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KEY FRP TECHNOLOGIES IN STRUCTURAL RETROFITTING AND STRENGTHENING

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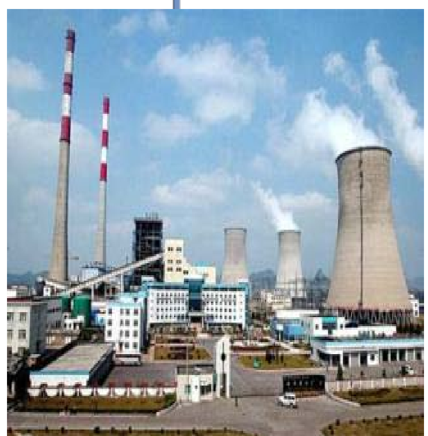
Outline

1. Background
2. Introduction of FRP and research status
3. Hybrid FRP technology
4. Prestressing FRP technology
5. Damage-controllable FRP structures
6. Integrated high performance FRP structures
7. Intelligent infrastructures
8. Summary

Background

Exhaustion of iron ore, large emission of CO_2 ,
great needs of steel for construction



LC economy， 1 ton steel(2 ton CO_2),steel CO_2(10%)

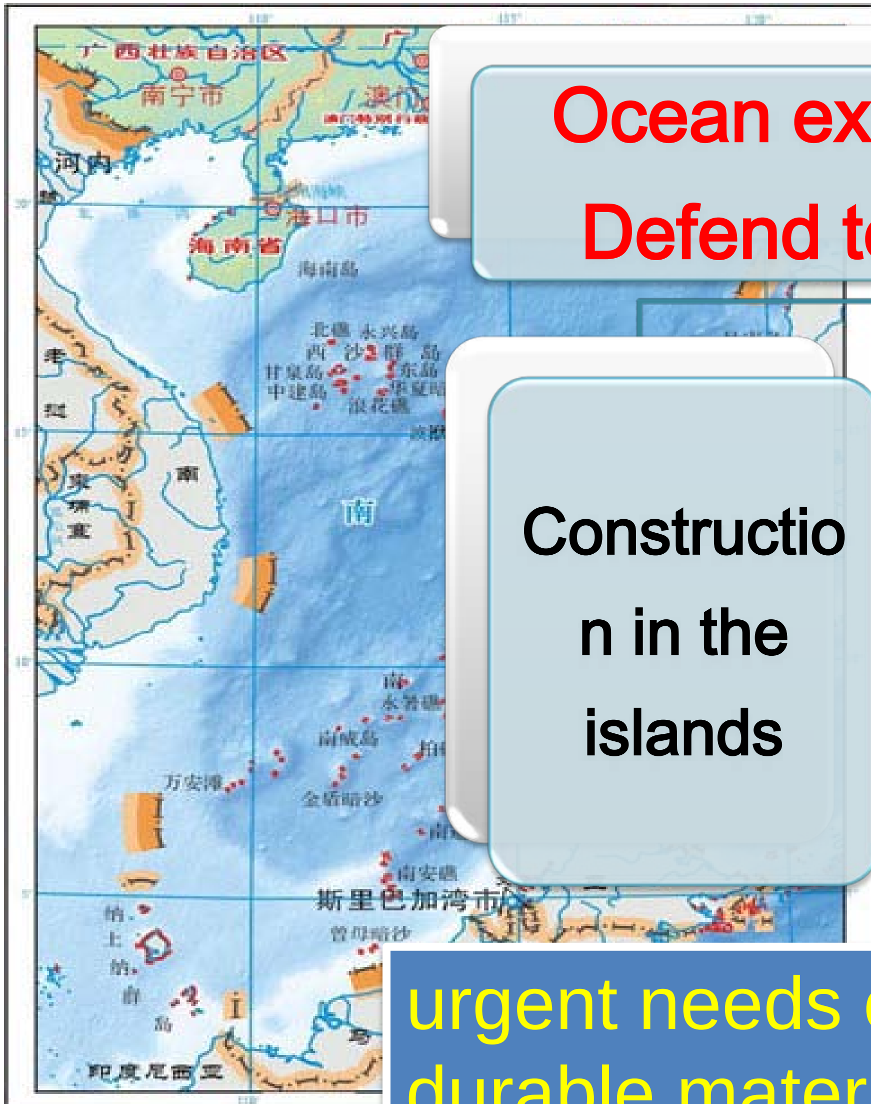
Iron ore 11.5 billion ton,0.6 billion/y， 20 y exhaustion

Future 20-30 years reach peak of civil infrastructure, exceeds total amount of aboard

Development of new resource materials

- Relief resource crisis
- low carbon emission
- Sustainable development

Background

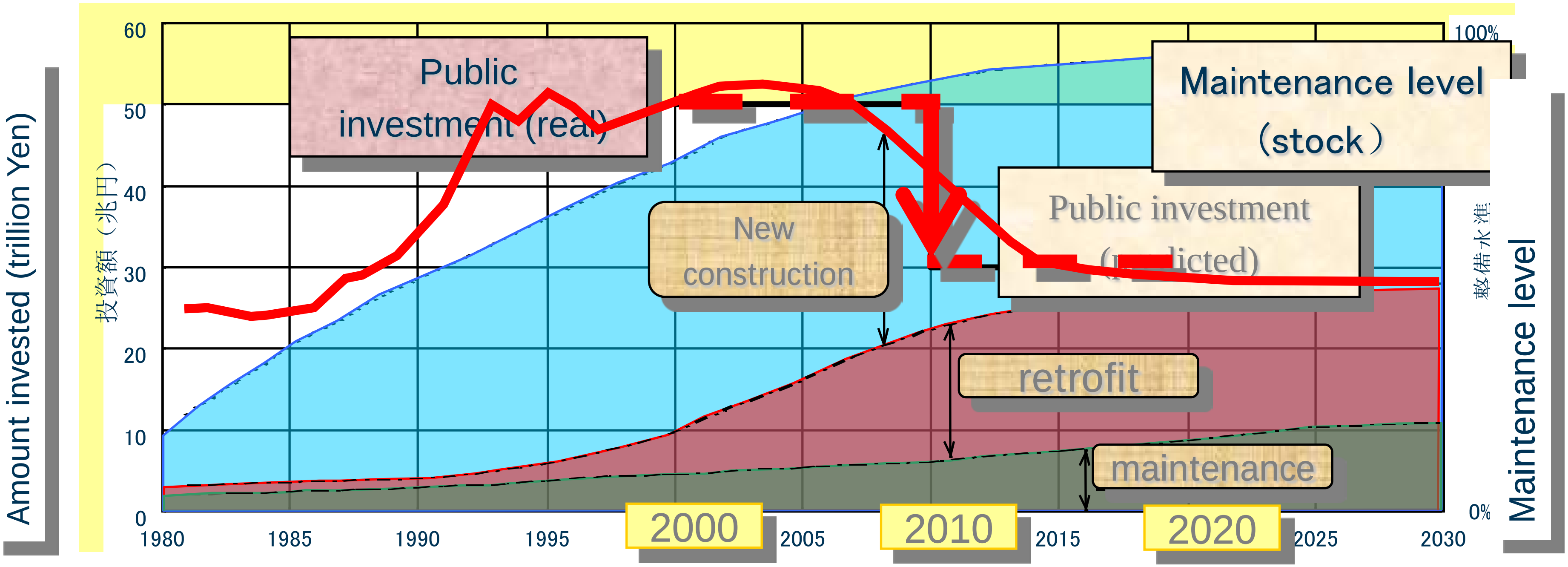


Ocean exploration and Defend territorial sea

- Constructio n in the islands
- Explore deep ocean resource

urgent needs of safe and durable materials and structures under corrosive environment

Lessons from developed countries



Long-term prediction of public investment in Japan

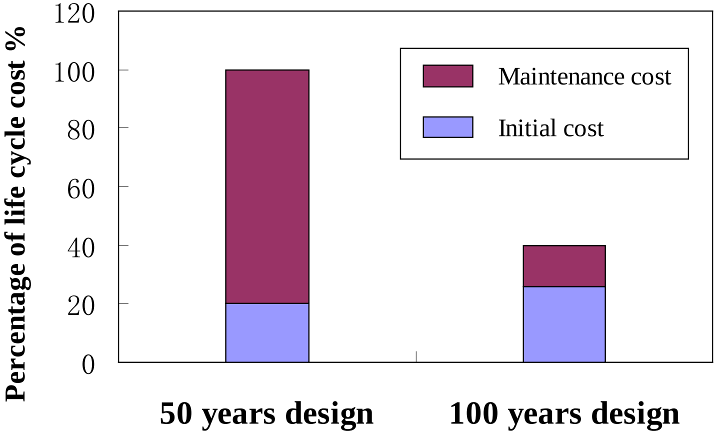
FHWA,US data：26.9% of 600905 bridges structural or functional deficiencies, retrofitting needs $17 billion/year, currently only 10.5 billion/year

Background

➢ Life cycle cost（LCC）minimization

LCC = initial investment+maintanence+retrofitting and rehabilitation+residual value

Five times law：reduce $ 1 in design stage, add $5 when find steel corrosion, add $25 when concrete longitudinal cracks, add $125 when serve damage



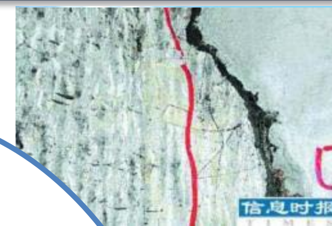
Minimization of LCC

Lesson from developed countries：improve structural life from current 50-100 years to 100-300 years, properly increase initial investment----------------one of the methods of realizing LCC Min.

Constructions problems

Safety and durability need improvement

I-25W bridge(US) collapse
corrosion of joints



irder bridge's severe
uch as Luoxi bridge,
l safety problems

Cracks, large deflection, and severe corrosion— Potential safety problems

Corrosion of stay cables, such as XizhiMen bridge in Beijing, removed after 20 years

Deflection of girder bridge, such as Huangshi bridge, deflected 33cm after 15 years

Constructions problems

Improve safety and extend life through lightweight

$$F_i(t) = -m_i[\ddot{x}_0(t) + \ddot{x}_i(t)]$$

Heavy weight ⇨ Section increase, Large seismic response ⇨ Cost increase, Safety decrease

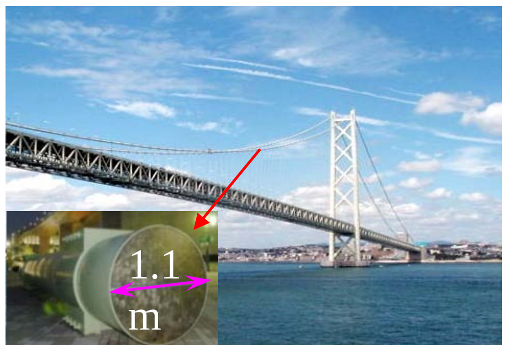
⇩

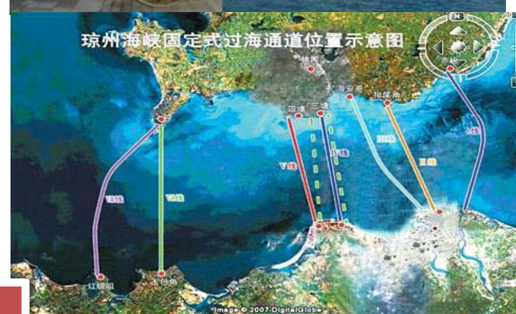
lightweight

⇩

Reduce cost
Improve safety
Extend life

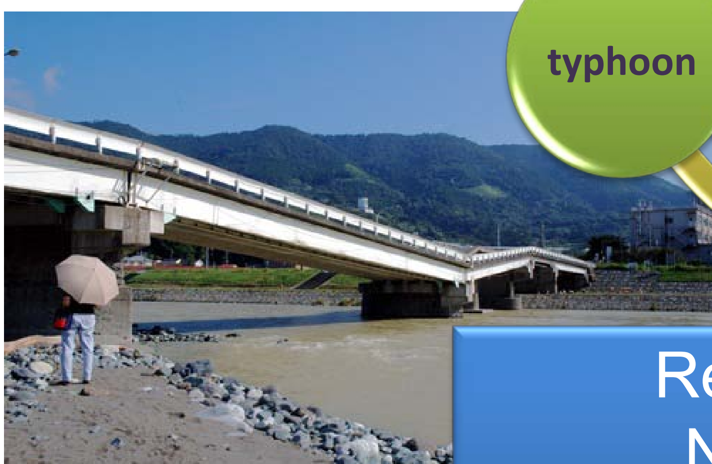
High rise building: over 85% selfweight





Longer span, steel is a restriction

Constructions problems



earthquake

tsunami

typhoon

blast

No collapse after large earthquake

recoverability after disaster, damage controllability

otherwise

Rescue blocked
Nobody'home
secondary disaster
economic stagnation

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FRP products for structural strengthening

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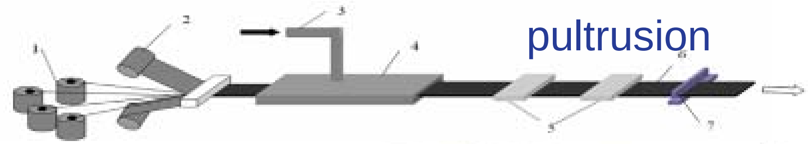
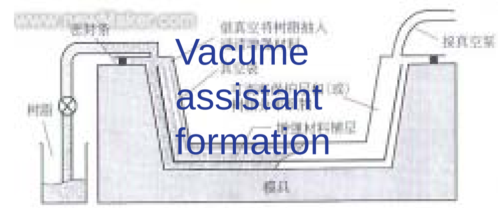
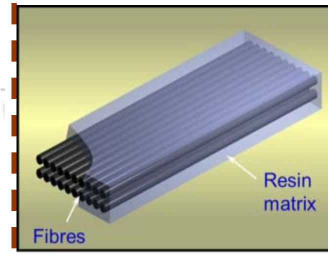
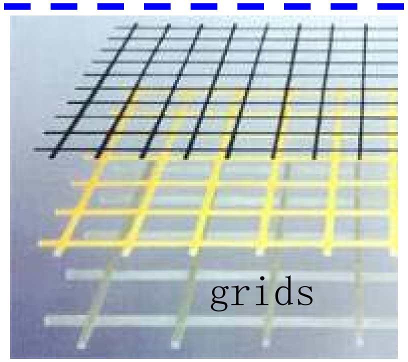
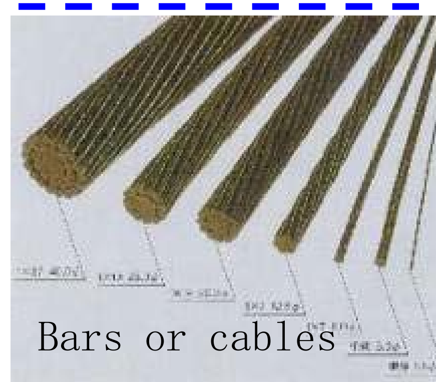
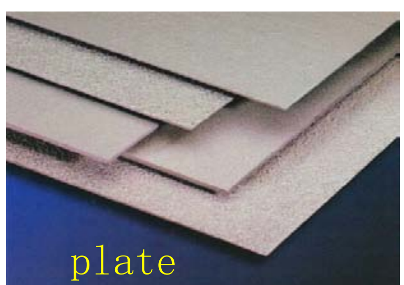






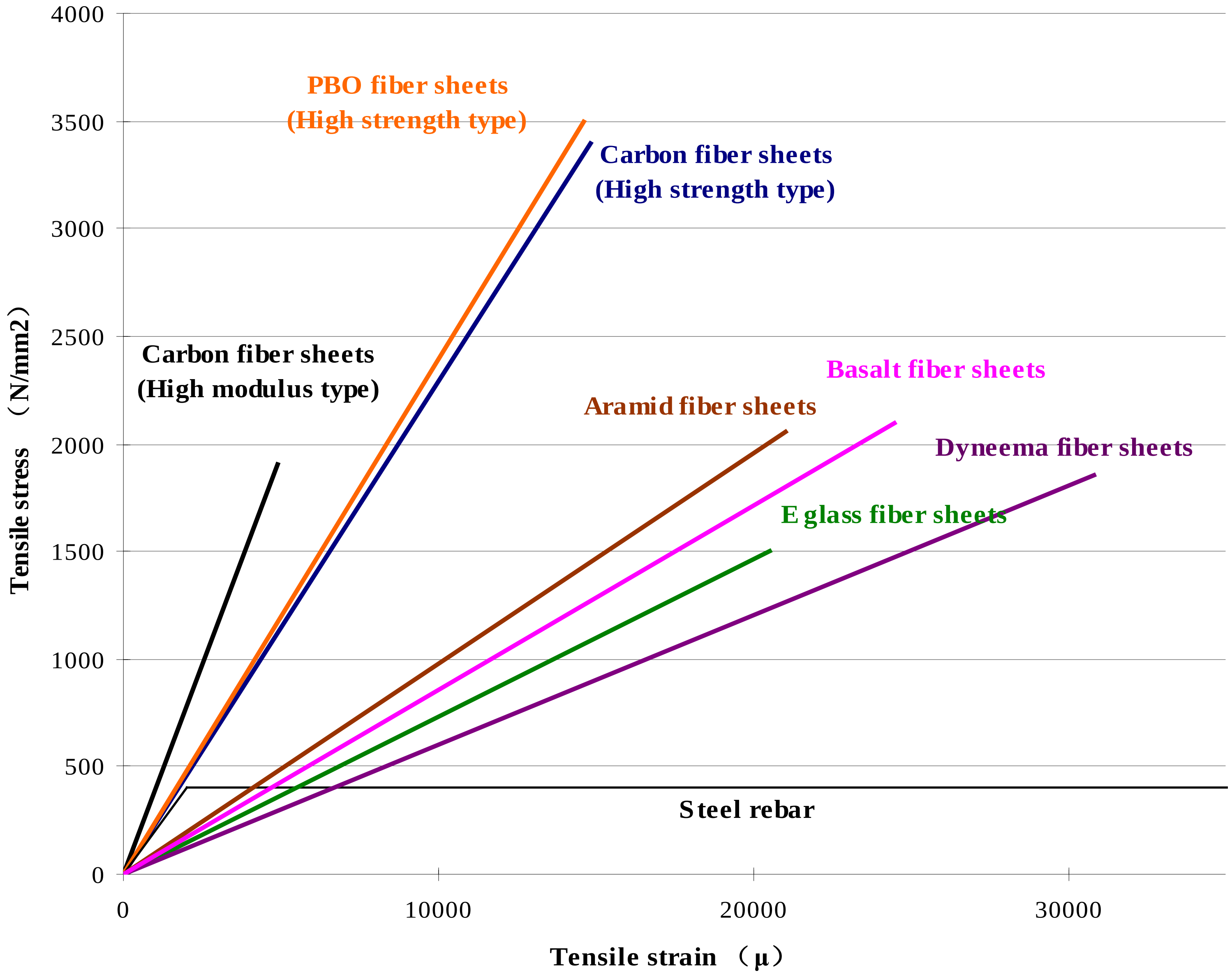




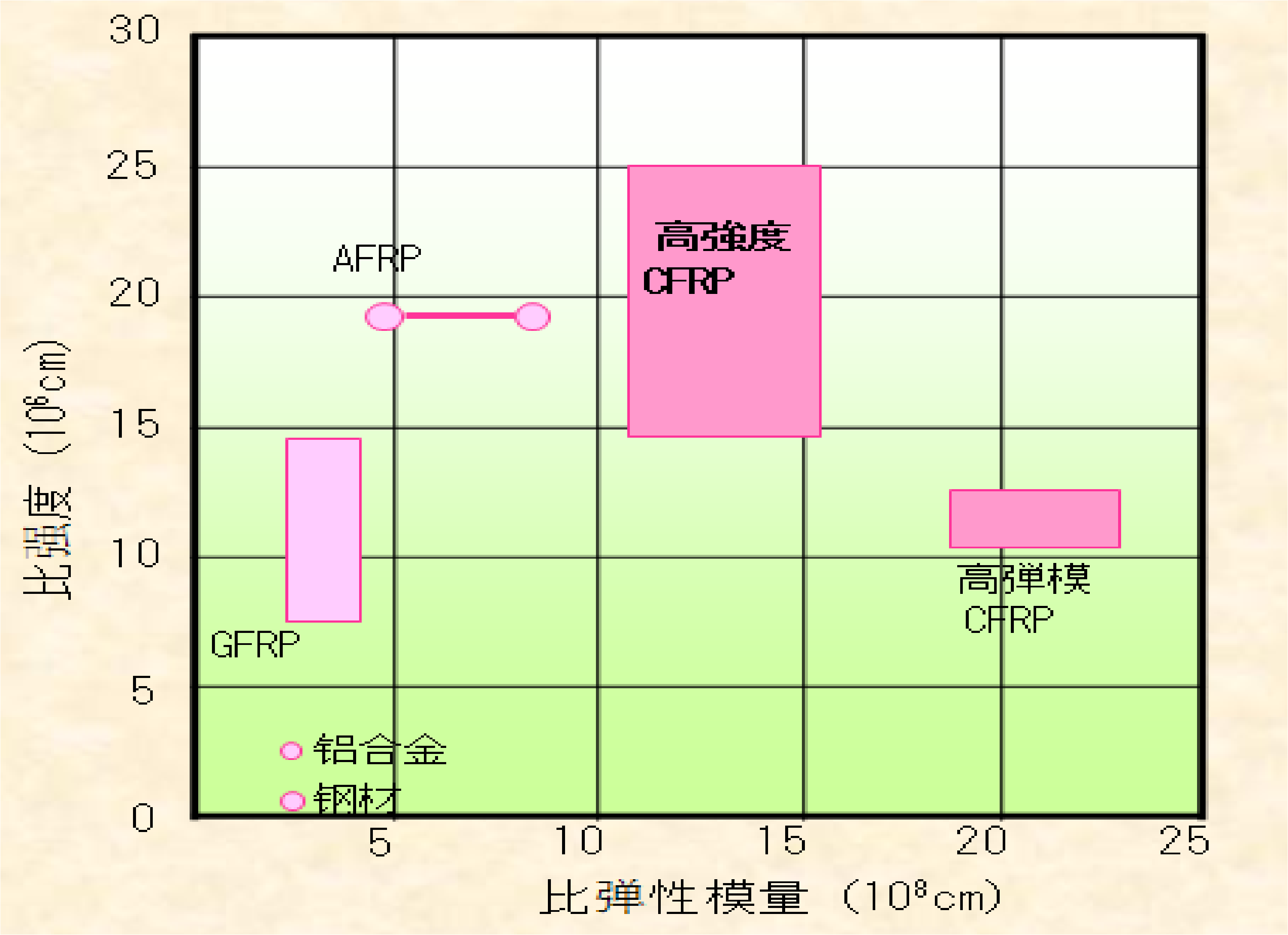


Various FRP products

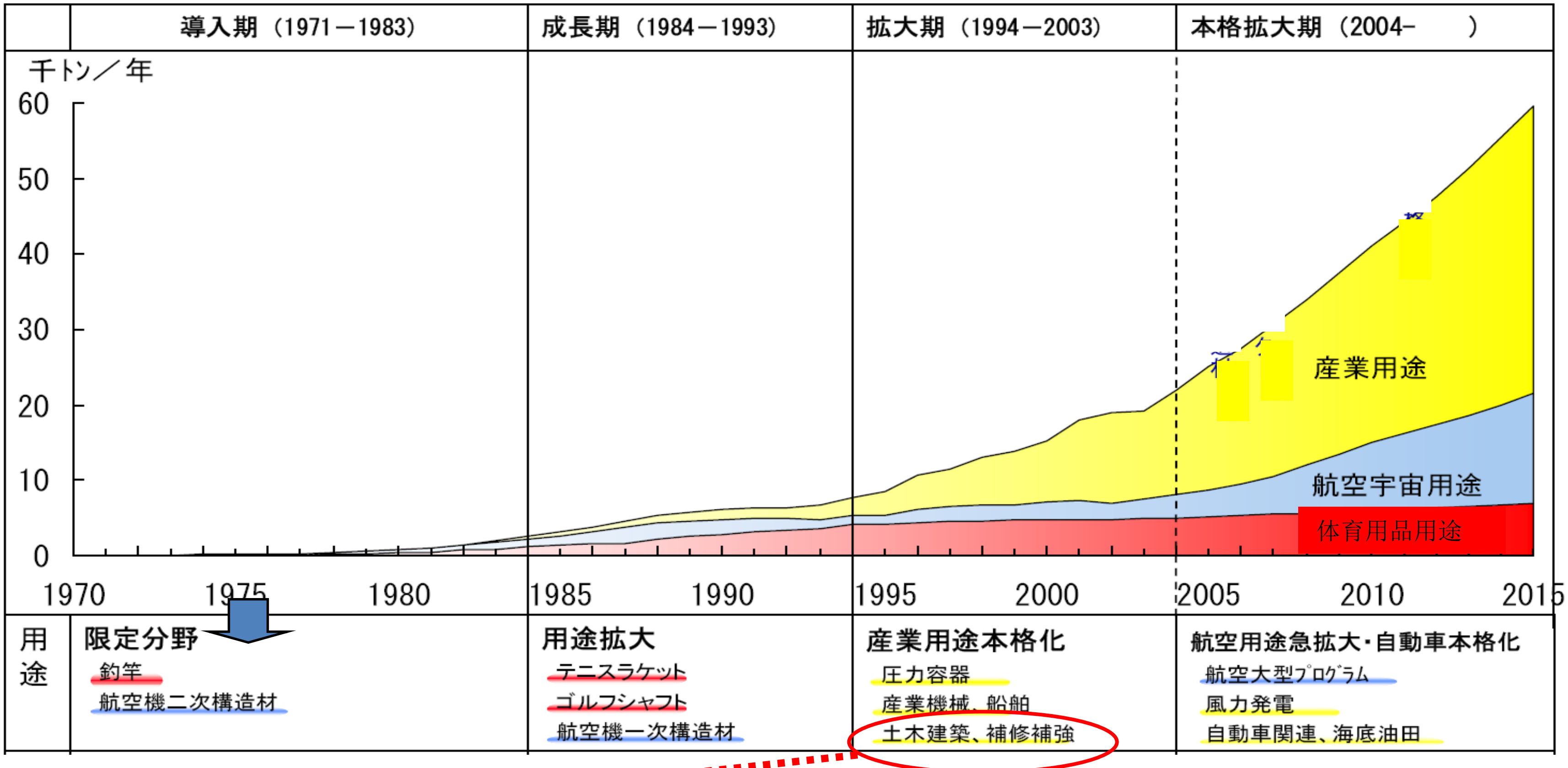
Mechanical properties of FRP



Mechanical properties of FRP



Development of FRP for construction (carbon FRP)



Beginning of 80’s, structural retrofitting and rehabilitation

90’s Hanshin Earthquake， for seismic strengthening

1990-2000, new structure (composite structures)

FRP for retrofitting structures

FRP bonded or wrapped

FRP profiles

Beam or plate

Seismic strengthening

chimney

FRP tubes for piers

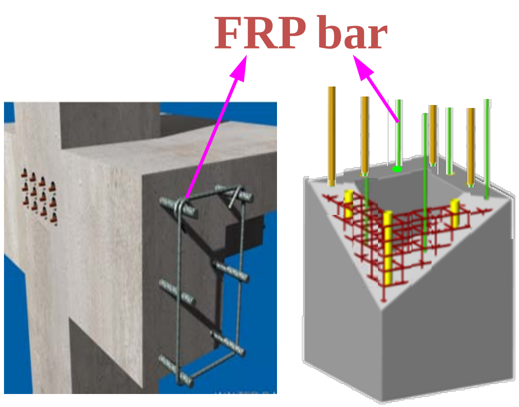
FRP bars or tendons

FRP NSM

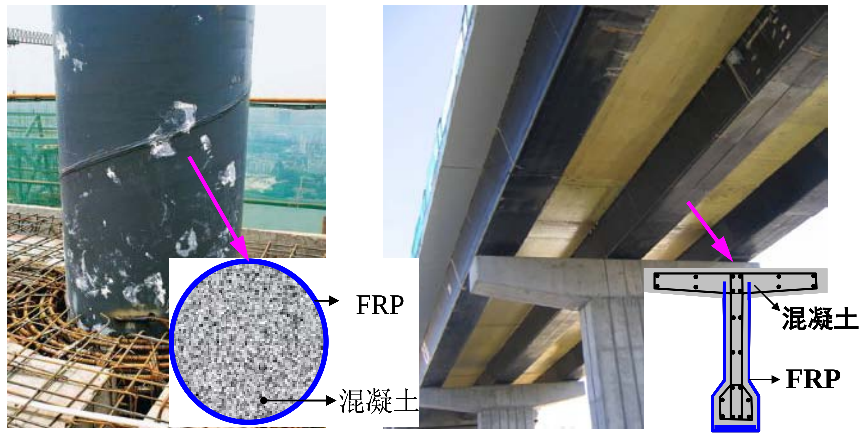
FRP cable externally strengthening

FRP for new construction

FRP replace steel bar



FRP-RC composite column/beam



FRP light roof

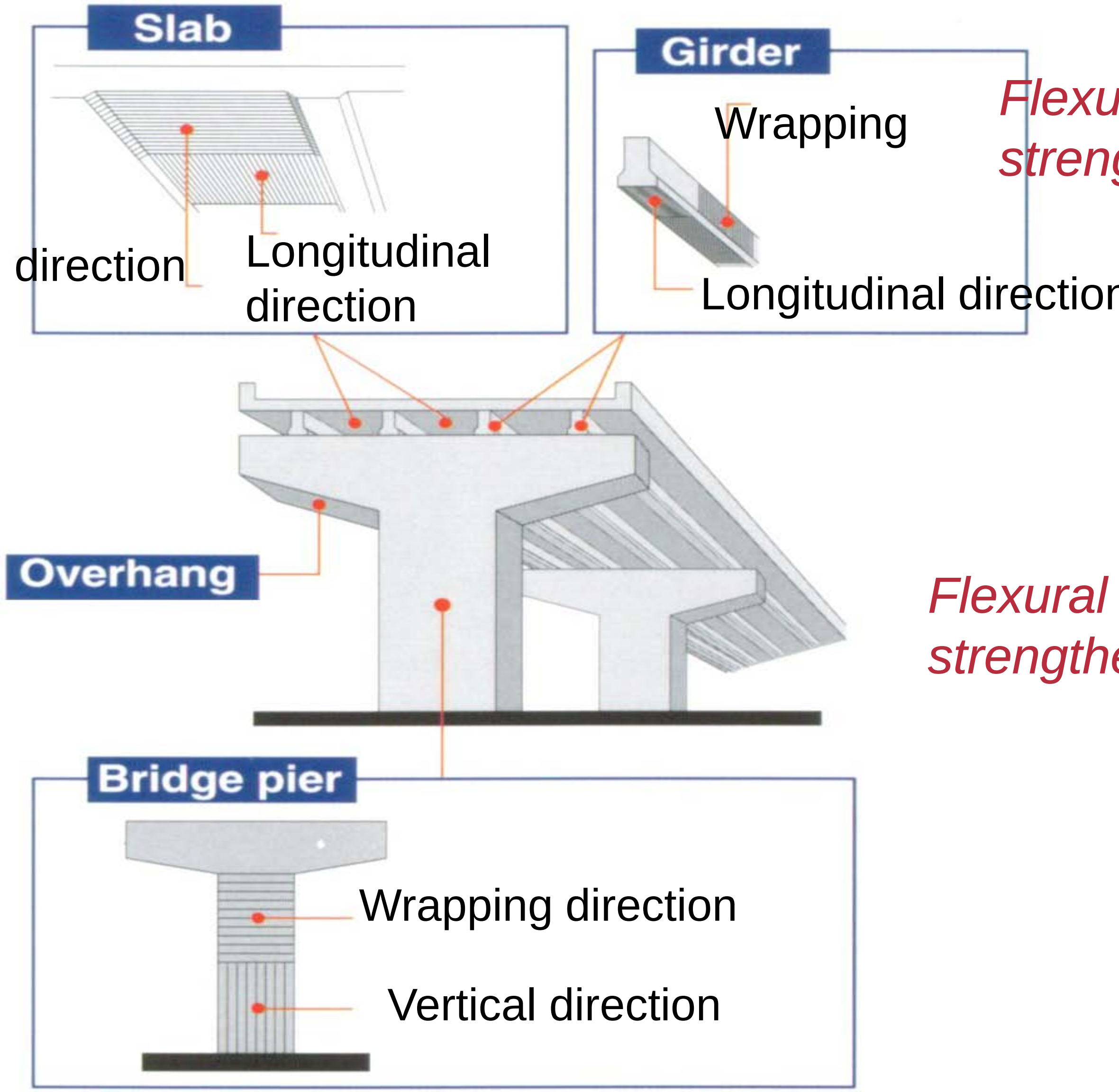
FRP cable structure

Offshore platform

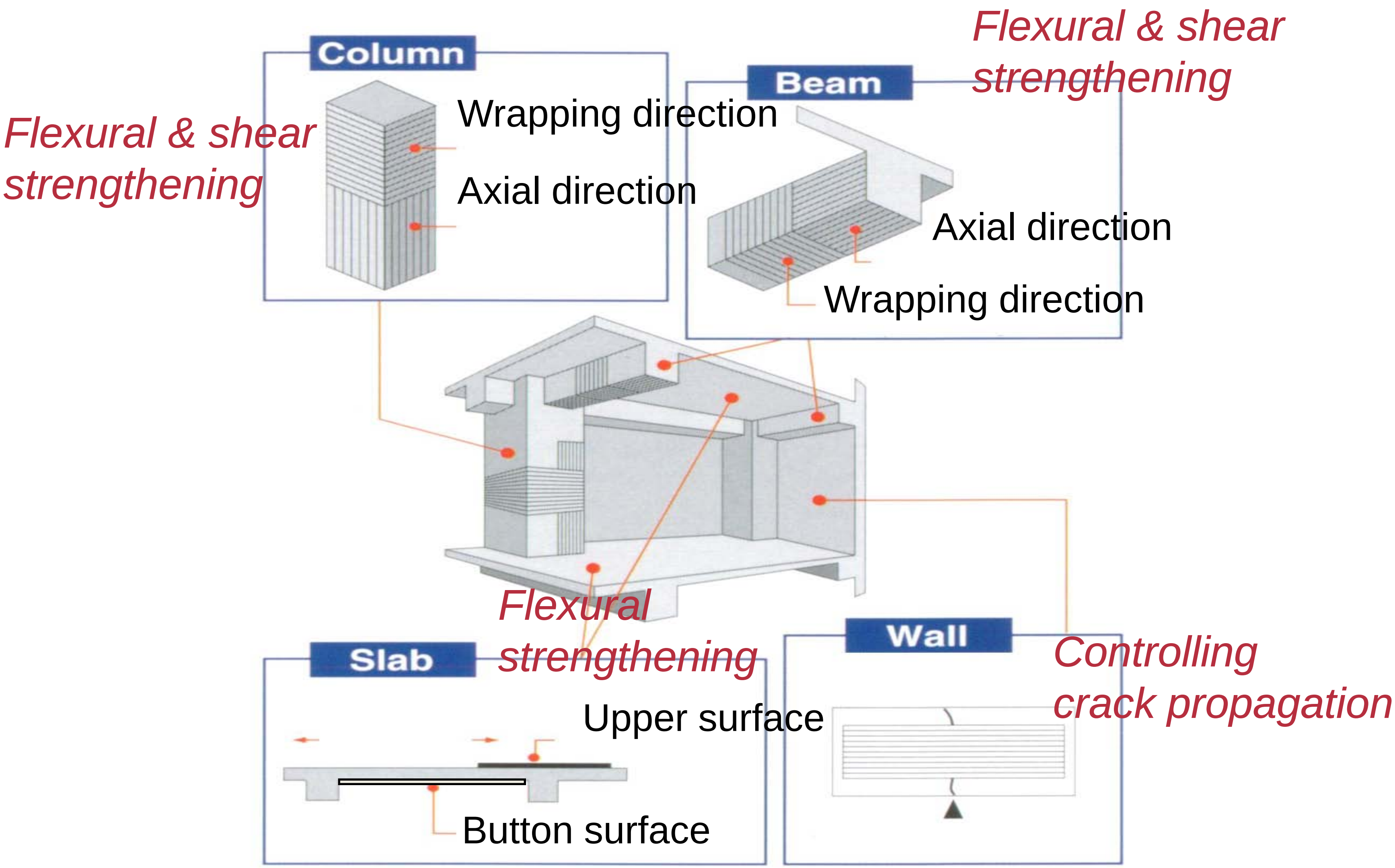
FRP desulfurization chimney

FRP tanks

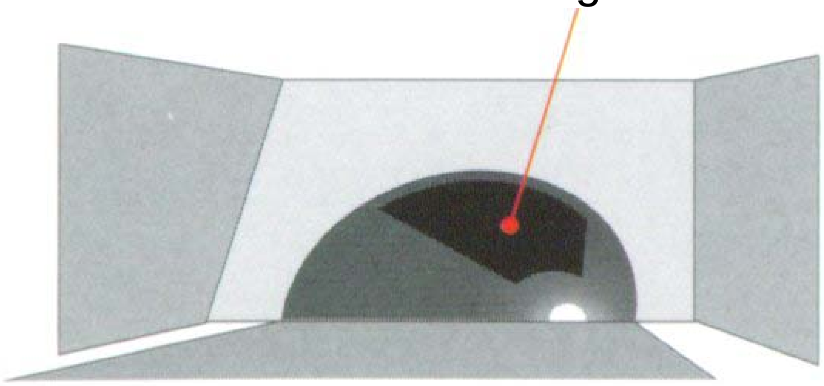
FRP techniques in bridge



FRP techniques in building



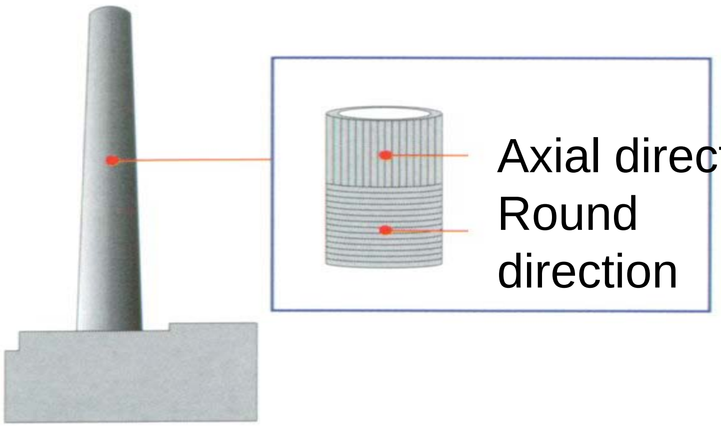
FRP techniques in special structure



Flexural strengthening
Controlling crack propagation
Concrete spalling resistance

Tunnel

Flexural strengthening
Controlling crack propagation
Concrete spalling resistance



Chimney, etc.

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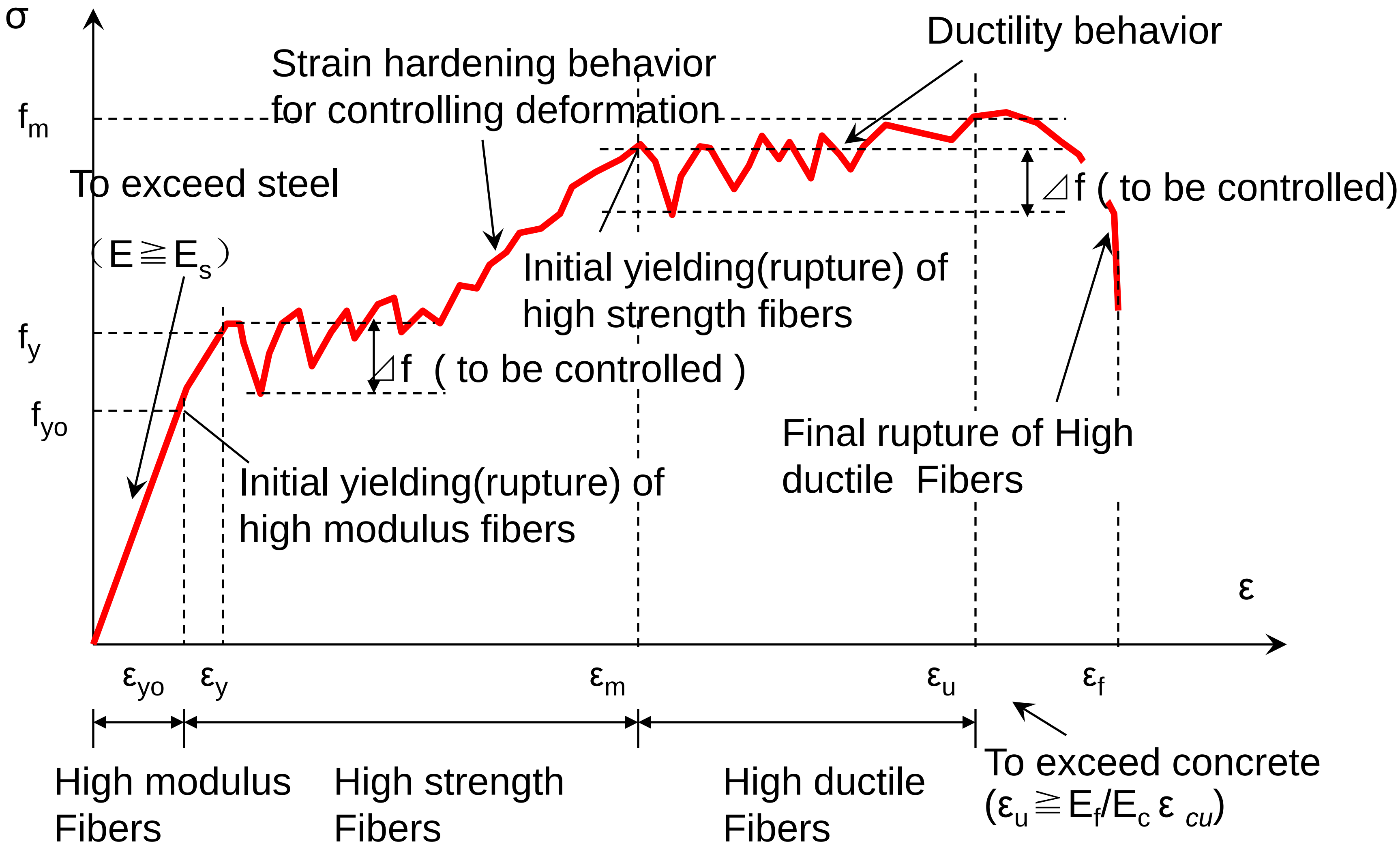
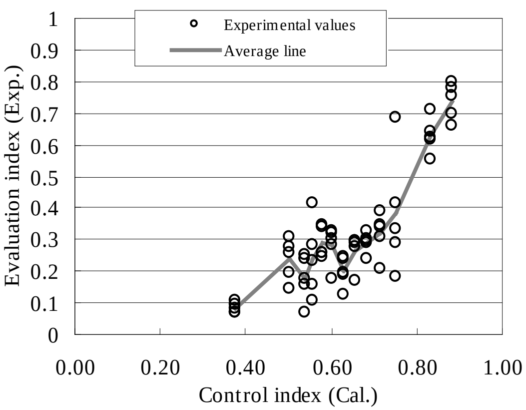
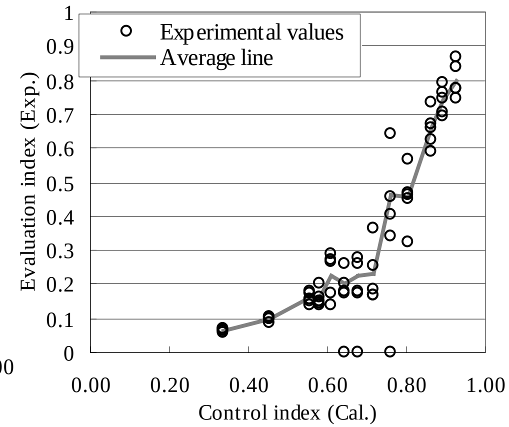
Hybrid concept of different fibers



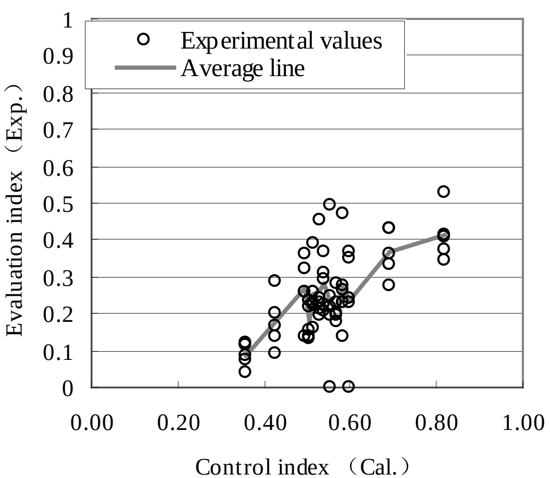
Stress drop control of hybrid FRP



HM/HS

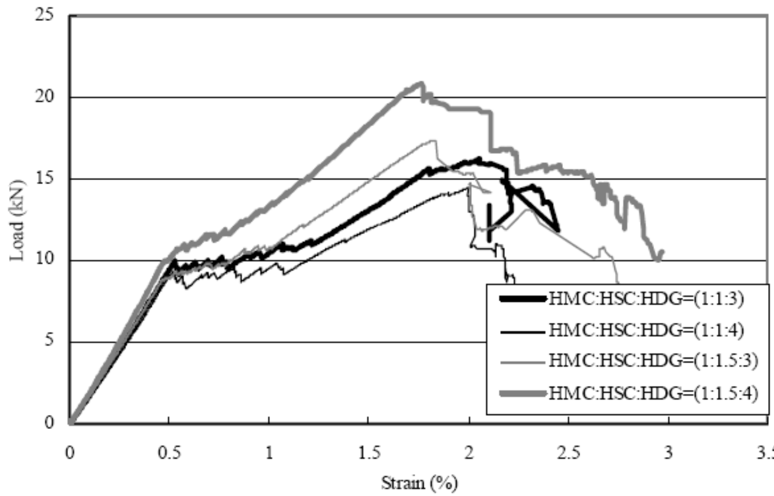


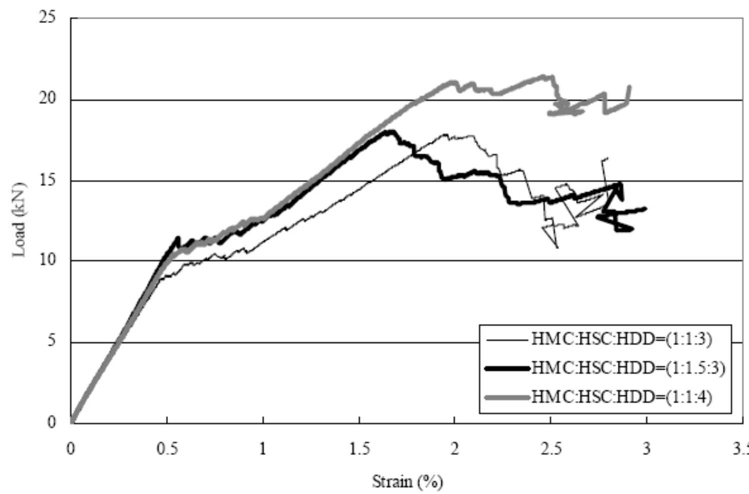
HM/PBO



HM/Dyneema

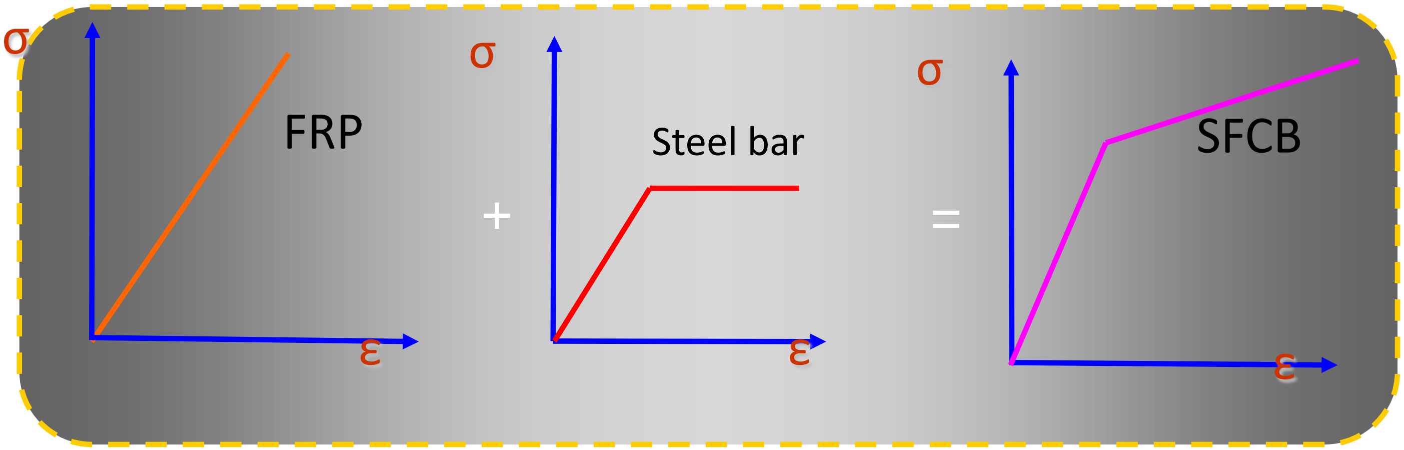
Realize hybrid effect through stress drop control

