Simulating Tornado Missile Impact on RC Structures

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Natural Phenomena Hazards

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CNEFS

Motivation

- USNRC issued a regulatory issue summary (RIS) "2015-06 Tornado Missile Protection"

- It requested for reevaluation of plant's current, site-specific licensing basis for tornado-generated missile protection

- Limited accuracy from empirical formulas

- Unstable and highly sensitive Finite Element studies
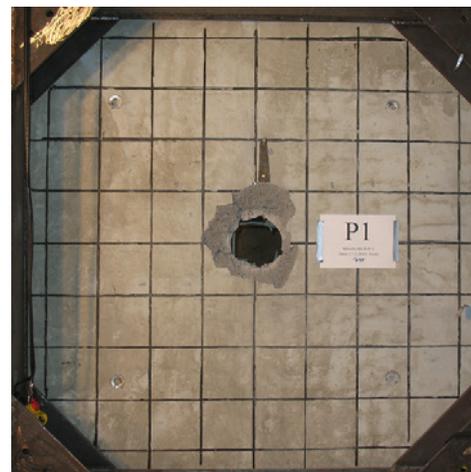
IRIS Impact Experiment

- **I**mproving **R**obustness assessment of structures **I**mpacted by missile**S** (IRIS) test conducted by VTT Technical Research Centre of Finland in 2010

- 28 and 29 teams participated in 2010 and 2012 to simulate this test
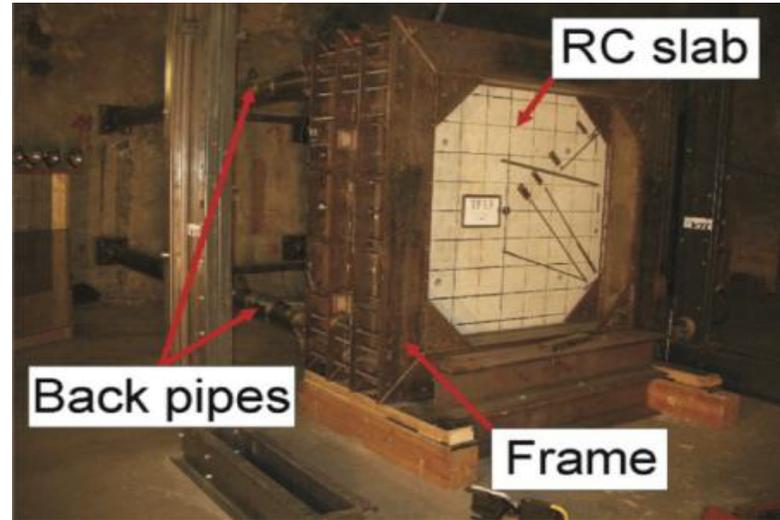
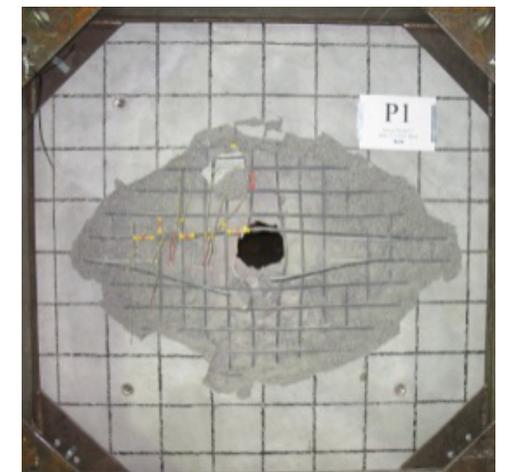
Test setup

Missile

Impacting face after Impact

Back face after Impact

Experimental Results

Test no.	Residual missile velocity [m/s]	Broken rebars Horizontal and Vertical	Mass of ejected concrete [kg]
IRIS P1	33.8	Front: 2H 2V Back : 1H 1V	30 – 60 kg
IRIS P2	45.8	Front: 2H 2V Back : 1H 2V	116 kg
IRIS P3	35.8	Front: 2H 2V Back : 2H 1V	121 kg

Simulation results from participants:

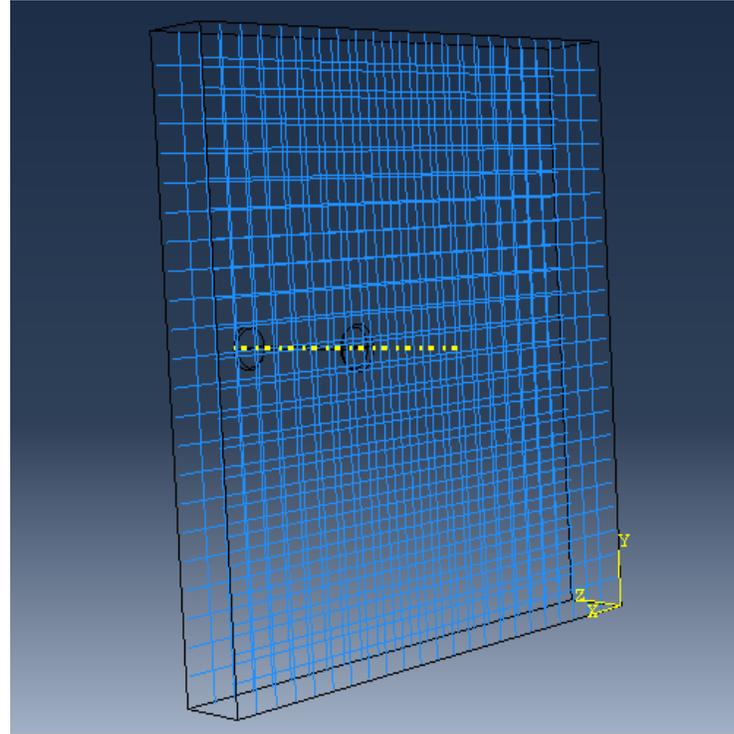| Result summary	Number of Participants	MEAN	C.O.V.	MIN	MAX
IRIS 2010 Residual Missile Velocity (m/s)	28	13	2.74	-41.8	92.5
IRIS 2012 Residual Missile Velocity (m/s)	29	32.2	0.53	-5.6	54

