Investigation into Impact Behavior of Reinforced Concrete Panel with Steel Liner Plates under Hard Projectile Impact

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I. Introduction

Research Background

❖ Current design status of nuclear power plant (NPP) structures

- Collapse of NPP structures is one of the most hazardous repercussions
- Thus, conservative design stance to ensure the safety of the NPP structures
- In NPP design codes, allowable yield strength of reinforcing steel is limited to Grade 60 (420MPa) [1]

➢ **Excessive amount of reinforcing steel is placed in NPP structures**

Fukushima accident (2011)

Nuclear power plant

Construction of Belarusian NPP II

Research Background

❖ Problems with excessive reinforcement in NPP structures

- Reinforcement congestion cause both economical and safety issues
  - High cost for labor and transportation
  - Defects in structures such as honeycomb caused by poor workability
- Prolonged reinforcement congestion issue could impact the viability of nuclear industry

➢ **Application of higher strength reinforcement is needed to reduce the rebar amount**

Problems with congested reinforcement

Research Background

❖ Necessity of impact-resistant design in NPP structures

- Importance of impact-resistant design in NPP structures has skyrocketed since the September 11 attack
- Large commercial aircraft collision has been adopted for the design criteria of NPP structures
- Structures suffer local damages when exposed to impact load such as aircraft collision

➢ **Various empirical formulas are suggested to assess the impact resistance of NPP structures in design codes**

➢ **Thus, it is necessary to check if empirical formulas can reflect the effect of application of high-strength**

Types of local damages under impact load

Research Background

❖ Issues in design codes for NPP structures

1. **Effect of rebar on impact resistance of RC panels is not considered in most empirical formulas [1-3]**
2. Effect of steel liner on impact resistance of RC panels is not considered

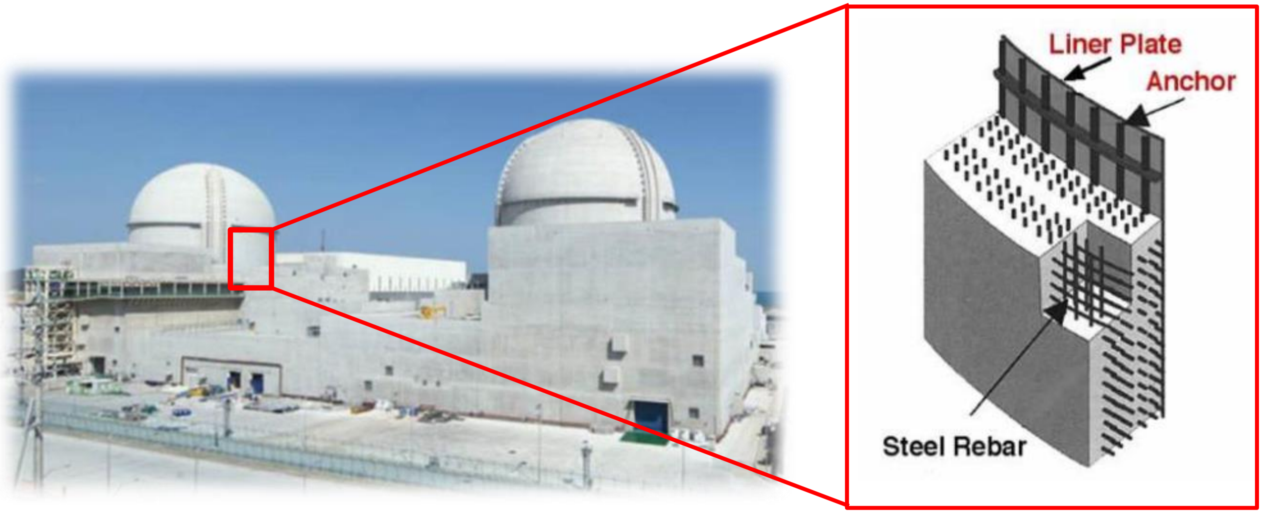
	Considered variables											
	Concrete target			Projectile				Reinforcement				
Empirical Formulas	Comp. strength	Thickness	Density	Mass	Impact velocity	Diameter	Nose shape	Ratio	Spacing	Diameter	Yield strength	Steel liner
Modified NDRC	O	-	-	O	O	O	O	-	NOT CONSIDERED			X
Bechtel	O	-	-	O	O	O	-	-				
S &W	-	O	-	O	O	O	-	-				
Chang	O	-	-	O	-	O	-	-				
CRIEPI	O	O	-	O	O	O	O	-				
Degen	O	-	-	O	O	O	O	-				
CEA-EDF	O	O	O	O	O	-	-	O				

Empirical formulas suggested by NPP design codes

Research Background

❖ Issues in design codes for NPP structures

1. Effect of rebar on impact resistance of RC panels is not considered in most empirical formulas
2. **Effect of steel liner on impact resistance of RC panels is not considered**
   - Lack of applicable formulas and limited test data for the design of steel liner in NPP structures



F.7.2.2 Reinforced concrete structural members protecting a required system or equipment that could be damaged by secondary missiles (fragments of scabbed concrete) shall be designed to prevent scabbing, or a properly designed scab shield shall be based on applicable formulas or pertinent test data. In the absence of scab shields, the concrete thickness shall be at least 20 percent greater than that required to prevent scabbing.

Scab shield in ACI 349-13 [1]

- Design guideline that could account for the effects of high-strength rebar and steel liner is needed

➢ **Investigation of the both effects of rebar and steel liner on impact resistance is needed**

Research Overview

❖ Research Objective

- Investigation of the mechanism and effects of rebar and steel liner on impact resistance of RC panels
- Suggestion of design factors and guideline for the impact resistance of RC panels in NPP structures

❖ Research Scope

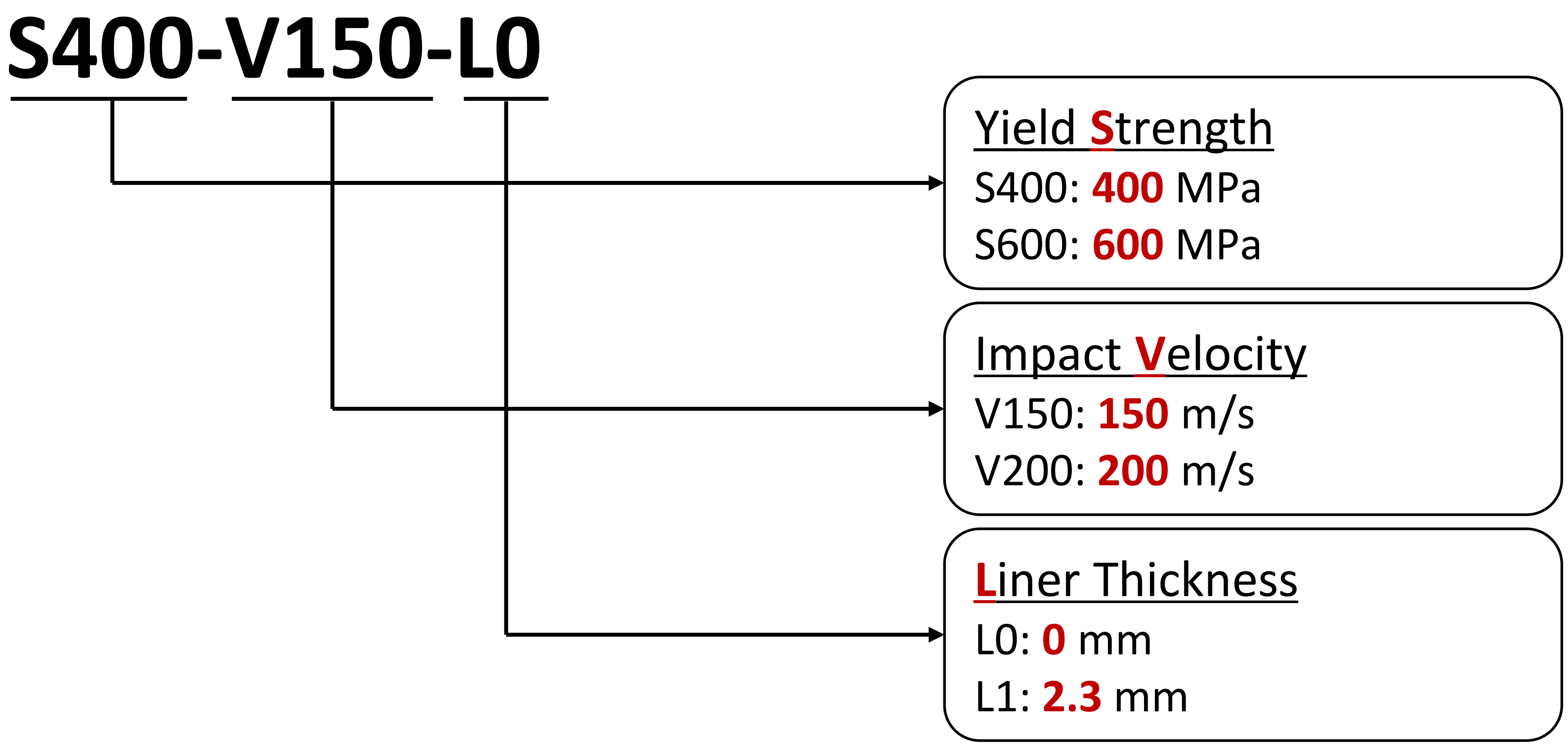
- Impact test of RC panels with steel liner
  - Establishment of test plan
  - Execution of test plan
  - Analysis of test results
- Parametric study through numerical simulation
  - Verification of numerical model
  - Numerical analysis on effects of rebar and steel liner on impact resistance of RC panel and its underlying mechanism
  - Suggestion of design factors and guideline

II. Impact Test of RC Panel with Steel Liner

Impact Test of RC Panel with Steel Liner

❖ Test variables

- Rebar yield strength: 400 and 600 MPa
- Impact velocity: 150 and 200 m/s
- Steel liner thickness: 0 and 2.3 mm



Impact Test of RC Panel with Steel Liner

❖ Test variables

- Rebar yield strength: 400 and 600 MPa
- Impact velocity: 150 and 200 m/s
- Steel liner thickness: 0 and 2.3 mm

