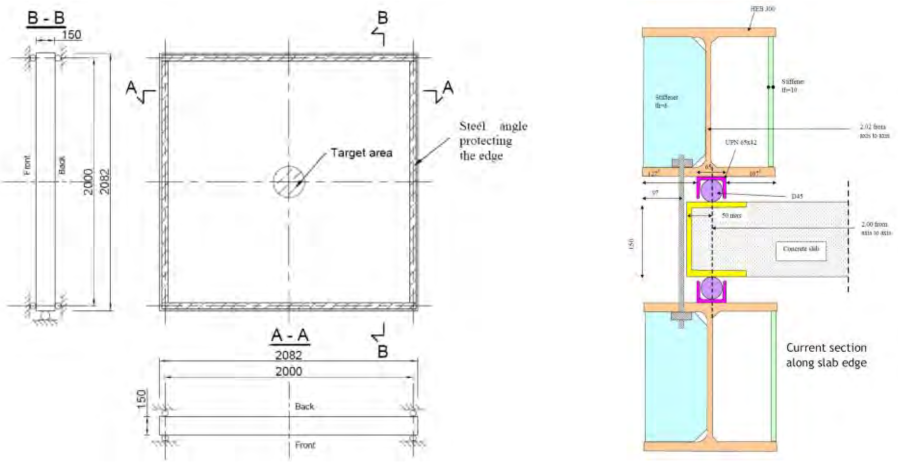
The target was a 2.1 m square (length and width), 0.15 m thick steel-reinforced concrete panel simply supported along its four edges as illustrated in Figure 1. The unsupported span, both in the length and width directions, was 2.0 m. Bending reinforcement consisted of 6 mm diameter A500HW steel bars spaced at approximately 5.6 cm running in both the length and width directions on each face (front and back) of the panel. Shear (through thickness) reinforcement consisted of 6 mm diameter A500HW steel bars oriented through the panel thickness with a length and width spacing of approximately 7.5 cm.

The missile impact velocity was 110.2 m/s. The response of the target was dominated by bending without significant target damage or failure. During the test, reaction forces at four target support posts were measured, along with displacements at five locations on the back face of the target. Strains in the concrete at three locations on the target face and strains in the bending steel-reinforcing bars at eighteen locations were also measured. The missile's velocity profile was also determined and post-test missile and target damage was recorded.

VTT Punching Test

The VTT Punching test made use of a relatively rigid 47.4 kg light weight concrete filled steel pipe missile with a 0.168 m outer diameter and total length of 0.64 m (not including a smaller diameter aluminum pipe attached to the trailing end of the missile used to determine its velocity during the impact). The pipe's wall thickness was constant along its length at 10 mm. The pipe was capped with a thick steel nose on its leading end.

The target was a 2.1 m square (length and width), 0.25 m thick steel-reinforced concrete panel simply supported along its four edges as illustrated in Figure 1. The unsupported span, both in the length



(a) Target (b) Support Detail at Edge of Target

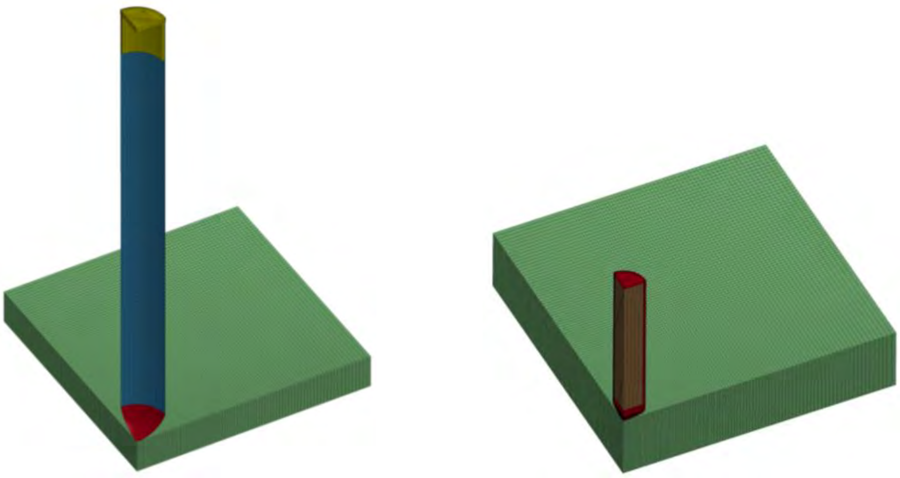
Figure 1. VTT Flexural and Punching Test Target Support Conditions (NEA/CSNI 2011).

and width directions, was 2.0 m. Bending reinforcement consisted of 10 mm diameter A500HW steel bars spaced at approximately 9.0 cm in both the length and width directions on each face (front and back) of the panel. No shear (through thickness) reinforcement was used.