(8 teams out of 29 in IRIS 2012 were within ±40% error)
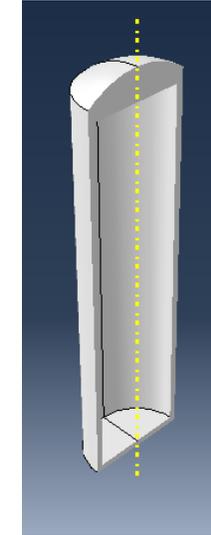
ABAQUS Model for Slab and Missile
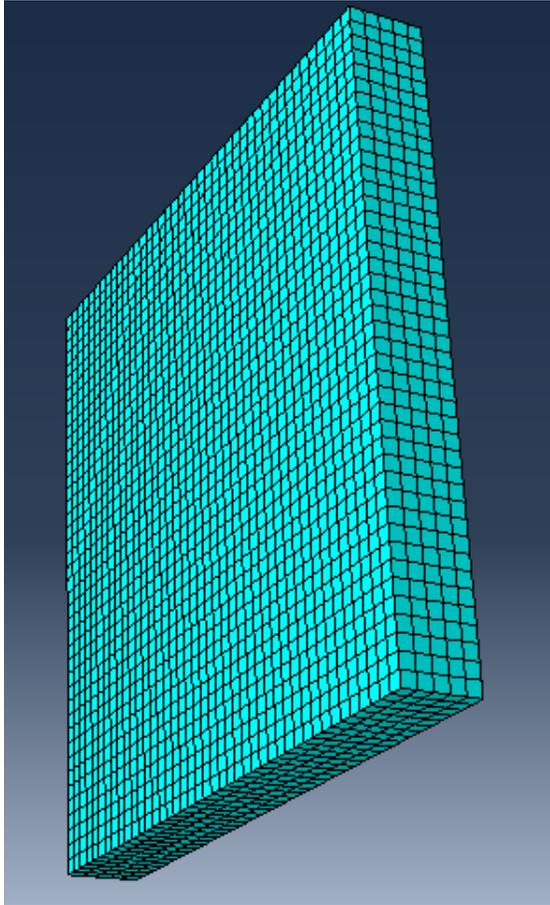
Concrete Slab
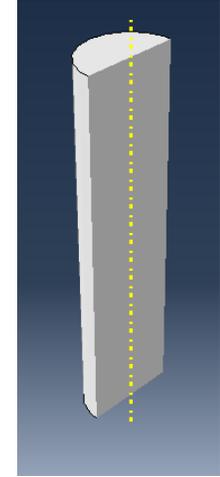C3D8R: An 8-node linear brick
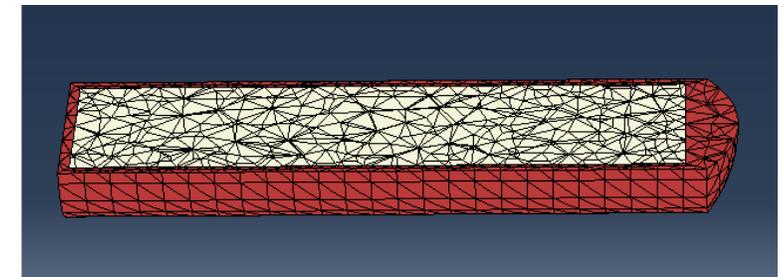50mm element

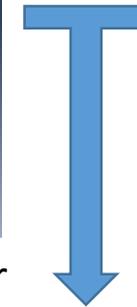2 Set of Vertical and Horizontal
Reinforcement
C3D8R: An 8-node linear brick
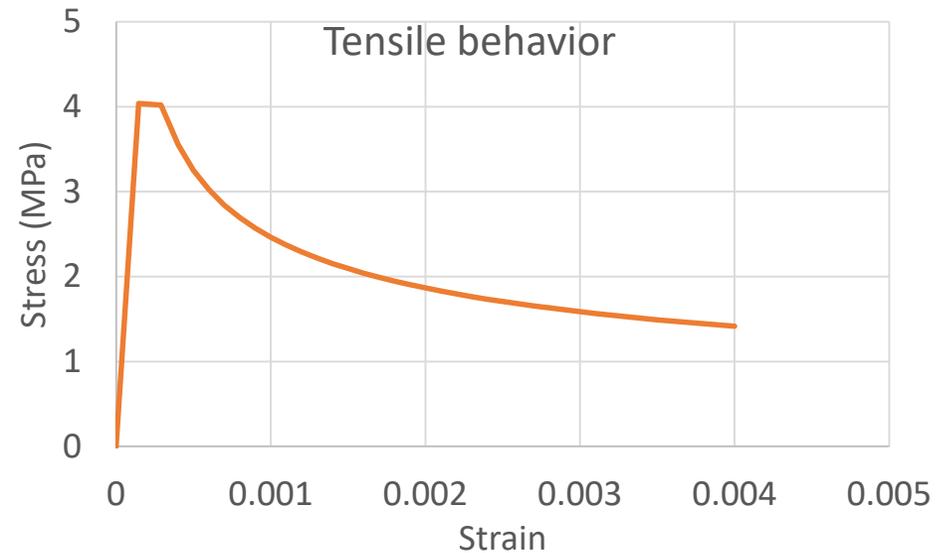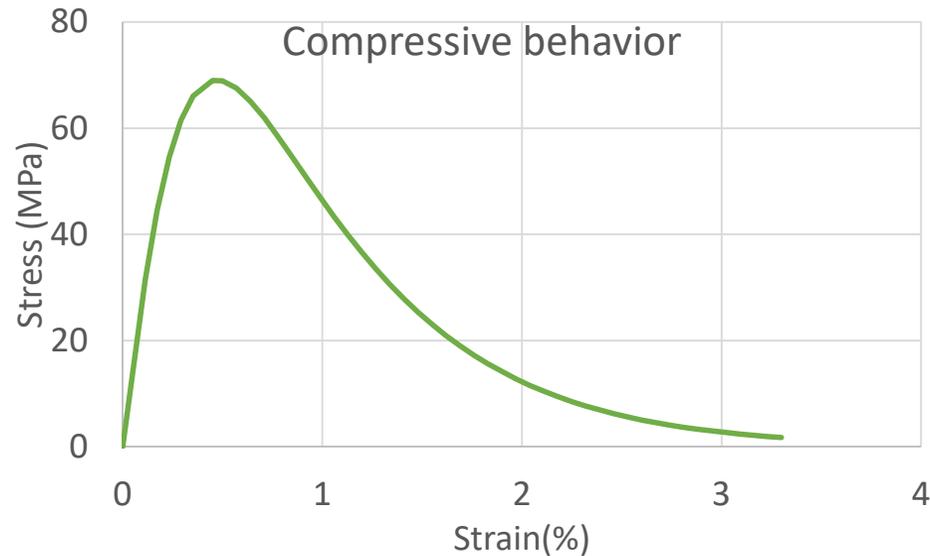25mm element

Steel cover

Concrete

Assembled missile
C3D10M: A 10-node modified quadratic tetrahedron
25mm element for both Concrete and Steel

