Repair and strengthening of bridge decks using UHPFRC

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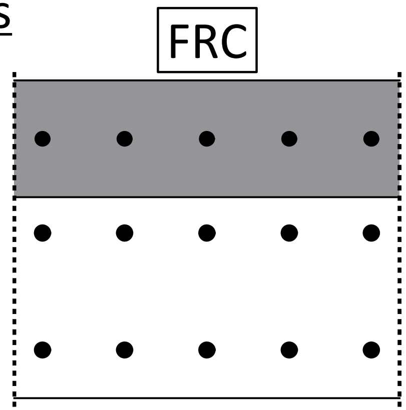
Outline

- Background and motivation
- Direct tension test
- Interfacial bond strength test
- Restrained shrinkage test
- Moving wheel load fatigue test
- Repair of Okaya Viaduct using UHPFRC

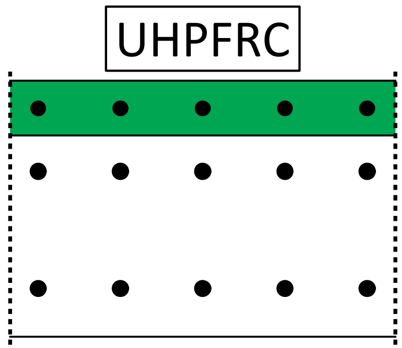
Repair and strengthening of bridge decks using UHPFRC

Conventional method for the repair and strengthening of bridge decks



- Overlay of fiber reinforced concrete (FRC) made of normal strength concrete with 1.3 vol.-% of steel fibers (l = 30 mm, d = 0.5 mm)
- Application of waterproofing on the top surface
- Thick FRC overlay required for improving the load-bearing capacity of bridge decks, leading to strengthening substructures and foundations

By using UHPFRC …

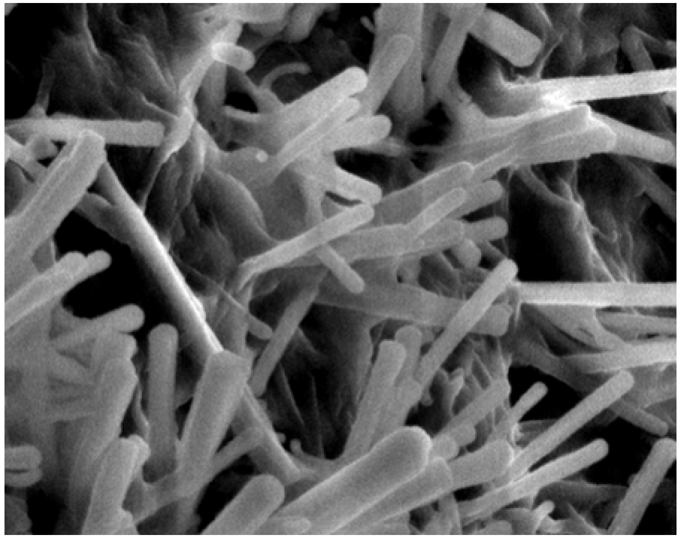


- Thinner overlay due to the high strength resulting in no strengthening of substructures and foundations
- No need to apply waterproofing due to the excellent transport property

→ More efficient solution for the repair and strengthening of bridge decks

UHPFRC mix used in the project

- ✓ Commercially available UHPFRC mix called “SUQCEM”
- ✓ Matrix densified by controlled ettringite (AFt) formation; thus, “AFt-UHPFRC”
- ✓ Microstructure of the AFt-UHPFRC formed by densely packed pozzolan particles
- ✓ Micropores of the hydration structure filled by numerous acicular ettringite crystals of 1 to 2 µm length

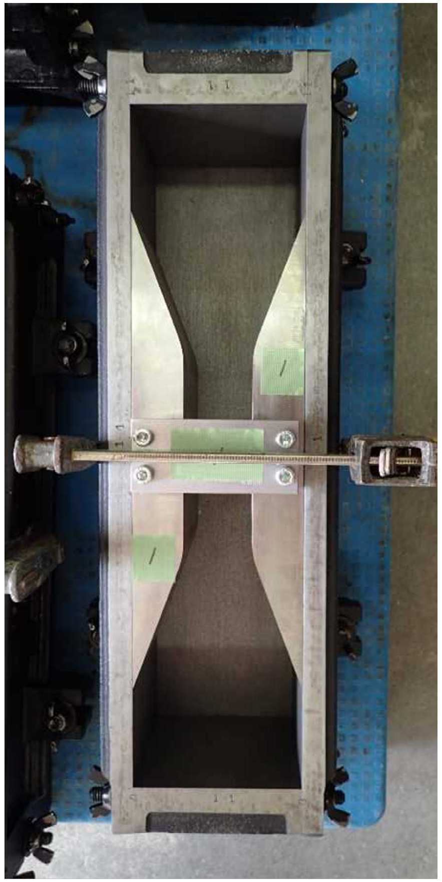


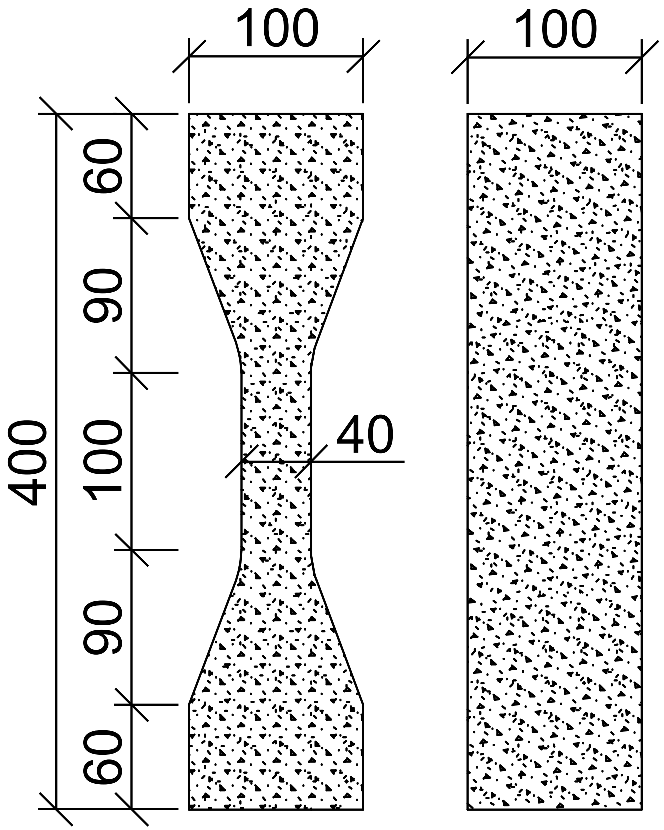
Ettringite crystals

Component	Mass [kg/m^3]	Remarks
Cement	927.0	Portland cement
Premixed materials	360.0	Pozzolanic material, calcium sulfoaluminate based additive
Sand	859.0	Manufactured sand, d_{max}< 2.5mm
Wollastonite	64.0	
Steel fiber	137.4	3.0 vol.-%, l = 15mm, d = 0.2mm
Superplasticizer	32.2	
Shrinkage reducing admx.	25.7	
Defoaming agent	6.4	
Water	195.0	Including water in the superplasticizer and defoaming agent, W/B=0.152

Direct tension tests of UHPFRC

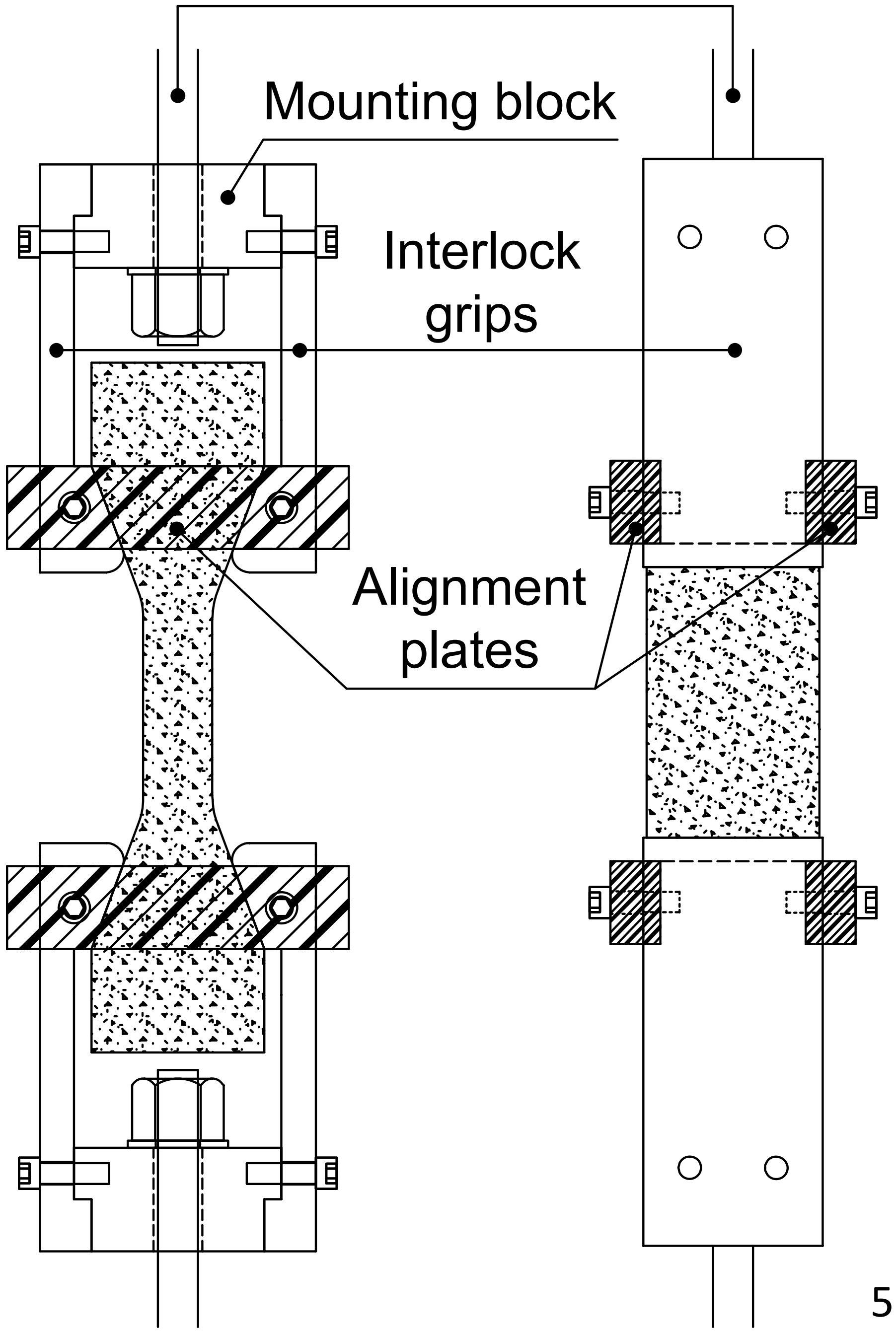
- ✓ Understand the strain hardening behavior achieved by increasing the fiber content to 3.0 vol.-%
- ✓ Understand the tensile property of the UHPFRC cured at normal temperature (w/o heat curing)





