Korea's Research Infrastructure for Extreme Events

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Examples of Extreme Events

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Examples of Extreme Events

Extreme Performance Testing Center (EPTC)

Contents

Contents

Definition of Extreme Events

- What is an extreme event?
  - Event whose return period is significantly greater than design life of structures
  - Load or environment such as impact, force, & temperature above normal range

Extreme Conditions

Extreme Load

| The load due to the collision of transport (vehicle / train / ship / aircraft)

| The load due to the collision of missiles

| The load due to the explosion such as explosives / oil / chemical

| Extreme load of natural disasters, such as earthquake / typhoon / tsunami

Extreme Environment

| Extreme temperature load / ultimate high and low temperature

| Extreme pressure environments of ultra-high pressure / vacuum state

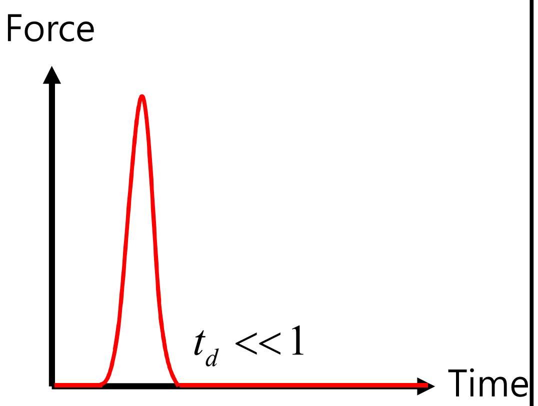
Behavior of Structures under Extreme Events

Characteristics of extreme load

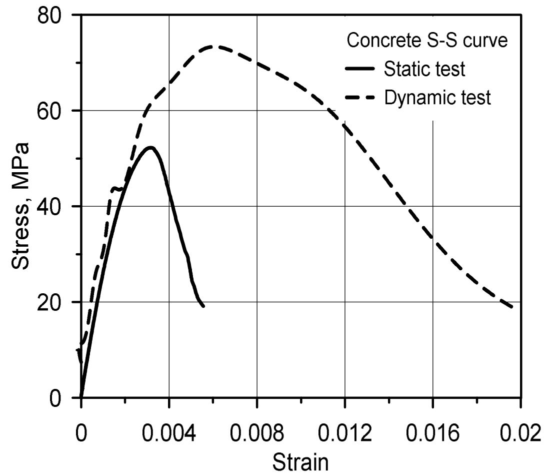
- Very large force during very short duration
  - Maximizing inertia effect and dynamic response
  - Too complex stress state due to stress wave propagation effect
- Structures deform at the range of high strain rate ($\dot{\varepsilon}$)
  - Material properties change due to strain rate effect

➡ Structures behave in a completely different way from the static state

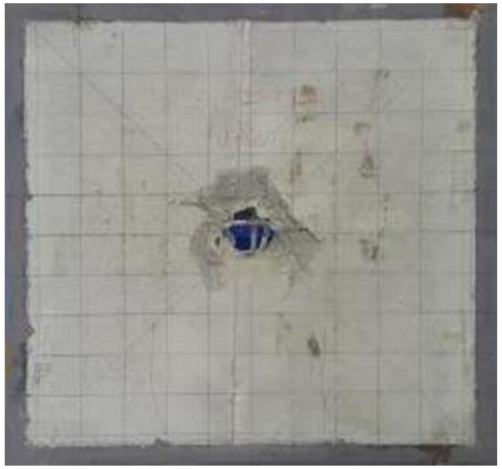
Extreme load



Strain rate effect



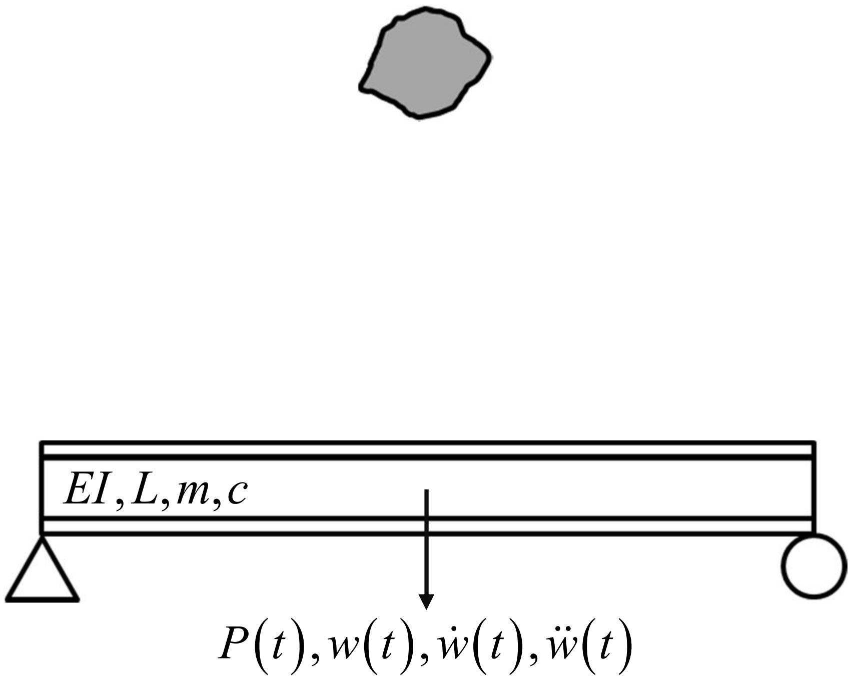
Different behavior

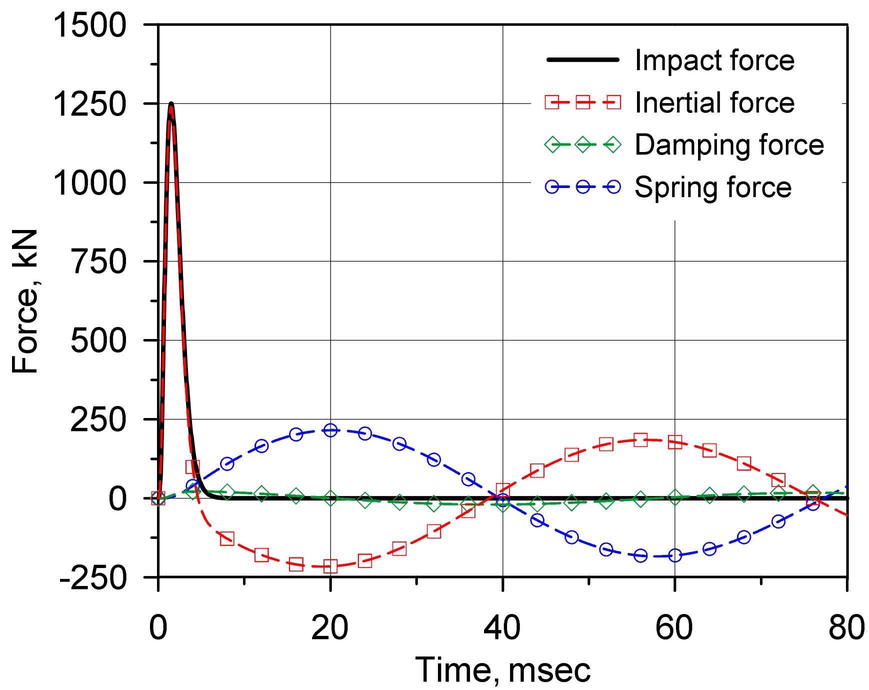


Behavior of Structures subjected to extreme loads

1) Global behavior

- Conventional flexural & shear behavior such as deflection & rotation
- Magnification of the responses of structures due to dynamic effect
- Free vibration due to tremendous inertial force resisting the excitation





Typical resisting forces of linear SDOF system subjected to impact load

Behavior of Structures under Extreme Events

Behavior of Structures subjected to extreme loads

2) Local behavior

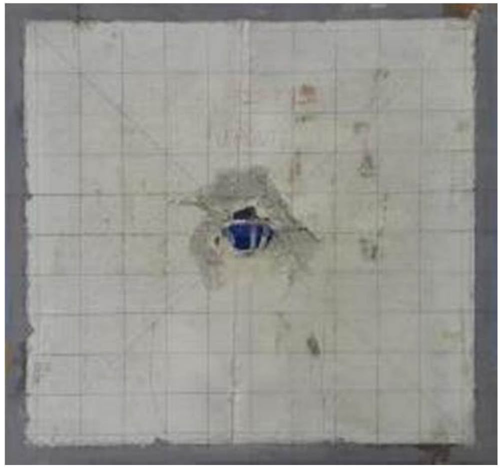
- Premature failure in local region before stress wave disperses in a whole structures
- Tri-axial stress state due to reflection & superposition of stress waves
- Three kinds of failure modes; penetration, scabbing, & perforation

➡ Behavior of structures must be evaluated in a different way from the static state

Penetration

Scabbing

Perforation



Necessity of Analytical/Numerical Approaches

Characteristics of full scale test

- Too expensive cost
- Limitation on test space & institute
- Too dangerous loading condition

➡ Analytical/numerical approaches are necessary to predict behavior of structure

Full Scale Test

F4 crash test (Sandia Nat'l Lab, USA)

Expensive

Huge space

Dangerous

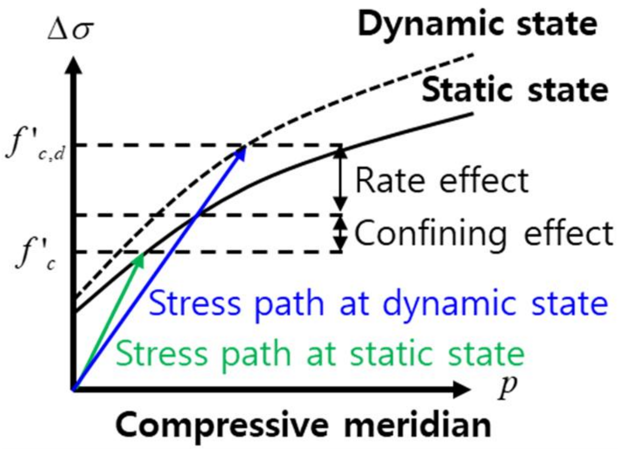
Procedure of Analytical/Numerical Approaches

What EPTC can do

Establishment of predictive model

- Accurate material model is needed
  - Failure surface & equation of state at high strain rate & high pressure

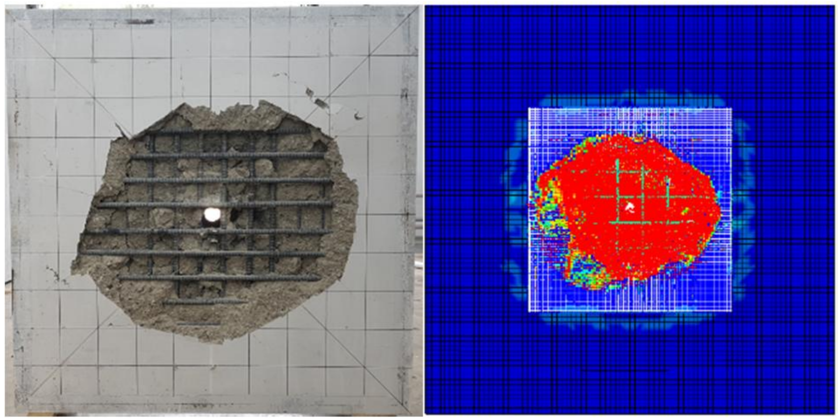
➡ Test in a material level is required



Validation of predictive model

- Result of reliable scaled-model test is needed to validate the predictive model

➡ Test in a member level is required



Parameter study about behavior of structures under extreme event

- Evaluation of resistance of structures subjected to extreme event
- Establishment of design method for structures against extreme event

Impact Tests Simulating Extreme Event

Necessity of Special Apparatus

Compared with conventional static/dynamic test, any kind of high speed loading test is NOT easy

High Rate Material Test

- Split Hopkinson Pressure Bar
- High speed hydraulic machine

Scaled Model Test

- Drop weight tester
- Pendulum impact tester
- Three kinds of gas guns

➡ To obtain parameters of material model to use as an input data for analysis

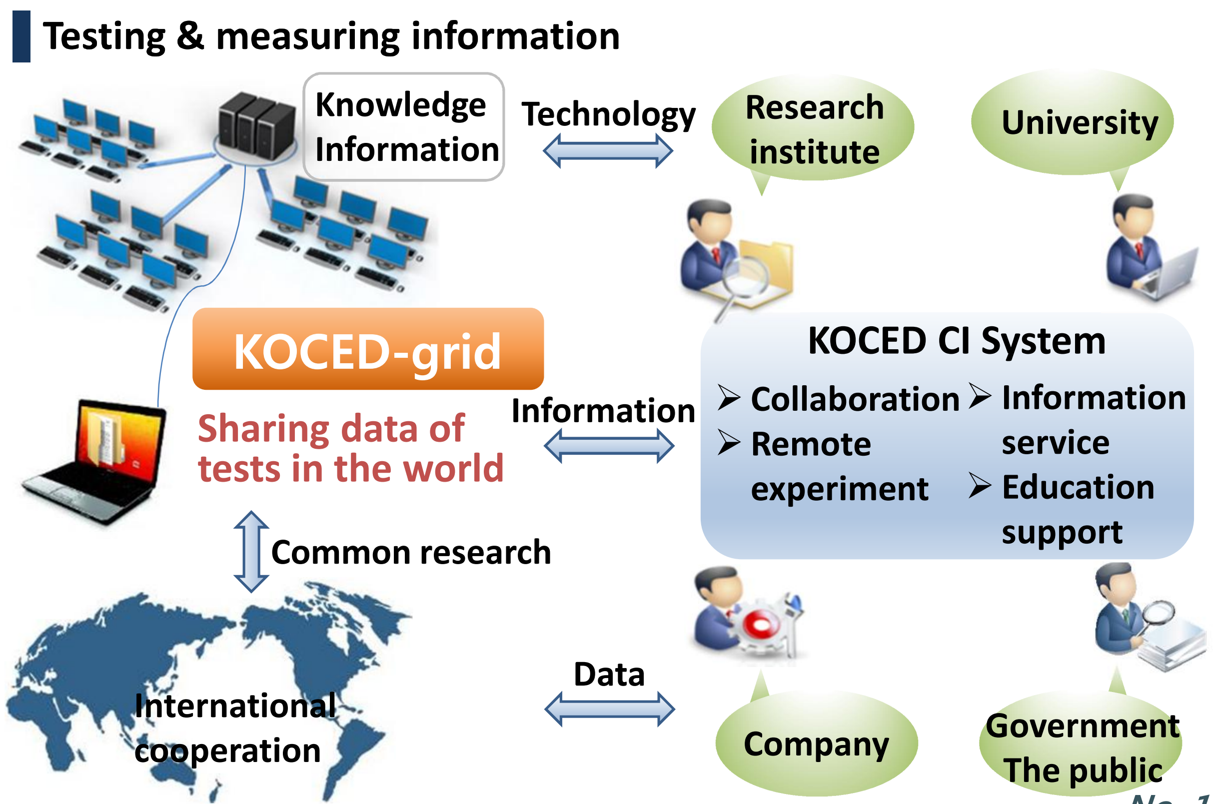
➡ To validate analytical/numerical prediction

Contents

KOCED (KOrea Construction Engineering Development)

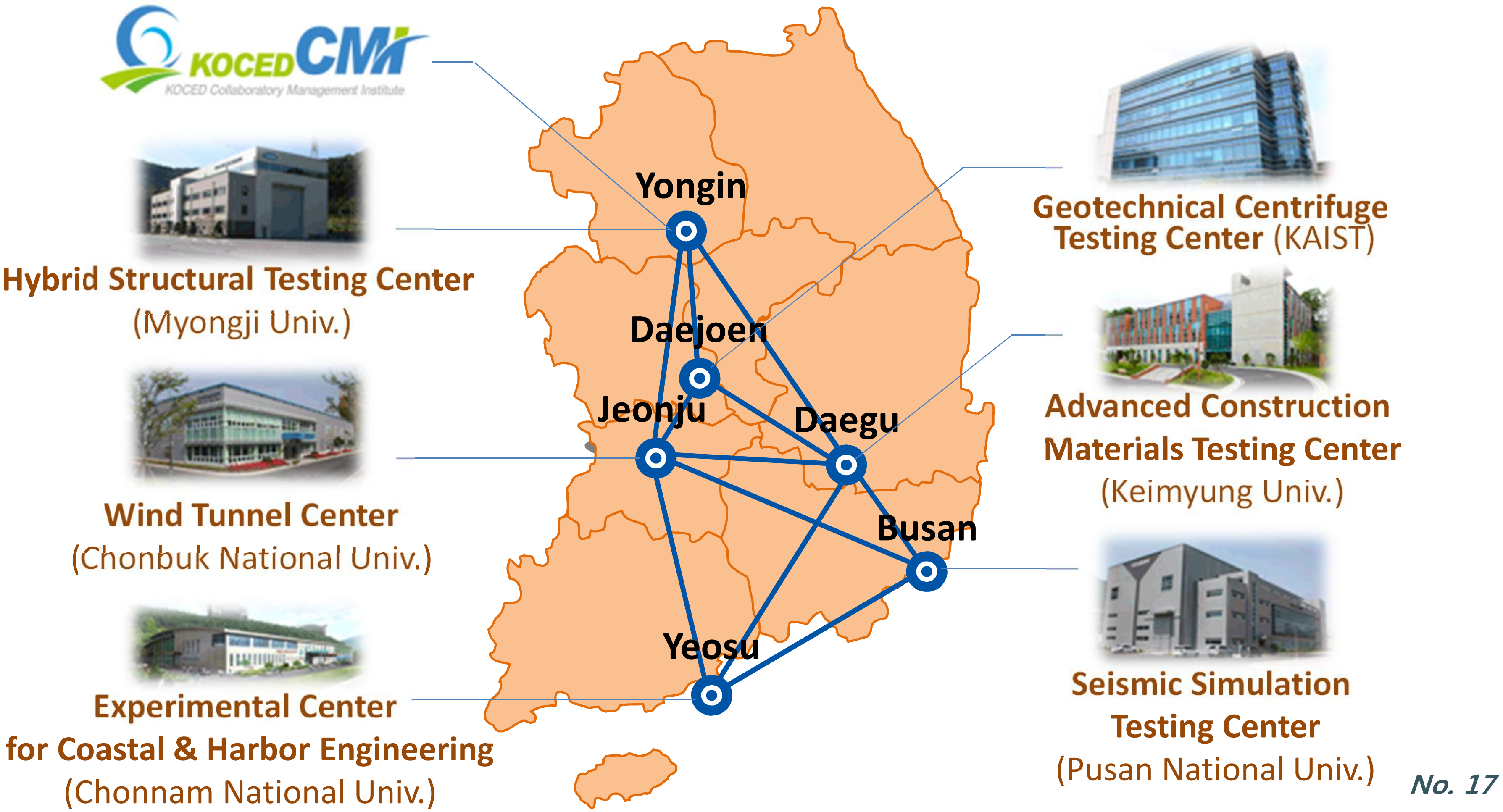
KOCED (KOrea Construction Engineering Development)