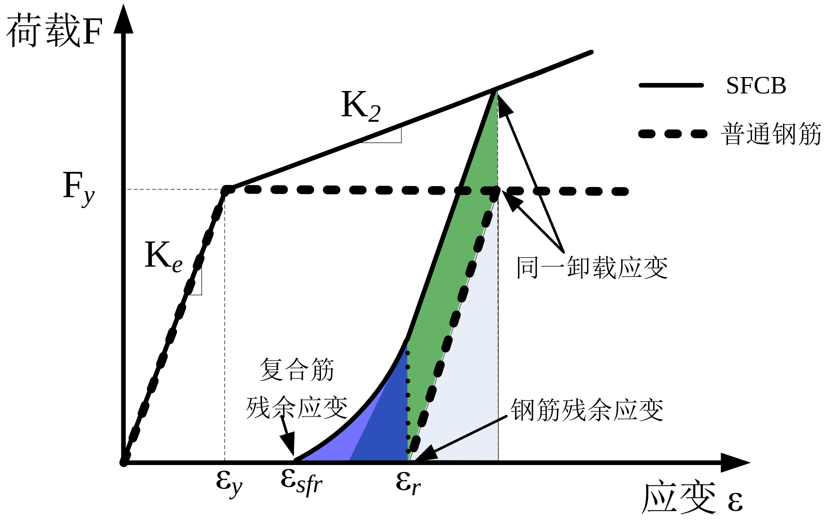




Experimental tests

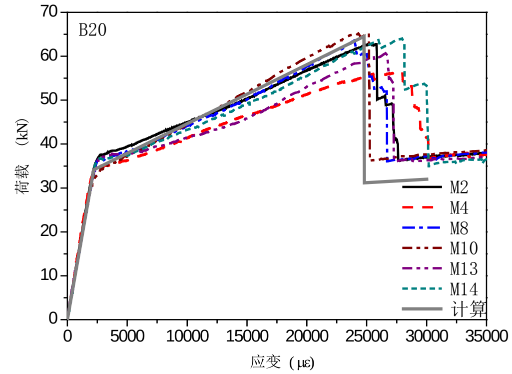
Hybrid concept of FRP and steel bar (SFCB)

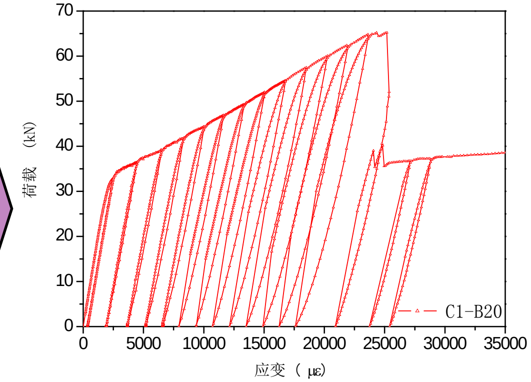


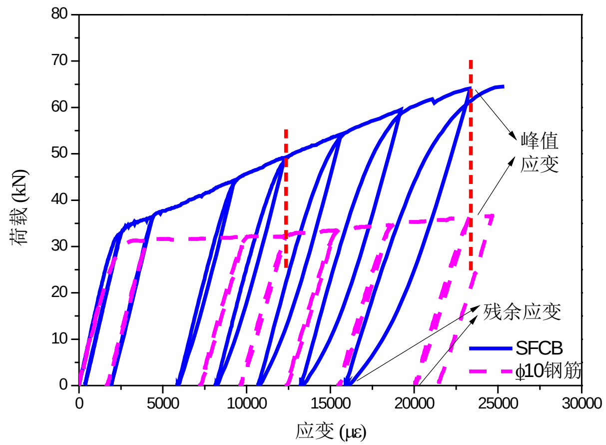


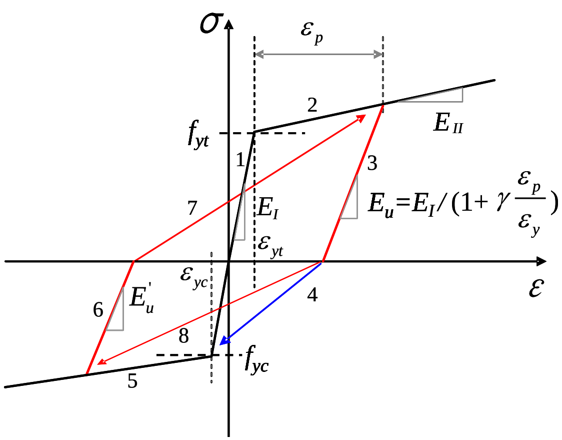
SFCB properties

SFCB



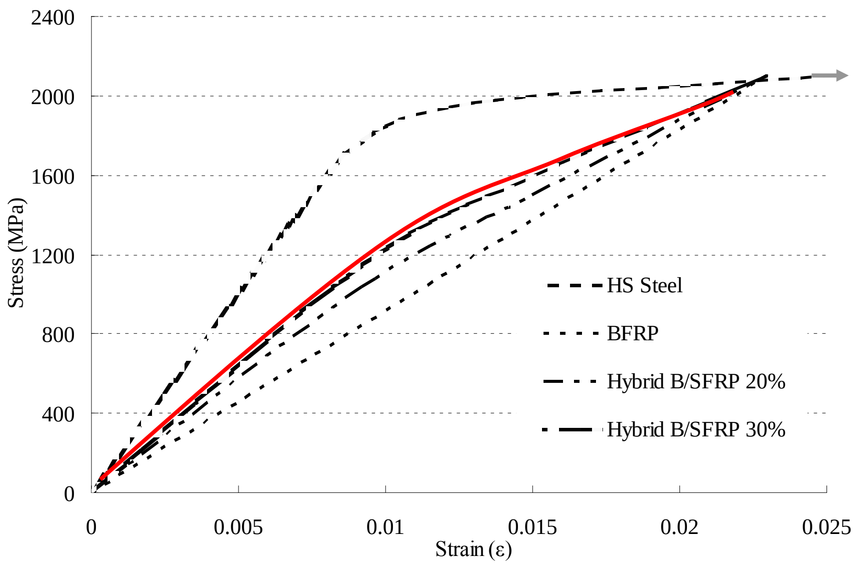




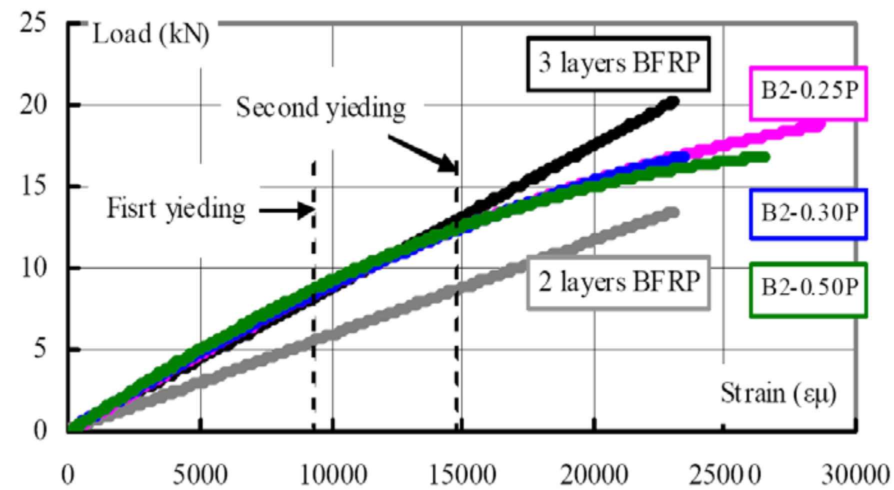


$$
\sigma_{sf} = \begin{cases} E_I \varepsilon_{sf} & , 0 \le \varepsilon_{sf} < \varepsilon_{sfy} \\ f_{sfy} + E_{II}(\varepsilon_{sf} - \varepsilon_{sfy}) & , \varepsilon_{sfy} \le \varepsilon_{sf} \le \varepsilon_{sfu} \\ f_{sfr} & , \varepsilon_{sfu} < \varepsilon_{sf} \end{cases}
$$

Hybrid of FRP and steel-wires



Stress-strain relation



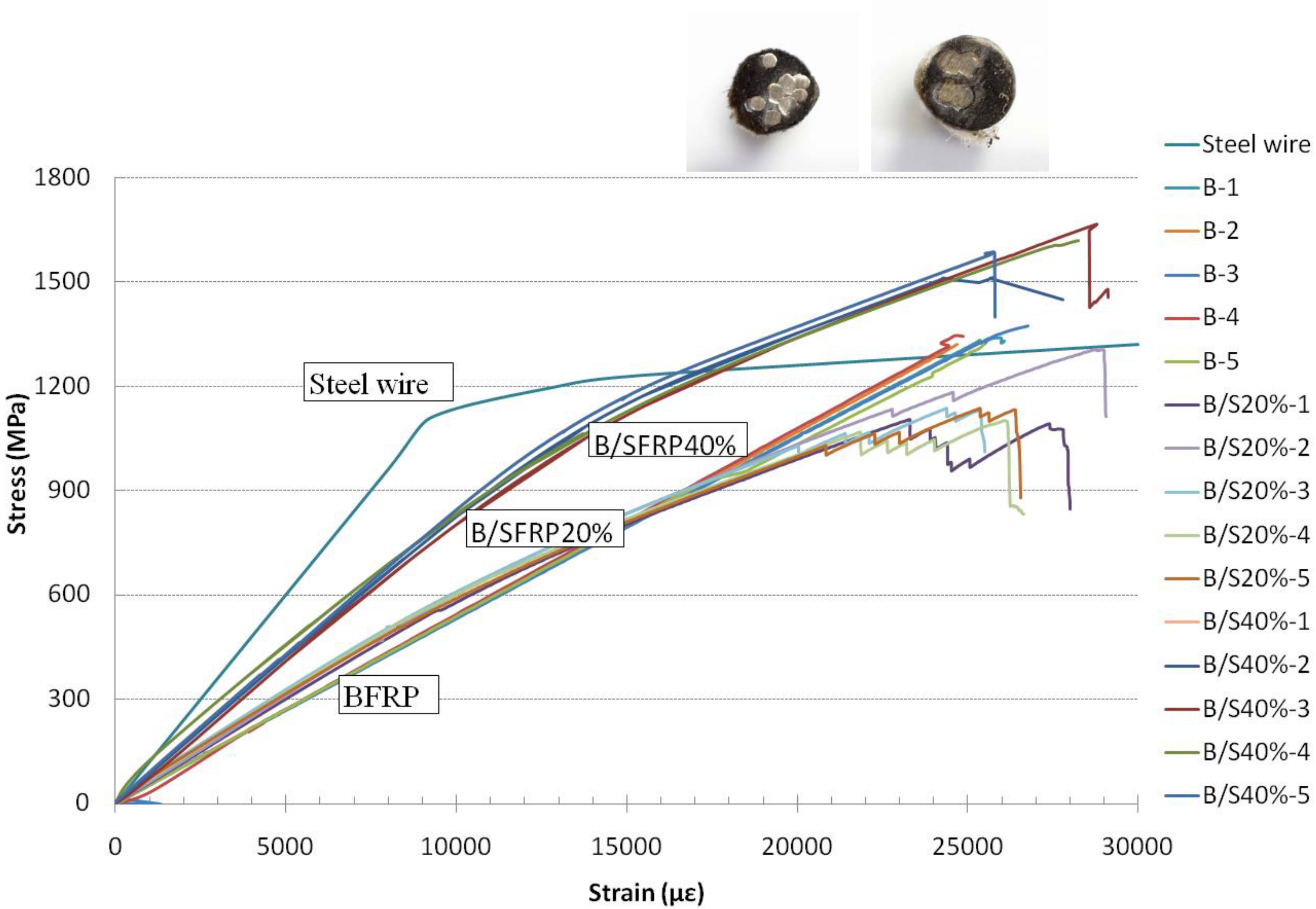
Optimization of steel wires

$$\sigma_{sf} = \begin{cases} E_I \varepsilon_{sf}, 0 \le \varepsilon_{sf} < \varepsilon_{sfy} \\ f_{sfy} + E_{II}(\varepsilon_{sf} - \varepsilon_{sfy}), \varepsilon_{sfy} \le \varepsilon_{sf} < \varepsilon_{sfu1} \\ E_{II}\varepsilon_{sf}, \varepsilon_{sfu1} \le \varepsilon_{sf} \le \varepsilon_{sfu2} \end{cases}$$

$$\left. \begin{aligned} V_{c临} &= \frac{1}{1 + \dfrac{E_c \varepsilon_c}{E_g(\varepsilon_g - \varepsilon_c)}} \\ V_{s临} &= \frac{1}{1 + \dfrac{E_s}{E_f}\left(\dfrac{\varepsilon_{sfy}}{\varepsilon_{sfu2} - \varepsilon_{sfu1}}\right)} \end{aligned} \right\}$$

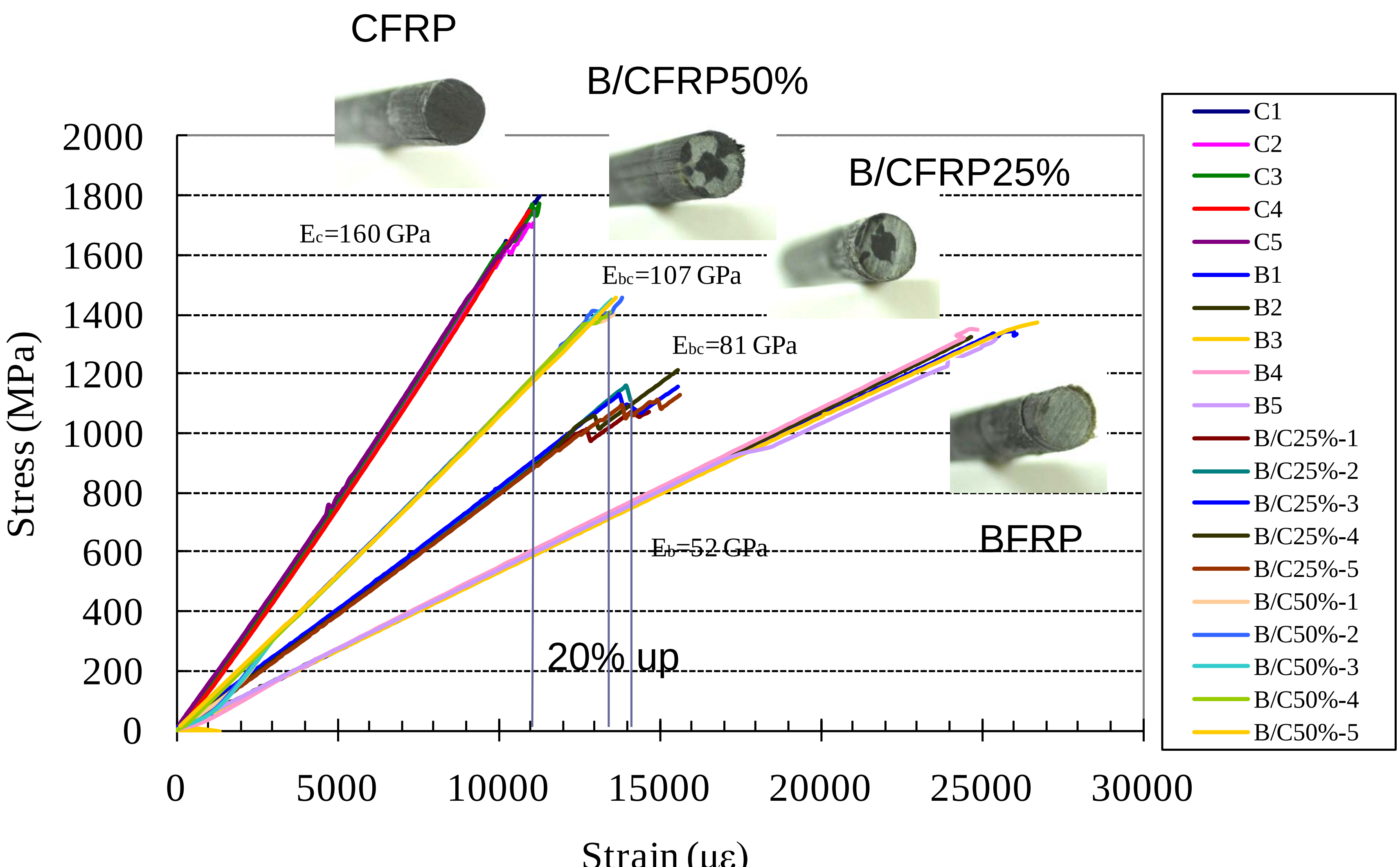
achieve max. strength through critical volume fraction

Stress-strain relationship of hybrid basalt and steel-wire FRP tendon



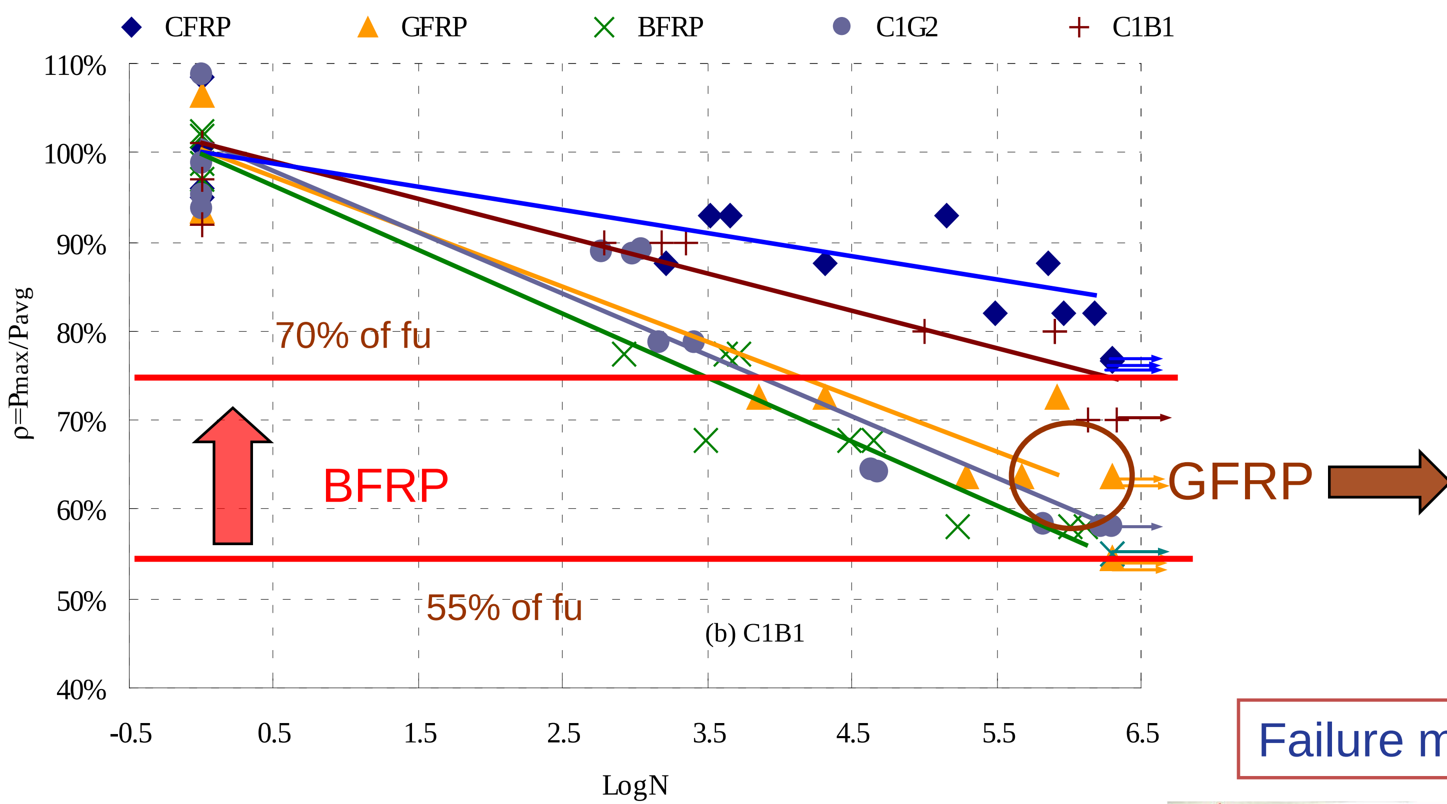
- Initial modulus increase
- Ductility remains

Stress-strain relationship of hybrid basalt and carbon FRP tendon



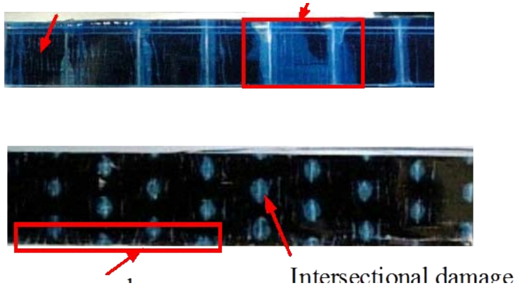
- Initial modulus increase
- potential strength of carbon fibers increase

Hybrid effect study
——fatigue strength



S-N curvers

Failure mode

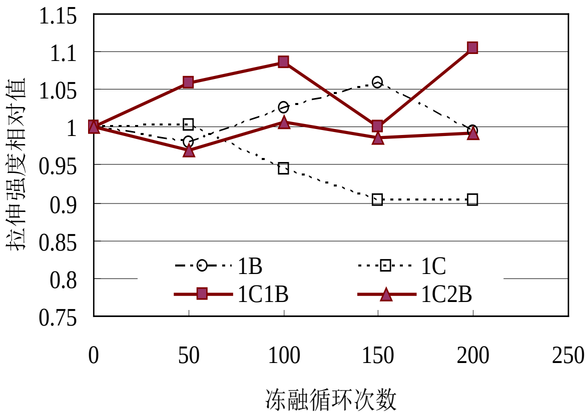


- hybrid B/CFRP
- hybrid B/GFRP

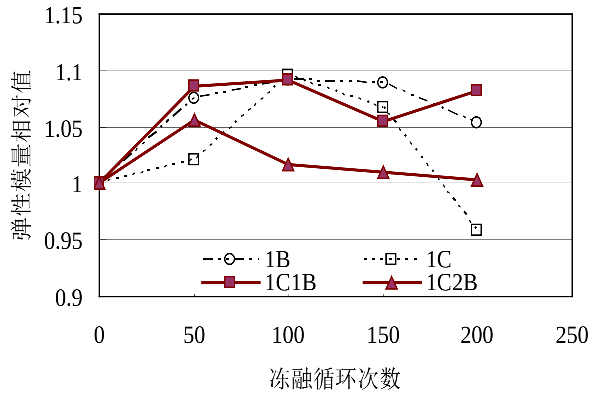
Hybrid effect study

——freeze-thaw behavior

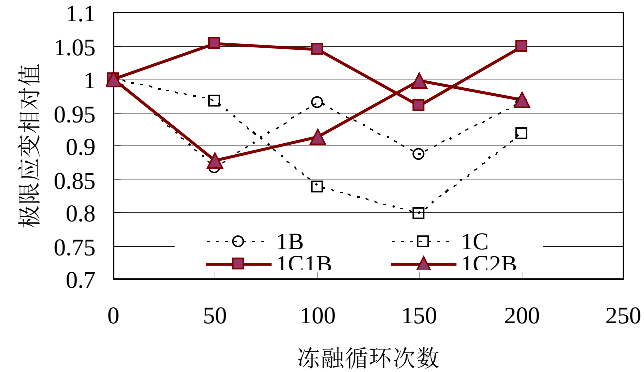
➢Tensile properties



（a） tensile strength

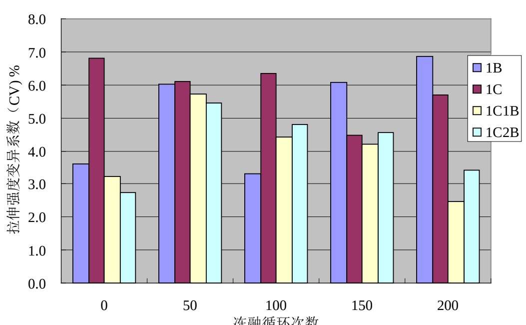


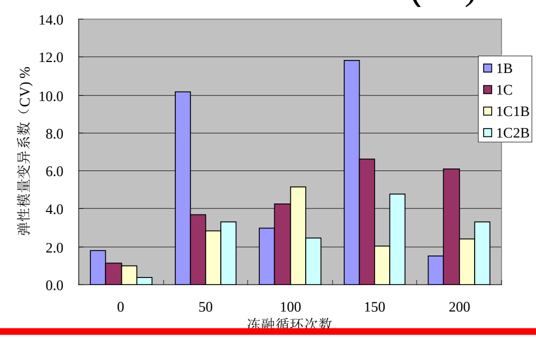
(b) elastic modulus

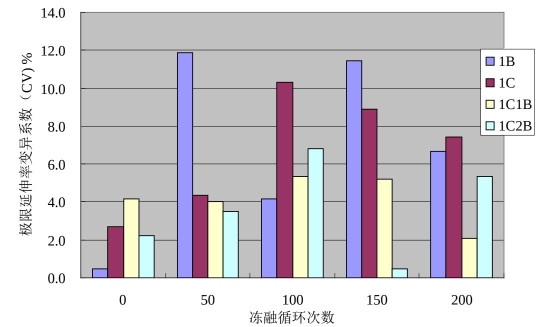


(c) failure strain

Coefficient Of Variation (Cv)

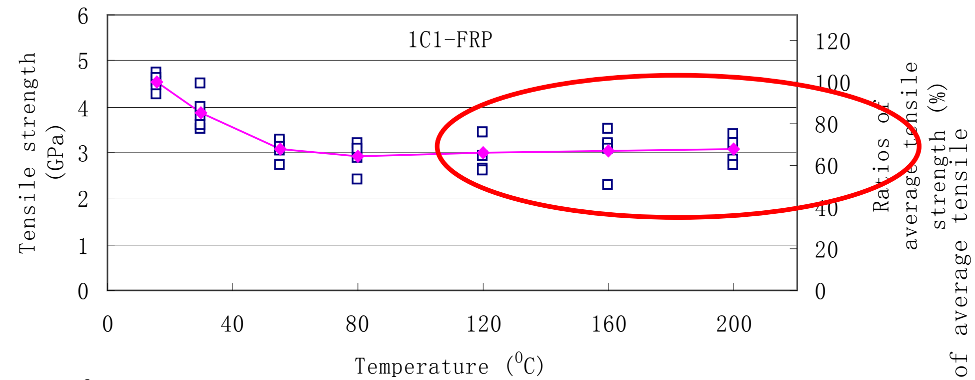


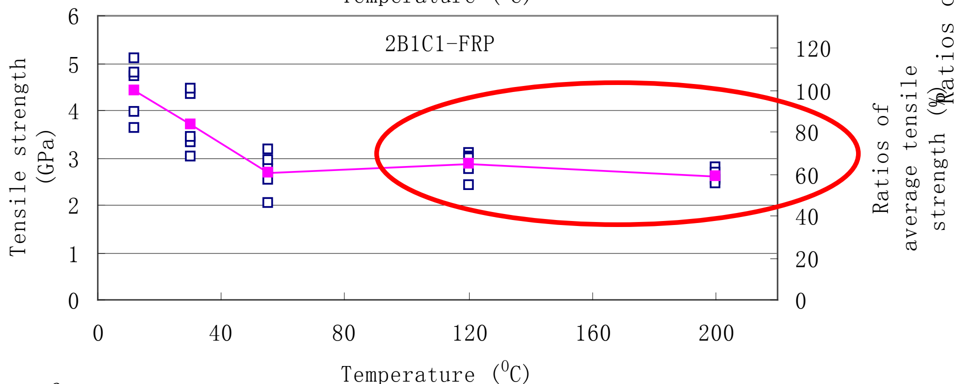


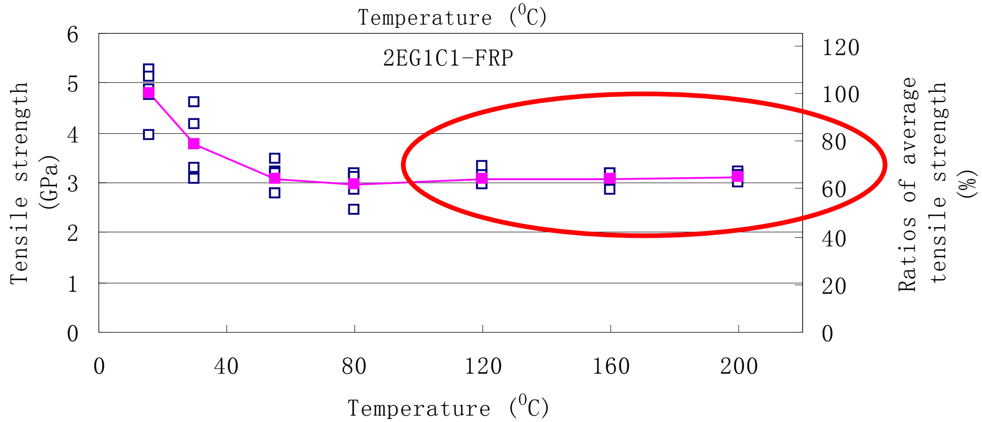


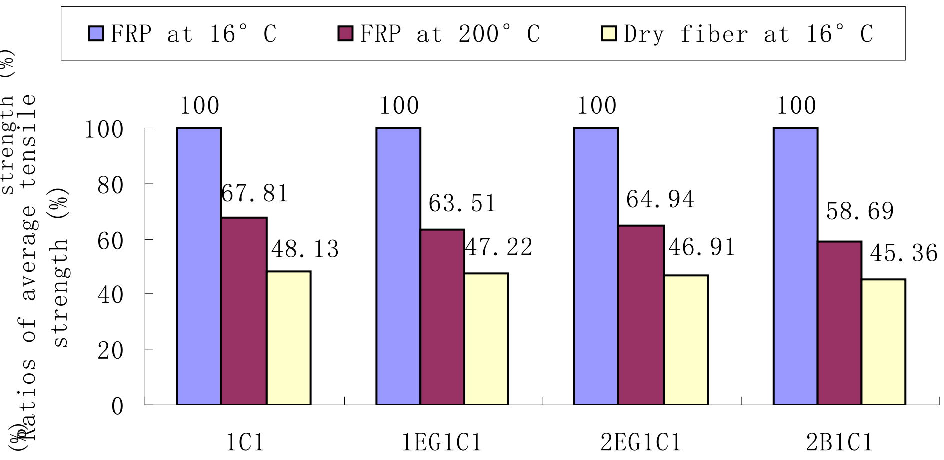
- Hybrid FRP superior than single type of FRP；
- Low Cv of hybrid FRP 。

Hybrid effect study
——under elevated temperatures





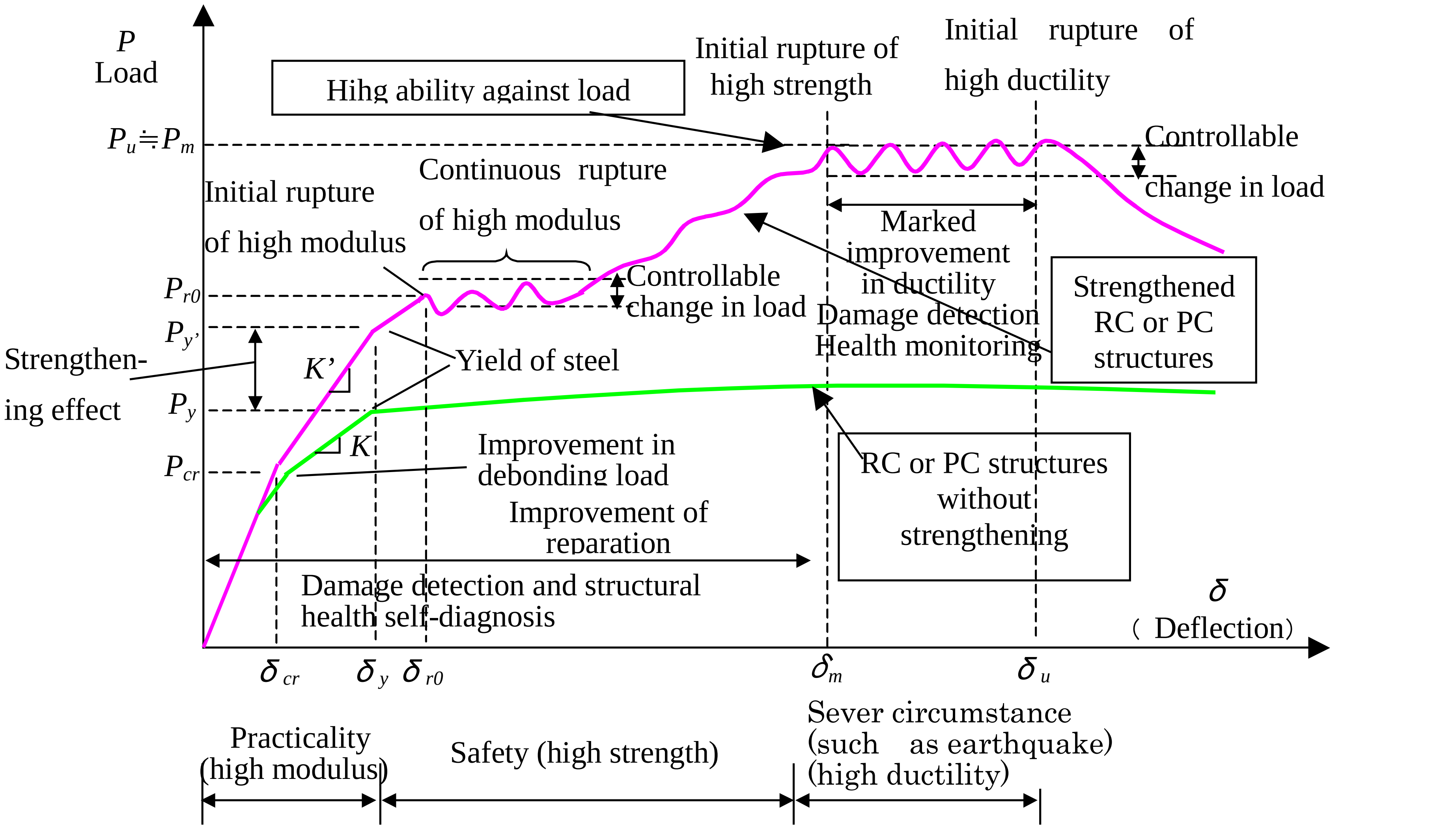




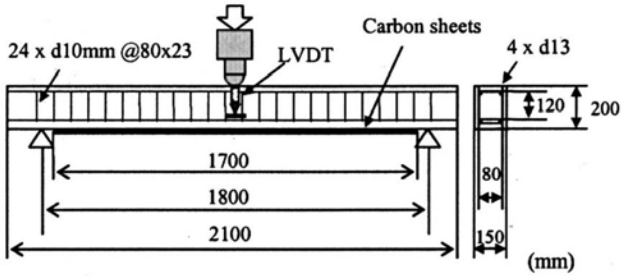
Effect:

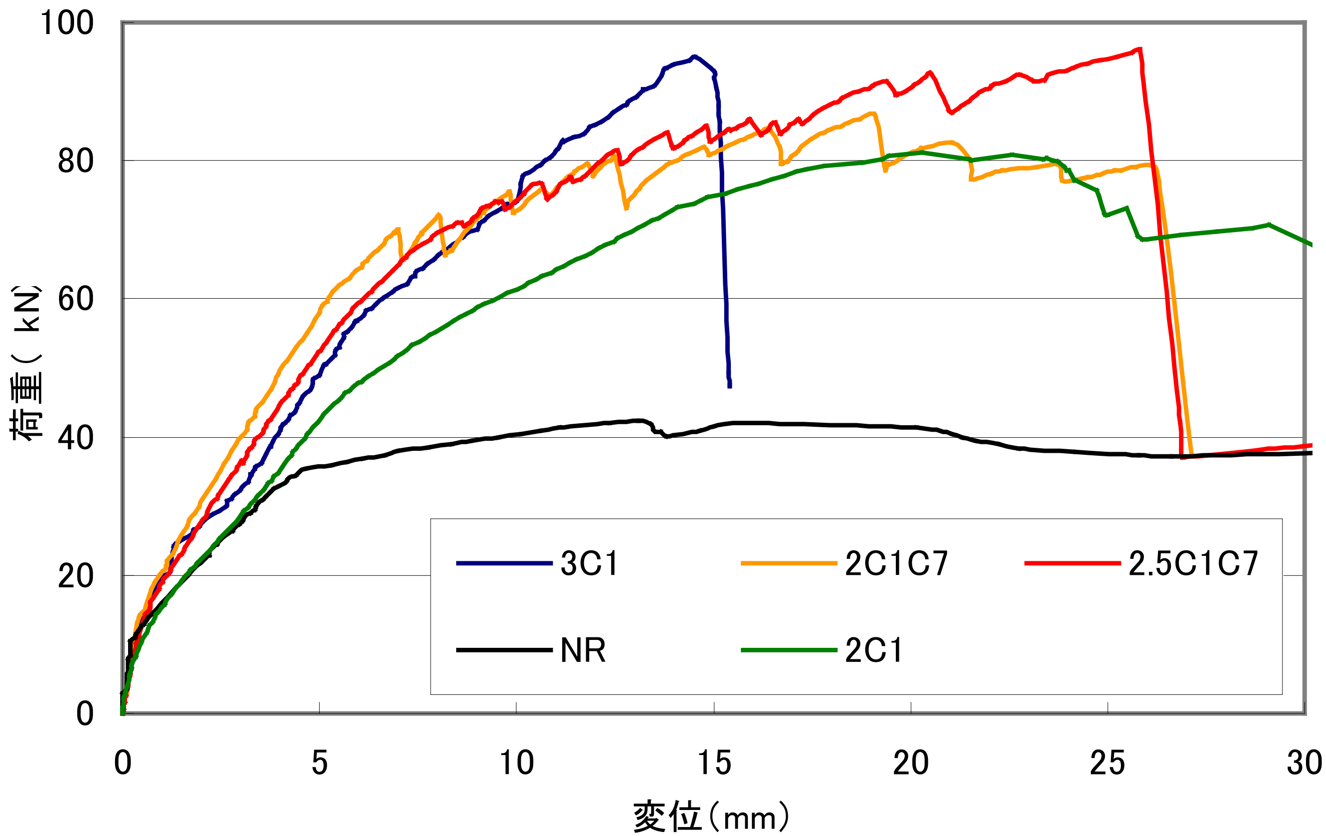
- ➢Improve stability of FRP under high temperature
- ➢Residual strength can be utilized for design

Hybrid FRP for strengthening structures



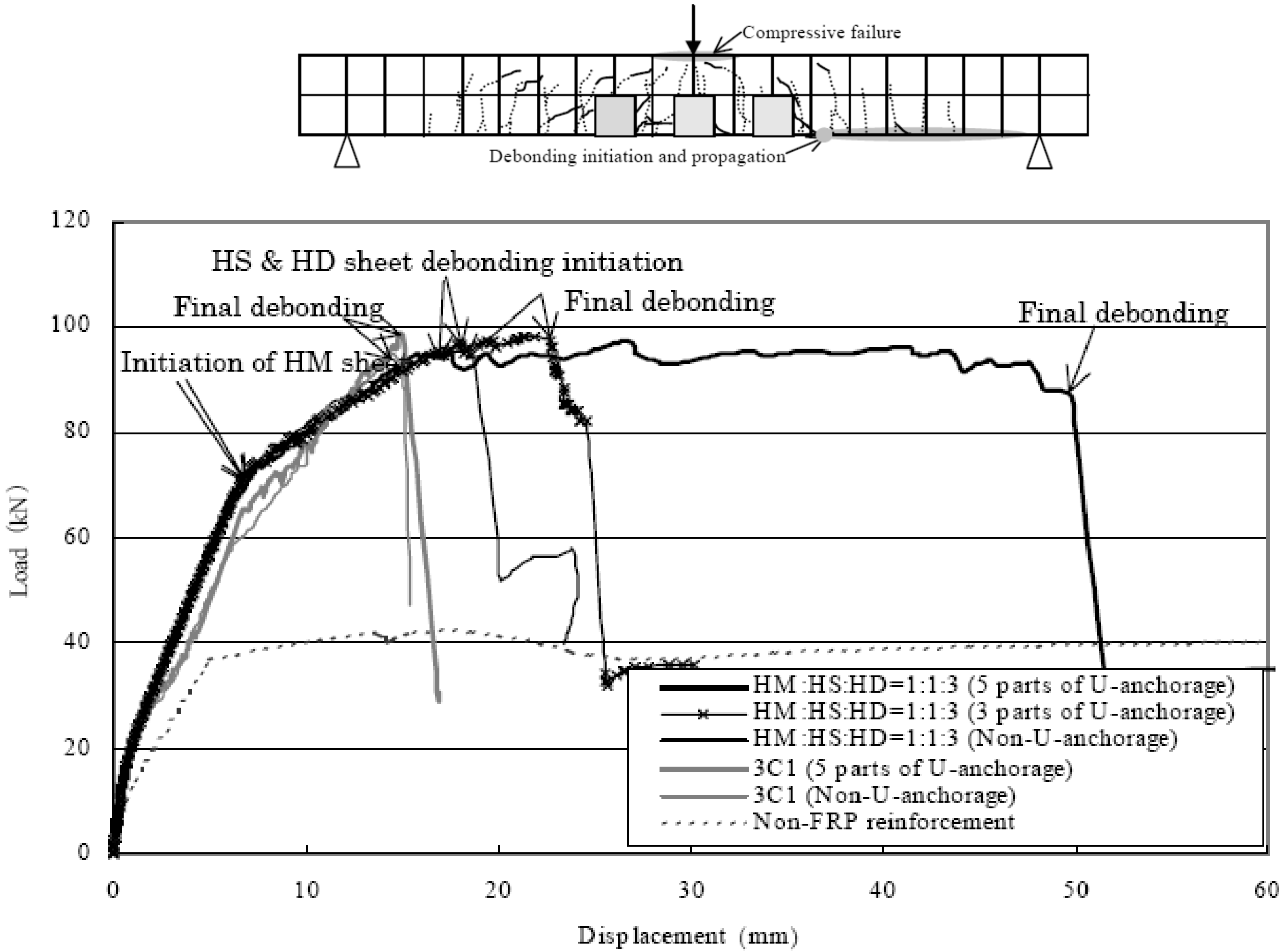
——Strengthening effect by hybrid FRP sheets





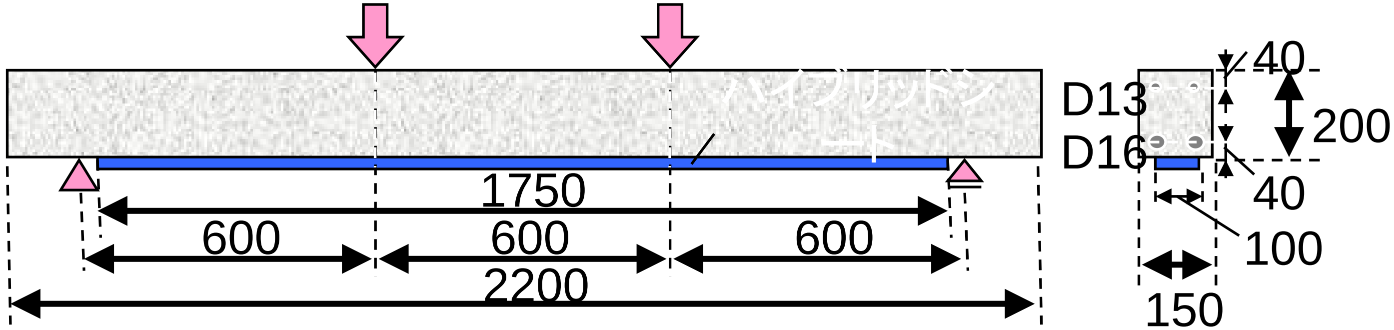
Two kinds of FRP:HS/HM FRP

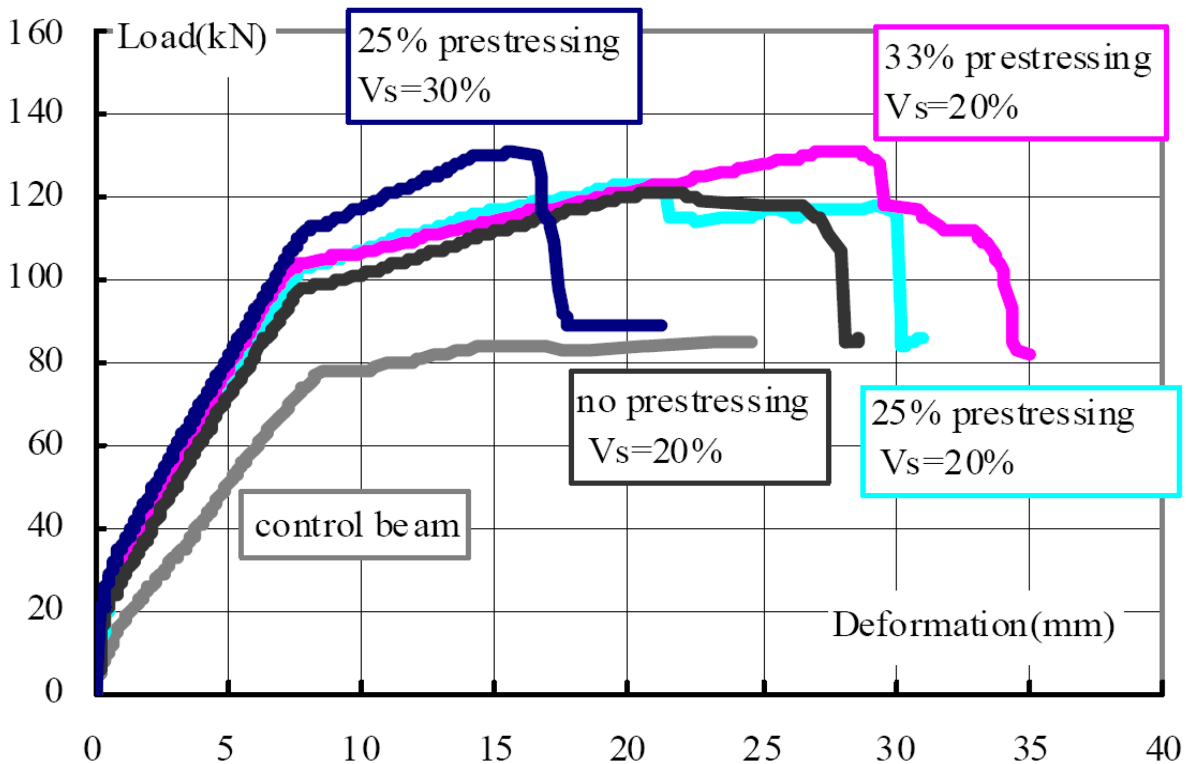
——strengthening effect by hybrid FRP sheets



