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NUMERICAL SIMULATION OF ROUND ROBIN EXERCISE IRIS-2012 FOR BENDING AND PUNCHING TEST

Sourav Acharya[1], Debashis Mukherjee[2], Ajai Pisharady[1], and L. R. Bishnoi[3]

[1]Scientific Officer, Siting & Structural Engineering Division, Atomic Energy Regulatory Board (AERB), Mumbai, India (sacharya@aerb.gov.in) (sourav_acharya@yahoo.co.uk)
[2]Manager, L&T Construction, Mumbai, India
[3]Head, Siting & Structural Engineering Division, Atomic Energy Regulatory Board (AERB), Mumbai, India

ABSTRACT

Protection of important reinforced concrete structures like nuclear structures against missile impact either environmentally generated or as a terrorist activity, is one of the topics of discussion in recent days, specifically after the incident of 9/11 in USA. Development of computational capability for assessment of structural integrity against missile impact is under progress around the globe and needs strong cutting edge technological competency as the simulation is highly complex in nature. IRIS-2012 is a round robin exercise to simulate or predict the response of missile and target numerically based on small scale experiments. This includes modeling and nonlinear analysis of a concrete slab, and simulation of missile impact and response of the structure. An attempt has been made in this paper to simulate the flexure test (impact by a soft/deformable missile) and punching test (impact by a hard/rigid missile) on a reinforced concrete slab. ABAQUS/Explicit Code is used for simulation. The analysis is technologically challenging and all the behavioral aspects of the problem cannot be simulated directly because of software limitations. To simulate impact of soft missile, multiple stress-strain property based on different strain rates was successfully introduced and a methodology was developed based on impact mechanics and wave propagation in solid media to simulate local responses of target due to impact of hard missile, such as spalling, scabbing, penetration and perforation.

INTRODUCTION

A round robin exercise (RRE) on ‘Improving the Robustness assessments methodologies for structures Impacted by missileS (IRIS-2012)’ was instituted jointly by IRSN, France and CNSC, Canada based on experiments conducted by VTT, Finland. Outcome of the RRE (1st phase) completed in 2010 was not encouraging. The IRIS-2010 exercise was on blind simulation of impact tests. The RRE (2nd phase) was floated again in the year 2012 to improve the simulation results so as to be close to the experiments. A team from AERB, India also participated in IRIS-2012 (2nd phase) for the first time. The experiments comprised of bending and punching test of reinforced concrete (RCC) slab with soft and hard/rigid missiles respectively. The scope of the exercise was post-test simulation of flexure as well as punching test using experimental data. The main objective of this exercise is to improve capability regarding damage assessment of NPP structure by commercial airplanes crashes. As this type of analysis is extremely complex in nature, experiments as well as simulations had been done using simple structures like RCC slab as target and steel cylinders as missiles, hard/soft.

SIMULATION OF BENDING TEST

Finite Element Model

The target was a 2.1m x 2.1m x 0.25m reinforced concrete slab with transverse/shear reinforcements. The target slab was modeled using solid elements, where as individual reinforcing steel including shear links were modeled using truss elements as shown in Figure 1(a), (b). The missile was modeled as shell. Figure 2(a) and (b) show a view of the missile and its assembly with the target before impact. Number of elements across slab thickness plays an important role in capturing the strain rate occurring in the model. Mesh-sensitivity study was conducted and 15 mm was taken as the mesh size so as to provide 10 elements across the slab. Similar element size was adopted for meshing the missile and reinforcing steel. Hourglass control and adaptive meshing option were utilized for numerical stability of the solution procedure.

(a) (b)

