



# Wind-borne missile impact on exterior RC walls and slabs in nuclear facilities

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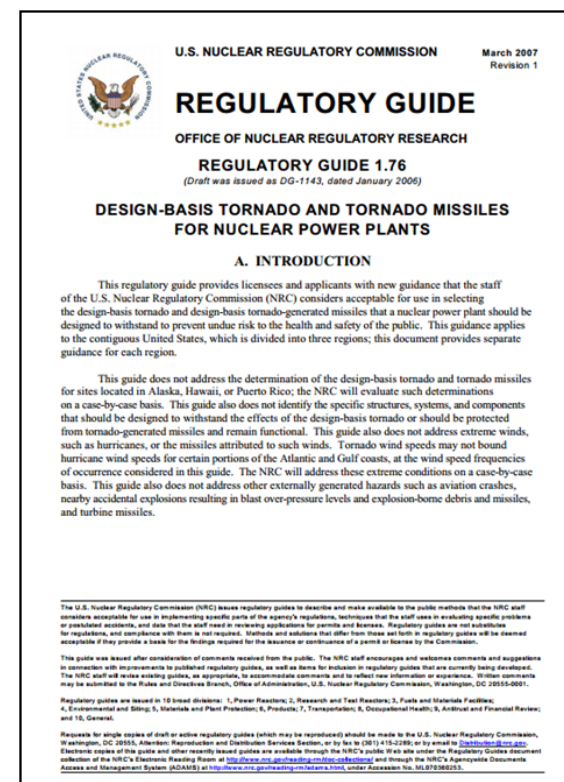
# Outline

- Overview
  - Regulatory guidance and standards
  - Evaluation of empirical equations
- Simulations of EPRI experiments
  - Smooth Particle Hydrodynamics (SPH)
  - Partial validation of numerical tools
- Parametric study
- Design guidance for wind-borne missile impact
- Summary and conclusions



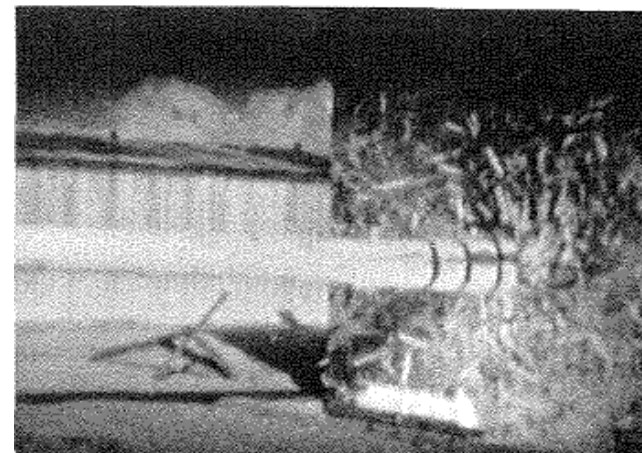
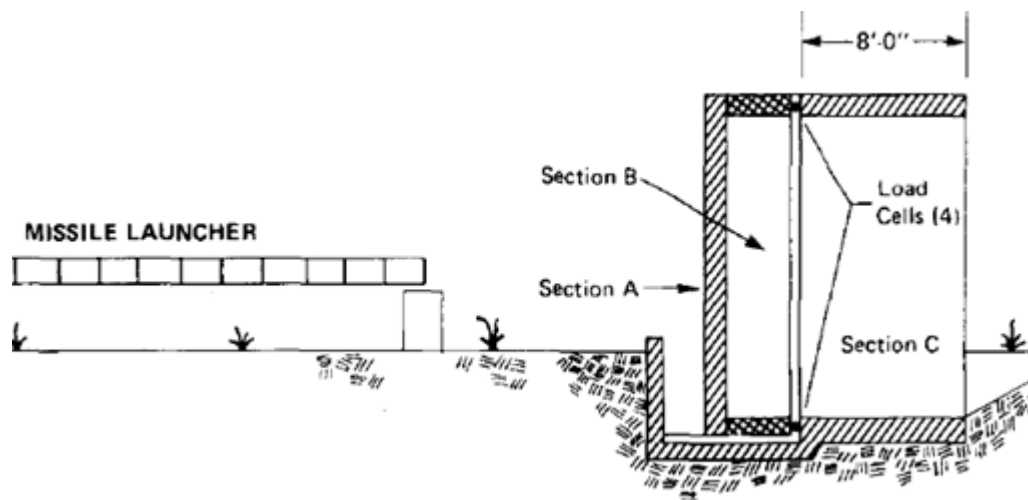
# Impact loadings

- Regulatory Guides
  - Tornadoes (RG 1.76)
  - Hurricanes (RG 1.221)
- ANSI/ANS-2.3-2011
- Missiles
  - Steel pipe, 150 mm dia., 5 m long, 130 kg
    - Maximum tornado velocity, 41 m/s
    - Maximum hurricane velocity, 94 m/s
  - Automobile, 1820 kg, specific size
    - Maximum tornado velocity, 41 m/s
    - Maximum hurricane velocity, 113 m/s



# Experiments

- Test data
  - EPRI and Calspan (Bechtel) tests at Sandia in the 1970s
  - 12, 18 and 24-inch (30.5, 46, and 609 cm) thick walls
  - Wooden utility poles, steel pipes, and steel rods
  - No repeat experiments conducted, limited metadata