Three kinds of FRP:HS/HM/HD FRP

——Strengthening effect by hybrid FRP-steel wire sheets





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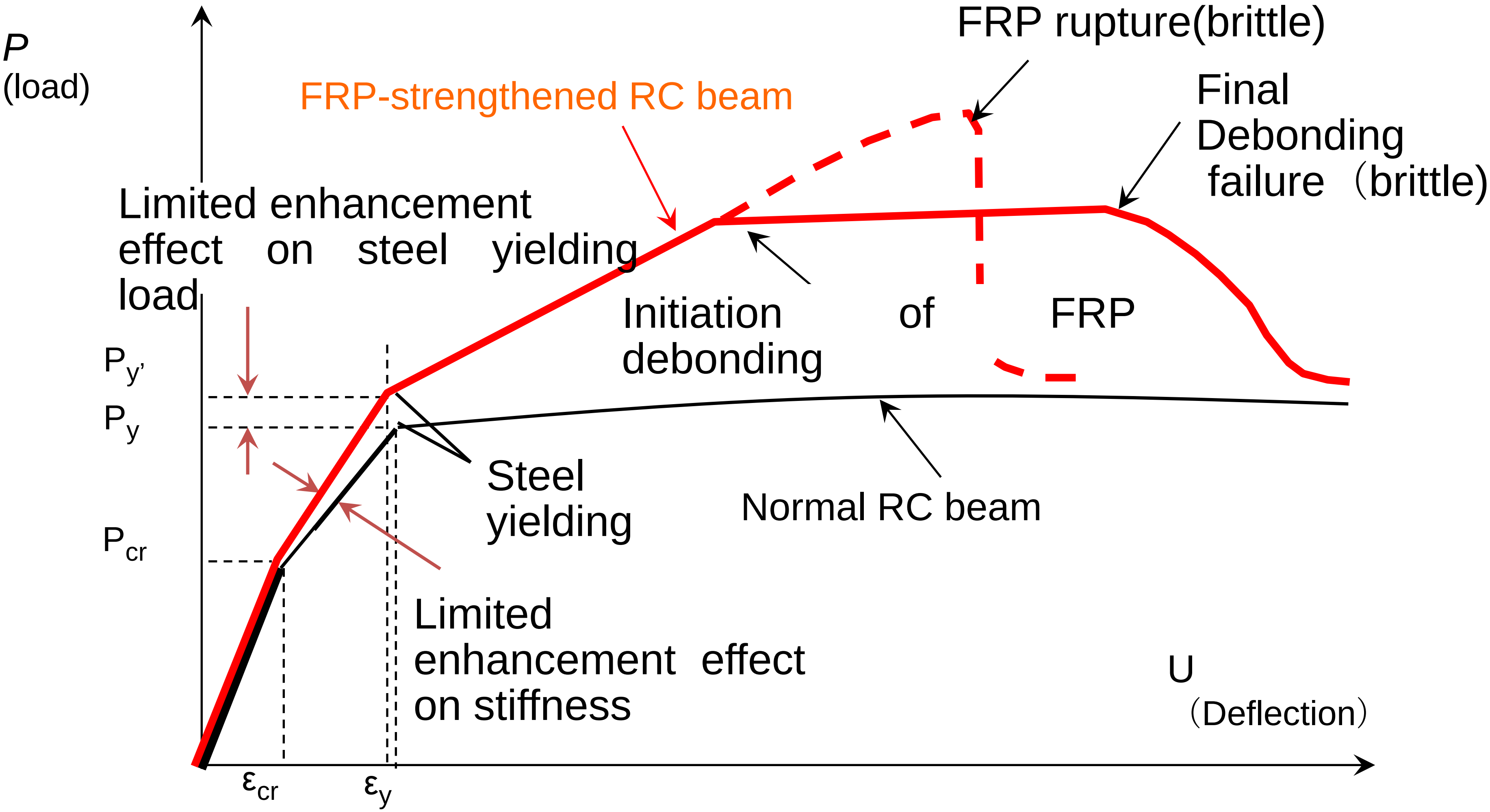
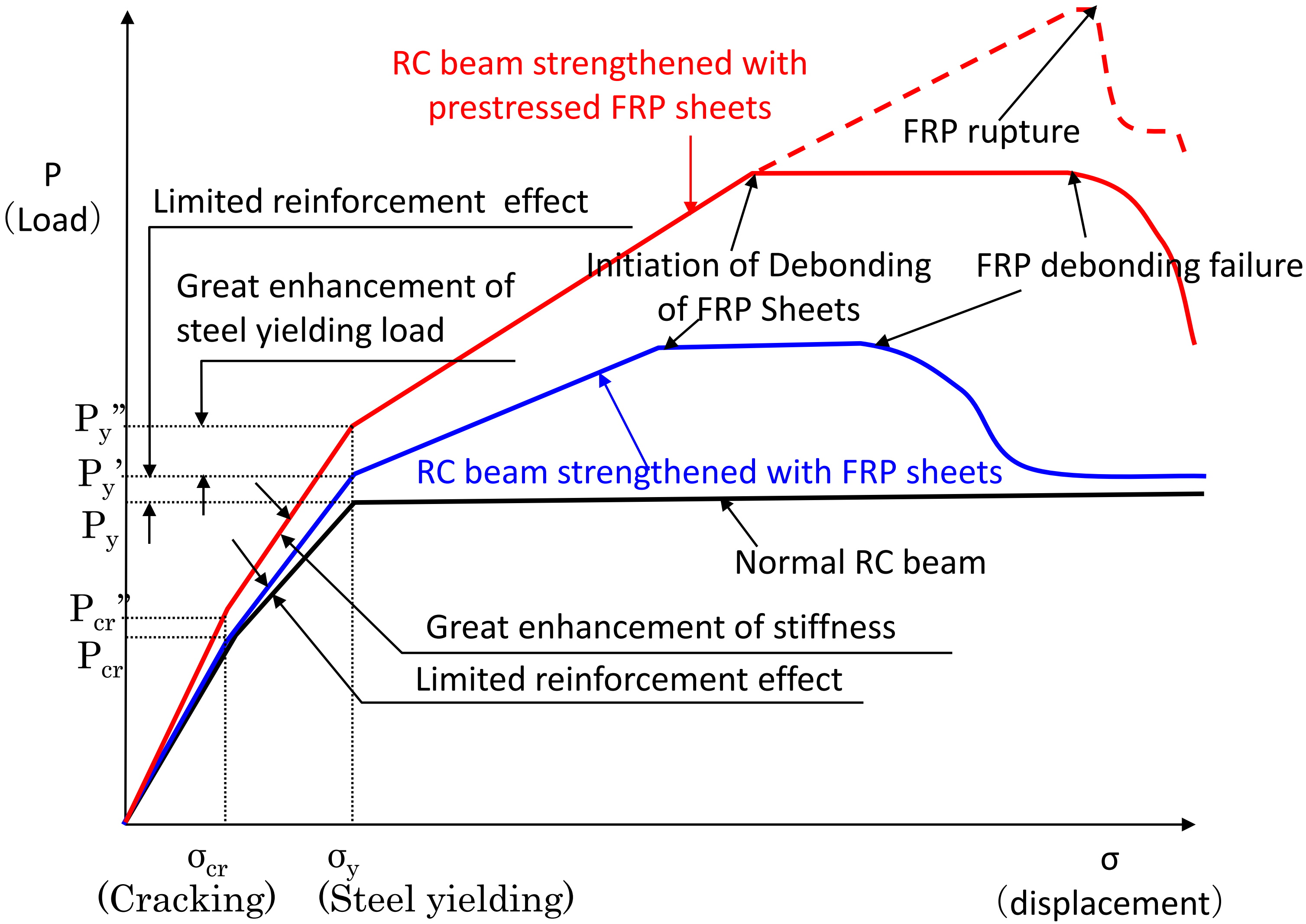
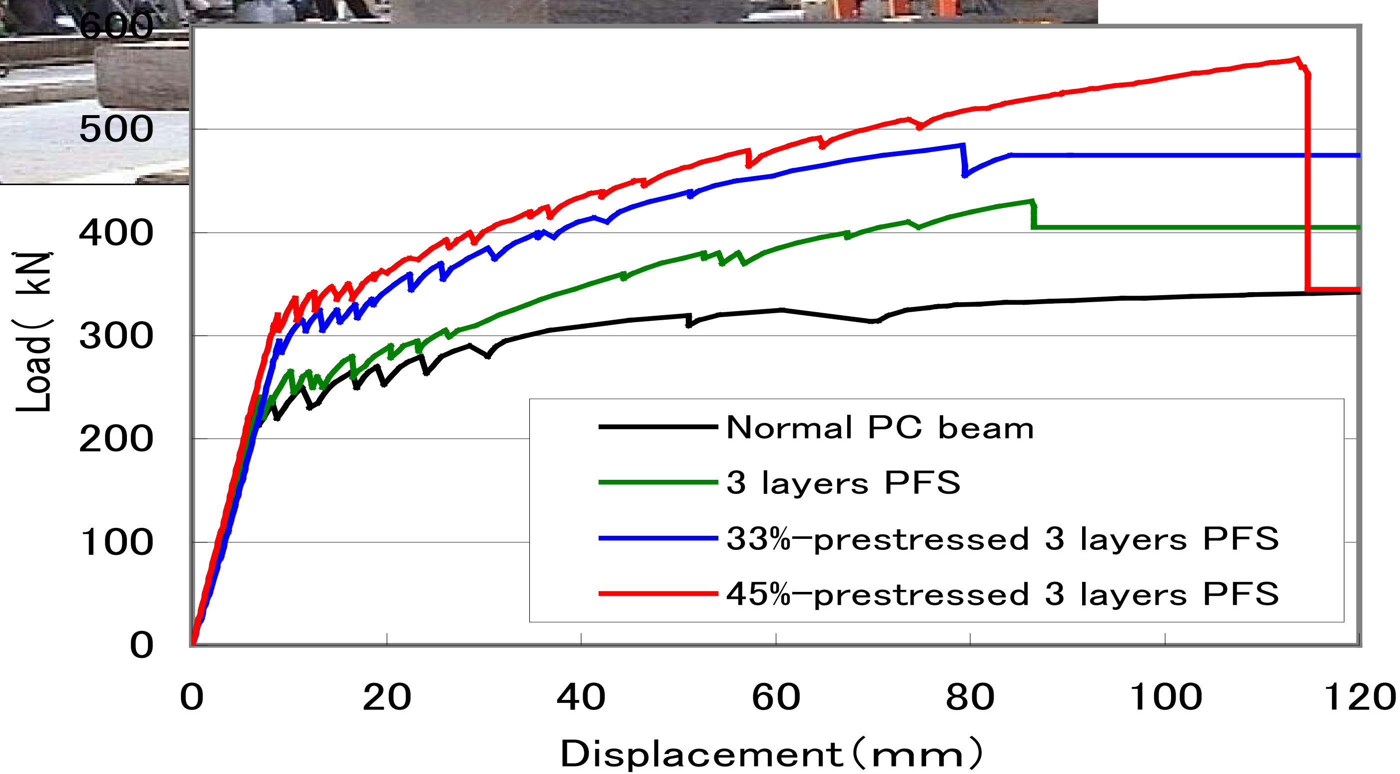
Deficiency of general external-bonded FRP sheets for strengthening



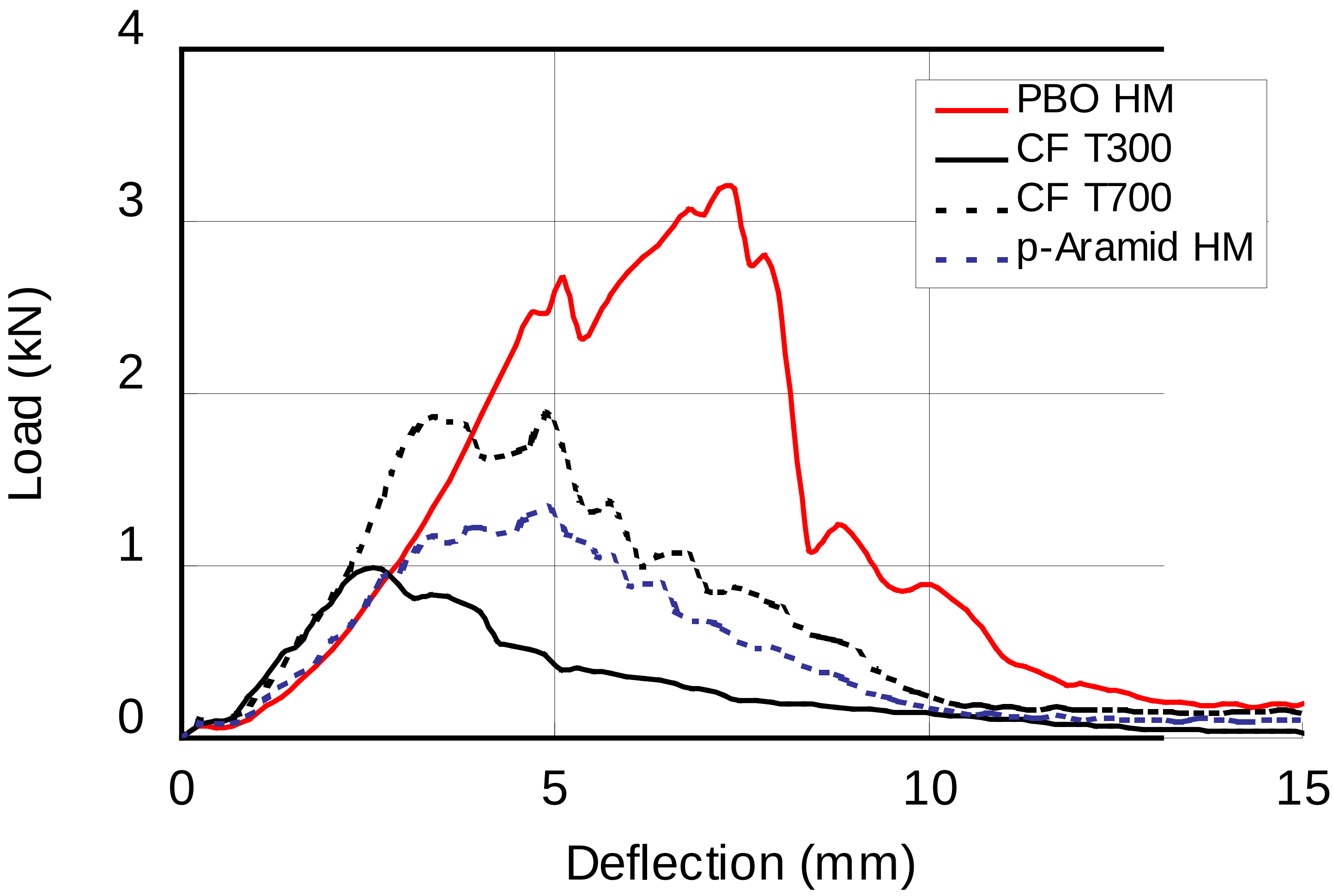
Advantages of prestressing FRP sheets for strengthening



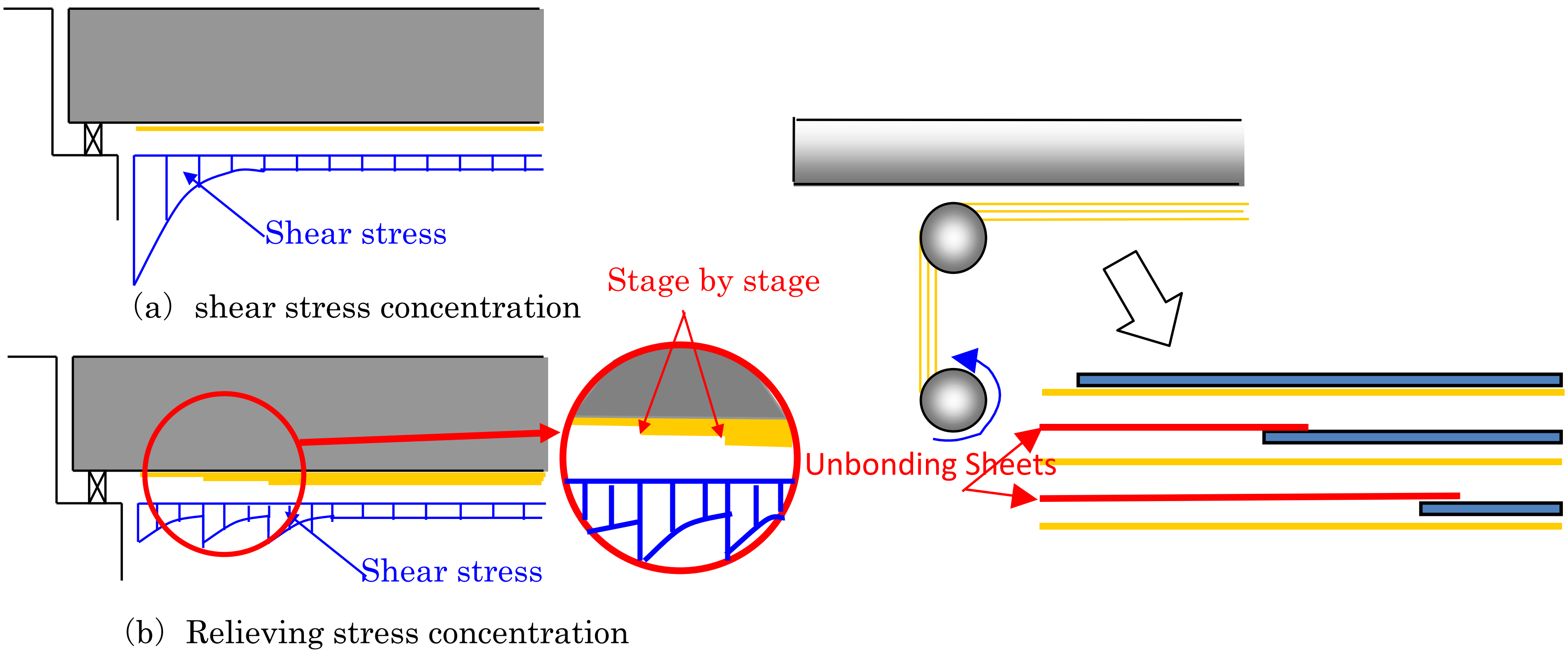
Demonstrate prestressing technique through public test



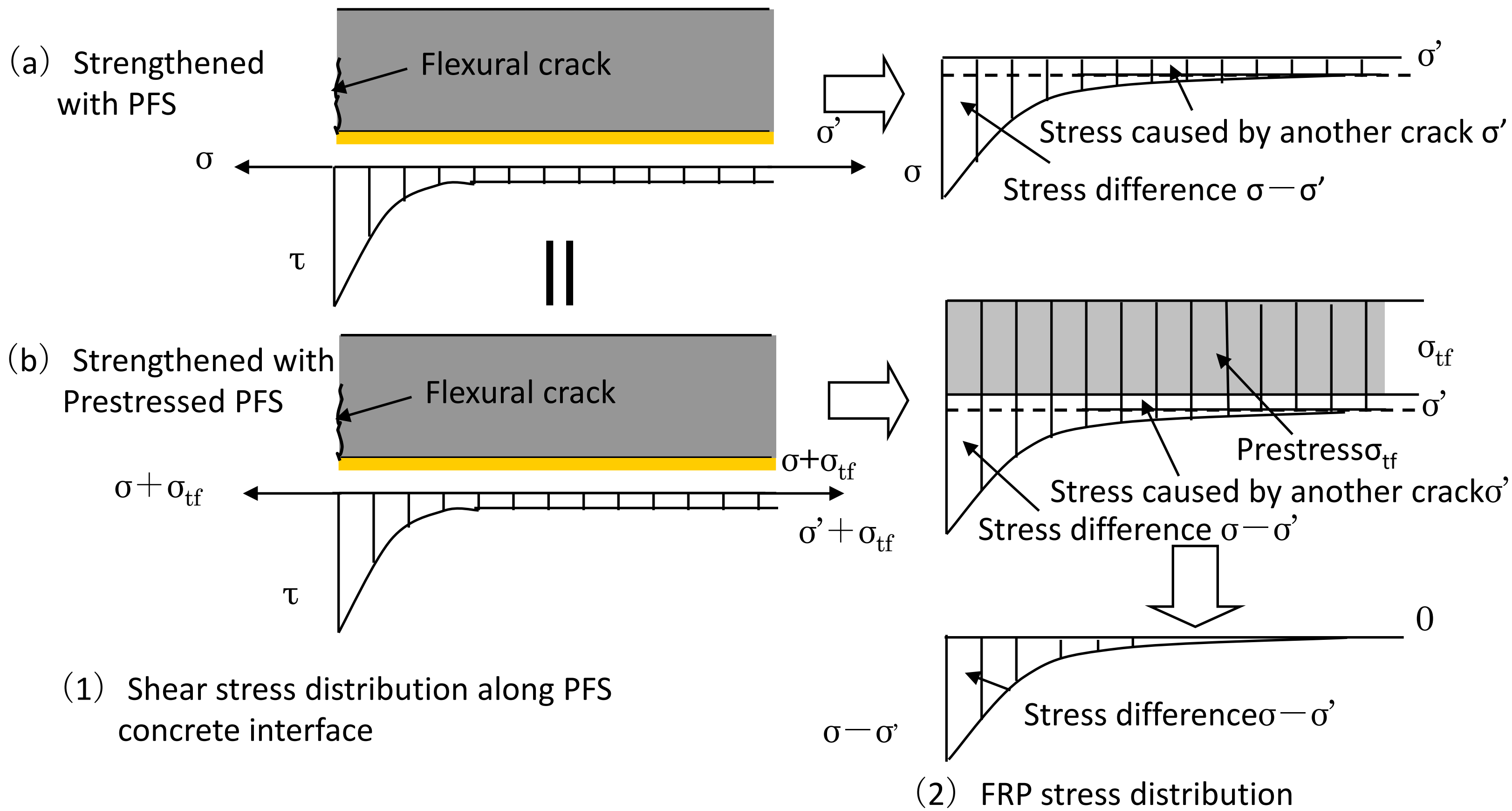
Ability of Energy Absorption From Impact Tests



COUNTERMEASURE FOR RELIEVING SHEAR STRESS CONCENTRATION AT PRESTRESSED FRP ENDS

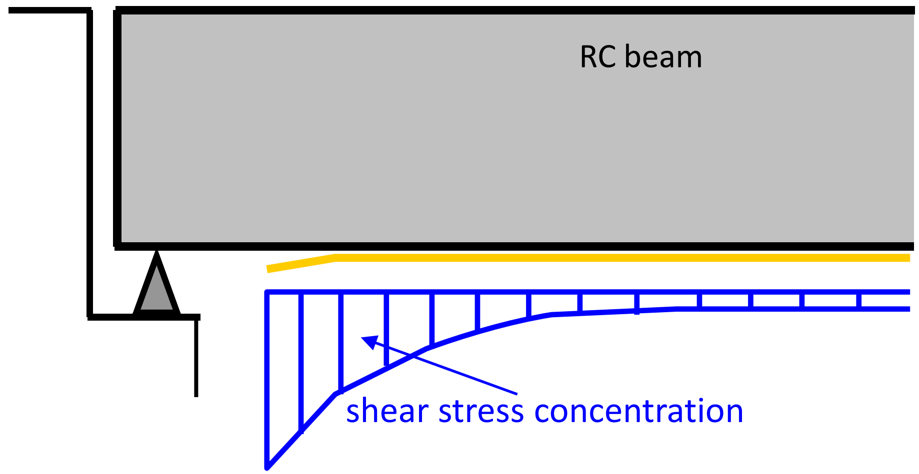


SHEAR STRESS DISTRIBUTION BETWEEN FLEXURAL CRACKS



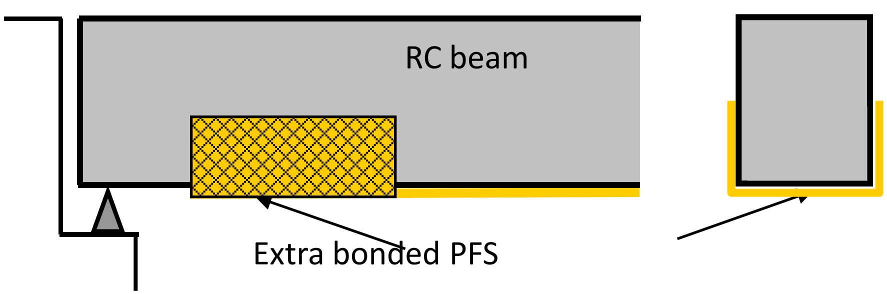
ANCHORAGE TREATMENT

- Stress concentration at FRP ends due to prestressing

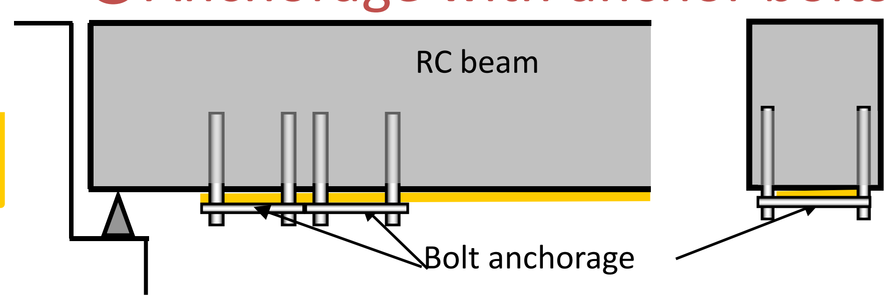


Anchorage Need

- Anchorage with extra bonded PFS



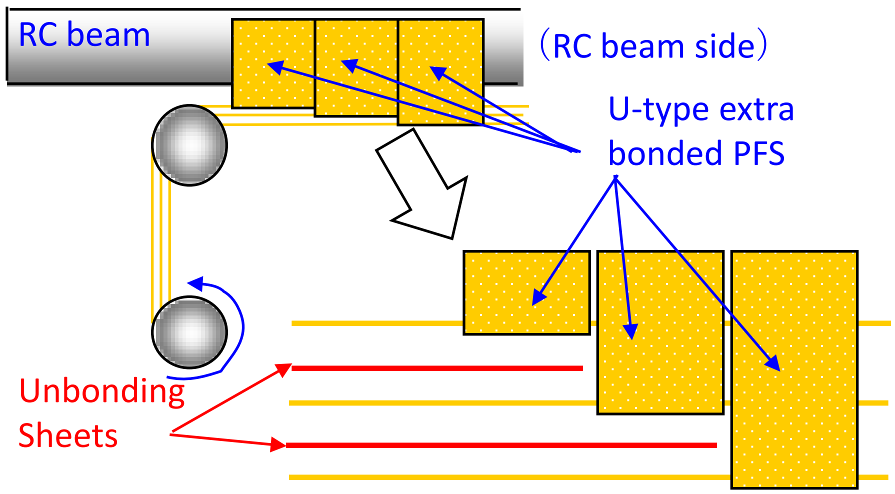
- Anchorage with anchor bolts

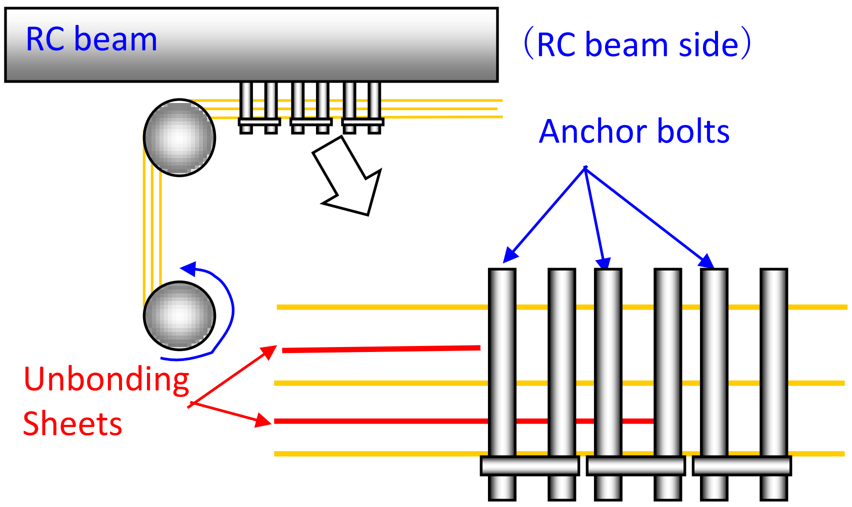


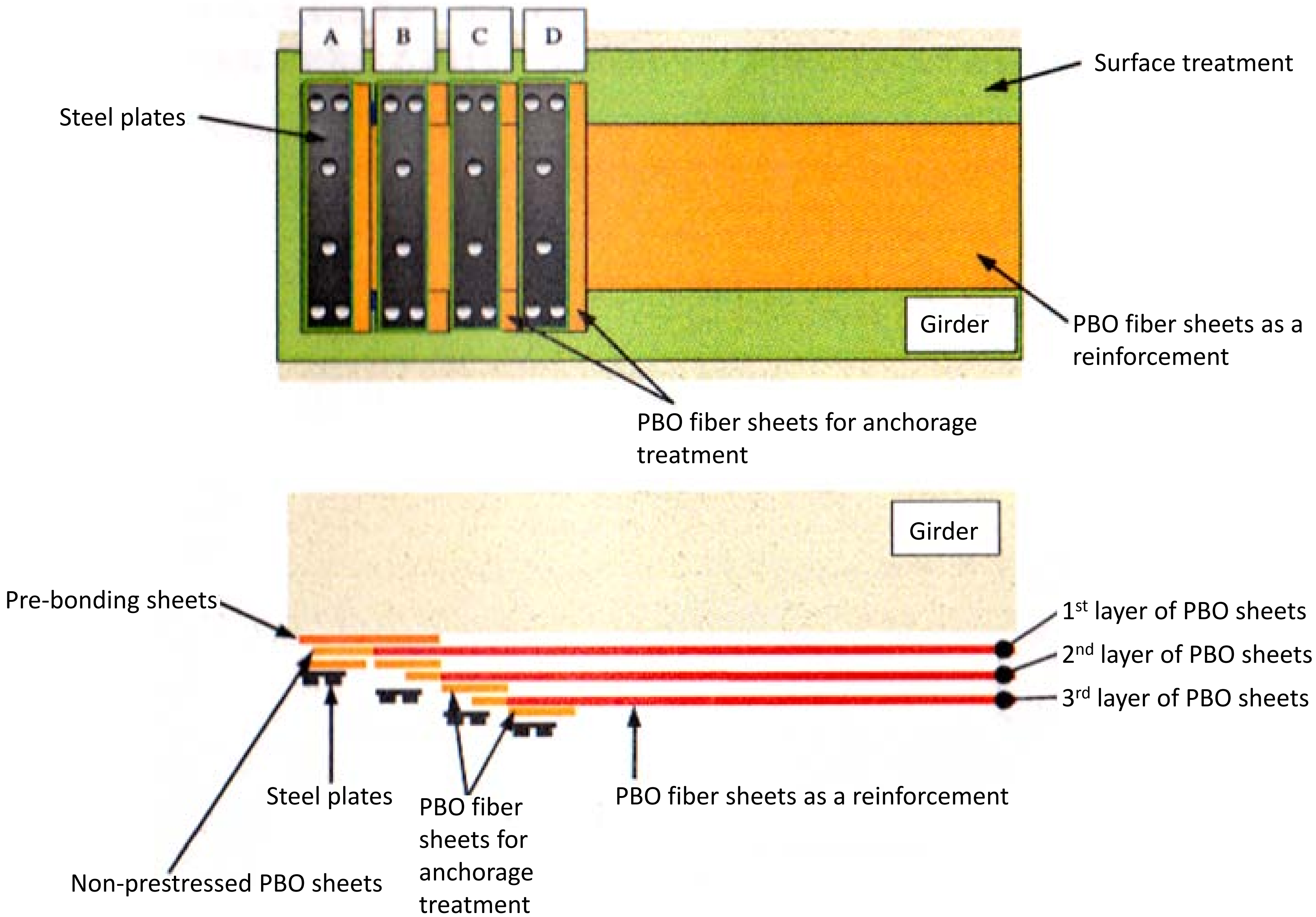
ANCHORAGE TREATMENT

①Anchorage with U-type extra bonded PFS

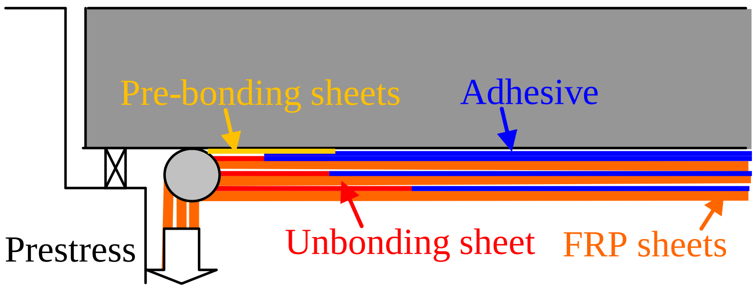
② Anchorage with bolts



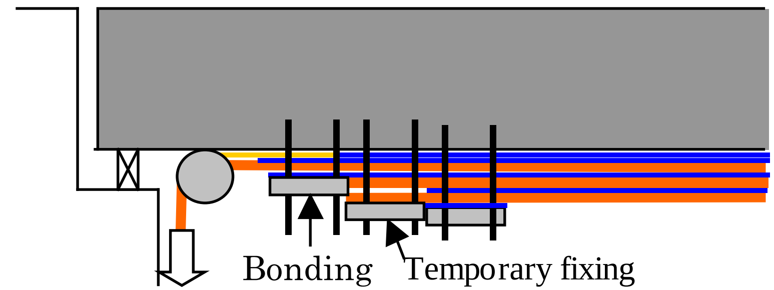



A
B
C
D
Surface treatment
Steel plates
Girder
PBO fiber sheets as a reinforcement
PBO fiber sheets for anchorage treatment
Girder
Pre-bonding sheets
1st layer of PBO sheets
2nd layer of PBO sheets
3rd layer of PBO sheets
Steel plates
PBO fiber sheets for anchorage treatment
PBO fiber sheets as a reinforcement
Non-prestressed PBO sheets

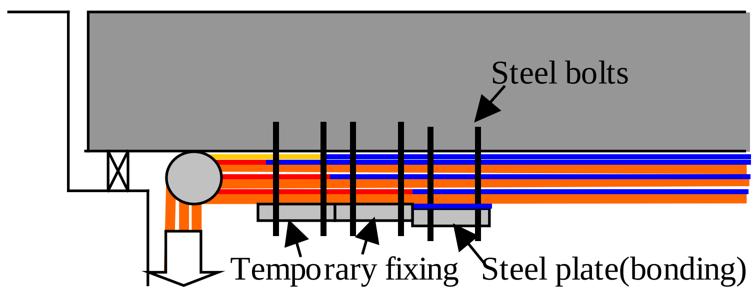
Process of Extra Anchorage Treatments



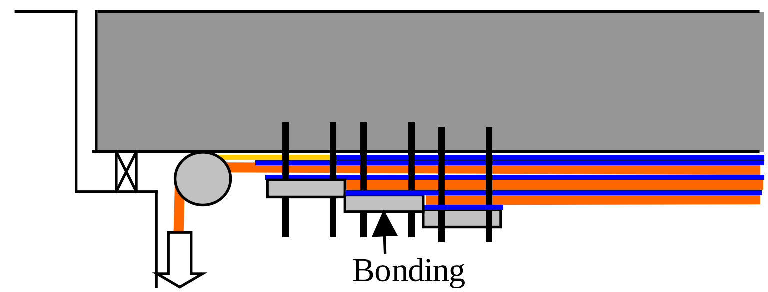
FRP Sheets Setting and Prestressing



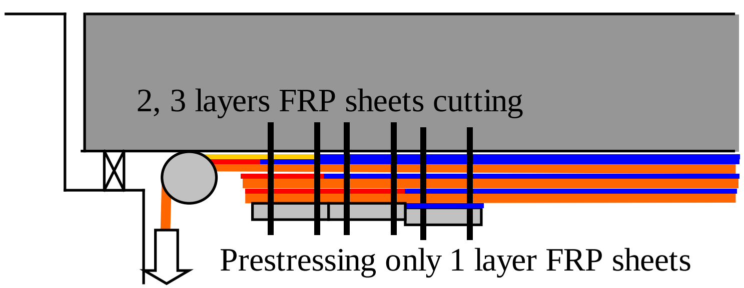
Bonding Outside Steel Plate



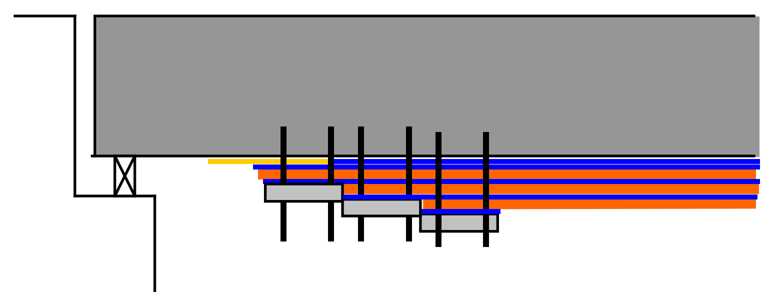
Steel Plates Temporary Fixing



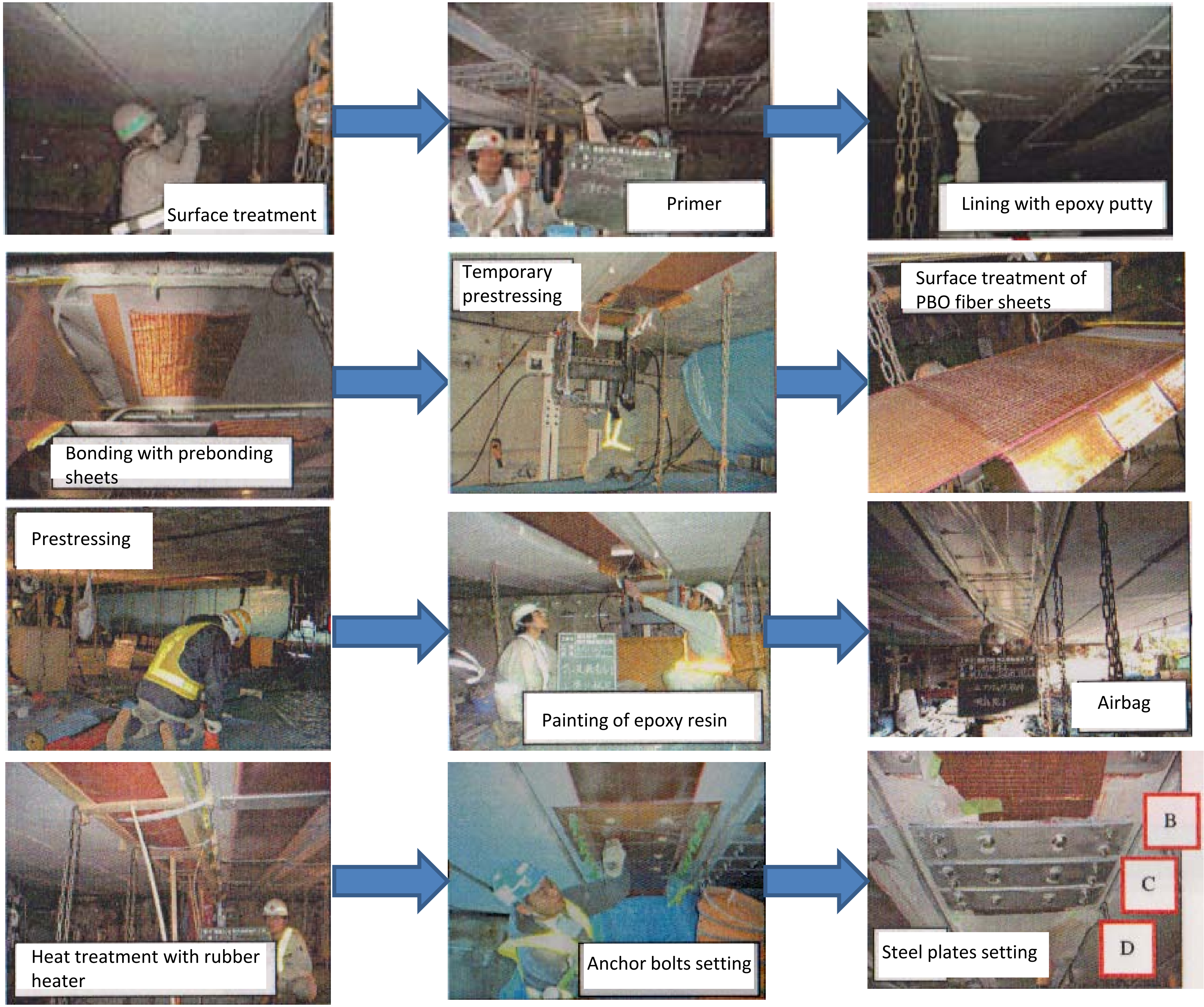
Bonding Second Steel Plate



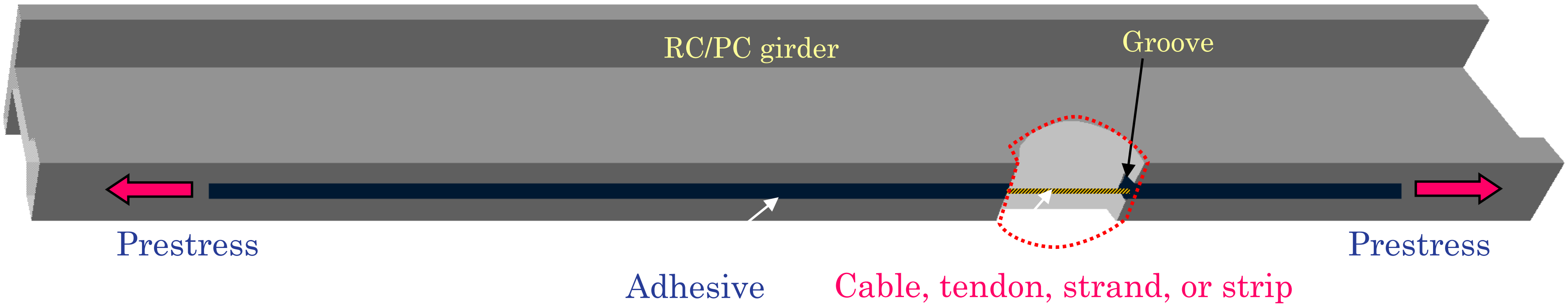
Cutting 2, 3 Layers of FRP Sheets

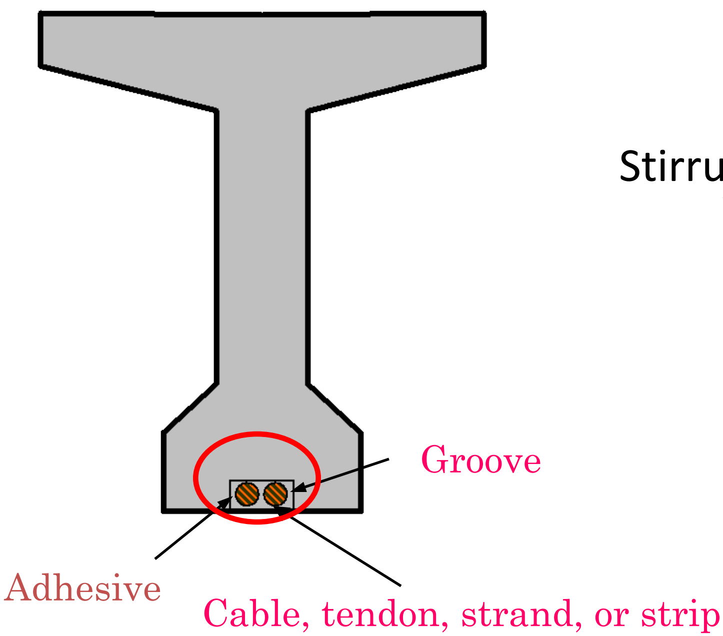


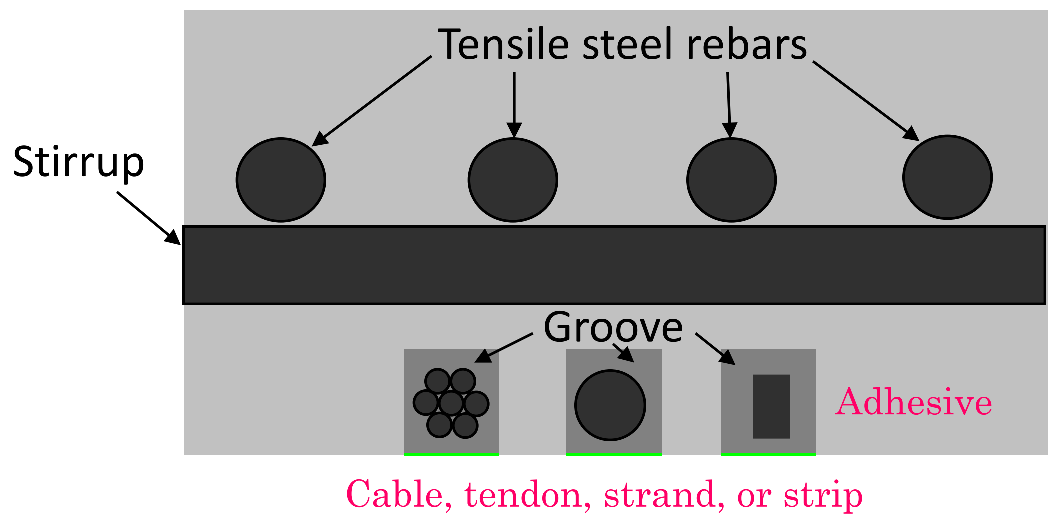
Release and Completion


Surface treatment
Primer
Lining with epoxy putty
Bonding with prebonding sheets
Temporary prestressing
Surface treatment of PBO fiber sheets
Prestressing
Painting of epoxy resin
Airbag
Heat treatment with rubber heater
Anchor bolts setting
Steel plates setting
B
C
D

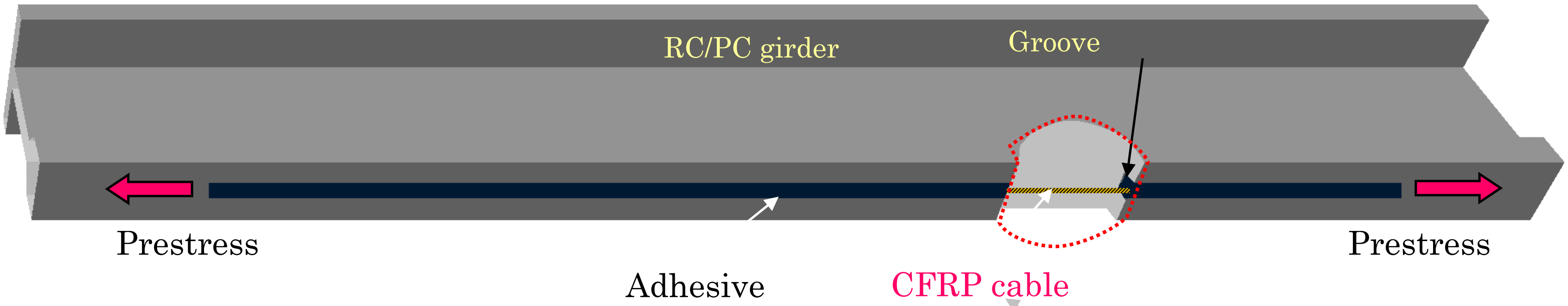
Structural Strengthening with Prestressed Near Surface Mounted (PNSM) FRP Cables