The missile impact velocity was 135.9 m/s. The response of the target was dominated by a shear punching failure in which the missile perforated the target and exited the back side with a residual velocity of 33.8 m/s. During the test, reaction forces at four target support posts were measured, along with displacements at five locations on the front face of the target. Strains in the concrete at two locations on the target face and strains in the bending steel-reinforcing bars at eight locations were also measured. The missile's velocity profile was also determined and post-test missile and target damage was recorded.

MODEL DESCRIPTION

All analyses were performed using the explicit transient-dynamic finite element code LS-DYNA produced by Livermore Software Technology Corporation (LS-DYNA 2011). Two separate models were constructed, one model for each test. Each model comprised a one-quarter symmetric representation of the reinforced concrete slab and missile (Figure 2).



(a) Flexural Test Model (b) Punching Test Model

Figure 2. VTT Missile Impact Tests Finite Element Model Meshes.

Mesh Discretization

The concrete portion of the target was represented using single integration point 8-node hexahedral elements. Each steel reinforcing bar within the target slab was modeled explicitly using Hughes-Liu beam elements. Steel reinforcement elements were attached to the hexahedral concrete target elements using the automatic lagrangian-in-solid constraint generation capability in LS-DYNA. The missiles were modeled with combinations of 4-node reduced integration Belytschko-Tsay shell elements with five integration points through the thickness and single integration point 8-node hexahedral elements. The numbers of elements comprising each component in each model and their approximate characteristic lengths are listed in Table 1.

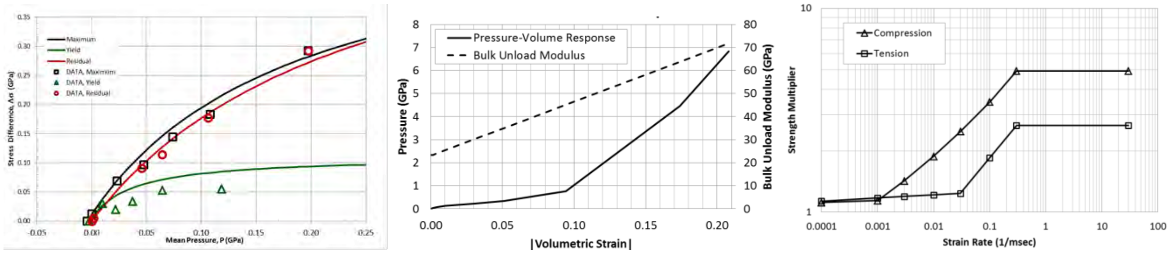
Table 1. Finite Element Model Mesh Properties.

Attribute	VTT Flexural		VTT Punching	
	# Elements[1]	El. Len. (mm)	# Elements[1]	El. Len. (mm)
Complete Model	180,632	---	290,085	N/A
Target – Concrete	162,000	8	267,300	8
Target – Steel Reinforcing	3,112	30	1,104	43
Missile – Shell	12,256	6	N/A	N/A
Missile – Hexahedral	3,264	6	21,681	8

[1] Numbers of elements listed are for the quarter symmetric model.

Material Constitutive Models

The material properties used are listed in Table 2. The target concrete material properties are based on data obtained from several uniaxial and triaxial compression tests. The Karagozian and Case (K&C) or *MAT_072R3 material model in LS-DYNA was used to represent the target concrete. The K&C concrete constitutive model is a three-invariant model that makes use of three failure surfaces to describe the compressive yield, maximum, and residual strengths of the concrete versus confining pressure (Figure 3a). A separate relationship describes the volumetric strain versus pressure response (Figure 3b). The K&C concrete constitutive model includes strain-rate effects through the use of a strain rate dependent strength multiplier. Figure 3c shows the specific compressive and tensile strain rate based strength multipliers used. The values given are based on those listed in the LS-DYNA user's manual (LSTC, 2010) for a standard strength concrete, but have been scaled down to achieve a better fit between the model and the test observed behavior of the target.