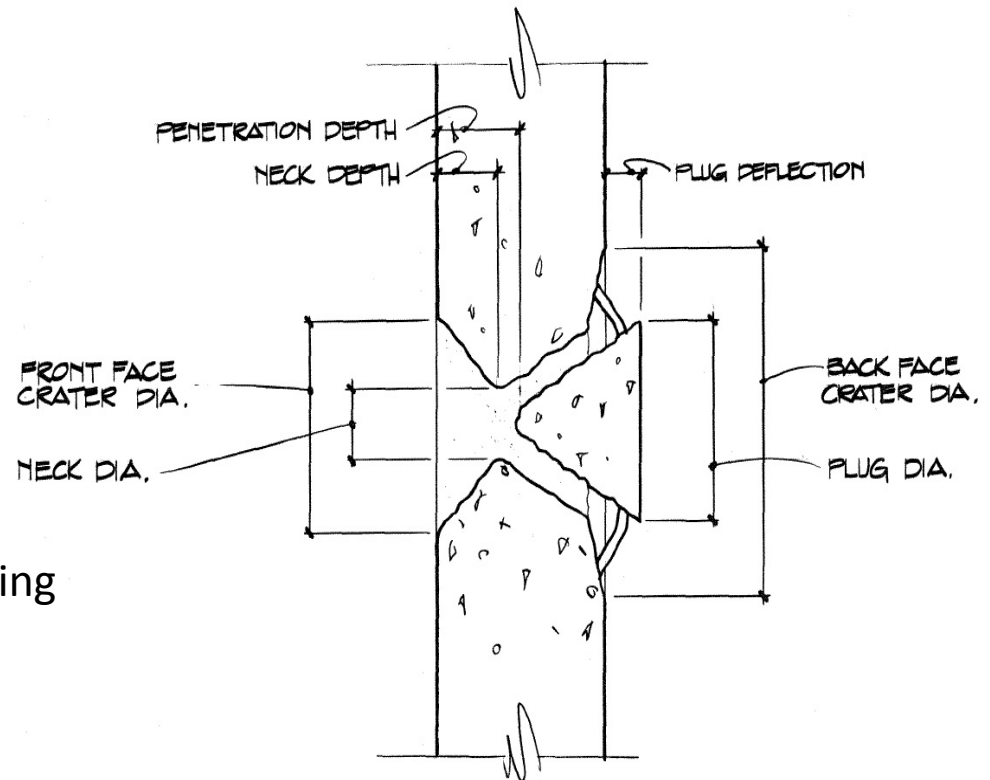


Stephenson, 1977

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# Design guidance

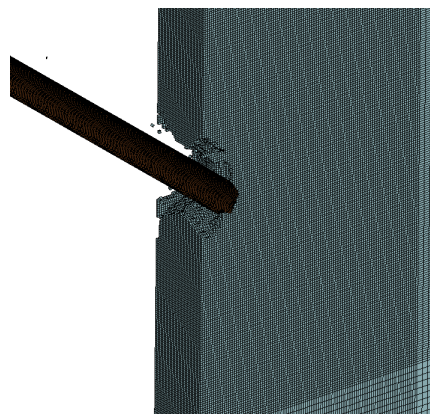
- ACI 349-13
- Global response
  - Equivalent SDOF models
- Local response
  - Empirical formulae
    - Penetration depth
    - Thickness to prevent scabbing and perforation
- Empirical formulae
  - Predictions of measured behavior poor



Stephenson, 1977

# EPRI test simulations

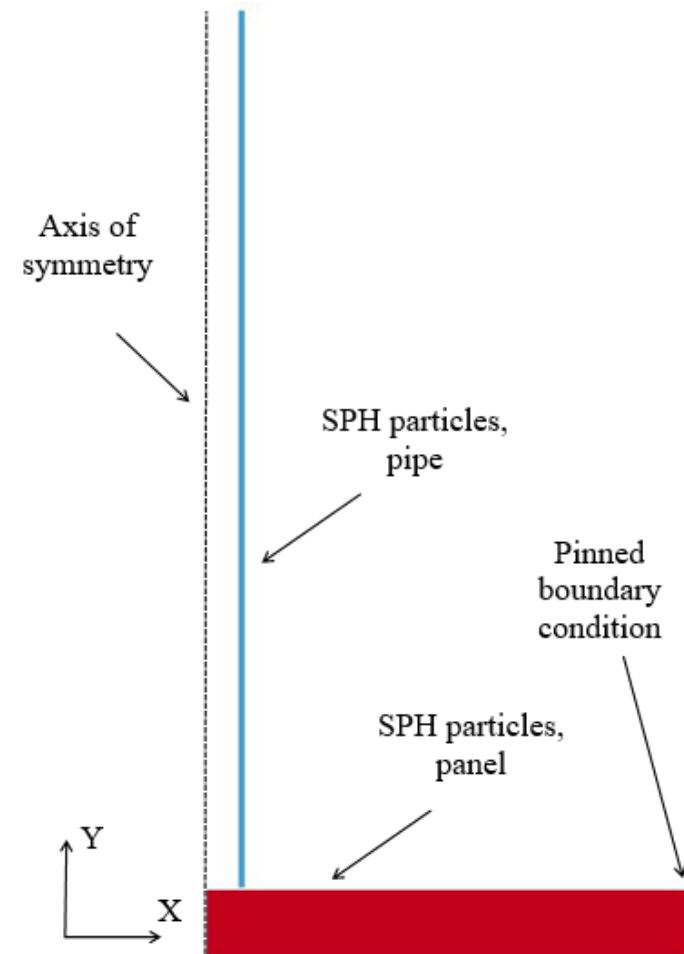
Test	Panel $t$ , mm (in)	$v$ m/s (fps)	$f'_c$ MPa (psi)	Projectile	Panel damage per Stephenson (1977)
11	305 (12)	30 (98)	24.8 (3600)	Schedule 40 pipe	Pipe penetrated panel , scabbing on the back face
10	305 (12)	44 (143)	25.5 (3700)	Schedule 40 pipe	Pipe perforated panel, scabbing on the back face
3	457 (18)	62 (202)	23.4 (3400)	Schedule 40 pipe	Pipe penetrated panel, scabbing on back face
8	610 (24)	62 (202)	26.2 (3800)	Schedule 40 pipe	Pipe penetrated panel, radial cracking on back face