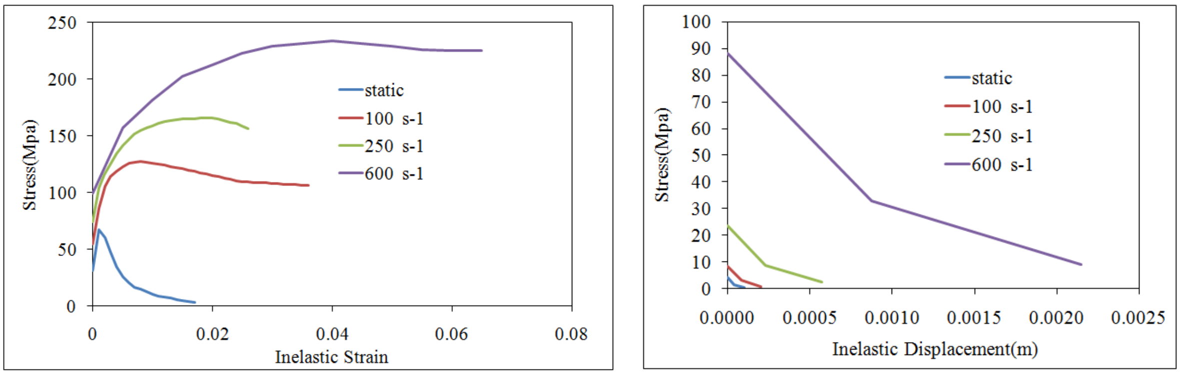
Figure 1.(a) Geometric model of RC Slab and (b) Reinforcement

(a) (b)

Figure 2. (a) Geometric model of soft missile and (b) assembly before impact

Material Model: Concrete

Nonlinear behaviour of concrete was modelled using the concrete damage plasticity (CDP) model available in ABAQUS/Explicit. A strain rate sensitive elasto-viscoplastic material model was employed. Stress-strain data in compression for different confinement pressures were provided by organiser of IRIS-2012. CEB (Comité Euro-International du Béton) recommends dynamic increase factors (DIF formulas) for concrete in both tension and compression, Malvar et al. (1998). These relations are used to convert the given confining pressures to equivalent strain rates, Figure 3(a). IRIS-2012 organisers also supplied cracking stress value for concrete in tension, without details of softening curve or fracture energy value (G_f). Bi-linear stress-displacement curve, proposed by Gylltoft and as reported by Leppanen (2002) was used for this purpose, which is based on stress-crack opening relationship. Fracture energy (G_f) is considered as 110 N/m assuming 20 mm as maximum aggregate size, JSCE (2008). The stress-strain curve for static case in tension is derived based on these data. The stress-strain curve of concrete in tension for different strain rates are derived from the static curve, as derived above, using formulation given by Malvar, et al. (1998). Figure 3 (b) shows the derived stress-displacement curve of CDP in tension for multiple strain rates.

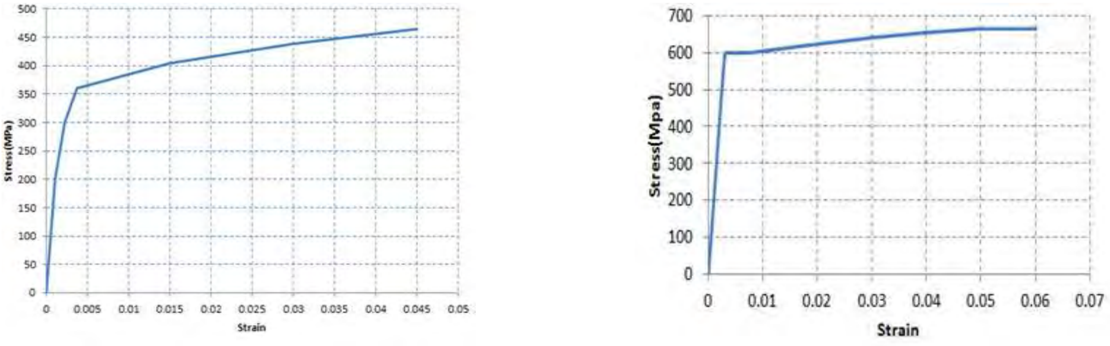


(a) (b)

Figure 3. Constitutive relationship of concrete at various strain rates (a) in compression and (b) in tension

Material Model: Steel

Both reinforcing and carbon steel (missile) were modeled using elastic-plastic stress-strain relations, Martin, O. et al. (2011), Figure 4. Strain rate effects were taken into account in reinforcement steel material model by specifying yield stress ratios, a factor, by which the yield strength of material increases with given strain rate; 1.43, 1.46 and 1.49 for 100, 250 and 600 s^{-1} strain rates respectively.



(a) (b)

Figure 4. Constitutive relationship of steel used in (a) missile and (b) reinforcing bars

Numerical Analysis

Literature on impact of soft missile reveals that supporting frame is sufficiently rigid to prevent large rigid body displacement of the test slab and may be neglected in modeling, Saarenheimo et al. (2011). Out of plane restraint was applied on both front and rear faces along all four edges at 50 mm inside the slab edge to simulate simple support condition. Initial position of the missile was a point contact with the target plate at center and velocity of 110 m/s was applied as a predefined field for simulation. The analysis was conducted using ABAQUS/Explicit technique for a duration of 100ms and output was extracted at 0.25ms interval. The stable time increment, observed throughout the analysis, was of the order of 1.12E-6 s or 1.12μs.