(a) Compressive Strength (b) Volumetric Response (c) Strain Rate Strength Multiplier

Figure 3. K&C Concrete Material Model Data.

The response of the steel materials comprising the missile and target reinforcement was modeled using either the piecewise linear plasticity model (*MAT_024) or plastic kinematic material model (*MAT_003). The *MAT_024 and *MAT_003 material models are elastic-plastic constitutive models that make use of a Mises yield criterion with associated plastic flow. For the *MAT_024 material model, the evolution of the yield surface is described by a piecewise linear effective-stress versus effective-plastic-strain relationship; whereas for the *MAT_003 material model a tangent modulus describes this behavior. Both models allow for strain rate effects to be included through the use of a Cowper-Symonds type strain rate based strength multiplier. The Cowper-Symonds rate multiplier acts to increase the material yield strength (σ_y^{static}) as the effective plastic strain rate ($\dot{\varepsilon}$) increases, in accord with the following relationship.

$$\sigma_y^{dynamic} = \sigma_y^{static} \times \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right] \tag{1}$$

Two constants, C and P, are required to define this relationship. The Cowper-Symonds strain rate based strength multiplier parameters given in Table 2 were taken from values found in the literature (Peixinho and Pinho 2007, Nordbert 2004).

The pseudo tensor material model (*MAT_016) was used to represent the lightweight concrete fill in the VTT Punching model missile. This constitutive model includes an automated input parameter generator that takes as input the unconfined compressive cylindrical specimen strength, which was

Table 2. Material Parameters.

Material/Property	VTT Flexural		VTT Punching
Target Concrete			
Modulus of Elasticity [GPa]	39.3		39.3
Poisson's Ratio	0.22		0.22
Density [kg/m^3]	2260		2260
Compressive Strength [MPa]	69.0		69.0
Tensile Strength [MPa]	4.04		4.04
Target Reinforcing Steel			
Designation	A500HW – 6 mm		A500HW – 10 mm
Modulus of Elasticity [GPa]	219		210
Poisson's Ratio	0.29		0.29
Density [kg/m^3]	7843		7843
Yield Strength [MPa]	600[a]		535[a]
Ultimate Strength [MPa]	715[a]		605[a]
Elongation to Failure (Test/Model), [%]	12[a]/3[a]		12[a]/3[a]
Rate Multiplier Constant C [1/sec], P	40, 5		40, 5
Missile Steel			
Designation	EN 1.4432	S355J2H	S355J2H and Fe52[c]
Modulus of Elasticity [GPa]	200	200	200
Poisson's Ratio	0.29	0.29	0.29
Density [kg/m^3]	7850	7738	7850
Yield Strength [MPa]	231[a]	500	231[a]
Ultimate Strength [MPa]	484[a]	1940	484[a]
Elongation to Failure [%]	N/A[b]	120	N/A[b]
Rate Multiplier Constant C [1/sec], P	100, 10	40, 5	100, 10

[a] Value given is engineering stress or engineering strain.
[b] Failure criterion not included for this material.
[c] Even though the steel portion of the missile is composed of these materials, EN 1.4432 properties were assumed.

assumed to be 20 MPa (ACI 2003). In addition, the material density was set so that the total mass of the missile in the VTT Punching model was equal to 47.4 kg.

Material Failure and Element Erosion

The effects of material degradation and failure are captured either directly by the material constitutive model or indirectly by element removal during the course of a simulation. The K&C concrete material model is the only constitutive model utilized that is capable of representing the strength/stiffness degradation of the material directly. All other material degradation and failure was captured via element removal; the most significant of which was removal of reinforcing steel beam elements once they had achieved a plastic strain in excess of 3%. Note that a value significantly below the measured strain to failure of 12% was selected because the model does a poor job of capturing the strain localization that occurs at crack interfaces in the real target. Instead, the model smears the strain that would normally occur locally at a crack over an element length. The value of 3% was somewhat arbitrarily selected but was found to provide a good match with test data. Element removal was also employed with the concrete target elements, largely to guard against numerical difficulties introduced by highly distorted elements. Concrete elements were removed once they had exceeded a plastic shear strain of 50%.