0°(normal), back face

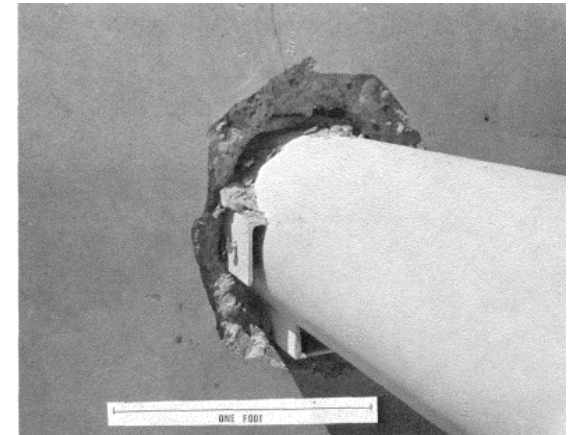
# SPH impact model

- Modeling in LS-DYNA
  - Axisymmetric SPH formulation
    - Rebar ignored
    - Concrete, pipe – SPH particles
    - Mass matching for SPH particles
  - Pinned boundary condition
  - JC material model for pipe
  - MAT072R3 model for concrete

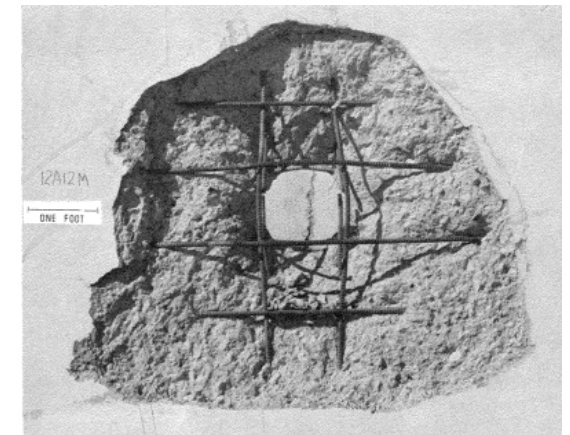


# EPRI Test 10

- Experiment
  - Projectile
    - 150 mm diameter Schedule 40 pipe
    - 337 kg, 4191 mm long
    - Impact velocity: 44 m/s
  - Concrete panel
    - 305 mm thick, 4.6 m x 4.6 m clear span
    - Reinforcement: 0.31 % EW EF
    - 25.5 MPa concrete
  - Damage to panel
    - Perforation, scabbing on back face

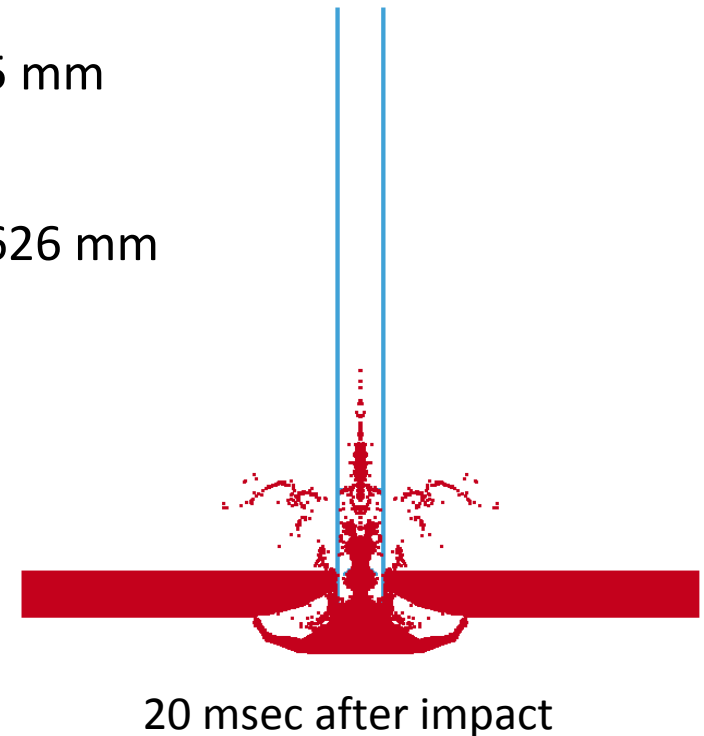
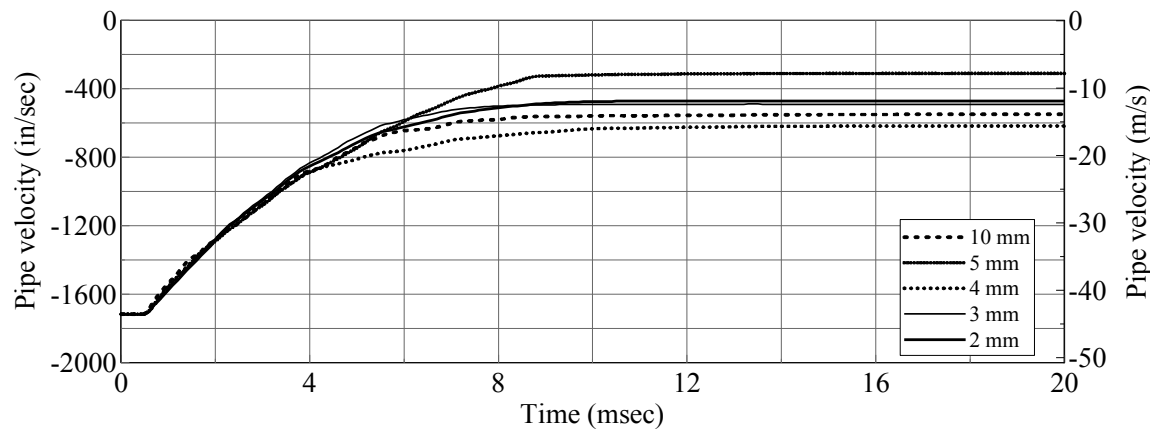


Stephenson, 1977



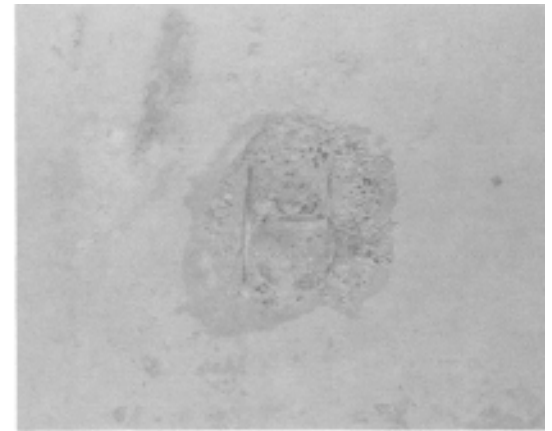
# EPRI Test 10

- LS-DYNA simulations, 2 mm mesh
  - Perforation observed in simulation and experiment
  - Front-face crater diameter
    - Simulation: 457 mm; experiment: 495 mm
  - Back-face crater diameter
    - Simulation: 1524 mm; experiment: 1626 mm