	Designation	Liner thickness, mm	Yield strength, MPa	Impact velocity, m/s
1	S400-V150-L0	0	400	150
2	S400-V200-L0			200
3	S600-V150-L0		600	150
4	S600-V200-L0			200
5	S400-V150-L1	2.3	400	150
6	S400-V200-L1			200
7	S600-V150-L1		600	150
8	S600-V200-L1			200

Impact Test of RC Panel with Steel Liner

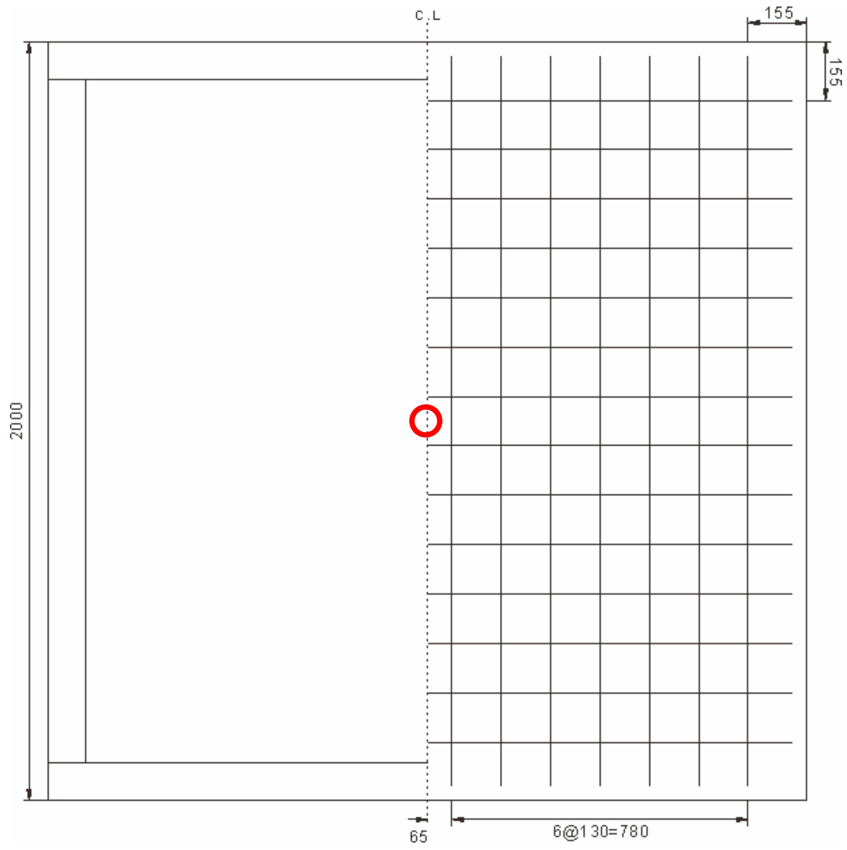
❖ Scaled RC panel of NPP structures

- Shin-Kori NPP 3 (APR 1400) scaled to the similarity ratio of 1 : 2.4
- To maintain similar global behavior, rebar spacing was adjusted for consistent value of ρf_y
  - Yield strength from material tests indicate more consistent global behavior of specimens

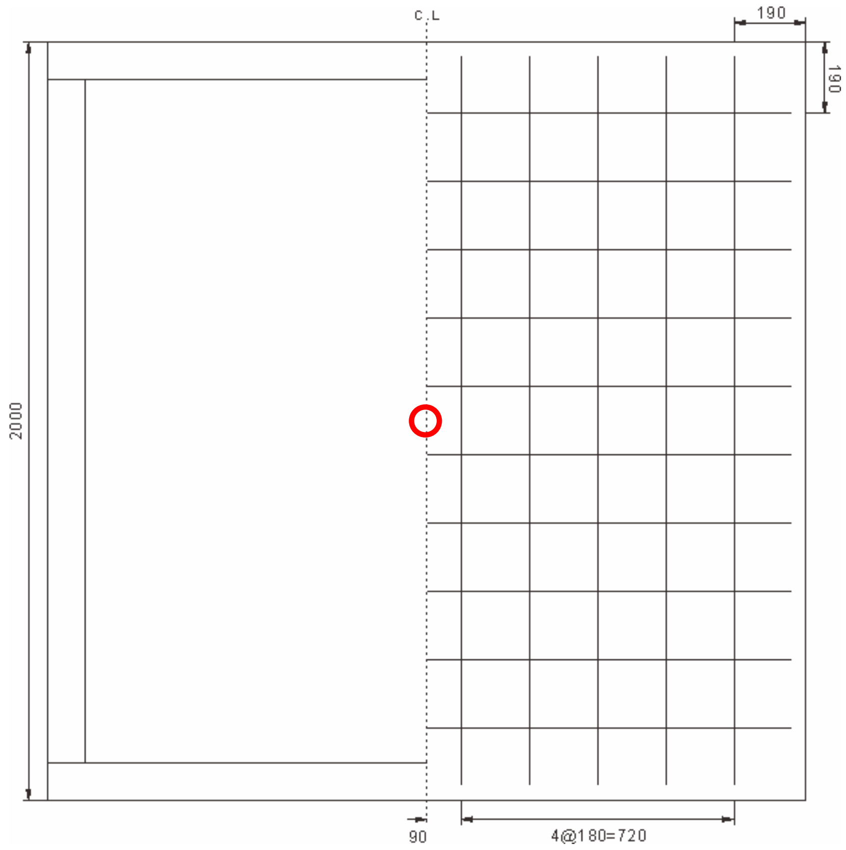
		Target panel		Test panel	
		Shin-Kori NPP 3	Scaled parameter	SD400 (Expected)	SD600 (Expected)
Material property	Nominal concrete strength, MPa	42		49	
	Nominal rebar yield strength, MPa	400		400 (484) [4]	600 (670)
Panel dimension	Rebar diameter	D57	23.9	D25	
	Panel thickness, m	1.2	0.5	0.5	
	Rebar spacing, mm	305	127.1	130	180
	Rebar ratio, %	0.92		0.87	0.63
	ρf_y, MPa	3.68		3.49 (4.21)	3.78 (4.22)

Impact Test of RC Panel with Steel Liner

- RC panel
  - No reinforcing crossed the center of the target
  - Reinforced with L-shaped frames around the corner to prevent premature at the supports



S400

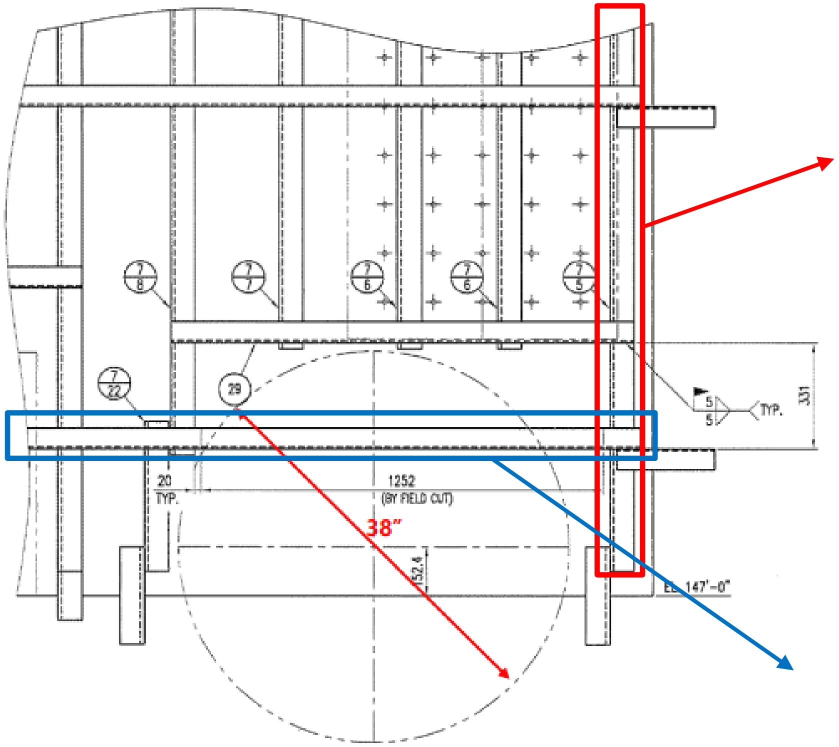


S600

Impact Test of RC Panel with Steel Liner

❖ Steel liner in NPP structures

- Nominal thickness of 6 mm [5] steel liner is reinforced with vertical and horizontal stiffeners
- Only angle stiffener is adopted as an agent for composite action according to spacing specification



CLP drawing

Angle stiffener

Channel stiffener

<u>Liner Plate (CLP)</u>

¼" thick (TYP.)

ASME SA-516 Gr. 60

<u>Angle Stiffener</u>

LK 3×3×1/2 – ASME SA-36

15" spacing (TYP.)