- In 2004, Korea Government launched a KOCED Project to improve technology in construction & transportation fields
  - Aims at to build large-scale cutting-edge test facilities
  - Connect the dispersive facilities by national R&D network (KOCED-Grid)



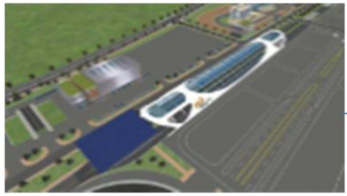
KOCED Phase I (2004~2009, **82 MUSD**)

- Six world-class test facilities constructed at six universities
  - Distributed throughout the Korean Peninsula
  - Connect the facilities by KREONET (Korea Research Environment Open NETwork)



KOCED Phase II (2013~2018, **144 MUSD**)

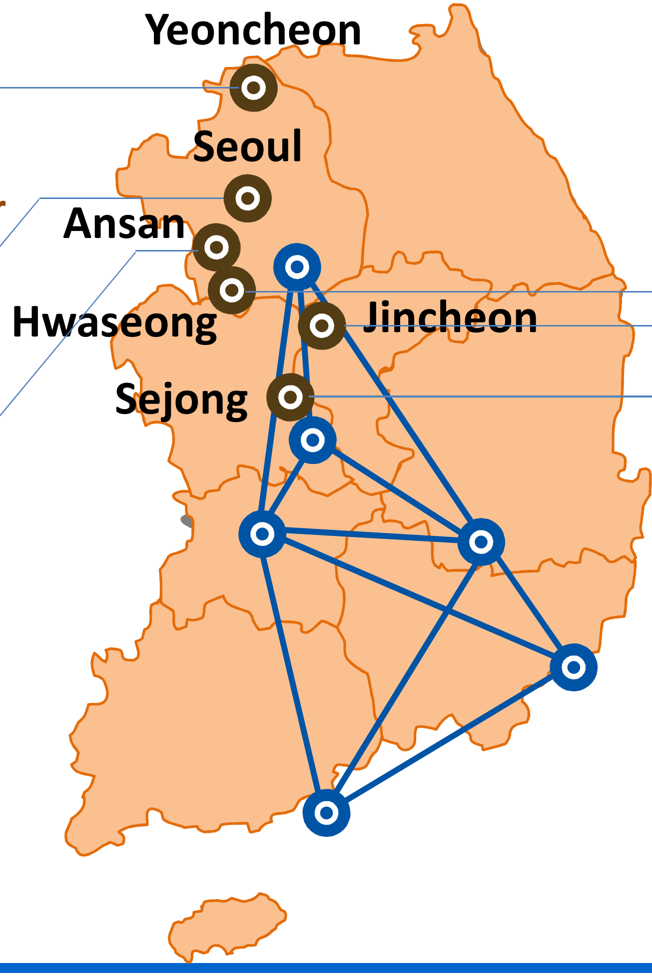
- Another six world-class test facilities constructed at univ. & institutes
  - Enlarging the fields: Basic civil construction → transportation, housing, road, etc.



Facilities to Reproduce Weather Conditions for Road (KICT)

Extreme Performance Testing Center (SNU)

Large Experimental Facility for Hydraulic Model Test (KRC)

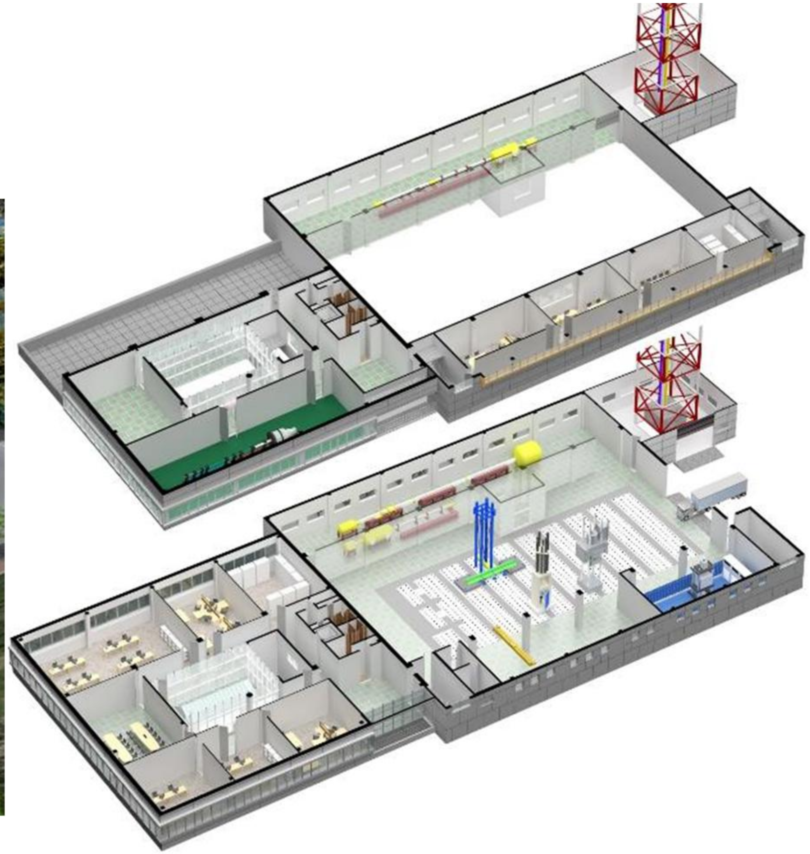


Driving Simulator Experiment Facilities (KECRI)

Multi-environmental Experiment Facilities for Climate Change (KCL)

Housing Performance Test Facilities for Improving Life Quality (LH)

Project Outline



Project

Establishment of Structural Performance Testing Facilities for Extreme Conditions

Sponsor

MOLIT (Ministry of Land, Infrastructure and Transport)

Period

4 years 10 months (2013.12.23 – 2018.10.22)

Budget 19.1 MUSD

Milestones of EPTC

To build an experimental facility with the highest specification and the most optimal condition for extreme performance testing

Hardware Construction

- Best specification of equipment
- Optimal location and condition
- Comfortable additional facilities

Software Development

- Development of test techniques for extreme conditions
- Development of analysis / performance assessment method
- Acquisition of experiment certification
- Development of the teaching material

Network Link

- Collaboration with KOCED testing center
- On-line data sharing
- Integrated use of similar experiment facility

Training

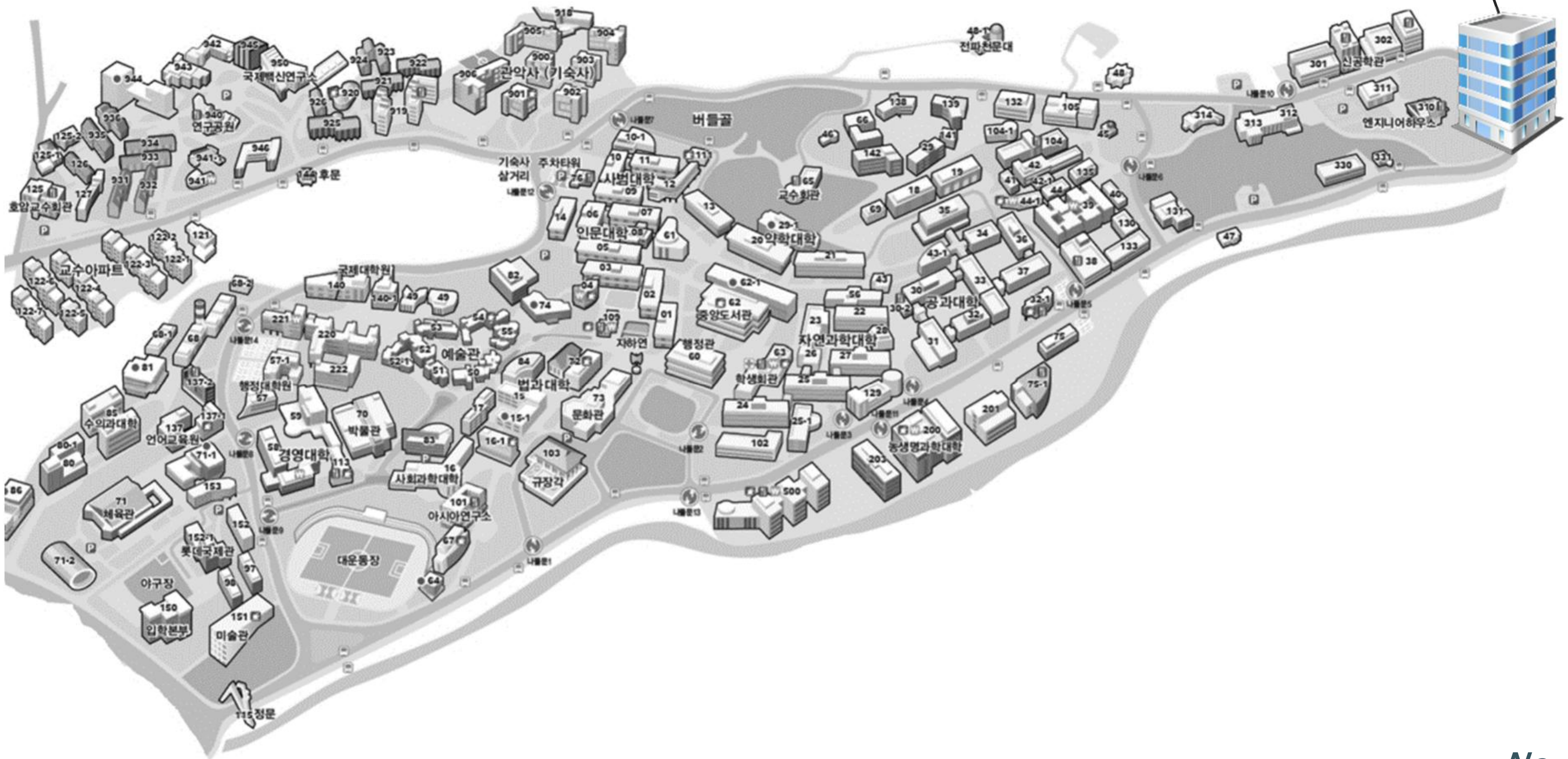
- Utilization of the SNU human infrastructure
- Development of specialized education program
- Activation of consigned education through industrial linkage
- Training of global leaders in the extreme engineering

Location

- Located in the top right of the SNU campus

Extreme Performance Testing Center

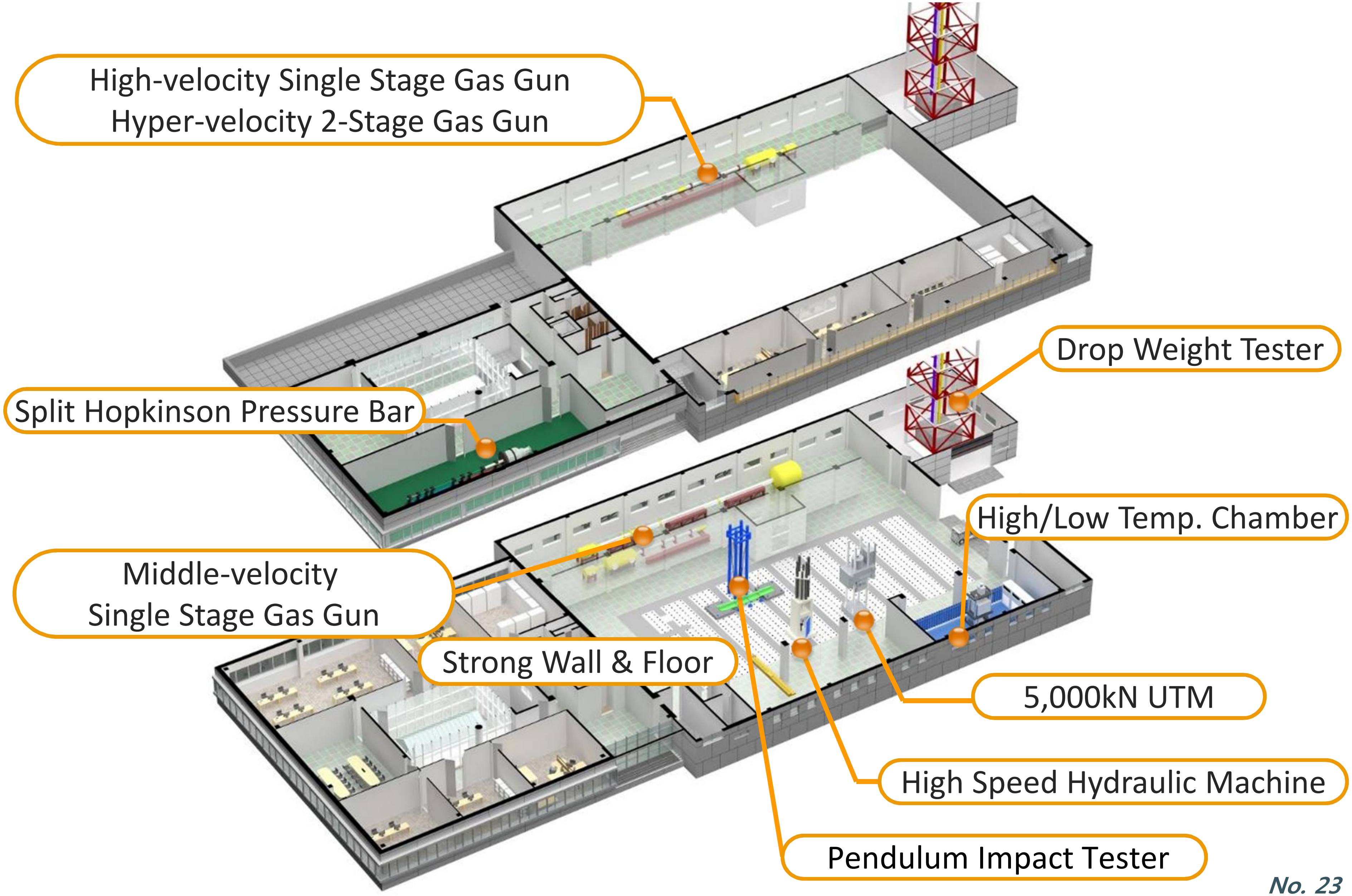
Bldg 316, Seoul National University
Gwanangno 1, Gwanakgu, Seoul, Korea