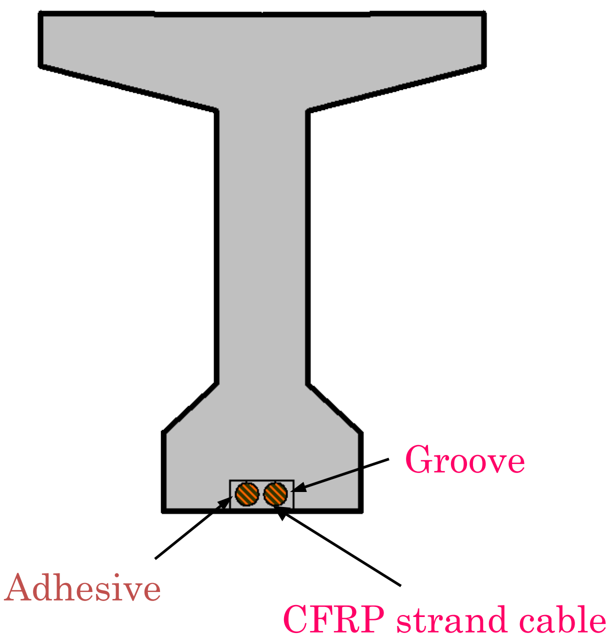




Structural Strengthening with Prestressed Near Surface Mounted (PNSM) FRP Cables

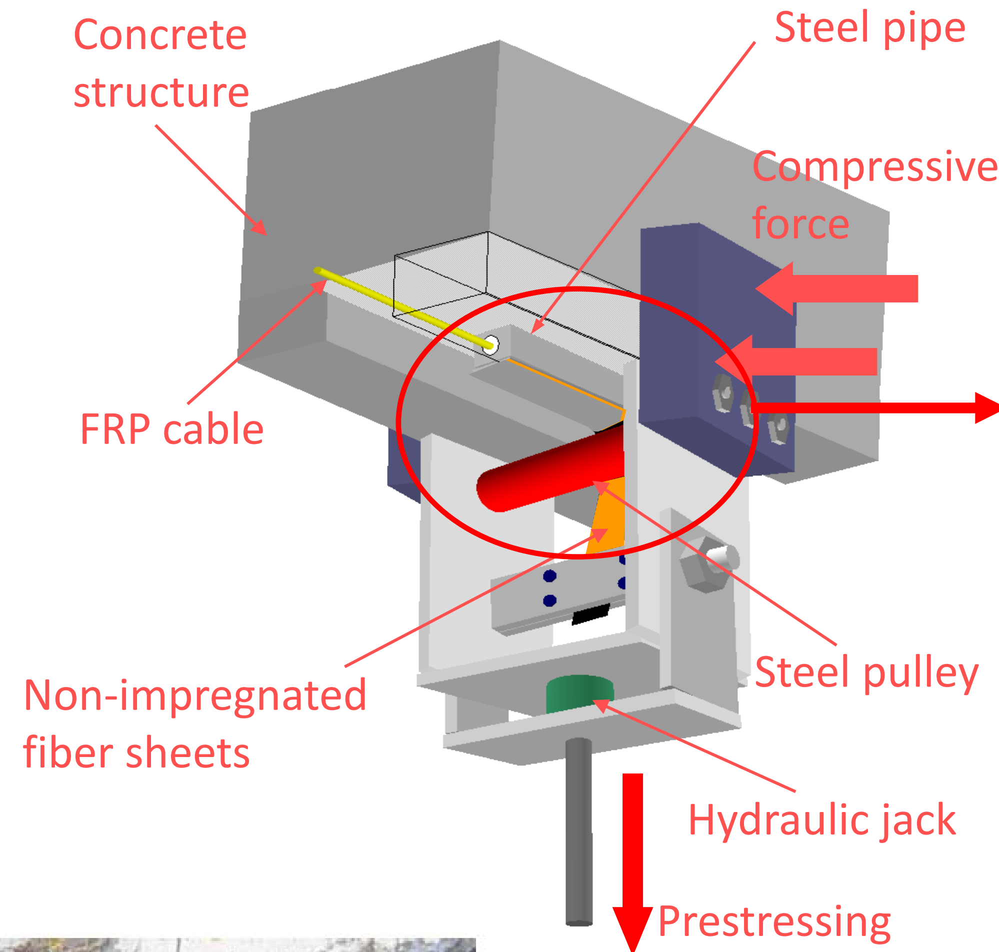


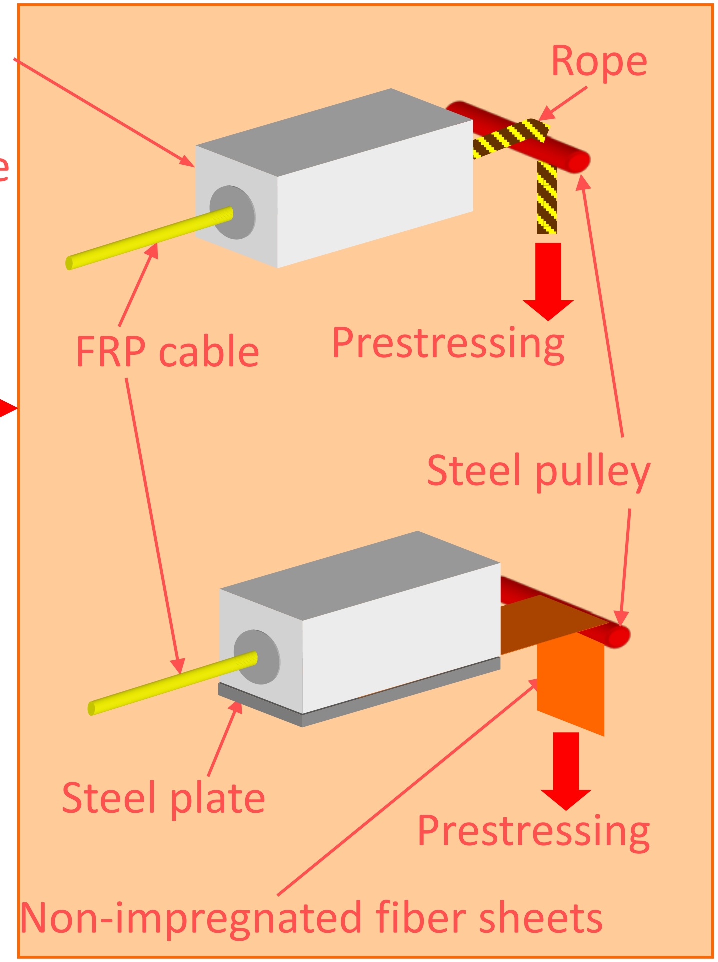
Summary of CFRP strand tendon



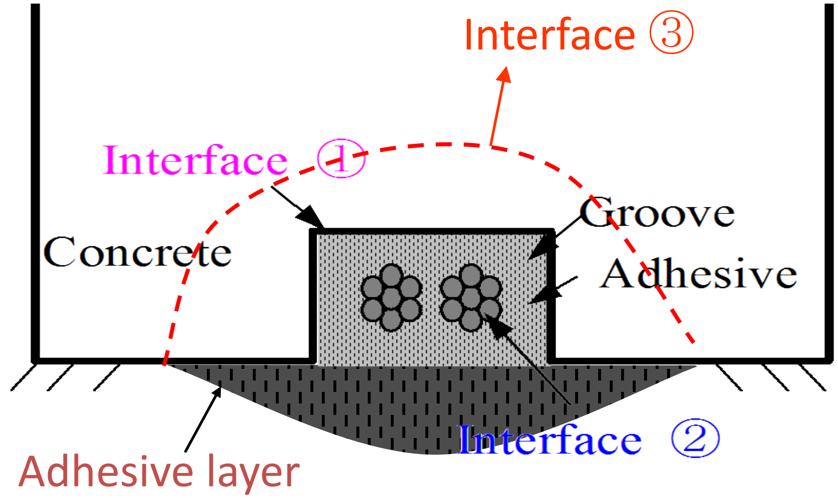
CFRP strand tendon	Modulus of elasticity (GPa)	94.9
	Tensile strength (MPa)	2,084
	Rupture strain (%)	2.2
	Relaxation ratio (20°C, 1000h, $0.7P_u$)(%)	3.0
	Nominal cross sectional area (mm^2)	42.78

Prestressing System





Interfaces of PNSM



Side view of the specimen

Change failure interface through adhesive layer

○Affinity between materials

FRP ◎ Epoxy putty or resin

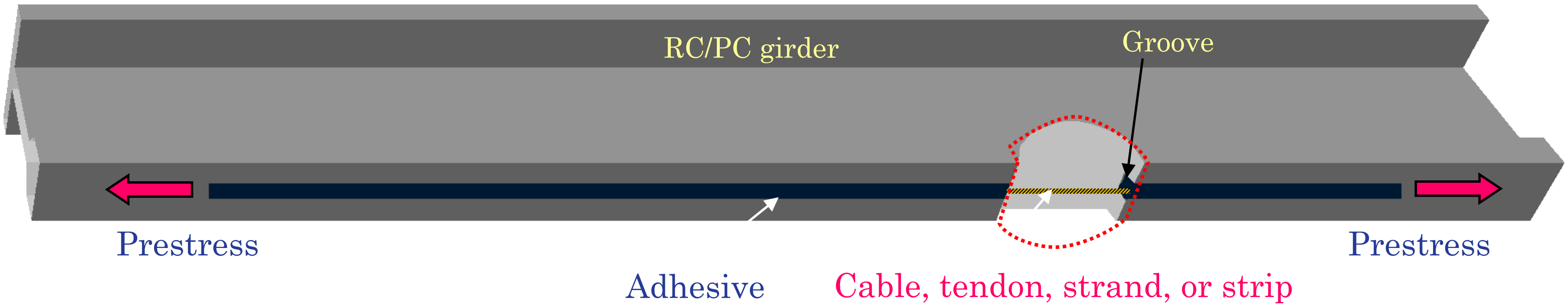
FRP × Cement mortar

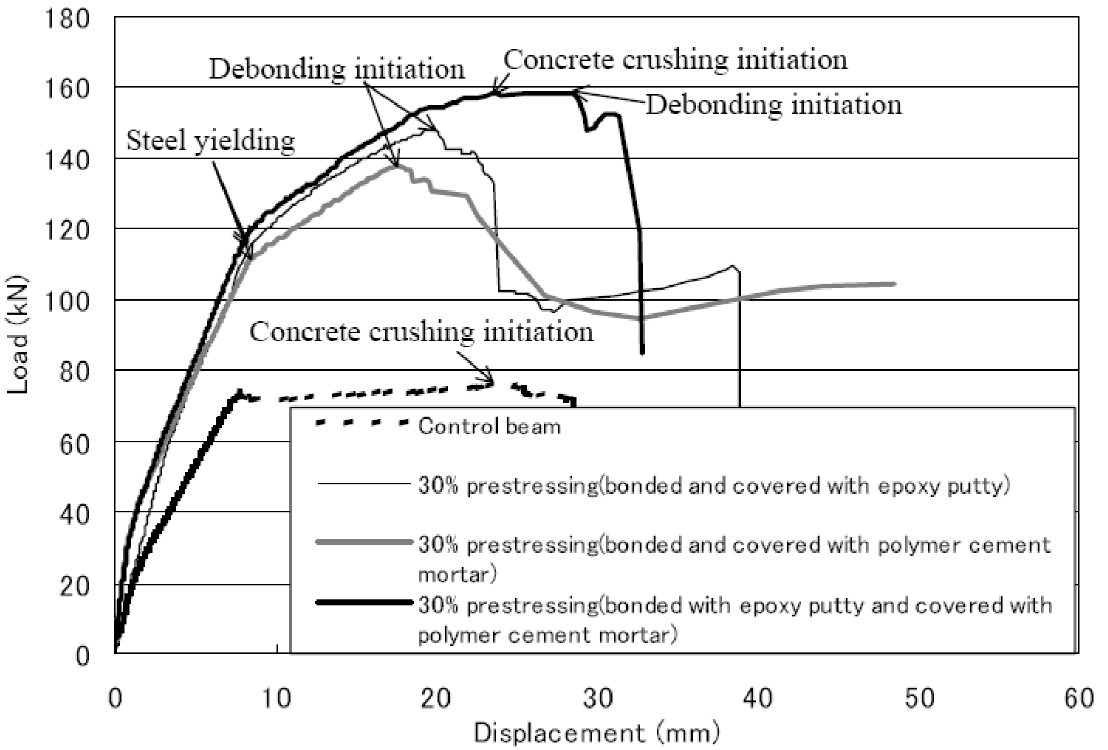
Epoxy putty or resin ○ Cement mortar

Epoxy putty or resin △ Concrete

Cement mortar ○ Concrete

——NSM FRP cables for strengthening structure

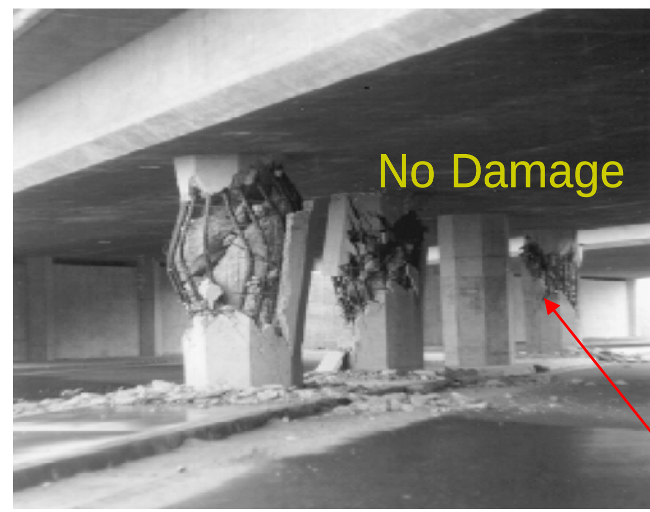




Outline

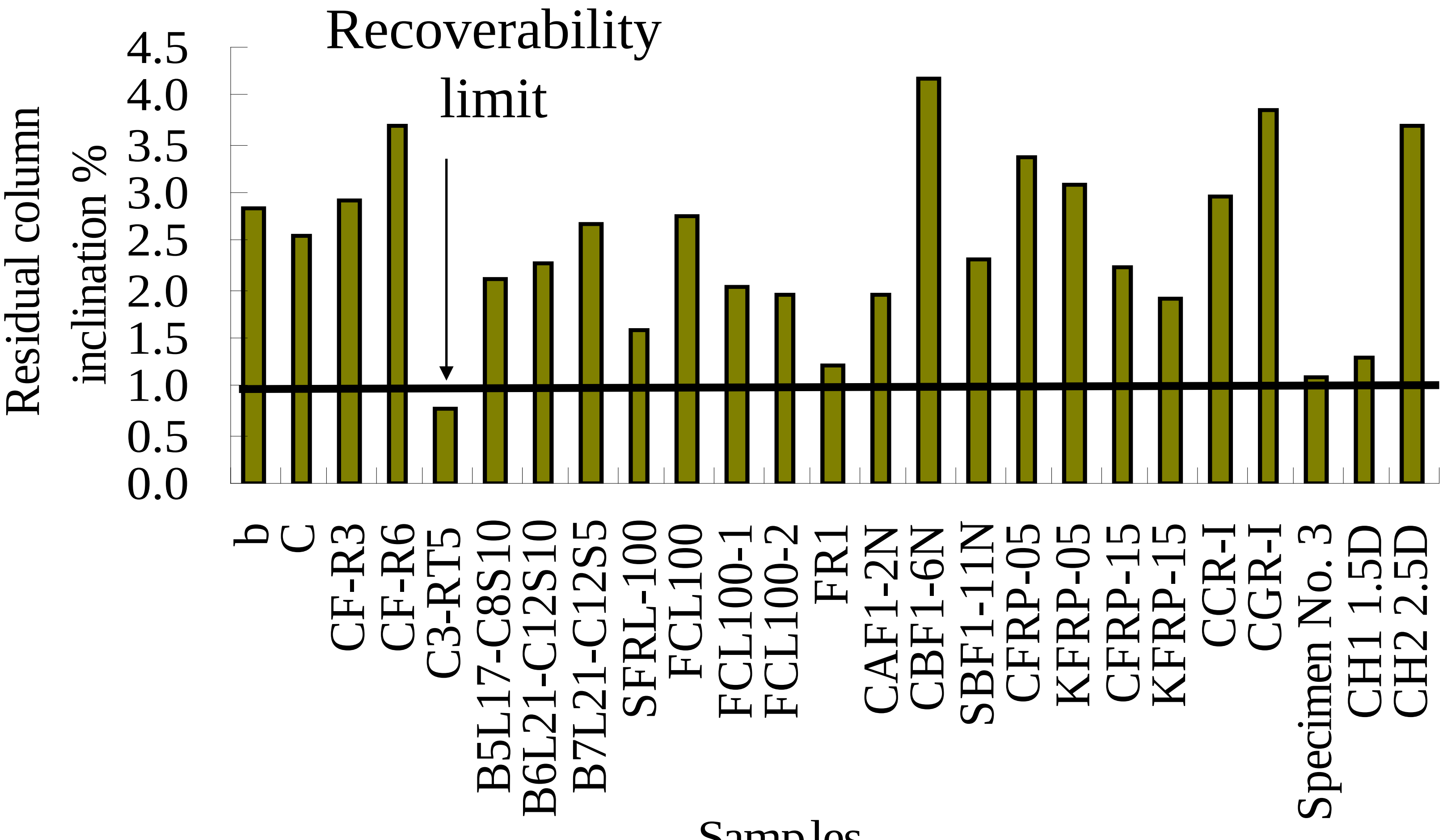
1. Background
2. Introduction of FRP and research status
3. Hybrid FRP technology
4. Prestressing FRP technology
5. Damage-controllable FRP structures
6. Integrated high performance FRP structures
7. Intelligent infrastructures
8. Summary

Facts

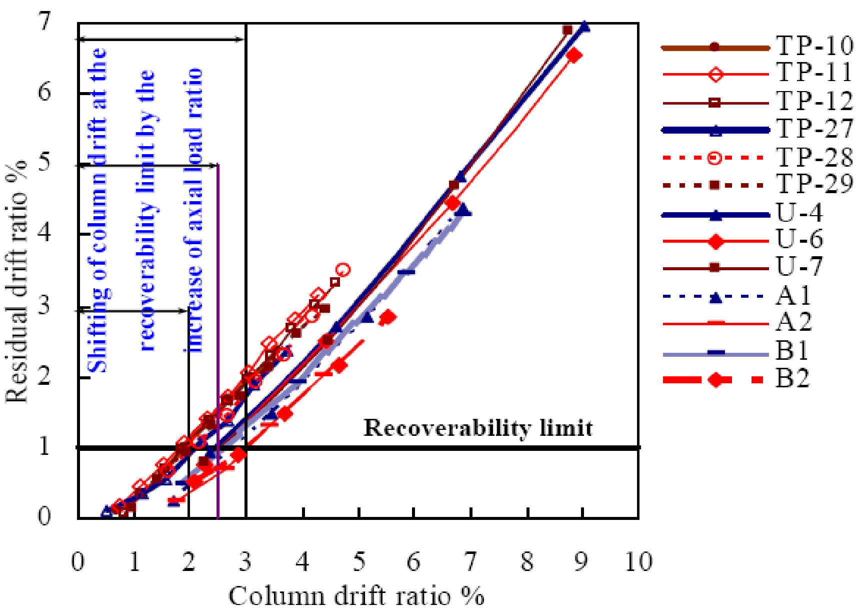


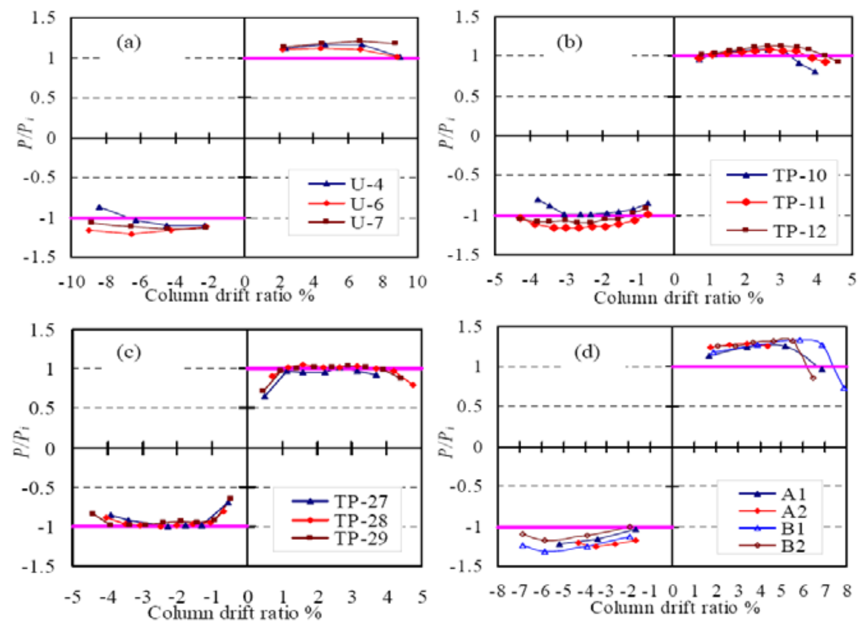
There are different damage levels under the effect of strong Earthquake.

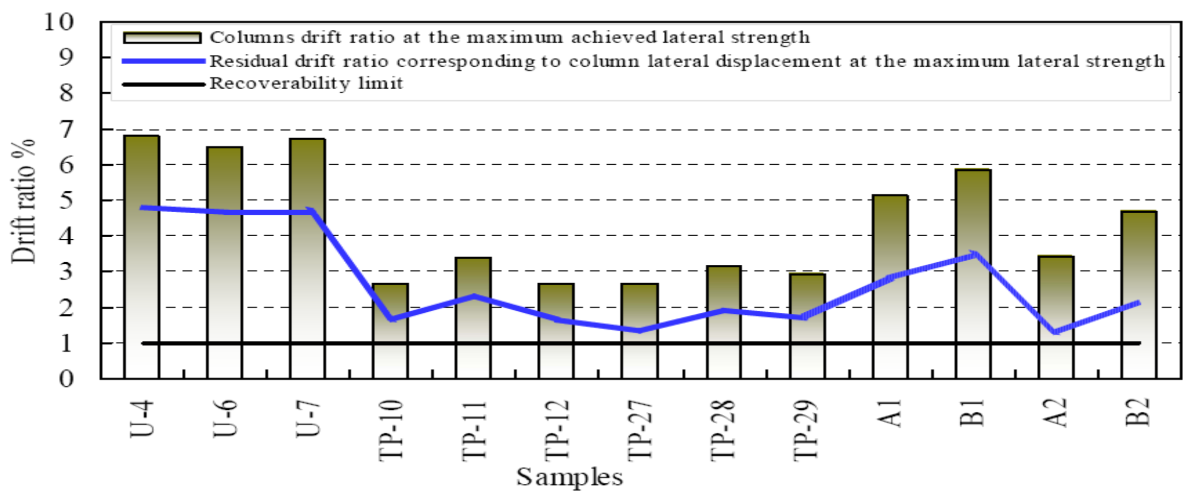
Seismic Performance Evaluation of FRP Retrofitted Columns Using Residual Deformation Index



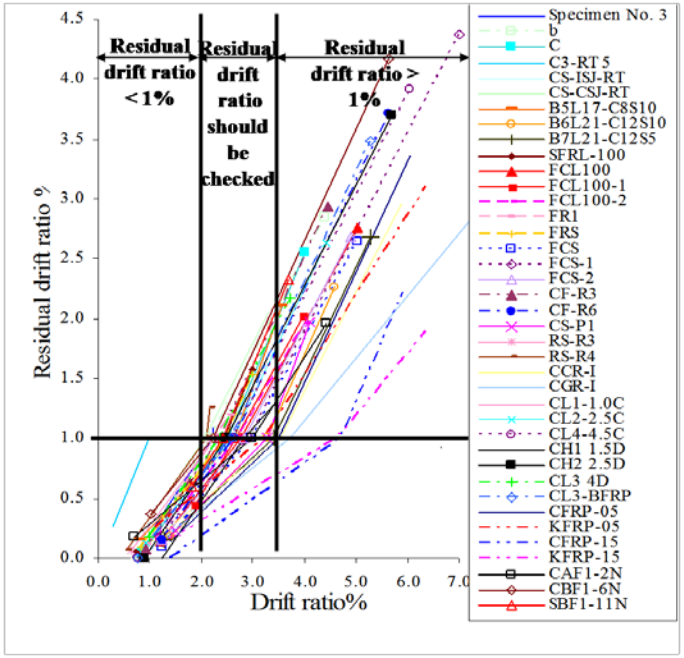
——Damage recoverability of common RC column

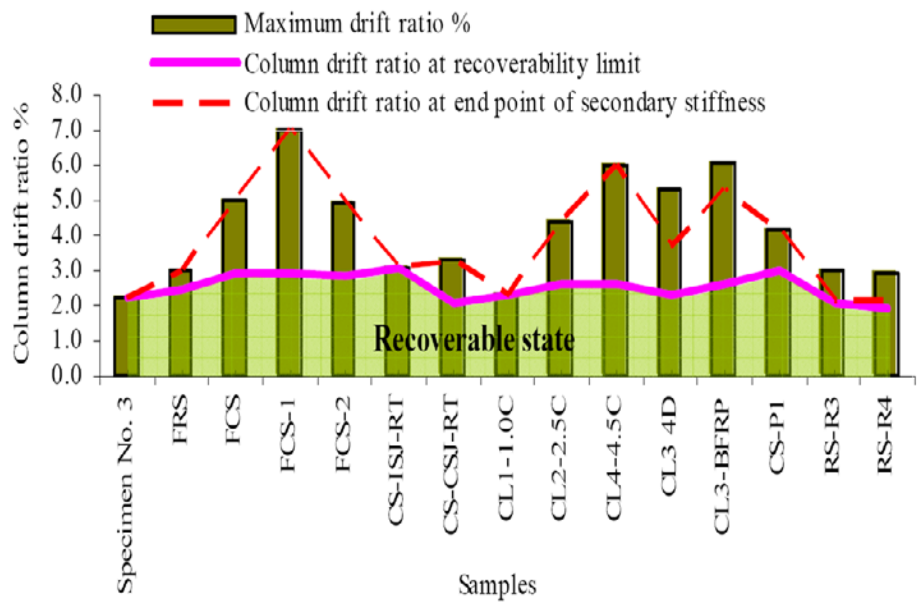






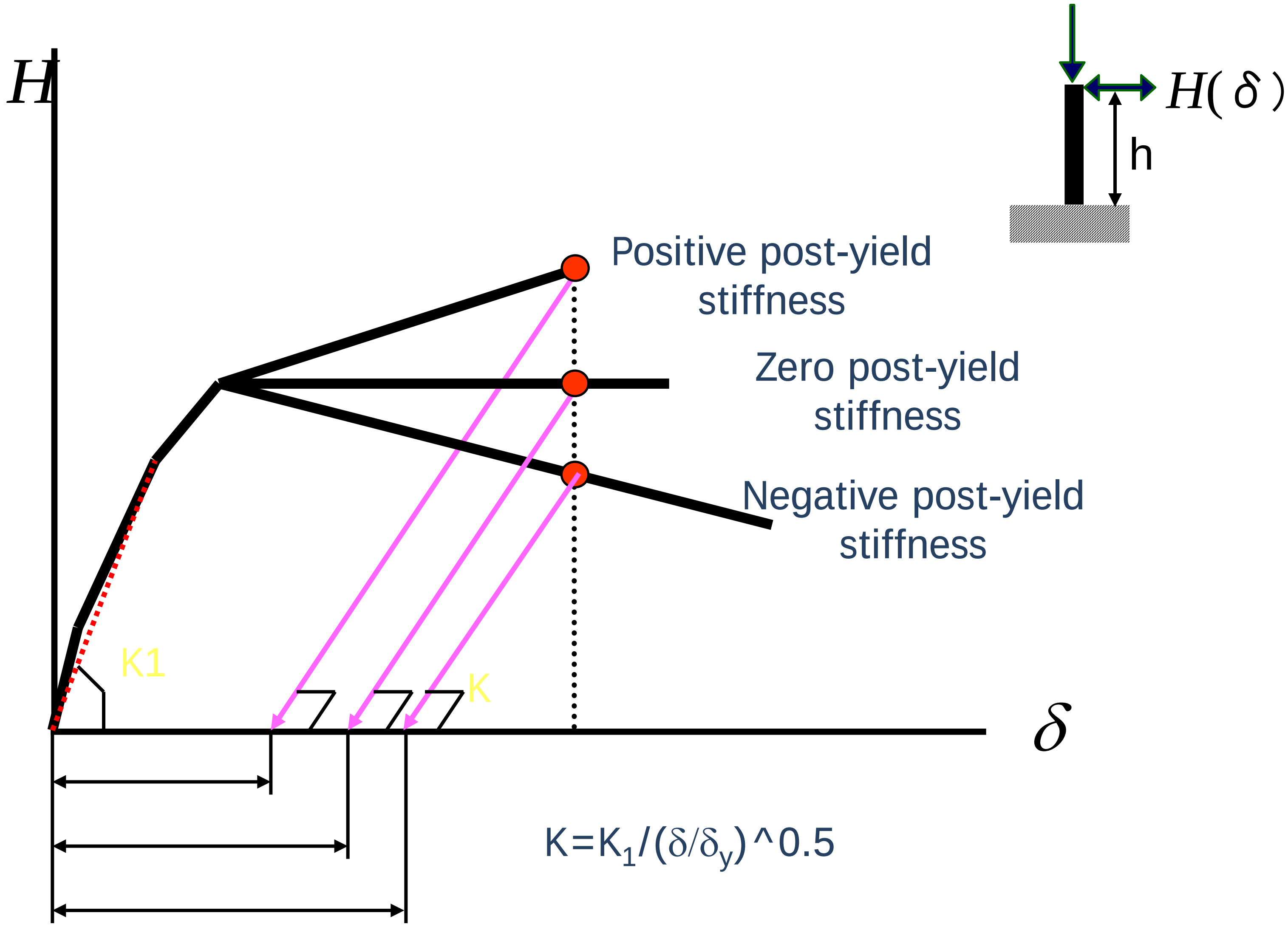
Seismic performance of FRP confined RC column FRP





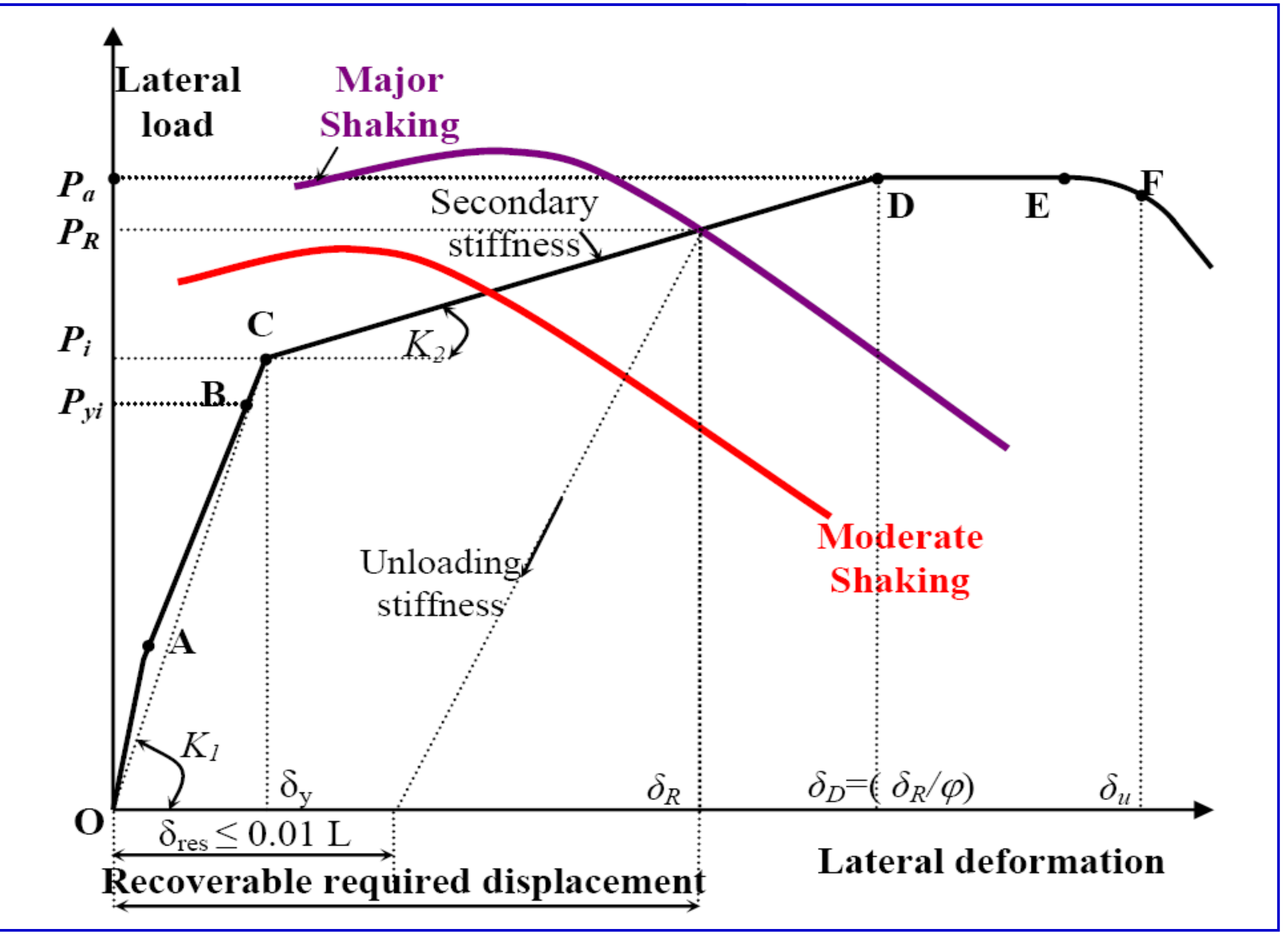
Column deficiency	Shear		Lap-splice		Flexural	
Cross-section	Circula	Rectangul	Circula	Rectangul	Circular	Rectangular
$\varphi = (\delta_{\delta res=0.01L}/\delta_D)$	0.53	0.89	0.591	0.672	0.565	0.686

Importance of Post-Yield Stiffness in Seismic Design



$K=K_1/(\delta/\delta_y)$^0.5

Design method of FRP confined RC column FRP



$$P_a \geq S_{es} W$$

$$S_{es} = S_s / \sqrt{2\mu_a - 1}$$

$$\mu_a = 1 + \frac{\delta_u - \delta_y}{\alpha \delta_y}$$

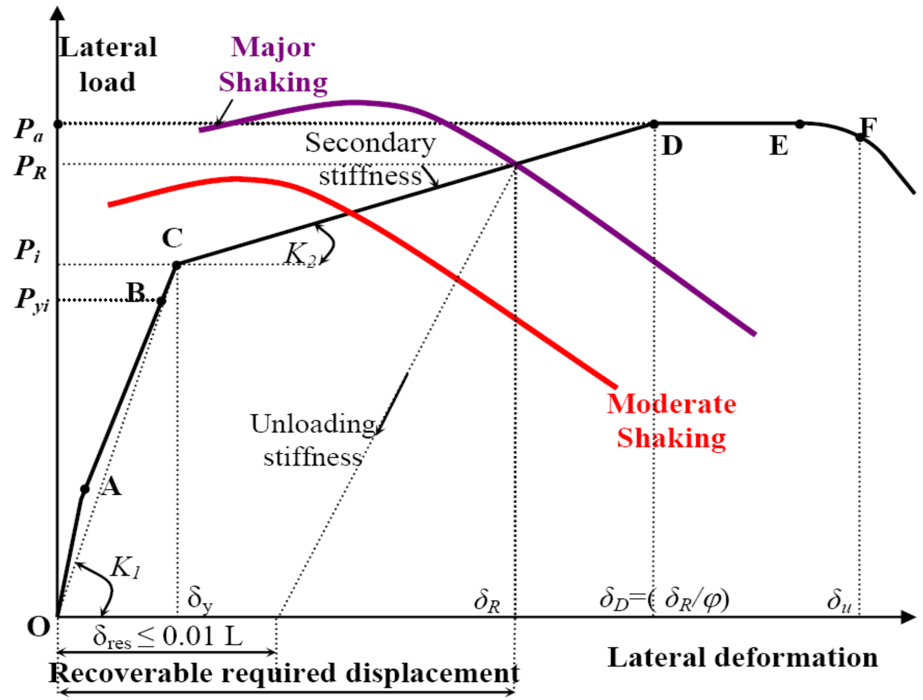
$$P_a = P_i \left(1 + 0.55 \frac{f_l}{f'_{co}} \right) = P_i \lambda$$

Assume the confinement ratio

$$P_R = P_i\left(1 + 0.55\varphi\frac{f_l}{f'_{co}}\right)$$

$$\mu_R = \frac{1}{2}\left\{\left(\frac{S_s W}{P_R}\right)^2 + 1\right\}$$

$$\delta_{u,req} = \delta_y\left\{\alpha\left(\mu_R - 1\right) + 1\right\}$$



$$\delta_{R\max} = \frac{0.01L}{C_R\left(1 - \frac{K_2}{K_1}\right)} + \delta_y$$

$$K_1 = \frac{P_i}{\delta_y}$$

$$K_2 = \frac{P_a - P_i}{\delta_D - \delta_y}$$

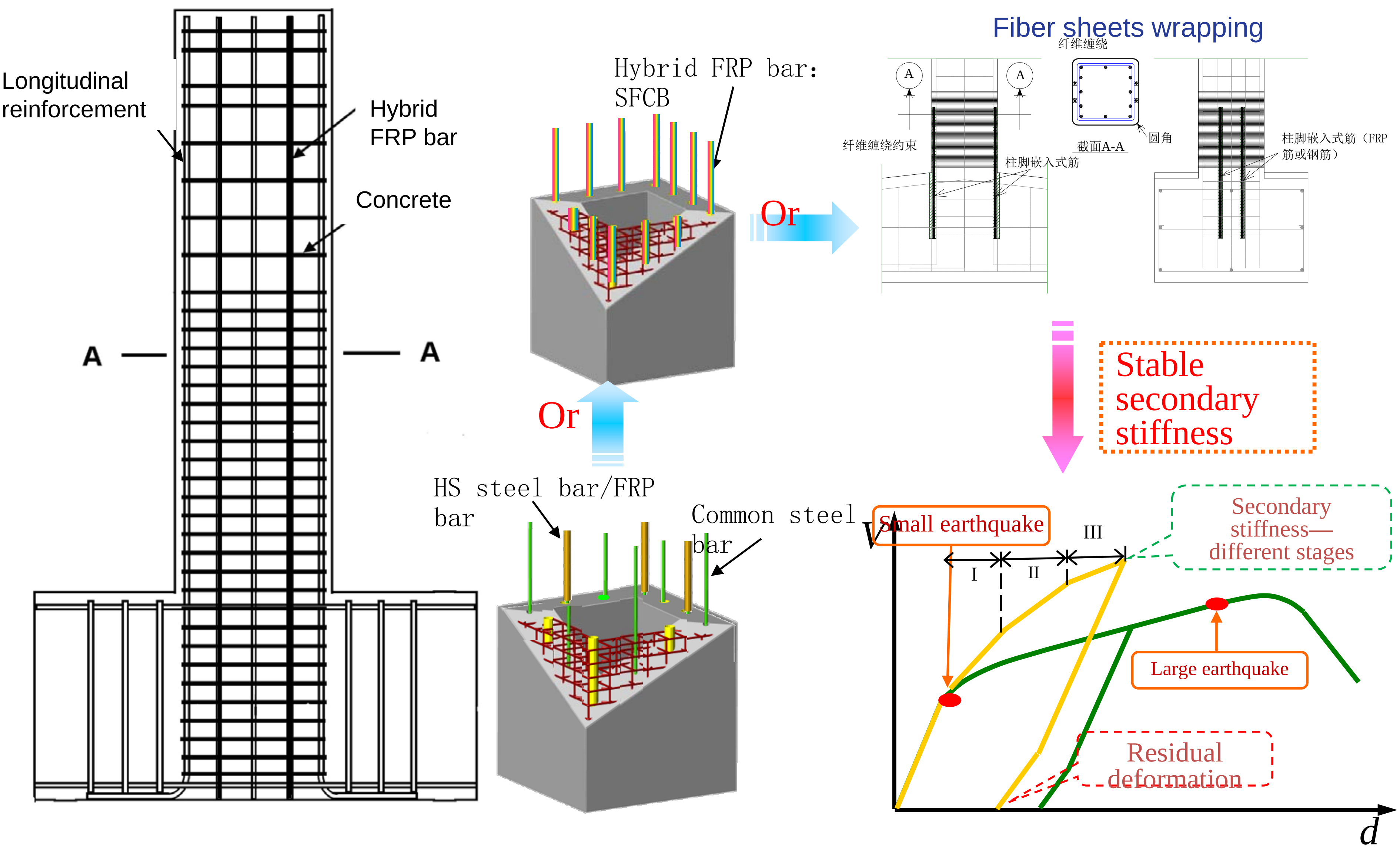
$$K_2 / K_1 = \frac{(\lambda - 1)}{\left(\frac{\mu_R}{\varphi} - 1\right)}$$

$$\delta_{R\max} = \frac{0.018L}{1 - \frac{(\lambda - 1)}{\left(\frac{\mu_R}{\varphi} - 1\right)}} + \delta_y$$

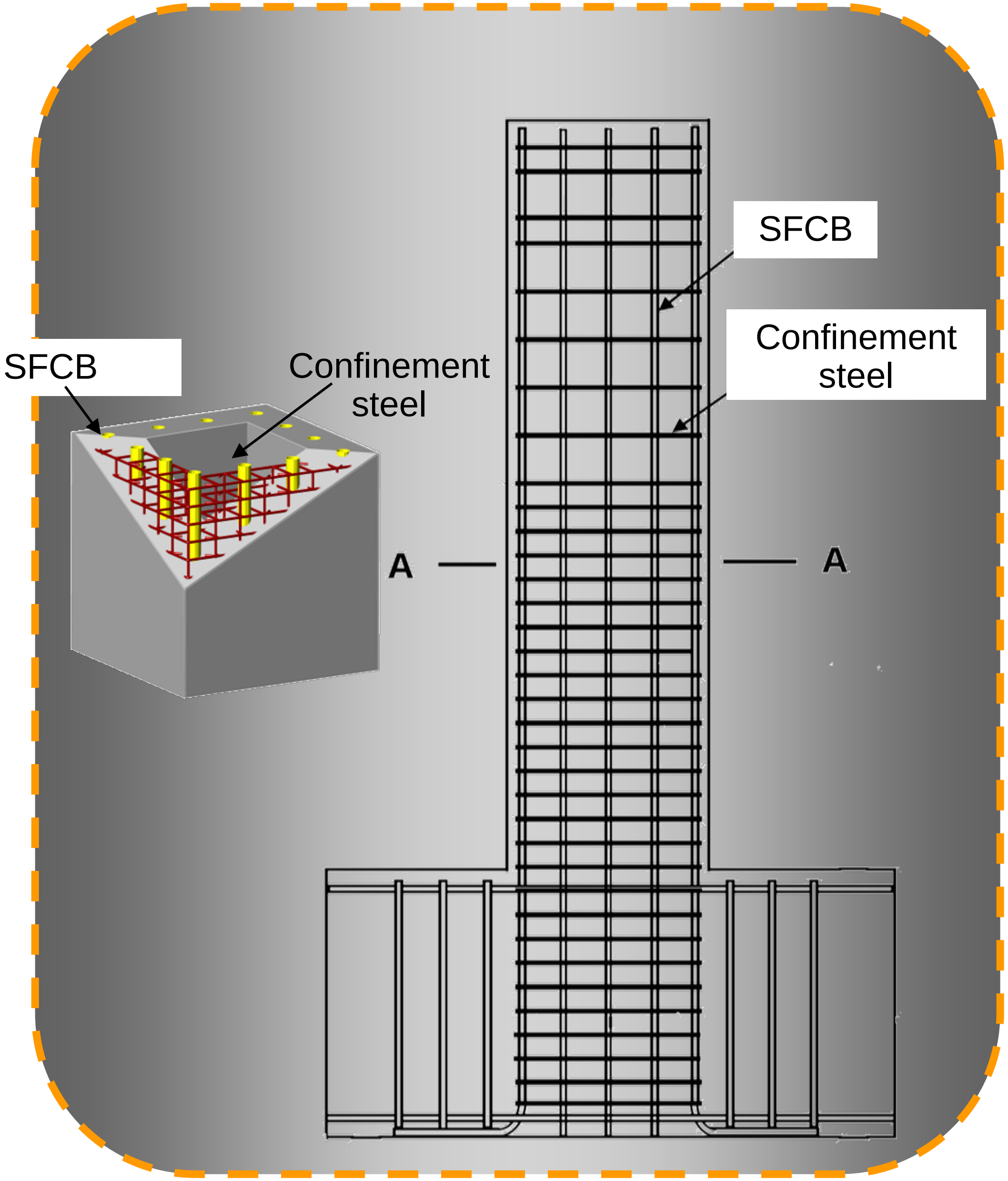
Check

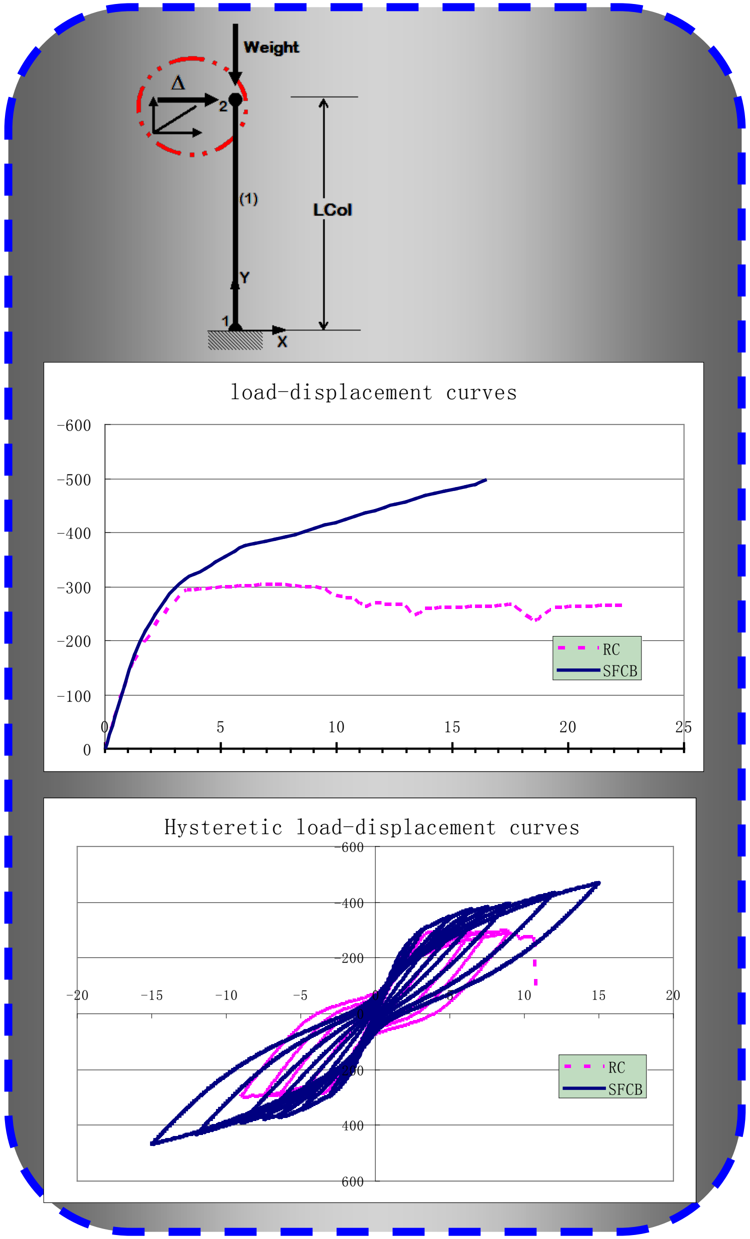
$$(\delta_R = \mu_R \delta_y) \leq \delta_{R\max}$$

New type damage-control aseismic structure



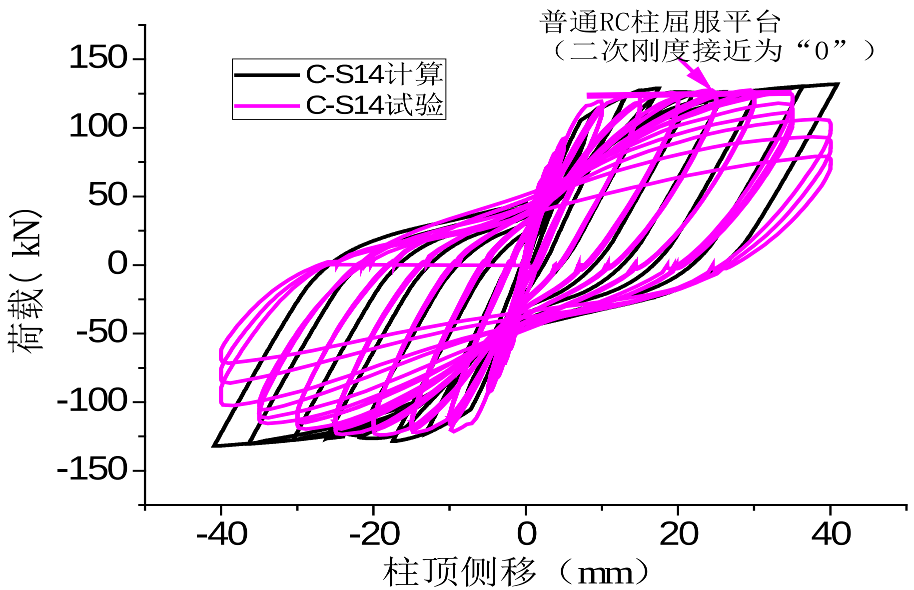
Numerical simulations on proposed column with SFCB



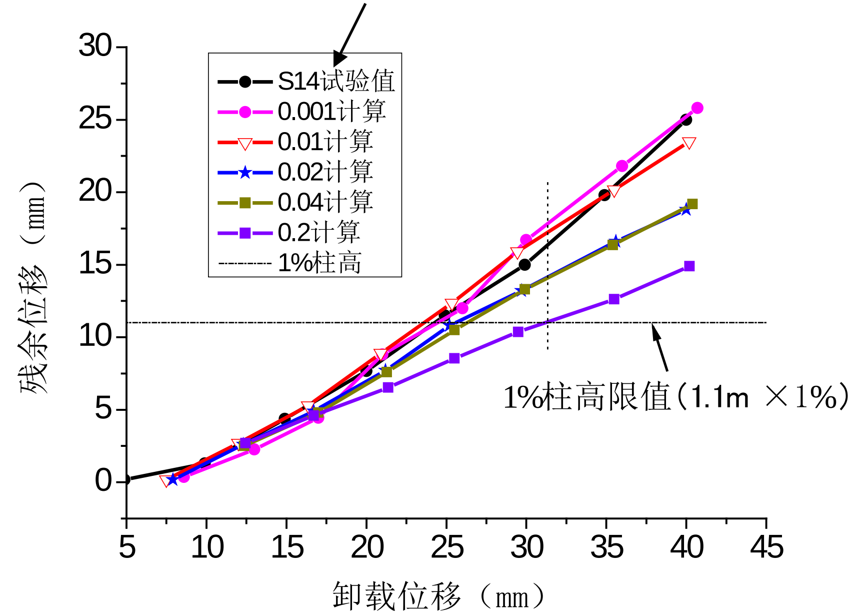


New type damage-control aseismic structure

Theoretical calculation of residual deformation of SFCB reinforced RC column



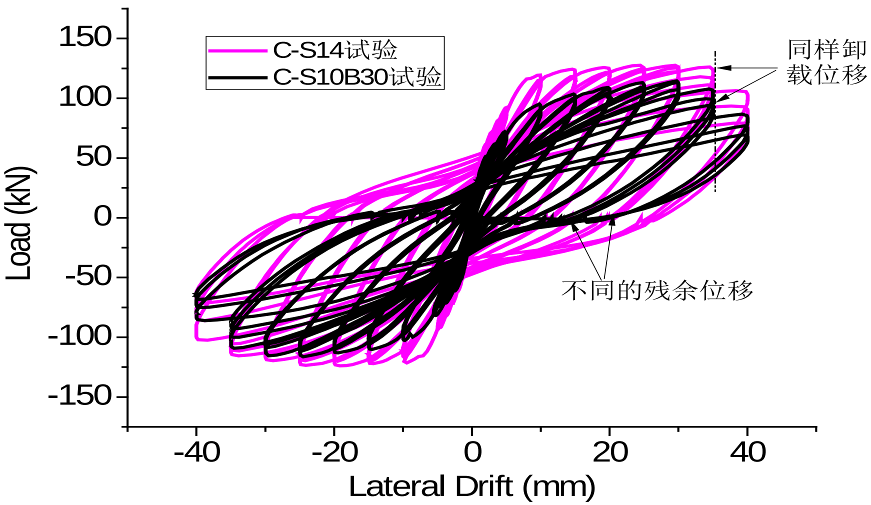
Experimental and theoretical hysteresis curves of common RC beams

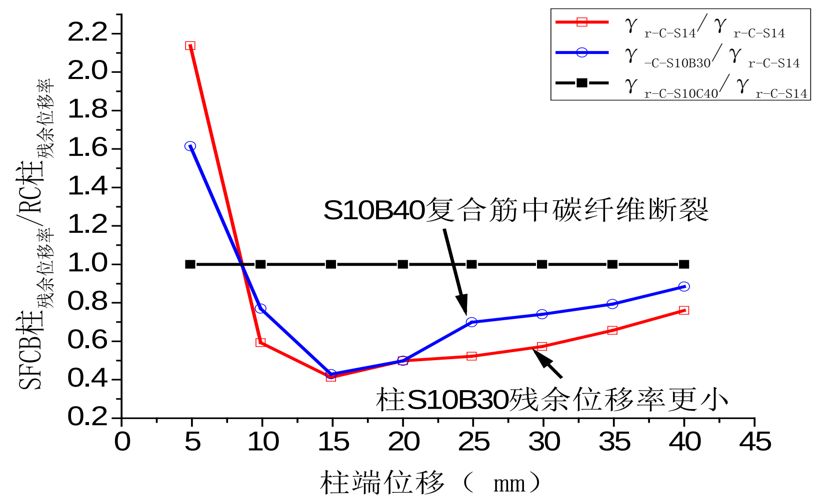


Comparison of residual deformation of SFCB reinforced column

New type damage-control aseismic structure

Comparison of residual deformation of SFCB column and normal RC column





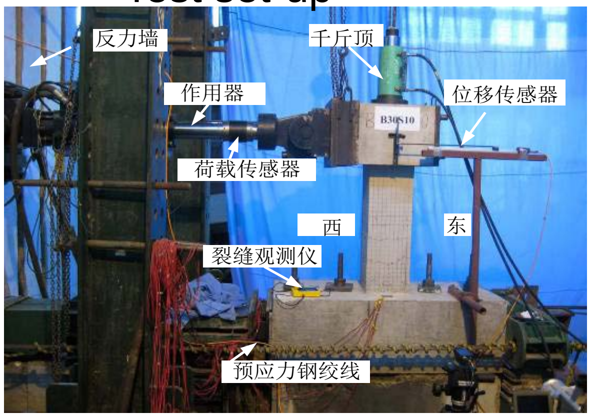
In small deformation, residual deformation of SFCB column is larger than that of RC column

In large deformation, residual deformation of SFCB column is smaller than that of RC column

In ultimate stage, with the fracture of FRP, similar residual deformation is shown for SFCB and normal RC column.