<u>Channel Stiffener</u>

CK 5×9 – ASTM A36

24" ~ 42" spacing

Impact Test of RC Panel with Steel Liner

❖ Scaled steel liner specification

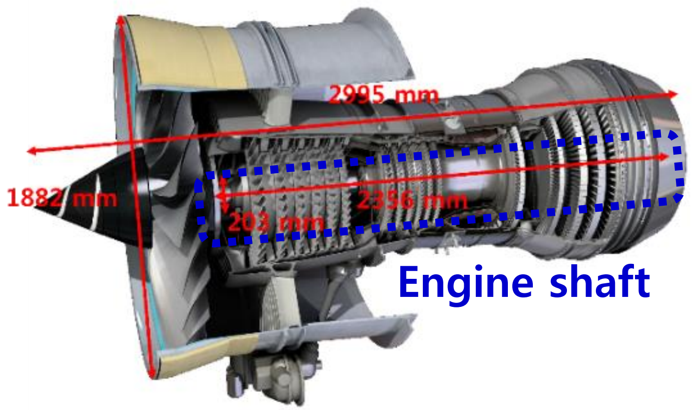
- Thickness of the steel liner scaled to the similarity ratio of 1 : 2.4
- Replacement of ASME SA-516 Gr. 60 with SS275 of similar yield and tensile strength
  - Similar yield strength from Material tests [6-7]

		CLP in NPP structure		**Test specimen**
		CLP in NPP structure (Expected)	Scaled parameter	**Available product (Expected)**
Liner plate	Material	ASME SA-516 Gr. 60	-	**SS275**
	Thickness, mm	6	2.5	**2.3**
	Min. yield strength, MPa	220 (295 [6])	-	**275 (311 [7])**
	Min. tensile strength, MPa	415 (430 [6])	-	**415 (480 [7])**
Angle steel	Material	ASME SA-36	-	**ASME SA-36**
	Size, mm	76.2 × 76.2 × 12.7	31.75 × 31.75 × 5.29	**40 × 40 × 5**
	Spacing, mm	381	158.75	**160**

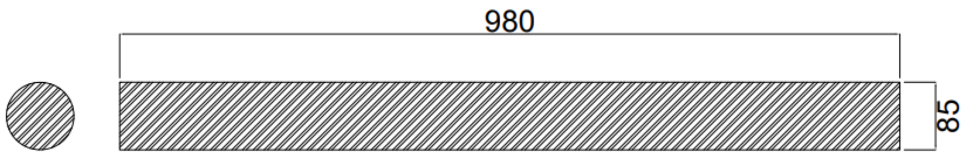
Impact Test of RC Panel with Steel Liner

❖ Hard (non-deforming) projectile for aircraft collision

- Engine shaft of commercial aircraft scaled to similarity ratio of 1 : 2.4



Boeing 757 turbo fan engine
(Recommended by DOE-STD-3014-2006 [3])

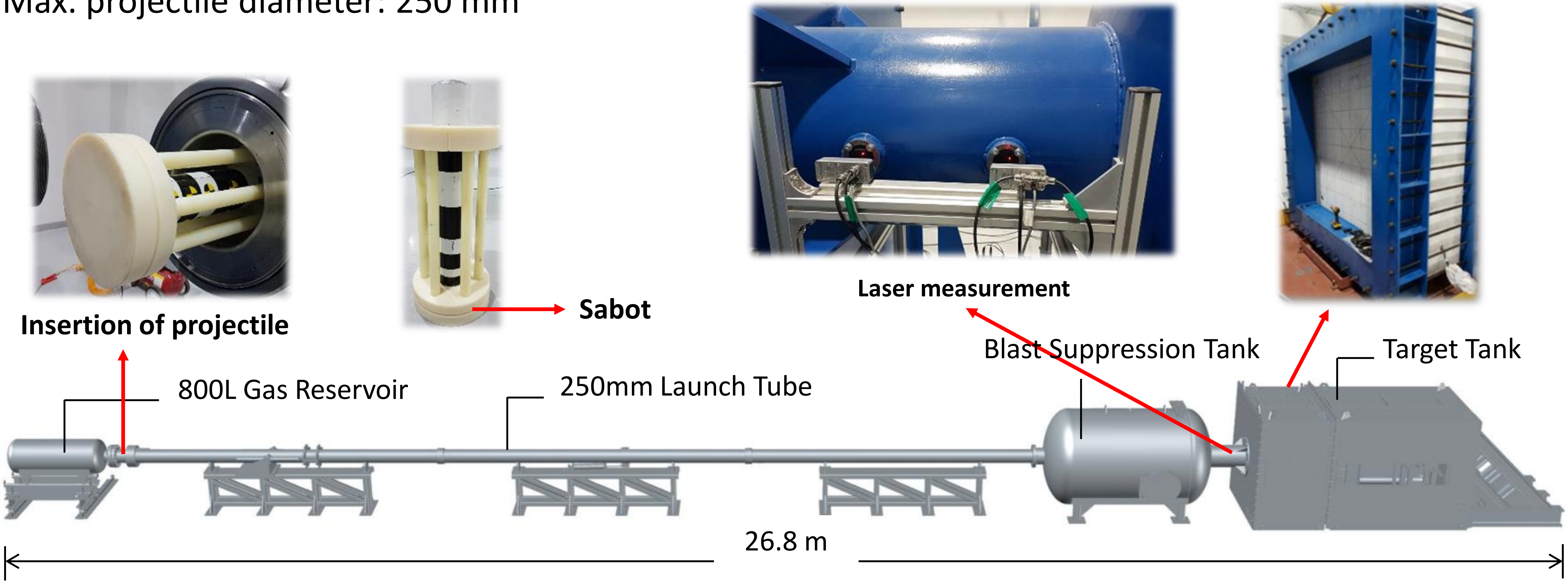


Projectile drawing (Unit: mm)

	Boeing 757 turbo fan engine	Scaled parameters	Projectile specimen
Dimension, mm	D203 × L2356	D84.5 × L981.7	D85 × L980 solid cylinder
Mass, kg	-	-	43.6
Material	-	-	SS275

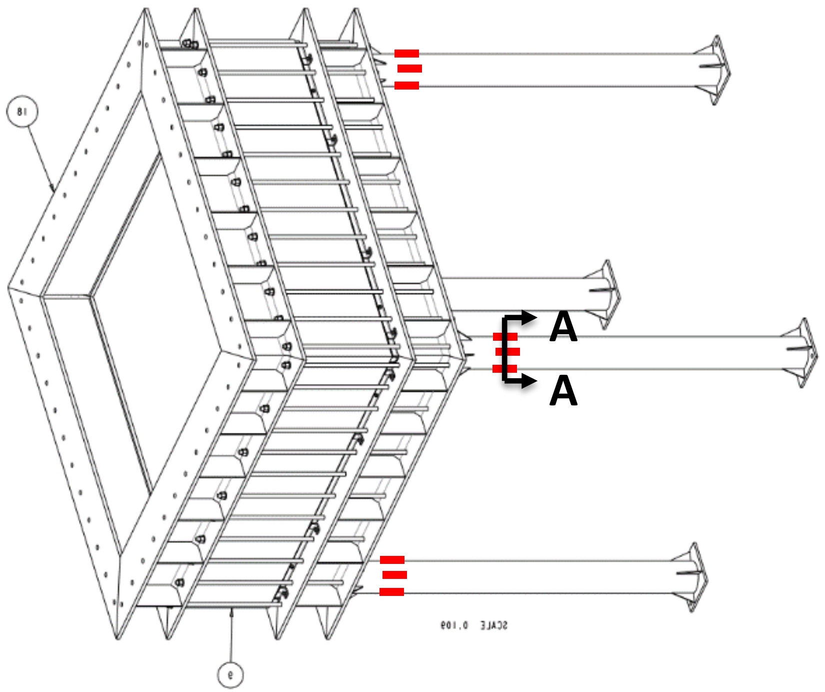
Impact Test of RC Panel with Steel Liner

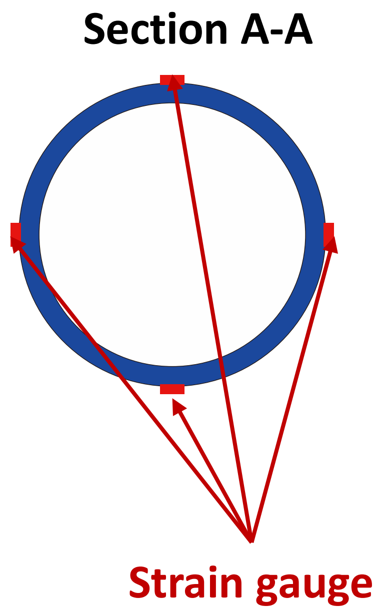
- Single stage gas gun (Extreme performance testing center located at SNU)
  - Max. projectile mass: 100 kg
  - Max. impact velocity: 470 m/s
  - Max. projectile diameter: 250 mm

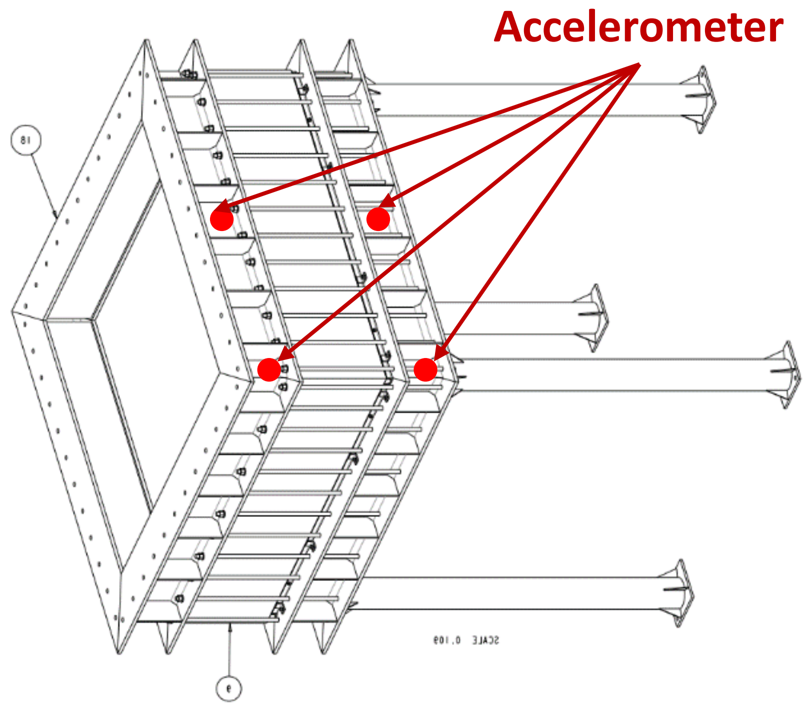


Impact Test of RC Panel with Steel Liner

- Measurement of reaction force and inertial force
  - Validity of impact tests can be verified
    - Impact force of the projectile is absorbed by the local failure of the panels
    - Obtained inertial force is needed to calculate pure reaction force induced from the test