Boundary Conditions

Appropriate symmetry boundary conditions were applied to all symmetry planes (target and missile). In addition, each target was supported against translation in the vertical direction at perimeter nodes on its top and bottom faces so as to approximately reproduce the support conditions illustrated in Figure 1. Missile components were given initial velocities consistent with the missile impact velocities measured for each test (VTT Flexural = 110.9 m/s and VTT Punching = 135.0 m/s).

SIMULATION RESULTS

Table 3 lists several key response characteristics for both the VTT Flexural and Punching tests. In general, both models were able to match the test measured response parameters reasonably well.

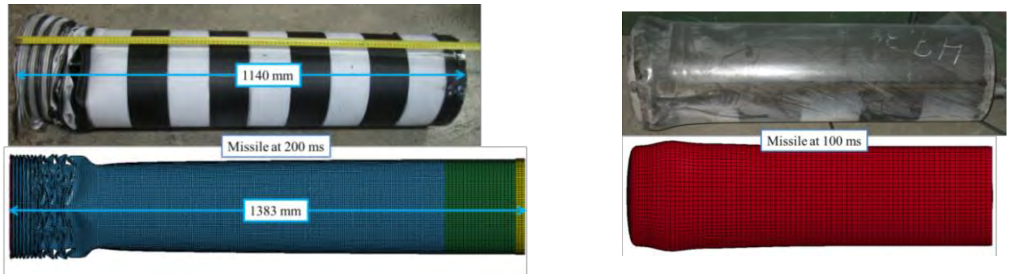
VTT Flexural Test

The flexural test model accurately predicted rebound of the missile without failure of the target (Figure 5). The model under predicted the shock duration and peak force, and over predicted the total impulse at the target supports, the peak target displacement, and missile length post-test (Table 3 and Figure 4a). It is worth noting that the values calculated for both the peak force and total impulse at the target supports can be significantly dependent on sampling rate and the data processing employed. The over prediction of target displacement and under predictions of shock duration and missile crush-up are consistent with a missile that is somewhat too strong. It is suspected that the strain rate strength enhancement parameters used for the missile steel may result in a missile material that is overly strain rate sensitive.

Figure 6a and b shows the measured and predicted target displacements at several target locations. The model relatively accurately matches both the peak and frequency of the target response; however, the vibrations induced in the target tend to damp out too quickly. This is very likely attributable to the behavior of the concrete constitutive model and its handling of material degradation under loading. In addition, the permanent displacement of the target at its center is over predicted by the model; however, the model error is only a small percentage of the overall span length of the target (~0.25%). The model predictions for target steel reinforcement strains (Figure 6c and d) are in relatively good agreement with the measured values except at the center of the target where the strains are only about one-third

Table 3. VTT Flexural and Punching Test/Model Key Response Characteristics.

Attribute	VTT Flexural			VTT Punching		
	Model	Test	Error	Model	Test	Error
Target Failure Type	None	None	---	Perforation	Perforation	---
Shock Duration (ms)	16.0	18.0	-11%	17.5	13	+34%
Peak Force (kN)	553	862	-35%	1150	1095	+5%
Total Impulse at Supports (kN.s)	5.8	5.0	+16%	2.5	2.8	-11%
Missile Post-Impact Length (mm)	1383	1140	+21%	---	---	---
Missile Residual Velocity (m/s)	---	---	---	38.9	33.8	+15%
Peak Target Displacement (mm)	32.2	28.9	+11%	8.5	5.2	+63%