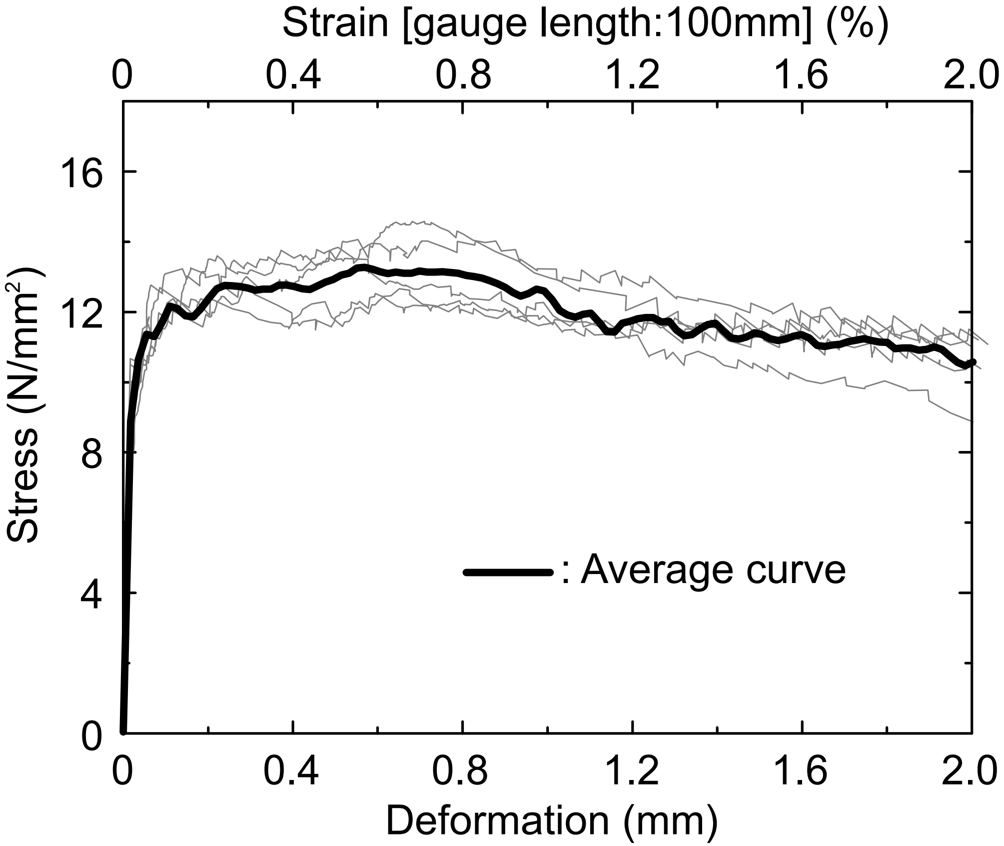
[unit:mm]

Direct tension tests of UHPFRC

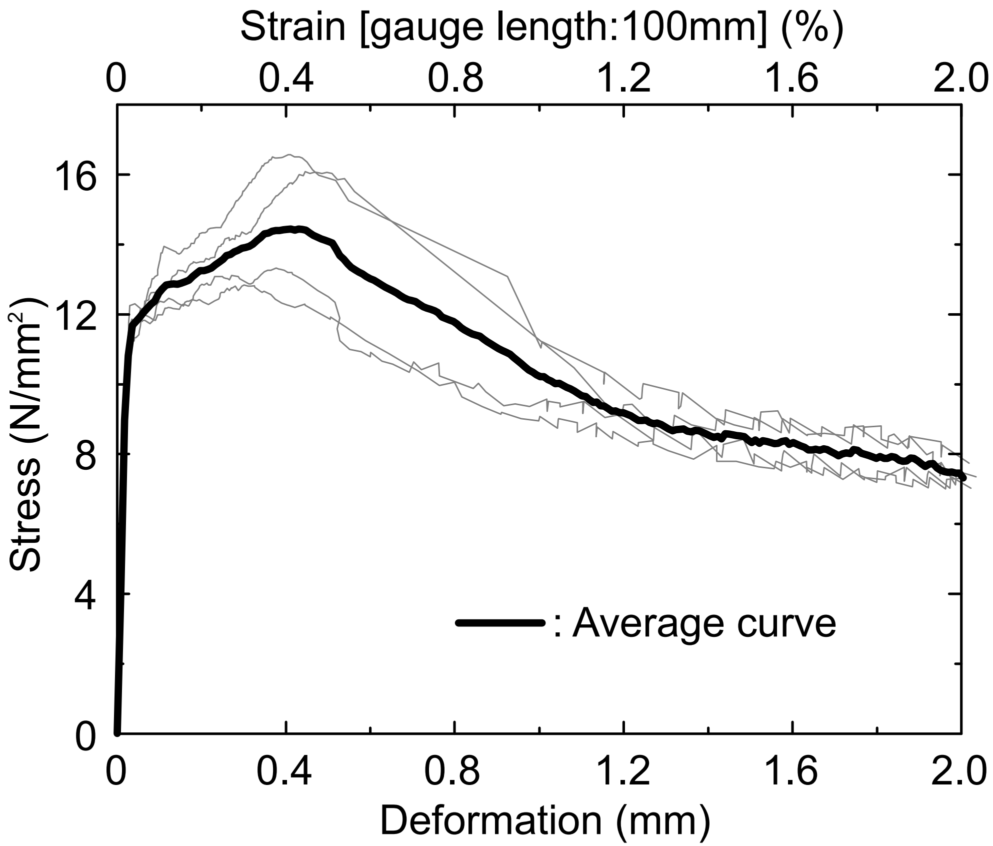


Comparison of tensile behavior : 1.75 vol.-% vs. 3.0 vol.-%

- ✓ [1.75 vol.-%] moderate decrease in stress in the softening domain because the 22mm long fibers delayed the increase in crack width
- ✓ [3.0 vol.-%] higher cracking strength and larger strain hardening due to its higher fiber volume fraction



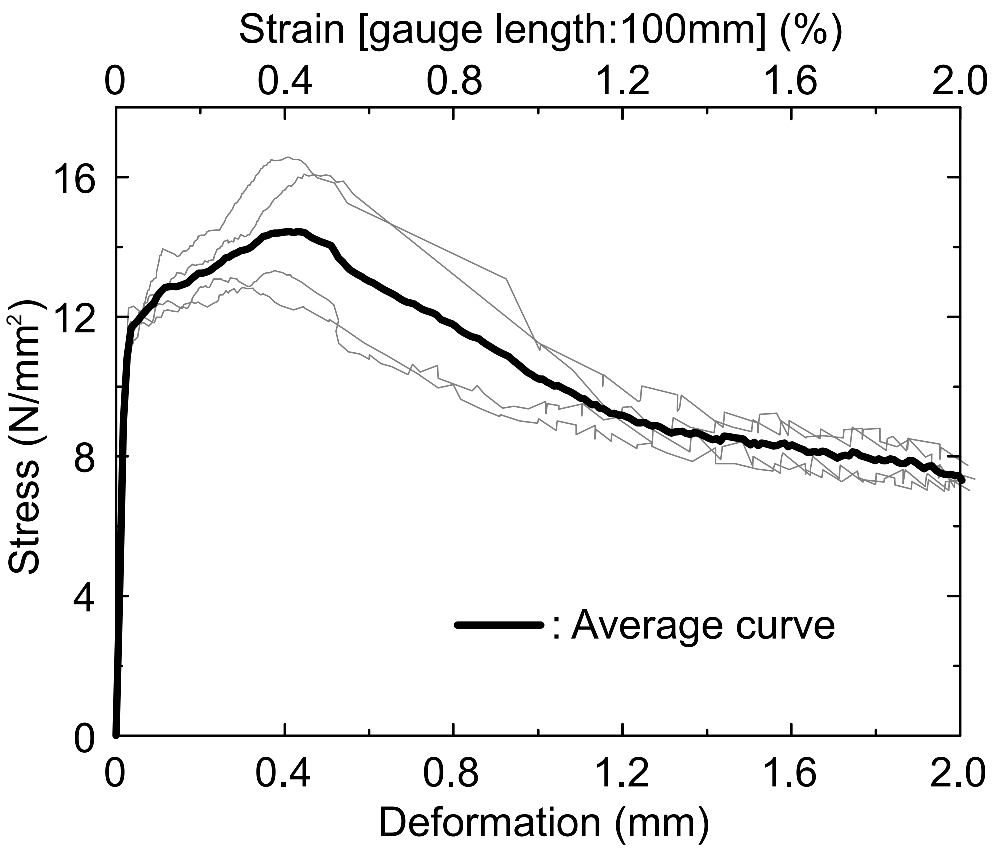
1.75 vol.-% (*l* = 15 and 22mm, *d* = 0.2mm)
20°C - 24hrs → 85°C - 24hrs



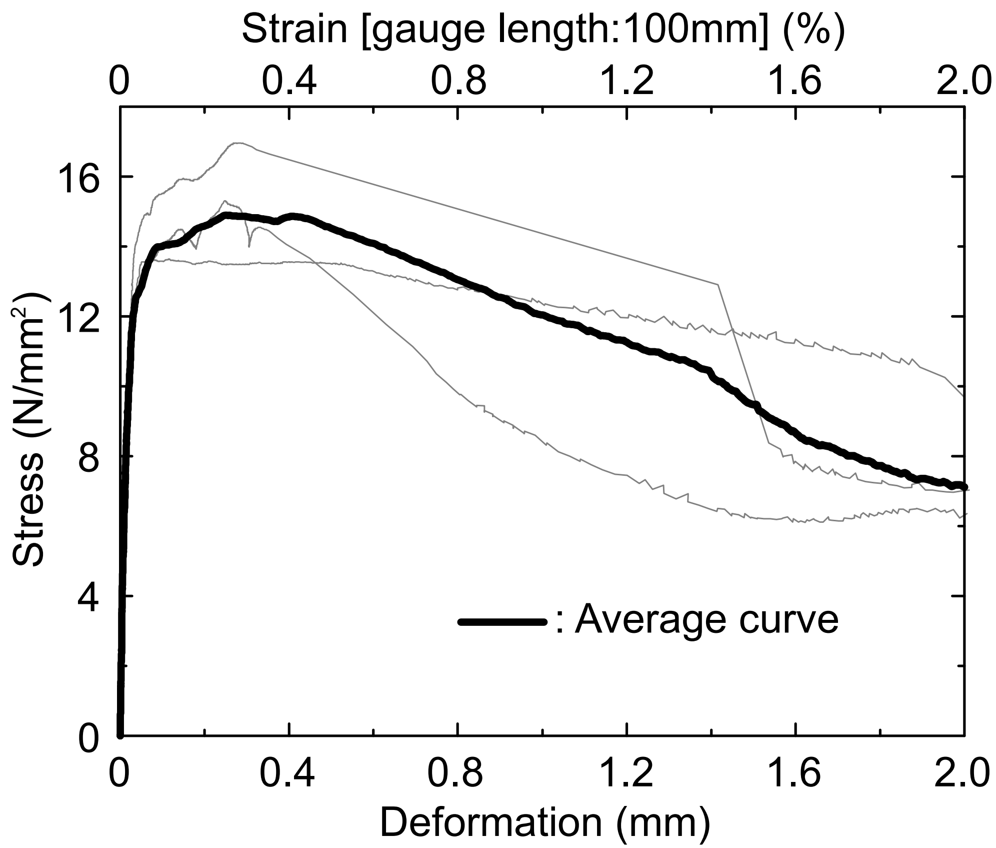
3.0 vol.-% (*l* = 15 mm, *d* = 0.2mm)
20°C - 24hrs → 85°C - 24hrs

Comparison of tensile behavior : w/ vs. w/o heat curing

- ✓ [w/ heat curing] larger strain hardening because of the higher fiber-matrix bond strength achieved by heat curing
- ✓ [w/o heat curing] higher cracking strength due to wollastonite