Concrete Damage Plasticity (CDP) model

Stress-strain curve for concrete used to define CDP model

Compressive behavior

Tensile behavior

Closed form equations :

$$\sigma_c = 2\frac{f_c'}{\varepsilon_{\max,\text{peak}}} K_0 \left(\varepsilon - \varepsilon_p\right)$$

$$K_0 = \exp\left\{\frac{-0.73\varepsilon}{\varepsilon_{\max,\text{peak}}}\left(1 - \exp\left(\frac{-1.25\varepsilon}{\varepsilon_{\max,\text{peak}}}\right)\right)\right\}$$

$$\varepsilon_p = \varepsilon_{\max,\text{peak}}\left(\frac{\varepsilon}{\varepsilon_{\max,\text{peak}}} - \frac{20}{7}\left(1 - \exp\left(\frac{-0.35\varepsilon}{\varepsilon_{\max,\text{peak}}}\right)\right)\right)$$

$$\sigma_i = \begin{cases} f_t & \varepsilon_{cr} \leq \varepsilon_i \leq 2\varepsilon_{cr} \\ \left(2\varepsilon_{cr}\big/\varepsilon_i\right)^{0.4} \times f_t & \varepsilon_i > 2\varepsilon_{cr} \end{cases}$$

From Syed (2012)

CDP Parameters

- From Rodríguez et al., 2013
  - Eccentricity = 0.1
  - f_{bo}/f_{co} =1.15
  - Viscosity Parameter = 0
- Based on tri-axial test validation
  - K = 0.64
- Based on parametric study
 - Dilation angel = 46^0

Where,

- **Dilation angle** = Controls amount of plastic volumetric strain developed during plastic shearing

- **Eccentricity** = A number where hyperbolic flow potential approaches its asymptote (default 0.1)

- f_{bo}/f_{co} = Ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (default 1.16)

- K = Ratio of the second stress invariant on the tensile meridian to that on compressive meridian (between 0.5 and 1)

- **Viscosity Parameter** = Zero for concrete

# Tri-axial test validation for CDP parameters
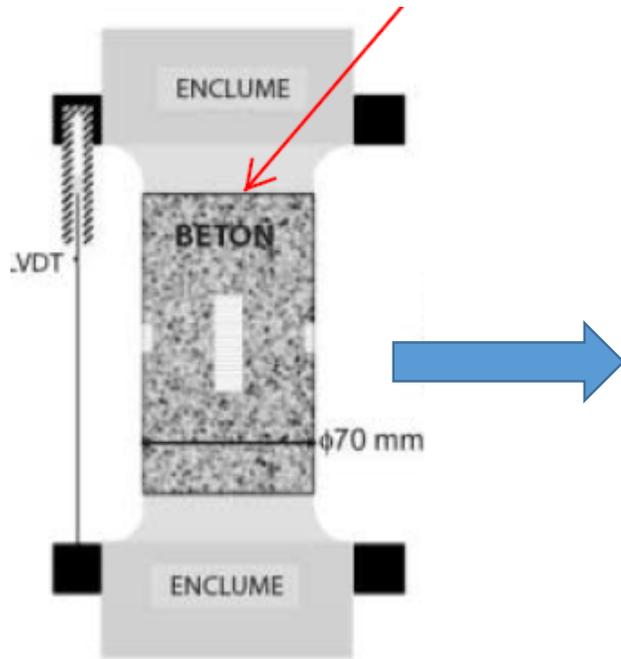
Test Cylinder
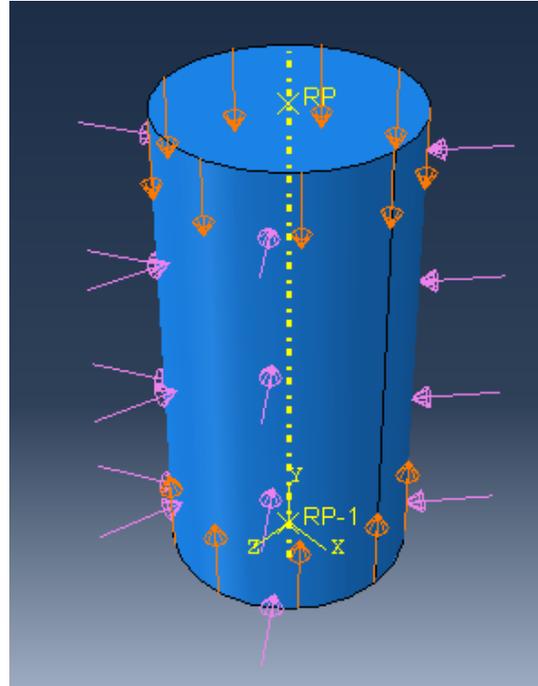
ABAQUS model

- IRIS has provided tri-axial tests result with confinement pressures of 100, 47, 26, 15.5 MPa

- Replicated tri-axial test in ABAQUS

- Stress-strain curves with different confinement pressure found to be changing with CDP parameter K

Where, K is Ratio of the second stress invariant on the tensile meridian to that on compressive meridian