SIMULATION OF PUNCHING TEST

Finite Element Model

The target was a 2.1m x 2.1m x 0.25m reinforced concrete slab without transverse/shear reinforcements. The target slab was modeled with solid elements, where as individual reinforcing steel was modeled using truss elements, Figure 5(a), (b). In case of rigid missile, the outer shell layer (made of steel) as well as filled light weight concrete was modeled using solid elements. Figure 6(a), (b) show the sectional view of outer steel layer 6(a) and light weight concrete 6(b) respectively. An aluminum pipe, which was attached as tail of the missile to trace the missile residual velocities in the experiment, was not modeled in simulation for simplicity.


(a) (b)

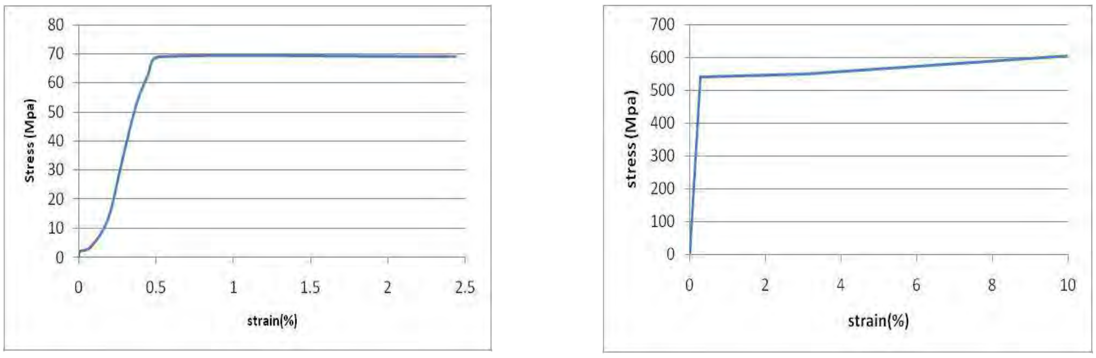
Figure 5. Geometric model of target, (a) concrete and (b) reinforcements


(a) (b)

Figure 6. Sectional view of missile (a) outer shell and (b) filled with light weight concrete

Material Model: Concrete

Concrete models available in ABAQUS/Explicit are concrete damage plasticity model (CDP), smeared crack model and brittle crack model. However, except brittle crack model, other constitutive models of concrete do not have the capability to simulate ‘element erosion’, ABAQUS-6.10(2010). In case of brittle model, the compressive behavior is always assumed to be elastic. Modeling of ‘element erosion’ is necessary for simulating penetration, perforation, spalling and scabbing of target in case of punching test. So, elastic-plastic constitutive relation (compression as well as tension) was used for concrete material of the target. Two different failure criteria, such as ‘shear failure strain’ and ‘tensile failure hydrostatic stress (cut-off stress)’ are incorporated in that model to simulate ‘element erosion’ of the target. The reinforcement steel is modeled as elastic-plastic material as per given data with ‘shear failure strain’ criteria. Figure 7 shows the constitutive relationship of concrete slab 7(a) and its reinforcements 7(b).

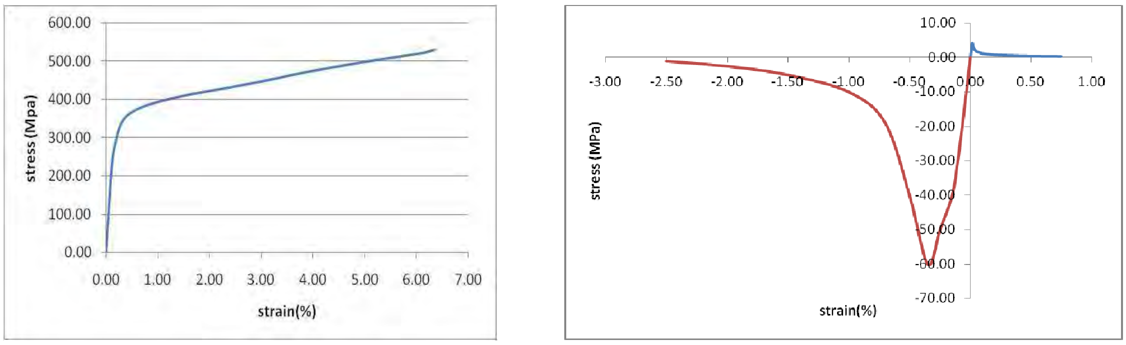


(a) (b)