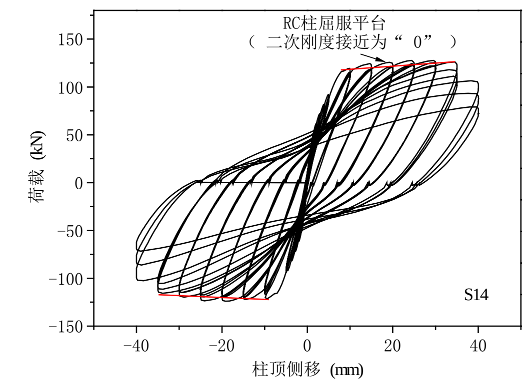
Experiment of SFCB strengthening RC column

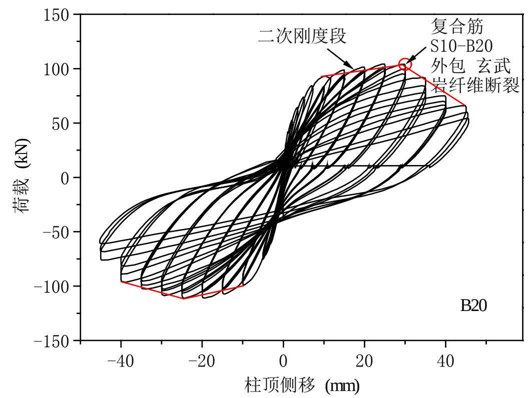
Test set-up

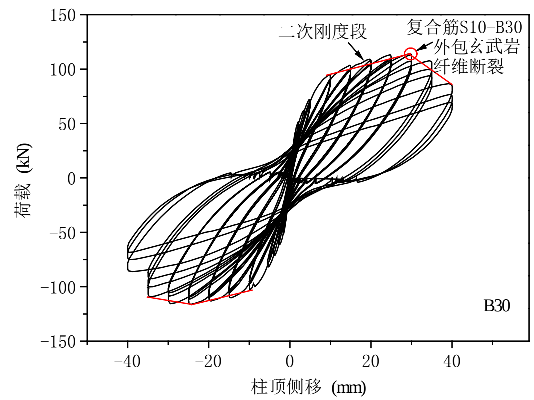


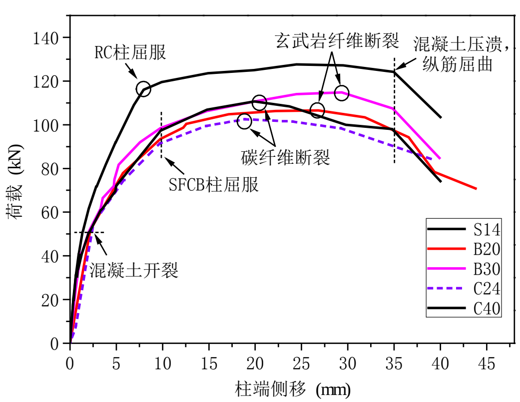
Concrete crush, rebar yield

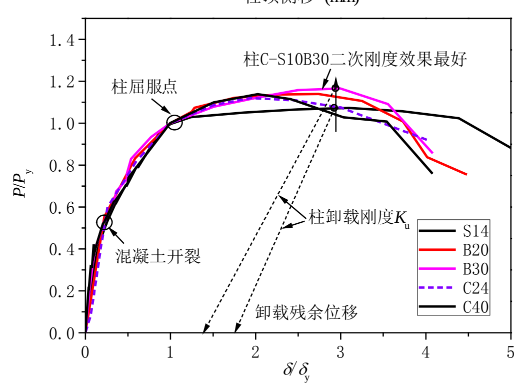
Partial fracture of fibers

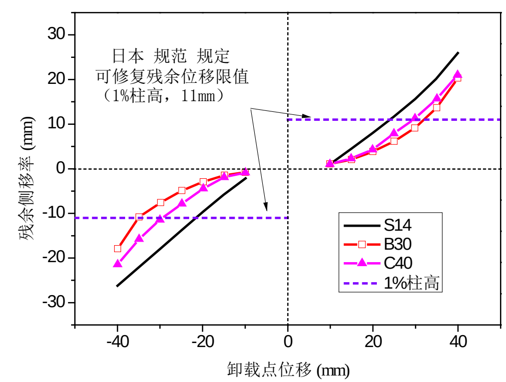




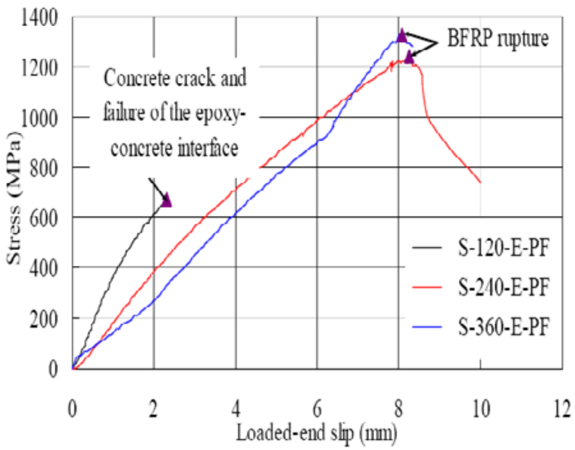


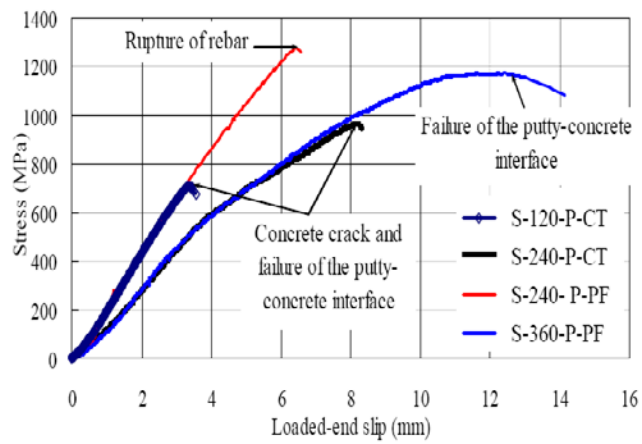


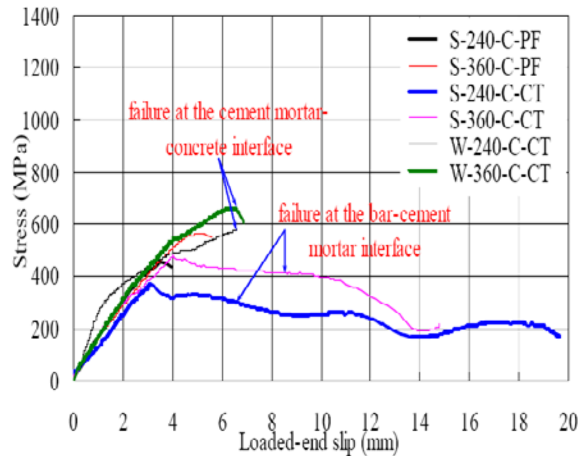




Bonding test of NSM BFRP bar in the column base








S-120-E-PF


S-240-E-PF

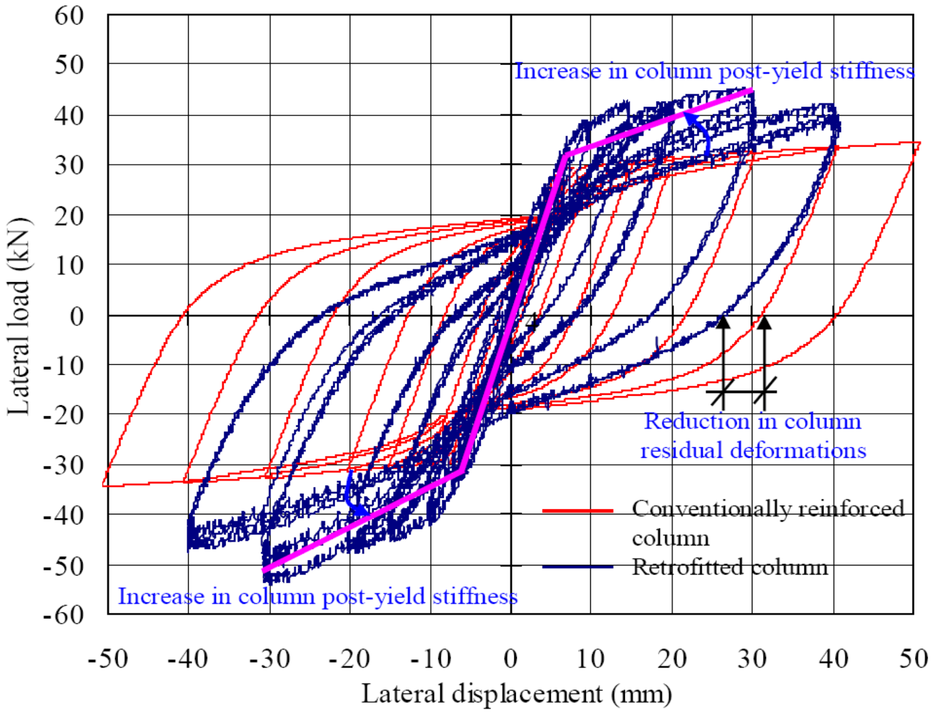

S-360-E-PF

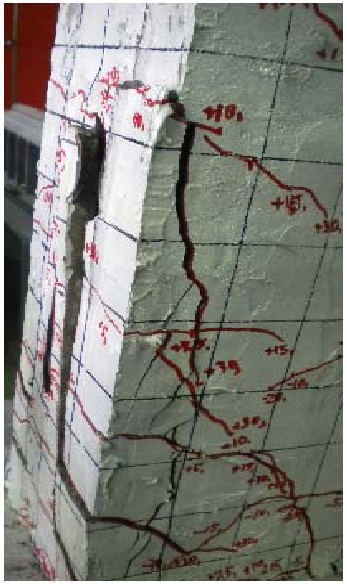

S-240-C-PF


W-240-C-CT


W-360-C-CT

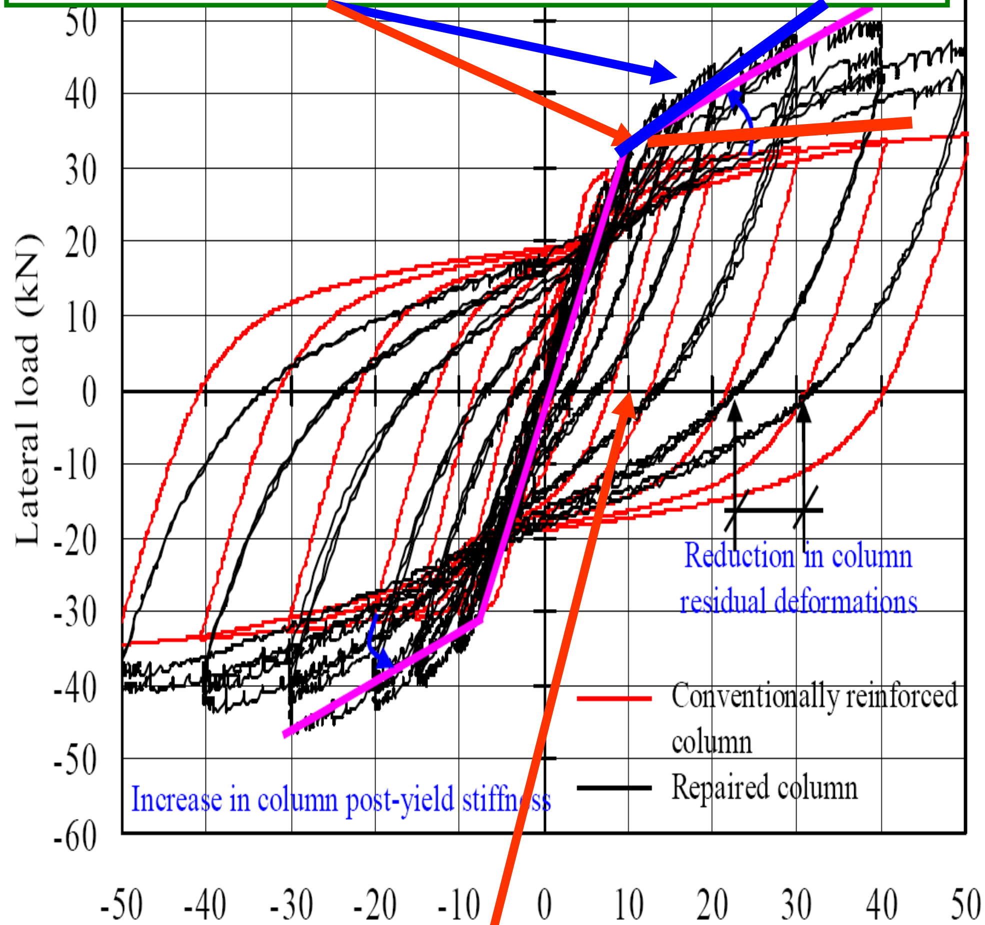
Strengthening effect of NSM BFRP bar in column base

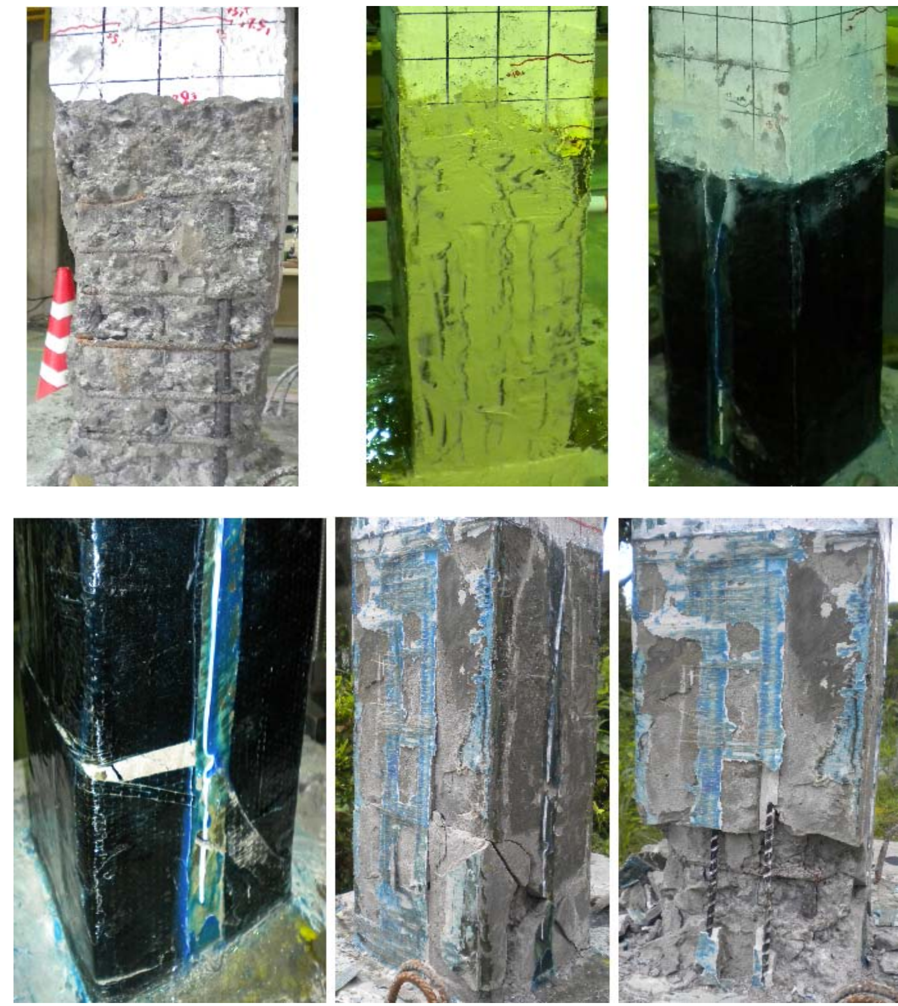




Strengthening of damaged RC column

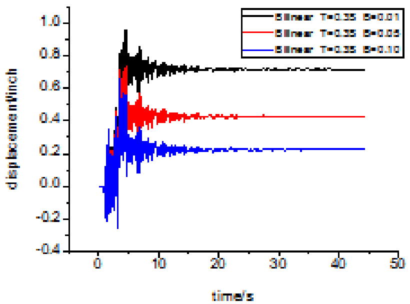
- Small secondary stiffness of RC column
- Secondary stiffness increase obviously



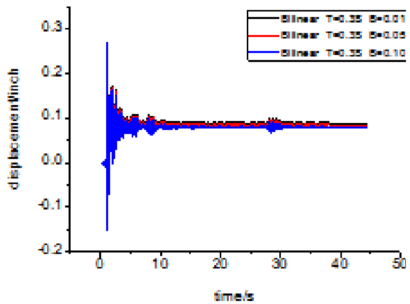


- Small residual deformation

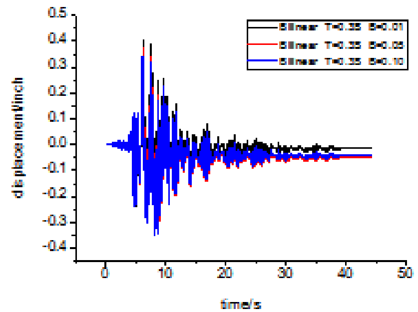
Dynamic response stability of different secondary stiffness structures



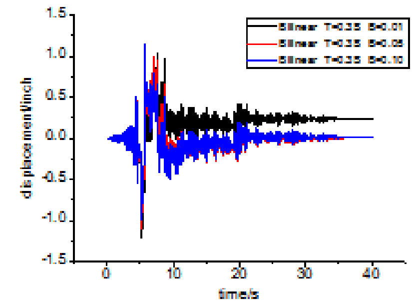
NGA0240



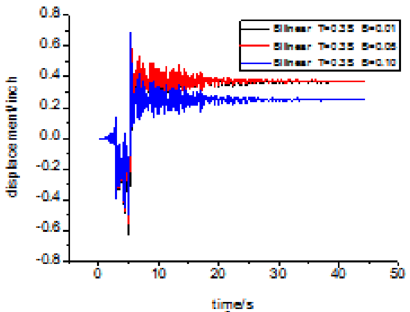
NGA0264



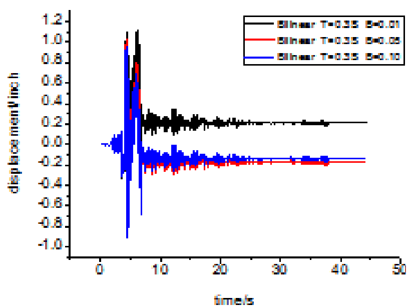
NGA0802



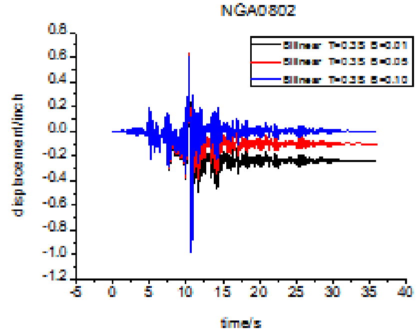
NGA0829



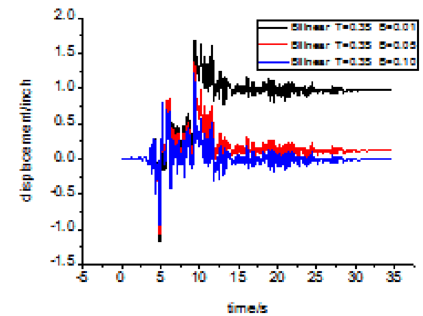
NGA0406



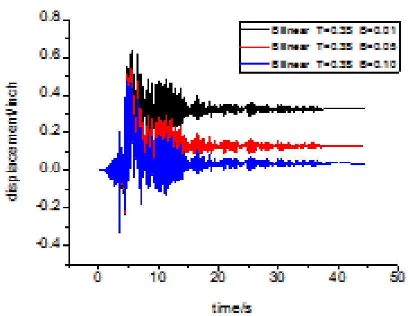
NGA0558



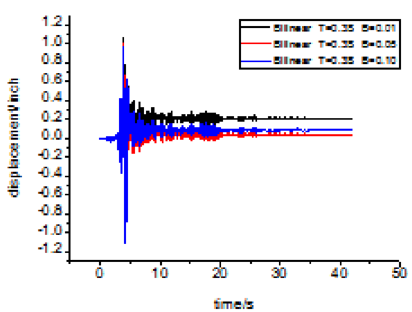
NGA1103



NGA1082



NGA0639



NGA0692

Stability of residual deformation under different:

- SDOF： sec. stiffness >5%；
- MDOF： sec. stiffness >3%。

Outline

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8. Summary and future work

Advanced FRP cables for integrated high performance long-span cable-stayed bridge

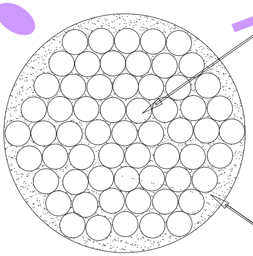
- ✓ **Disadvantages of conventional steel cable:**
  large sag effect, durability, etc

- ✓ **Limitations of current CFRP cables:**
  high cost, aerodynamic stability, etc

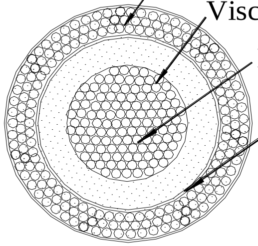
Solution

BFRP, hybrid basalt/carbon FRP, hybrid basalt/steel-wire FRP cables

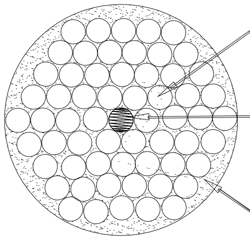
- High strength
- Light weight
- Fatigue and corrosion resistance
- Relative low cost



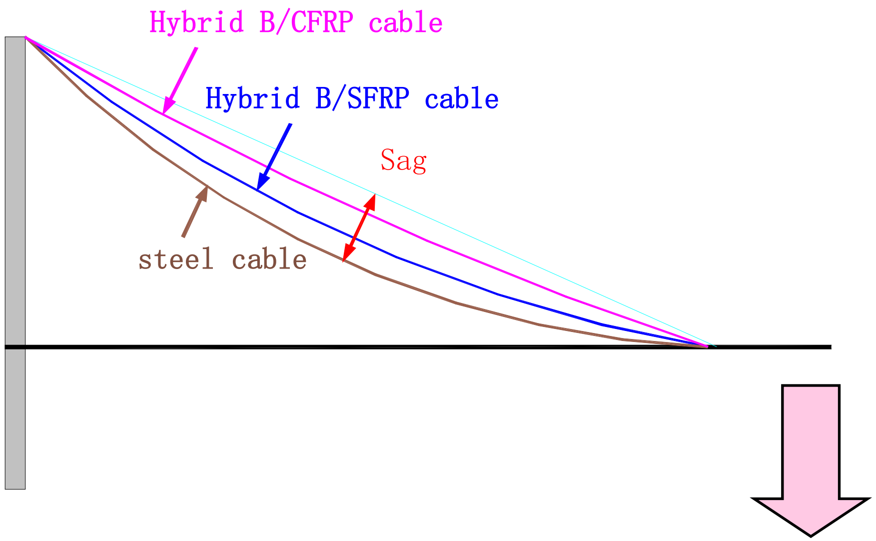
Smart damping

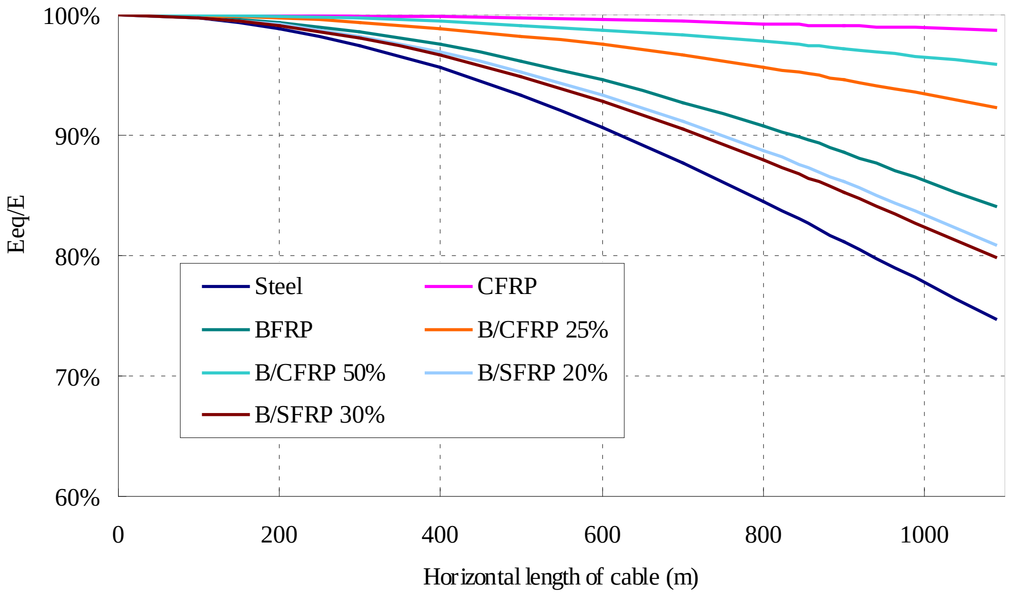


Smart sensing



Superior static and dynamic behavior in long-span cable-stayed bridge

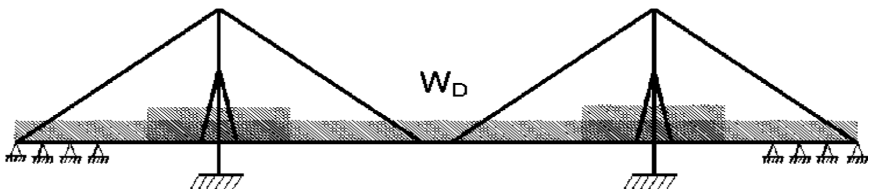


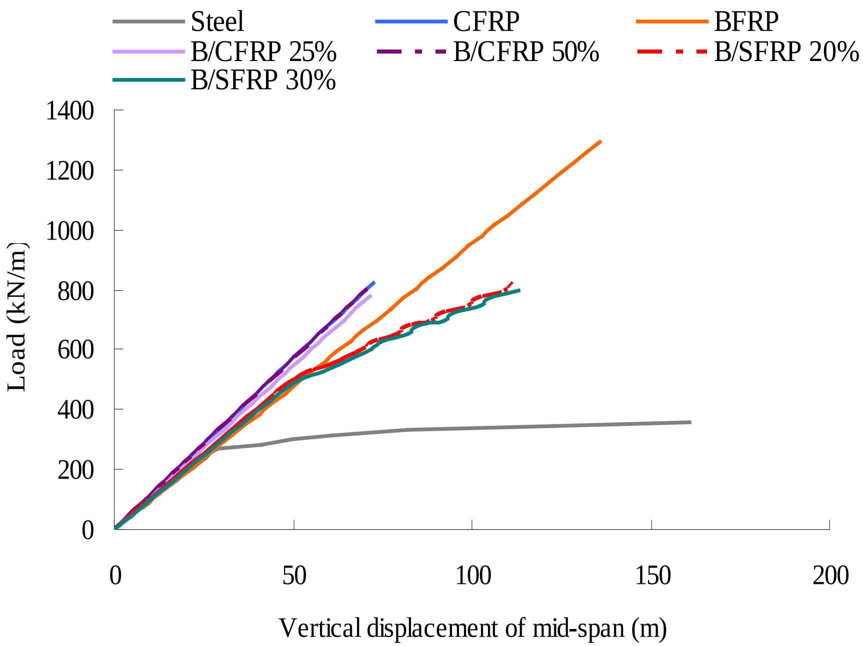


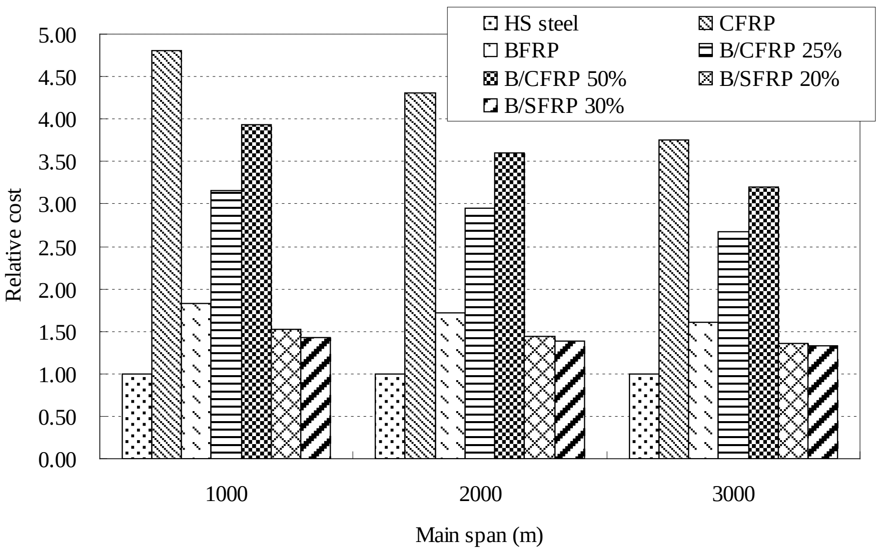
Reduce sag effect, increase efficieny

Equivalent modulus increase suitable for long span bridges

Superior static behavior in long-span cable-stayed bridge





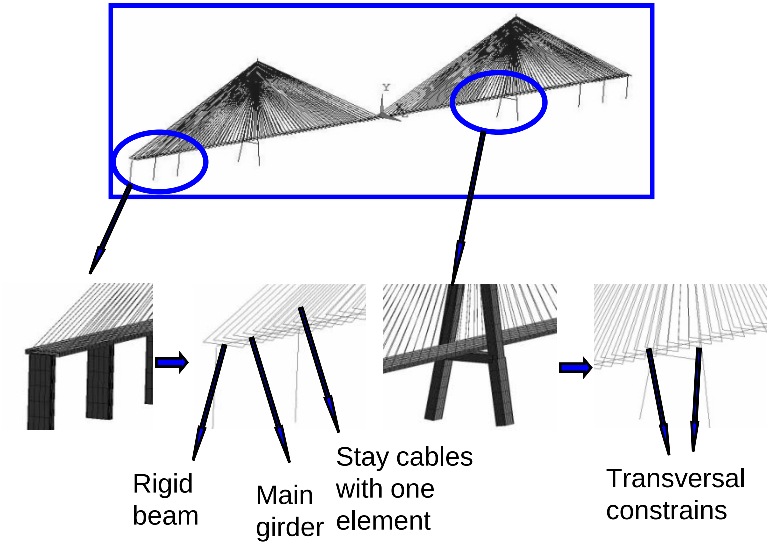


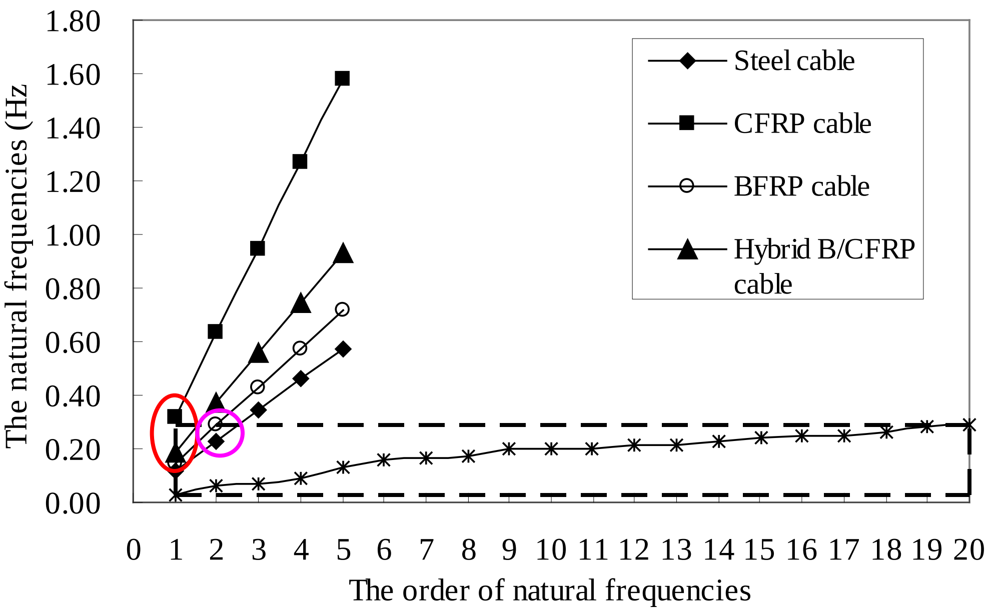
Superior static behavior compared with steel cable-stayed bridge

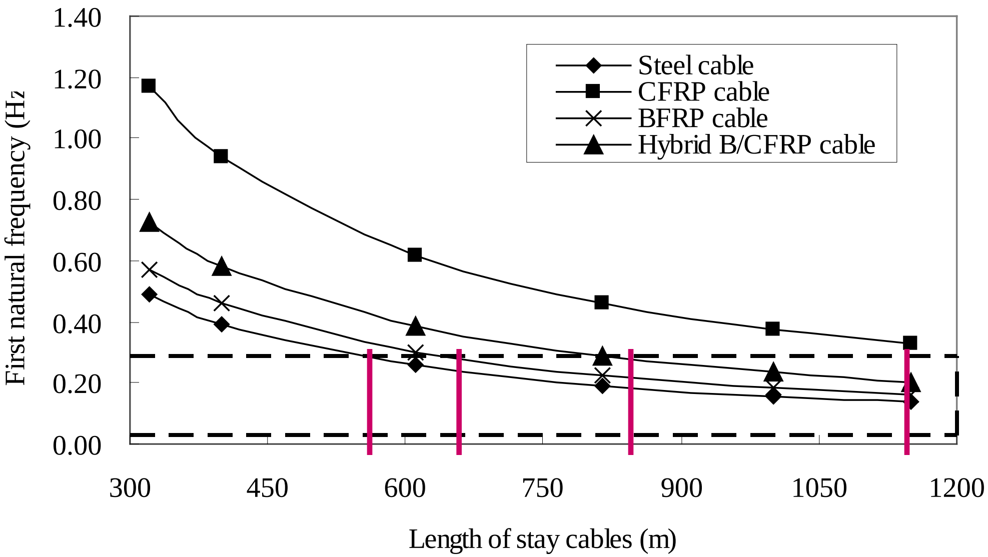
Cost comparable to steel cable-stayed bridge

Superior dynamic behavior in long-span cable-stayed bridge

Lower risk of resonance between cables and bridge





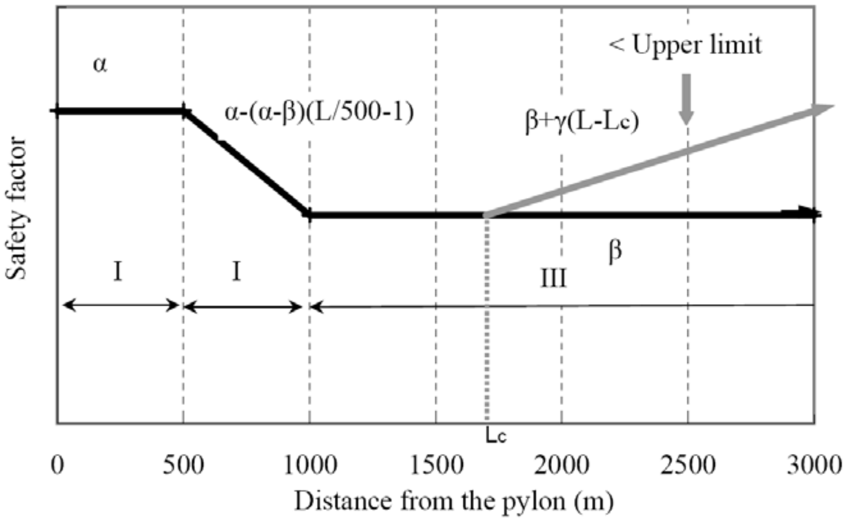


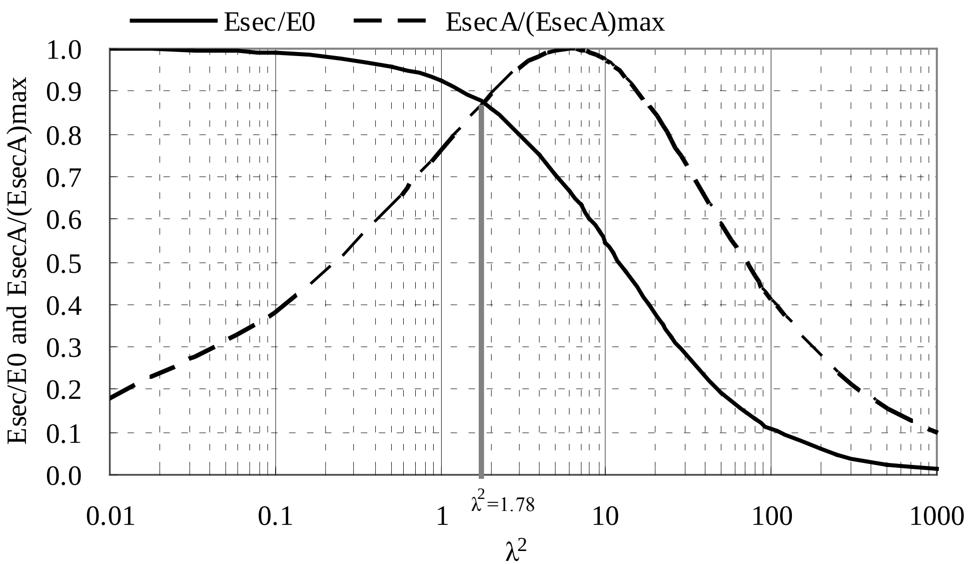
Possibility of resonance between bridges and the longest cables in different orders

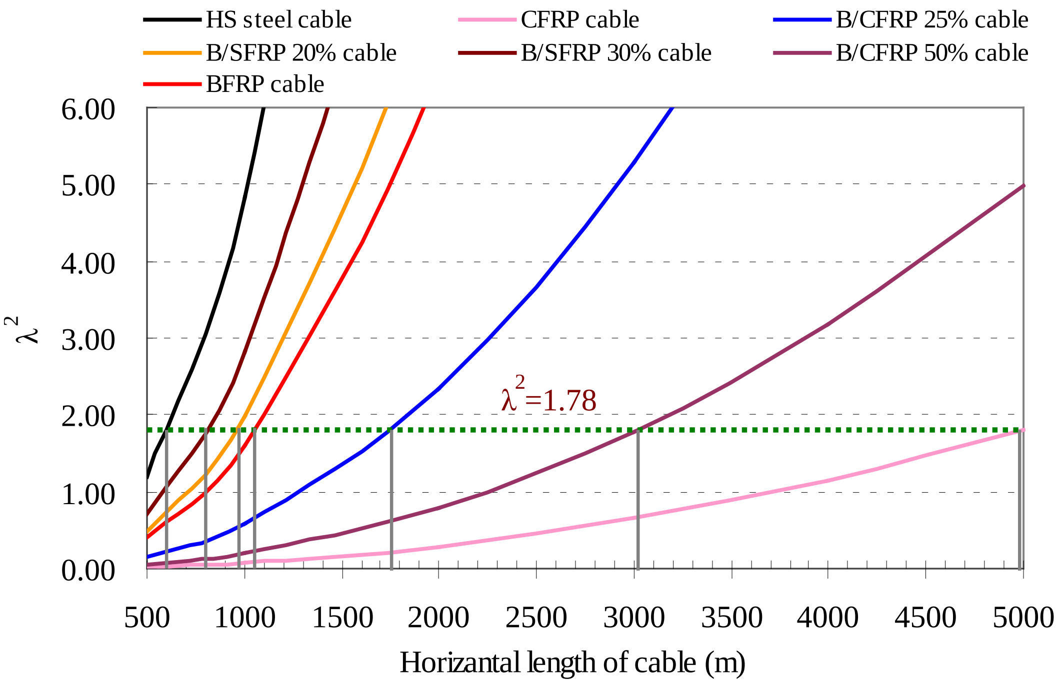
Possibility of resonance between bridges and cables in different lengths

Advanced FRP cables

applicable length for each kind of cable







Three-stage design method based on strength and stiffness efficiency optimization

Applicable length of different kinds of cables

A critical issue for FRP cables in long-span cable-stayed bridge

Cable length increase

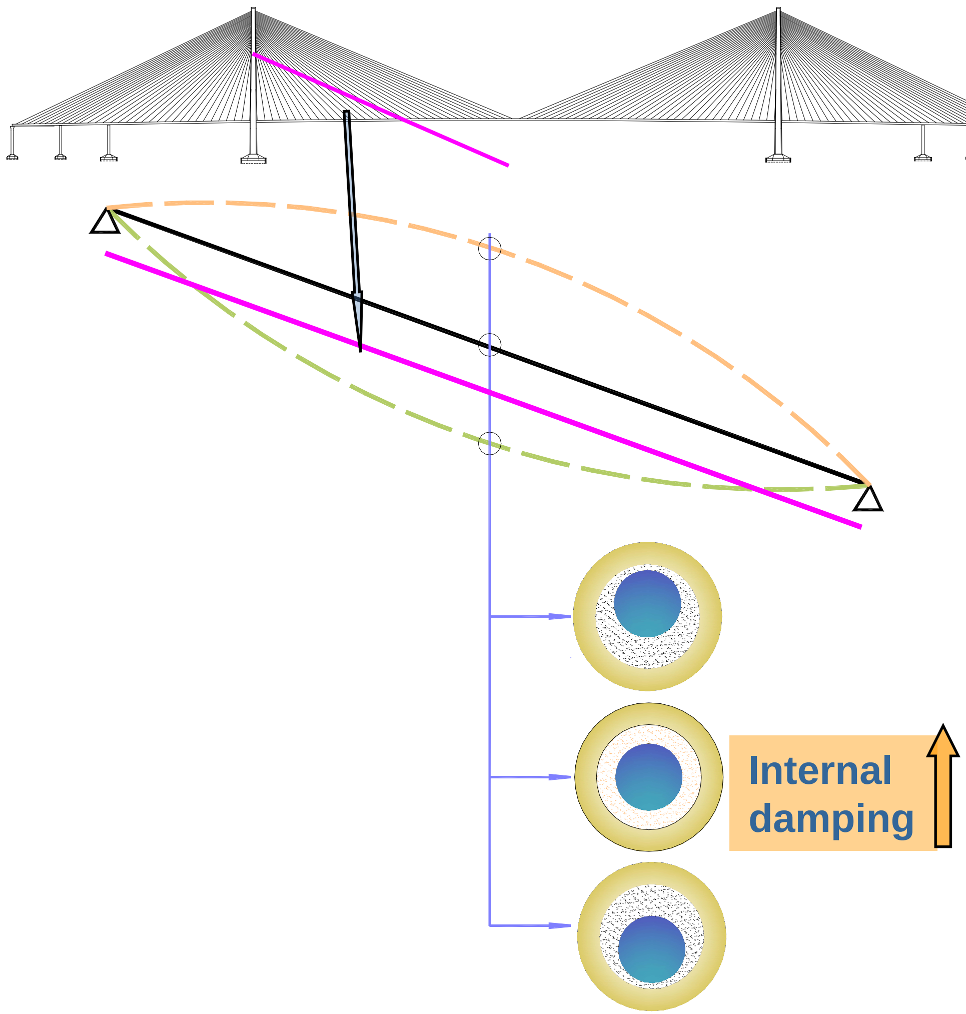
- **Scruton number** $S_c = \dfrac{2\delta m_e}{\rho D^2}$ — Aerodynamic stability
- **Wind effect** — Larger load
- **Natural freq** — Easier resonance

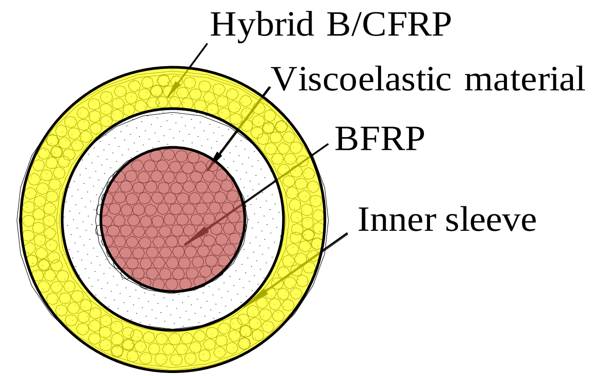
Thus, vibration will be a problem

Damping treatments are necessary

- Passive control (Internal damper / external damper) → **In usual, not effective for long cable**
- Active control → **Extra power or potentially unfavorable actuating**
- Semi-active control → **Under development**

Principle and Design along cross-section of cable



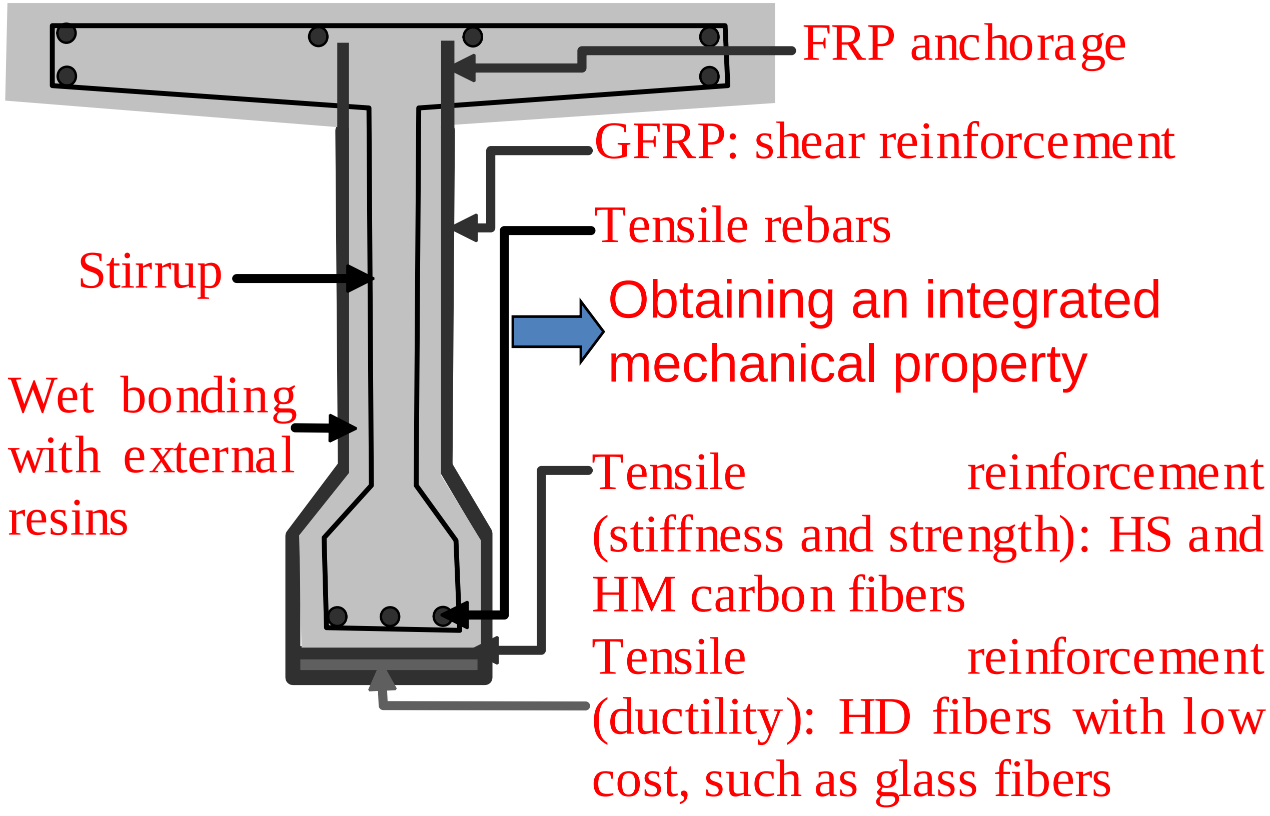


Smart damper design

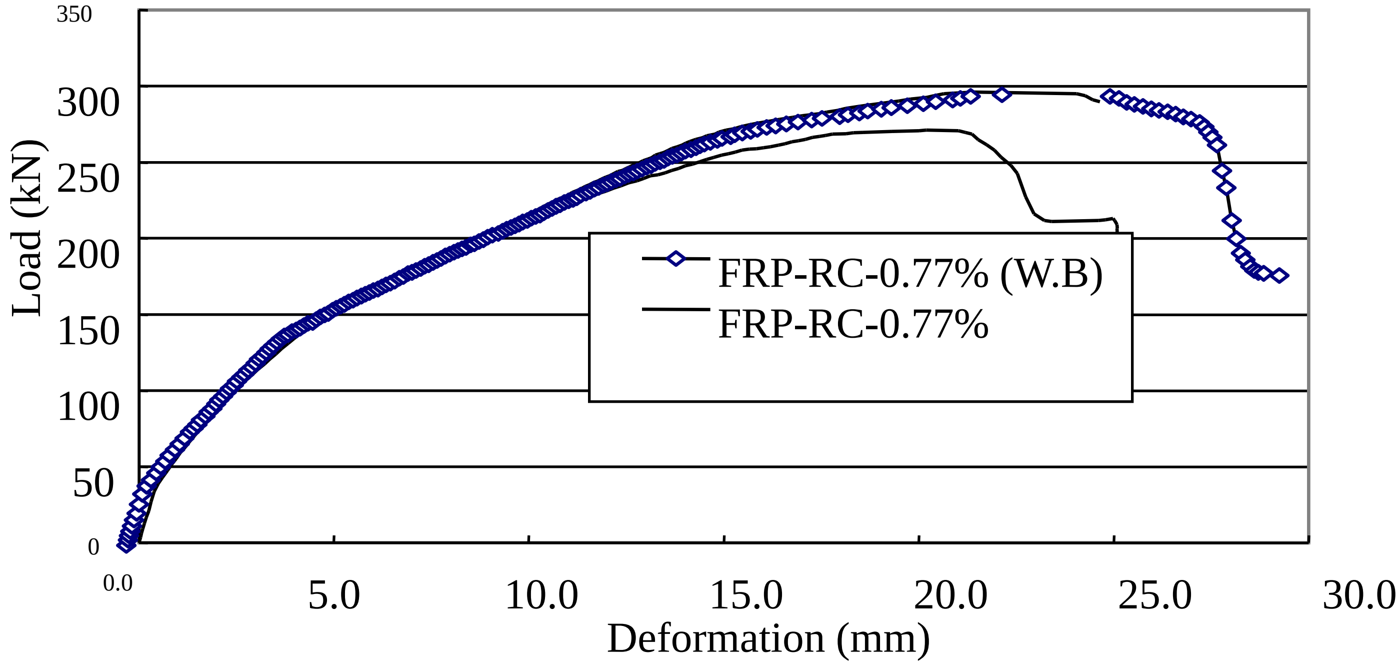
Inner cable } Different
Outer cable } natural freq.