Generating value of CDP parameter *K*

- *K* is selected based on comparison of experimental and analytical stress-strain curve for each confinement pressure
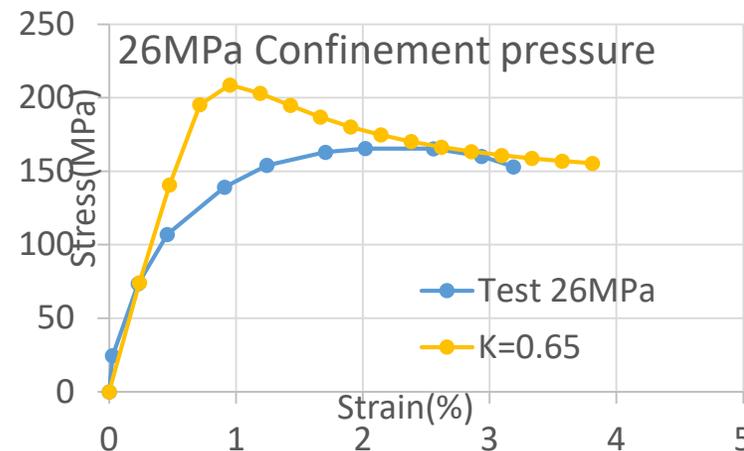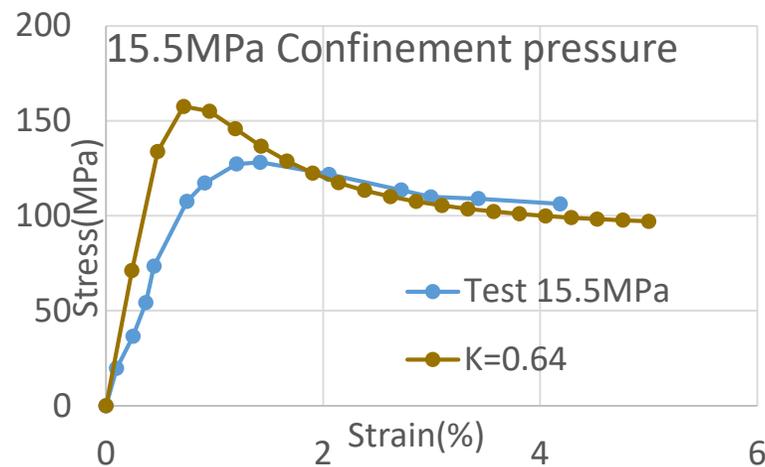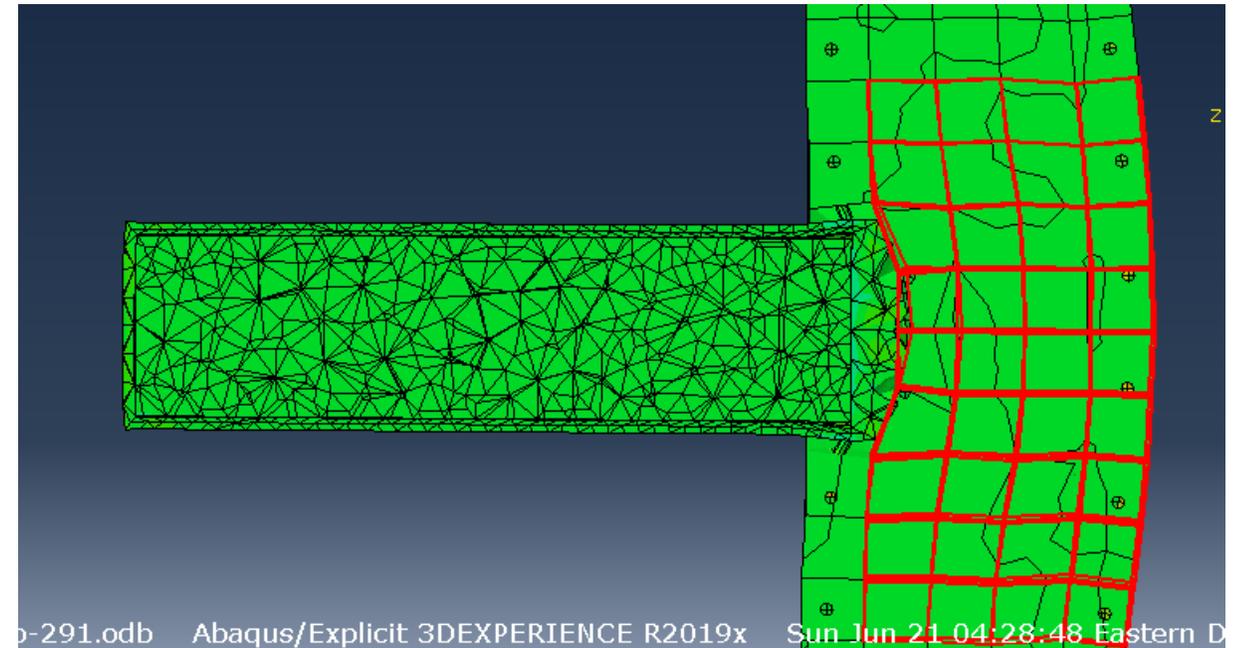

| Confinement Pressure (MPa)	*K*
15.5	0.64
26	0.65
47	0.67
100	0.705

Confinement Pressure

- Check normal stresses (S_{11} & S_{22}) for the highlighted elements during impact

- Stresses vary from 0-30MPa with majority in the range of 10-15MPa

- 15.5MPa confinement pressure will be most accurate

Confinement Pressure (MPa)	K
15.5	0.64
26	0.65
47	0.67
100	0.705

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11

Relation between K and confinement pressure

- Imran and Pantazopoulou (1996) performed tri-axial test with different strength and confinement pressure

- Use that data to match it with the ABAQUS model and plot the relationship between *K*, confinement pressure, and strength of concrete

K vs Confinement pressure
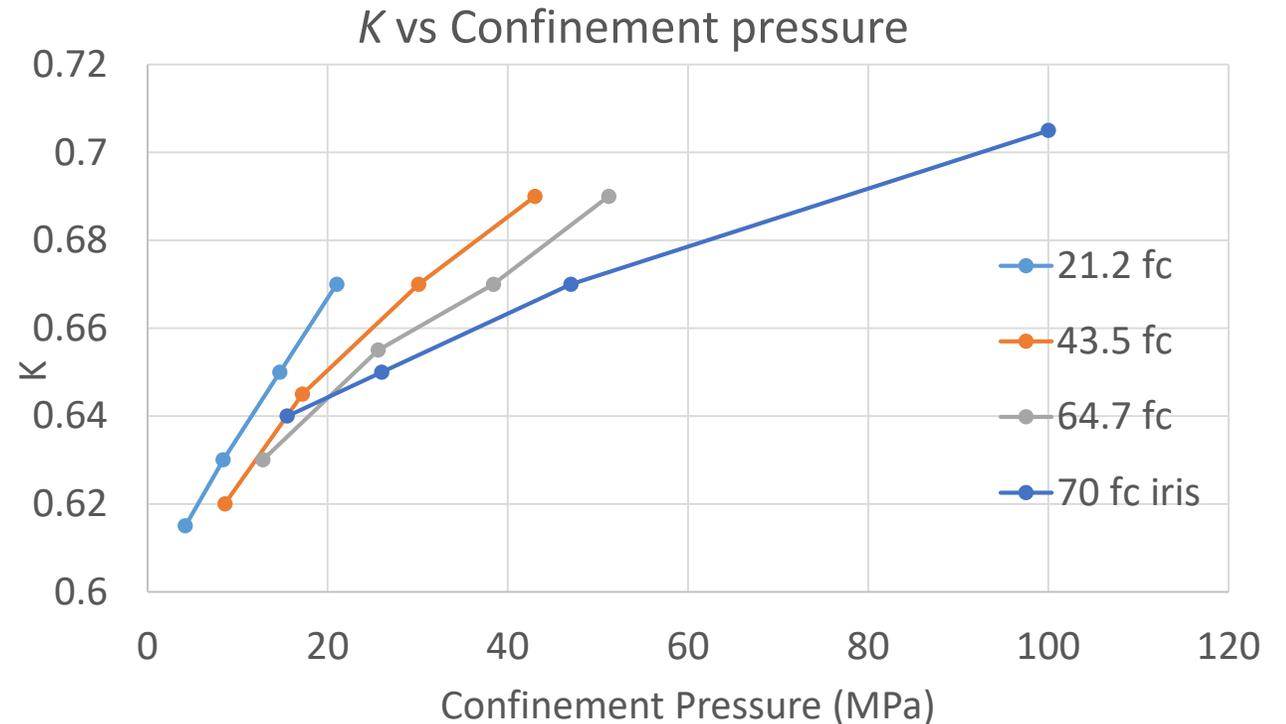
CDP in ABAQUS : Failure Criteria