Figure 7. Constitutive relationship of (a) target concrete slab and (b) reinforcing steel

Material Model: Missile

Outer steel layer of the missile is modeled as elastic-plastic material without any ‘element erosion’ criteria and the filler concrete is modeled using CDP material with low density (1520 Kg/m^3). Figure 8 shows the constitutive relationship of outer steel layer 8(a) and light weight concrete fill 8(b) of rigid missile.



(a) (b)

Figure 8. Constitutive relationship of missile (a) outer shell and (b) low density concrete fill

Numerical Analysis

The target slab is 'partitioned' based on its failure criteria due to missile impact. Based on literature on impact mechanics, Polanco-Loria et al. (2008), Tuomala et al. (2011) and Walley et al. (2005), it is understood that thickness near to impact zone of target undergoes inertial compaction, whereas at other side or back side of target experiences tensile stress and creates scabbing. The compressive shock wave returns/reflects from back faces and converts into tensile shock wave and creates spalling at front face. So, it is assumed that 1/4th thickness of the target slab near impact zone fails in shear (simulate penetration) and remaining areas of target fail in hydrostatic tensile stress (simulate perforation) or cut-off stress. The 'shear failure' zone is cylindrical with diameter nearly equal to missile diameter and the length is equal to 1/4th thickness of the slab. The concrete at boundary zone (50 mm from edge) is assumed to be elastic without any failure to ascertain numerical stability of the analysis preventing 'element erosion' at support locations.

The 'shear failure' of reinforcement steel is assumed at uniaxial strain of 18% (uniaxial failure strain of this steel is 20% as per supplied test data). The uniaxial tensile stress of target concrete is 4 MPa, where as supplied experimental data shows an enhancement of this tensile stress nearly to 20 MPa under high 'strain rate' of 200 s^{-1}. Thus, cut-off stress of concrete target is considered as 20 MPa. Simulations are done considering various values of 'shear failure' of concrete of target slab. A 'shear failure' strain value of 18% produces a good match of trail velocity with experiments and other responses of target and missile.

The supporting frame is not modeled. The target is simply supported at four sides of front as well as back faces, 50 mm inside the edges. The target is also simply supported at bottom, mid thickness line. The movement of missile is allowed only in perpendicular direction of target surface, thus restrained from any rigid body rotation during penetration/perforation. The missile is placed just in contact with target before analysis to simulate the analysis immediately at the impact. The missile velocity of 135 m/s is applied in 'predefined field' of initial step. ABAQUS/Explicit Code is used with automatic time steps, where 'stable time increment' is 1.4 μs (microsecond). The analysis is simulated for 100ms (millisecond). The responses of missile and target are extracted at an interval of 25 ms and 100 ms respectively.