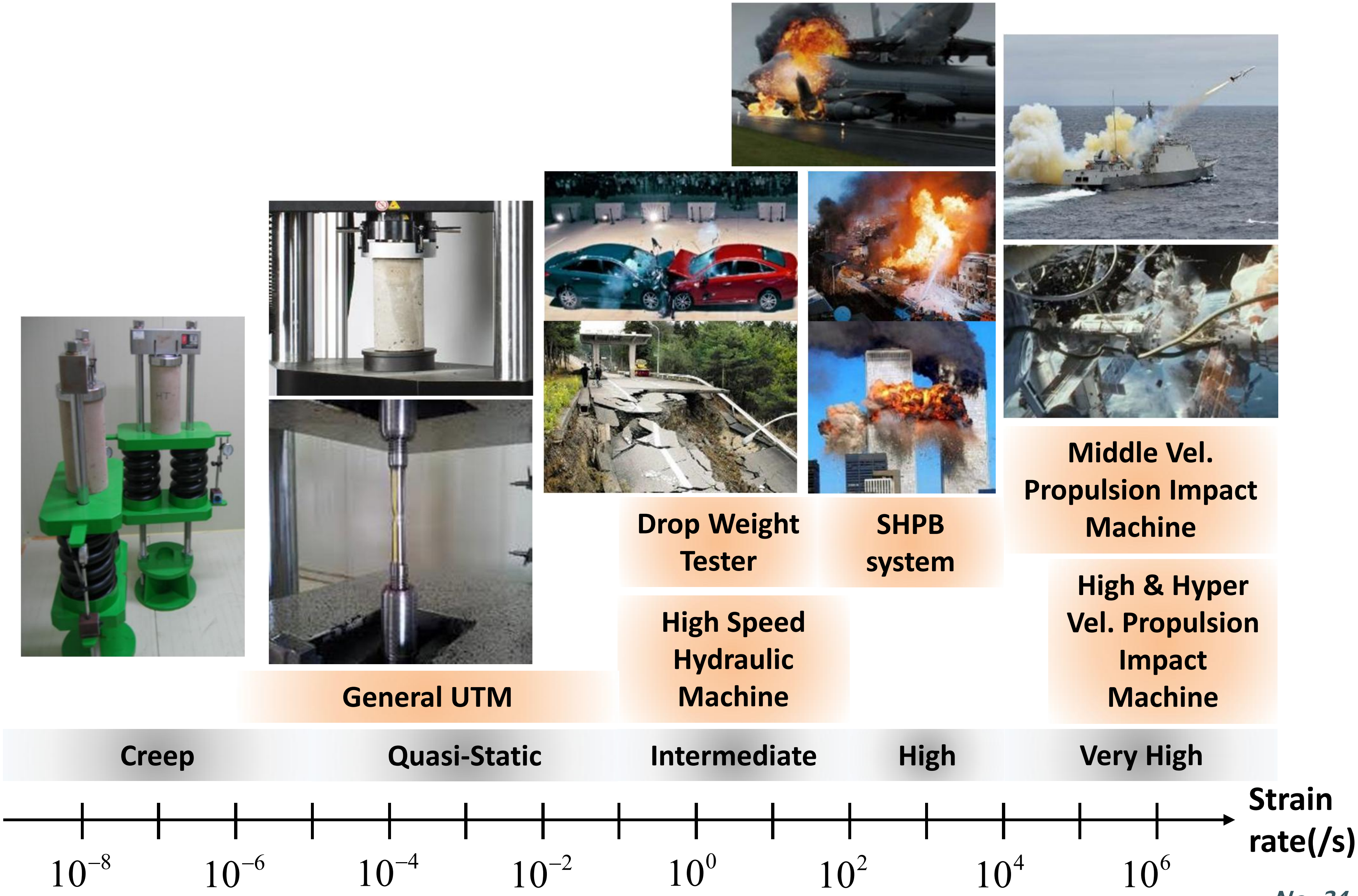
Building Outline

- **Building scale** 4-story research building + testing facility
- **Area** Site area: 5,742 m^2 (Building area: 2,423 m^2)

Major Experimental Equipment



Feasible Strain Rate Ranges



Contents

Types of Apparatus of EPTC

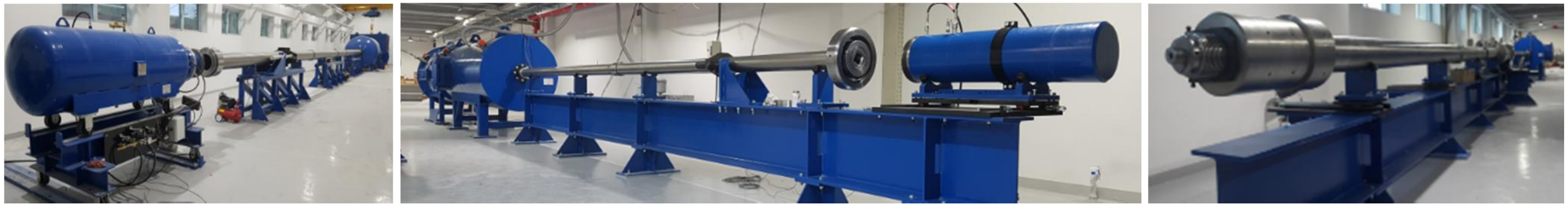
- **High rate material test**
  - Split Hopkinson Pressure Bar (SHPB)
  - High speed hydraulic loading machine
- **Scaled model test for global behaviors**
  - Drop weight tester
  - Pendulum impact tester
- **Scaled model test for local behaviors**
  - 3 kinds of gas guns

High rate material test

Global behavior test

Scaled model test

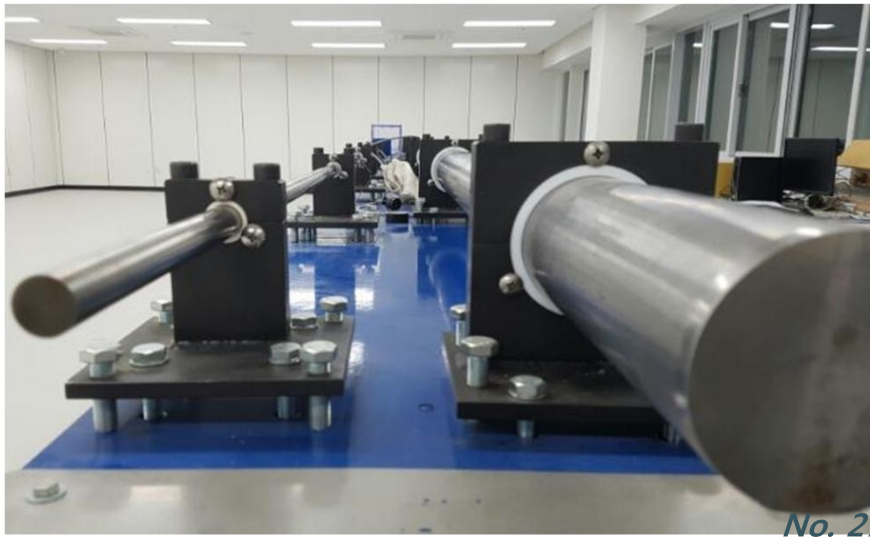
Local behavior test



(1) Split-Hopkinson-Pressure-Bar (SHPB)

High rate compression tests at high strain rate

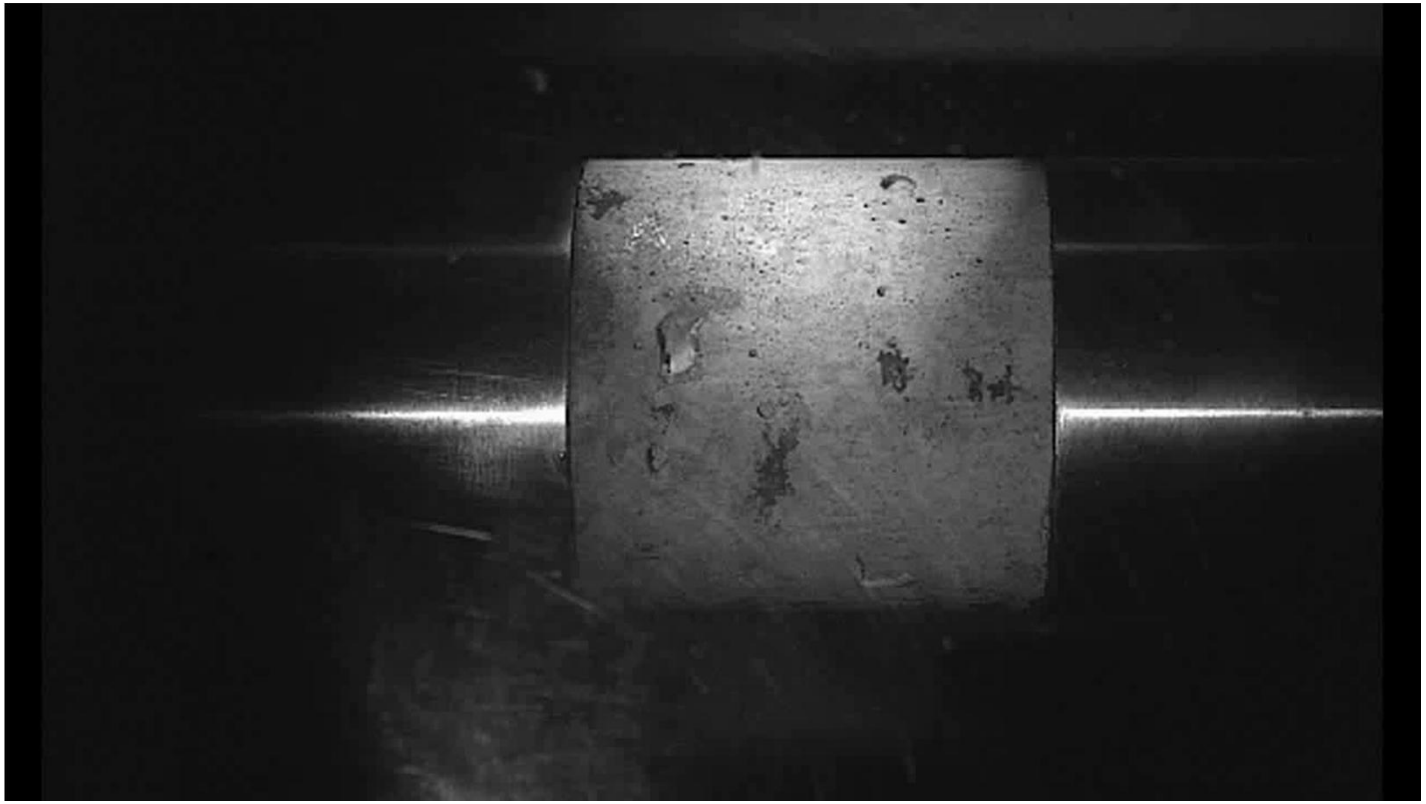
- 19 mm system for test of homogenous materials at strain rates up to 10^4/s
- 75 mm system for test of non-homogenous materials at strain rates up to 10^3/s



(1) Split-Hopkinson-Pressure-Bar (SHPB)

Application

- Obtain high rate material properties test at high strain rate in various fields
  - Construction materials such as concrete, UHPC, FRC, steel, etc.
  - Mechanical, aerospace & marine materials such as aluminum, titanium, alloy, plastic, etc.



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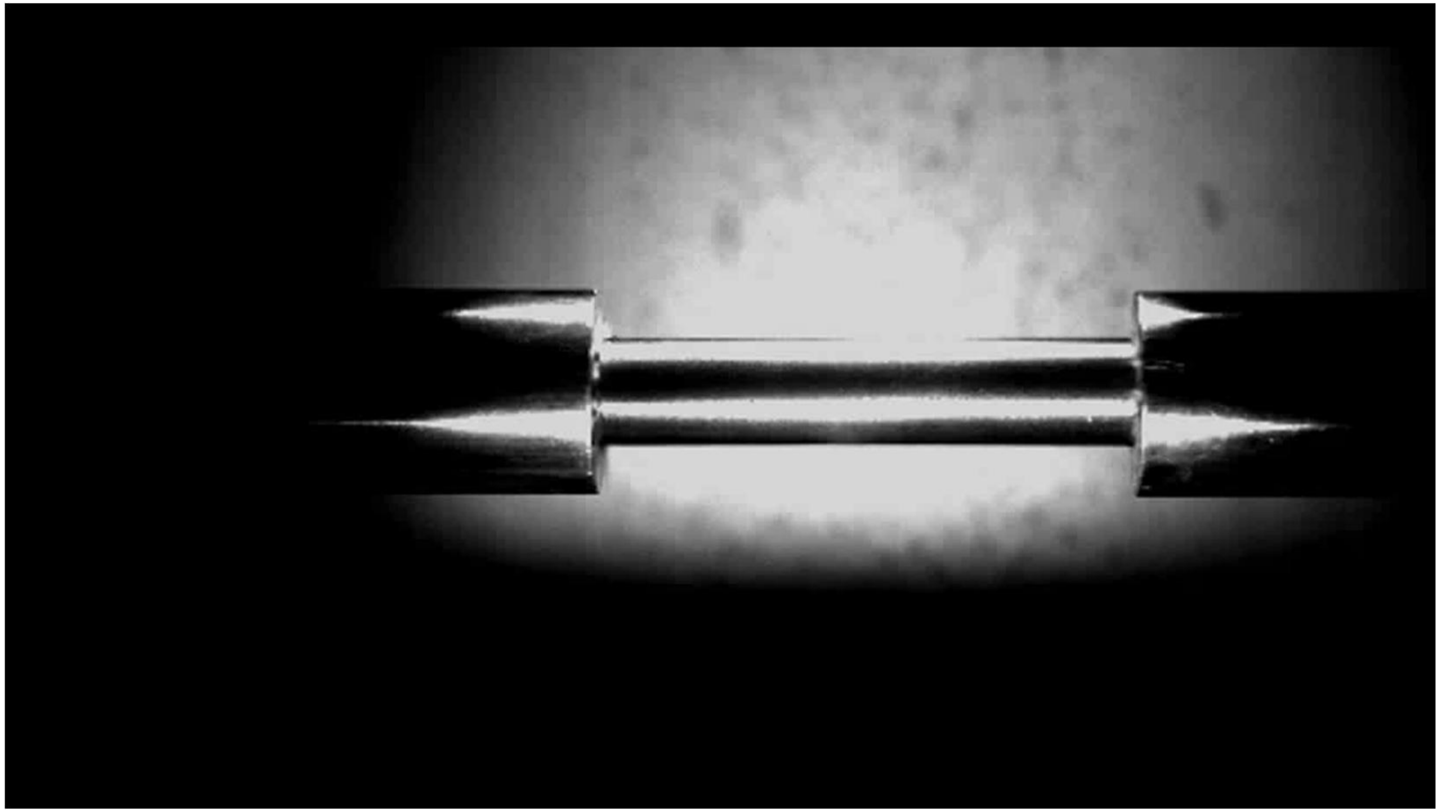
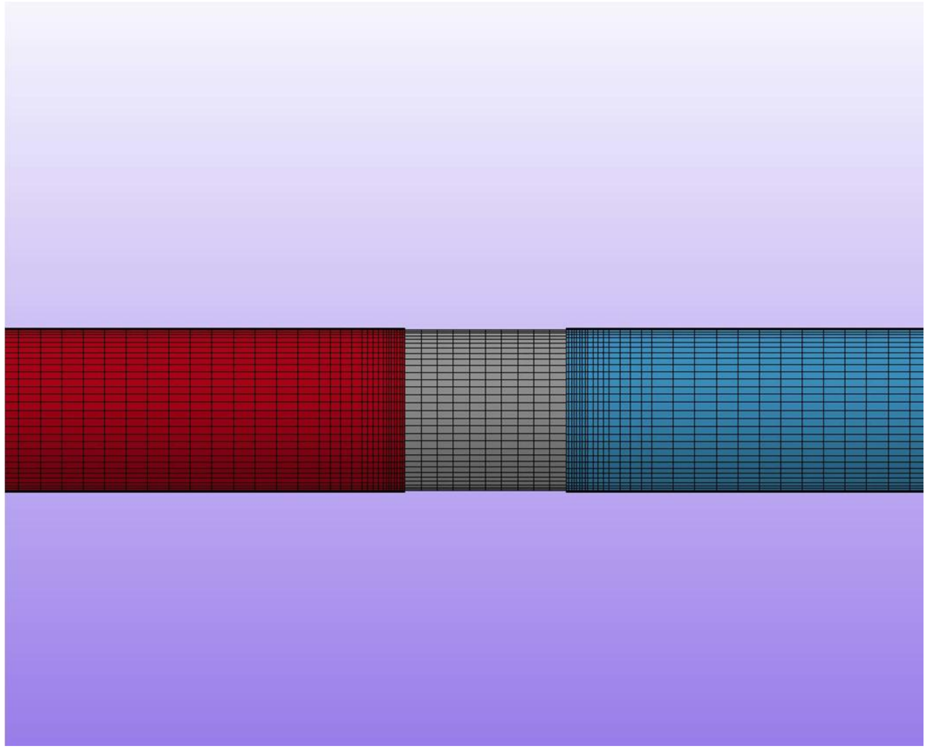
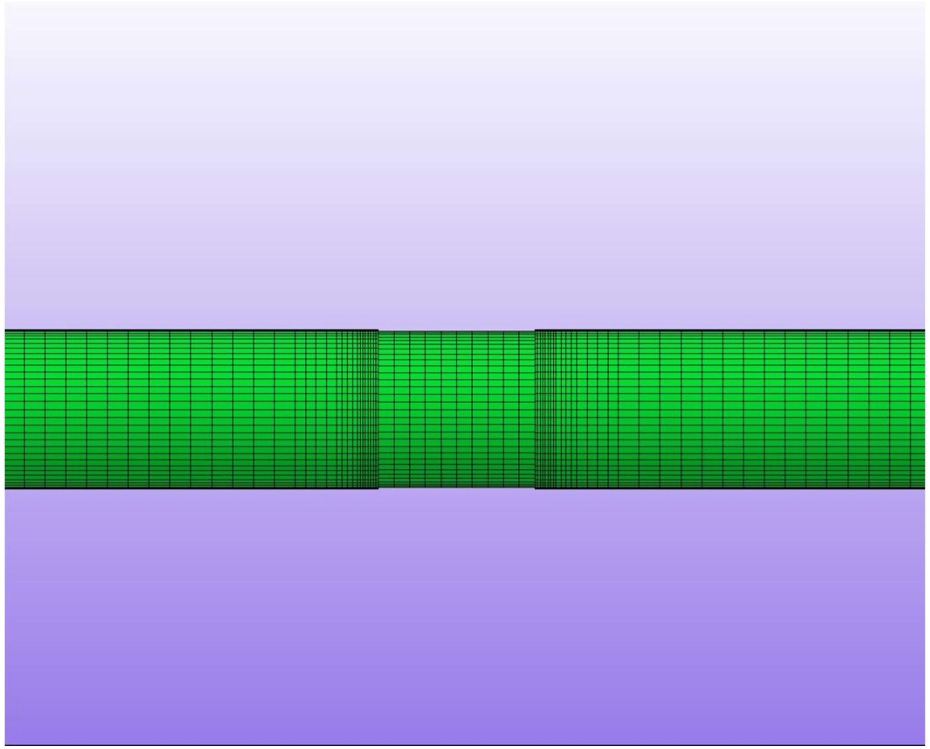