- Elements which distort more than a specified criteria are removed

- Compressive failure strain is taken at 0.01% of maximum compressive stress

- The tensile strain at failure is assumed to be 0.02

- **Failure Criteria inputs in ABAQUS:**

    ε_t^{in} = 0.02, ε_c^{in} = 0.0673 (at 0.01% of fc from generated stress-strain plot)

    d_t = 0.99, d_c = 0.99

Where,

ε_t^{in}, ε_c^{in} = Inelastic strain at failure in tension and compression

d_t, d_c = Tensile and Compressive damage parameter

# Material properties: Reinforcement bar and Missile

Reinforcement Bar

- For plastic behavior the data is generated based on yield (≈ 540MPa) and ultimate (≈ 605.3MPa) stress (Rouquand et al., 2011)

- Ductile damage is defined to represent the failure and deletion of elements
  - Failure strain of 0.3 is applied (Rodríguez et al., 2013)

Missile

- Material properties for both the steel and concrete part of missile are defined using available data (Shehata et al., 2011)

Contact between rebar and concrete

- Embedded region is used to constrain rebar and concrete slab
- It constrains rebar's (8-noded 3d brick element) translational degrees of freedom to concrete
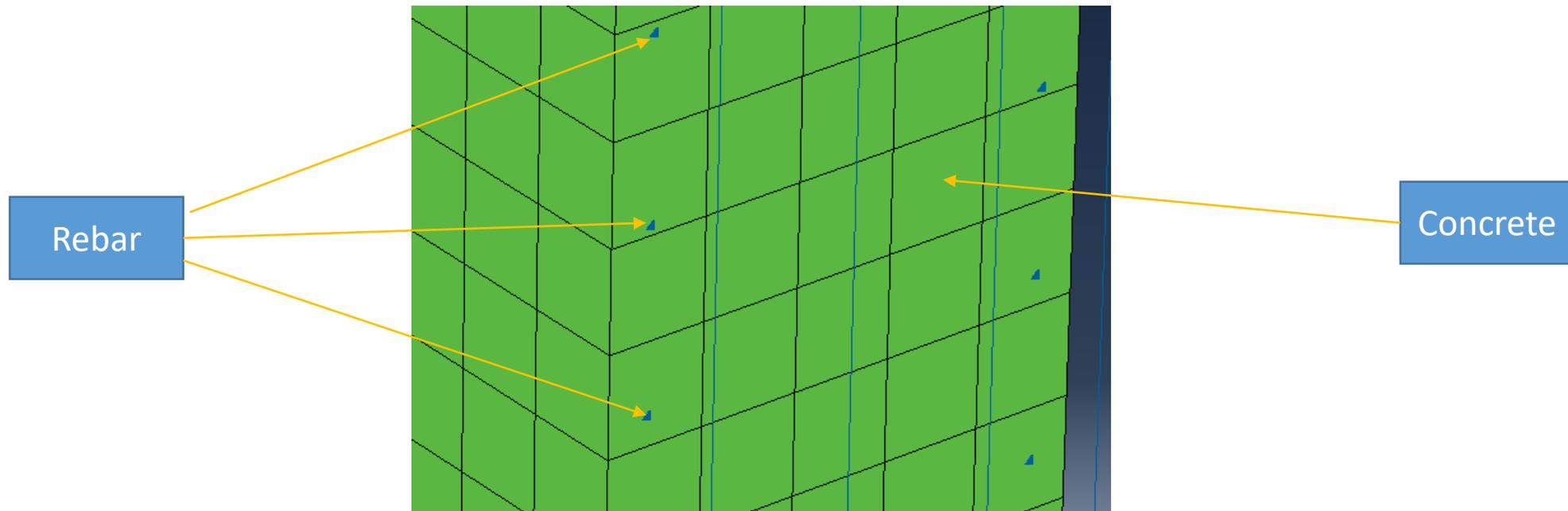
Interaction

- Surface to surface contact is used for missile and concrete interaction

- Surface to node contact is used for missile and rebar interaction

- Penalty-based friction method is used to define contact with friction coefficient of 0.3

- This method computes the contact forces based on penetration depth and normal velocity using spring-damper model
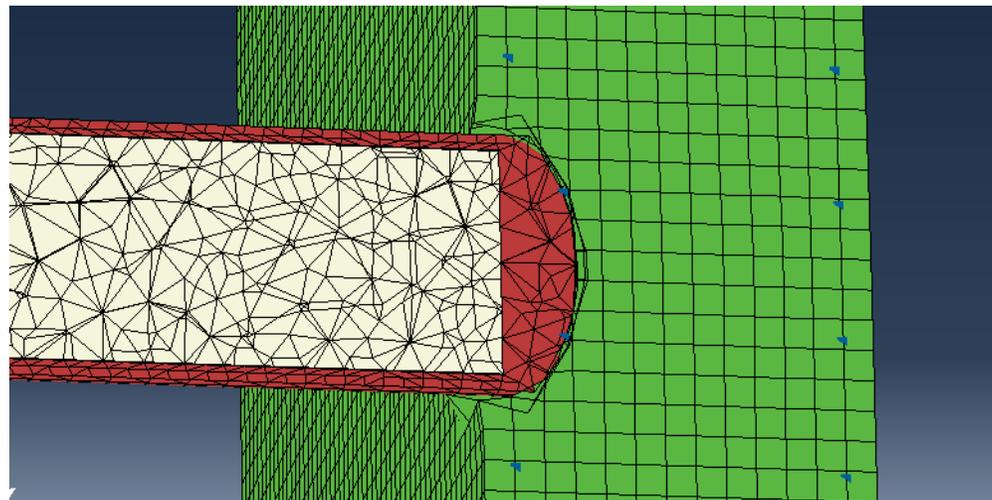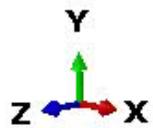
Boundary Condition and Initial Condition