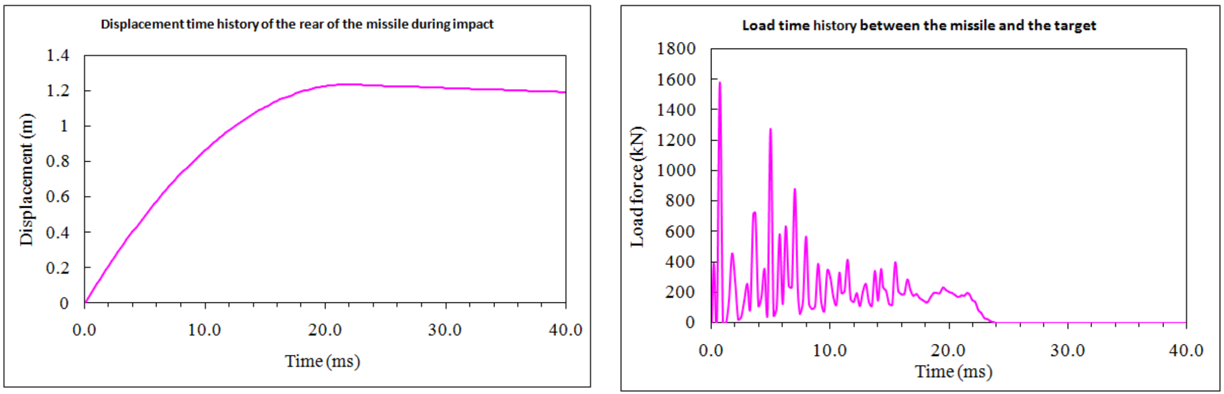
RESULTS

Bending Tests

The soft/deformable missile reduced to a length of 1.03m from its original length of 2.05m, i.e. almost half of its length, after the impact, Figure 9. The undamaged length of missile is 0.915m. The impact completed within 22 ms. Thereafter the missile lost its contact with the slab/target and bounced back after the impact. The load time history or contact force between missile and target also confirms the response, Figure 10(b). The displacement time history at the rear end of the slab (at centre of the slab) and reaction force time history generated at support are shown in Figure 11 (a) & (b) respectively. It is seen that the maximum displacement, 30mm, at the center of the slab closely matched with the experimental values, but the simulation failed to predict recovery after the impact. The simulated slab behaves stiffer than expected. The total impulse generated in the impact was estimated to be 5.52kN-s. The above observations were found to be in good agreement with the studies conducted by other researchers using Riera method, Saarenheimo A. (2011). Figure 12 shows the plastic equivalent strains in the concrete after the impact. The plastic equivalent strains indicate the plastic zones in concrete slab created due to impact. The shear cone angle was formed by the plastic zone and approximate angle was 36°. Almost no plastic strain was developed at back face of the slab. CDP model does not simulate any 'element erosion' criteria, so crater due to spalling or scabbing could not be simulated.

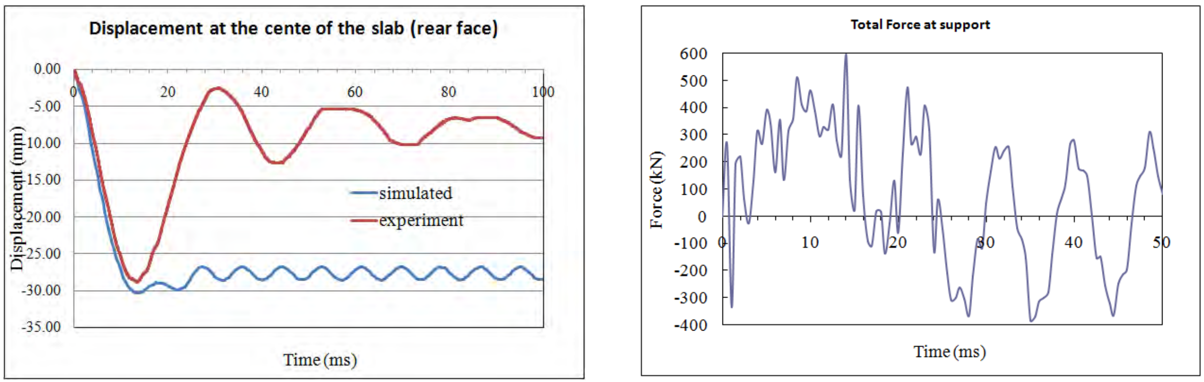
(a) (b)

Figure 9. (a) Deformation of missile just after the impact and (b) longitudinal section of deformed missile



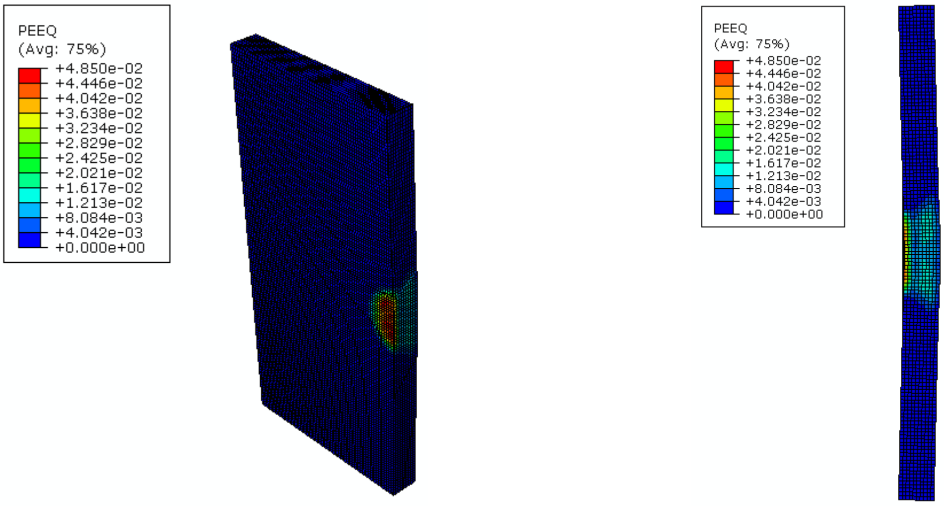
(a) (b)