(1) Split-Hopkinson-Pressure-Bar (SHPB)

Numerical simulation

- Impact velocity : 20 m/s
- Striker bar length : 300 mm
- Compressive strength of concrete : 40 MPa
- Pulse shaper : O.D. 51 × I.D. 47 × T. 3 mm





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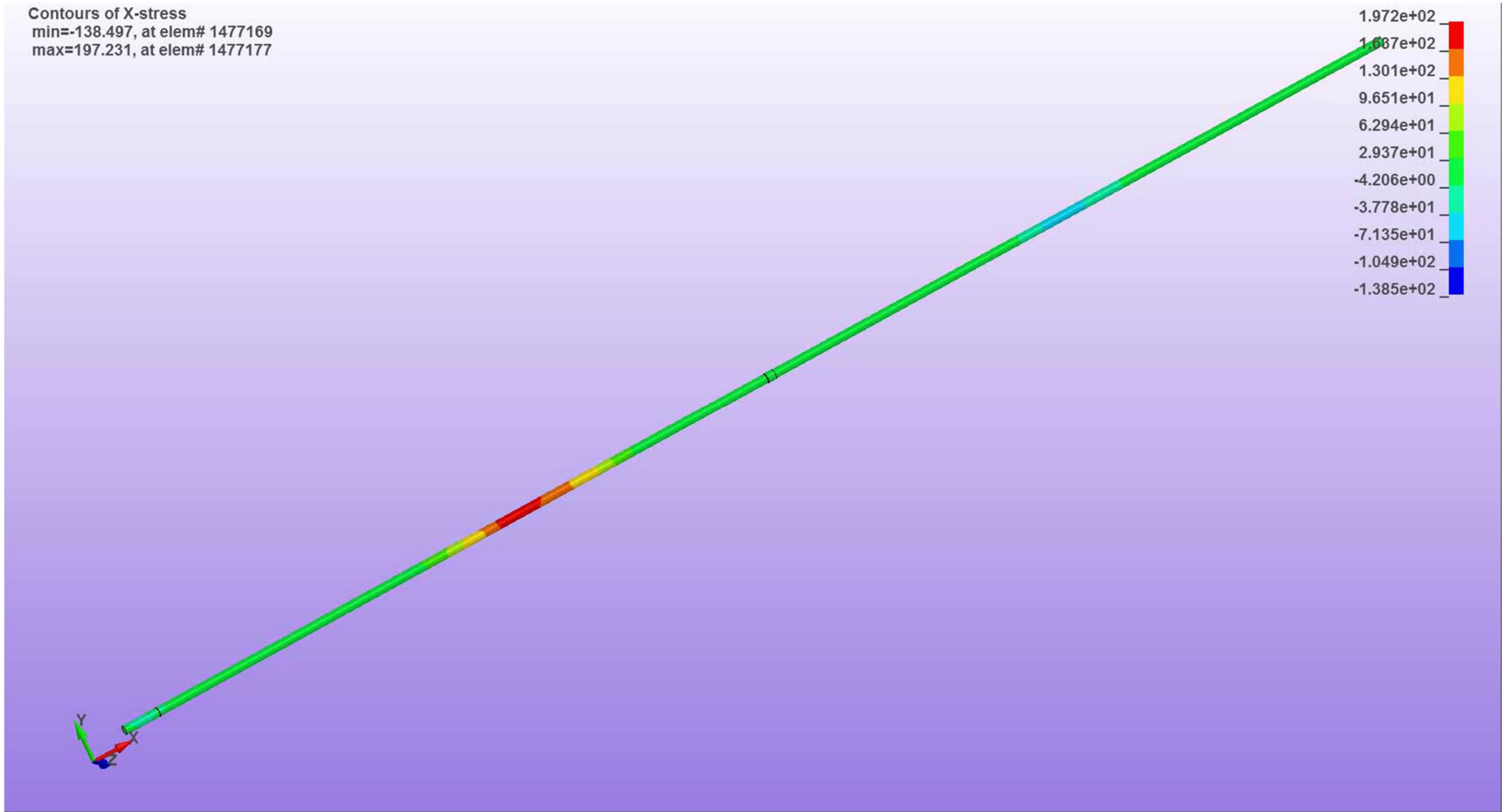
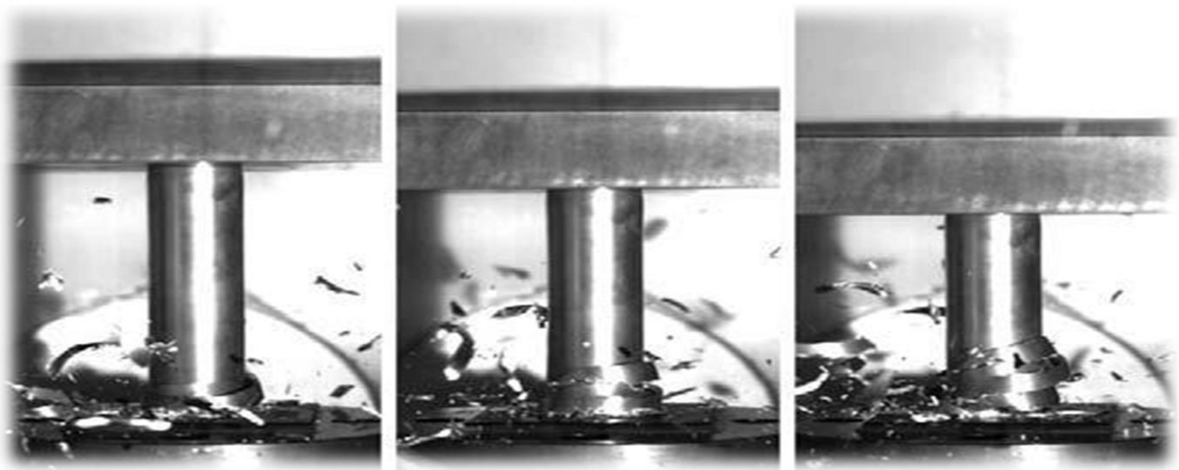


(2) High Speed Hydraulic Loading Machine

- **Investigate the behavior of material at high strain rate**
  - Compressive load at 5 m/s load rate : 320 kN
  - Tensile load at 10 m/s load rate : 330 kN

- **Application**
  - Compressive, tensile, flexural test at high strain rate in various fields
    - Construction materials for bridge, building, & plant
    - Mechanical, aerospace, & marine materials for aircraft, vehicle, & vessel



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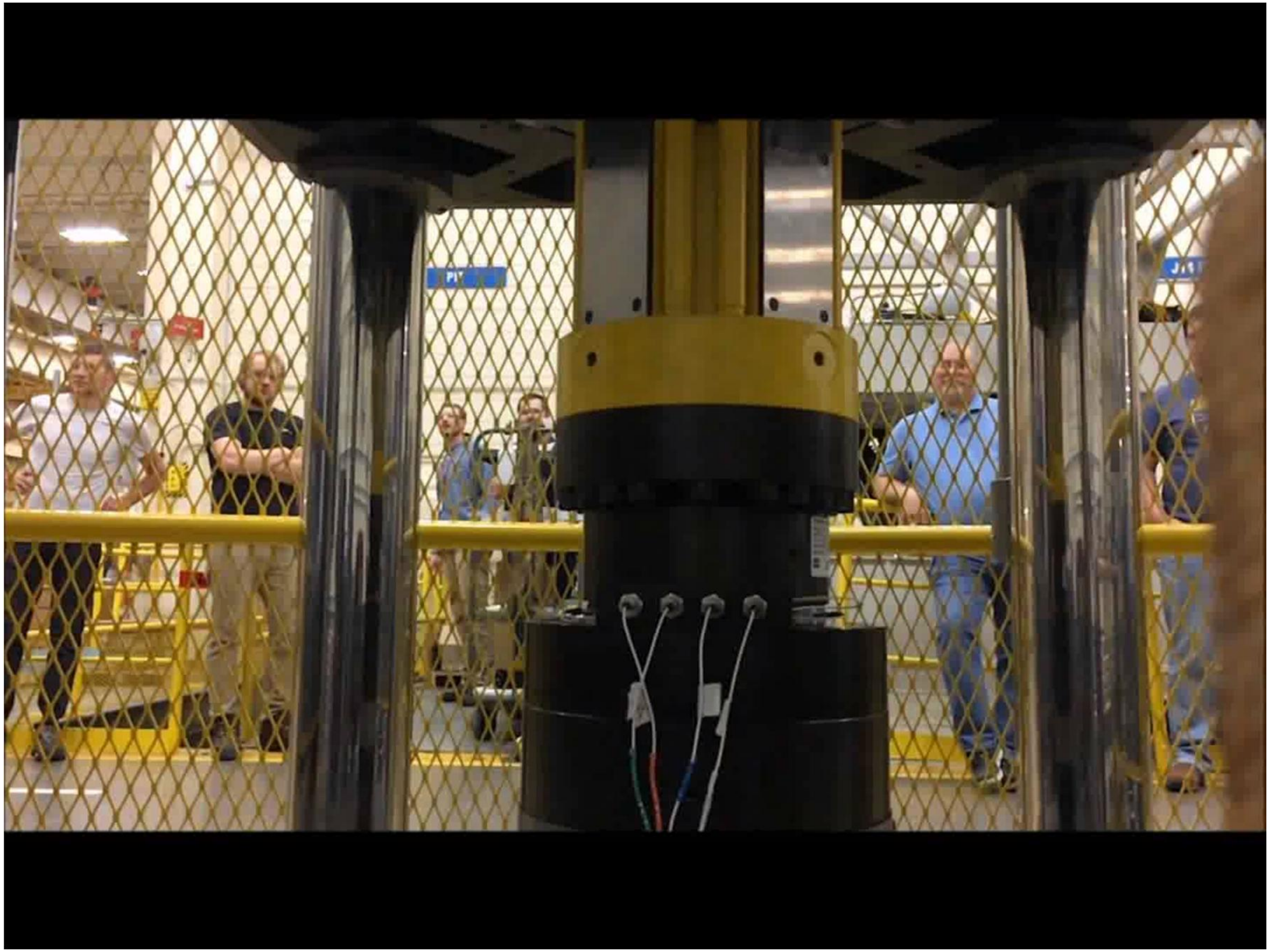


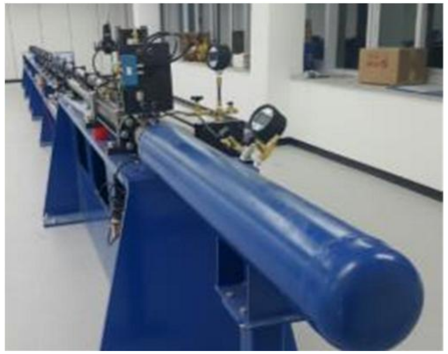
(2) High Speed Hydraulic Loading Machine

Evaluation of Material Properties at High Strain Rates

Small size

Split Hopkinson Pressure Bar

(~10^4/s)

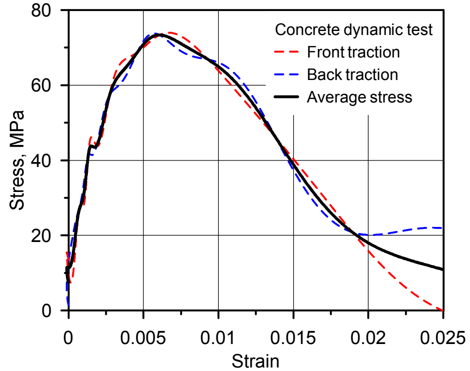


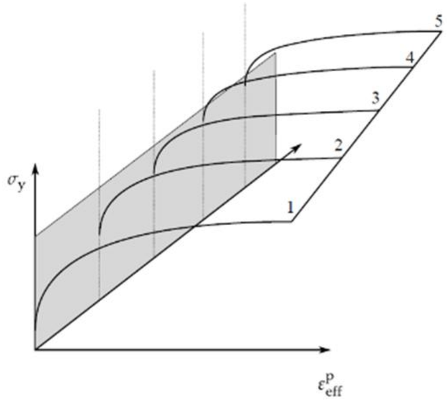
Large size

High speed hydraulic machine

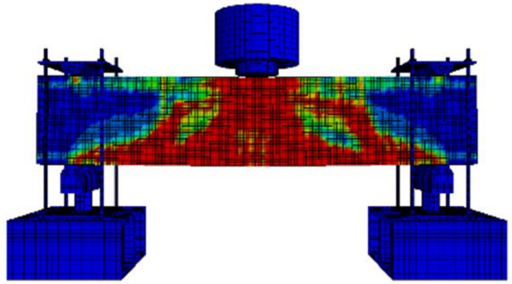
(330kN, ~10m/s)

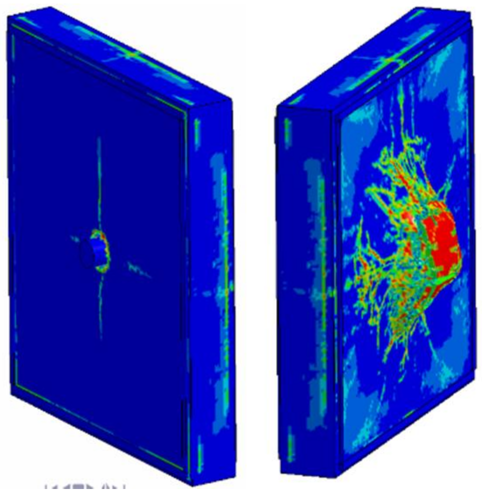
Obtain Stress-strain curves for various sizes of specimen at various strain rates





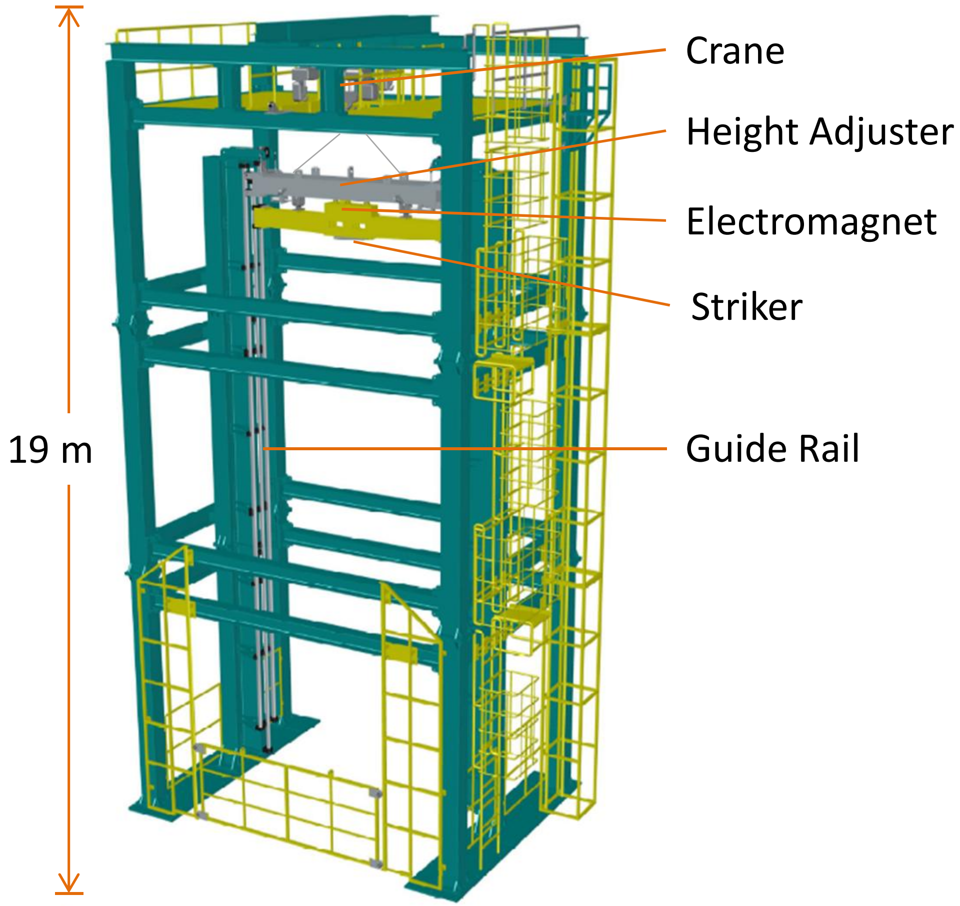
Extract collision analysis parameters / Improve the accuracy of the material model