- Concrete slab is fixed at all the edges

- Initial velocity of 135 m/s is applied to the missile in direction towards the Slab
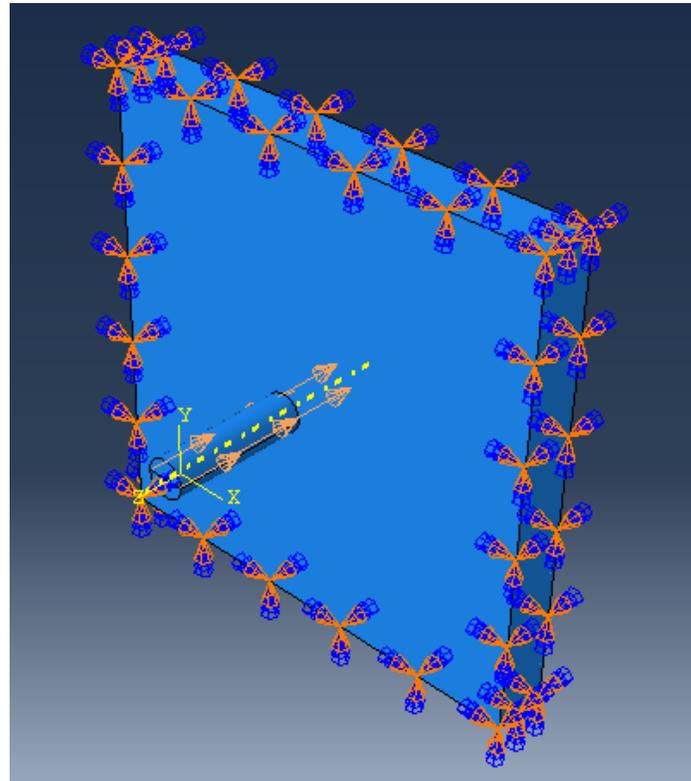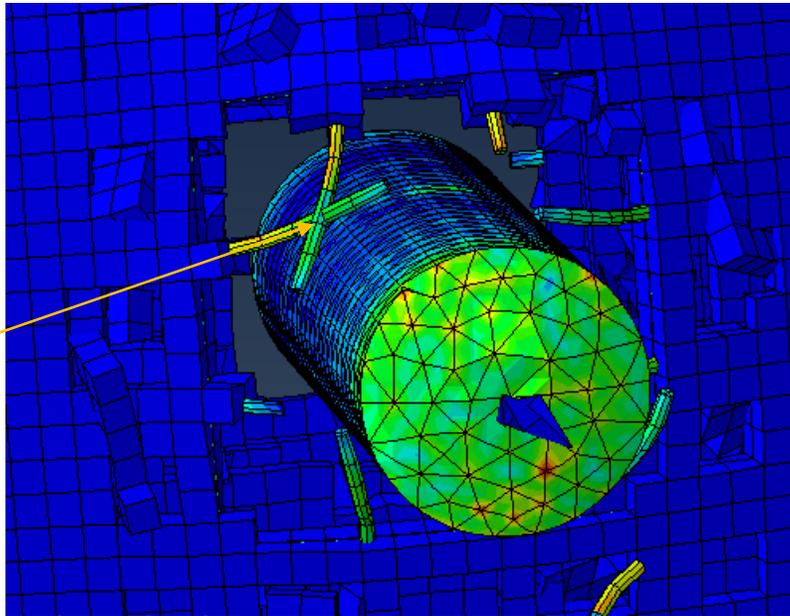
Simulation
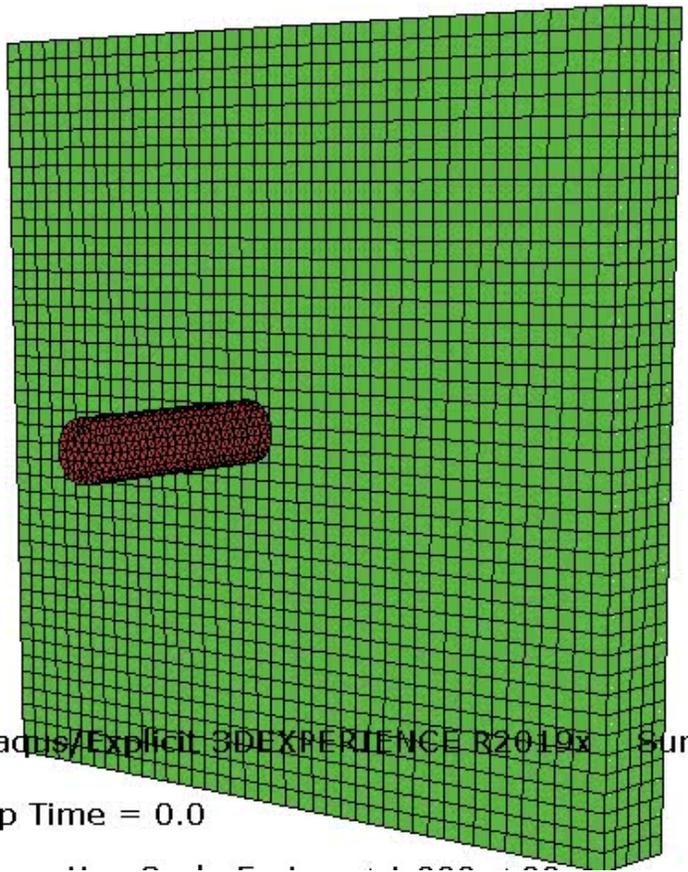
Step: Step-1   Frame: 0
Total Time: 0.000000

ODB: Job-34.odb   Abaqus/Explicit 3DEXPERIENCE R2019x   Sun Mar 15 12:09:53 Eastern Daylight Time 20
Step: Step-1
Increment   0: Step Time = 0.0

19

Observed failures

- 2 rebar in horizontal and 2 in vertical directions are broken

Rear face during impact

- Ejected mass of concrete after impact from ABAQUS is 101.31 Kg

- It is very close to experimental results which are 60, 116 and 121 Kg for three tests

Comparison of Results

Result	Experimental (from 3 tests)	ABAQUS model
Exit velocity (m/s)	33.8, 45.8 and 35.8	35.16
Broken rebars in Horizontal and Vertical directions	Front: 2H 2V Back : 1H 2V	Front: 2H 2V Back : 2H 2V
Mass of ejected concrete (kg)	60, 116 and 121	101.31

- Only 8 teams out of 29 in IRIS 2012 participants were within ±40% of experimental residual velocity