Dissipating vibration energy by interaction between inner and outer cables ⇐ **Compression of viscoelastic material**

Integrated high performance composite beam



Performance confirmation of wet-bonding technique



FRP-RC composite structure

Vacuum assisted resin infusion (VARI) for FRP profiles


Fiber laying

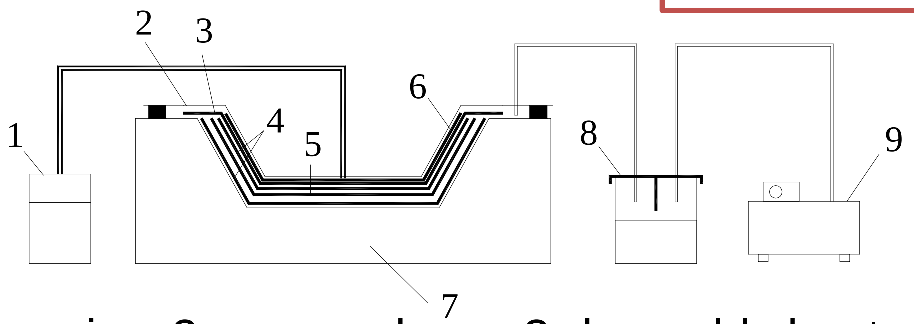

Demould sheet


Diversion medium


Seal bag


Pipe for vacuum

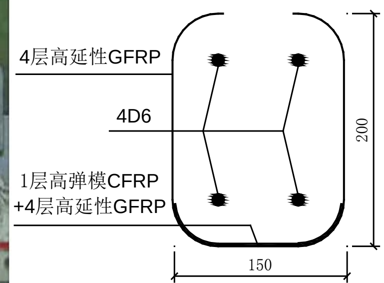
Production procedure



1-resin； 2-vacuum bag； 3-demould sheet ； 4-fibers； 5-core material； 6- Diversion medium； 7-mould； 8-resin collector； 9-vacuum pump

FRP-RC composite structure

Wet-bonding composite beam



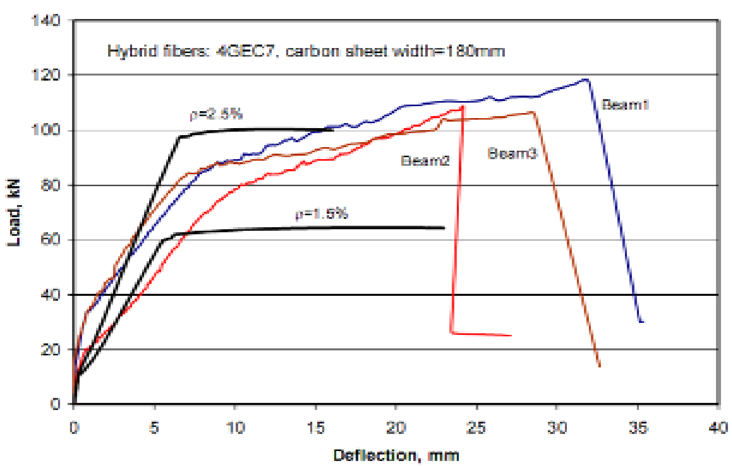
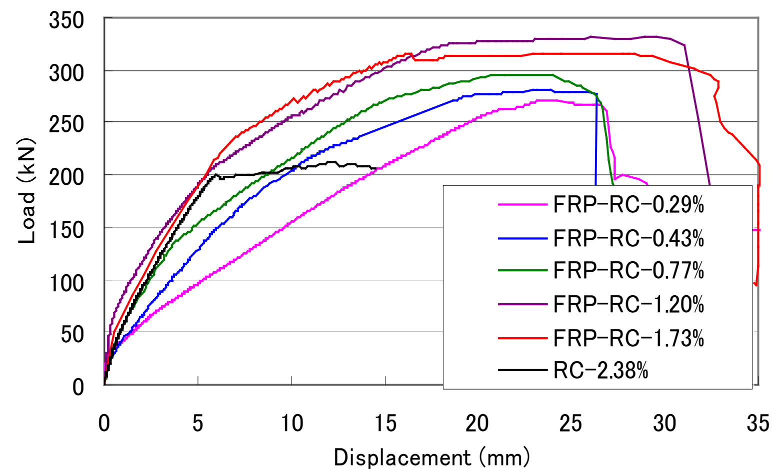
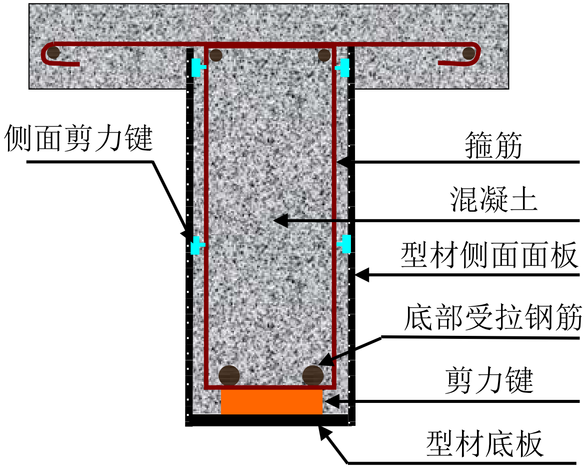


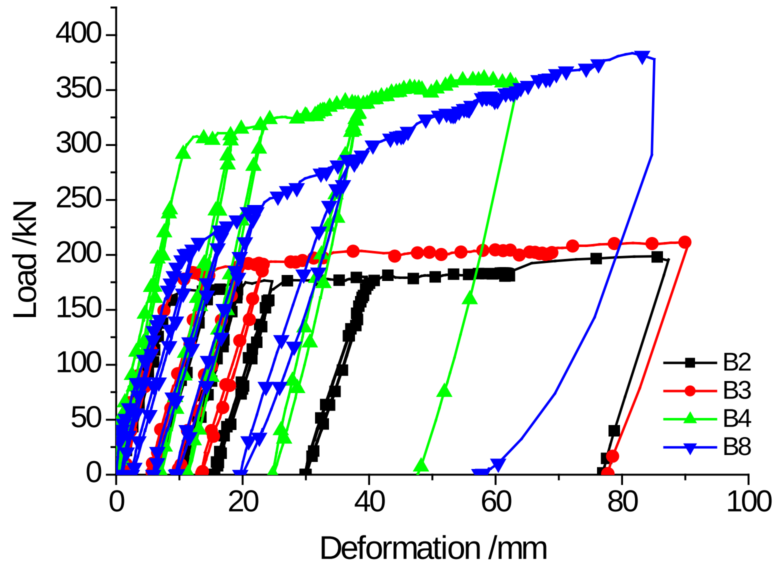
Fig. 5: Typical load – deflection curves of FRP-concrete composite beams



FRP-RC composite structure

Wet-bonding plus shear studs composite beam





- ➢ reliable bonding of interface between concrete and FRP
- ➢ superior flexural behavior under fatigue loads

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WHY INTELLIGENT INFRASTRUCTURES?

ENVIRONMENT

HUMAN

INFRASTRUCTURE

SUSTAINABLITY

Structure	建（けんken）
Strong and Ductile	堅（けんken）
Healthy and Durable	健（けんken）
Sensing and Inspections	検（けken）
Reduction of Life Cycle Cost	倹（けんken）
Unexpected Failures or Disasters	険（けken）
Ecology and Environment	圏（けんken）
Smart	賢（けんken）

建・堅・健・検・倹・険・圏・賢

Intelligent Infrastructure System(What?)
(Intelligent Infrastructure+Secure Space)

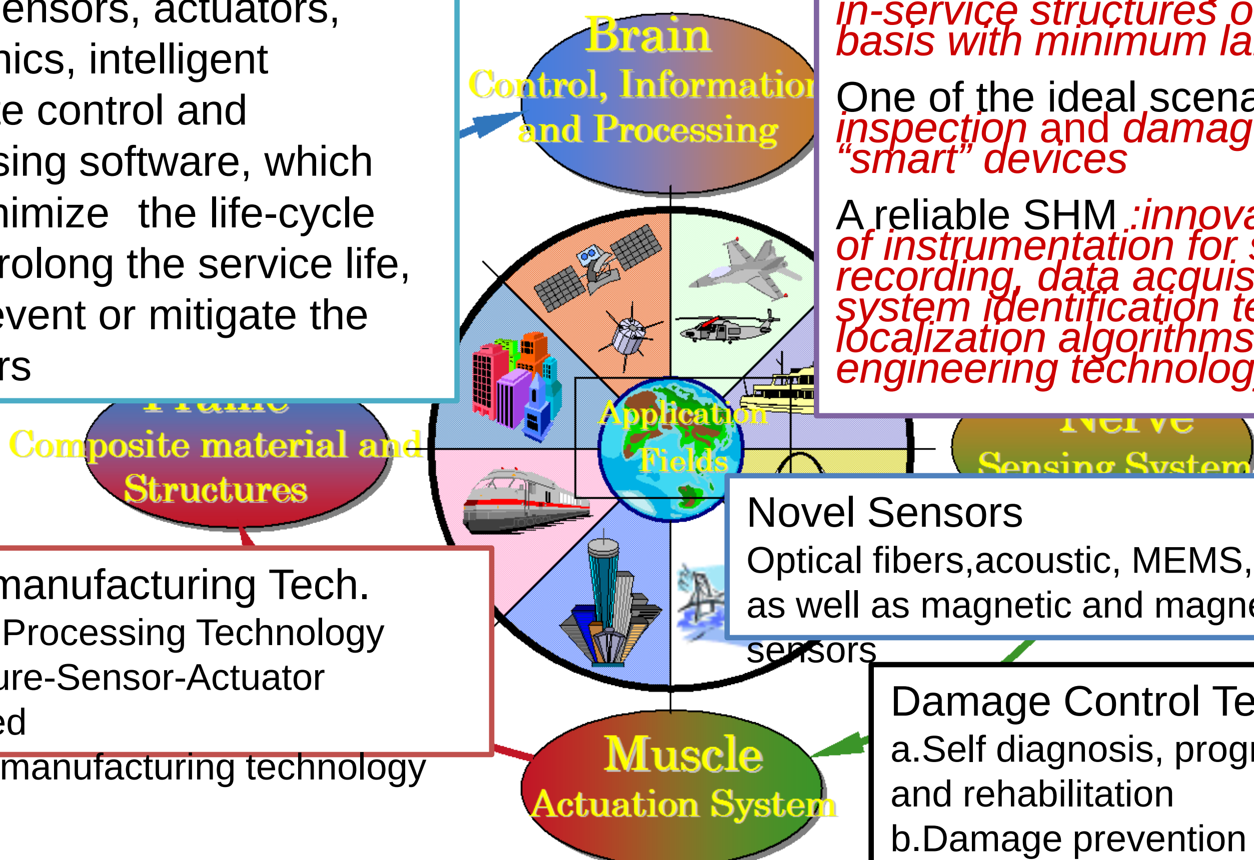
Intelligent Infrastructure will be made of multi-functional materials integrated with smart sensors, actuators, electronics, intelligent compute control and processing software, which can minimize the life-cycle costs prolong the service life, and prevent or mitigate the disasters

Structural Health Monitoring(SHM)

The essence and definition of SHM:*measurement, inspection, and assessment of newly constructed and/or in-service structures on a continuous basis with minimum labor requirement*

One of the ideal scenarios:*real-time inspection and damage detection through "smart" devices*

A reliable SHM :*innovative improvement of instrumentation for sensing and recording, data acquisition technology, system identification technique, damage localization algorithms and civil engineering technology*



Novel Sensors

Optical fibers,acoustic, MEMS, PZT, composite fibers as well as magnetic and magnetostrictive type sensors

Smart manufacturing Tech.

a.Smart Processing Technology
b.Structure-Sensor-Actuator integrated system manufacturing technology

Damage Control Techniques

a.Self diagnosis, prognosis, healing, repair and rehabilitation
b.Damage prevention and mitigation

Actuator materials and elements

a.Ceramic, fiber actuators
b.High-performance shape memory alloy

Active and Adaptive Structural System

.Adaptive control system for smart large-scale and complex structures

Issues and challenges in infrastructure

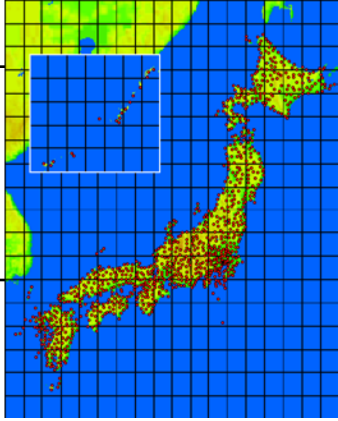
- **Seismic behavior** — Reparability under moderate earthquake No collapse under strong earthquake
- **Durability** — Steel structures, concrete structure due to cracks
- **Fire resistance** — Steel structures
- **Safety** — Conventional construction without self-diagnosing and self-monitoring
- **SHM** — Difficulty in long-distance distribution of conventional SHM methods

Advanced FRP + Advanced FOS

Safety + Durability

Urban scale expansion・High density

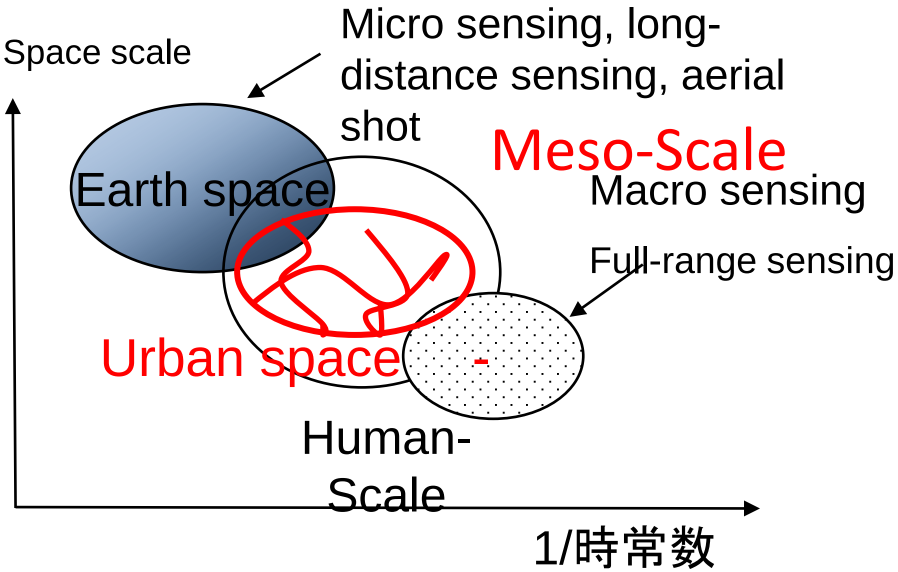
＝Vulnerability↑



K-net Earthquake detection

Earthquake, typhoon, torrential rain, extreme temperature, terrorism…..

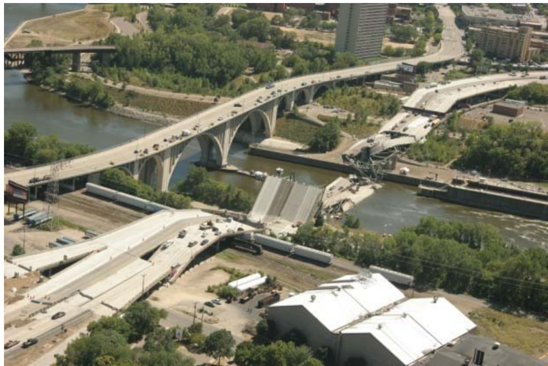
Risk＝Danger X Vulnerability



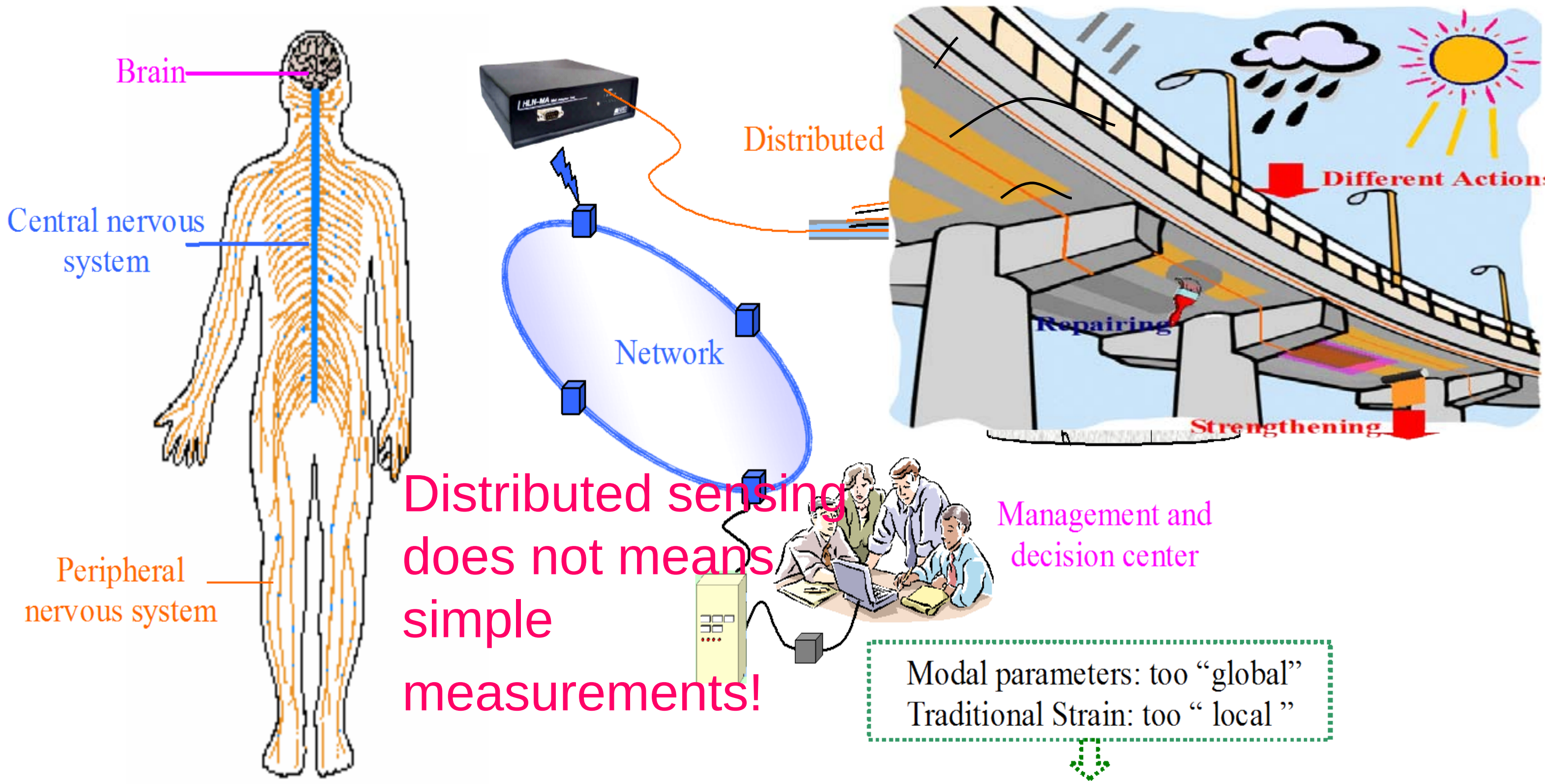
Sensing and monitoring of risk, danger and vulnerability

Evaluation of urban system in terms of assumptions

Safety



CHALLENGES IN Early Diagnosis and Long-term Prognosis Solution: DISTRIBUTED SENSING TECHNOLOGIES



Human nervous system

Distributed sensing system

Distributed sensing does not means simple measurements!

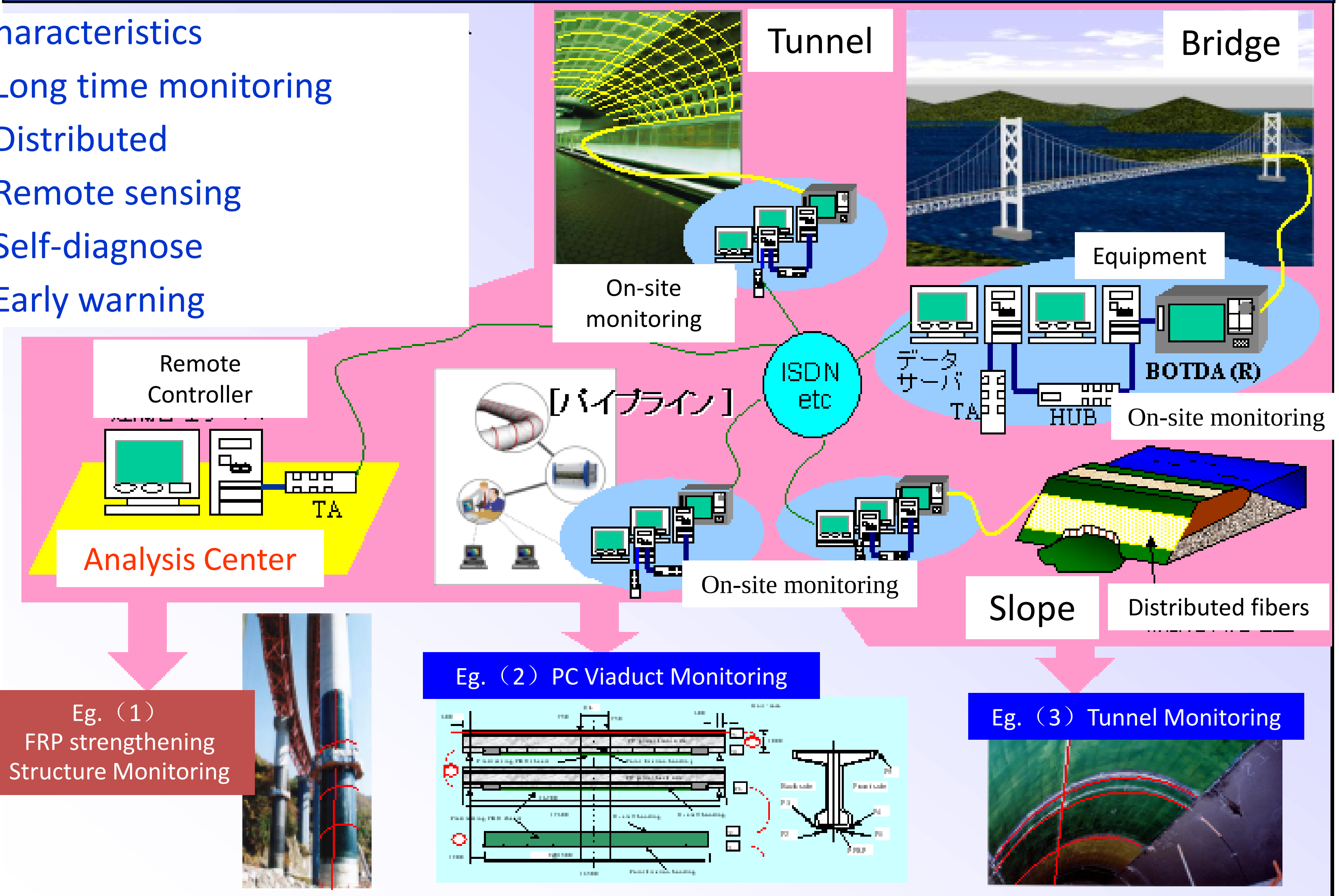
How to realize a distributed sensing for damage detection

1. Very dense distribution of using smart point sensors –useful ?
2. *Continuous or partially continuous wiring of using line Macro strain sensors including long –gauge sensors – natural !*

Distributed Remote Monitoring for Urban Systems

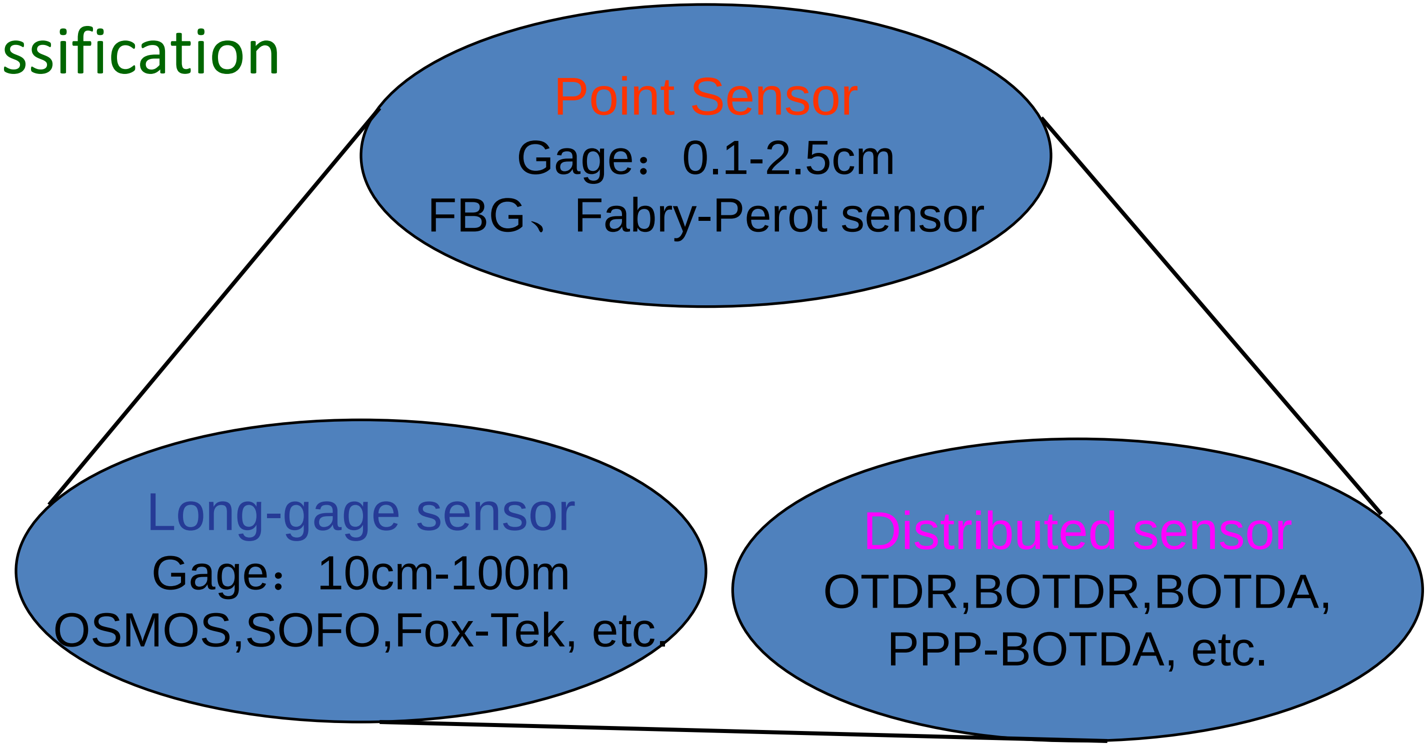
Characteristics

- Long time monitoring
- Distributed
- Remote sensing
- Self-diagnose
- Early warning



High Resolution Fiber Sensing Technology

■ Classification



■ Characteristics

- ✧ Robust to noises
- ✧ Easy for deployment
- ✧ Fast transmission

■ Quantities to be monitored

- ✧ Structural stress, displacement
- ✧ temperature, humidity
- ✧ Frequency ▪dynamic stress spectra
- ✧ Crack▪plastic stress▪damage
- ✧ dynamic and static loads
- ✧ Chemistry quantities such as PH

Fiber optic sensors

FOS

Transduction mechanism
- Intensity
- Interferometric
  - Phase
  - Frequency
  - (e.g.Mach-Zehnder, Michelson, Fabry-perot sensor)
- Spectrometric (e.g. FBG)

Application
- Physical sensors
- Chemical sensors
- Bio-medical sensors

Sensing manner
- Extrinsic
- Intrinsic

Sensor placement
- Localized
- Multiplexed (e.g. multiplexed FBG sensor array)
- Distributed (e.g. BOTDR, BOTDA)

	FBG	Brillouin	FP	FOPS	LCDS
Linear response	yes	yes	yes	yes	yes
Absolute measurement	yes	no	yes	yes	yes
Range to resolution	high	low	high	low	high
Mechanical strength	high	high	low	high	High
Multiplexing/Distributing	M	D	M	M	M
Dynamic sampling rate	high	low	high	low	low
Potential cost	low	high	low	low	low

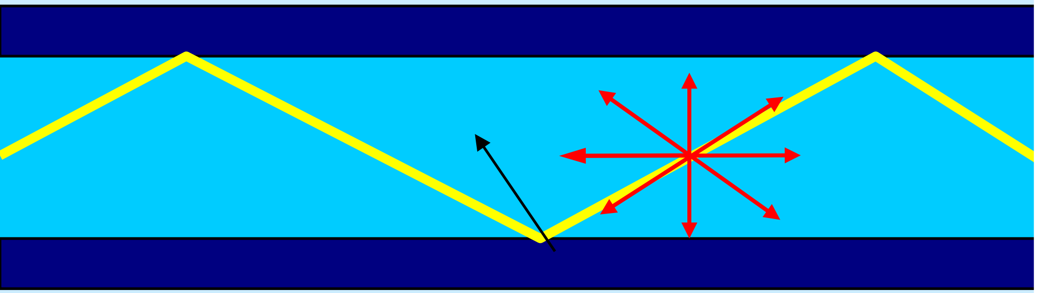
Distributed Fiber Optics Sensing

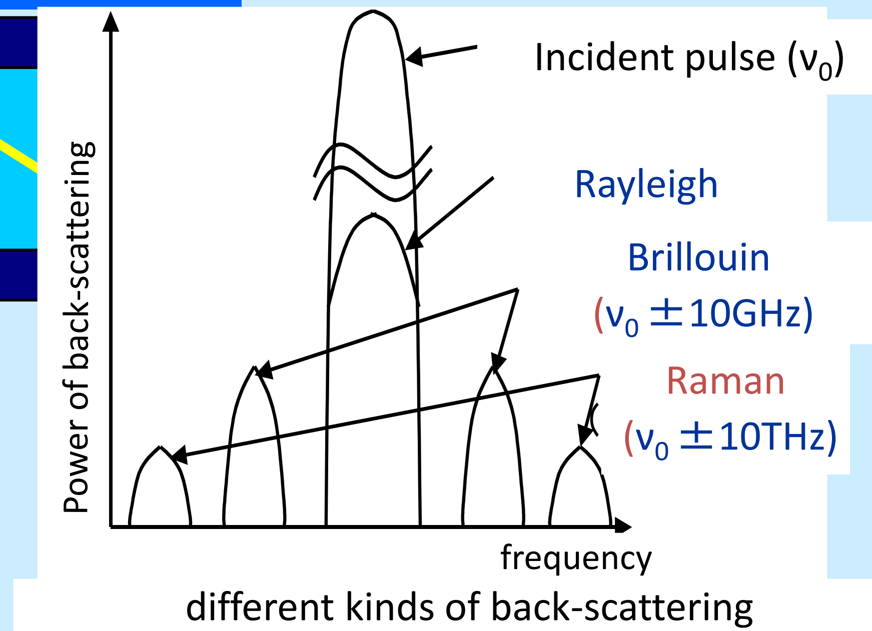
BOTDR:Brillouin Optical Time Domain Reflectometry

BOCDA:Brillouin Optical Correlation Domain Analysis

PPP-BOTDA: Pulse Pre-pump Brillouin Optical Time Domain Analysis

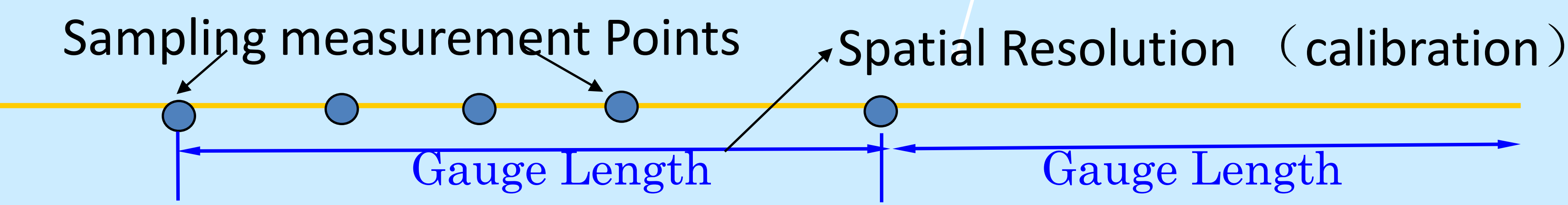
Back-Scattering (reflected signal)





1.Thousands of measurement points along a long-distance cable

2.Static measurement only



Distributed Fiber Optic Sensing Based on PPP-BOTDA (Sub-PI: Zhishen Wu, Professor at Ibaraki University)

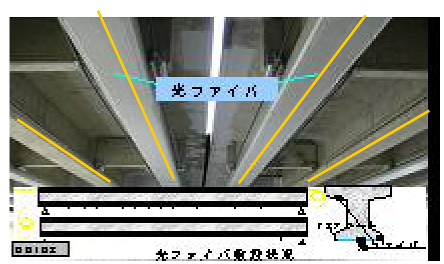
- To realize distributed, long-distance and real- time measurements in high-resolution and high-accuracy with direct frequency modulation and frequency stabilization techniques
- To promote applications of Brillouin –based distributed sensing technique in civil engineering and other large-scale structures

Type		Spatial resolution	Accuracy	Sampling rate
Pre-sent	B-OTDR	100cm	±50μ	Several minutes
	PPP-BOTDA	10-20cm	±30μ	Several minutes
Target		**10cm**	**Under ±10μ**	**Real-time(3～10Hz)**

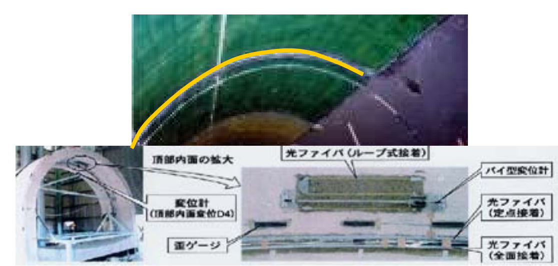
PPP-BOTDA: Pre-pump pulse-Brillouin Optical Fiber Time Domain Analysis

Measures: strain and temperature distributions and other environmental factors

Example 1 : long-term monitoring for highway viaducts



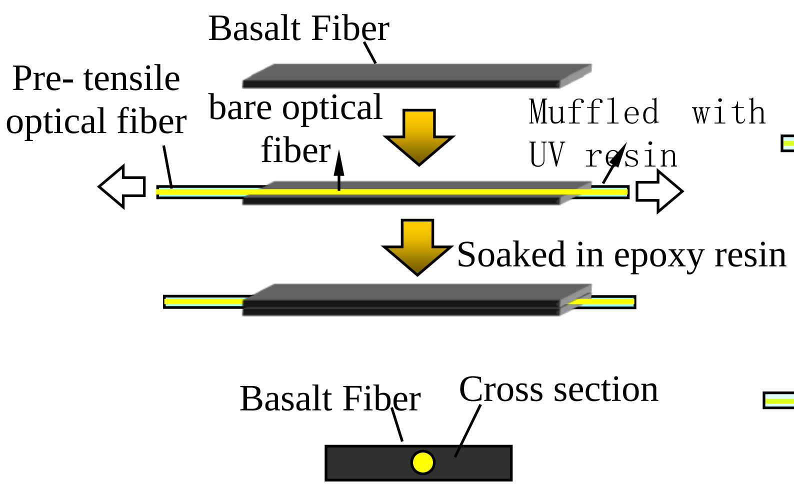
Example 2 : long-term monitoring for railway tunnels



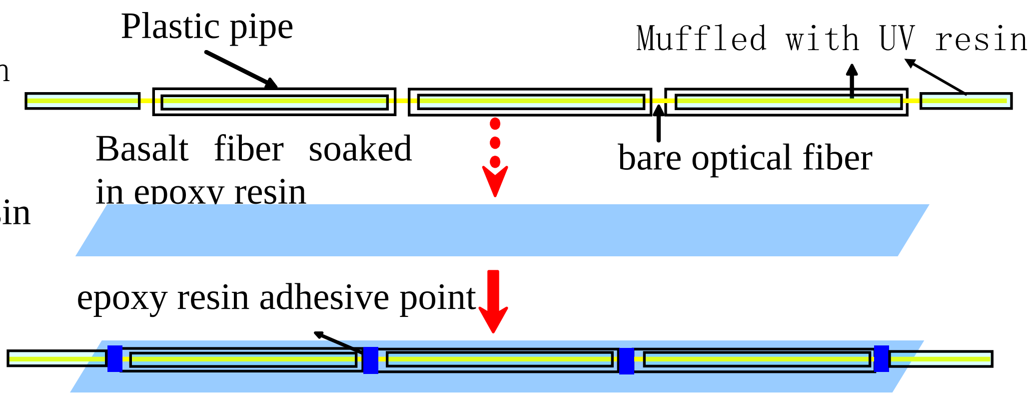
Pilot tests with real structures

Key Technologies for Intelligent Structures

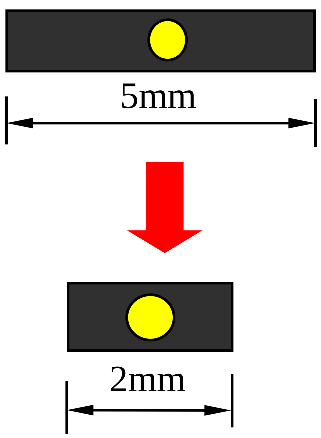
- Non-slip grating

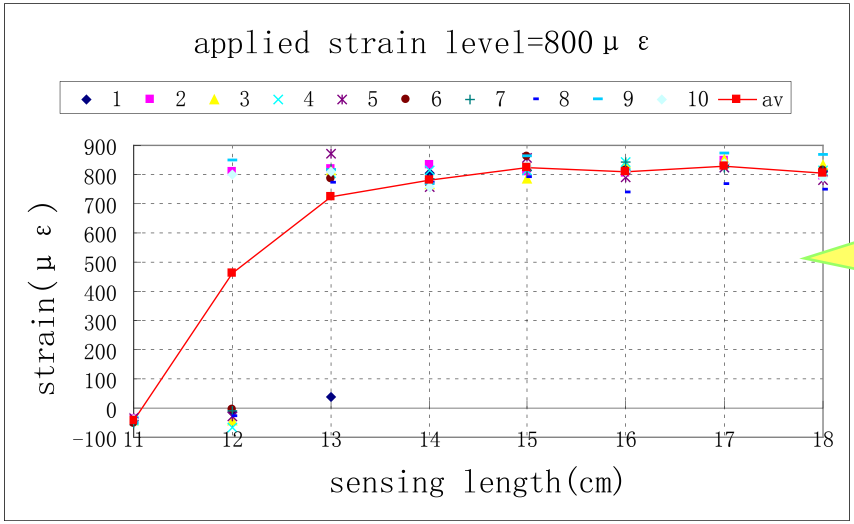


Overall bonding Package



Point bonding Package





Critical testing length can be as short as13cm

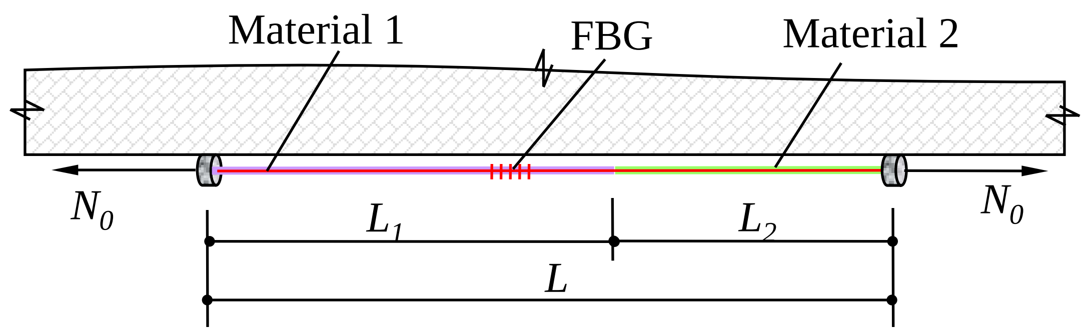
High Sensitivity FBG Sensor

Why to develop

- Stress usually is small
- Heavy noises
- Crack due to corrosion
- Ambient environment vibration testing

Basic Principal

- FBG measured stress: ε_1
- Average stress within the gage length L: $\bar{\varepsilon}$



Suppose:

$$\alpha_E = \frac{E_1 A_1}{E_2 A_2}$$

$$\alpha_L = \frac{L_1}{L}$$

$$\Rightarrow \varepsilon_1 = \eta \cdot \bar{\varepsilon}$$

$$\eta = \frac{1}{\alpha_L + \alpha_E - \alpha_L \alpha_E}$$

Sensitivity Increment Coefficient

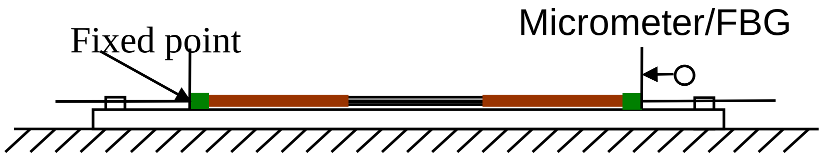
When $\alpha_E = 1$ $\Rightarrow$ $\varepsilon_1 = \bar{\varepsilon}$

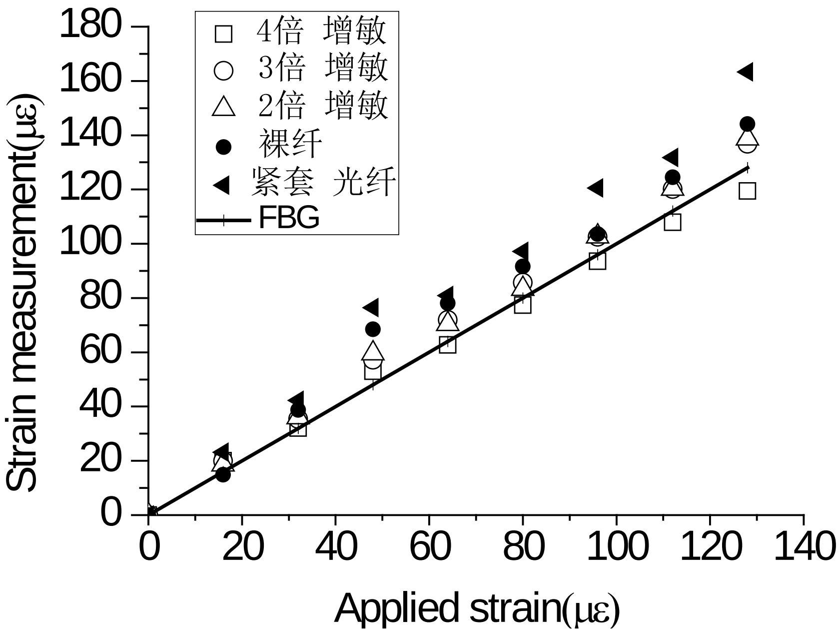
When $E_1 << E_2$ $\alpha_E \to 0$ $\Rightarrow$ $\eta \approx \frac{1}{\alpha_L} = \frac{L}{L_1}$