3.0 vol.-% (l = 15 mm, d = 0.2mm)
20°C - 24hrs → 85°C - 24hrs

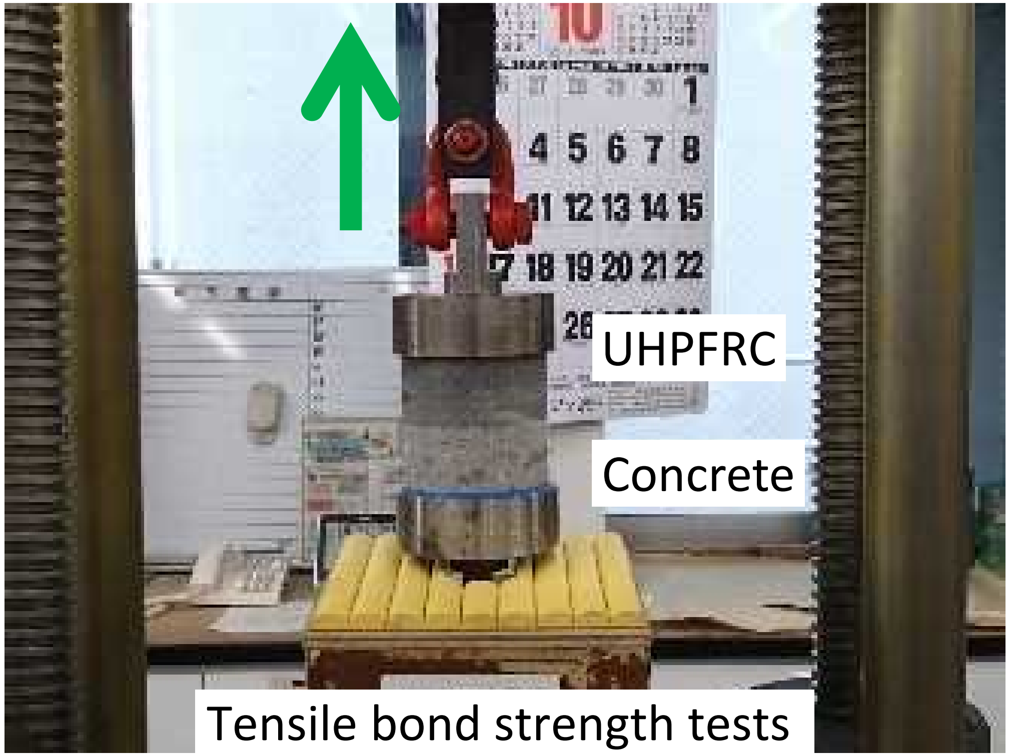


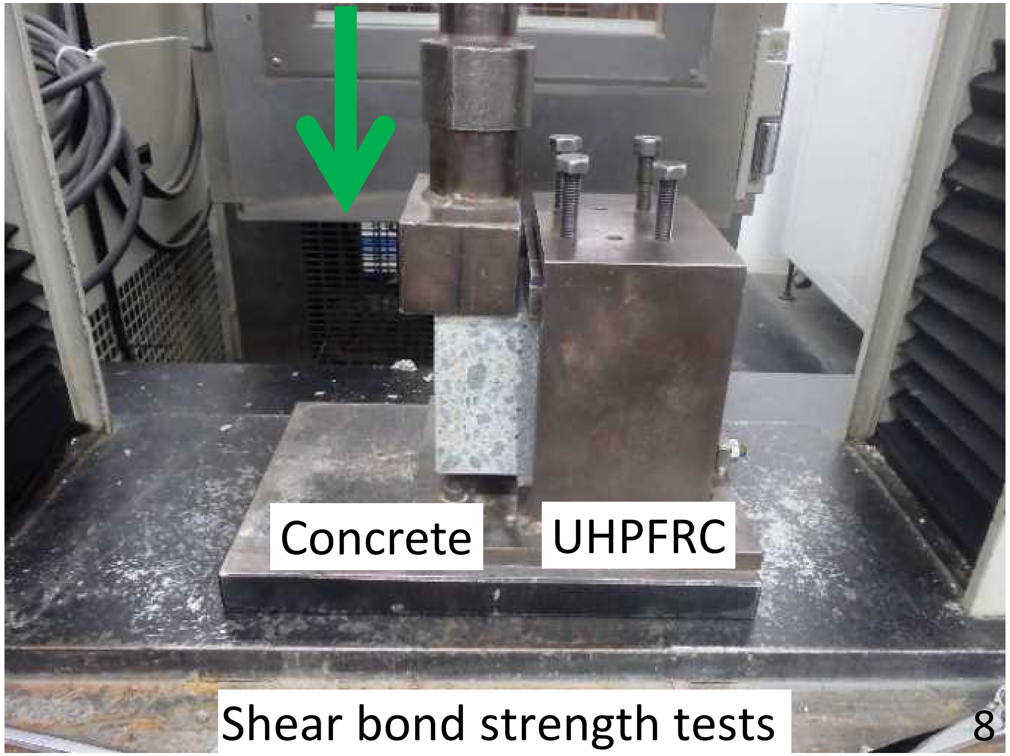
3.0 vol.-% (l = 15 mm, d = 0.2mm)
w/ wollastonite
20°C & sealed - 28days

UHPFRC – concrete interfacial bond strength tests

- ✓ Focus on the adhesive at the interface (Is it necessary or not?)
- ✓ Tensile bond strength tests using composite cylinder specimens (ϕ100mm, 50mm+50mm)
- ✓ Shear bond strength tests using composite cube specimens (100×100mm, 50mm+50mm)

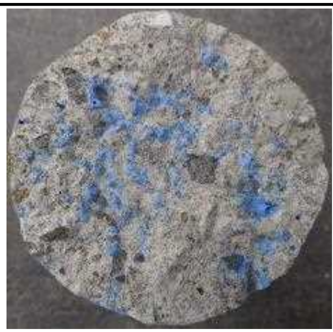
(https://www.kozobutsu-hozen-journal.net/libraries/search/detail.php?id=12)





Results of tensile bond strength tests

Specimen	No.	Tensile bond strength (N/mm^2)
w/o epoxy adhesive	1	2.31
	2	2.20
	3	2.45
	Average	2.32
w/ epoxy adhesive	1	2.79
	2	3.14
	3	2.84
	Average	2.92

Specimen	1	2	3
w/o epoxy adhesive			
w/ epoxy adhesive			

Results of shear bond strength tests

Specimen	No.	Shear bond strength (N/mm^2)
w/o epoxy adhesive	1	4.17
	2	6.28
	3	5.64
	Average	5.36
w/ epoxy adhesive	1	3.34
	2	4.81
	3	4.60
	Average	4.25

Specimen	1	2	3
w/o epoxy adhesive			
w/ epoxy adhesive			

Restraint of shrinkage by substrates

Total shrinkage strain of UHPFRC : 600μm/m～

→ Large autogenous shrinkage due to low W/B

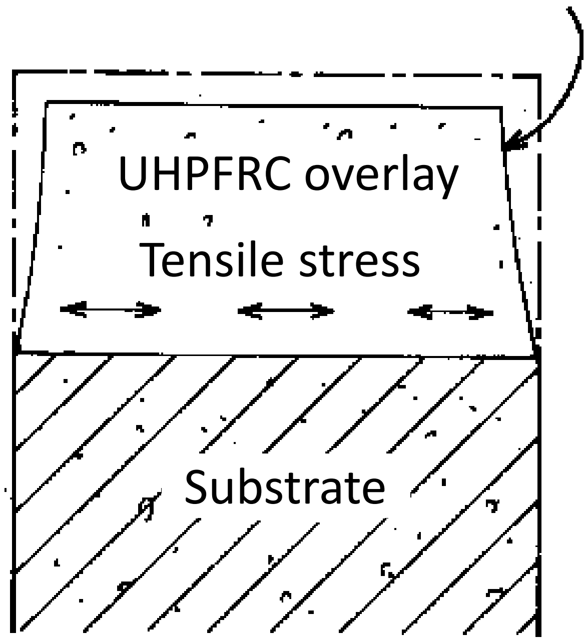
Does restrained shrinkage stress exceed the cracking strength of UHPFRC?

⬇

At early age before hardening of UHPFRC,

1. Tensile creep strain caused by restrained shrinkage stress (tensile stress)
2. The tensile creep counteracts the shrinkage
3. Decrease of the shrinkage strain

➔ **Decrease of restrained shrinkage stress**



Need to understand the early age behavior of UHPFRC restrained by substrates

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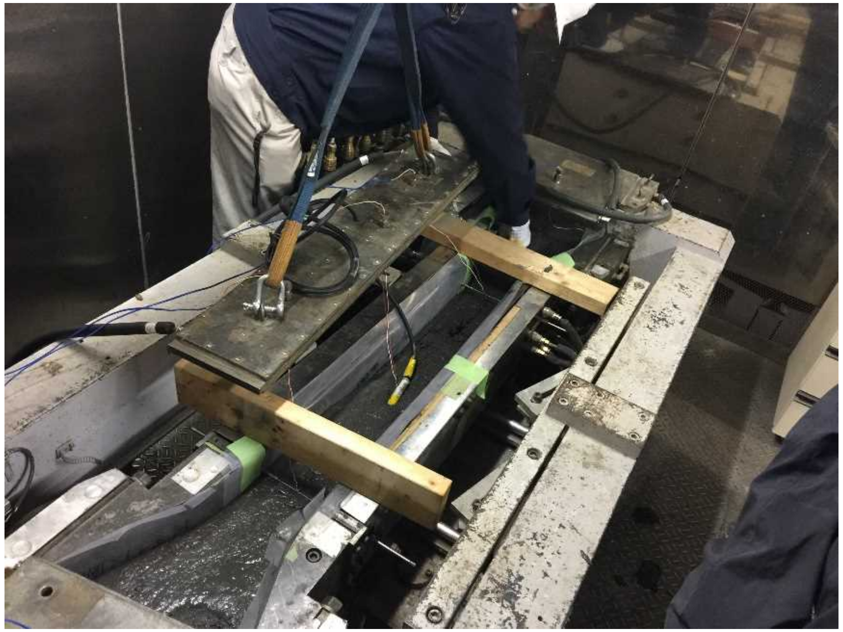
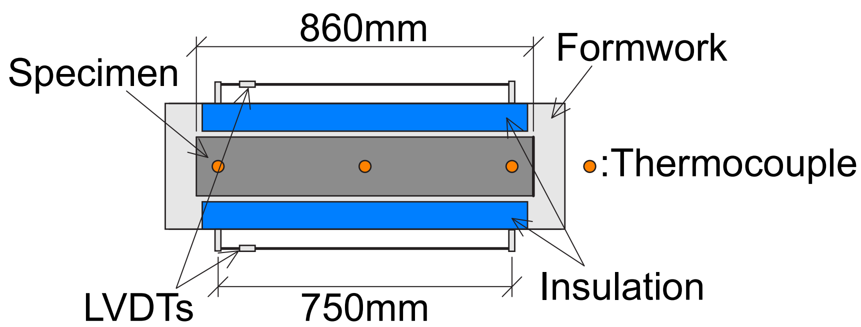
Restrained shrinkage test using TSTM