(a) Flexural Test Missile

(b) Punching Test Missile

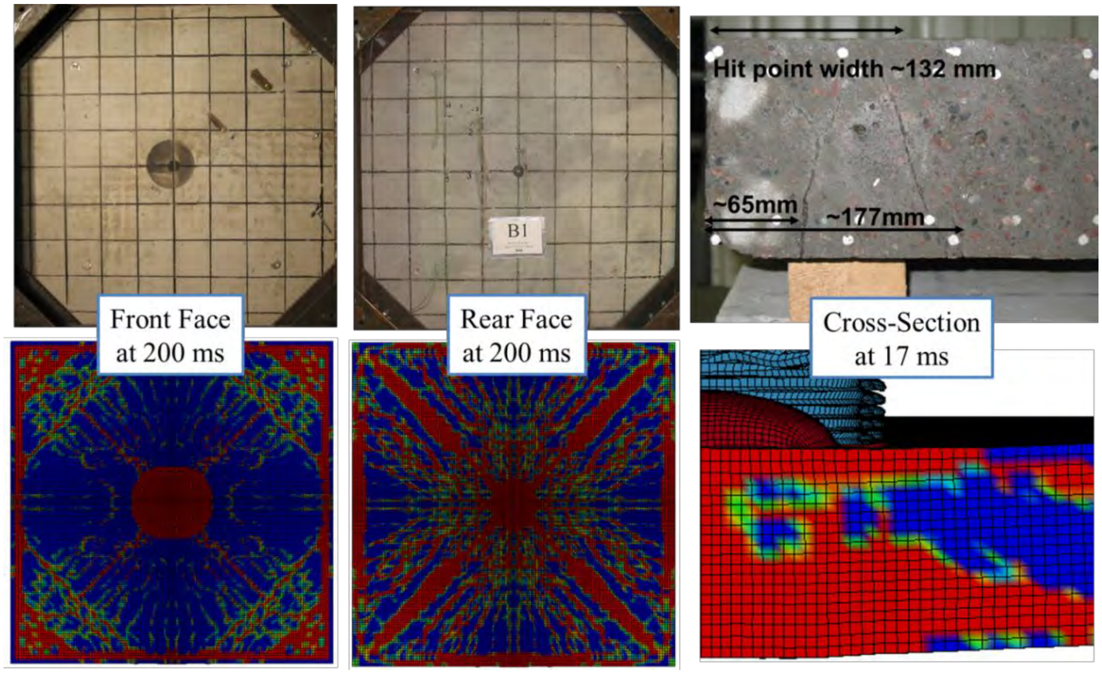
Figure 4. VTT Flexural and Punching Test/Model Missile Deformation.

of those measured in the test. As mentioned earlier, the model does a poor job of capturing the strain localization that occurs at crack interfaces in the real target. Instead, the model smears the strain that would normally occur locally at a crack over the entire length of a reinforcing steel element (see Table 1).

VTT Punching Test

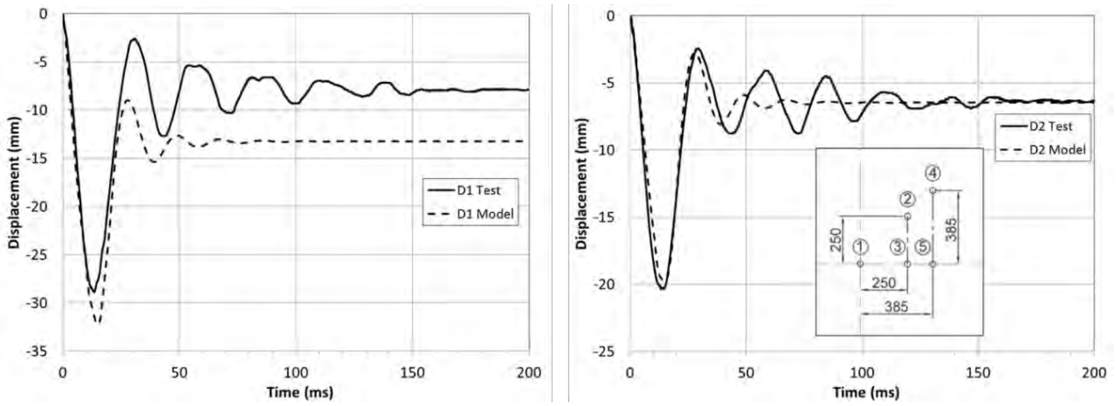
The punching test model accurately predicted perforation of the target by the missile (Figure 7). The model slightly under predicted the impulse at the target supports, and over predicted the shock duration, peak force, peak target displacement, and residual missile velocity (Table 3). Again, both the peak force and total impulse at the target supports can be significantly dependent on the sampling rate and data processing techniques employed. Comparison of the failure cone produced within the model with that observed in the test (Figure 7b and c) indicates that the model relatively accurately reproduces the failure observed in the test. The over predictions of target displacement, impulse at the target supports, and missile residual velocity appear to be consistent with a target punching failure that is somewhat too protracted or that requires too much force to initiate, and a failure mechanism that does not consume enough energy. This is undoubtedly largely dependent on the response and failure characteristics of the target concrete material model; however, some of the discrepancies may be attributable to other factors (e.g., the neglect of friction forces). It is also worth noting that the model does not include a detailed representation of the supporting frame, which may play a part in the test observed response.