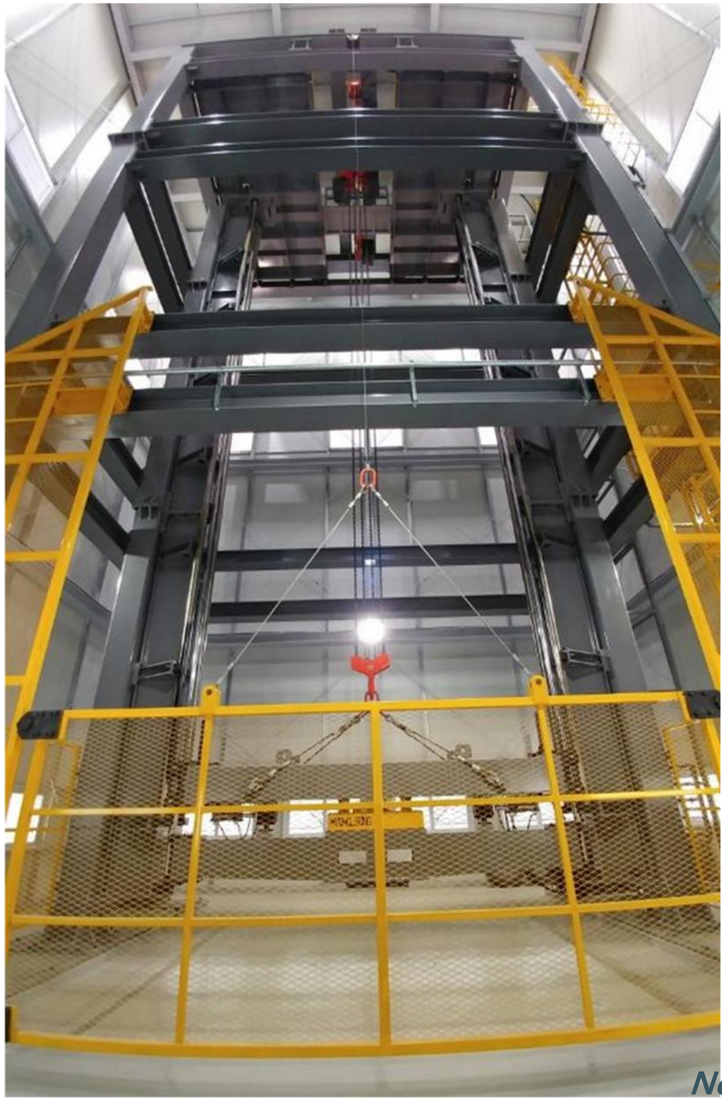




(3) Drop weight tester

- **Allows to simulate the impact of heavy mass and low speed impact**
  - Weight : ~ 3.0 ton
  - Height : ~ 15 m
  - Mounted specimen area : 4.5 m x 4.5 m

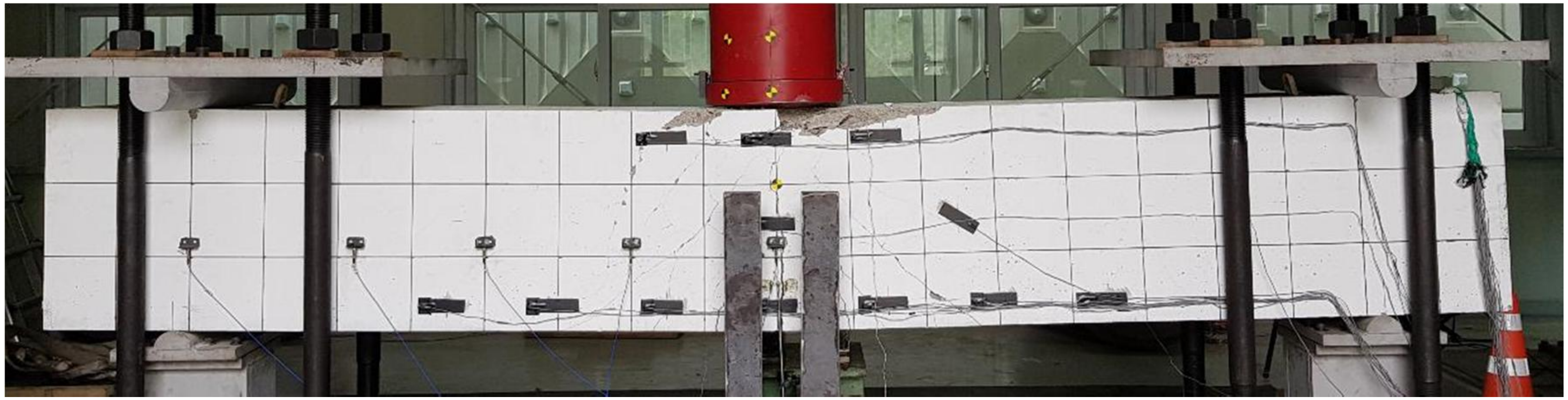


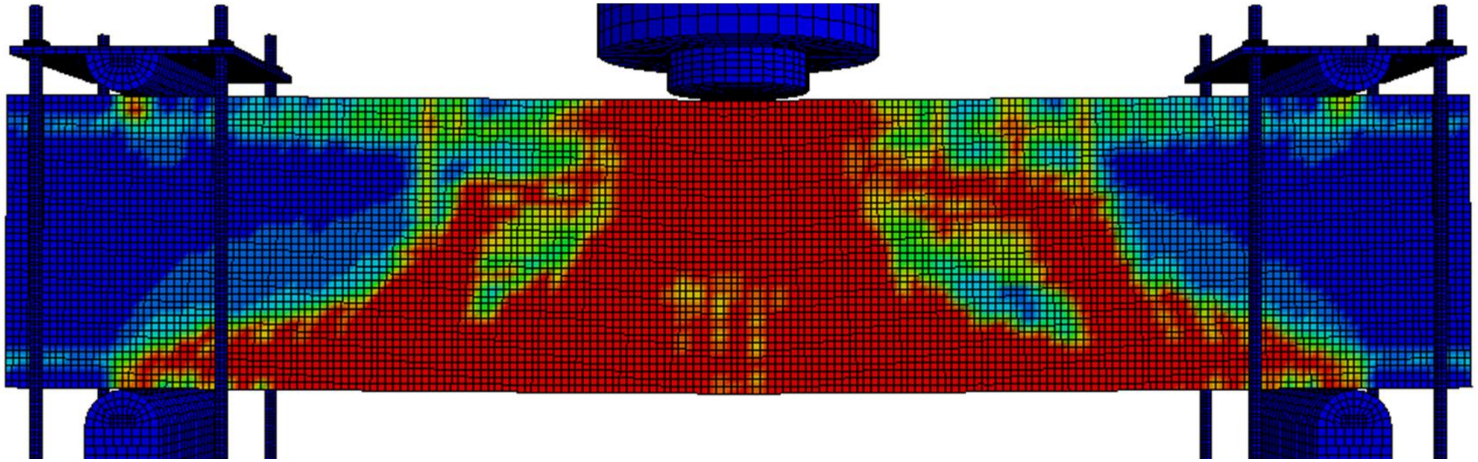


(3) Drop weight impact tester

Application

- Perform full scale test of impact events
  - Verify a protective performance of wall of plant, harbor structure, bridge pier, vehicle, vessel, aircraft, etc.





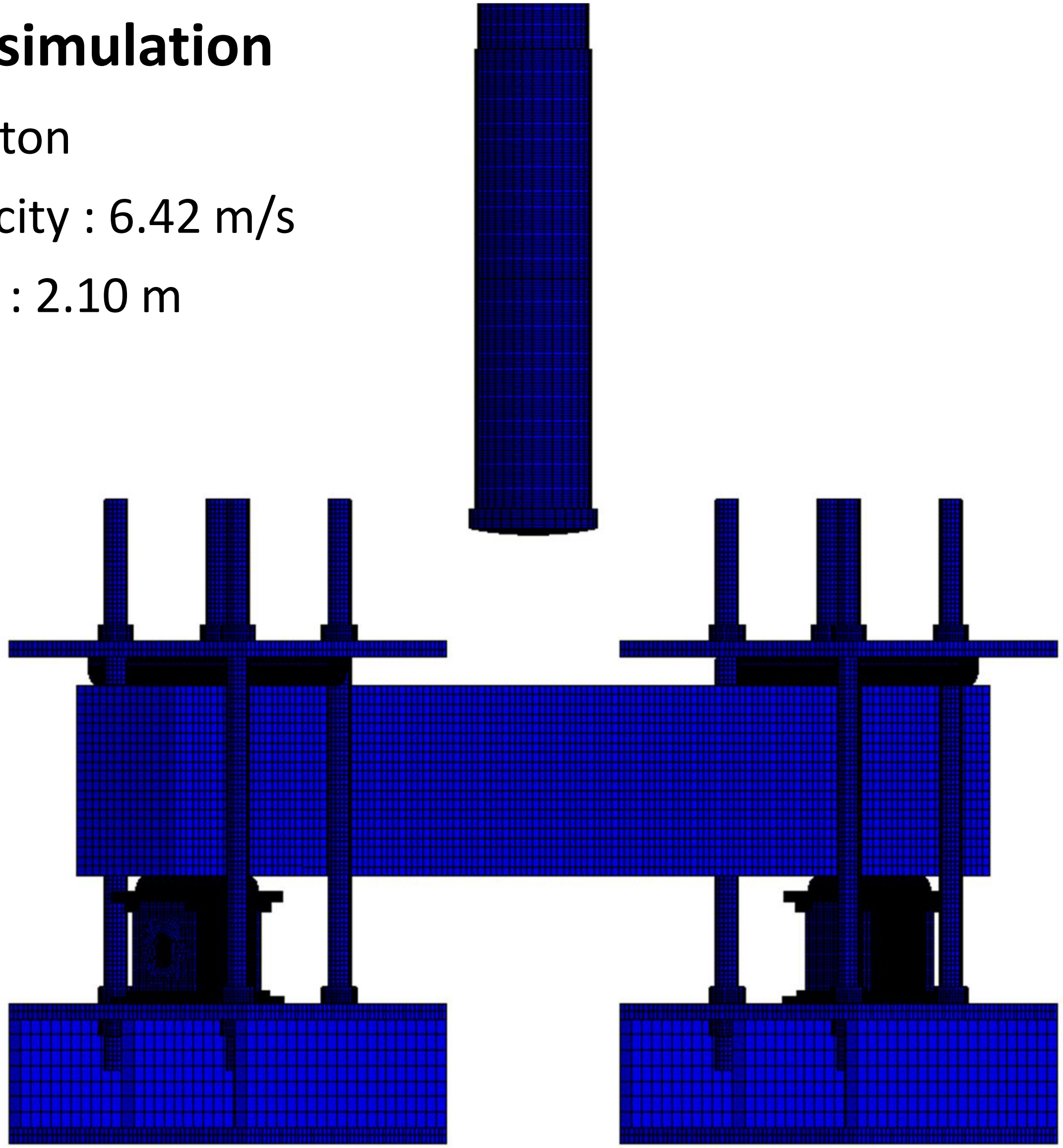
(3) Drop weight impact tester

Application

- Perform full scale test of impact events
  - Verify a protective performance of wall of plant, harbor structure, bridge pier, vehicle, vessel, aircraft, etc.

(3) Drop weight impact tester

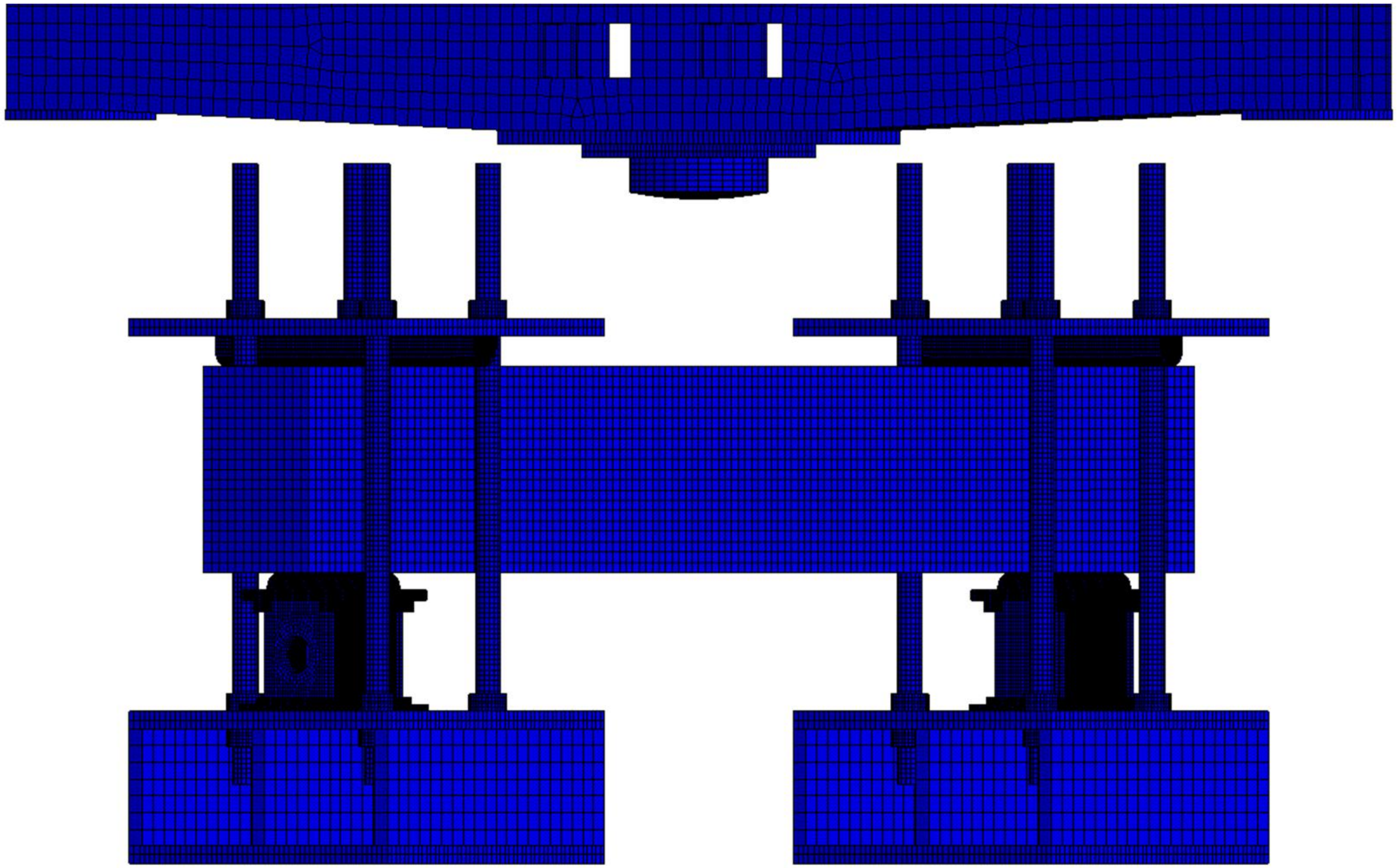
- **Numerical simulation**
  - Mass : 1.45 ton
  - Impact velocity : 6.42 m/s
  - Drop height : 2.10 m



(3) Drop weight impact tester

Numerical simulation

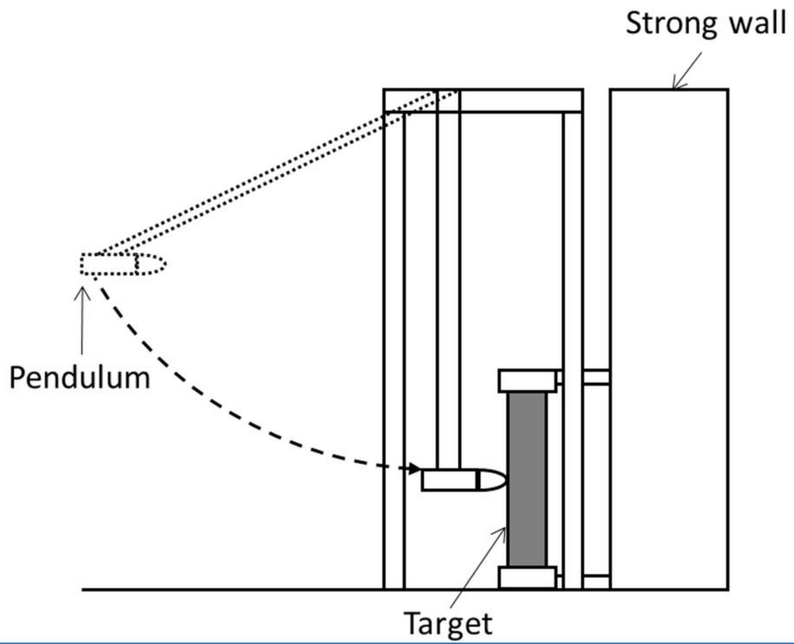
- Mass : 2.51 ton
- Impact velocity : 4.89 m/s (= Drop height : 1.22 m)



(4) Pendulum Impact Tester

- **Real scale impact tester**
  - Pendulum mass : 800 ~ 2,000 kg
  - Maximum vertical height : 5 m
  - Apply horizontal impact

- **Application**
  - Test of retaining wall for landslide
  - Simulation of ship impact for pier & pile



Specialized for Crash Simulation

- **Specialized to simulate the crash phenomenon in infra-structures**
  - Simulate low velocity but large crash energy
  - Collision of structures bored in ground by vehicle, ship, floating ices

Drop-weight impact tester

- Max. weight : 3 ton
- Max. height: 15 m
- Max. velocity : 17.2 m/s
- Crash energy : ~ 441 kJ

Implementation of massive crash energy

Pendulum impact tester

- Max. weight : 0.8 ~ 2 ton
- Max. height : 5 m
- Max. velocity : 9.8 m/s
- Crash energy : 39.2 ~ 100 kJ
- Horizontal impact loading

Medium crash energy for the bored specimen

(5) Middle Velocity Propulsion Impact Machine

- **A single stage gas gun handling a large and heavy projectile**
  - Projectile diameter : ~ 250 mm
  - Impact velocity : 50 ~ 470 m/s
  - Projectile mass : 10 ~ 100 kg
  - Max. size of target : 2.1 m x 2.1 m (B x H)

(5) Middle Velocity Propulsion Impact Machine

Application

- Simulate aircraft engine and missile impact
- Assess the protective performance of nuclear power plant, ocean plant, large vessel, etc.