- After doing parametric study on this model, it is found that the results are very sensitive to the Dilation angle, parameter K and the failure criteria of the CDP model
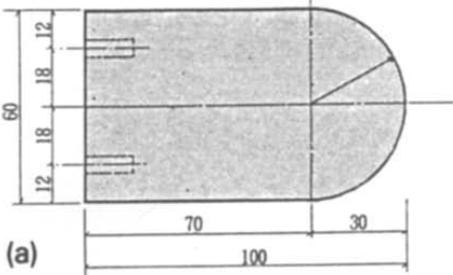
Tests by Kojima (1991): Setup
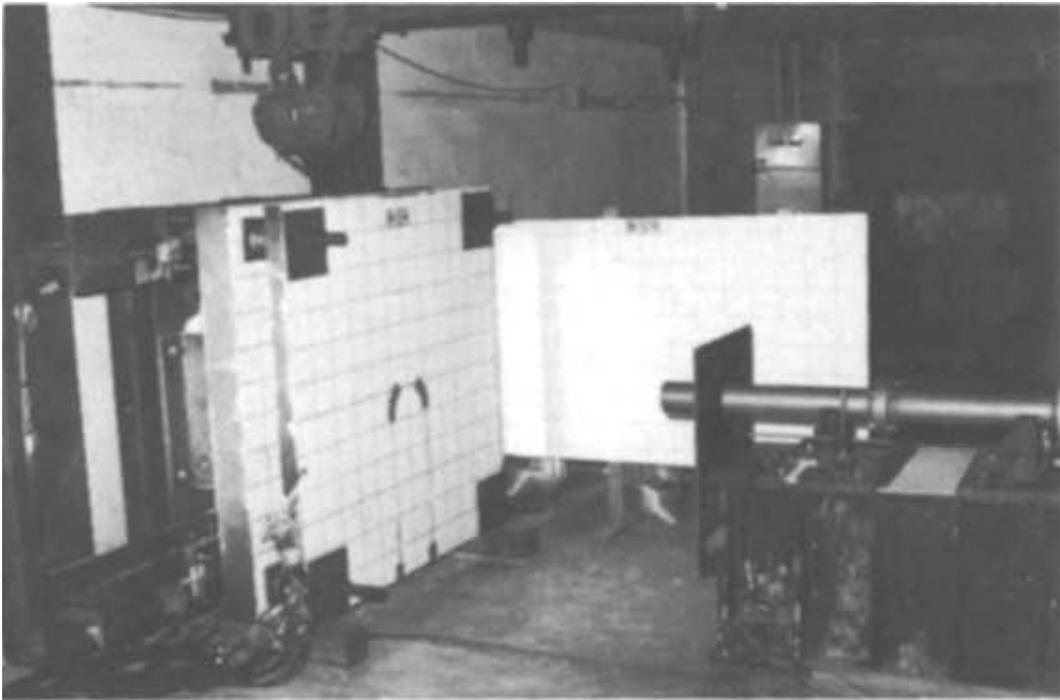
Test setup
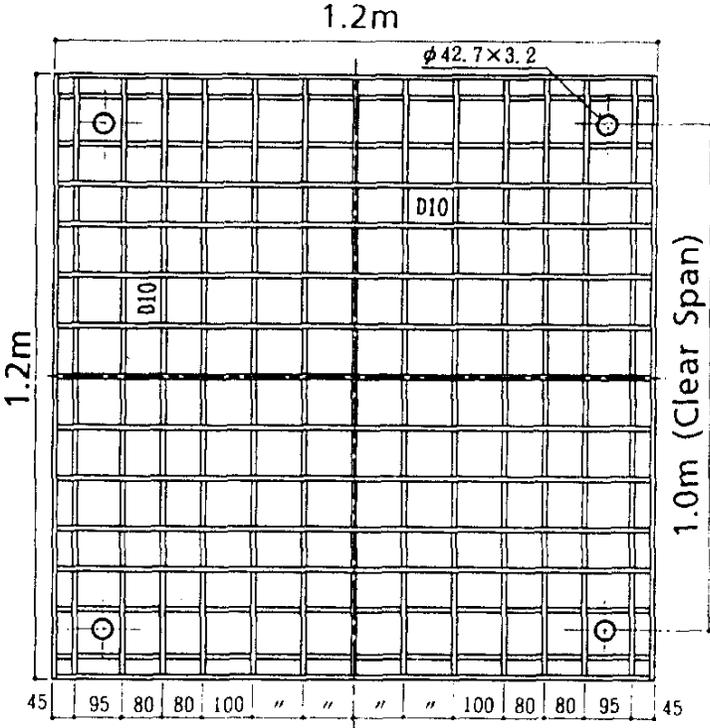
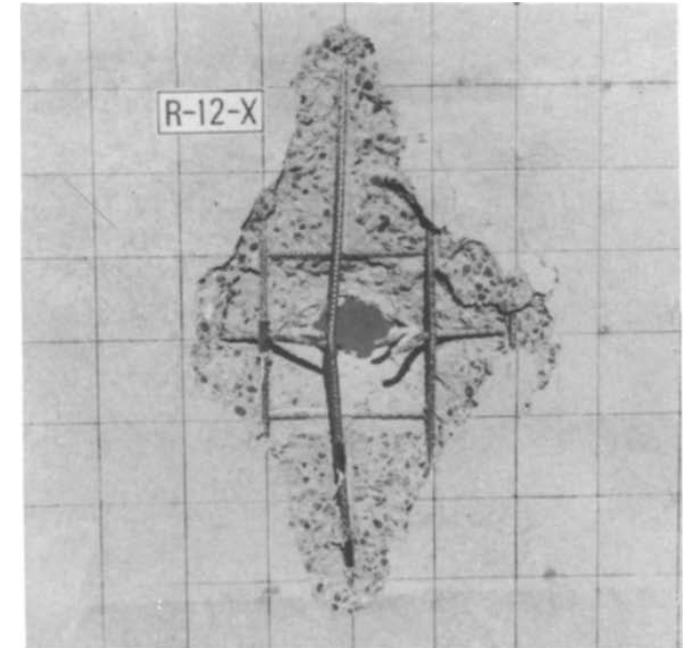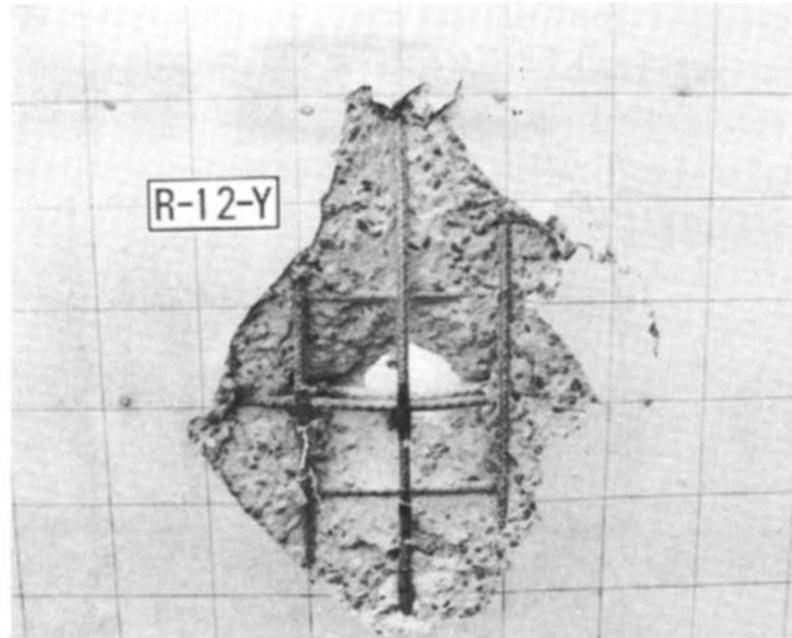