Restrained shrinkage test using TSTM

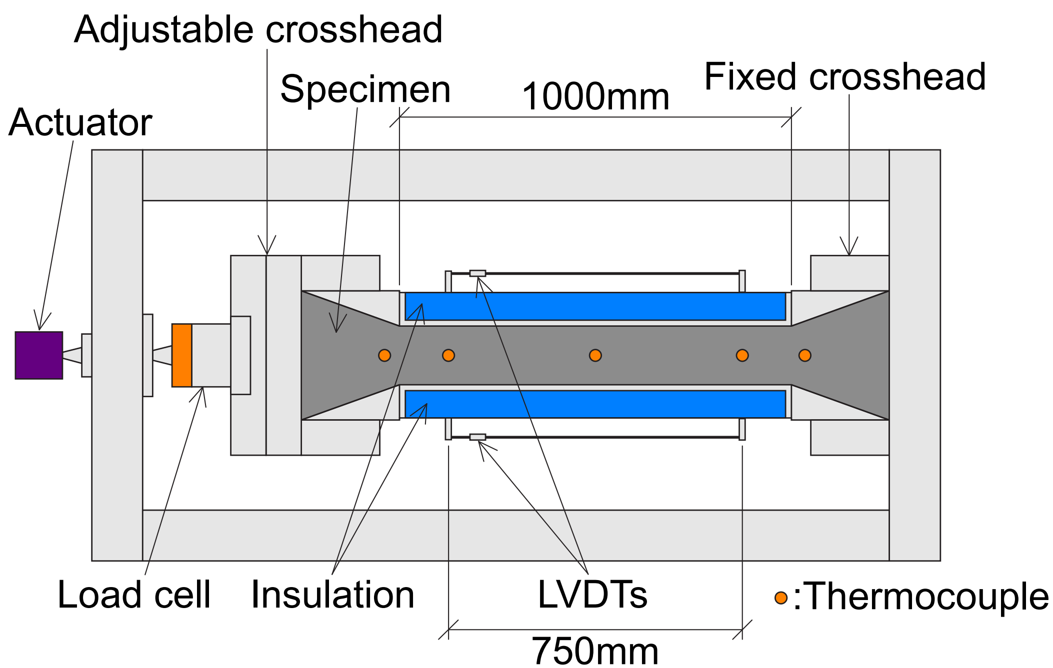


Temperature **S**tress **T**esting **M**achine

- ✓ Consists of free shrinkage setup and restrained shrinkage setup
- ✓ Simulate various restrained conditions using a load cell and an electromechanical actuator linked to a closed loop system
- ✓ Create a quasi-isothermal condition using a cooling pipe surrounding the molds



Free shrinkage setup



Restrained shrinkage setup

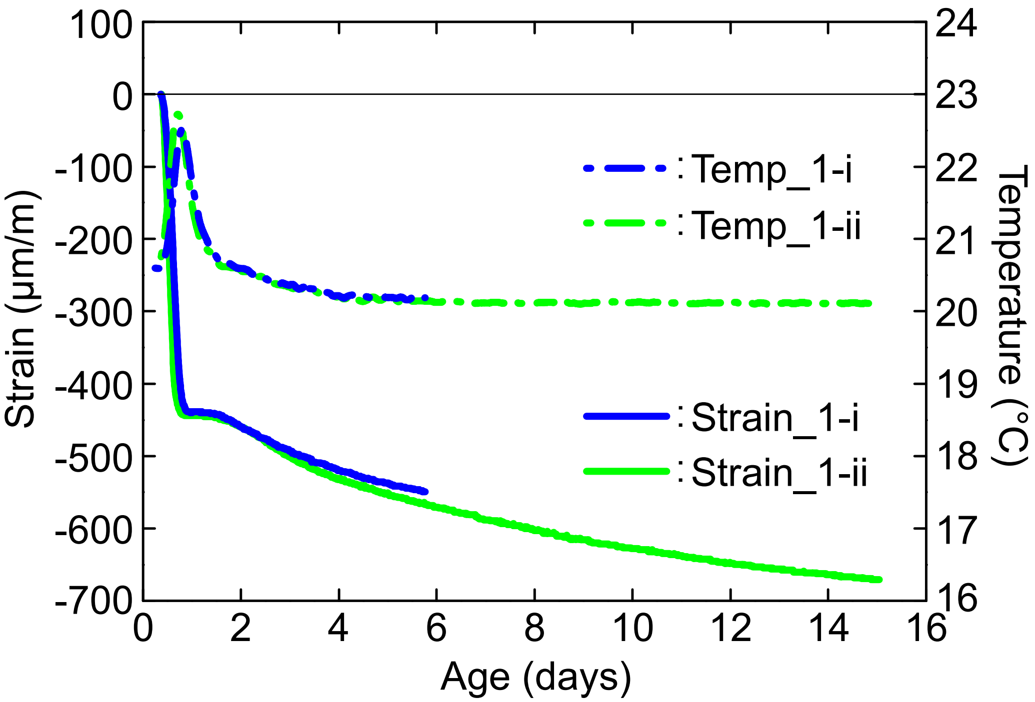
Results of restrained shrinkage test 1

<u>Test condition</u>

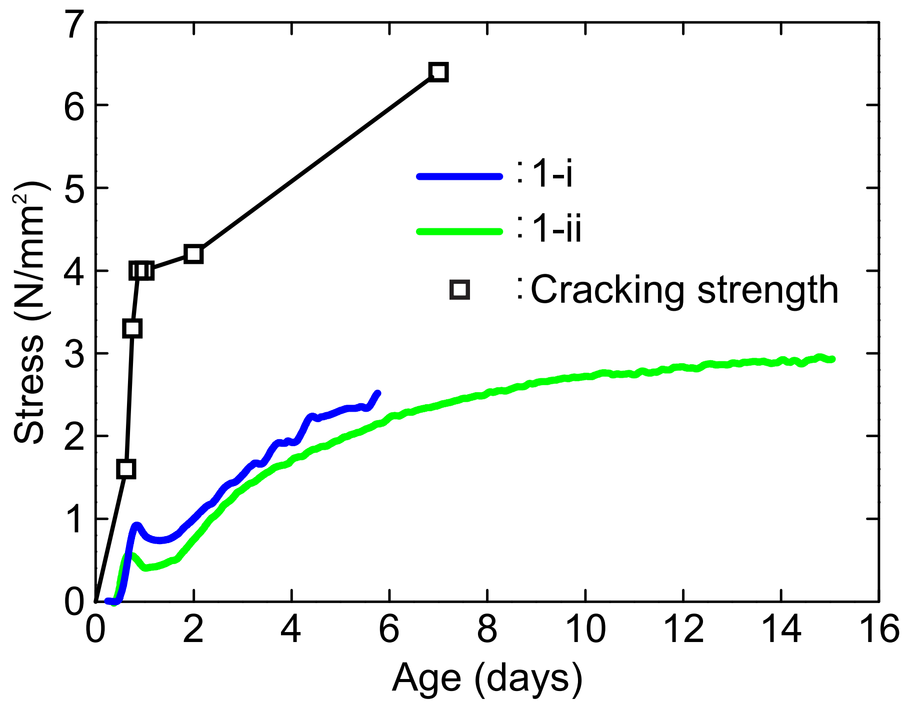
✓ Restraint condition : full restraint

✓ Temperature : 20°C

✓ Test duration : six days and fifteen days



Free strain and specimen temperature



Restrained shrinkage stress

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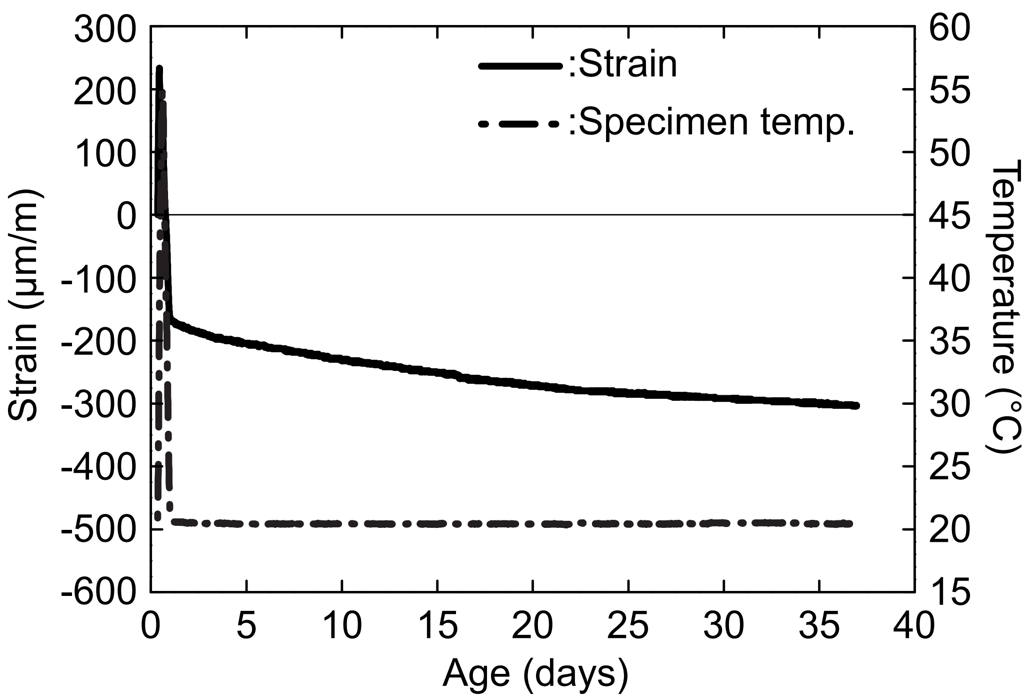
Tensile creep relaxed restrained shrinkage stress, and no cracking occurred.

Results of restrained shrinkage test 2

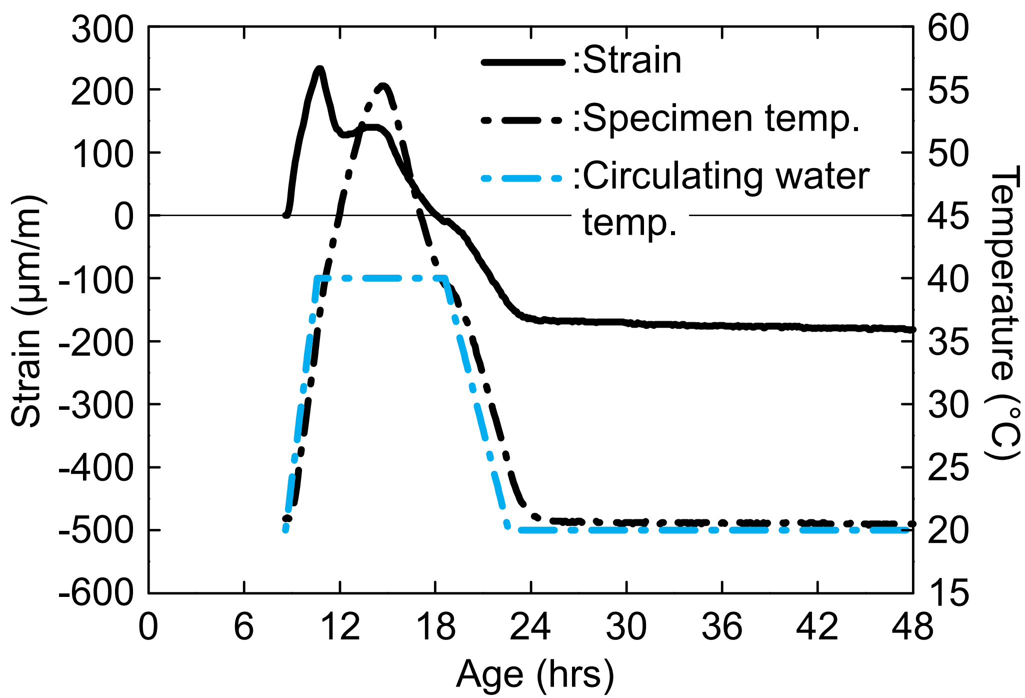
Test condition

- ✓ Restraint condition : full restraint
- ✓ Simulate the temperature history of a heat curing process
- ✓ Test duration : 37 days