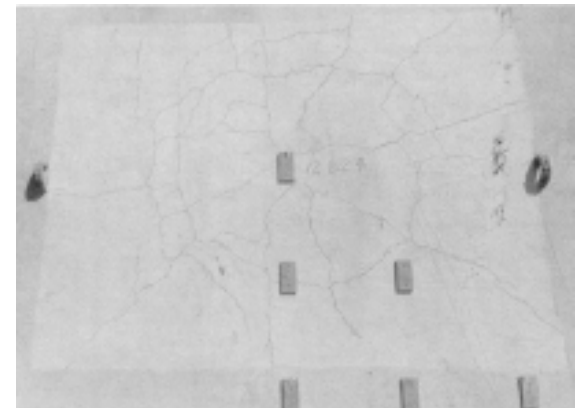


# EPRI Test 8

- Experiment
  - Projectile
    - 150 mm diameter Schedule 40 pipe
    - 337 kg, 4191 mm long
    - Impact velocity: 62 m/s
  - Concrete panel
    - 610 mm thick, 4.6 m x 4.6 m clear span
    - Reinforcement: 0.27 % EW EF
    - 26.2 MPa concrete
  - Damage to panel
    - Penetration, radial cracking on back face

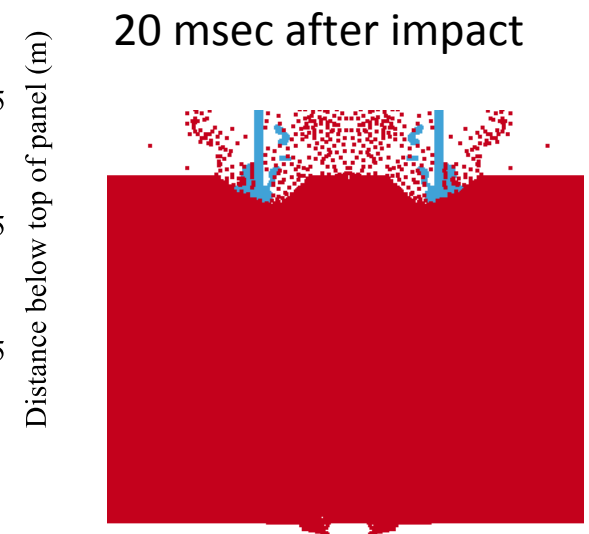
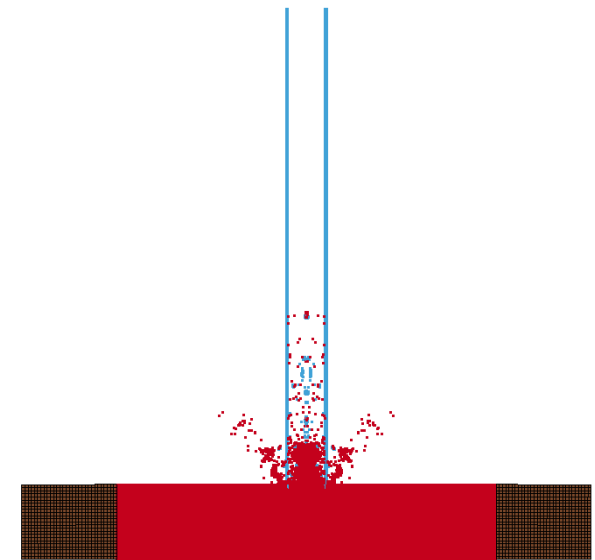
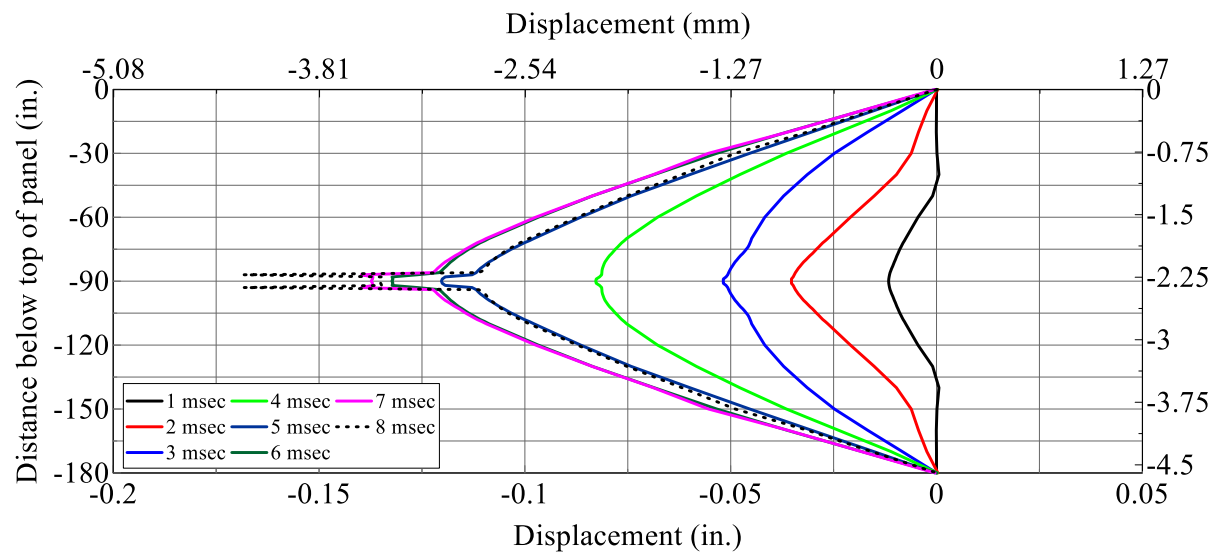