(5) Middle Velocity Propulsion Impact Machine

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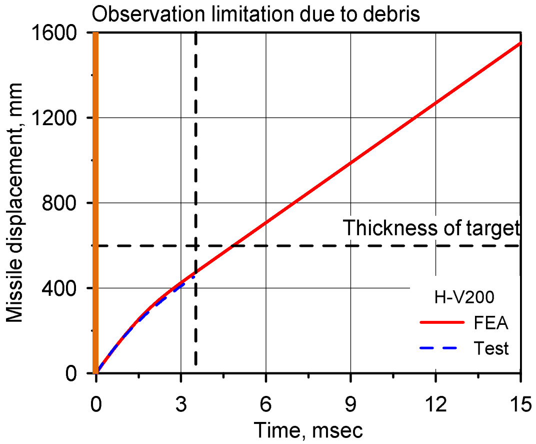
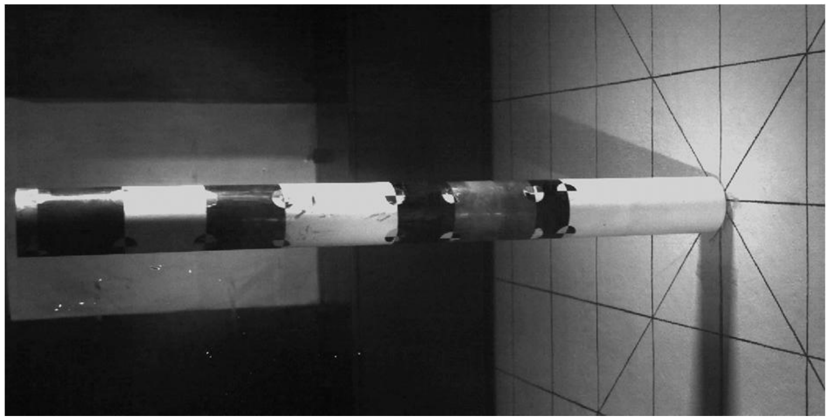
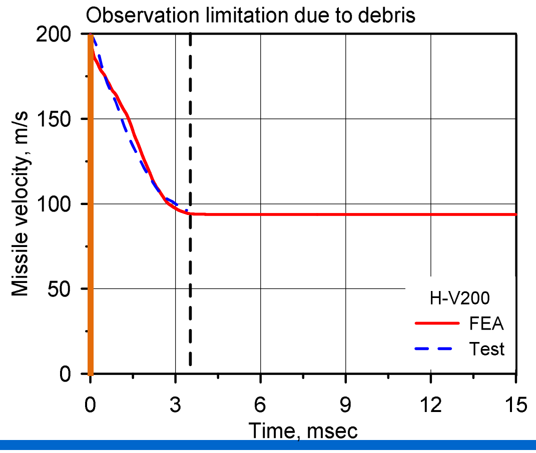
(5) Middle Velocity Propulsion Impact Machine

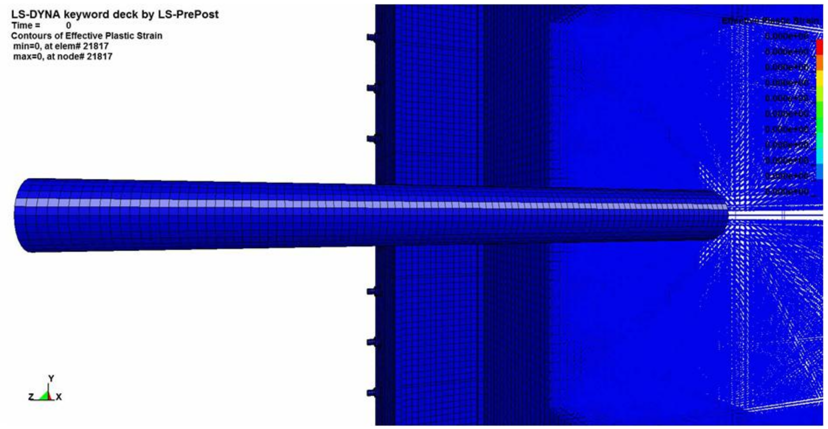
Numerical simulation

- Projectile : Steel cylinder (Size: φ85×980 mm, Mass: 43.6 kg)
- Impact velocity : 199.6 m/s (447 mph)
- Failure mode : Perforation









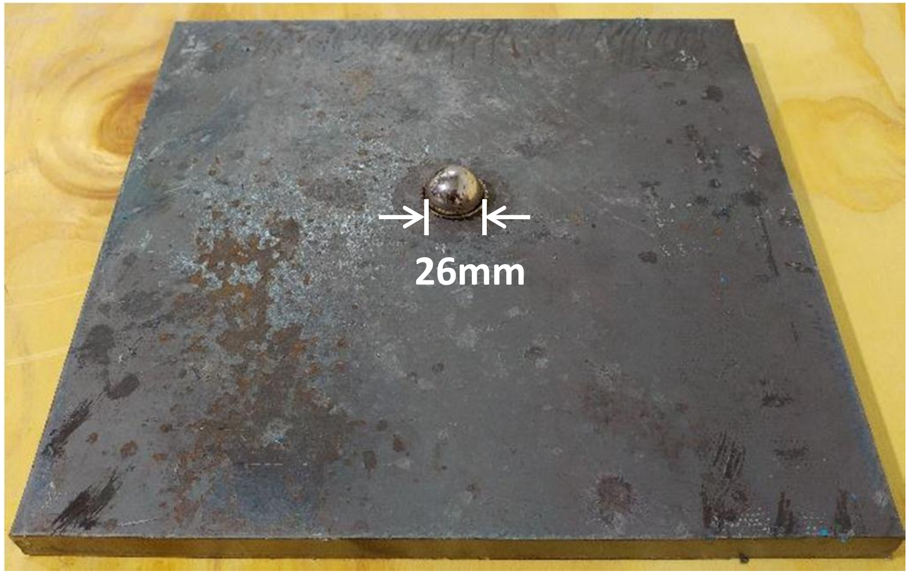
(6) High Velocity Propulsion Impact Machine

- **A single stage gas gun assessing the fracture behavior of materials**
  - Projectile diameter : ~ 60 mm
  - Impact velocity : 0.5 ~ 1.2 km/s
  - Projectile mass : 0.5 ~ 5 kg
  - Max. size of target : 0.7 m x 0.7 m (B x H)

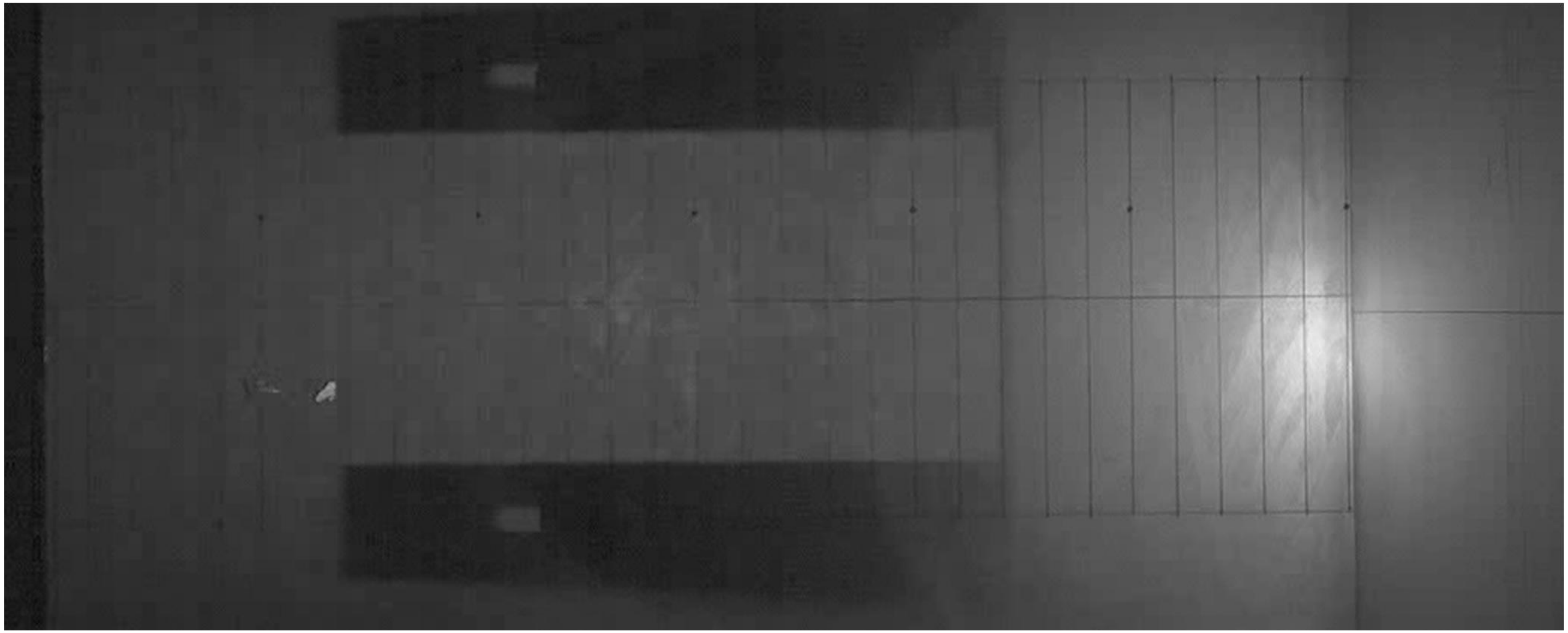
(6) High Velocity Propulsion Impact Machine

Application

- Verification of performance of bullet & bulletproof equipment
- Verification of performance of new materials in various fields
  - Protective & explosion proof materials (Defense field)
  - Long span bridge/Skyscraper/Plant materials (Construction field)
  - High-speed train/Aircraft/Vehicle/Vessel material (Mechanical, aerospace & marine fields)



(6) High Velocity Propulsion Impact Machine



(6) High Velocity Propulsion Impact Machine

(6) High Velocity Propulsion Impact Machine

Numerical simulation

- Projectile : Tungsten carbide sharp projectile (Size: φ10.8×43.4 mm, Mass: 51 g)
- Impact velocity : 1,000 m/s (2,237 mph)
- Failure mode : Perforation

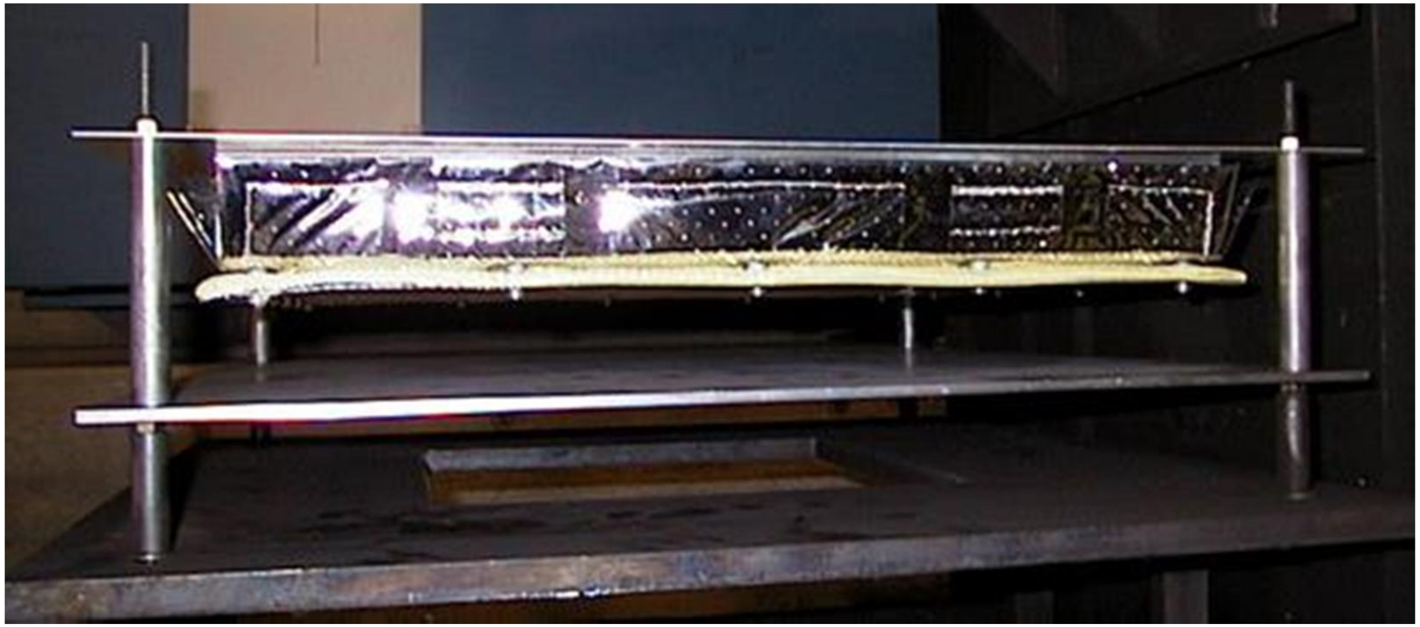
(7) Hypervelocity Propulsion Impact Machine

- **A two stage gas gun applicable for aerospace and aviation field**
  - Projectile diameter : ~ 25 mm
  - Projectile mass : 25 ~ 200 g
  - Impact velocity : 2.6 ~ 7 km/s
  - Max. size of target : 0.5 m x 0.5 m (B x H)

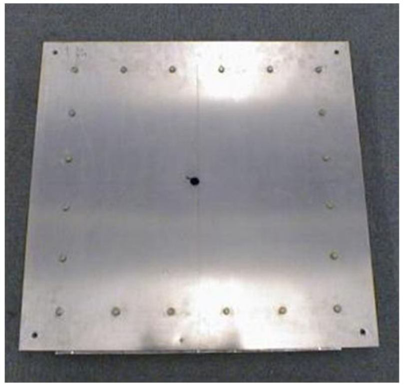
(7) Hypervelocity Propulsion Impact Machine

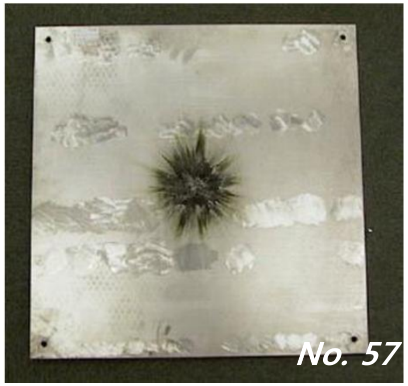
Application

- Simulation of space debris impact
  - Verification of safety of spacecraft & satellite for space debris impact
  - Simulation of geologic formation in planets