Time	Temp.	Remarks
0h	20°C	Add water
8.6h		Initial setting
8.6h ~ 10.6h	+10°C/h	Heating period of 2hrs
10.6h ~ 18.6h	40°C	Curing period of 8hrs
18.6h ~ 22.6h	-5°C/h	Cooling period of 4hrs
↓	20°C	Constant temperature
37days		End of the test

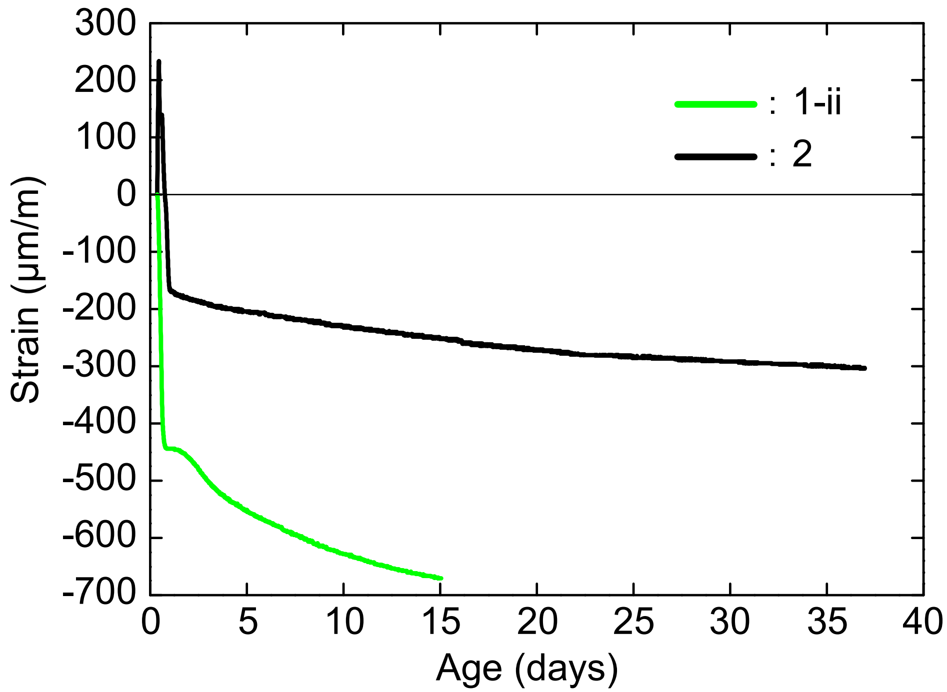


Free strain and specimen temperature

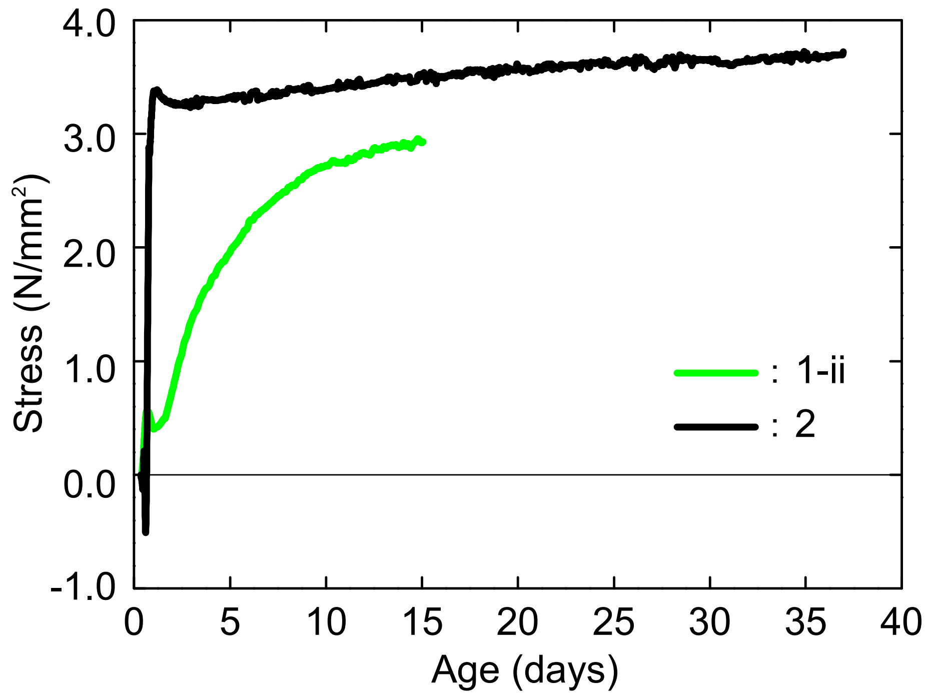


Strain and temperature for 48 hours

Comparison of free strain and restrained shrinkage stress



Free strain



Restrained shrinkage stress

Low shrinkage doesn't necessarily lead to low restrained shrinkage stress when the strength development is rapid.

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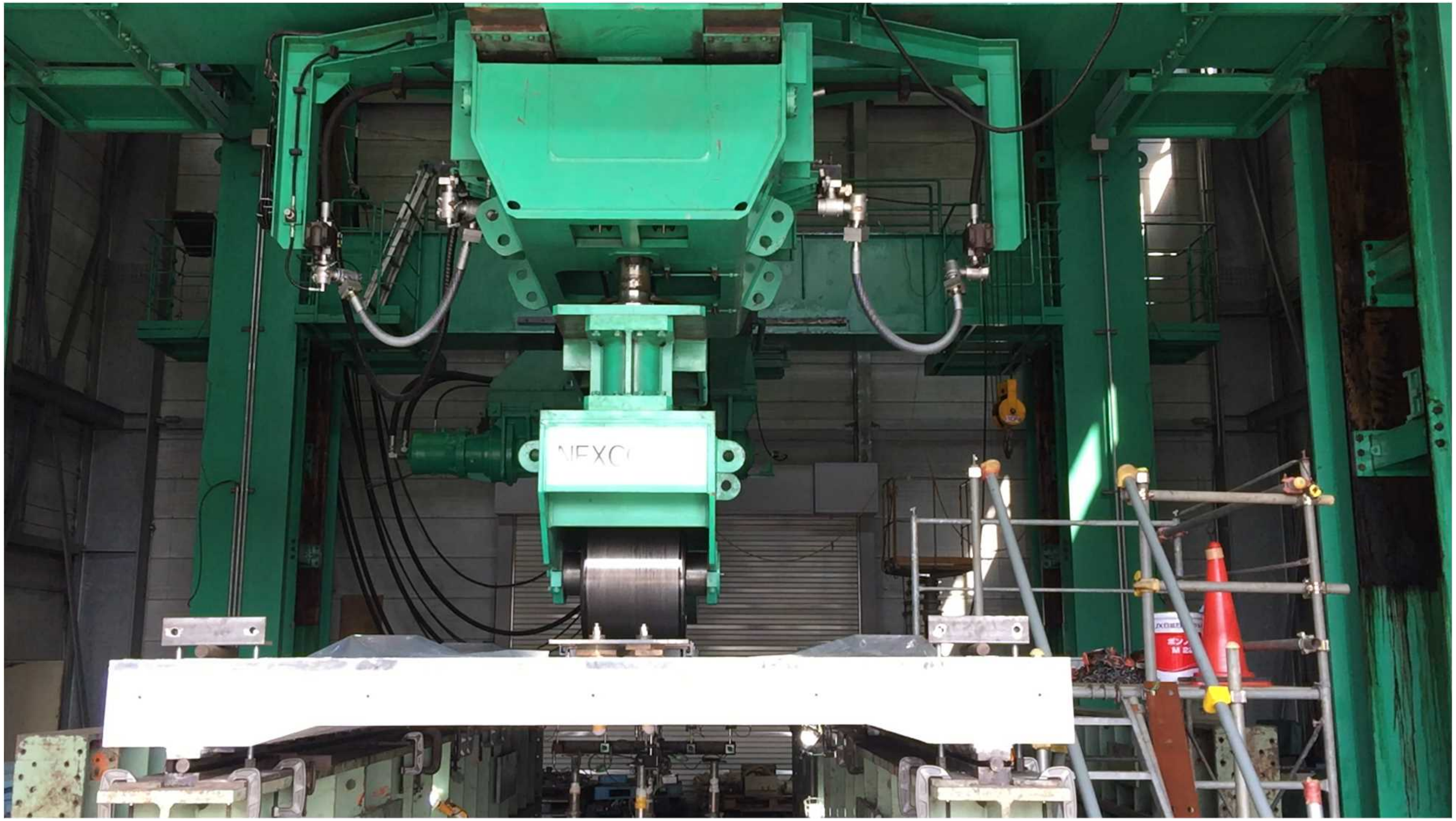
<u>Need to carefully consider the use of heated blanket curing, expansive additives, and hardening accelerators</u>

Full scale fatigue test of a UHPFRC – RC composite deck slab

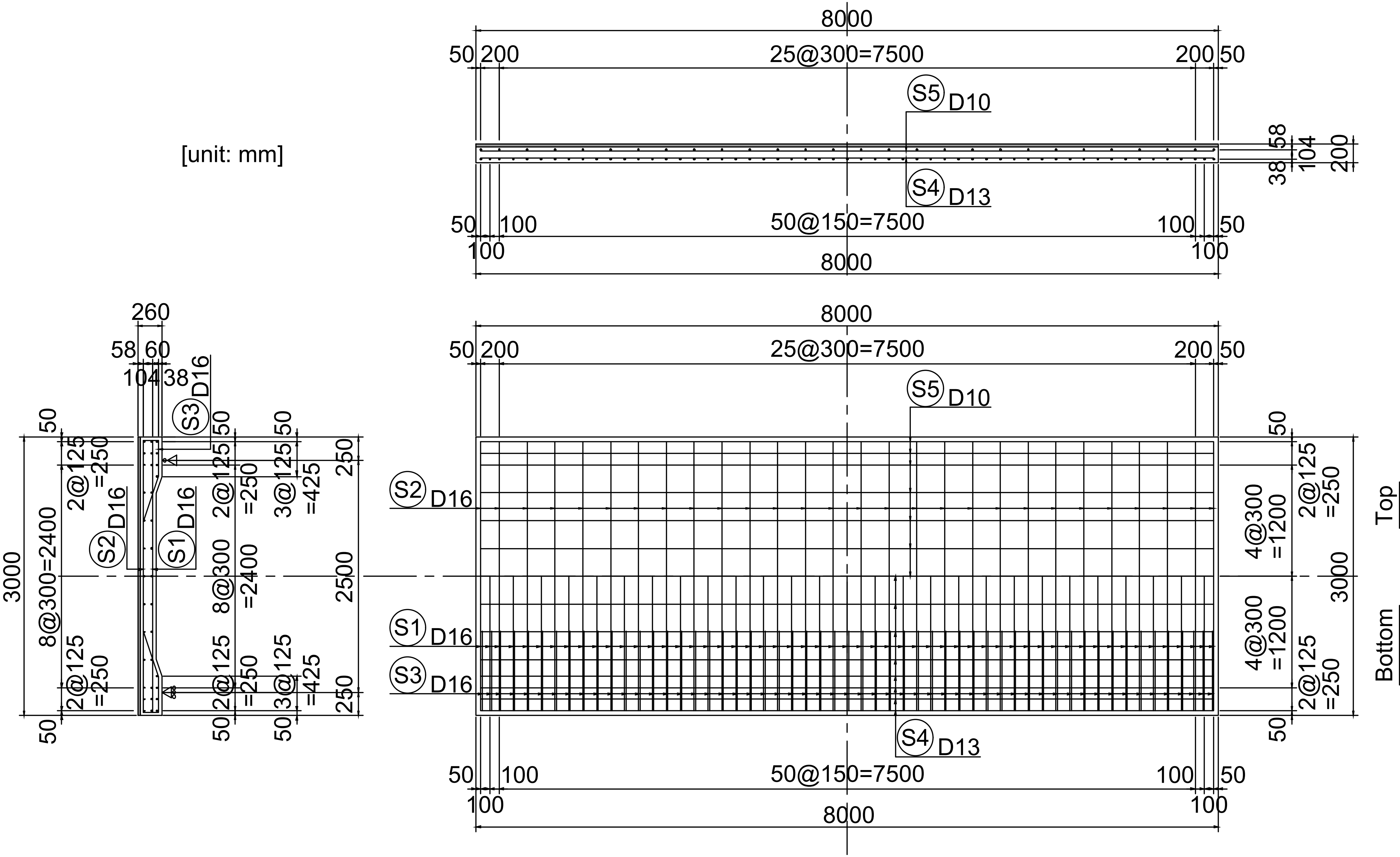
Fatigue test of bridge deck slabs using moving wheel loads

- ✓ Moving wheel loads cause shear force reversal torsional moment reversal in bridge decks, which is difficult to reproduce by repeated point loads.
- ✓ Abrasion of crack faces occurs on bridge decks twice as much as those subjected to repeated point loads, resulting in a shorter fatigue life.