Slab

Missile

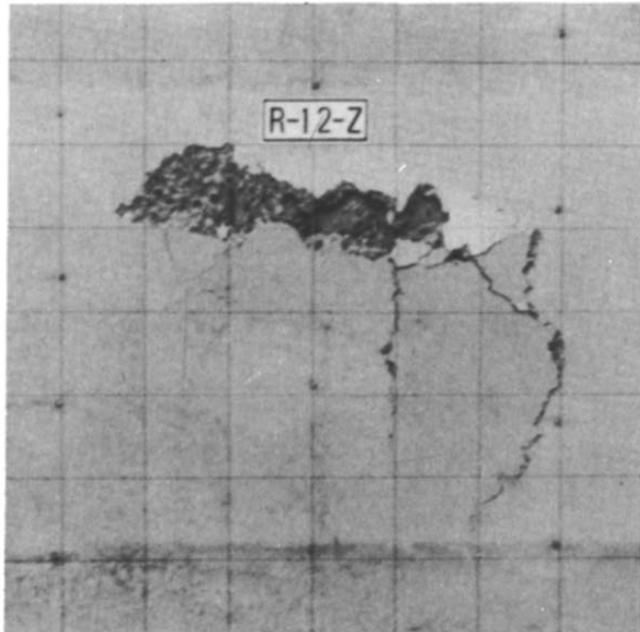# Damaged slab after impact

Impact
Velocities:

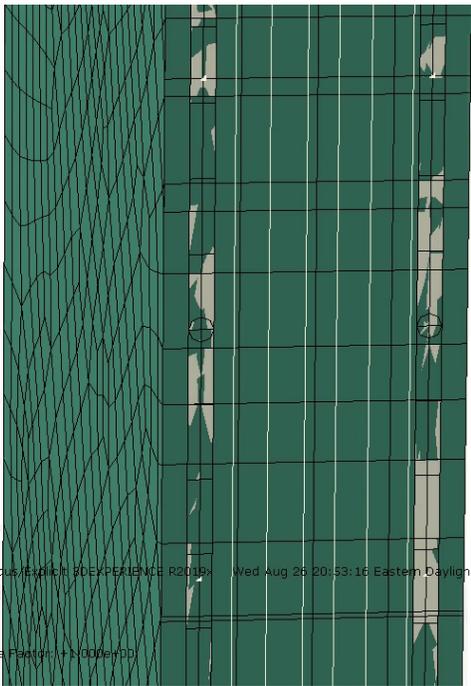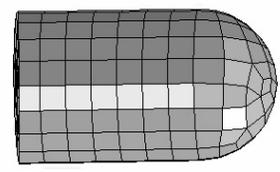95 m/s   164 m/s   215 m/s

Back face of Damaged slab after impact with different impact velocities

Parameters for Blind Predictive Analysis

- Stress-Strain curve is generated with closed form equations

- Other CDP parameters are selected based on learnings from previous study

  - ε_c^{in} = 0.052 at 0.01% of fc from generated stress-strain plot, ε_t^{in} = 0.02

  - Confinement pressure comes out to be around 12-15 MPa and for f_c of 27MPa.

  - K = 0.64

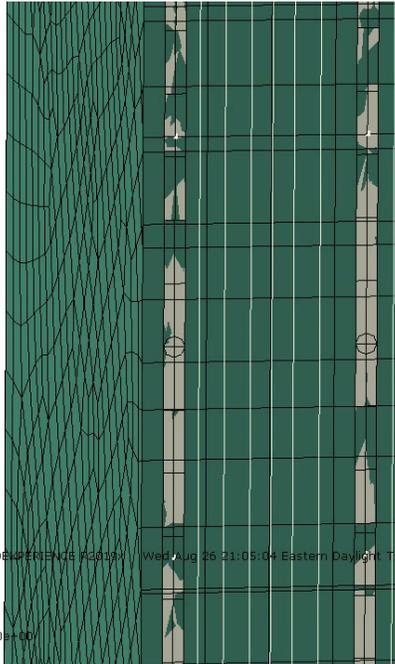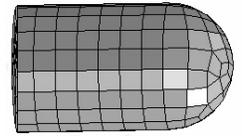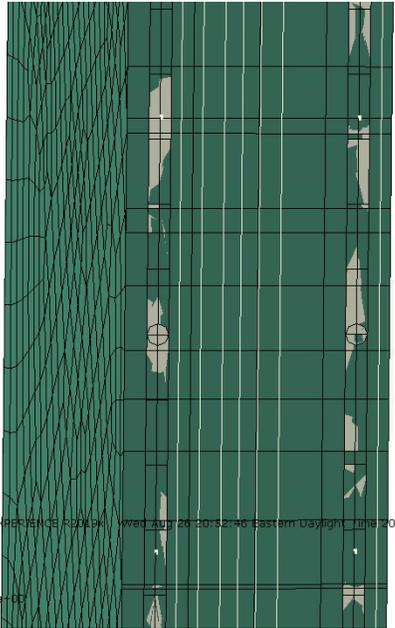- The missile is rigid and equivalent point mass is assigned

Simulations

164 m/s

95 m/s

215 m/s

Results Comparison

Using Failure criteria: $\varepsilon_t^{in} = 0.02$, $\varepsilon_c^{in} = 0.052$

Velocity (m/s)	Penetration depth in mm		# of broken Rebars	
	Test	ABAQUS model	Test	ABAQUS model
95	45	47.6	0	0
164	100	103.0	1	2
215	Full perforation	Full perforation	3	4

Summary

IRIS test

- Failure criteria: ε_t^{in} = 0.02, ε_c^{in} = 0.0673 (at 0.01% max stress)
- Dilation angle: 46

Result	Experimental (from 3 tests)	ABAQUS model
Exit velocity (m/s)	33.8, 45.8 and 35.8	35.16

Tests by Kojima

- Failure criteria: ε_t^{in} = 0.02, ε_c^{in} = 0.052 (at 0.01% max stress)
- Dilation angle: 46

Velocity (m/s)	Penetration depth (mm)	
	Test	ABAQUS model
95	45	47.616
164	100	103
215	Full perforation	Full perforation

Conclusions

- Results are found to be sensitive to the dilation angle, *K*, and failure criteria
- CDP parameter *K* is dependent on confinement pressure and strength of concrete
- Surface interaction between missile and reinforcement bar is simulated better with solid element compared to 2-noded frame element
- Proposed approach can predict:
  - exit velocity of impacting object after perforation
  - penetration depth when there is no perforation