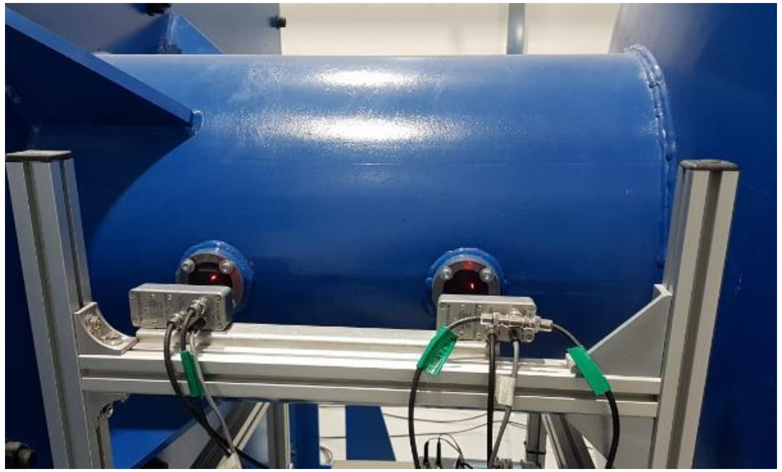




Impact Test of RC Panel with Steel Liner

❖ Measurement of striking and residual velocity

- Obtained velocity of projectile can be used to evaluate the impact resistance of RC panels
  - Striking velocity — Laser interrupt system
  - Residual Velocity — High-speed camera



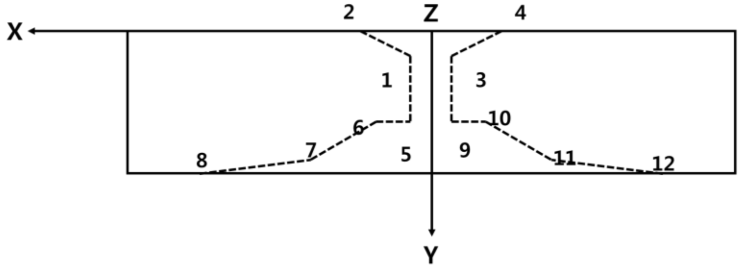
Laser interrupt system

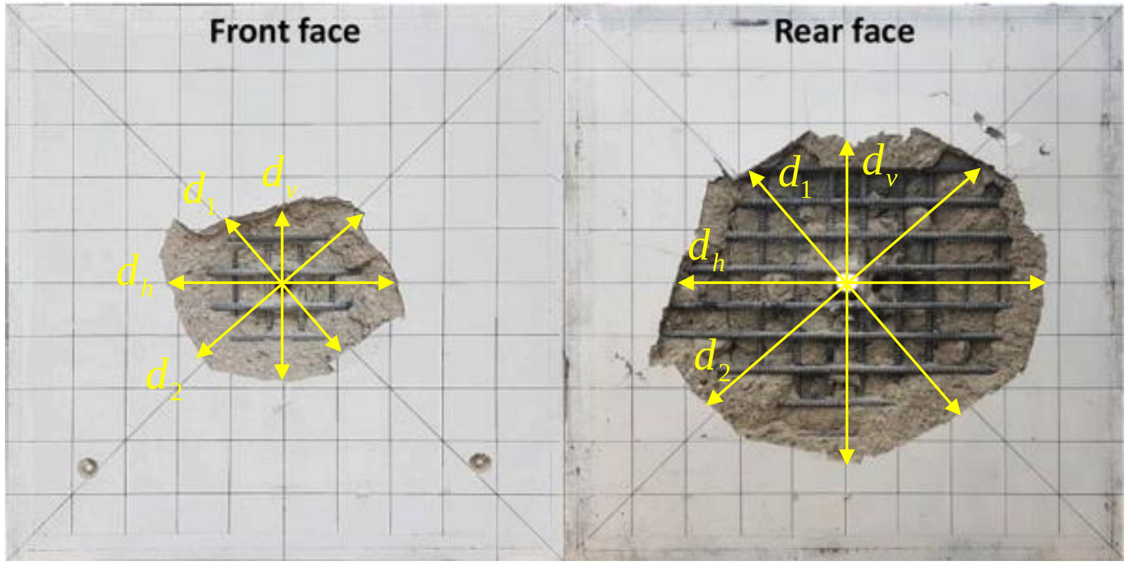
High-speed camera

Video of projectile at rear face

Impact Test of RC Panel with Steel Liner

- Measurement of failure shape
  - Depth, diameter and area of craters can be used to assess the impact behavior of RC panels



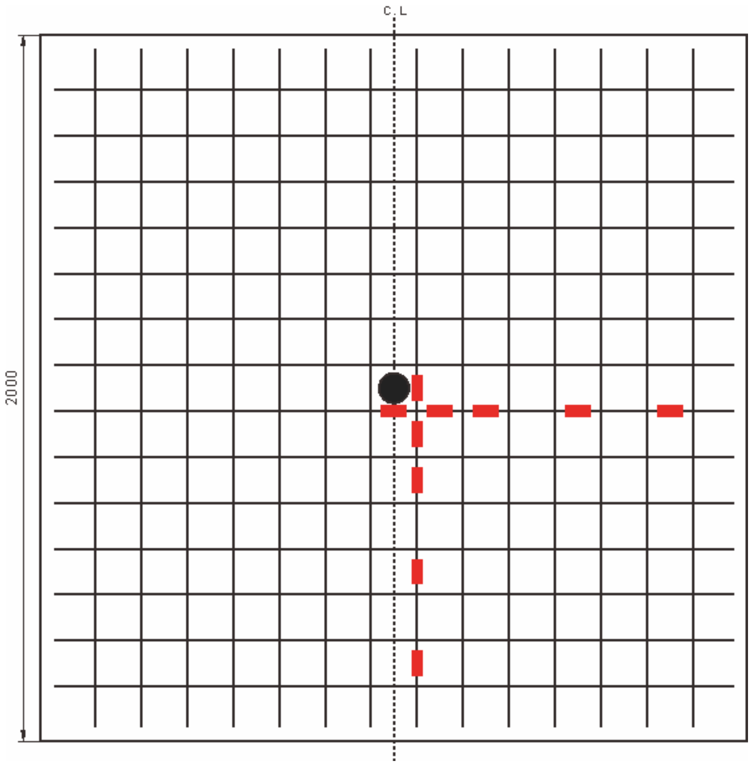


Equivalent diameter of craters

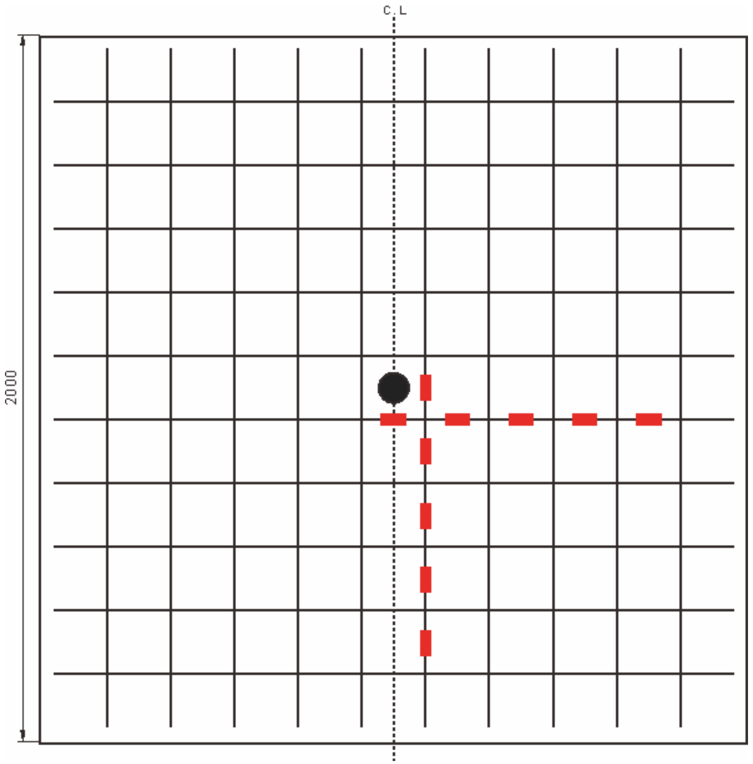
$$D_m = \left(d_h + d_v + d_1 + d_2\right) / 4$$

Impact Test of RC Panel with Steel Liner

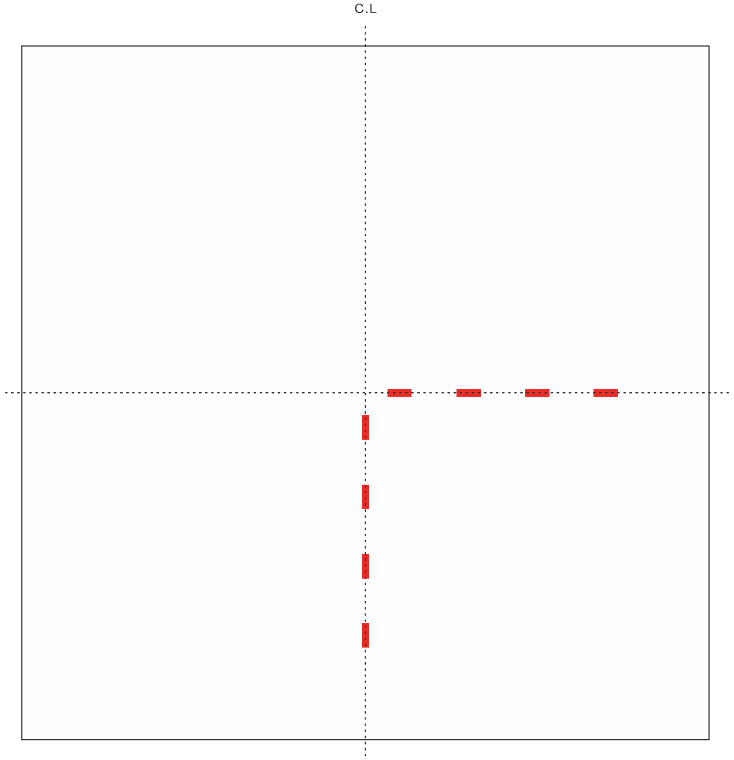
- ❖ Strain of reinforcing steel and steel liner
  - Evaluating the area in which the rebar and steel liner has yielded to investigate their impact behavior
  - Obtained responses will be used to verify the numerical model for parametric study