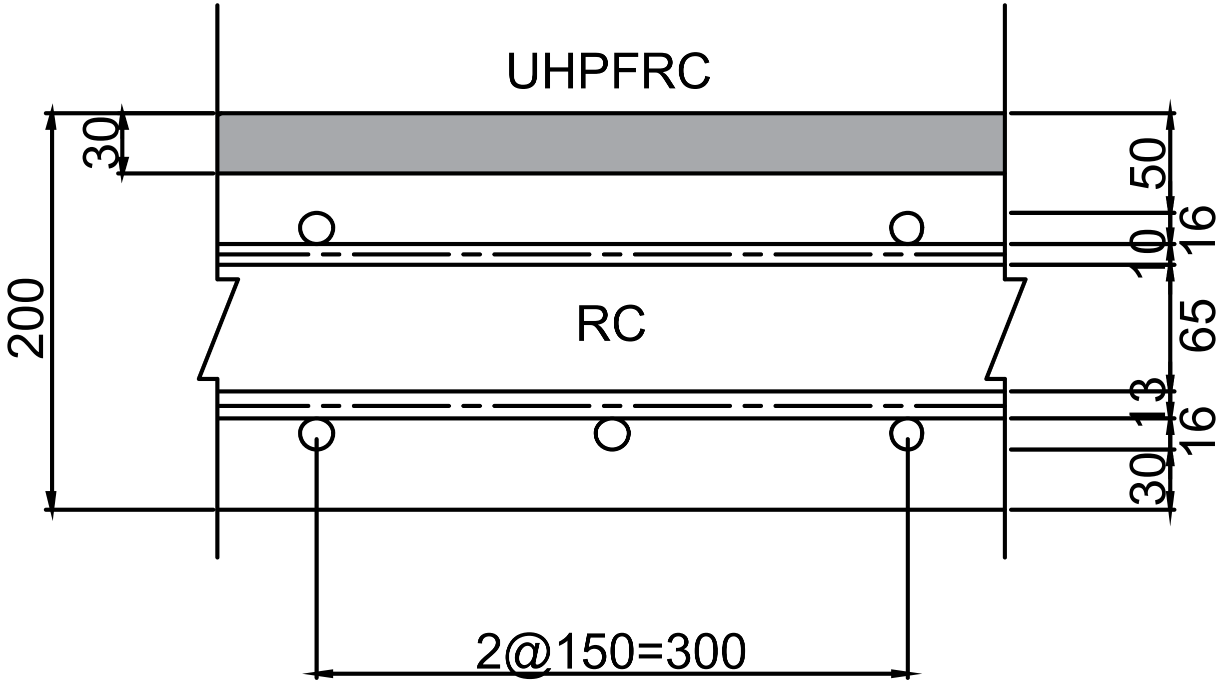


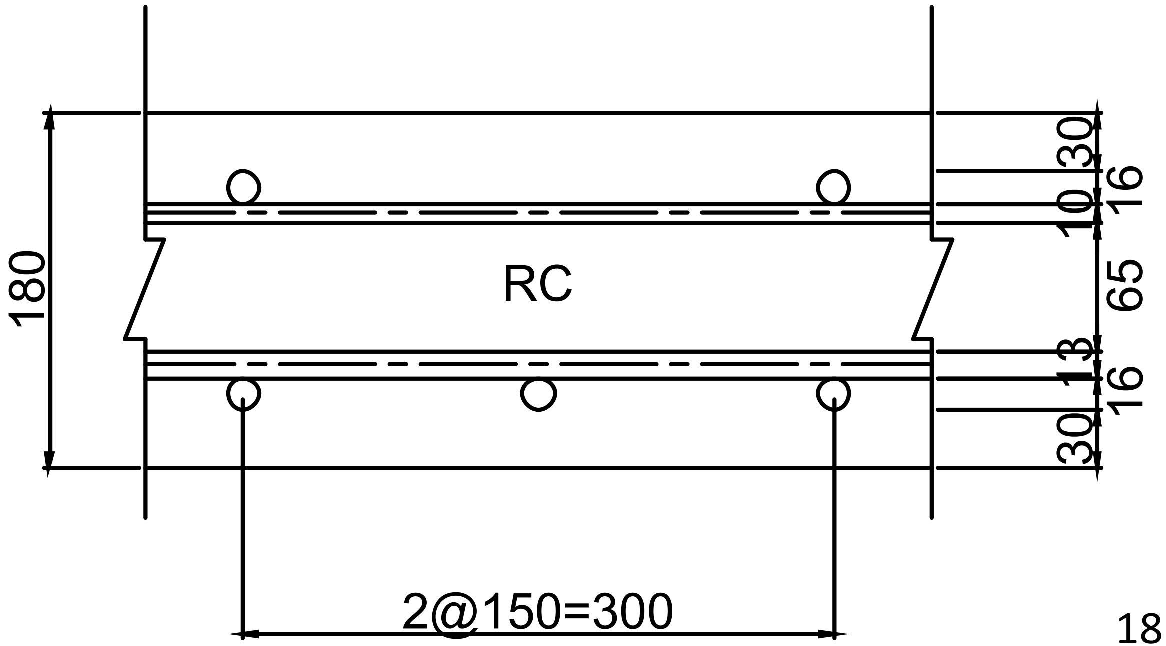
UHPFRC – RC composite deck slab specimen

[unit: mm]



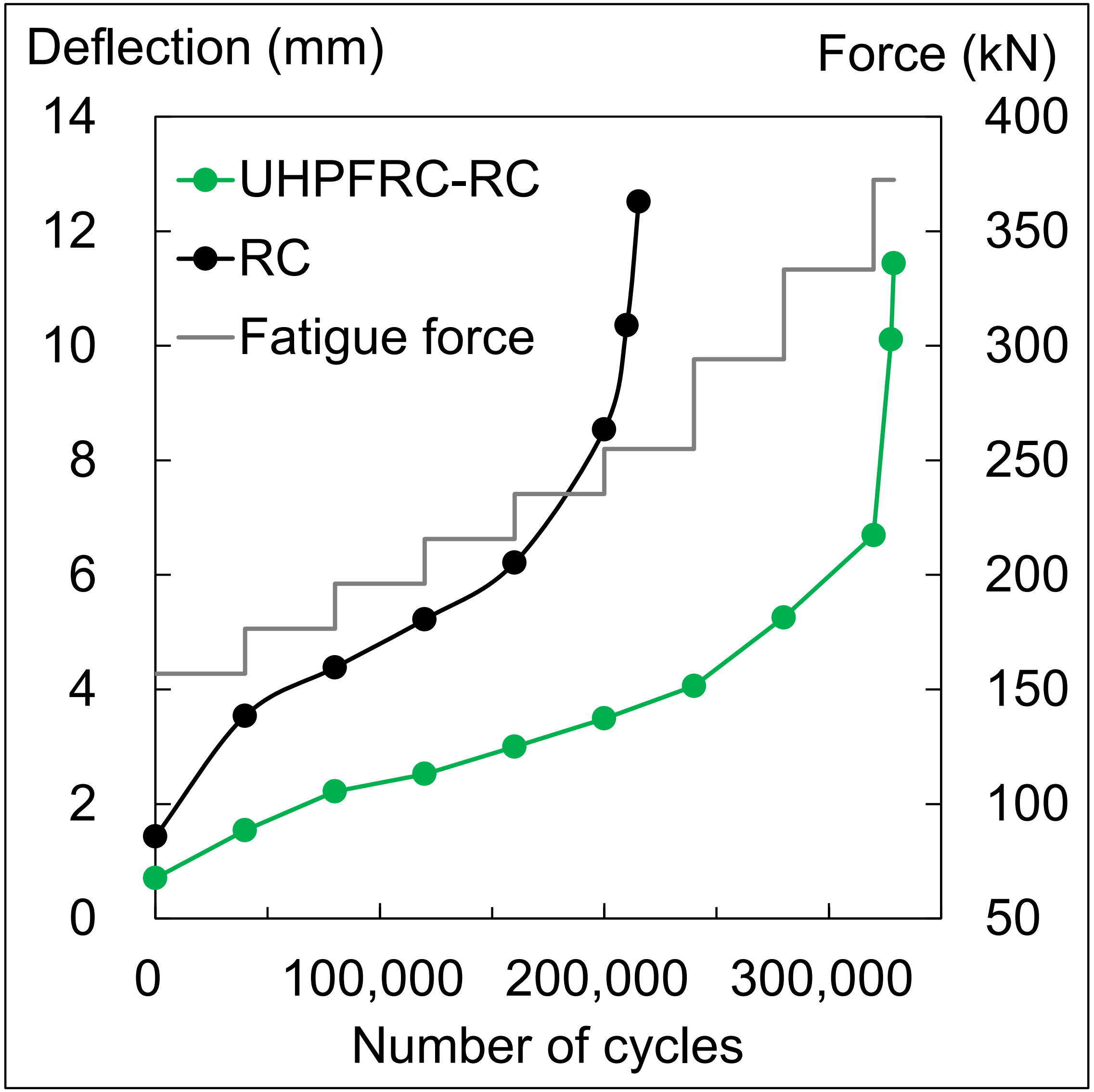
UHPFRC – RC composite deck slab specimen