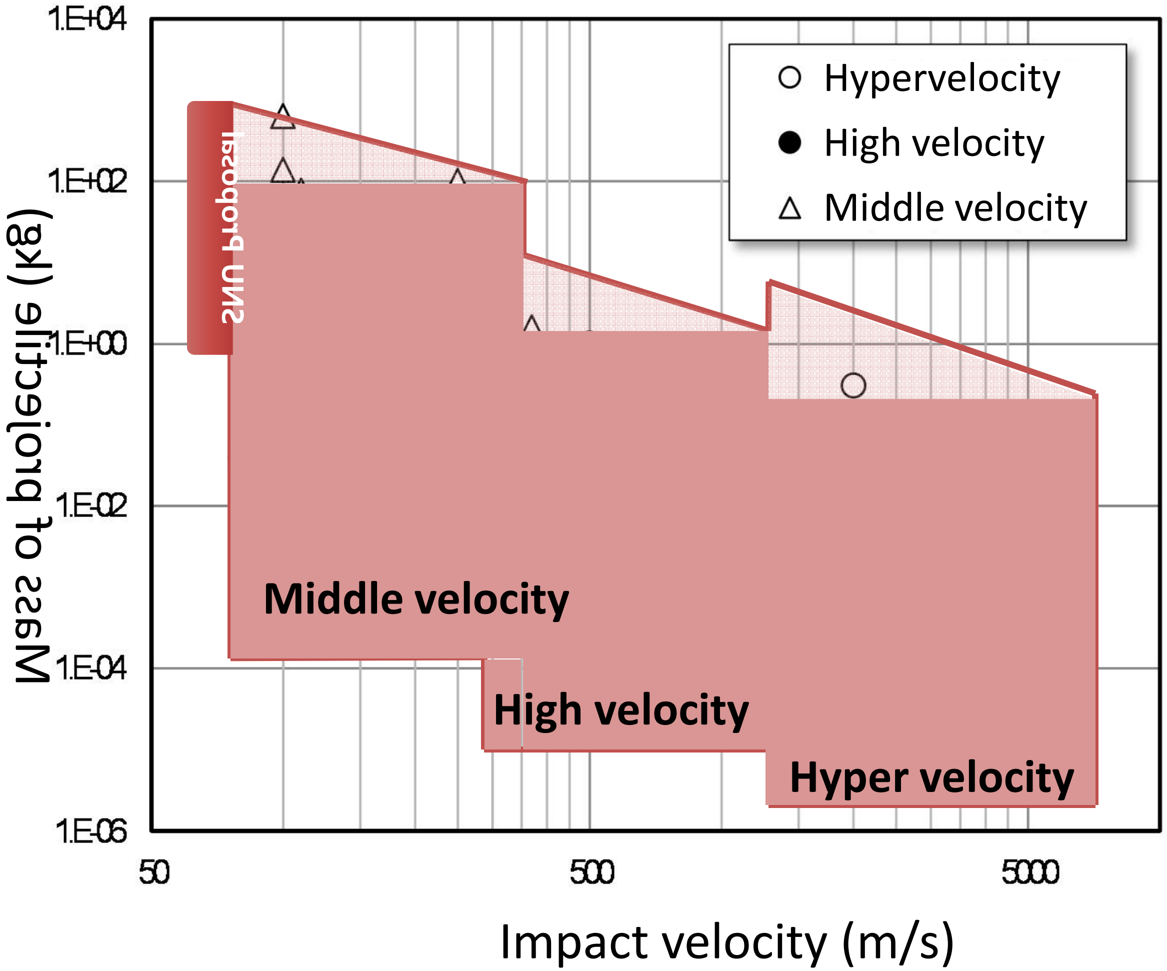
Debris Impact Test of International Space Station(ISS) Wall





Cover World-class Experiments

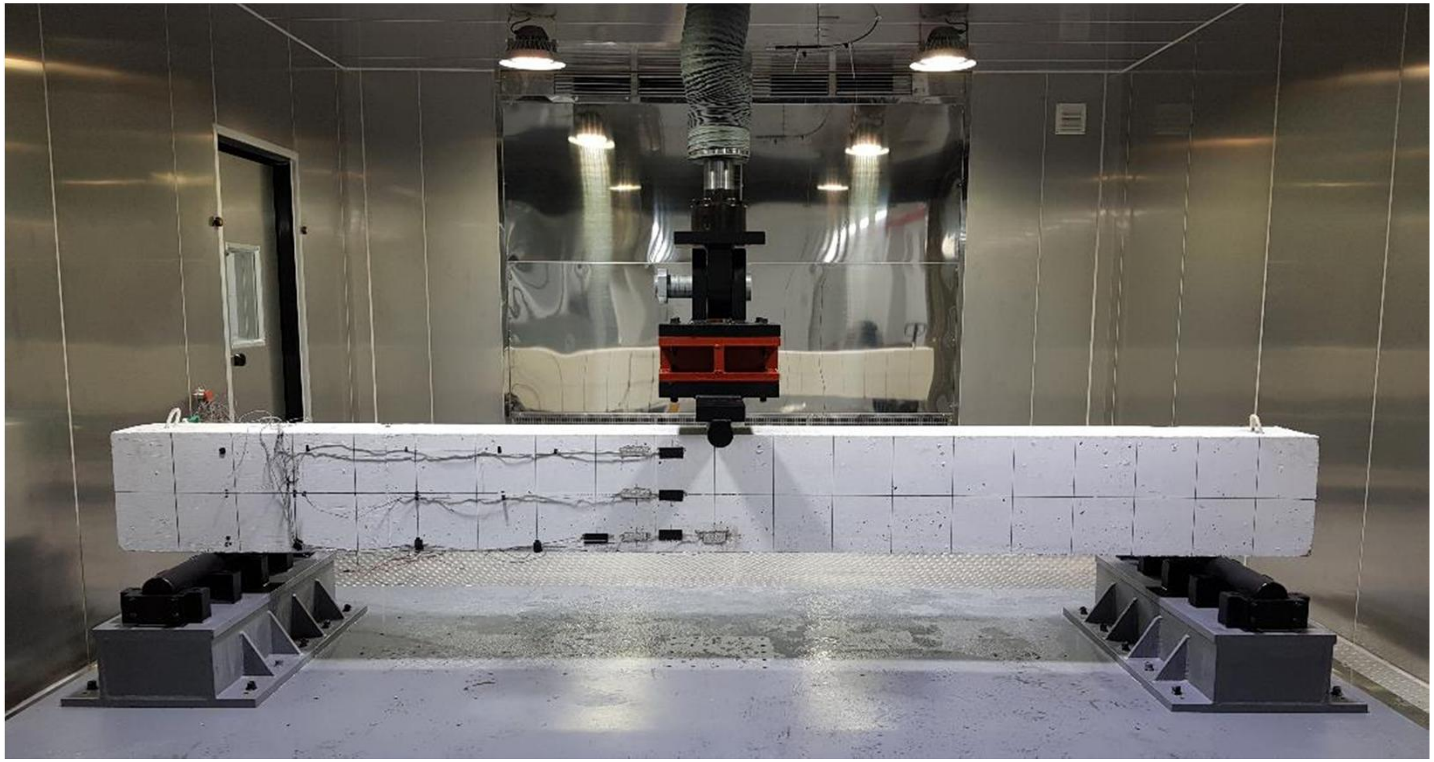
- **Able to perform all of the international impact experiment cases**



(8) Extreme Temperature Chamber

Simulate extreme hot & cold environment on the earth

- Temperature range : -60 – 60 ℃ (covers polar and equator region)
- Chamber size : 12 m(L) x 5 m(B) x 3 m(H)
- A 500 kN dynamic UTM in the chamber
  - To evaluate the performance of the material and members under extreme temperature



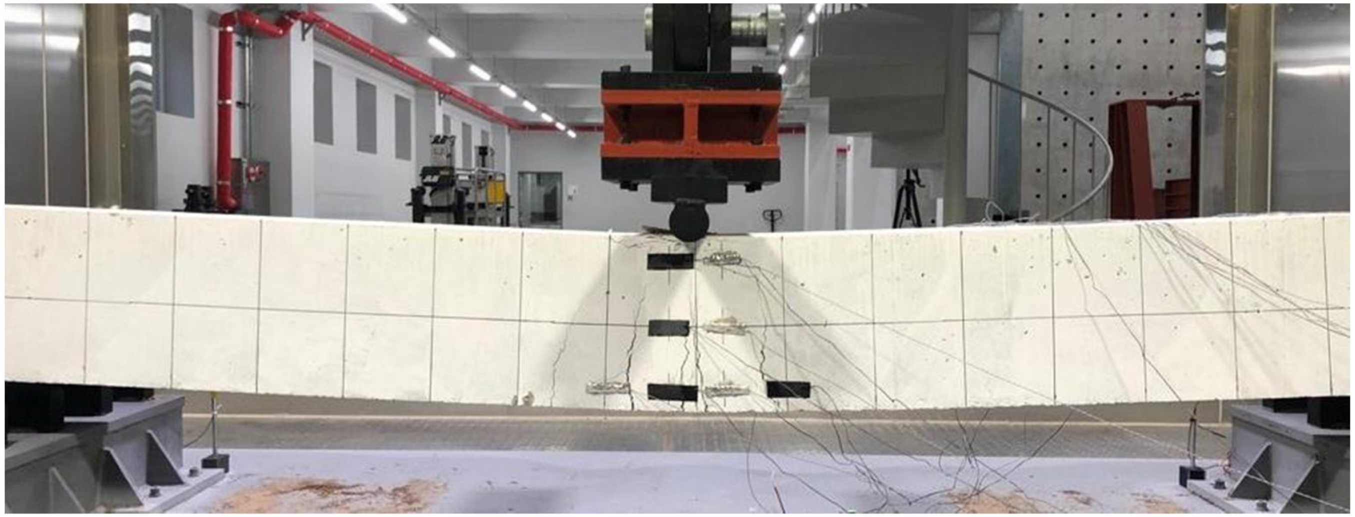
(8) Extreme Temperature Chamber

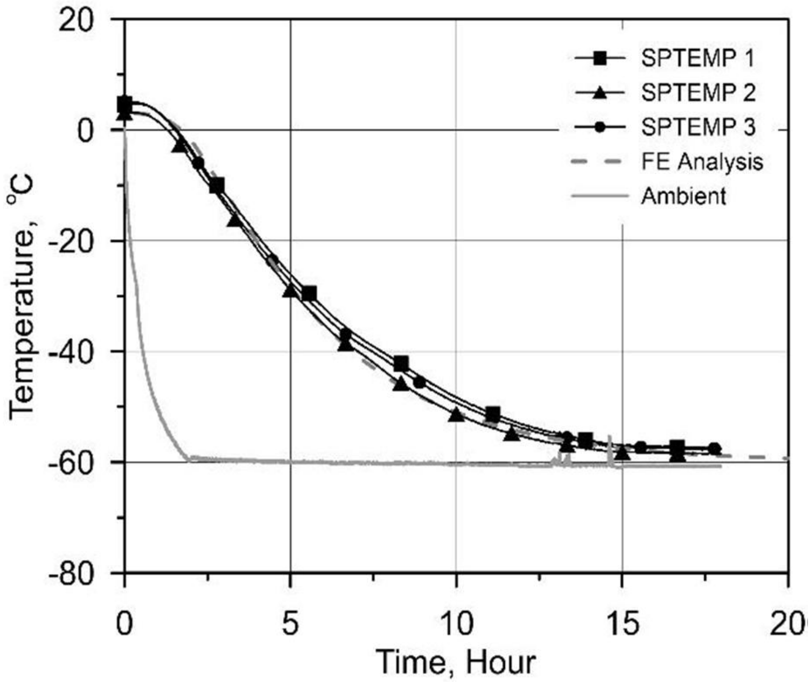
Application

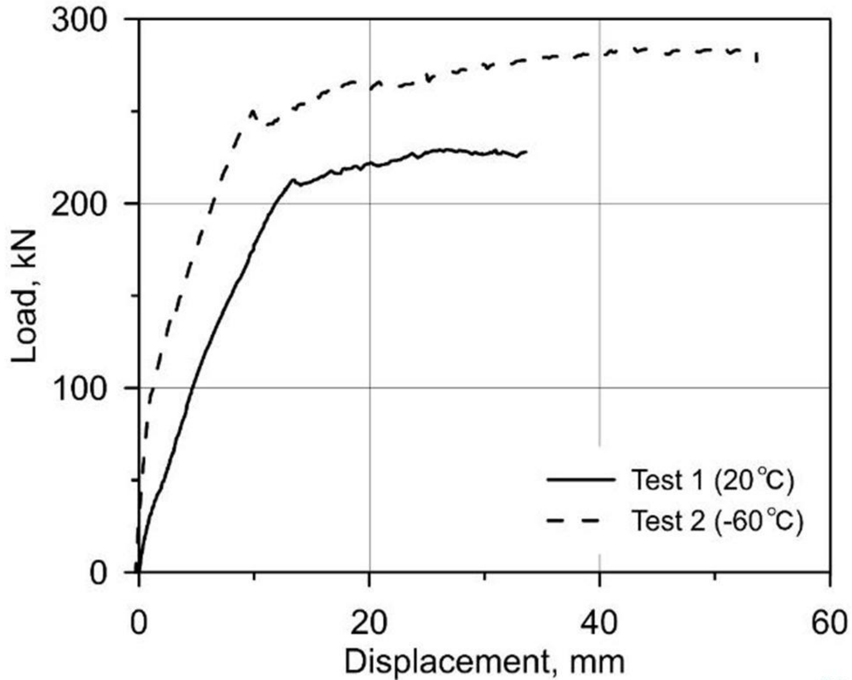
- Performance test of member & material in high/low temperature
  - Verification of performance of vehicle, aircraft, & wind power supplier
  - Verification of qualities of materials such as concrete, aluminum, titanium, magnesium, alloy, etc.

- Development & Verification of construction method in hottest & coldest places
  - Simulation of frost heaving due to freeze-thaw of the ground
  - Assessment of weld-ability on low temperature
  - Assessment of freezing behavior of pipe lines

(8) Extreme Temperature Chamber







(9) 5,000kN UTM

Dynamic UTM

- Force : ±5,000 kN
- Stroke : 500 mm

Application

- Quasi-static & dynamic test of large members
- Investigate 2nd performance test of the damaged members

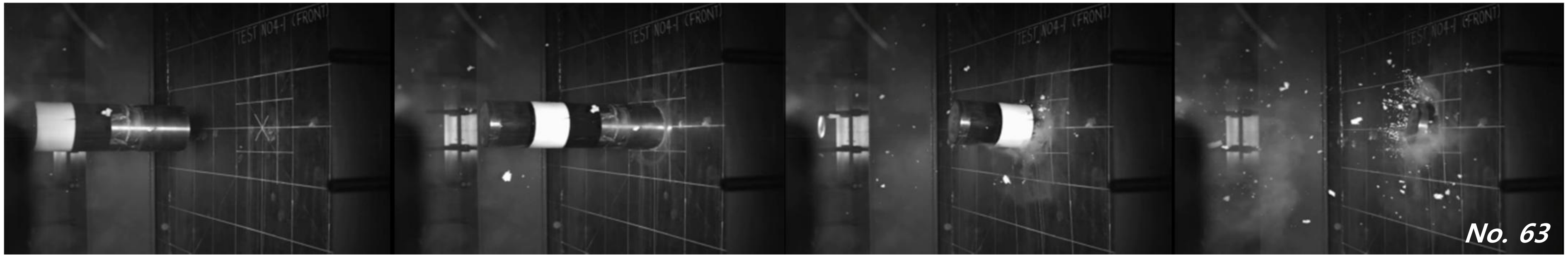
(10) Measurement Equipment

High-speed camera

- Phantom V711
  - Max. resolution : 1,024 x 800 pixels at 7,530 FPS
  - Max. frame rate : 153,200 FPS with 256 x 128 pixels
  - Exposure time : 1 μs
- Photron FASTCAM SA-Z
  - Max. resolution : 1,024 x 1,024 pixels at 20,000 FPS
  - Max. frame rate : 300,000 FPS with 256 x 128 pixels
  - Exposure time : 0.159 μs

Application

- High-speed events like high velocity impact, collision event etc.



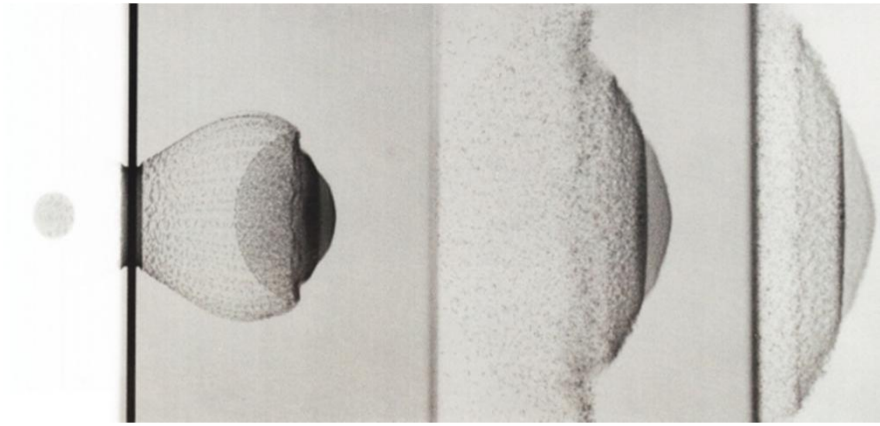
(10) Measurement Equipment

Flash X-ray system

- 450 kV single X-ray tube
- 2 Pulsers with 4 Tube heads
- 14'' x 17'' Image Plate
- Maximum steel penetration : 55 mm
- Limit Film-to-Source distance : 7.6 m
- Exposure time : 25 ns

Application

- Capture images when the field of view is not ensured due to dust & explosion
- Suitable for Capturing hyper-speed events like hyper-velocity impact, shock dynamics, high energetic materials, explosively formed projectiles, etc.