SD400



SD600



Steel liner

Impact Test of RC Panel with Steel Liner

❖ Strain of reinforcing steel and steel liner

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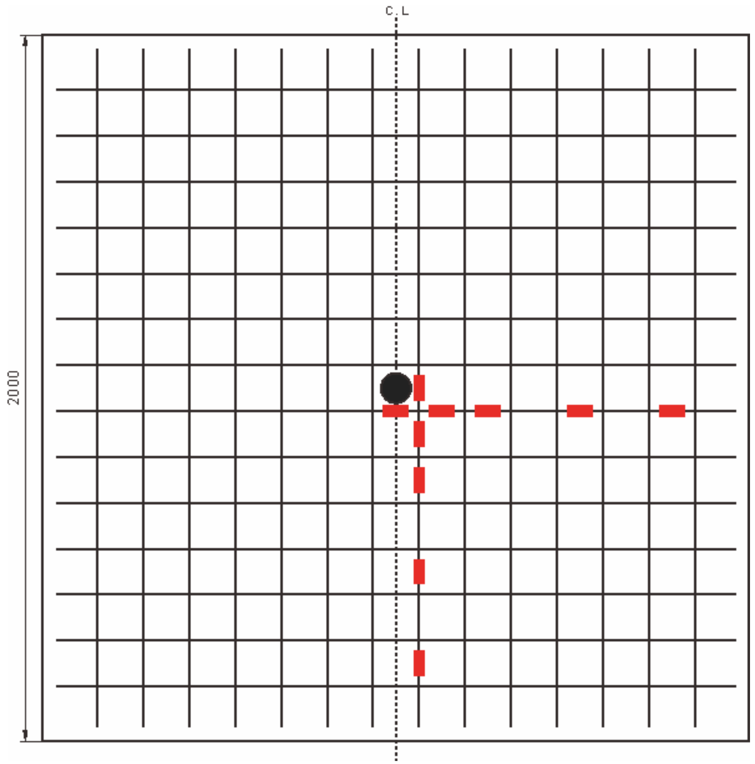
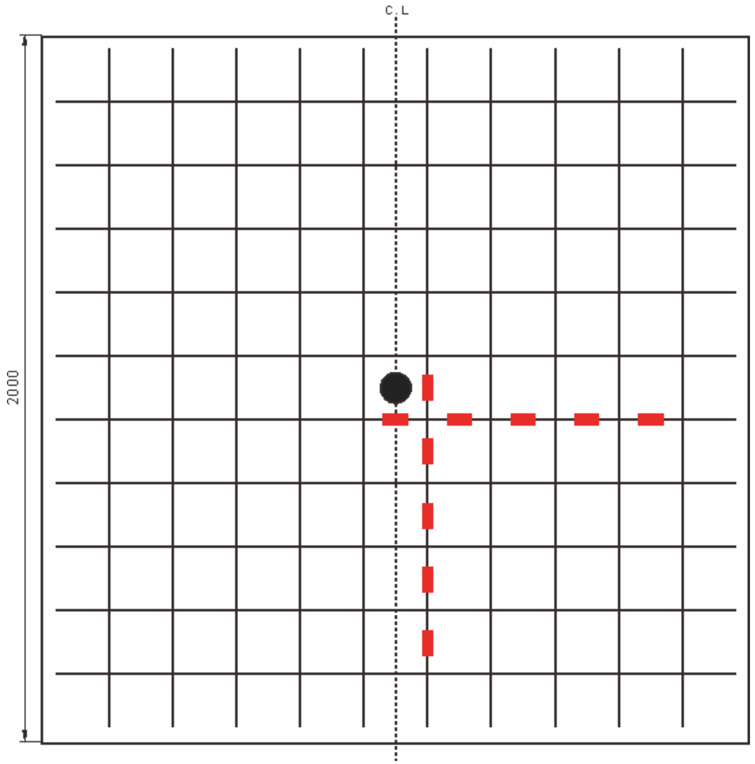
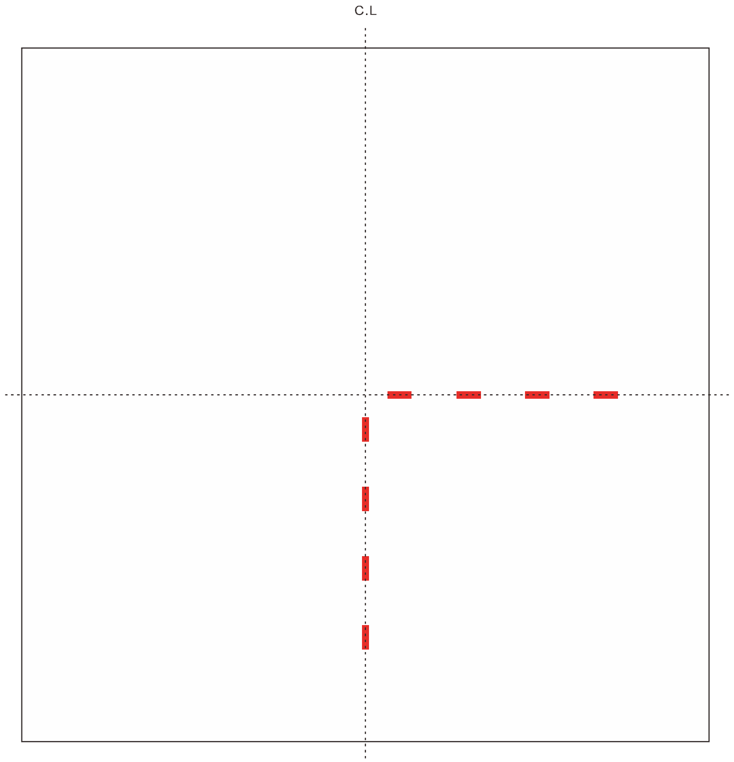


SD400



SD600



Steel liner

III. Numerical Analysis Program

Numerical Analysis Modeling

❖ Impact test of RC panels by Lee et al. [4]

- Experimental investigation into the effect of reinforcing steel on impact resistance of RC panels under impact loadings
- Variables in impact tests
  - Impact velocity: 100 – 200 m/s
  - Reinforcing steel: spacing & yield strength
- Test cases with scabbing and perforation failure were selected for the verification of numerical models

	Designation	Projectile				RC panel		
		Mass, kg	Diameter, mm	Length, mm	Impact velocity, m/s	Compressive strength, MPa	Yield strength, MPa	Rebar diameter & spacing, mm
1	V150-SD400	43.6	85	950	151.6	49	400	D25@130
2	V200-SD400				199.6			
3	V150-SD600				152.4		600	D25@180

Numerical Analysis Modeling

❖ Impact test of RC panels by Lee et al. [4]

- Experimental investigation into the effect of reinforcing steel on impact resistance of RC panels under impact loadings
- Variables in impact tests
  - Impact velocity: 100 – 200 m/s
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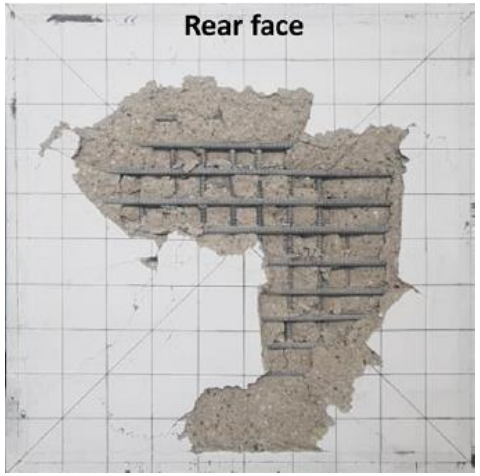


V150-SD400

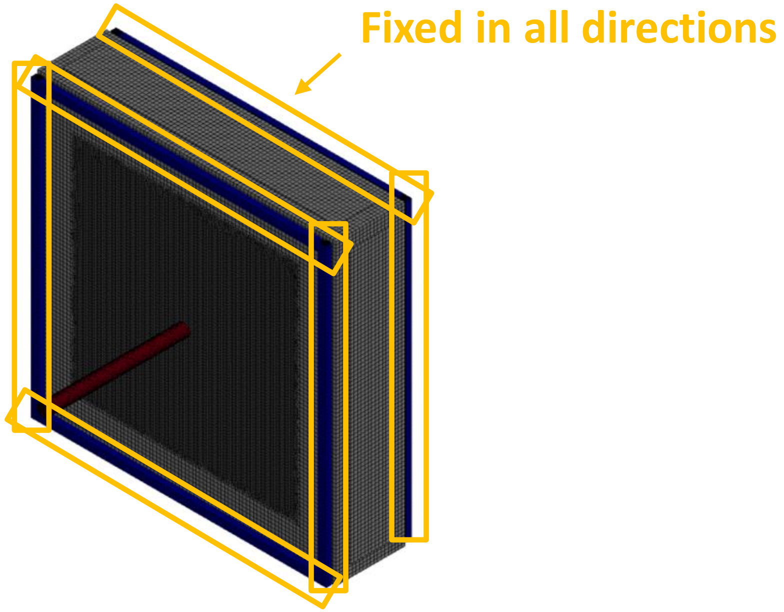
V200-SD400

V150-SD600

Numerical Analysis Modeling

❖ RC panel - material model

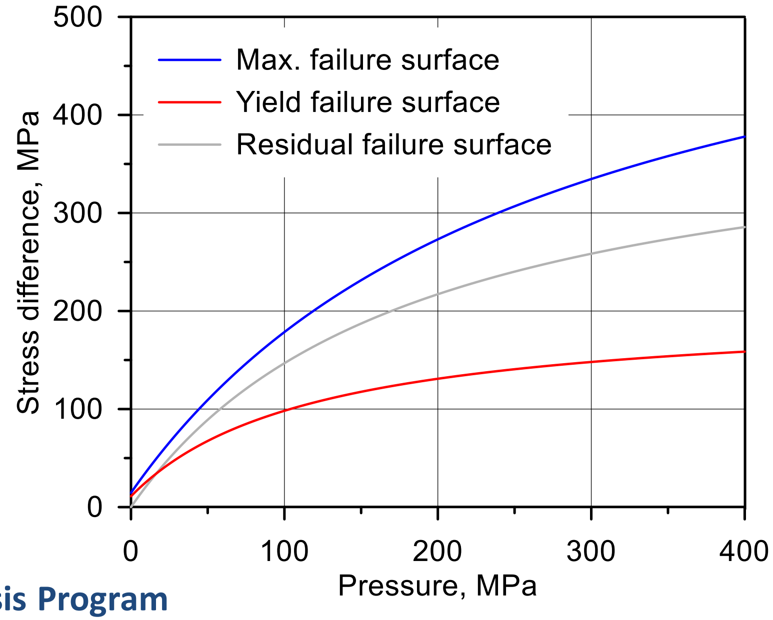
- Initial condition
  - Initial velocity of hard projectile was input considering impact velocity measured in the tests
- Contact condition
  - Automatic surface to surface option was used for contact among panel, projectile and supports with 0.2 for static and 0.1 for dynamic frictional coefficient (Referring to Deb et al. [8])
- Boundary condition