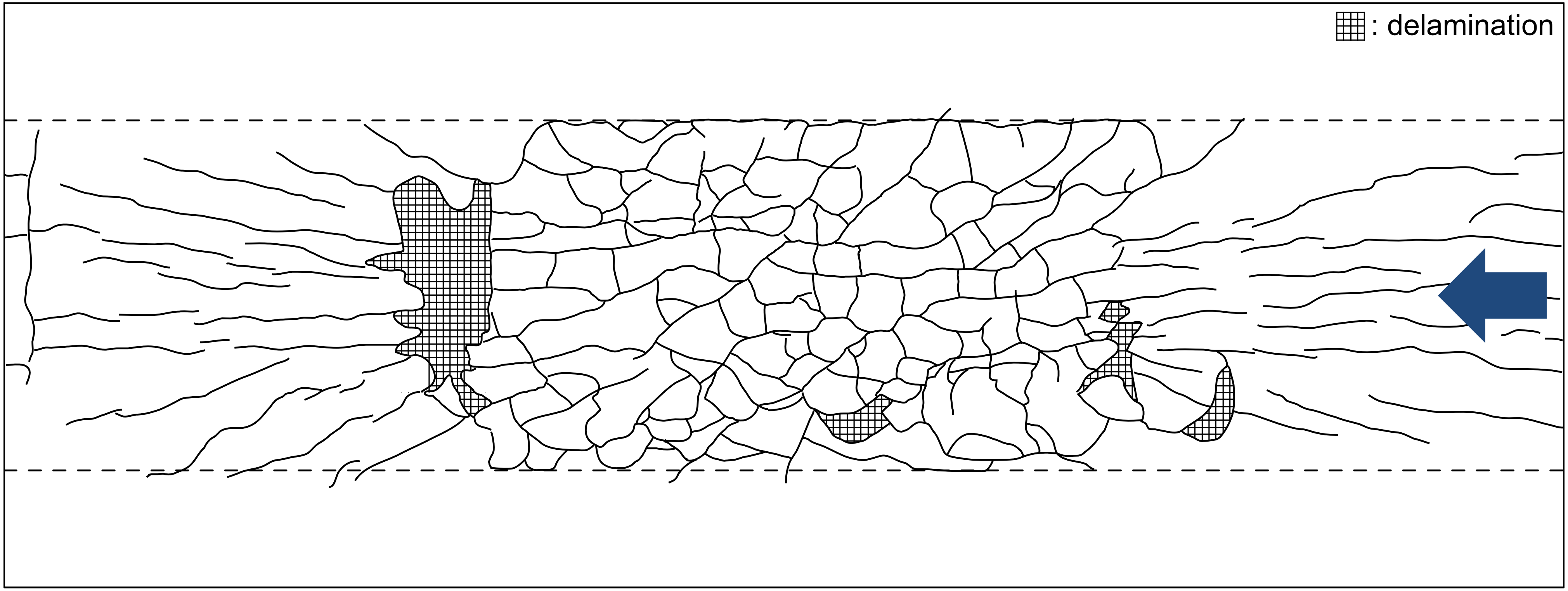


Stepwise increasing fatigue loading and deflection growth

Step	Load (kN)	Number of cycles
1	156.9	40,000
2	176.5	40,000
3	196.1	40,000
4	215.7	40,000
5	235.3	40,000
6	254.9	40,000
7	294.1	40,000
8	333.3	40,000
9	372.5	9000
	Failed	329,000

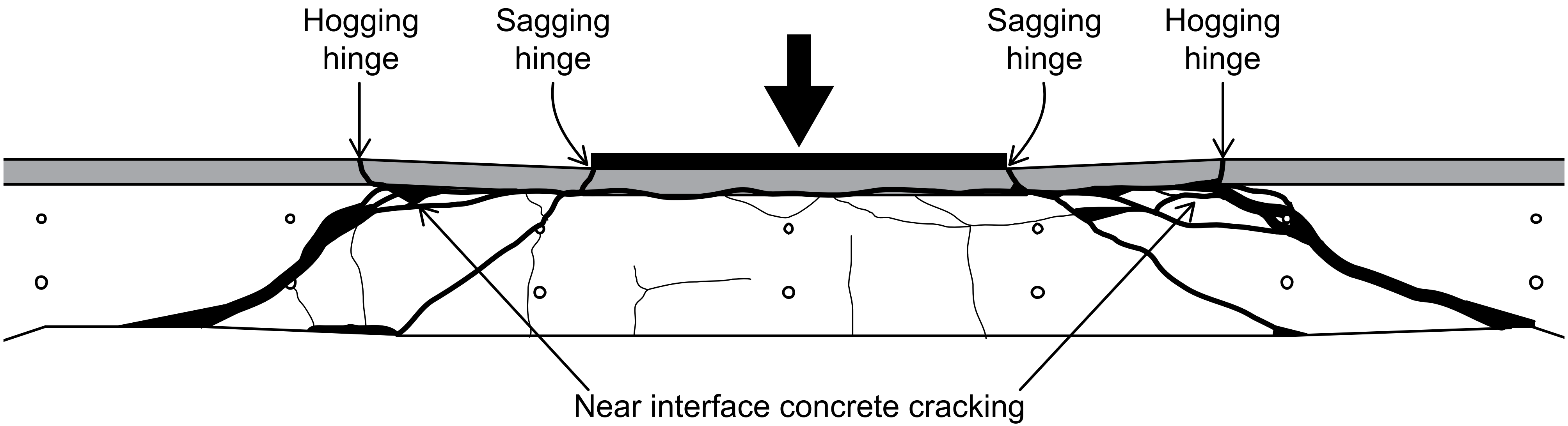


Crack pattern on the bottom surface of the failed specimen

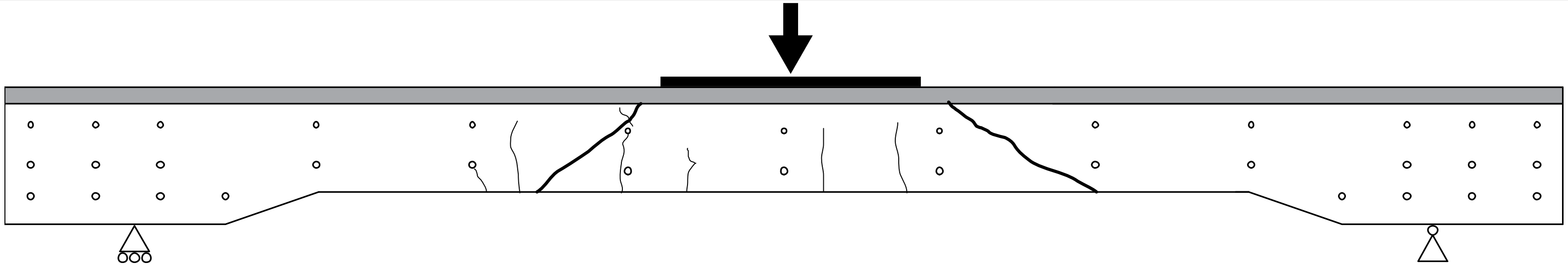


Bottom surface of a fatigue damaged RC bridge deck

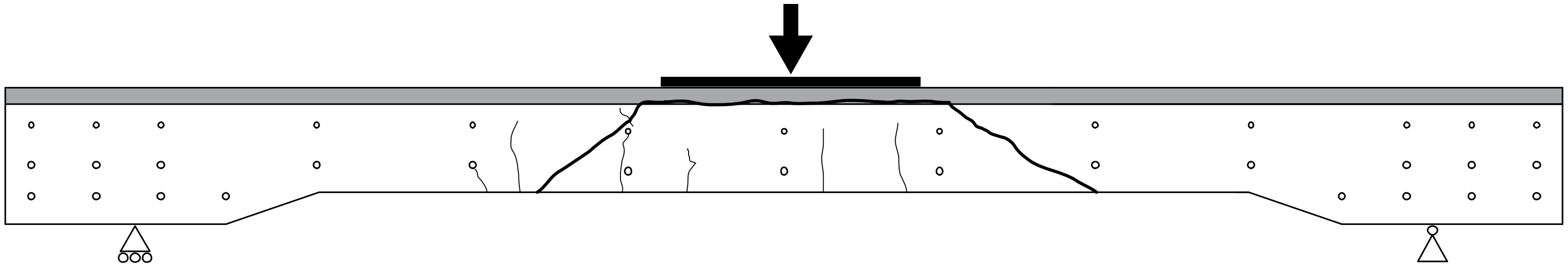
Transverse cut section at the center of the failed specimen



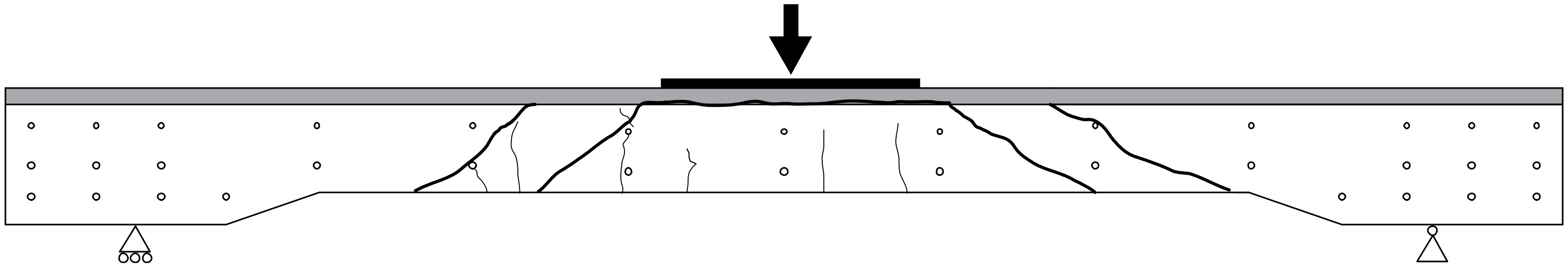
Failure process of the UHPFRC – RC composite deck slab



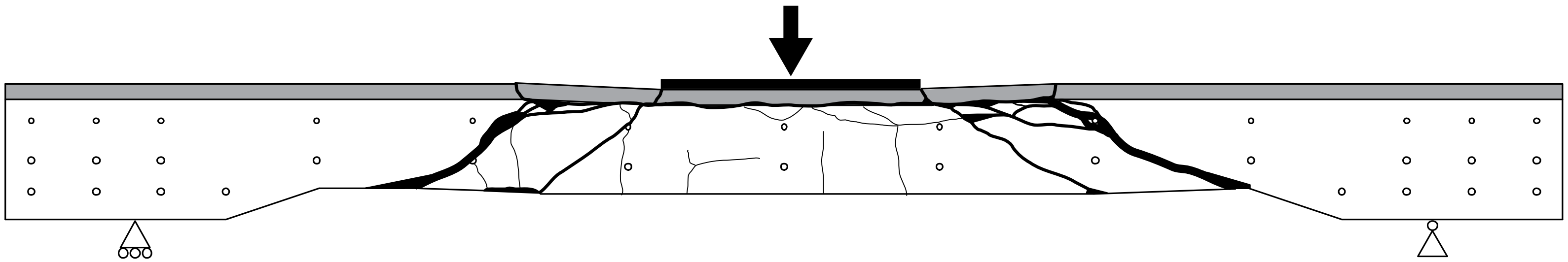
1. Development of the shear cracks closer to the center of the specimen



2. Debonding of the UHPFRC layer beneath the contact area of the moving wheel load



3. Development of a punching cone along the compression arch



4. Near-interface concrete cracking and double curvature bending of the UHPFRC layer followed by failure

Fatigue life of the UHPFRC – RC composite deck slab

<u>*S-N* relationship for RC deck slabs</u>

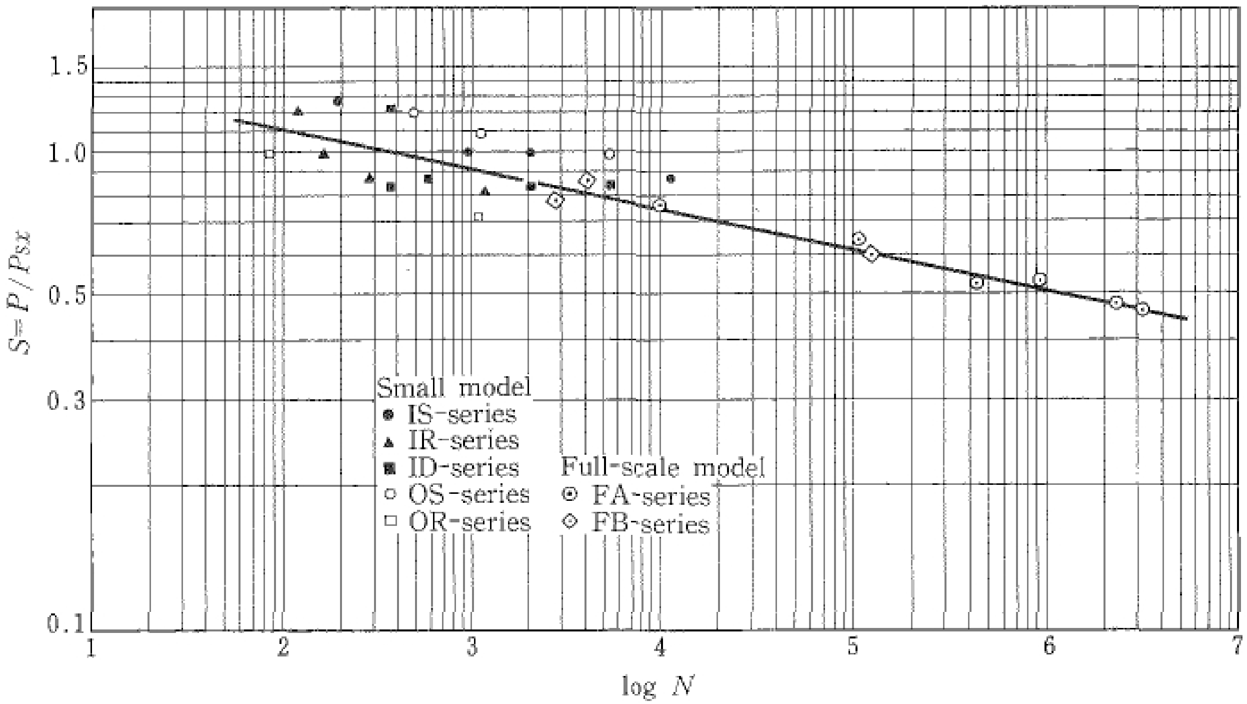
$$\text{Log}\frac{P}{P_{sx}}=-\frac{1}{12.76}\text{Log}N+\text{Log}1.52$$