Stephenson, 1977



# EPRI Test 8

- LS-DYNA simulations, 3 mm mesh
  - Did not predict penetration depth
  - Behavior similar to that observed in the experiments



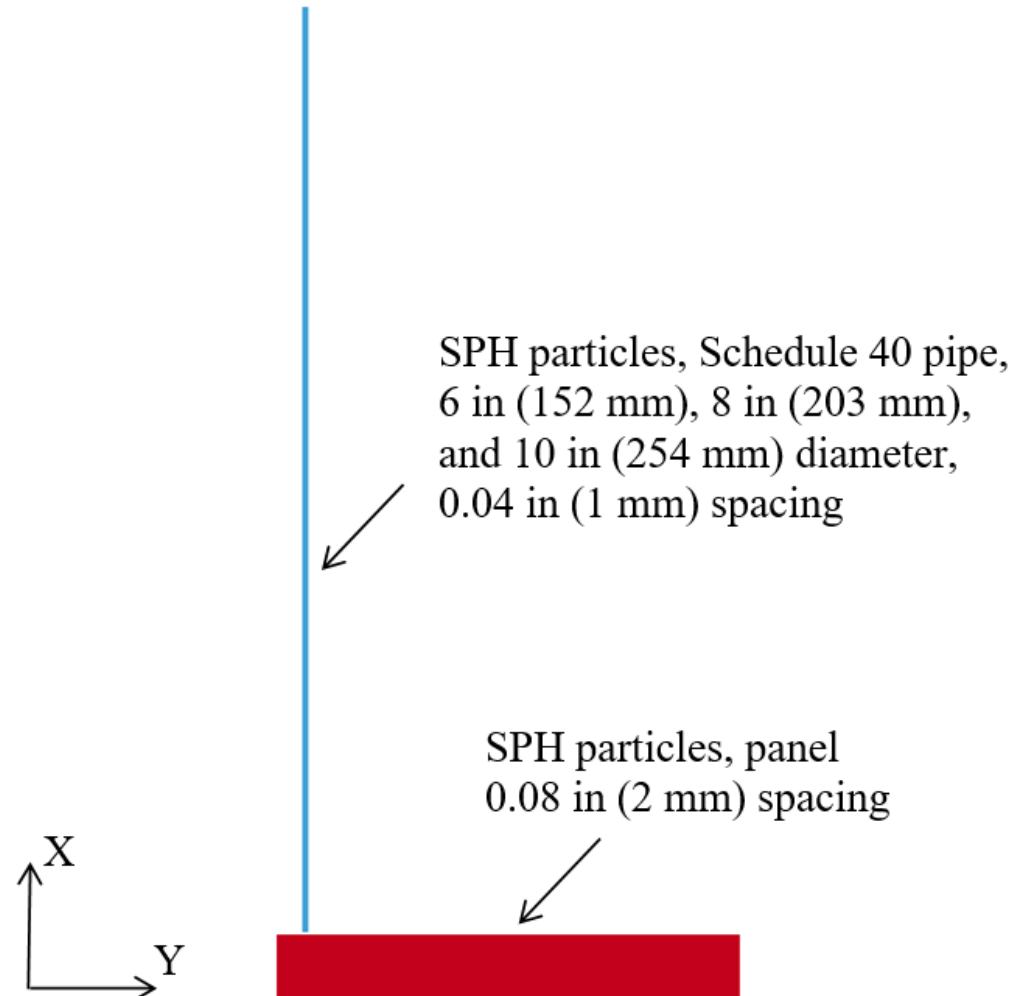
# Parametric study

- Design guidance for wind-borne missile impact
- Schedule 40 pipe focus of simulations
- 305 mm, 381 mm, 460 mm, and 650 mm thick panels

	Low	Medium	High
$d$ , in (mm)	6 (152)	8 (203)	10 (254)
Mass, lb-sec <sup>2</sup> /in (kg)	0.74 (130)	1.11 (195)	1.57 (276)
$v$ , in/sec (m/sec)	1575 (40)	2756 (70)	3937 (100)
$f'_c$ , psi (MPa)	4351 (30)	5801 (40)	7251 (50)
$f'_t$ , psi (MPa)	435 (3)	580 (4)	725 (5)

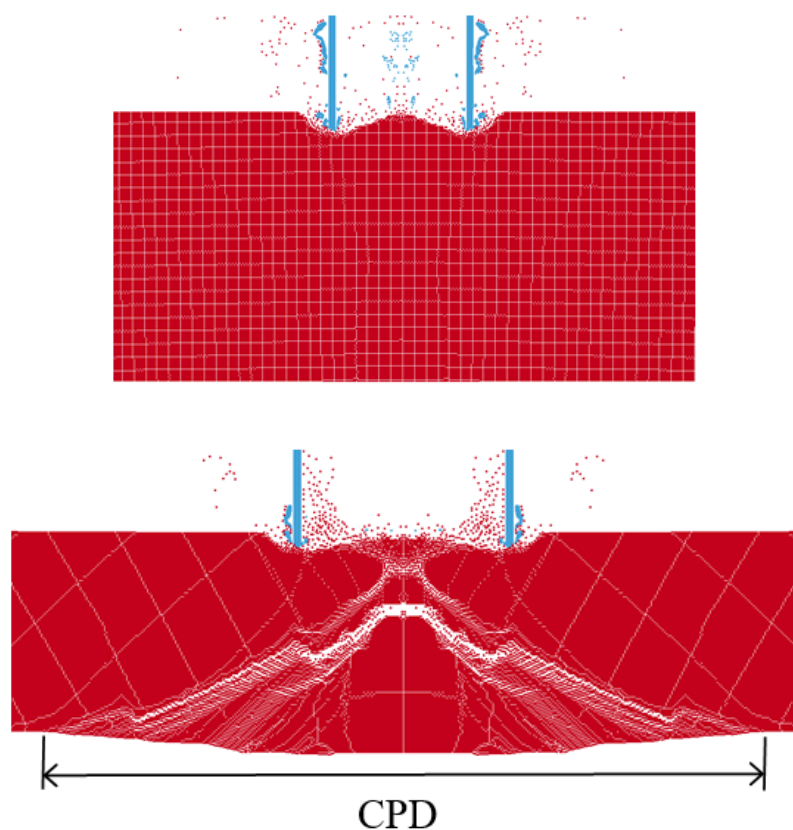
# Numerical models

- 12 SPH models
  - Axisymmetric
- MAT072R3
- Particle spacings based on mesh convergence study
- 153 simulations