Numerical Analysis Modeling

❖ RC panel - material model

- Karagozian & Case concrete (KCC) model (MAT072R3) [9-11]
- Erosion criterion (MAT_ADD_EROSION) was considered due to severe mesh distortion
  - Maximum principal strain = 0.1 (Referring to Luccioni et al. [12])
- Model parameters
  - Failure surface — Auto-generating parameters (Wu and Crawford [10])
  - Uniaxial tensile strength — fib MC2010 [13]



$$a_0 = 14.5915 \text{ MPa} \qquad a_{0y} = 11.0225 \text{ MPa}$$

$$a_1 = 0.4463 \qquad a_{1y} = 0.625$$

$$a_2 = 0.001637 \text{ MPa}^{-1} \qquad a_{2y} = 0.005216 \text{ MPa}^{-1}$$

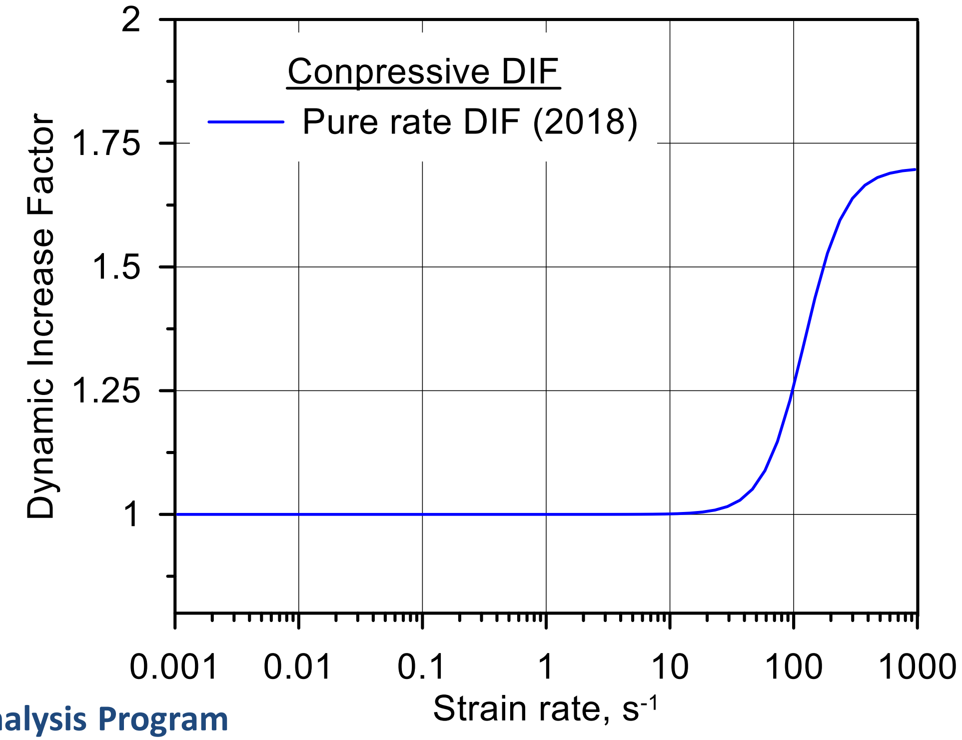
$$f_t = 3.94 \text{ MPa} \qquad a_{1f} = 0.4417$$

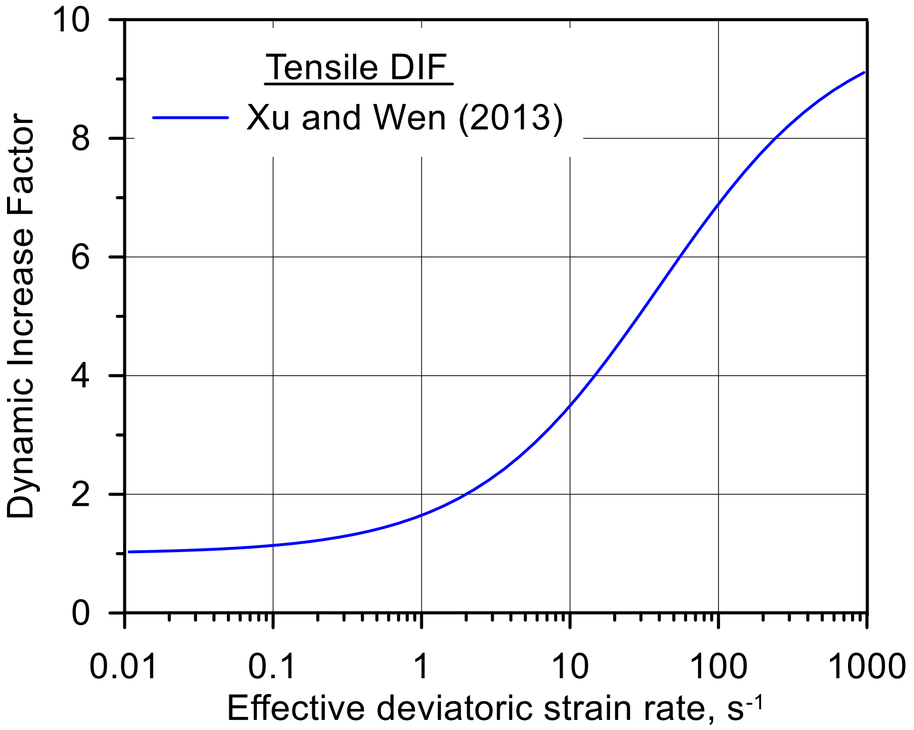
$$a_{2f} = 0.002397 \text{ MPa}^{-1}$$

Numerical Analysis Modeling

❖ RC panel - material model

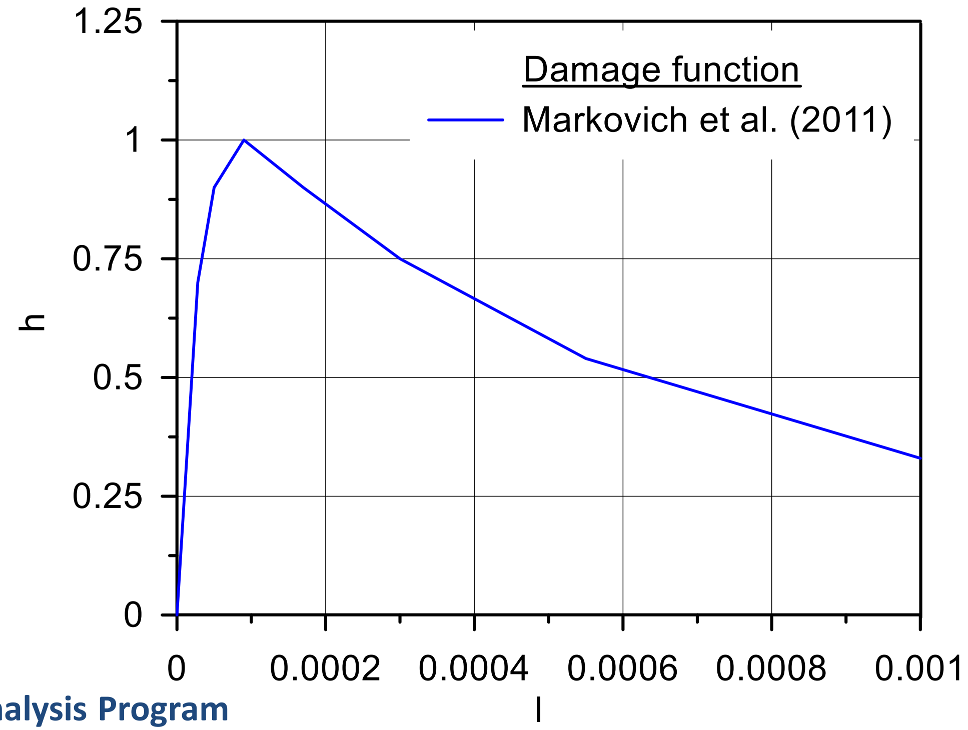
- Model parameters
  - Compressive DIF — Pure rate DIF (Lee et al. [14])
  - Tensile DIF — Xu and Wen [15]
  - Localization width — 25 mm ($1G_{max}$)
  - Associativity parameter — 0.9 (Well-confined normal strength concrete [11])





Numerical Analysis Modeling

- RC panel - material model
  - Model parameters
    - Damage function ($\eta - \lambda$ relation) — Markovich et al. [16]
    - Damage scaling factors (b_1, b_2, b_3) — b_1=0.93, b_2=2.18 (Wu and Crawford [10]); b_3=1.15 (default)
    - Equation of state — Scaled EOS of (Wu and Crawford [10])