Development of New Distributed Long Gage High Sensitivity Fiber Stress Sensor

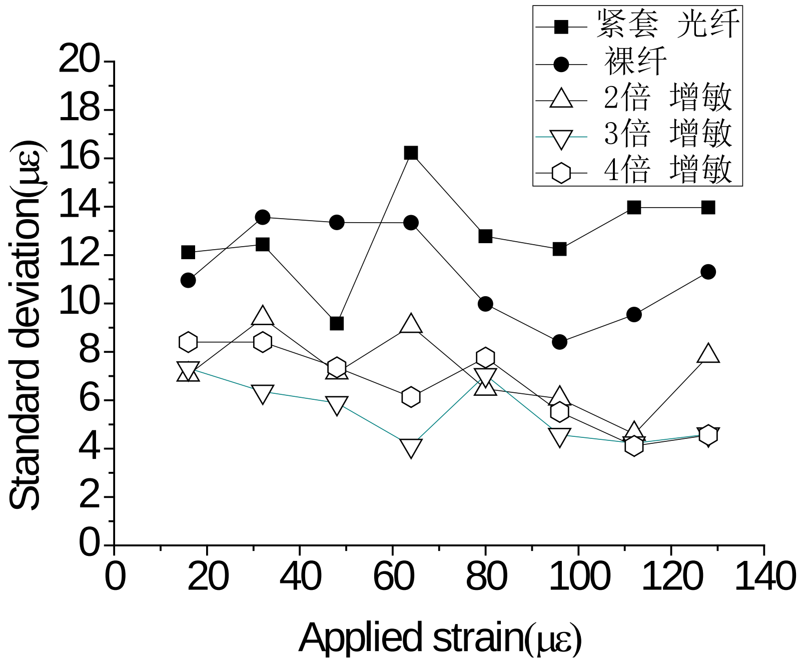
- Verification—Stretch

1. bare optical fiber, tight buffer fiber , high sensitivity fiber (η=2~4)
2. Stress step 16$\mu\varepsilon$， repeat 10 times





Measured Stress



Measured Standard Deviation

Measurement result of new fiber sensor is more closer to the real one, with smaller Standard Deviation

Measuring Principal of Long-Gage Distributed FBG Sensors

Characteristics of Traditional FBG Sensors:

(1)High resolution;

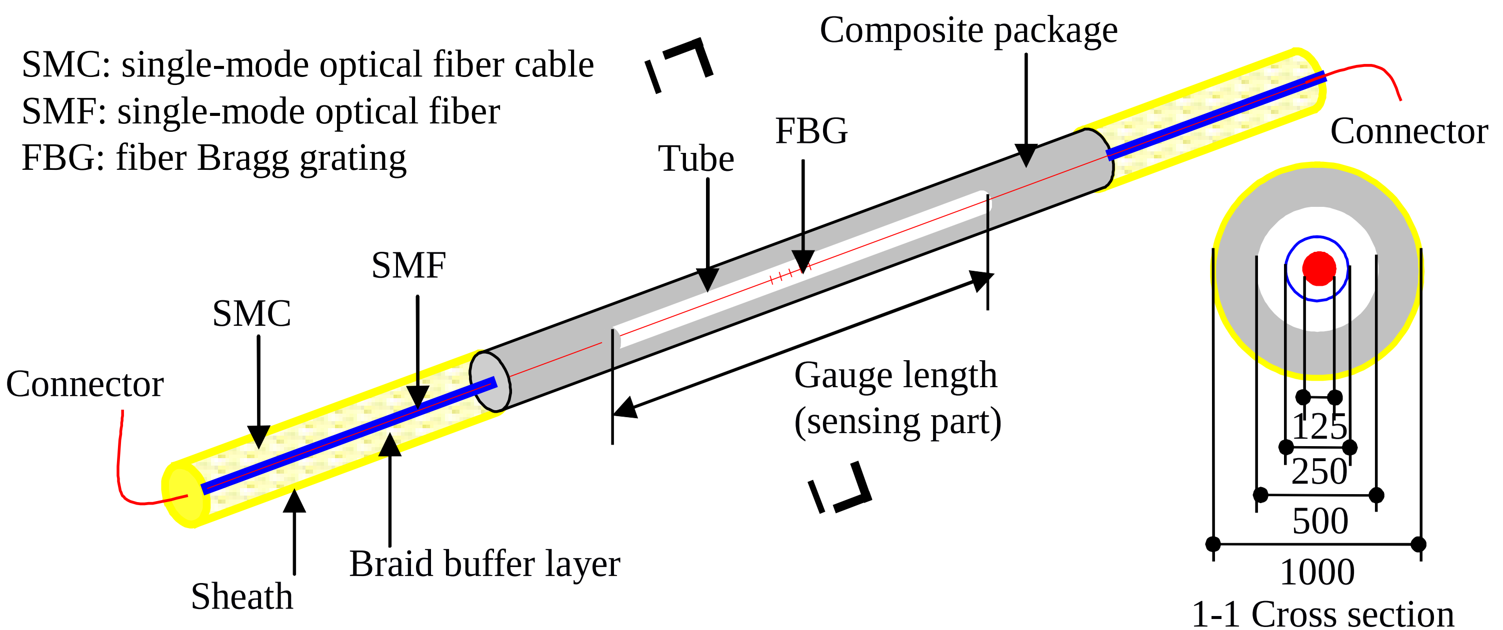
(2)Good dynamic performance;

(3)Distributed measurement;

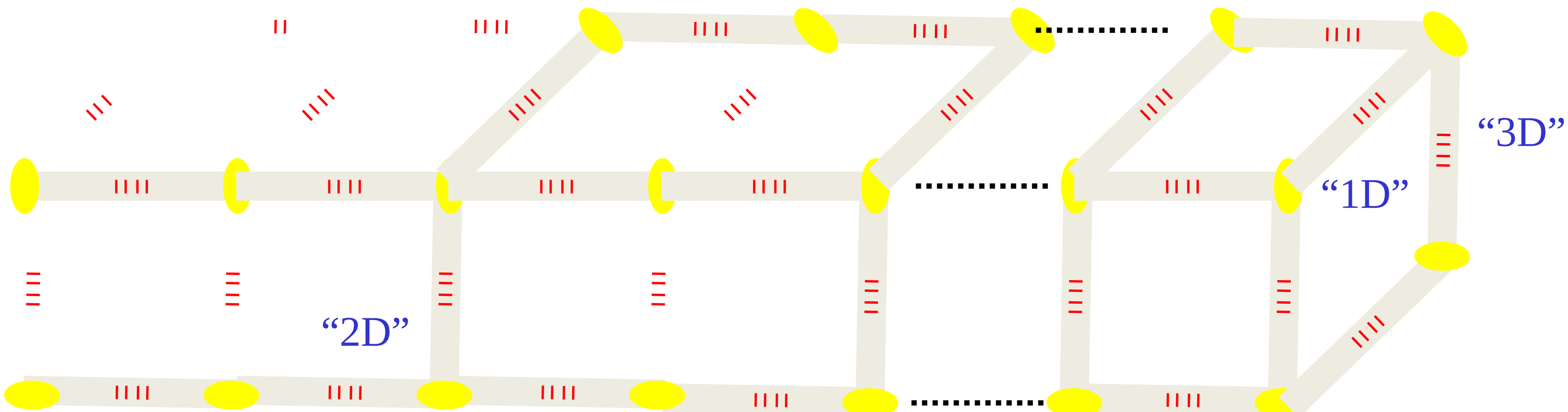
(4)Typical point sensor，small gage

Series FBG Sensors

Distributed long-gage FBG sensors

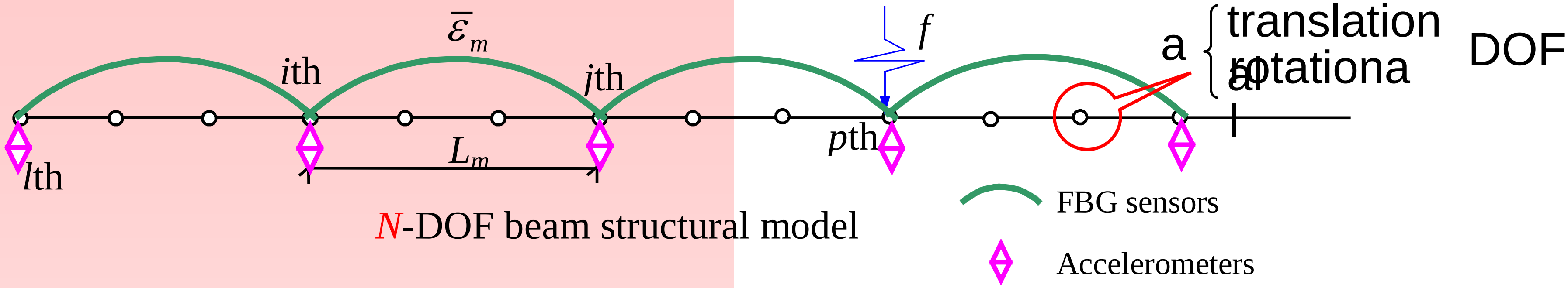


A packaged long-gage FBG sensor



Distributed long-gage FBG sensors

Dynamic measurements



The dynamic displacement measurements can be written as:

$$\{v_n(t)\} = \{v_1(t), v_2(t), \cdots, v_n(t), \cdots, v_N(t)\}^T$$

Measurements from L accelerometers:

$$\{a_l(t)\} = \begin{Bmatrix} a_1(t) \\ a_2(t) \\ \vdots \\ a_l(t) \\ \vdots \\ a_L(t) \end{Bmatrix} = \begin{Bmatrix} \ddot{v}_1(t) \\ \ddot{v}_2(t) \\ \vdots \\ \ddot{v}_l(t) \\ \vdots \\ \ddot{v}_L(t) \end{Bmatrix} = [A]_{L\times N} \cdot \begin{Bmatrix} \ddot{v}_1(t) \\ \ddot{v}_2(t) \\ \vdots \\ \ddot{v}_n(t) \\ \vdots \\ \ddot{v}_N(t) \end{Bmatrix}$$

$$= [A]_{L\times N} \cdot \{\ddot{v}_n(t)\}$$

Measurements from M FBG sensors:

$$\{\bar{\varepsilon}_m(t)\} = \begin{Bmatrix} \bar{\varepsilon}_1(t) \\ \bar{\varepsilon}_2(t) \\ \vdots \\ \bar{\varepsilon}_m(t) \\ \vdots \\ \bar{\varepsilon}_M(t) \end{Bmatrix} = \begin{Bmatrix} \eta_1 \cdot (v_{i1}(t) - v_{j1}(t)) \\ \eta_2 \cdot (v_{i2}(t) - v_{j2}(t)) \\ \vdots \\ \eta_m \cdot (v_{im}(t) - v_{jm}(t)) \\ \vdots \\ \eta_M \cdot (v_{iM}(t) - v_{jM}(t)) \end{Bmatrix} = [B]_{M\times N} \cdot \begin{Bmatrix} v_1(t) \\ v_2(t) \\ \vdots \\ v_n(t) \\ \vdots \\ v_N(t) \end{Bmatrix}$$

$$= [B]_{M\times N} \cdot \{v_n(t)\},$$

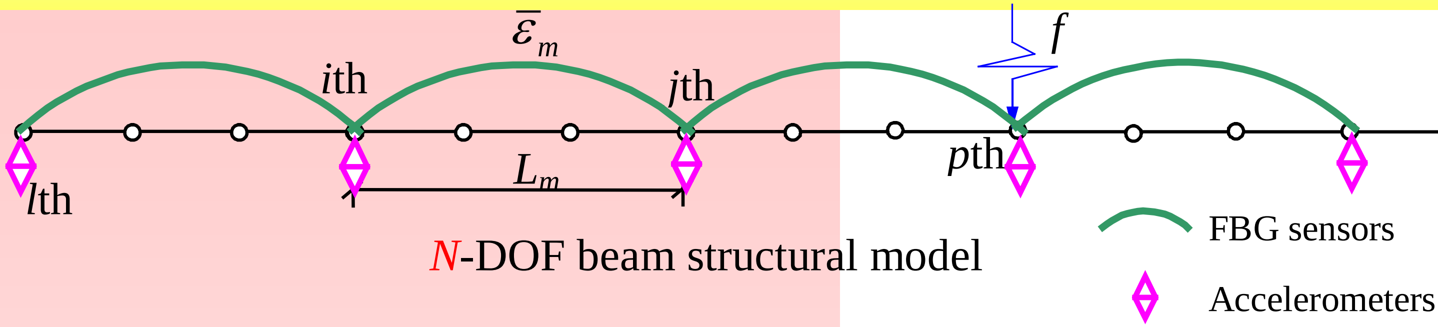
where

$$\eta_m = \frac{h_m}{L_m}$$

“acceleration” — From the view of temporal domain… — close to “displacement”

“translational” — From the view of spatial domain… — “rotational”

Theoretical modal analysis



N-DOF beam structural model

$$\eta_m = \frac{h_m}{L_m}$$

Acceleration FRF

$$H^{a}_{lp}(\omega) = \frac{v_l(\omega)}{P_p(\omega)} = \sum_{r=1}^{N} \frac{-\omega^2 \varphi_{lr}\varphi_{pr}}{M_r\left(\omega_r^2 - \omega^2 + 2j\xi_r\omega_r\omega\right)}$$

Macro-strain FRF

$$H^{\bar{\varepsilon}}_{mp}(\omega) = \frac{\bar{\varepsilon}_m(\omega)}{P_p(\omega)} = \sum_{r=1}^{N} \frac{\eta_m\left(\varphi_{ir} - \varphi_{jr}\right)\varphi_{pr}}{M_r\left(\omega_r^2 - \omega^2 + 2j\xi_r\omega_r\omega\right)}$$

Considering magnitude

$$\left|{}_rH^{a}_{lp}(\omega)\right| = \frac{\varphi_{lr}\varphi_{pr}}{M_r\sqrt{\left(\left(\frac{\omega_r}{\omega}\right)^2 - 1\right)^2 + \left(2\xi_r\frac{\omega_r}{\omega}\right)^2}}$$

$$\left|{}_rH^{\bar{\varepsilon}}_{mp}(\omega)\right| = \frac{\eta_m\varphi_{pr}\left(\varphi_{ir} - \varphi_{jr}\right)}{M_r\sqrt{\left(\omega_r^2 - \omega^2\right)^2 + \left(2\xi_r\omega_r\omega\right)^2}}$$

➡ Frequency, damping ratio — same

$$\left|{}_rH^{a}_{lp}(\omega = \omega_r)\right| = \frac{\varphi_{pr}}{2\xi_r M_r}\cdot\varphi_{lr}$$

$$\left|{}_rH^{\bar{\varepsilon}}_{mp}(\omega = \omega_r)\right| = \frac{\varphi_{pr}}{2M_r\xi_r\omega_r^2}\cdot\underline{\eta_m\left(\varphi_{ir} - \varphi_{jr}\right)} \rightarrow \delta_{mr}$$

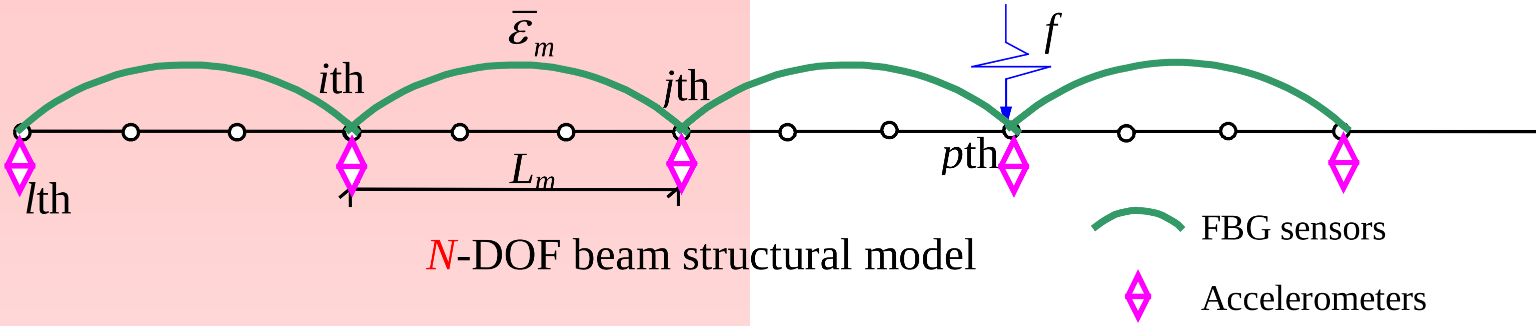
➡ Mode shape

$$\left\{\varphi_{1r}, \varphi_{2r}, \cdots, \varphi_{lr}, \cdots\right\}^T$$

➡ Modal macro-strain vector (MMSV)

$$\left\{\delta_{1r}, \delta_{2r}, \cdots, \delta_{mr}, \cdots\right\}^T$$

Modal parameters



N-DOF beam structural model

The complete set of the rth-order mode shape (including translational and rotational DOFs) can be written as:

$$\{\lambda_{nr}\}^T = \{\lambda_{1r}, \lambda_{2r}, \cdots, \lambda_{nr}, \cdots \lambda_{Nr}\}^T$$

Mode shape based on accelerometers:

$$\{\varphi_l\}_r = \begin{Bmatrix} \varphi_1 \\ \varphi_2 \\ \vdots \\ \varphi_l \\ \vdots \\ \varphi_L \end{Bmatrix}_r = [A]_{L\times N} \cdot \begin{Bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \\ \vdots \\ \lambda_N \end{Bmatrix}_r$$

MMSV based on FBG sensors:

$$\{\delta_m\}_r = \begin{Bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_m \\ \vdots \\ \delta_M \end{Bmatrix}_r = \begin{Bmatrix} \eta_1 \cdot (\lambda_{i1} - \lambda_{j1}) \\ \eta_2 \cdot (\lambda_{i2} - \lambda_{j2}) \\ \vdots \\ \eta_m \cdot (\lambda_{im} - \lambda_{jm}) \\ \vdots \\ \eta_M \cdot (\lambda_{iM} - \lambda_{jM}) \end{Bmatrix}_r = [B]_{M\times N} \cdot \begin{Bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \\ \vdots \\ \lambda_N \end{Bmatrix}_r$$

The same mapping relations as dynamic measurements!!

MMSV: average curvature mode shape

Modal Analysis on Macro-strain Measurements from Distributed Long-gage Fiber Optic Sensors

Macro-strain Frequency Response Function (FRF)

$$\frac{{}_rH_{lp}^{d}(\omega)}{{}_rH_{mp}^{\bar{\varepsilon}}(\omega)} = \frac{{}_rA_{lp}^{d}}{{}_rA_{mp}^{\bar{\varepsilon}}} = \frac{\varphi_{lr}}{\delta_{mr}} = \frac{\varphi_{lr}}{\eta_m(\varphi_{ir} - \varphi_{jr})}$$

Macro-strain FRF is close to a displacement FRF rather than a velocity or acceleration one, more sensitive indicator at low modes

The identified resonant frequency and damping ratio from dynamic macro-strain measurements hold the same precision as those from conventional transducers

Representations of Macro-strain FRF

$${}_rH_{mp}^{\bar{\varepsilon}}(\omega) = {}_r^RH_{mp}^{\bar{\varepsilon}}(\omega) + j \cdot {}_r^IH_{mp}^{\bar{\varepsilon}}(\omega)$$

$$\left|{}_rH_{mp}^{\bar{\varepsilon}}(\omega)\right| = \sqrt{\left[{}_r^RH_{mp}^{\bar{\varepsilon}}(\omega)\right]^2 + \left[{}_r^IH_{mp}^{\bar{\varepsilon}}(\omega)\right]^2} = \frac{A_{mp}^{r}}{\sqrt{\left(\omega_r^2 - \omega^2\right)^2 + \left(2\xi_r\omega_r\omega\right)^2}}$$

Magnitude

$$\phi_H = \arctan\frac{{}_r^IH_{mp}^{\bar{\varepsilon}}(\omega)}{{}_r^RH_{mp}^{\bar{\varepsilon}}(\omega)} = \arctan\left[\frac{-2\xi_r\omega_r\omega}{\omega_r^2 - \omega^2}\right]$$

Phase

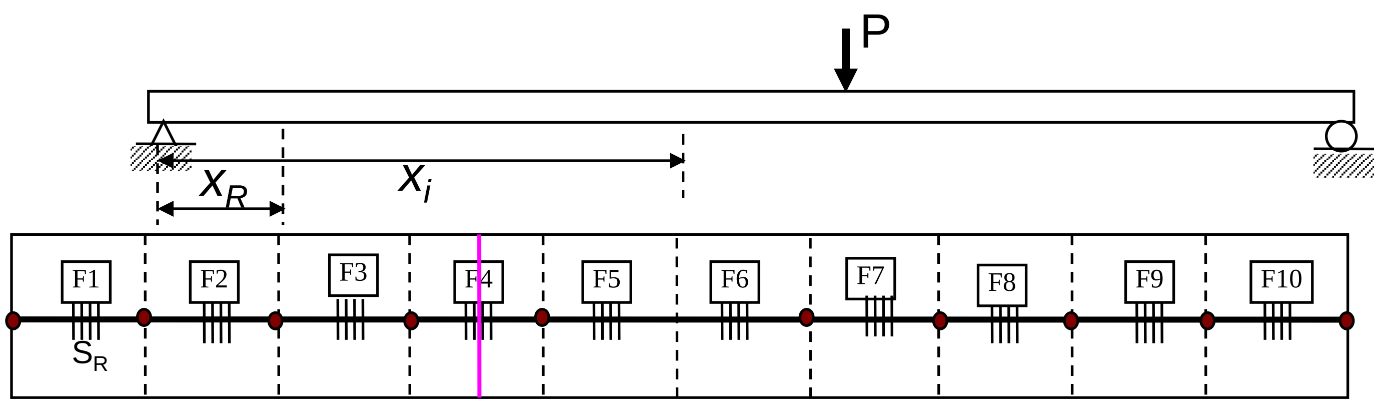
Identification based on Statistics of Relative Static Long Gage Stress

Intact

$$\gamma_i = \frac{\varepsilon_i}{\varepsilon_R} = \frac{x_i}{x_R}$$

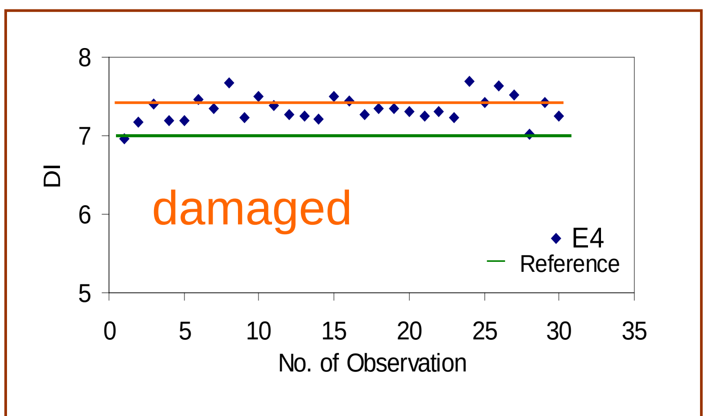
Damaged

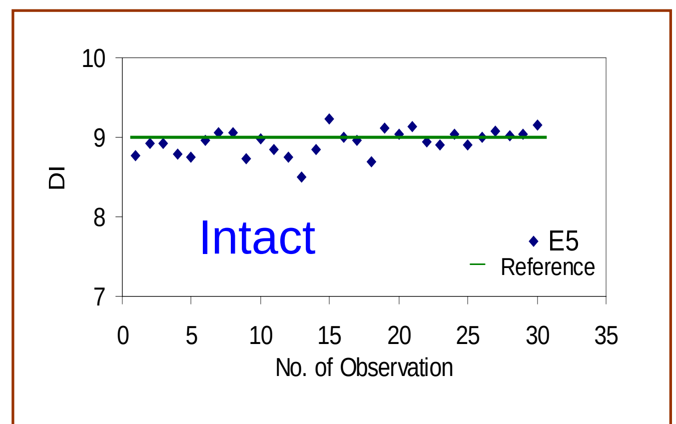
$$\gamma_i^* = \frac{\varepsilon_i^*}{\varepsilon_R} = \frac{1}{\beta}\frac{x_i}{x_R} \quad (0 \le \beta \le 1)$$



Robust to noise

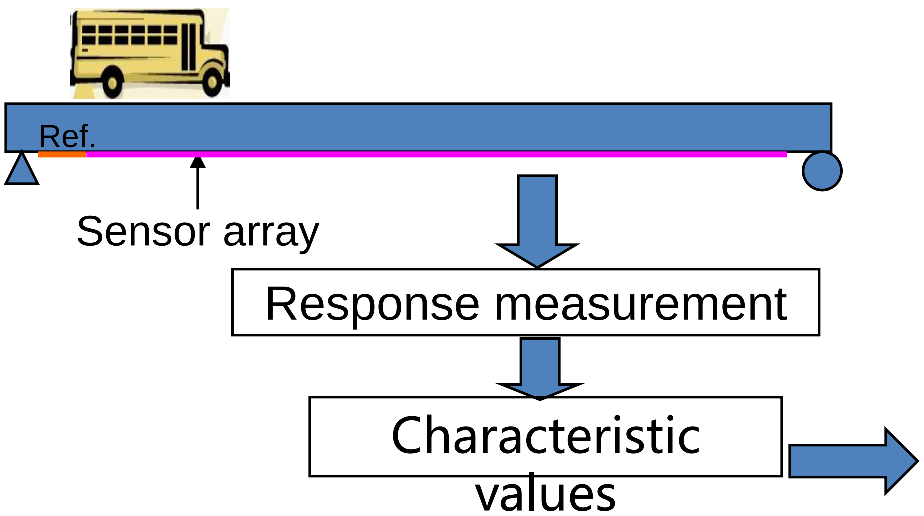
Increase the identification ability

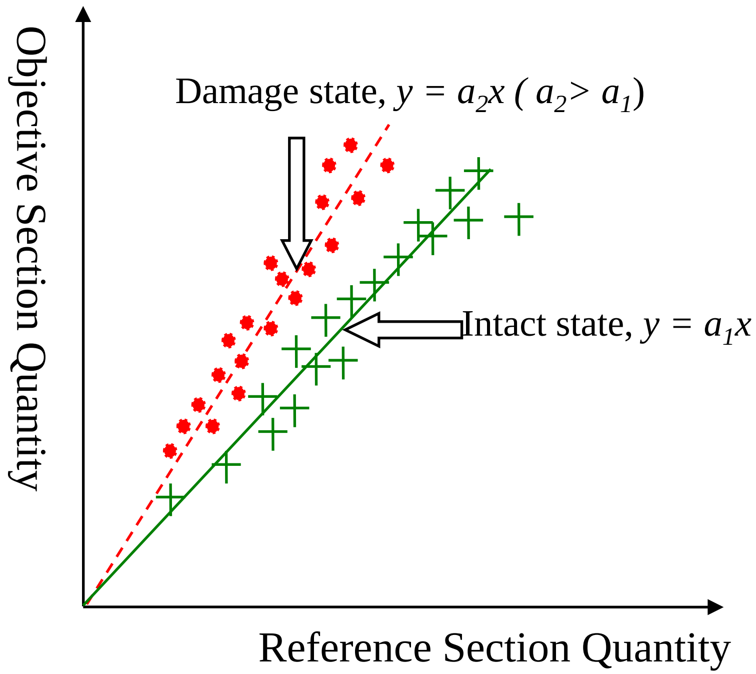




Damage Identification with Output Only

- ❖ For certain structure conditions, ratios of stress (time domain) and stress modal (frequency domain) of two monitored sections are constant
- ❖ Slopes of fitting lines will also be constant
- ❖ Damage will make the slopes change
- ❖ Robust to environment and noise





Conventional typical non-model based DI identification

Dynamic measurements by conventional methods

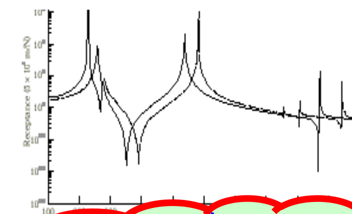
Displacement and/or acceleration Data

Noisy and too global

Displacement Mode shapes

+

Frequency shifts

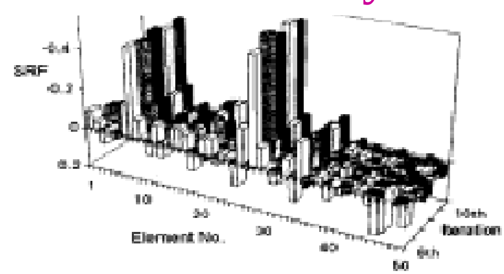


Accurate but insensitive to damage

Numerical differentiation errors

Mode s

Modal flexibility



MSC changes

Inaccu

for civil SHM

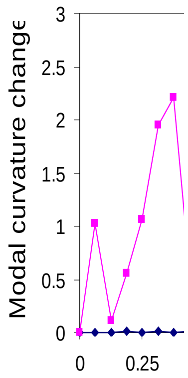
Modal Flexibility

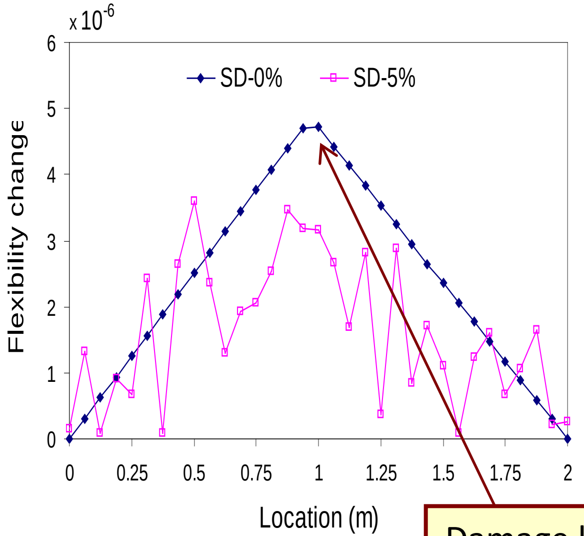
Flexibility curvature

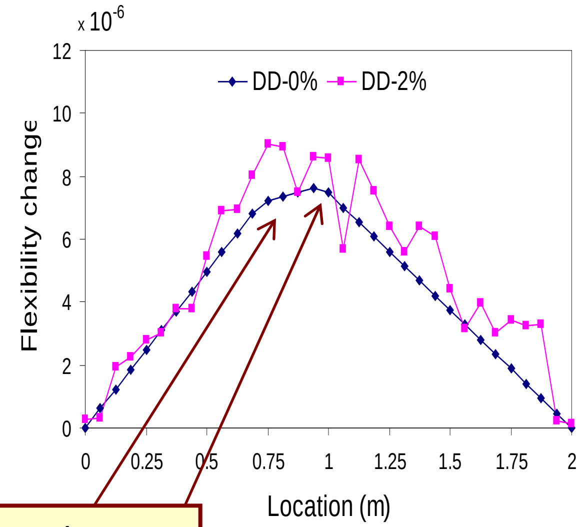
Uniform load surface

Promising but unreliable for damage detection in civil structures

Damage identification with 2% noise based on displacement measurement





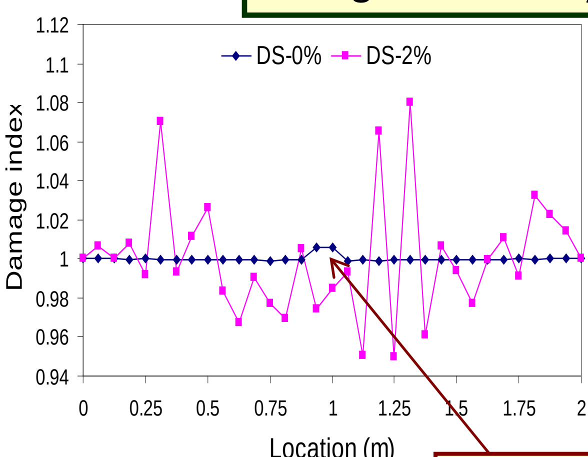


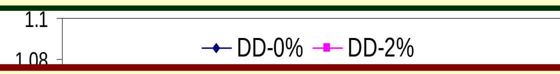
rvature and
mage index
solutely
amage
2% noise.

Change in l

Damage locations

Change in flexibility method from displacement data





Modal flexibility methods are also limited by 2% noise. The method is ineffective for damage localization in civil structures.

further magnified by
ical differentiation

Damage locations

Strain Energy-based damage indices from displacement data

Modified typical non-model based DI identification

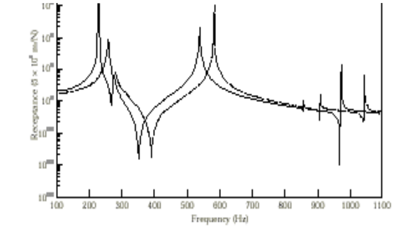
Dynamic strain measurements using long-gauge FBG sensors

Sensitive to local damages and robust to noise

MacroStrain Data

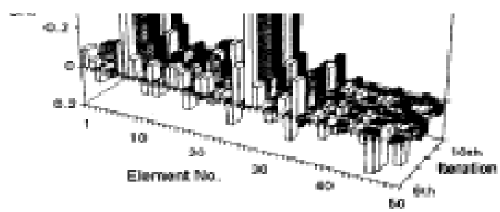
Strain Mode Shapes

Frequency shifts



Moc

MMS-flexibility Methods



Modal curvature changes

nergy Damage

Gr
an
SHM

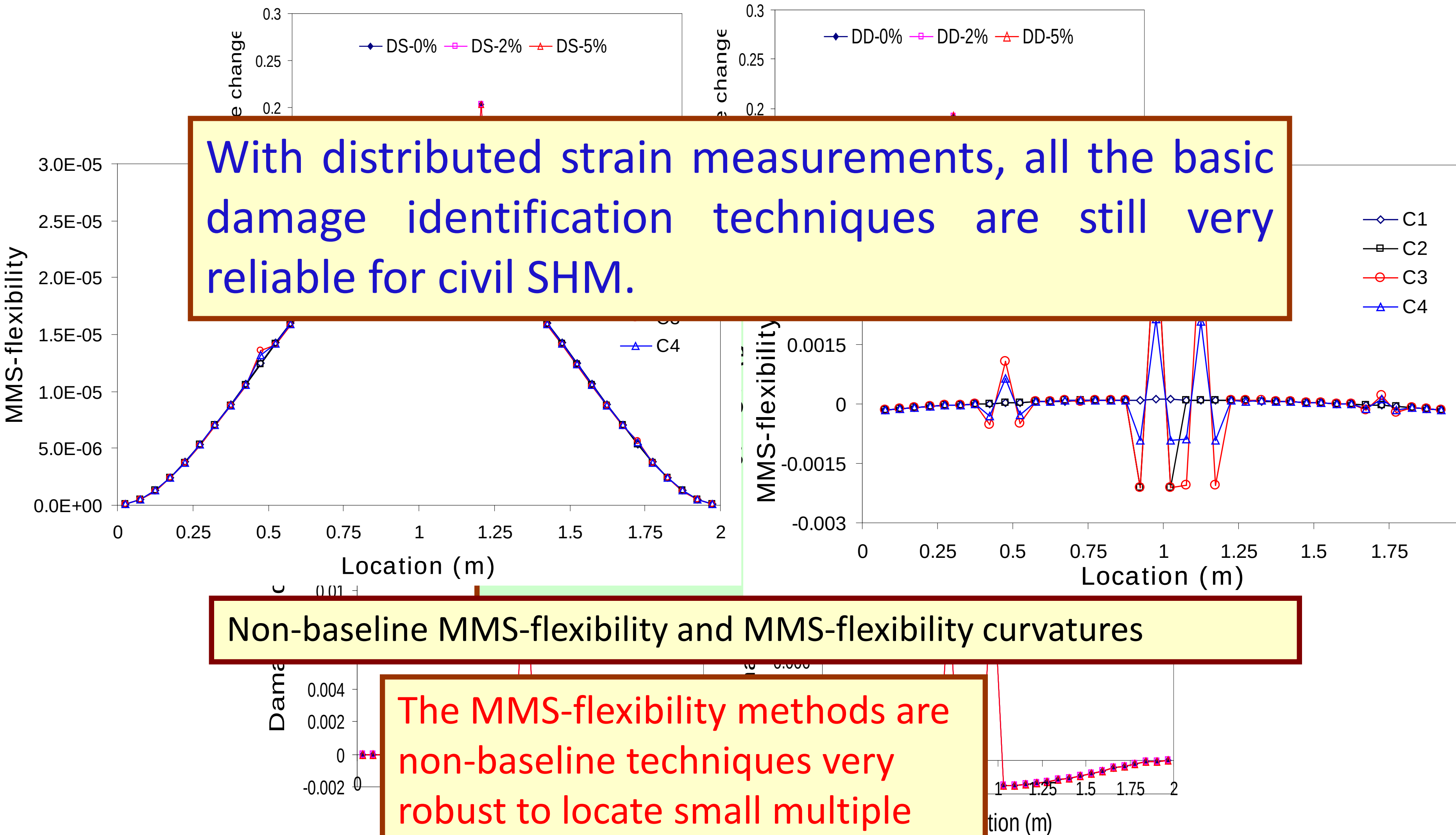
MMS-Flexibility

MMS-Flexibility curvature

Uniform load surface

Significantly enhanced for multiple damage localization even without baseline information

Damage identification with 5% noise based on distributed strain measurement



With distributed strain measurements, all the basic damage identification techniques are still very reliable for civil SHM.

Non-baseline MMS-flexibility and MMS-flexibility curvatures

The MMS-flexibility methods are non-baseline techniques very robust to locate small multiple damages localization.

Strain e … train data

Material and Structure Intelligentialization

Distributed Optical Fiber—Basalt Fiber Self-Sensing Bar

\+

Distributed Optical Fiber Sensing

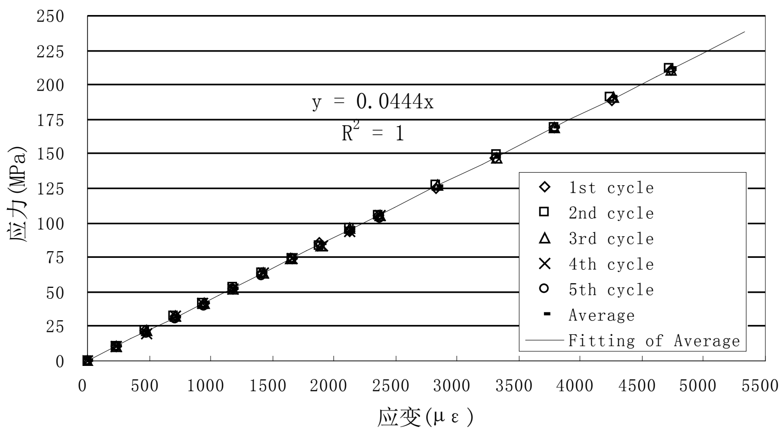
Basalt fiber packaged optical fiber sensor

Production

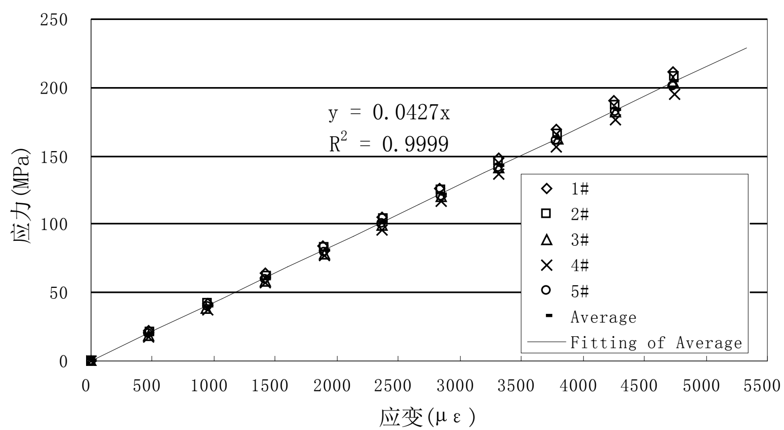
Basalt Fiber Self-Sensing Bar

Characteristics of Self-sensing Bar

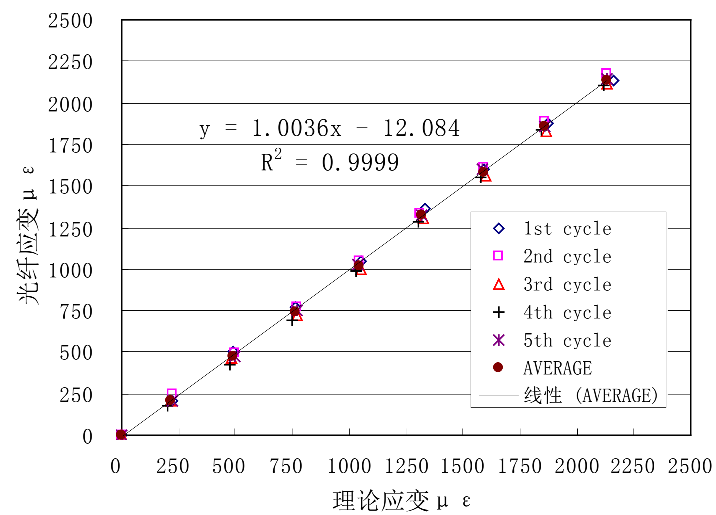
Strain-Stress（different cycle）



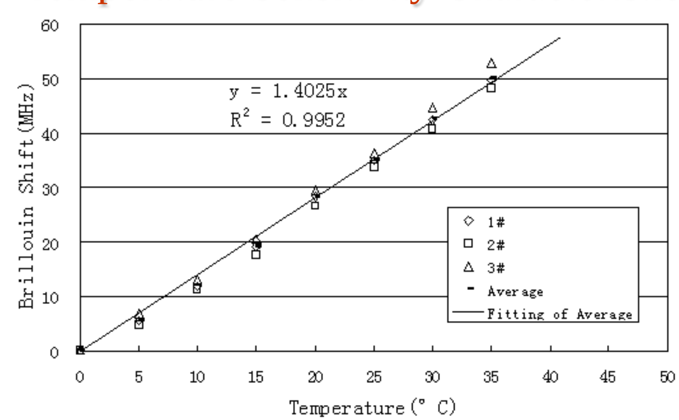
Strain-Stress（different sample）



Stress Sensitivity Characteristics



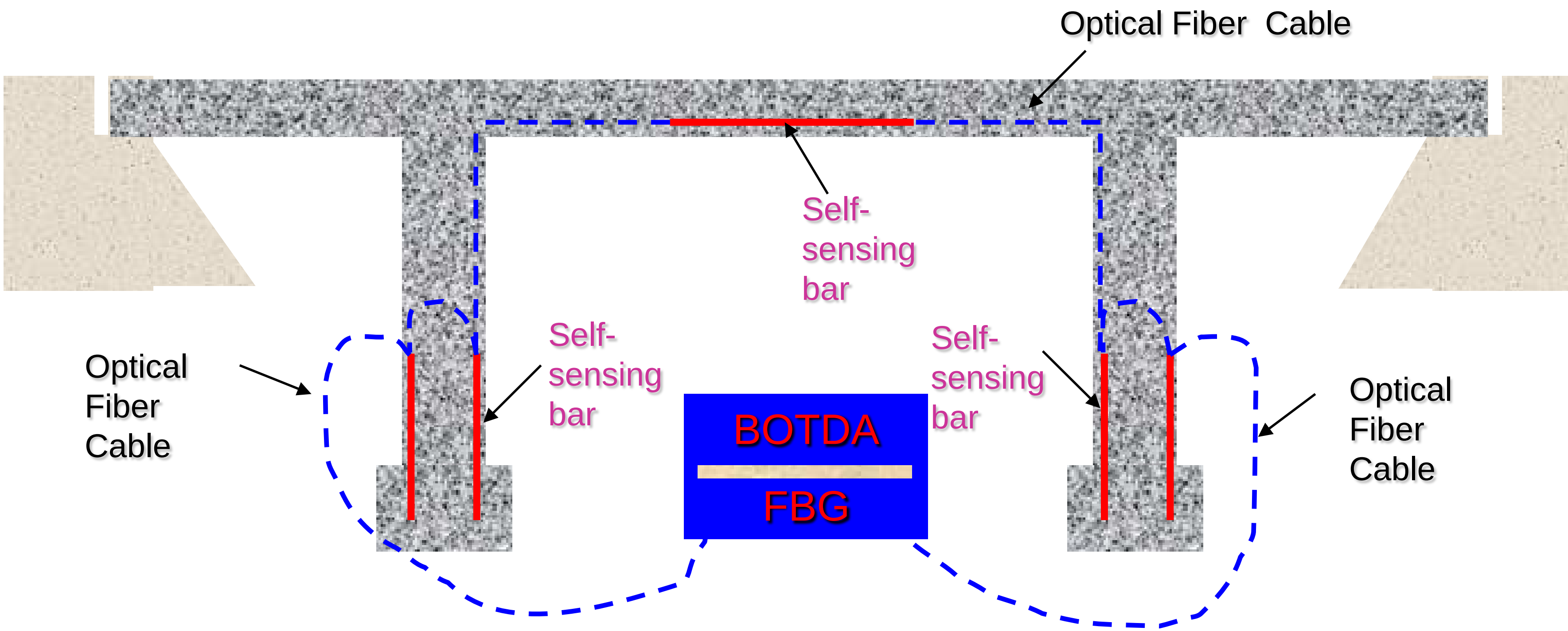
Temperature Sensitivity Characteristics



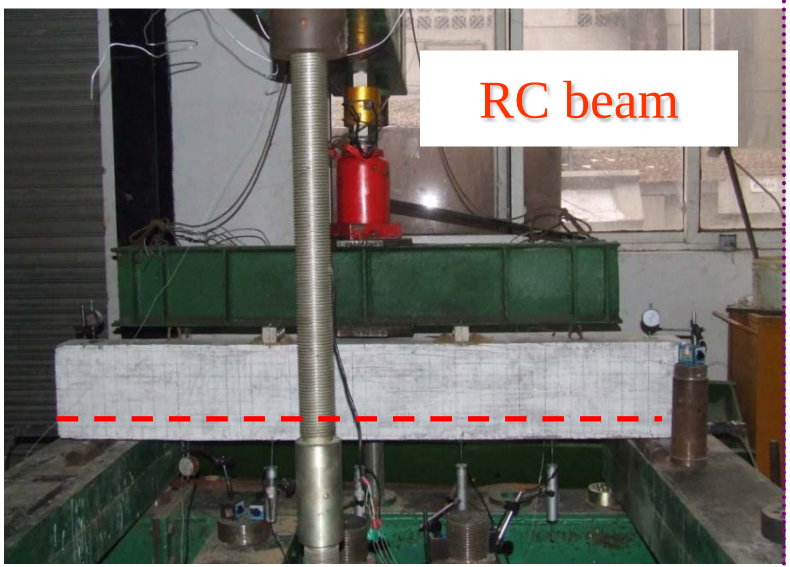
Mechanical characteristics

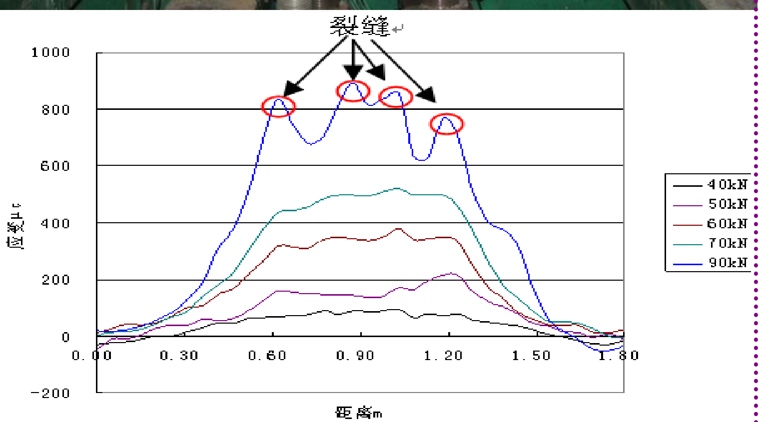
Sensing characteristics

Structural Strengthening and Health Monitoring based on Self-sensing Bar

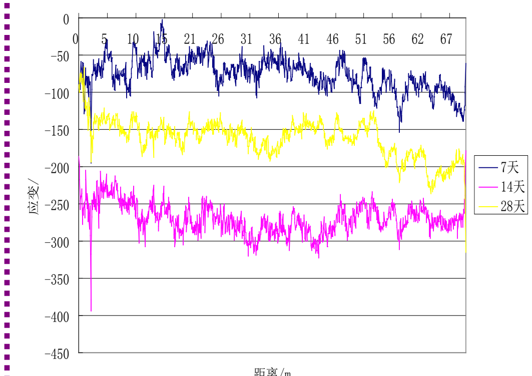


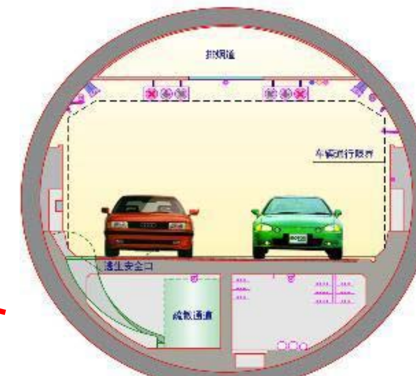
Engineering applications of smart BFRP rebar



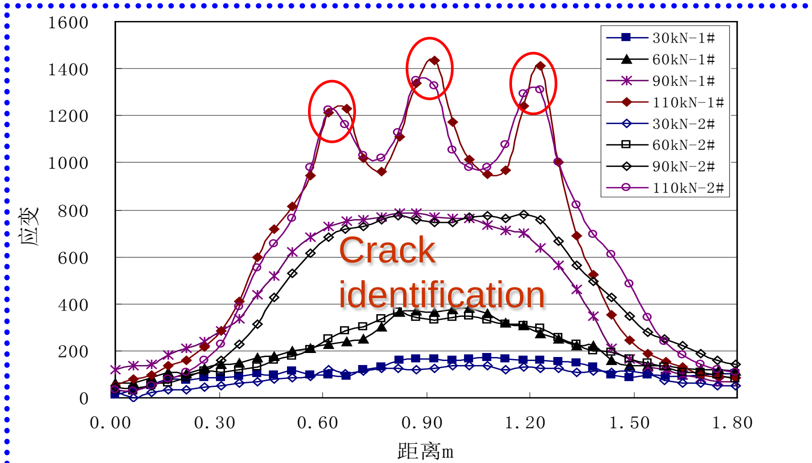


Smart rebar

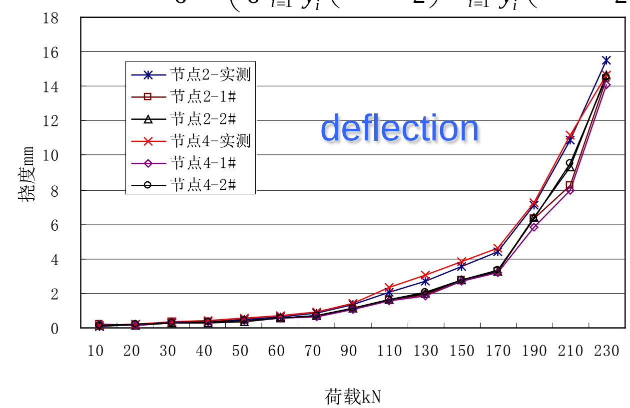




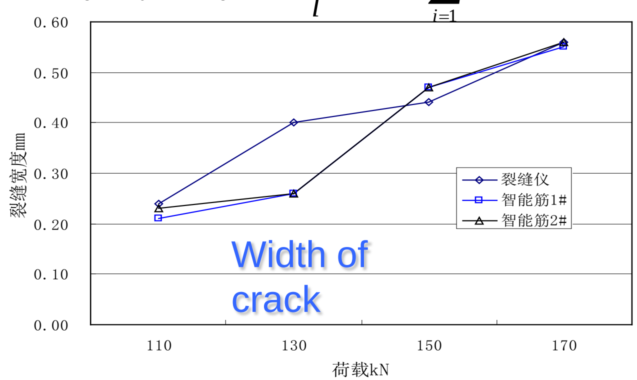
Application research of smart BFRP rebar

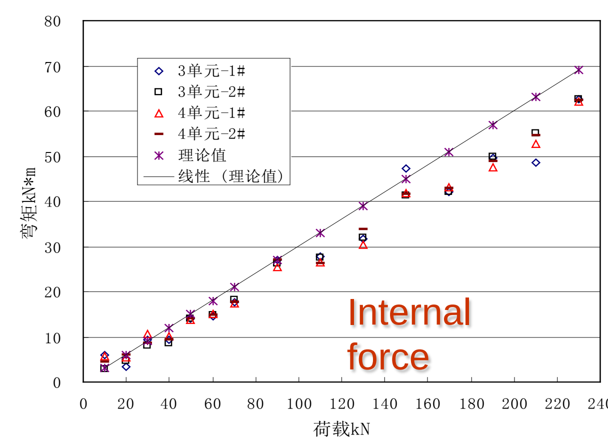


$$v_p = M'_p = -(\frac{l}{6})^2 * \left(\frac{p}{6} \sum_{i=1}^{6} \frac{\overline{\varepsilon}_i}{\overline{y}_i} \left(6 - i + \frac{1}{2} \right) - \sum_{i=1}^{p} \frac{\overline{\varepsilon}_i}{\overline{y}_i} \left(p - i + \frac{1}{2} \right) \right)$$



$$\omega = (\overline{\varepsilon}_s - \overline{\varepsilon}_c) l \approx \overline{\varepsilon}_s l = \frac{\int_l \varepsilon * dl}{l} * l = \sum_{i=1}^{n} 1/2 * (\varepsilon_i + \varepsilon_{i+1}) * \Delta l$$



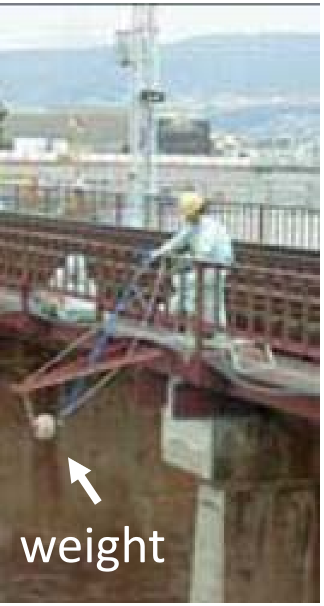


Application to Transportation Infrastructure

Manual checking by watching

Time consuming and laborious

Natural frequency measurement using Hammer Excitation Method（30kgf）



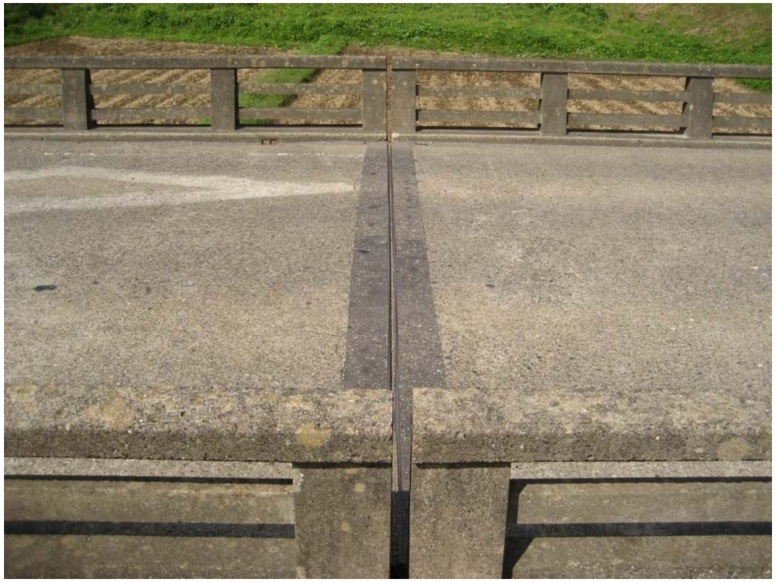
Traditional testing method is time consuming and laborious, but only “rough” testing.