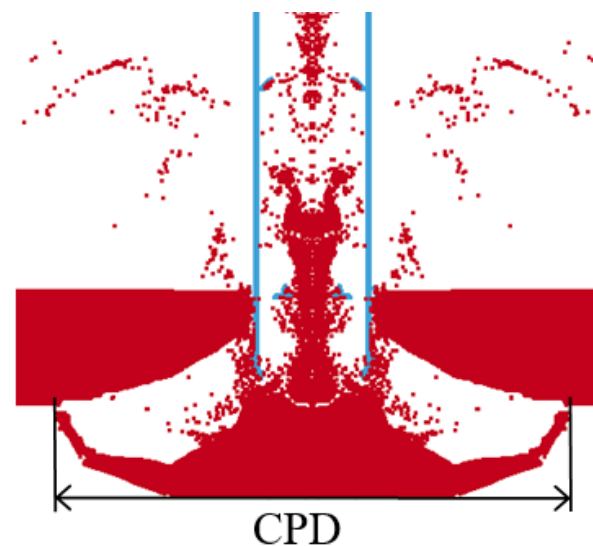


# Characterization of damage

Non-perforation - exit velocity is zero

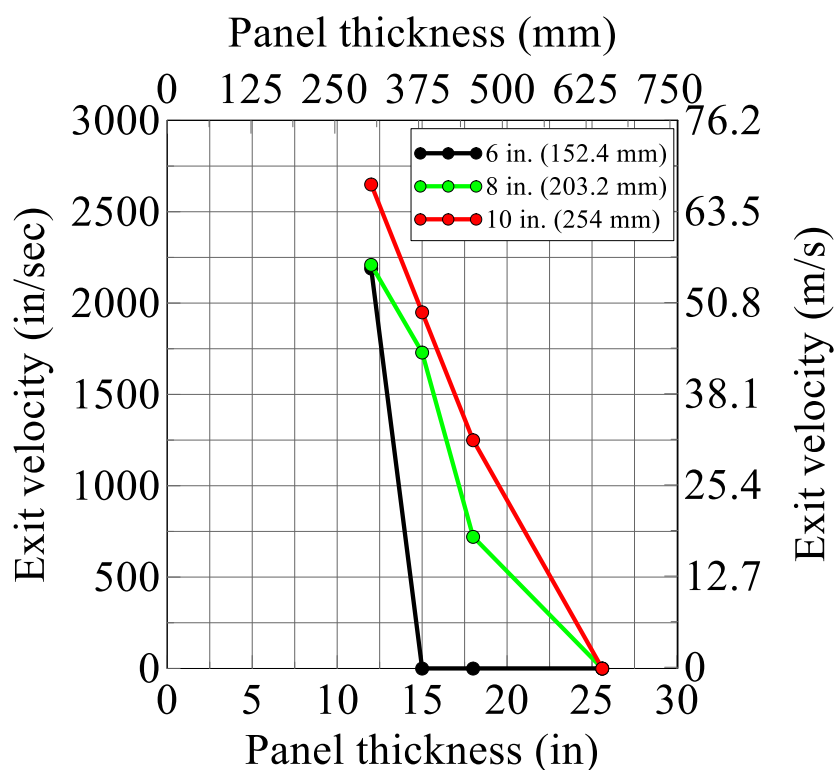


Perforation - exit velocity is greater than zero

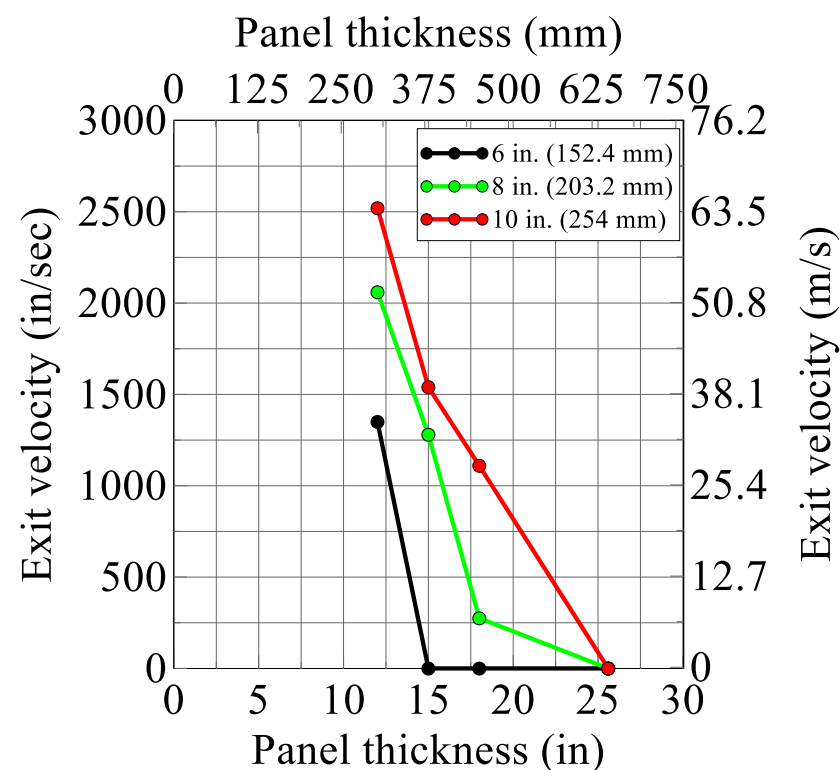