Figure 10.(a) Displacement time history of the missile and (b) Load time history between missile and target



(a) (b)

Figure 11.(a) Displacement and (b) force time history of the target

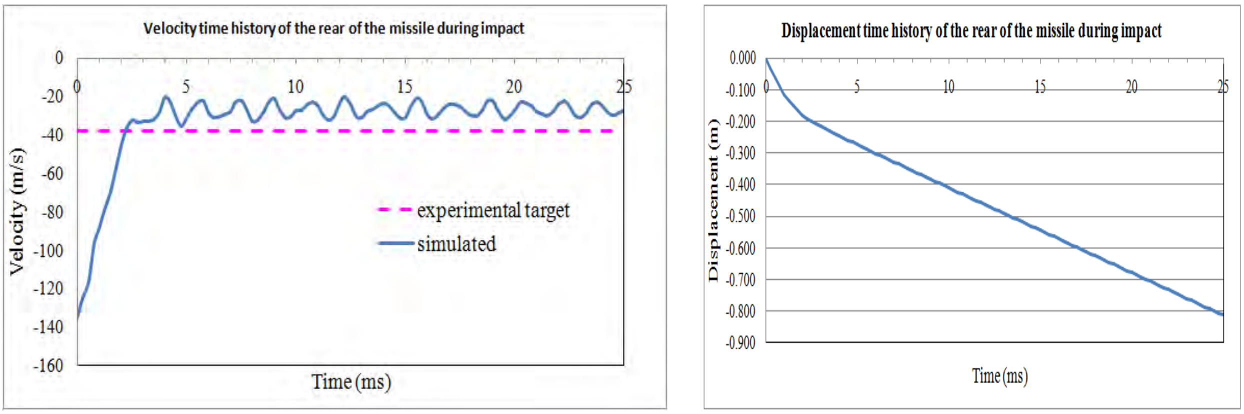


(a) (b)

Figure 12. Plastic equivalent strains in the slab after the impact (a) front face and (b) across the thickness.

Punching Test

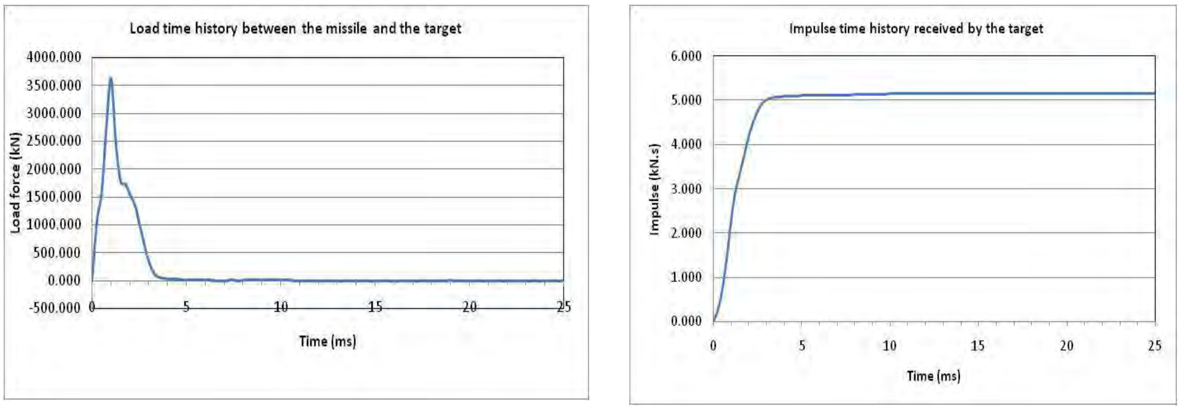
The trail velocity of the missile is found to be 33.4 m/s. The trail velocity of the missile is measured at the time, when the missile has just perforated the target fully (estimated as 2.75 ms). Figure 13 shows the missile velocity 13(a) and displacement 13(b) time histories. The experimentally measured trail velocity of missile was 38.3m/s, which is close to the simulated value.