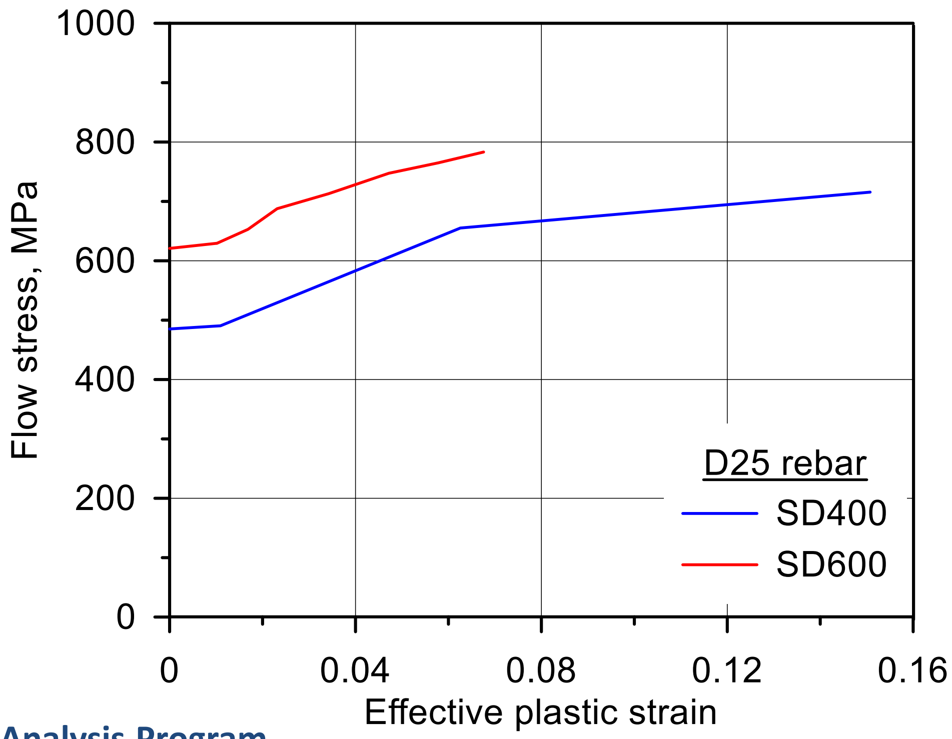
EOS 008 Tabulated compaction

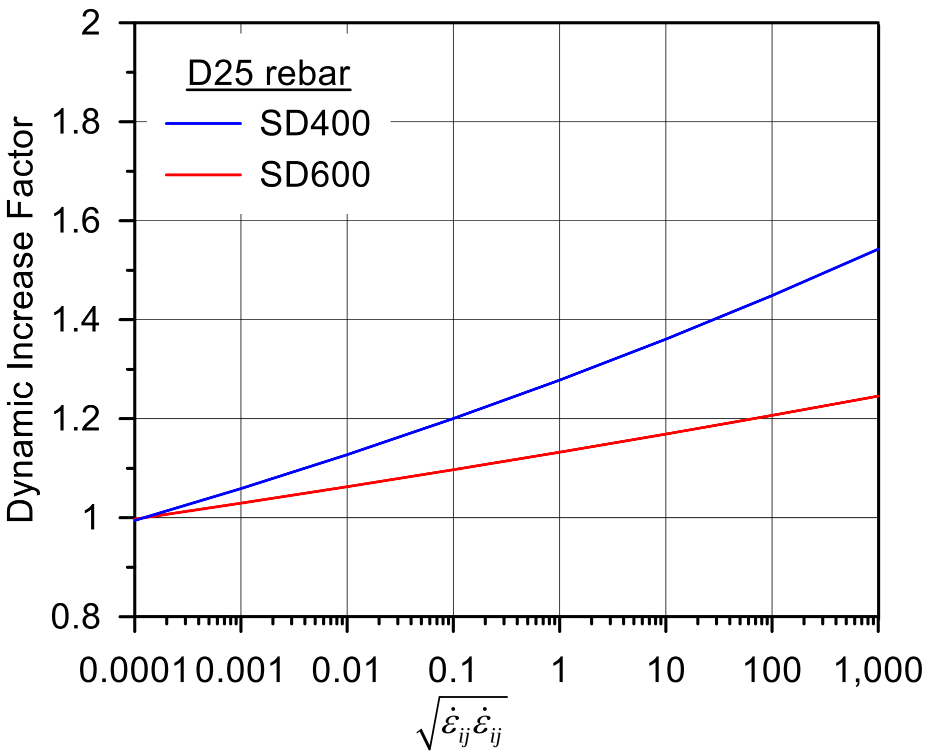
ε_v	p, MPa	K_u, MPa
0	0	18650
-0.0015	28	18650
-0.0043	61	18911
-0.0101	98	19858
-0.0305	186	23634
-0.0513	281	27409
-0.0726	398	31185
-0.0943	609	34036
-0.174	3556	76570
-0.208	5439	93251

Numerical Analysis Modeling

❖ Rebar – material model

- Piecewise linear plasticity model (MAT024)
  - Linear properties $\mathrm{E} = 200\ \mathrm{Gpa}$ $\rho = 7{,}850\ \mathrm{kg/m^3}$ $\nu = 0.26$
  - Hardening model Isotropic hardening model based on rebar coupon test (Lee et al. [4])
  - DIF Yield strength DIF by Malvar formula [17,18]





Numerical Analysis Modeling

- Projectile - material model
  - Rigid model (MAT020)
    - Linear properties $\mathrm{E} = 200\ \mathrm{GPa}$ $\rho = 7{,}850\ \mathrm{kg/m^3}$ $\nu = 0.29$

- Frame – material model
  - Linear elastic model (MAT001)
    - Linear properties $\mathrm{E} = 205\ \mathrm{GPa}$ $\rho = 7{,}850\ \mathrm{kg/m^3}$ $\nu = 0.29$

Numerical Analysis Result

❖ Penetration depth and residual velocity of projectile

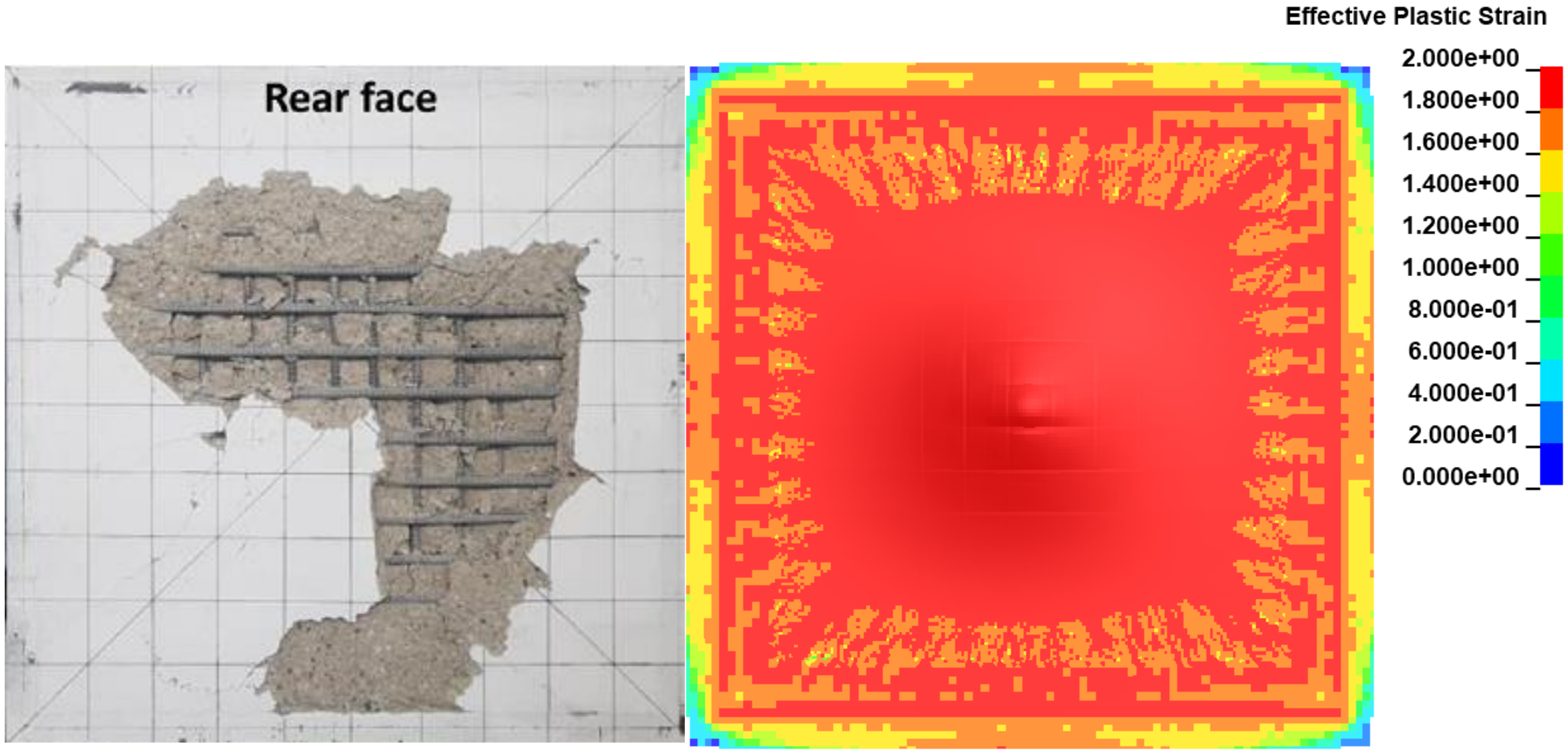
- Results from numerical model can predict both penetration depth and residual velocity of projectile reasonably
- For case of V150-SD600, the error was about 53% due to the low residual velocity measured in the test

Designation	Impact velocity, m/s	Failure mode		Penetration depth, mm			Residual velocity, m/s		
		Test	Model	Test (a)	Model (b)	{(b)-(a)}/(a)	Test (a)	Model (b)	{(b)-(a)}/(a)
V150-SD400	151.6	Scabbing	Scabbing	391	370	**-5.37%**	-	-	-
V200-SD400	199.6	Perforation	Perforation	-	-	-	97.2	100.3	**2.88%**
V150-SD600	152.4	Perforation	Perforation	-	-	-	15.2	23.3	**53.3%**

Numerical Analysis Result

❖ Damage contour of rear face of the panels

- Damage contour obtained from numerical simulation predict the scabbed area of RC panels reasonably