Figure 8a and b show measured and predicted target displacements at several target locations. The model does not match the peak displacement precisely or capture the oscillatory response observed in the test target following missile perforation. This is likely attributable to how the concrete constitutive model handles material degradation and failure; however, it also plausible that exclusion of the target support structure form the model removes a potential feedback mechanism that could drive this oscillatory response. In addition, the permanent displacement of the target at every displacement measurement location is over predicted by the model, indicating too much energy is transferred to the target or that the damage imparted by a given amount of energy is somehow over estimated. The model predictions for the

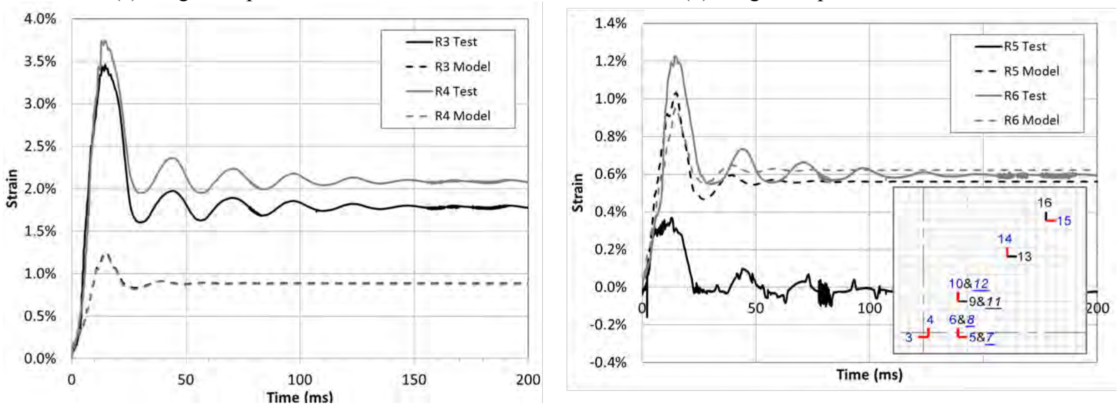


(a) Front Face of Target (b) Rear Face of Target (c) Cross-Section of Target

Figure 5. VTT Flexural Test/Model Target Response.