(a) (b)

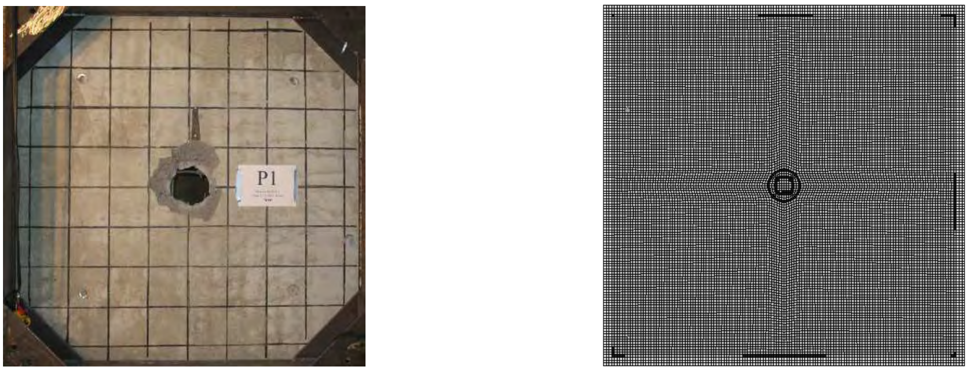
Figure 13. Time histories of missile (a) velocity and (b) displacement

The total impact duration is found to be nearly 5.0 ms after that no contact force is observed. Figure 14 shows the load time history between missile and target 14(a) and impulse time history received by the target 14(b). Figure 15 shows the comparative study of spalling of target in experiment 15(a) and simulation 15(b). Figure 16 shows the comparative study of scabbing of target in experiment 16(a) and simulation 16(b). The model could also simulate the shear cone failure through the thickness of the slab.



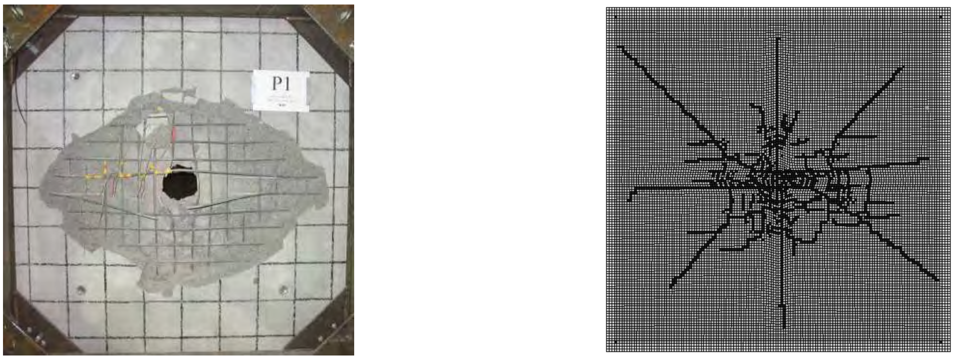
(a) (b)

Figure 14. (a) Load time history between missile and target and (b) impulse time history of the slab



(a) (b)

Figure 15. Spalling of target at front face; (a) experiment and (b) simulation (black areas are eroded elements)



(a) (b)

Figure 16. Scabbing of target at back face; (a) experiment and (b) simulation

CONCLUSIONS

The following conclusions can be drawn from the simulations:

- Concrete Damage Plasticity model, available in ABAQUS/Explicit, can simulate the flexure test considering multiple stress-strain properties for various strain rates.
- The maximum value of compressive strain in the front end of the slab and the peak value of support reactions for flexure test were in good agreement with the results observed experimentally.
- The free-vibration behavior of the slab, post impact, could not be captured properly resulting in lower recovery of slab displacement.
- The scabbing and spalling behavior during impact of soft missile could not be simulated using CDP model available in ABAQUS/Explicit.
- Zoning of target based on stress wave propagation could simulate local damage responses such as spalling, scabbing during simulation of punching test.
- Penetrations as well as perforation of hard missile during punching test are highly dependent on ‘element erosion’ criteria of different materials given as input to ABAQUS/Explicit.

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