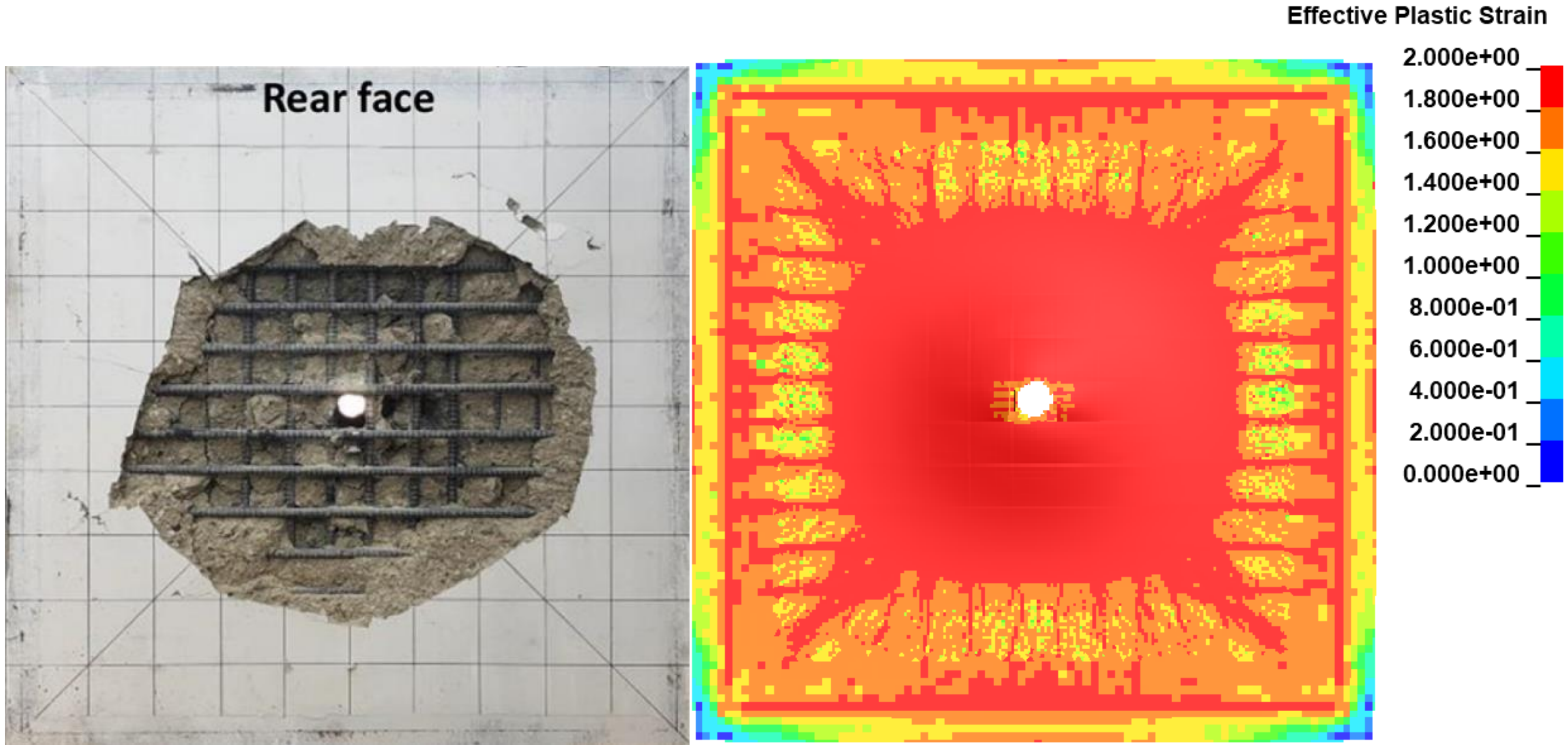


V150-SD400

Numerical Analysis Result

❖ Damage contour of rear face of the panels

- Damage contour obtained from numerical simulation predict the scabbed area of RC panels reasonably

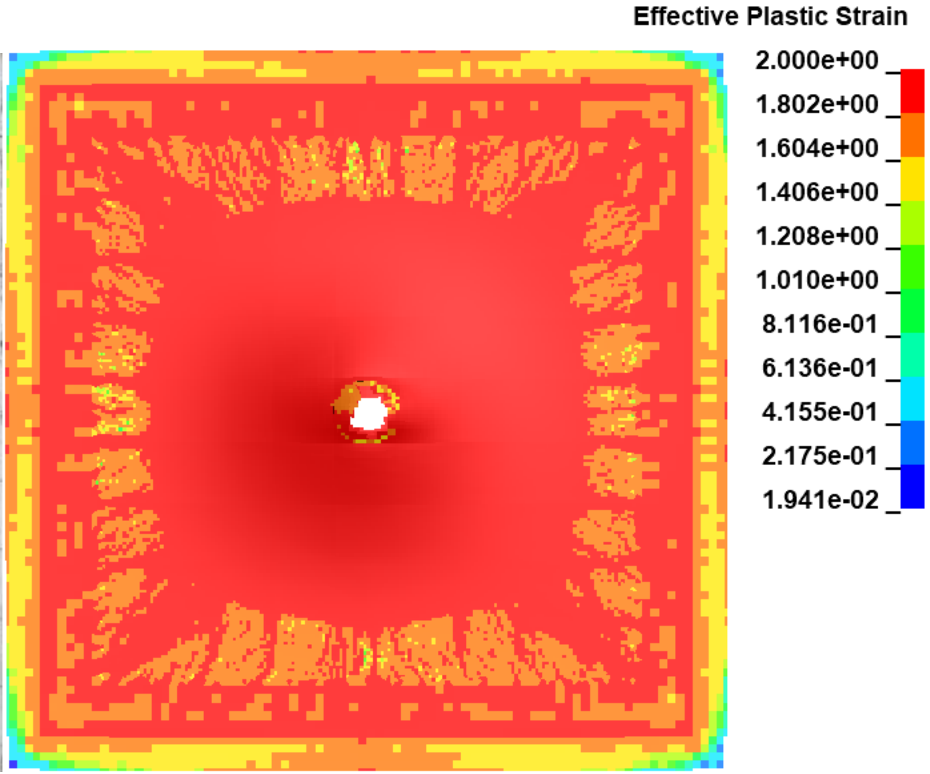


V200-SD400

Numerical Analysis Result

❖ Damage contour of rear face of the panels

- Damage contour obtained from numerical simulation predict the scabbed area of RC panels reasonably



V150-SD600

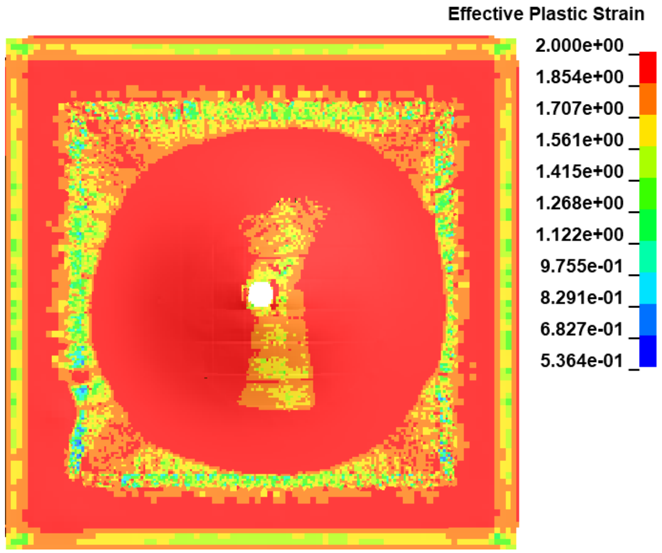
Numerical Analysis Result

❖ Effect of bonding condition on Impact behavior of projectile and target

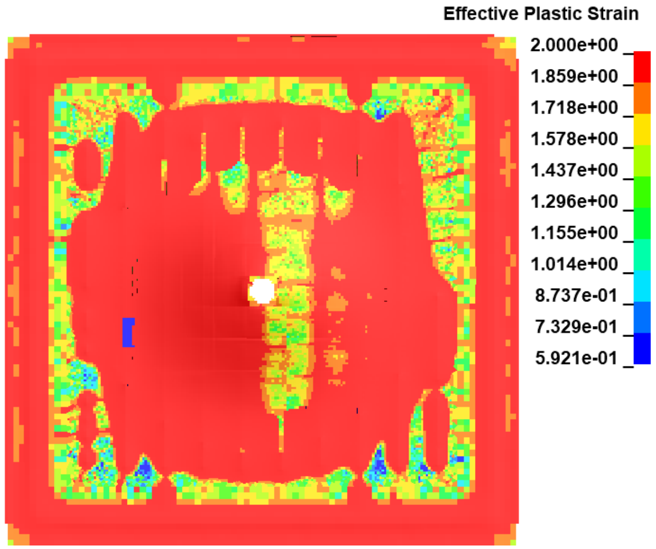
- Bonding condition of steel liner was numerically analyzed
  1. Full merge: all nodes of RC panel and steel liner were merged
  2. Partial merge: nodes at angle stiffener were merged with RC panel
- Predicted residual velocity of projectile showed similar values

➢ **Current bonding condition will reproduce composite action between RC panels and steel liner**

Bonding condition	Residual velocity, m/s
No steel liner	100.0
Full merge	53.0
Partial merge	54.7



Full merge



Partial merge

IV. Concluding Remark

Concluding Remark

❖ Conclusion

- Test program was planned to investigate the effects of rebar and steel liner on impact resistance of RC panels
  - Main variables were yield strength of rebar, steel liner and impact velocity

- Numerical model was verified with test results from prior research on impact test of RC panels (Lee et al. [4])
  - Erosion criterion was empirically determined
  - Penetration depth and residual velocity of projectile were predicted with reasonable errors
  - Damage contour of the rear face of RC panels were predicted at an appropriate level

- Effect of bonding condition of steel liner on impact behavior of projectile
  - Bonding between RC panel and steel liner were numerically simulated to validify the spacing of angle stiffener
  - Current boding condition will reproduce complete composite action

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Thank you