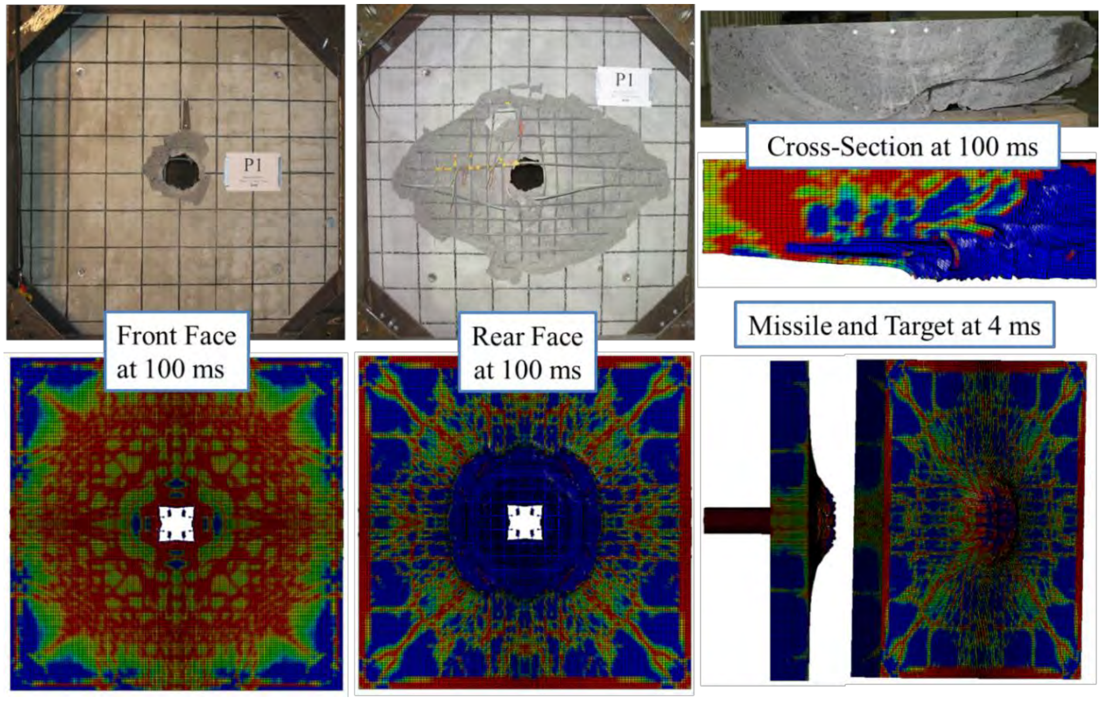


(a) Target Displacement – Location 1 (b) Target Displacement – Location 2



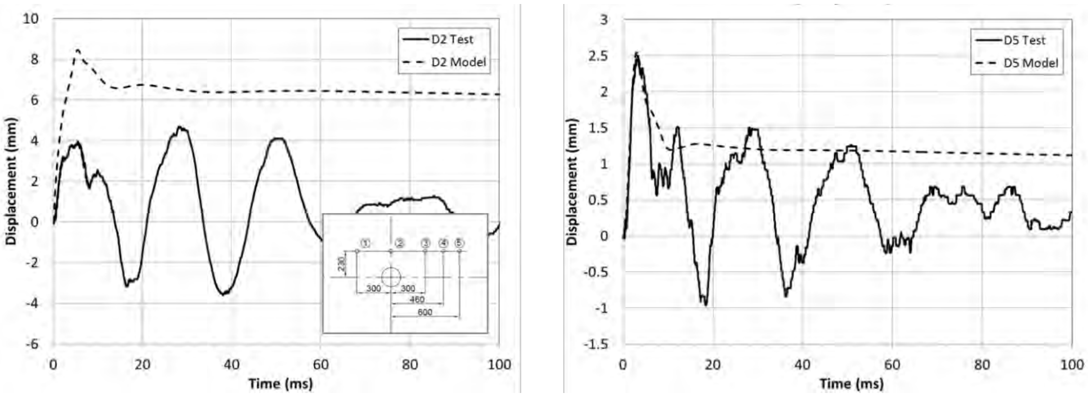
(c) Target Steel Reinforcing Strains – Locations 3, 4 (d) Target Steel Reinforcing Strains – Locations 5, 6

Figure 6. VTT Flexural Test/Model Target Displacements and Reinforcing Steel Strains.

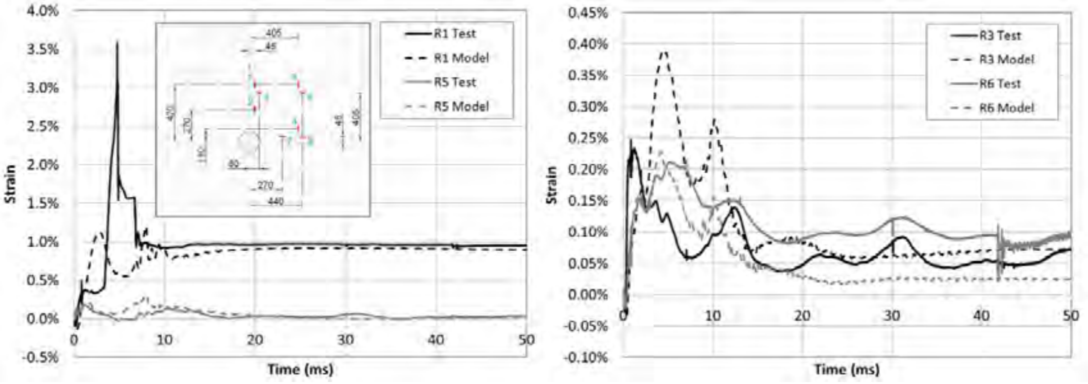


(a) Target Front Face (b) Target Back Face (c) Target Cross-Section and Full View

Figure 7. VTT Punching Test/Model Target Response.