With optical fiber sensing based monitoring, efficiency of monitoring and hence the safety of structure can be significantly enhanced.

SHM System of Kawane Bridge

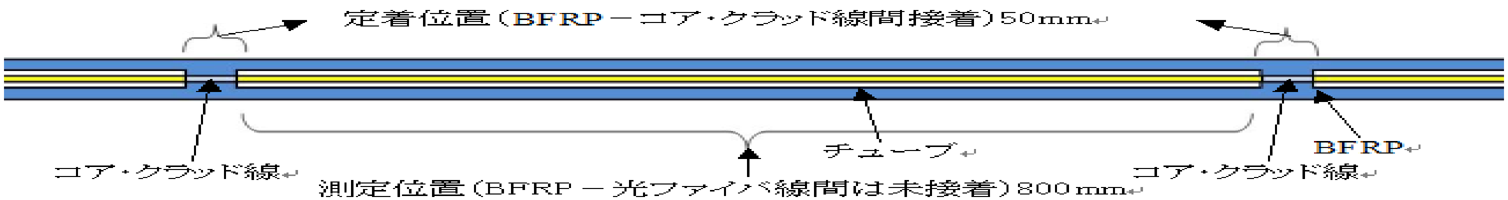
Kawane Bridge

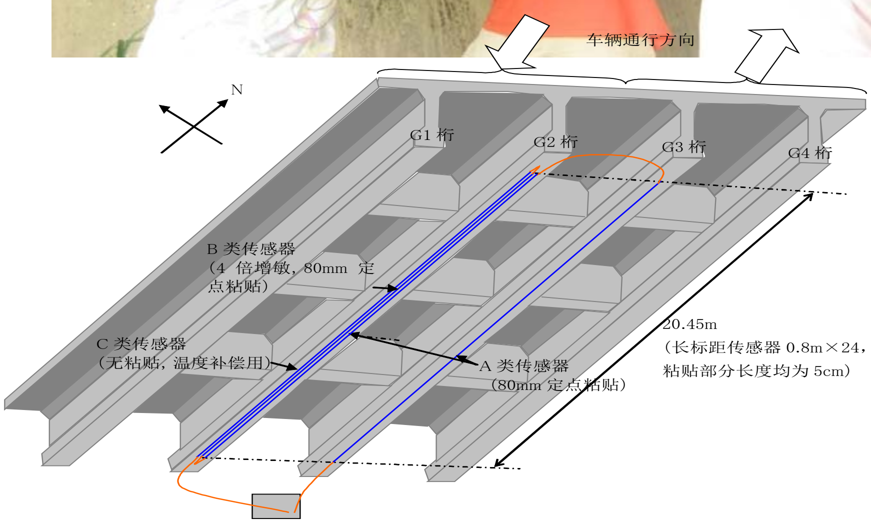
- Type: RC Structure
- Age: 45 years
- Location: Ibaraki, Japan
- Length: about 127 m



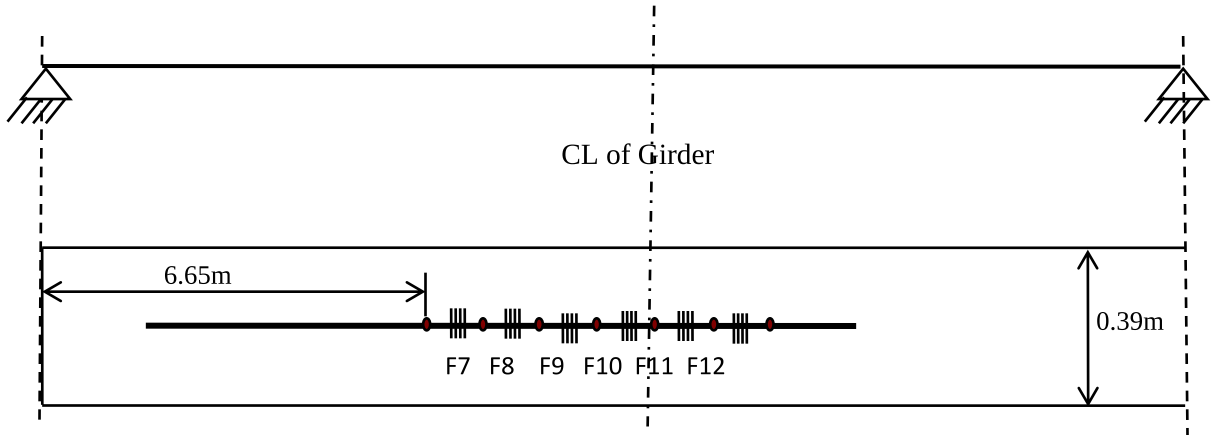
On-site Testing

Long Gage FBG sensor

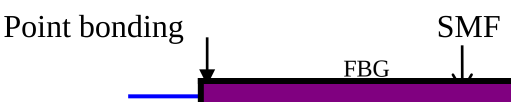




SHM System of Kawane Bridge



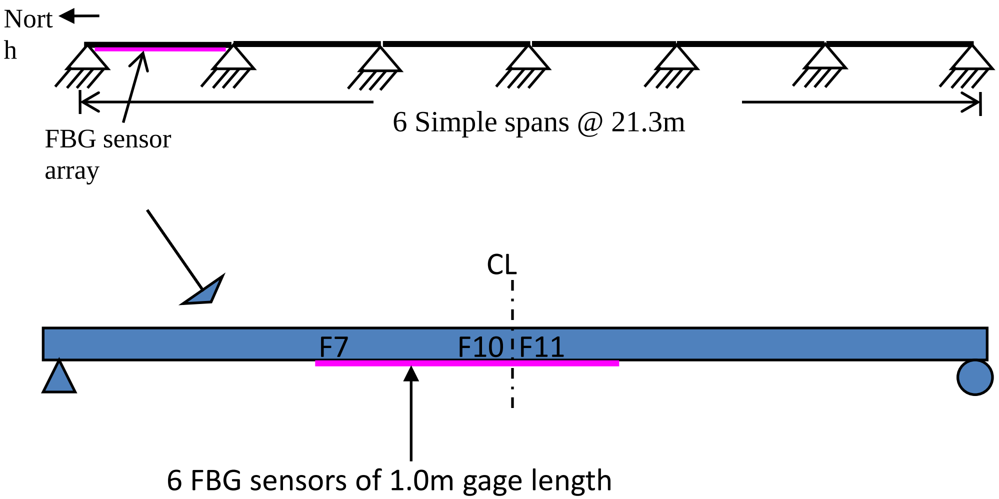
Sensor Locations

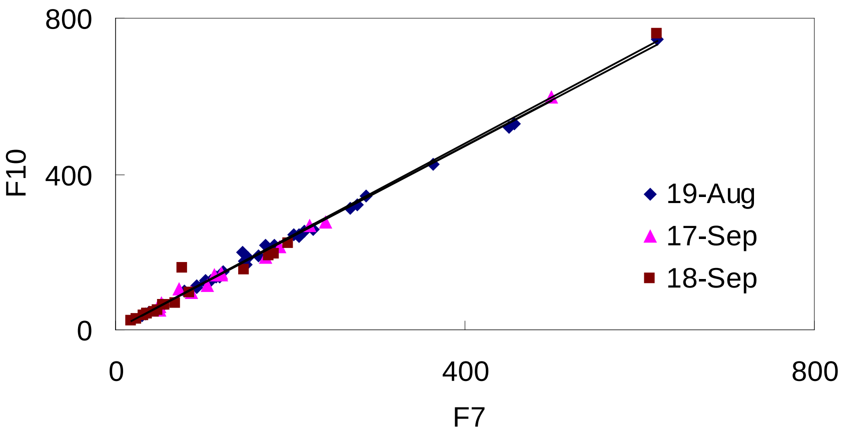


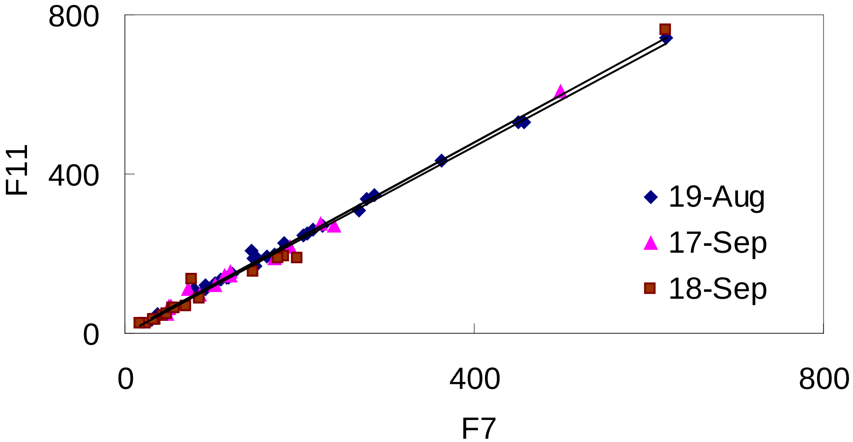
Monitoring Results（1）

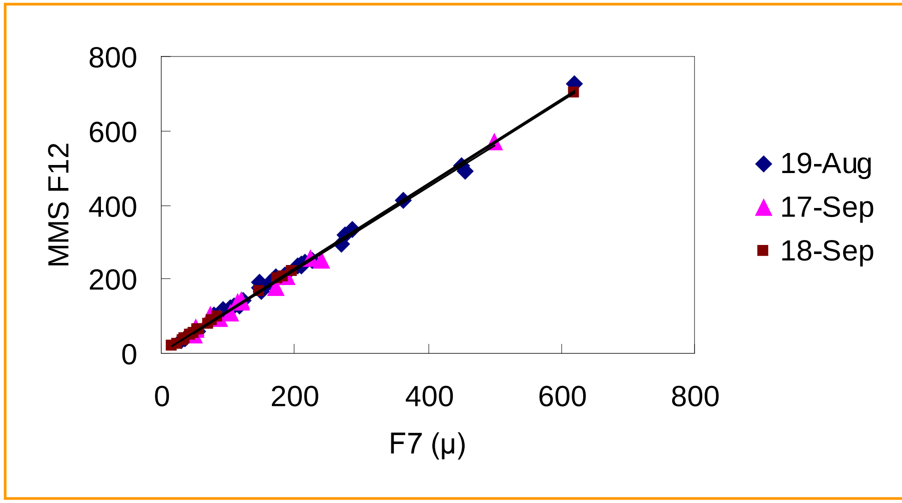
Date	Weather Condition	Average air temperature (^oC)	First modal frequency (Hz)
August 19, 2008	Sunny	27.3	4.81
September 17, 2008	Sunny	26.4	4.91
September 18, 2008	Rainy	23.3	5.02

Results of monitoring



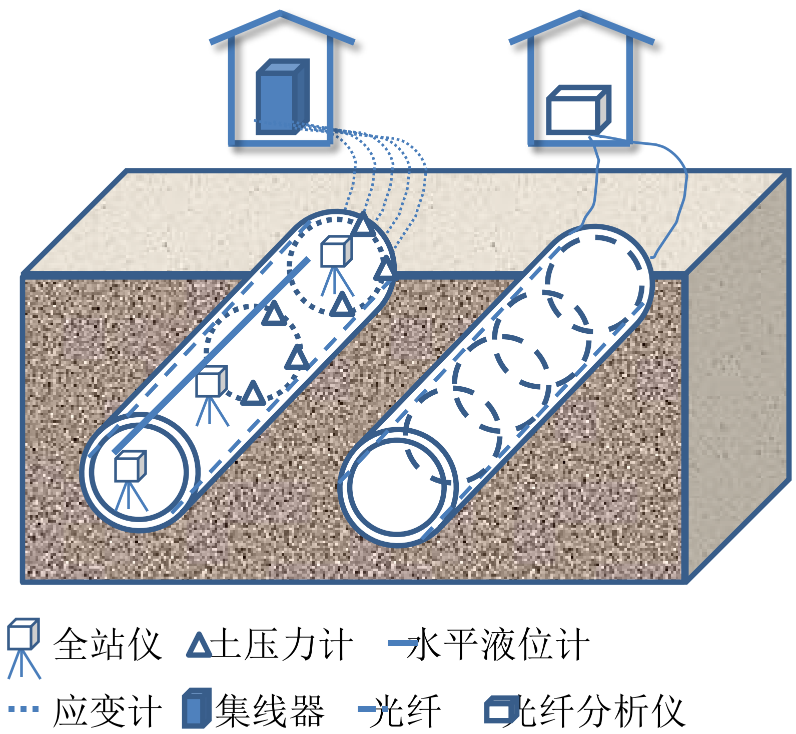






Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

- Tunnel Monitoring



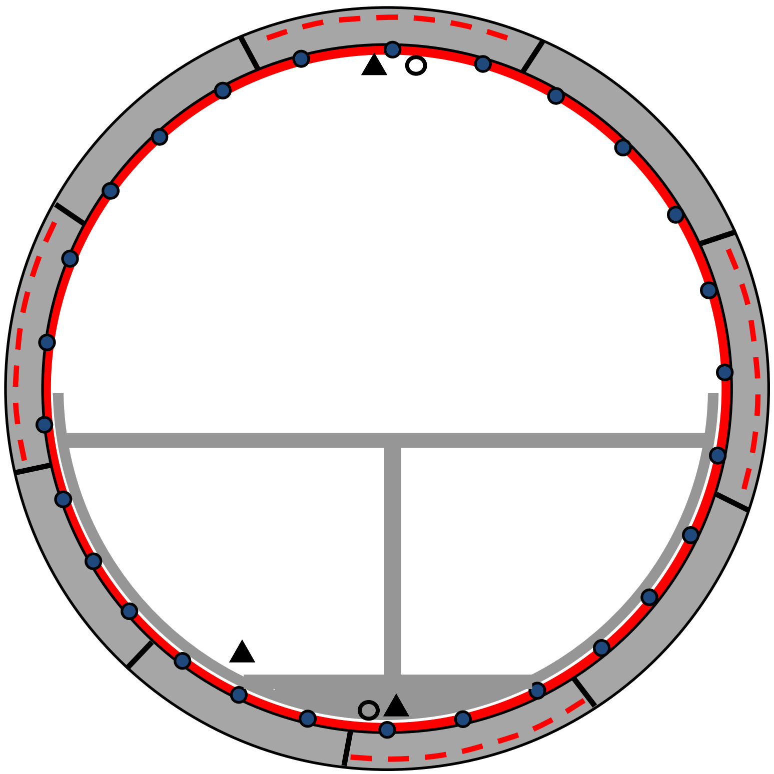
Traditional method	Optic fiber-based monitoring
Test Quantity Limited	*Test Quantity Increased*
Point testing	Distributed testing
multiple sensor types	*Few Types*
Short time monitoring	*Long time monitoring*
Expensive for large scale monitoring	*Cheap for large scale monitoring*

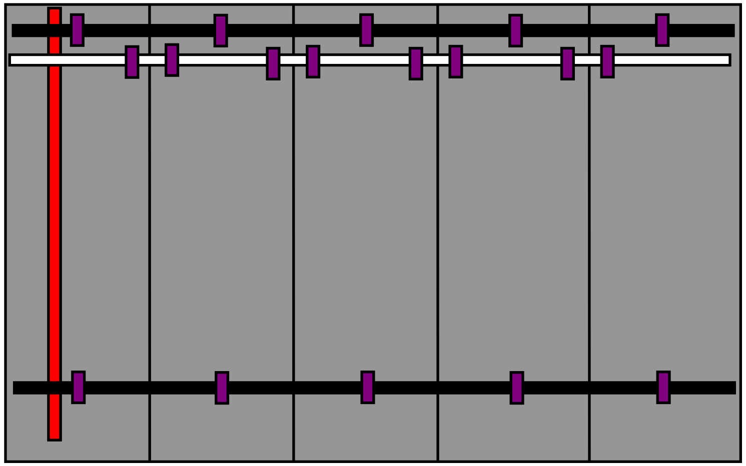
Applications

- Structural linear
- Key-positions unknown
- Multi-section, multi-item, synthetic monitoring
- Long time & severe environment monitoring
- Anti-Electromagnetic Interference

Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

- Overall Implementing Plan





- - - - : Embedded fiber sensor（concrete stress monitoring）

——— : Surface deployed fiber sensors（tunnel diameter monitoring）

▲ : Surface deployed fiber sensors（tunnel subsidence monitoring）

○ : Surface deployed fiber sensors（seam monitoring of tunnel lining segments）

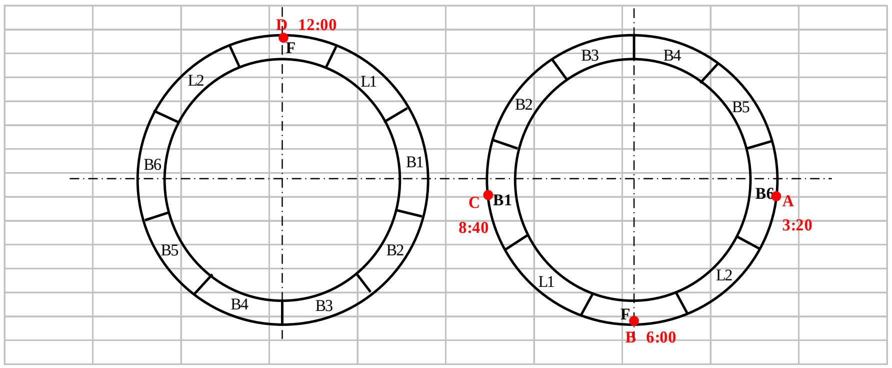
● ▮ : Special clamping devices

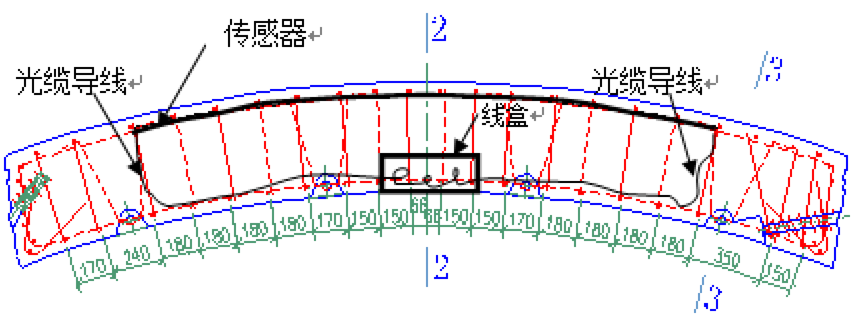
Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

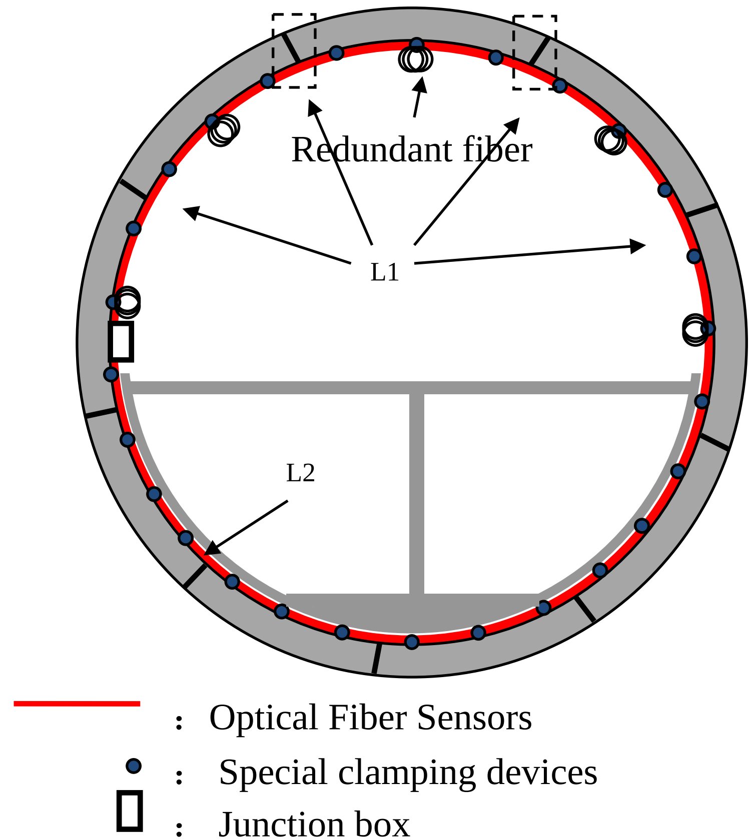
- Implementing Plan

Inner-force monitoring

Diameter monitoring

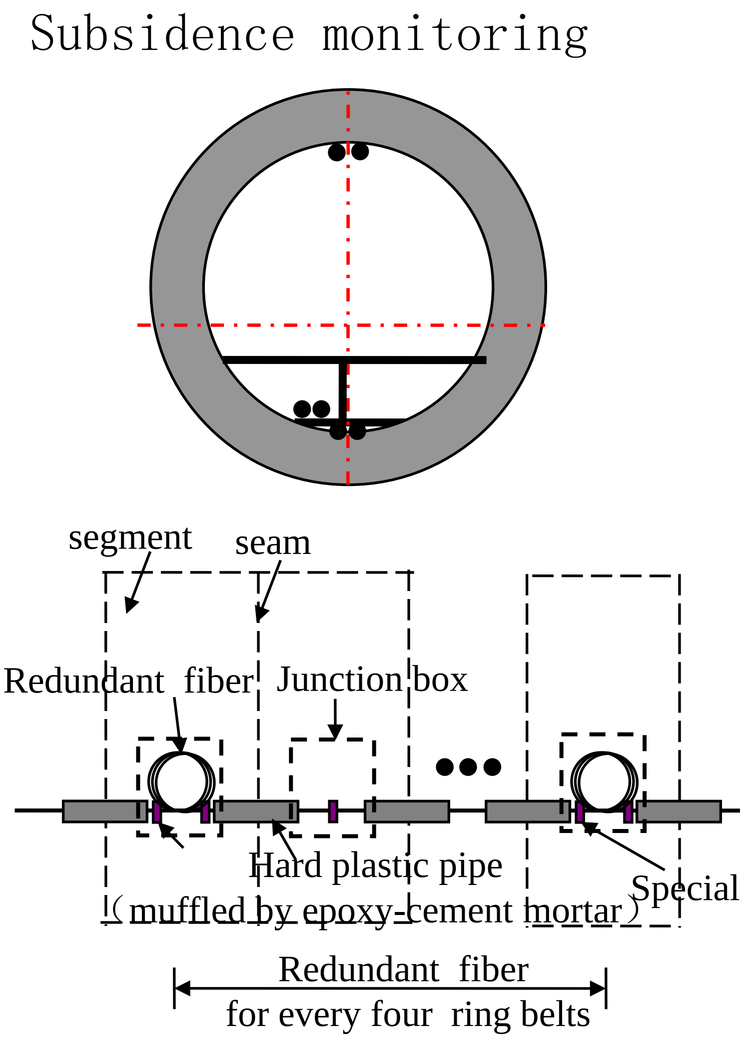


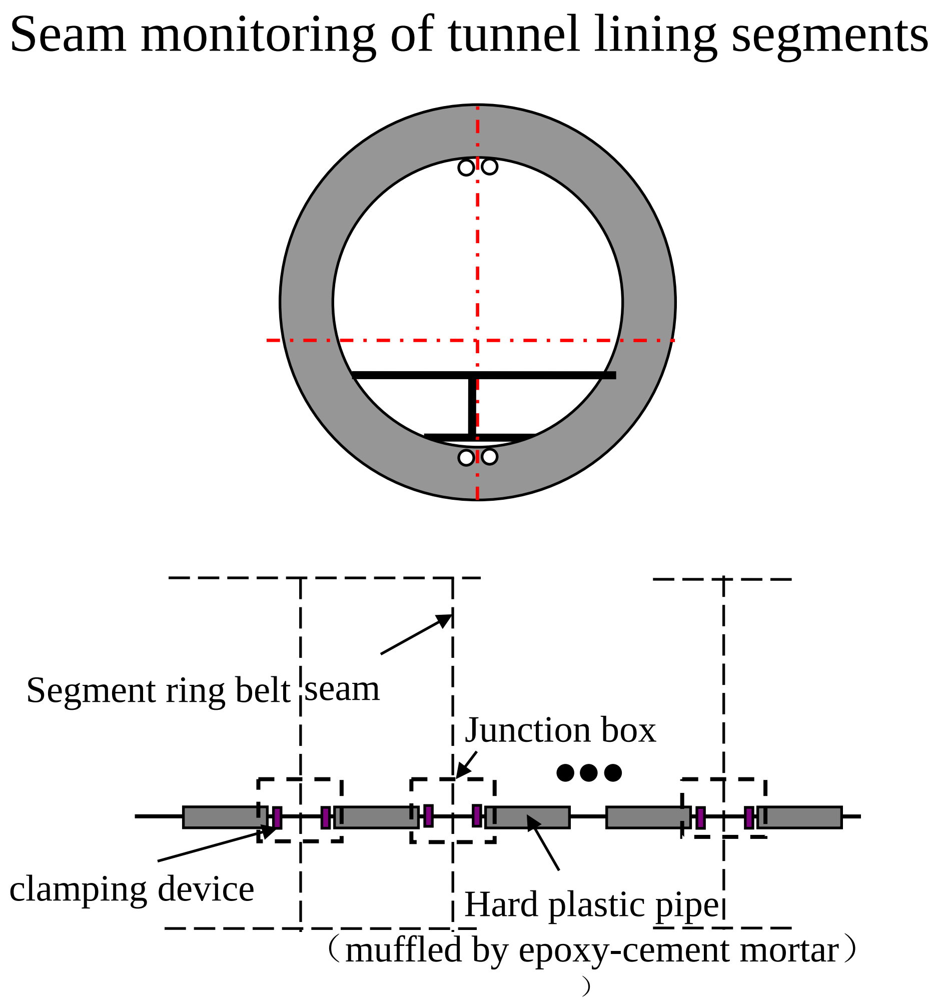




Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

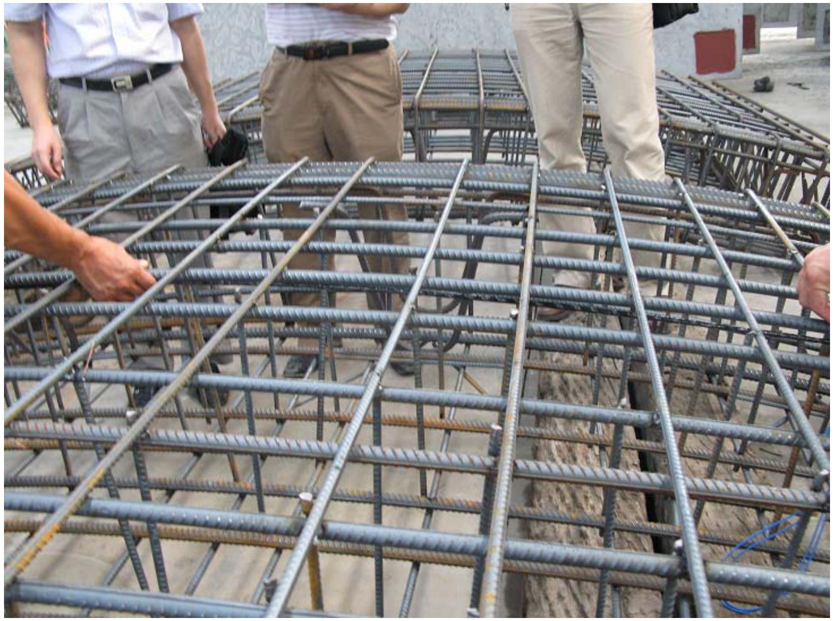
- Implementing Plan





Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

- Real Deployment of Sensors for Inner Force Monitoring

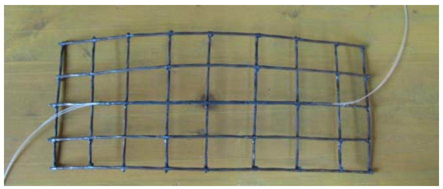


Optical sensor at the bottom of the main reinforcement

Junction box fixing

Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

- Model-based Experiments
  - Model making

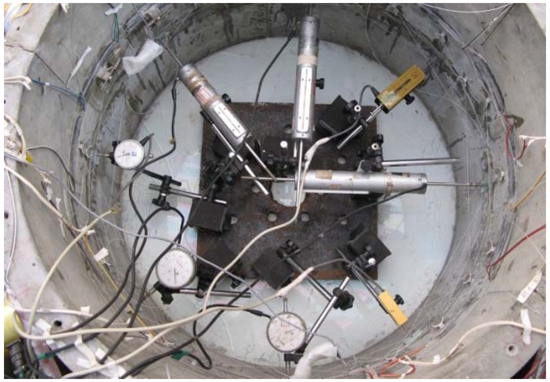



  - Segments assembling



Qingchun Lu Tunnel Monitoring Using Distributed Optical Fiber Sensing Technology

- Model-based Experiments
  - Optical Fiber Sensor Deployment Loading



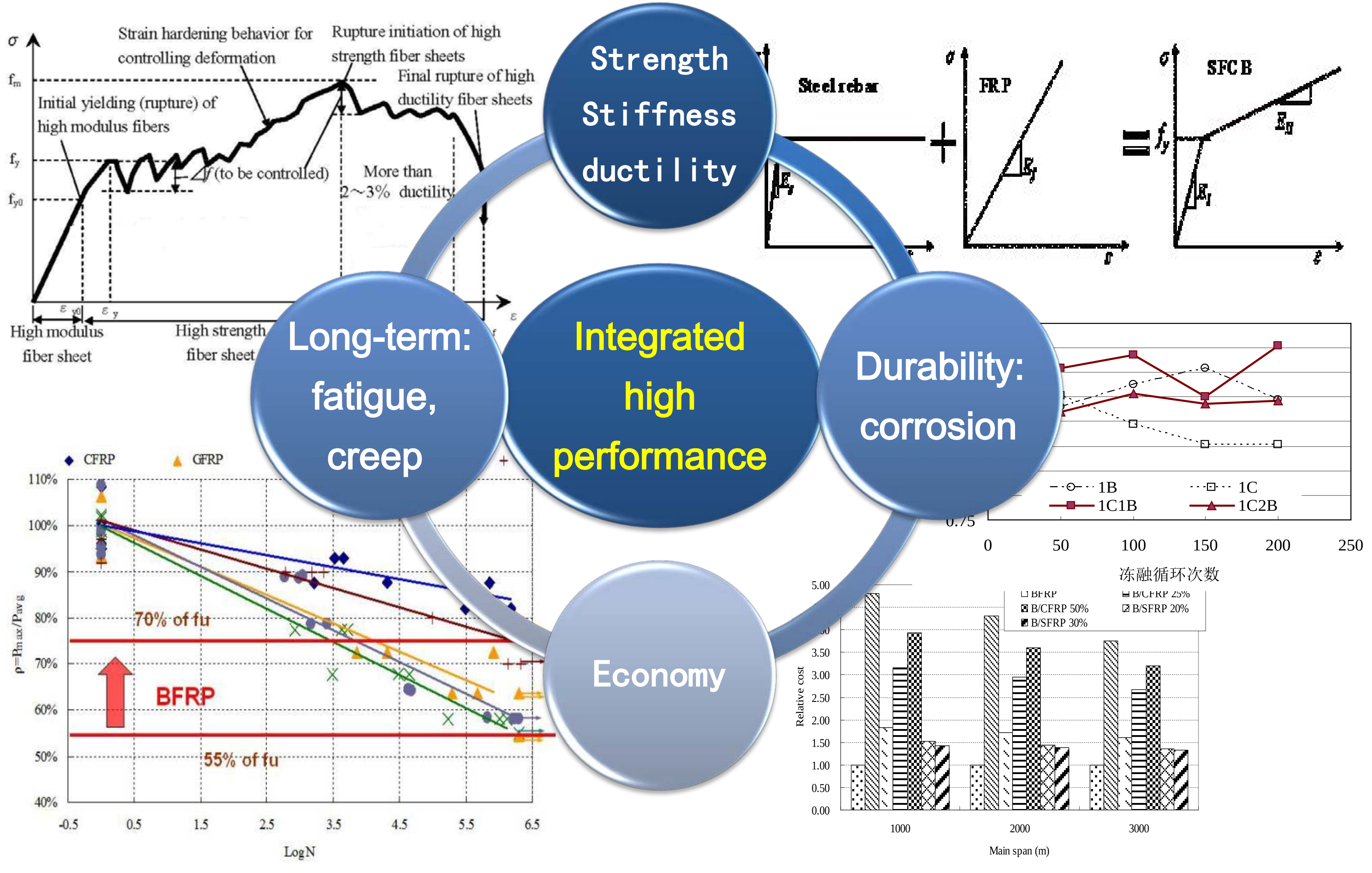
Outline

1. Background
2. Introduction of FRP and research status
3. Hybrid FRP technology
4. Prestressing FRP technology
5. Damage-controllable FRP structures
6. Integrated high performance FRP structures
7. Intelligent infrastructures
8. Summary and future work

Summary

- ✓ Enhance FRP by hybridization
- ✓ Sufficiently use FRP by prestressing
- ✓ FRP realizing Damage-controllable structures
- ✓ FRP achieving integrated high performance structures
- ✓ Combining optic sensors with FRP: Self-sensing FRP bar

Future work: Enhancement of integrated behavior of FRP



Future work: Mechanism and design method of large-sized structure with FRP

Current: small sized structure

FRP confined column less than 200mm

Size effect of FRP

Strength and failure strain variable

fracture mechanism of large-sized structures, unclear!

Safety factor deficiency

Based on reliability

Brittle material → Ductile member → Ductile structure

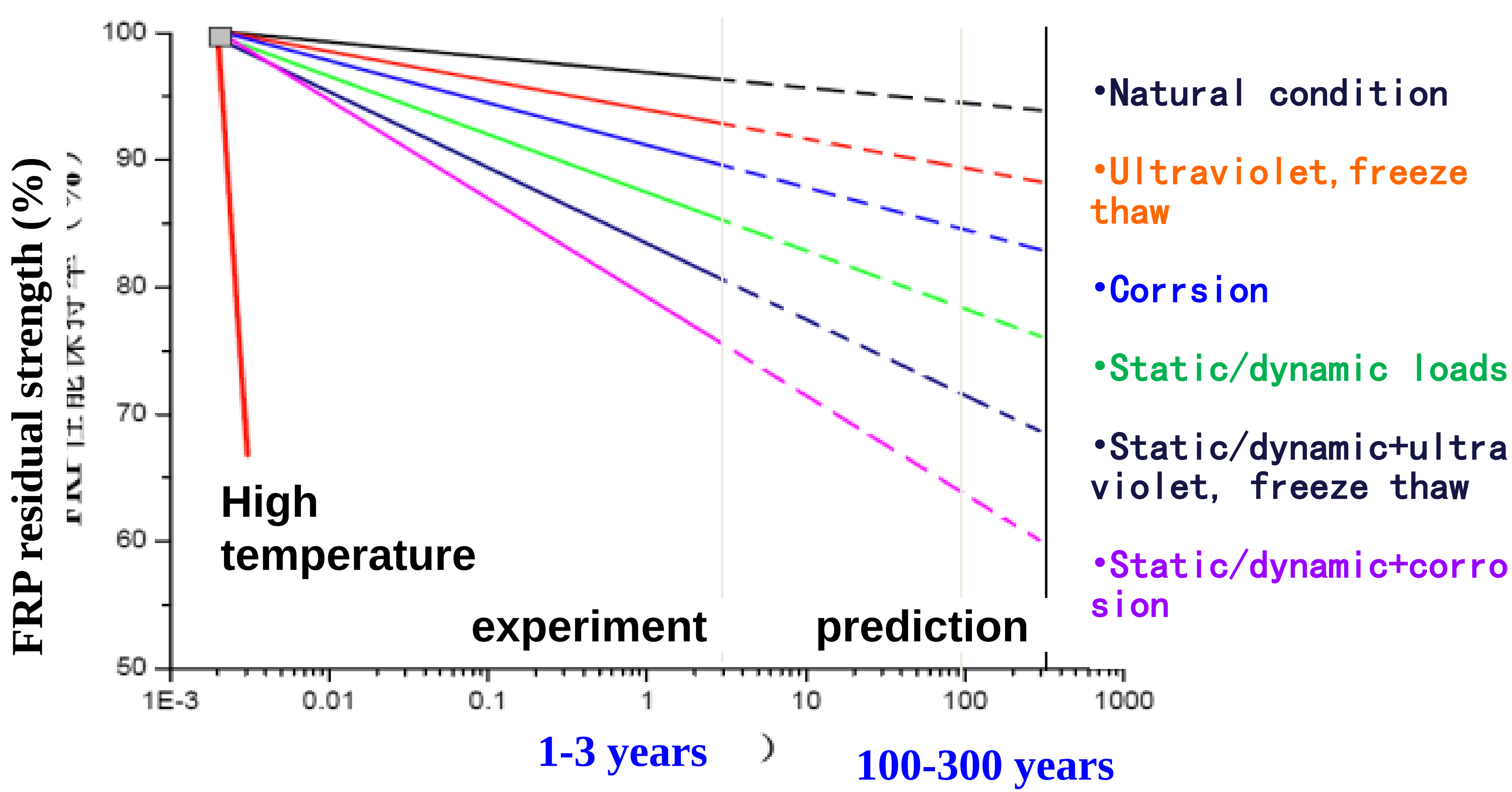
refer

Strength design

Damage allowable design

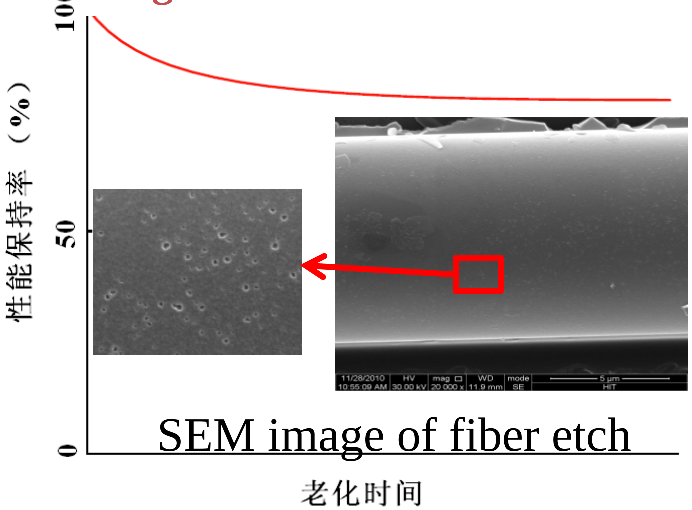
Fracture controllable design

Future work: Fatigue and creep behavior FRP under muti-field coupling and life controllability

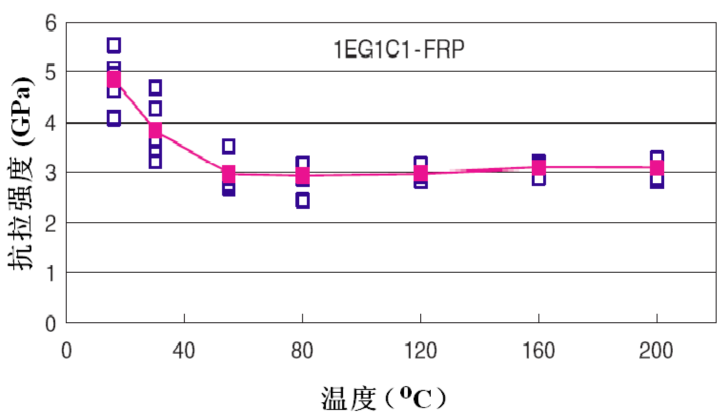


Future work: FRP under ultimate severe conditions

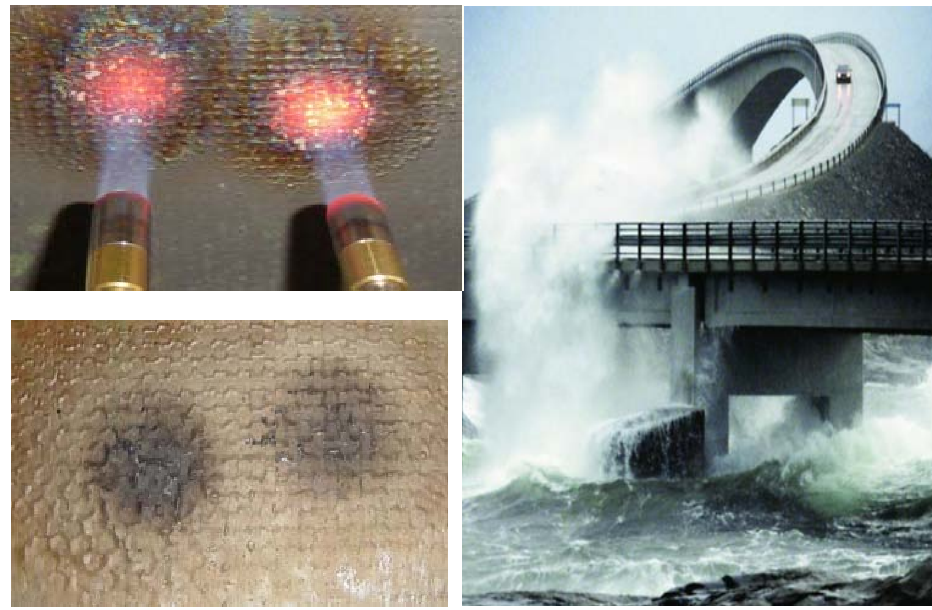
Degradation of FRP



SEM image of fiber etch



Residual strength under high temperature



High temperature, such as fire, severe corrosive environments

Future work: Disaster mechanism and recoverability of FRP structures under extreme loads

Seismic behavior

RC column

RC column with FRP

Anti-blast behavior

RC wall

RC wall with FRP

Thank you for you attention

And questions?