P : wheel load
P_{sx}: punching shear resistance of RC deck slabs
N : number of cycles

$$P_{sx}=2B(f_{cv}\cdot X_m+f_{ct}\cdot C_m)$$

$$B=u+2d_d$$

f_{cv} : shear strength of concrete (= $0.656 f_{cc}^{0.606}$)
X_m : depth of neutral axis
f_{ct} : tensile strength of concrete (=$0.269 f_{cc}^{2/3}$)
C_m : concrete cover for transverse rebars in tension
f_{cc} : compressive strength of concrete
u : longitudinal length of bearing surface of wheel load
d_d : effective depth for transverse rebars



P_{eq} = 100kN

<u>UHPFRC – RC composite deck slab</u>
N_{eq} = 411billion

<u>RC deck slab</u>
N_{eq} = 75billion

<u>Equivalent number of cycles N_{eq}</u>

$$N_{eq}=\sum_{i=1}^{n}\left(\frac{P_i}{P_{eq}}\right)^{12.76}\times n_i$$

P_i : wheel load at the i-th load level
P_{eq}: equivalent wheel load
n_i : number of cycles of wheel load P_i

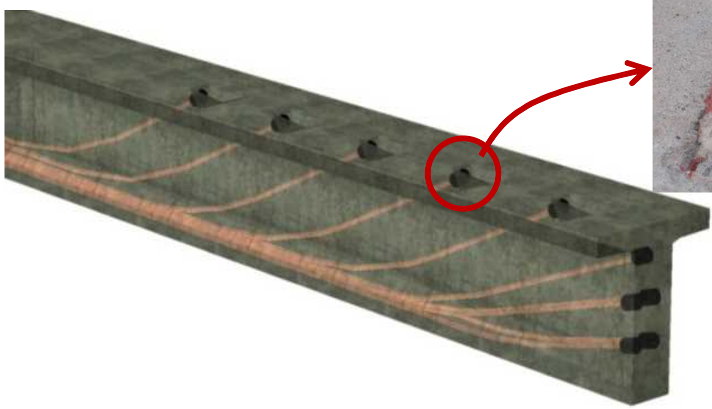
30 mm thick UHPFRC overlay increases the fatigue life of RC decks by about five times.

Repair of Okaya Viaduct using UHPFRC

- Located in Okaya, Nagano Prefecture, and opened in 1986
- Five span post-tensioned box girder bridge (L = 593m, 102+126+148+126+87.88m)
- Balanced cantilever construction method

<u>Causes of deck deterioration</u>

- ✓ No waterproofing applied to the top surface of the deck
- ✓ Insufficient concrete cover thickness
- ✓ Poor quality concrete used for anchorage pour backs



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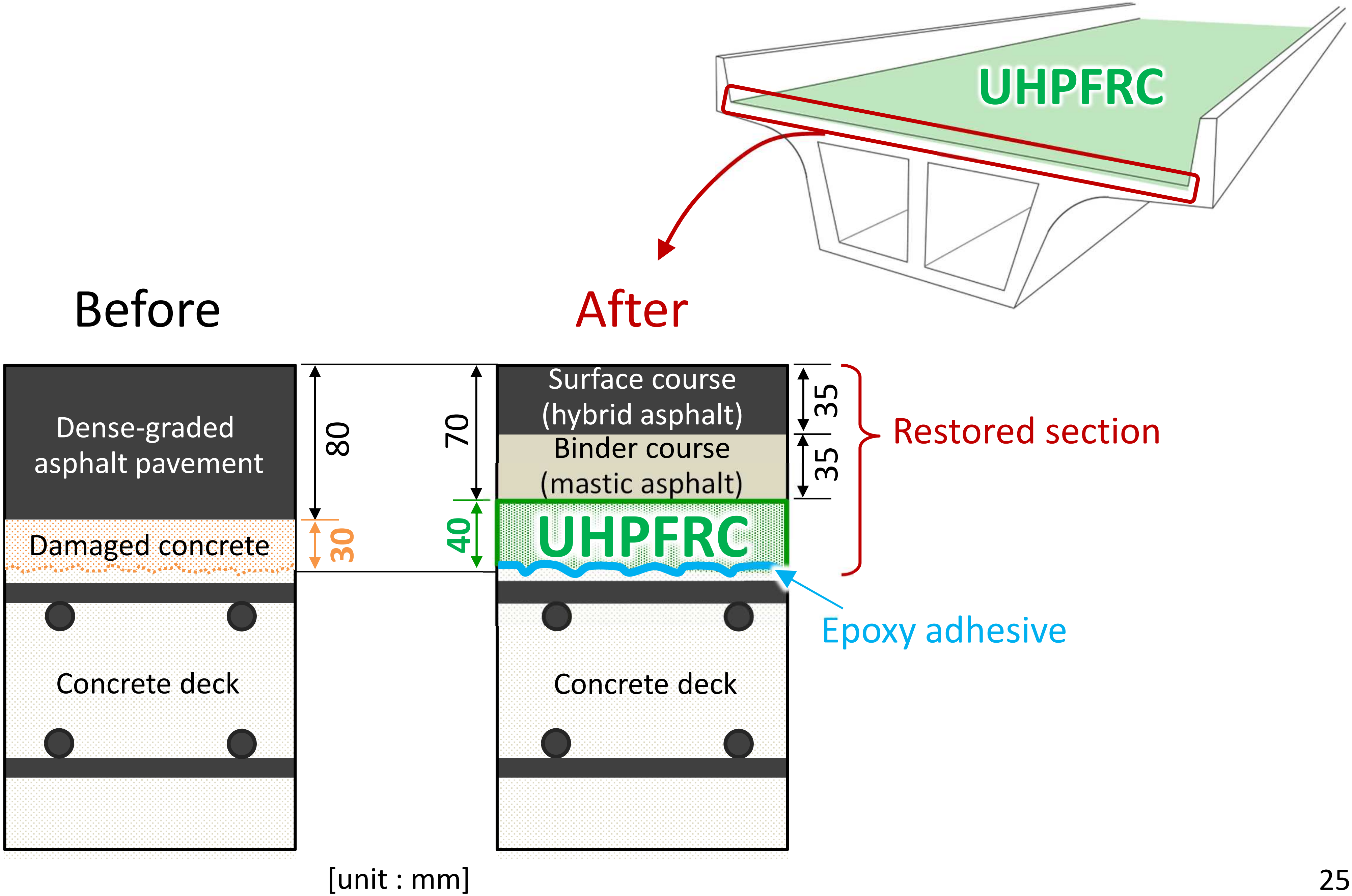
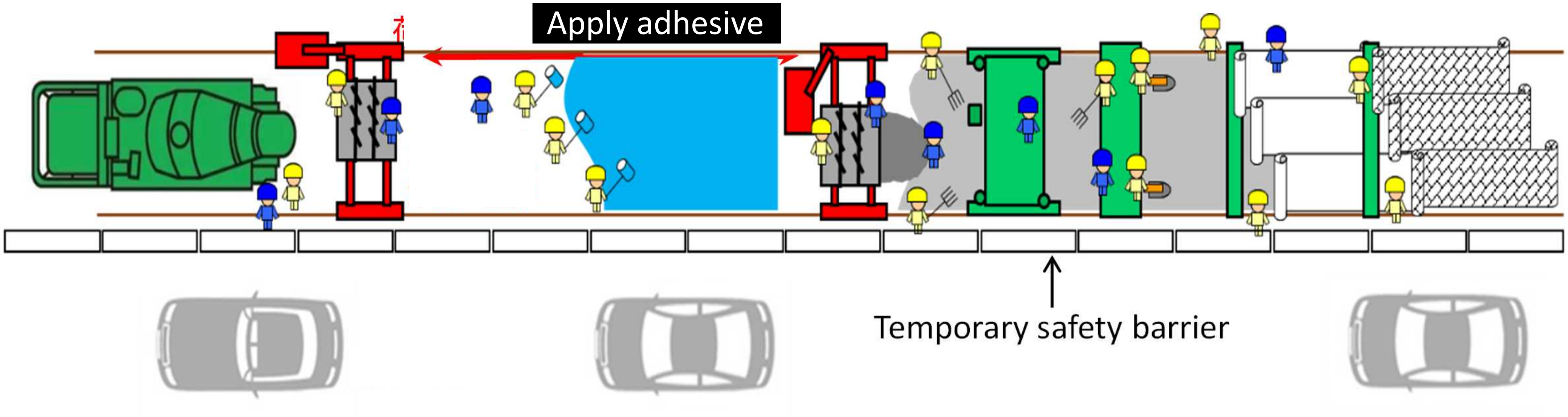
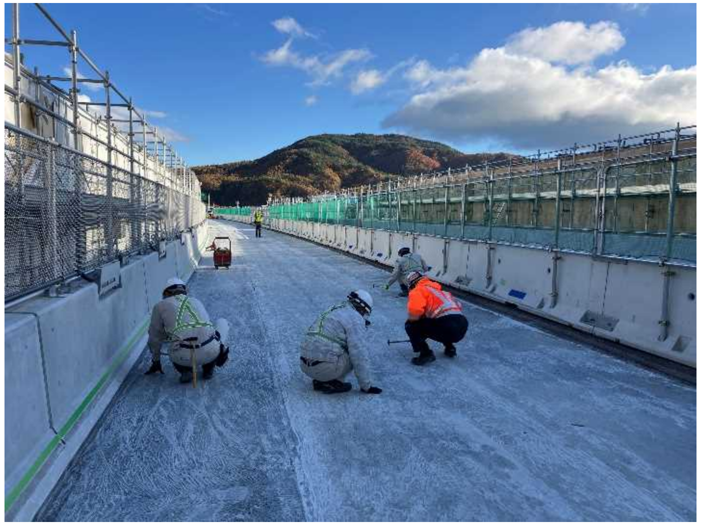


UHPFRC overlay construction process

Transport UHPFRC from a temporary batching plant | Transport within the site | Place and spread | Finish and cure



UHPFRC overlay construction process



Seismic retrofitting of bridge piers with UHPFRC jackets