# Results

- Panel thickness, impact velocity = 100 m/s



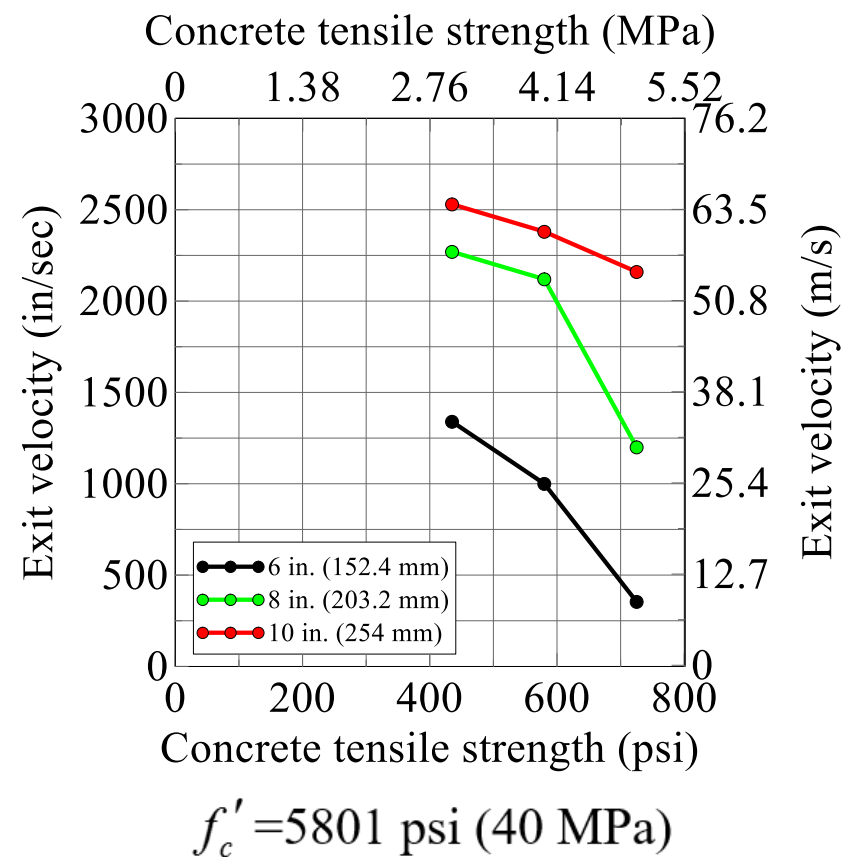
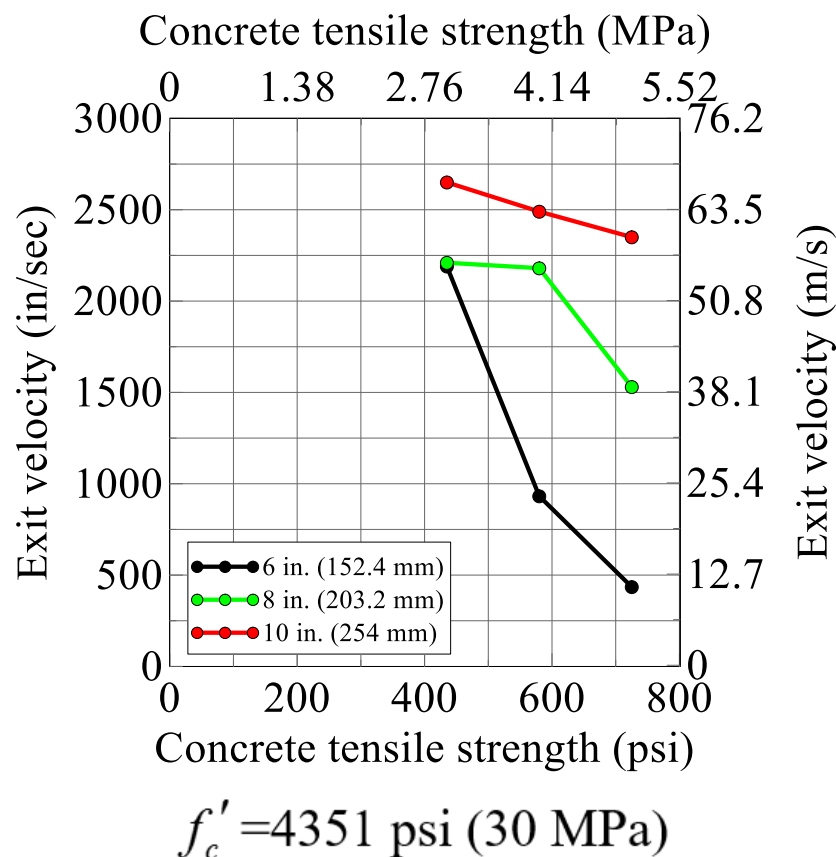
$f'_c = 4351$  psi (30 MPa),  $f'_t = 435$  psi (3 MPa)



$f'_c = 7251$  psi (50 MPa),  $f'_t = 435$  psi (3 MPa)