(a) Target Displacement – Location 2 (b) Target Displacement – Location 5



(c) Target Steel Reinforcing Strains – Location 1, 5 (d) Target Steel Reinforcing Strains – Locations 3, 6

Figure 8. VTT Punching Test/Model Target Displacements and Reinforcing Steel Strains.

target steel reinforcement strains (Figure 8c and d) are in relatively good agreement with the measured values except in a few instances where significant strain levels are obtained and the model strains are only about one-third of those measured in the test. Again, this may be attributed to the model's inability to accurately capture strain localization at crack interfaces.

CONCLUSIONS

As part of its participation in the second phase of the IRIS round robin exercise, Sandia National Laboratories, for the United States (US) Nuclear Regulatory Commission (NRC), constructed two finite element models used to simulate (with the commercially available code LS-DYNA) two separate tests involving the impact of either a soft (flexural test) or a hard (punching test) missile into a steel reinforced concrete panel target. Results from these analyses have been presented here and a comparison made between the model response and test observed behavior. In general, the numerical models were able to match the test observed behavior with reasonable accuracy. Simulation predictions more closely matched test results for the flexural test model in which only modest damage was imparted to the target, but good agreement was also observed for the punching test model in which the missile perforated the target. In many instances, detailed response parameters were not precisely reproduced by either model. For example, target displacements or reinforcing steel strains were not exactly recreated in every instance, but the general behavior of each test, namely whether the missile caused failure of the target, was correctly predicted. From this work it would appear that the largest challenges facing the analyst in the simulation of such events remains twofold: (1) the unavailability of sufficient test data to fully characterize the response of materials for the environments involved (i.e., test data covering the full extent of strains, strain rates, and pressures of interest), and (2) the limitations of current methodologies for accurately modeling material degradation and failure within numerical frameworks. Despite these challenges, numerical methods are capable of producing results reasonable enough to make accurate and useful predictions in extreme situations involving missile impacts into steel reinforced concrete structures.

REFERENCES

ACI (2003). *Guide for Structural Lightweight-Aggregate Concrete*, Report ACI 213R-03, American Concrete Institute, Farmington Hills, MI.

Adeli, H., Amin, A., (1985). Local effects of impactors on concrete structures. *Nuclear Engineering and Design*, 88, 301-317.

Bangashi, Y., (1982). "Containment vessel design and practice," *Progress in Nuclear Energy*, 11, 107-181.

Bignon, P., Riera, J., (1980). "Verification of methods of analysis for soft missile impact problems," *Nuclear Engineering and Design*, 60, 311-326.

Guirgis, S., Guirguis, E., (2009). "An energy approach study of the penetration of concrete by rigid missiles," *Nuclear Engineering and Design*, 239, 819-829.

Kennedy, R., (1975). "A Review of Procedures for the analysis and design of concrete structures to resist missile impact effects," *Nuclear Engineering and Design*, 37, 183-203.

LS-DYNA (Version mpp971d Dev, Revision: 6922) [Software], (2011). Livermore, California: Livermore Software Technology Corporation, Livermore, CA.

LSTC (2010). *LS-DYNA Keyword User's Manual Volume 1 and Volume 2*, Version 971 / Rev. 5 (Beta). Livermore Software Technology Corporation, Livermore, CA.

Nordbert, Hans., (2004). *Note on the Sensitivity of Stainless Steels to Strain Rate*, Research Report No. 04.0-1, Sheffield Hallam University, AvestaPolarit Research Foundation.

Peixinho, N., and A. Pinho, (2007). "Study of viscoplasticity models for the impact behavior of high-strength steels," *Journal of Computational Nonlinear Dynamics*, 2, 114-123.

Riera, J., (1979). "A Critical Reappraisal of nuclear power plant safety against accidental aircraft impact," *Nuclear Engineering and Design*, 57, 193-206.