(10) Measurement Equipment

DAQ system

- A/D measuring frequency : 1 MHz
- Minimum time interval : 1 μs
- The number of channels : 64 channels
  - 16 channels : accelerometer
  - 48 channels : displacement meter, strain gauge, load cell, etc.
- Capable of acquiring data at high rates

Site panorama (End of construction)

- **The date of the end : 2017.02.07.**

Contents

High Rate Material Test - SHPB

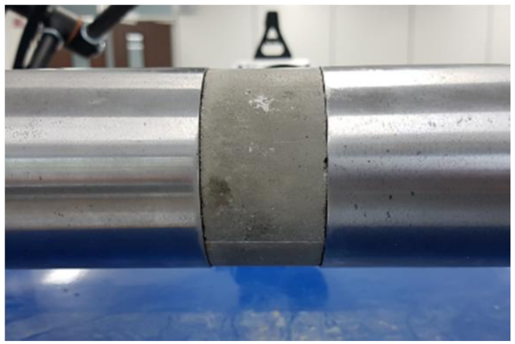
1) Pure rate effect on dynamic increase factor for concrete compressive strength

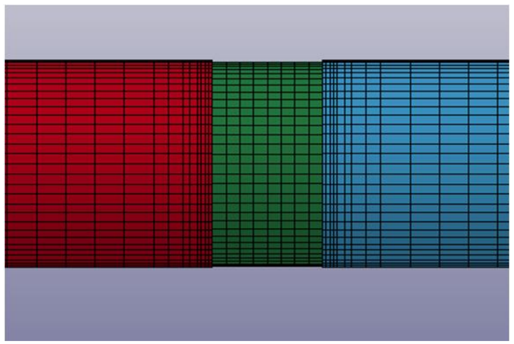
- Dynamic increase factor (DIF) is overestimated in high rate material test due to inertial effect
- Axial strain acceleration & geometry of specimen which are NOT material properties influence the results of high rate material test
- Pure rate effect was figured out from the result of concrete SHPB test

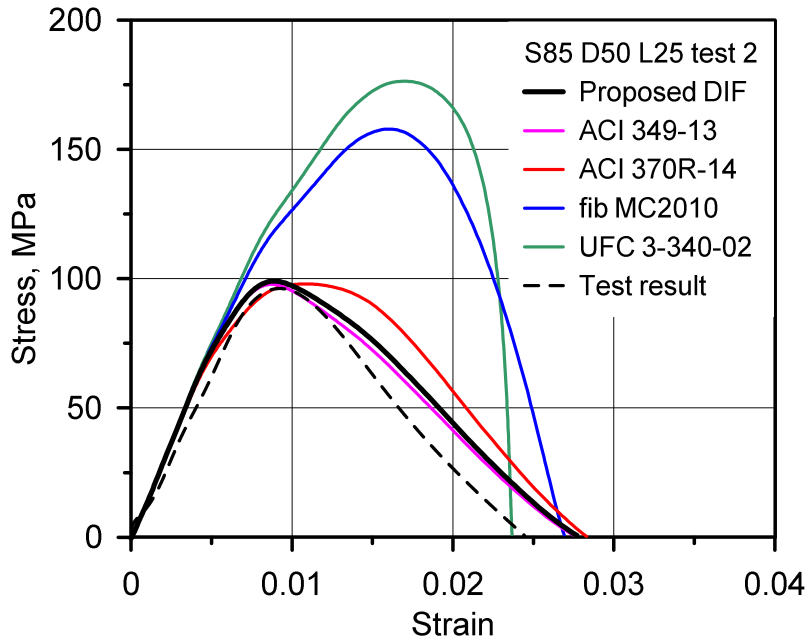
➡ Semi-analytical formula of DIF was suggested and validated

$$DIF_{apparent} = DIF_{rate} + \frac{\Delta f_{inertia}}{f_{c,static}}$$

$$= \left(\frac{\dot{\varepsilon}_s}{10^{-5}}\right)^{0.0147} + 0.3501\frac{d_s^{\,2}\rho_s\ddot{\varepsilon}_s}{f_{c,static}} + 0.4100\frac{l_s^{\,2}\rho_s\ddot{\varepsilon}_s}{f_{c,static}}$$





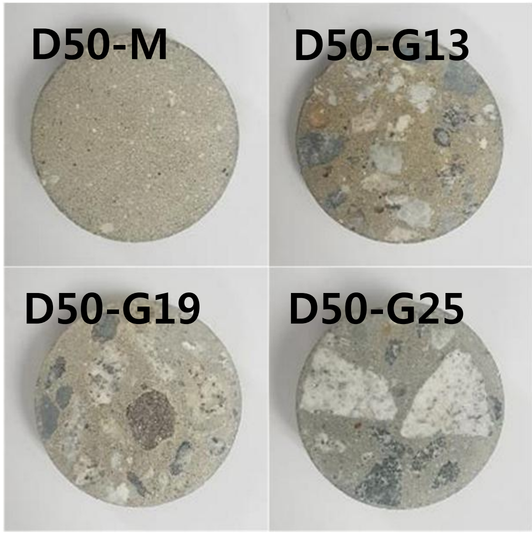


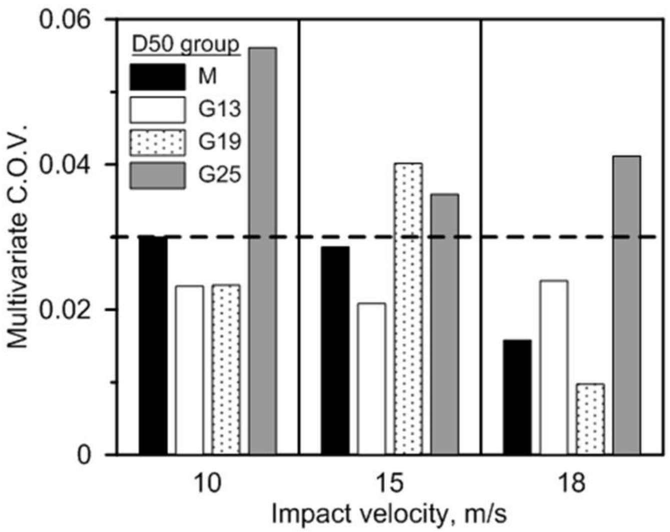
High Rate Material Test - SHPB

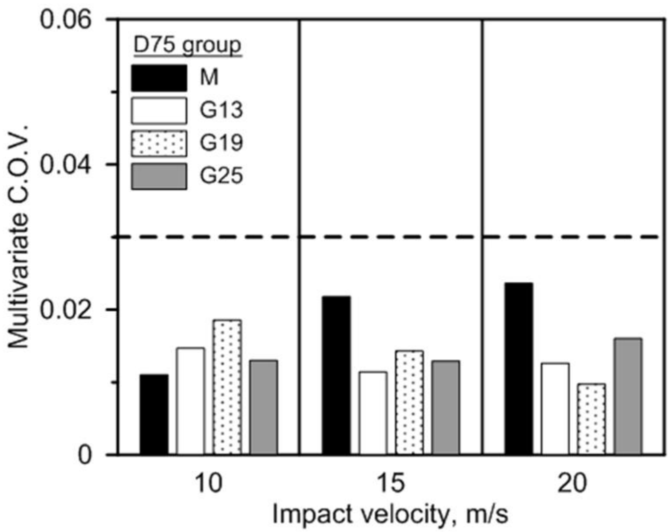
2) Effect of maximum aggregate size on dynamic increase factor of concrete compressive strength

- Small size aggregate has been used in many studies about concrete high rate test due to lack of standard test method
- Effect of maximum aggregate size on DIF was investigated from SHPB test results

➡ Guidance of maximum aggregate size for concrete SHPB test was suggested





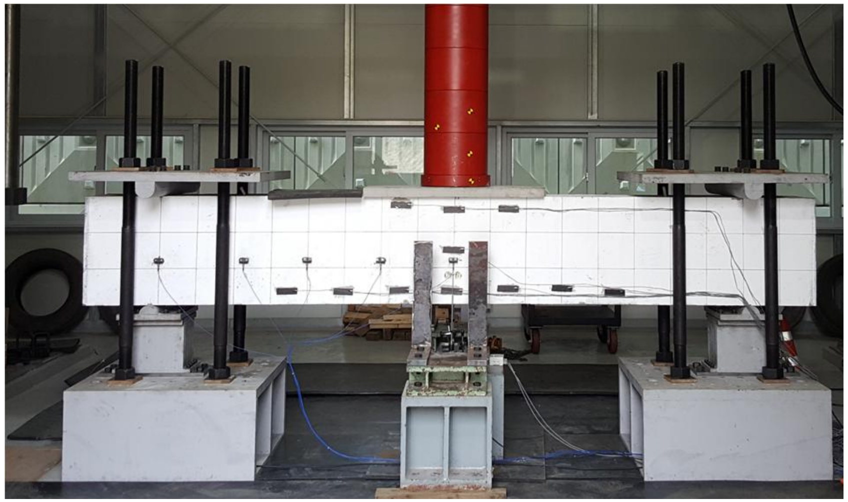


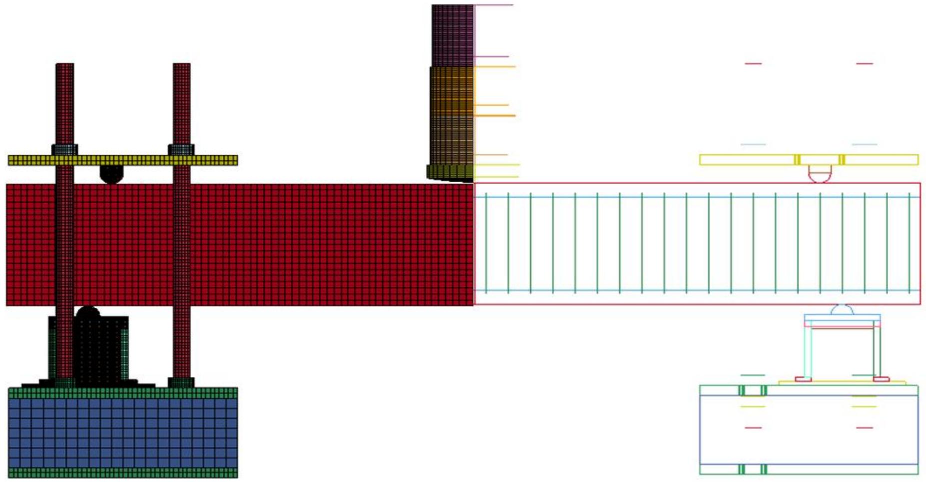
Scaled Model Test – Drop Weight Impact Test

1) Impact resistance evaluation of RC beam subjected to drop weight loading

- Limitations in the empirical formulas for evaluating impact resistance of RC beam
  - Limited impact energy level to represent the real event
  - Insufficient parameters to simulate various impact scenario
- Drop weight impact test and parametric study by FEA were conducted to overcome these limitations

➡ New empirical formula to evaluate the impact resistance of RC beam was suggested





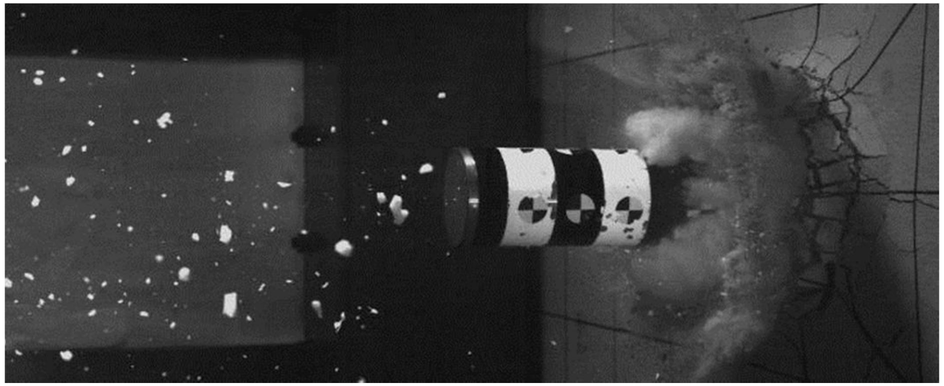
Scaled Model Test – Middle Velocity Gas Gun

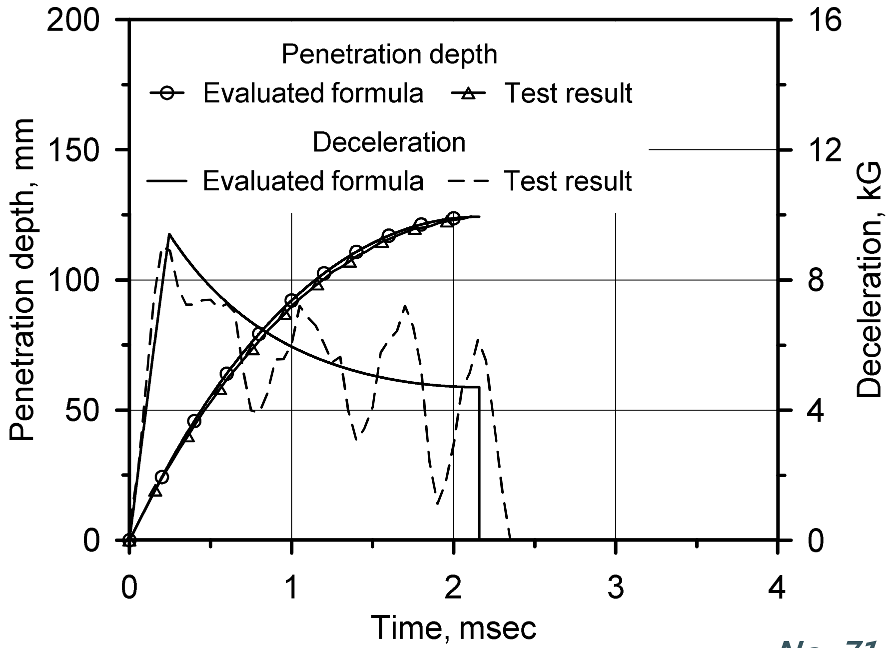
2) Evaluation of penetration depth for RC panel subjected to hard missile impact

- Existing semi-analytical formula of penetration depth was validated only for non-structural plain concrete target
- Experimental research was conducted to modify and validate the semi-analytical formula for RC panel

➡ Modified semi-analytical formula was suggested for applicability to RC panel

$$x_{pen} = \frac{2m}{6.62\pi d^2 \rho N} \ln\left(1 + \frac{N \rho V_1^2}{5.11 f_c}\right) + (0.15 + l_{nose})d$$





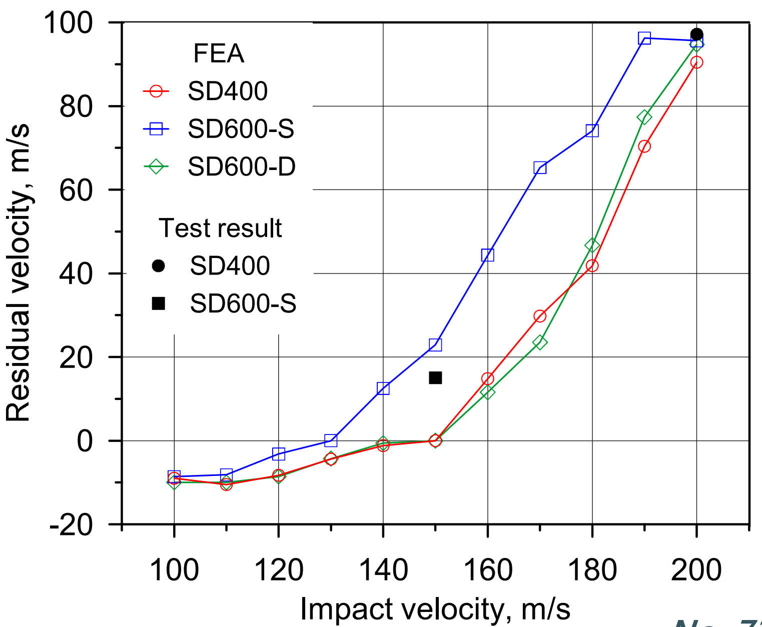
Scaled Model Test – Middle Velocity Gas Gun

3) Effect of high-strength reinforcing steel on impact resistance of RC panel subjected to hard missile impact

- High-strength rebar can be used to solve an issue of excessive placement of rebar in NPP structures
- Experimental/numerical researches were conducted to investigate applicability of high-strength rebar in NPP structures

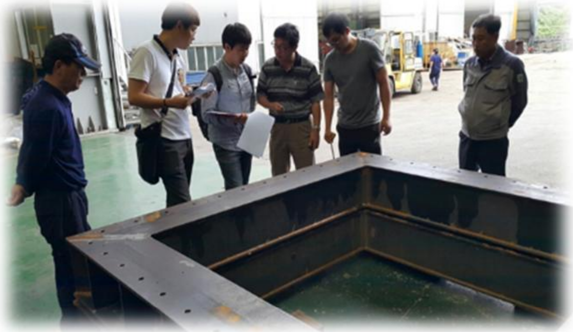
➡ Guidance was suggested to apply high-strength rebar to NPP structures

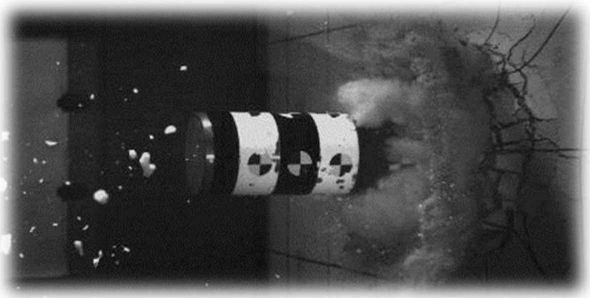
Rear faces of targets at 150 m/s impact velocity

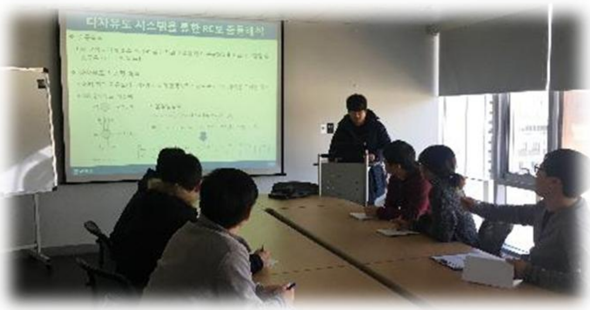


Concluding Remarks







Thank you…