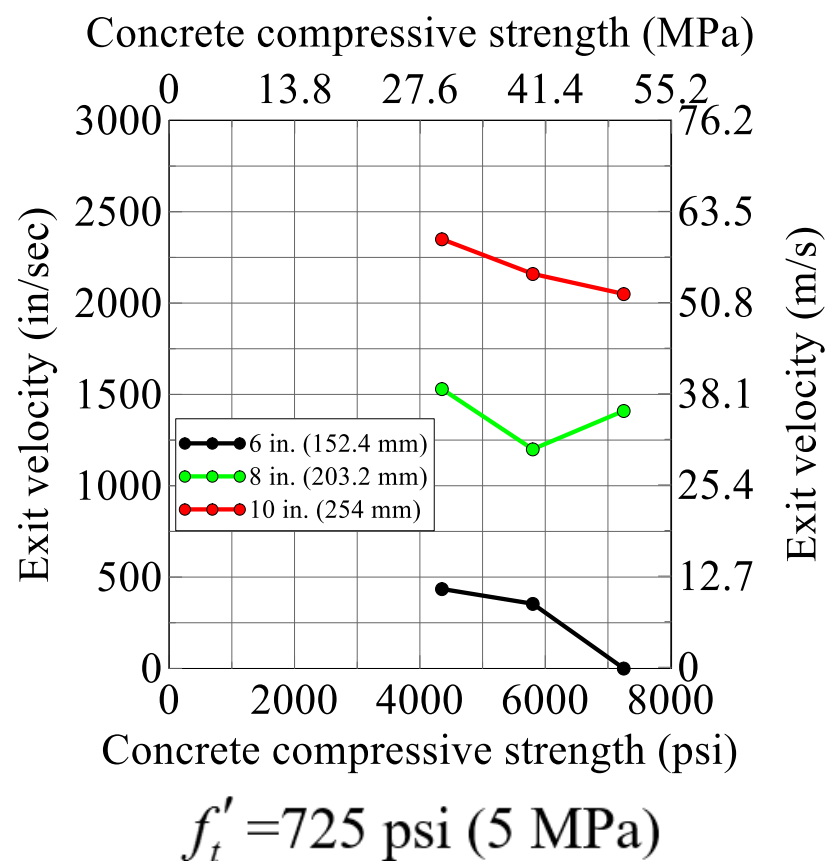
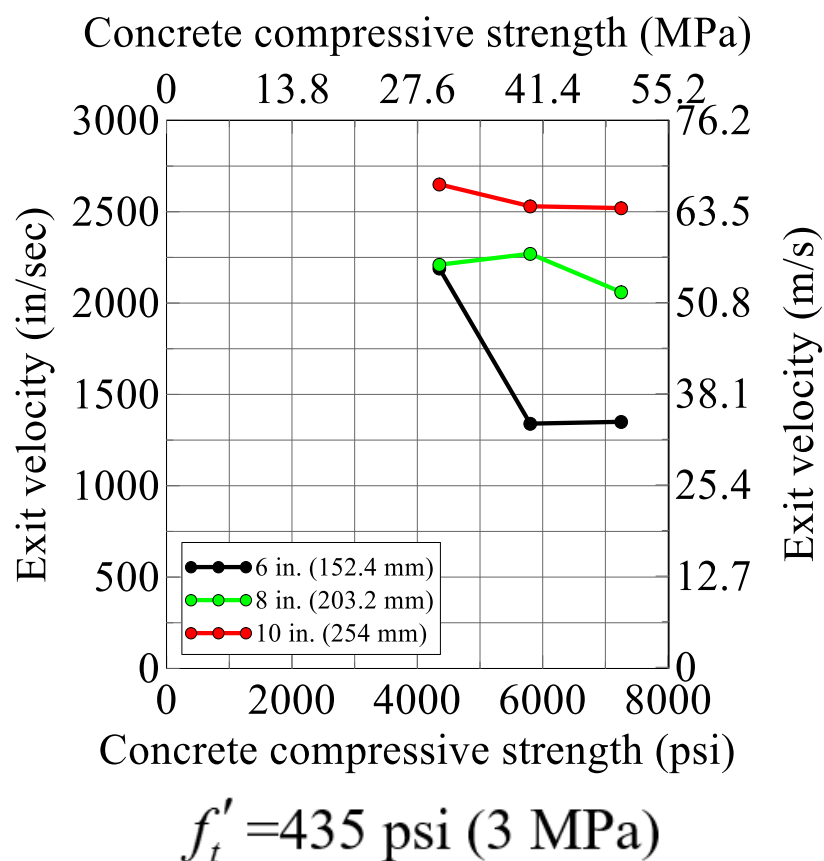
# Results

- Concrete tensile strength, impact velocity = 100 m/s



# Results

- Concrete compressive strength, impact velocity = 100 m/s



# Design guidance

- Minimum panel thickness
- Different Schedule 40 pipes
- Impact velocities per RG 1.76 (T), 1.221 (H), ANSI/ANS-2.3-2011

Minimum panel thickness,  $f_c' \geq 30$  MPa (4351 psi),  $f_t' \geq 3$  MPa (435 psi)

Impact velocity, m/s (in/sec)	Schedule 40 pipe diameter, mm (in)	Prevent perforation, mm (in)	Prevent scabbing, mm (in)
40 (1575)	152 (6)	305 (12)	381 (15)
	203 (8)	305 (12)	381 (15)
	254 (10)	381 (15)	460 (18)
44.7 (1760)	152 (6)	305 (12)	381 (15)
	203 (8)	381 (15)	460 (18)
	254 (10)	381 (15)	559 (22)
55.9 (2201)	152 (6)	305 (12)	460 (18)
	203 (8)	460 (18)	559 (22)
	254 (10)	460 (18)	650 (25.6)
100 (3937)	152 (6)	381 (15)	460 (18)
	203 (8)	650 (25.6)	838 (33)
	254 (10)	650 (25.6)	914 (36)

Minimum panel thickness,  $f_c' \geq 50$  MPa (7251 psi),  $f_t' \geq 5$  MPa (725 psi)

Impact velocity, m/s (in/sec)	Schedule 40 pipe diameter, mm (in)	Prevent perforation, mm (in)	Prevent scabbing, mm (in)
40 (1575)	152 (6)	305 (12)	305 (12)
	203 (8)	305 (12)	381 (15)
	254 (10)	305 (12)	381 (15)
44.7 (1760)	152 (6)	305 (12)	305 (12)
	203 (8)	305 (12)	381 (15)
	254 (10)	305 (12)	460 (18)
55.9 (2201)	152 (6)	305 (12)	305 (12)
	203 (8)	305 (12)	381 (15)
	254 (10)	381 (15)	559 (22)
100 (3937)	152 (6)	305 (12)	381 (15)
	203 (8)	460 (18)	460 (18)
	254 (10)	650 (25.6)	650 (25.6)

# Closing remarks

- Empirical equations for missile impact
  - Two data sets evaluated
- *Validation* of SPH model
  - Four impact tests
- Axisymmetric SPH model for parametric study
  - Investigated parameters that affect impact resistance
  - Panel thickness and tensile strength
- Additional tests needed to develop robust numerical models
  - Empirical equations for panel thickness

# Smooth Particle Hydrodynamics (SPH)

- Domain is divided into a set of discrete mass particles
- No node-to-element connectivity matrix; large distortion of mesh possible
- Computationally expensive

