April 3rd – 4th, 2023
ACI Spring Convention, San Francisco

ACI / JCI – 6th Joint Seminar on Advancing the Design of Concrete Structures

Session 3 Design for Seismic Performance

New design codes for foundation members considering their ultimate conditions

Sam Kono (Tokyo Institute of Technology)

Seismic design for buildings in Japan

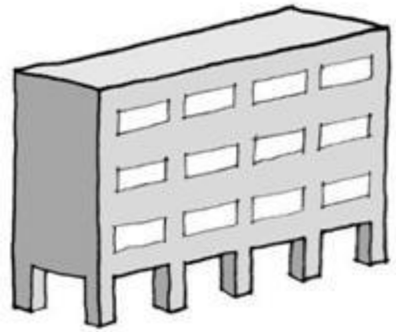
- 1st level design (Intermediate EQ)
  - Allowable stress design for Cb=0.2
    (Cb:Base shear coefficient)

- 2nd level design (Severe EQ)
  - Lateral load carrying capacity check for Cb=0.3 (MRF) ～0.55 (Wall)

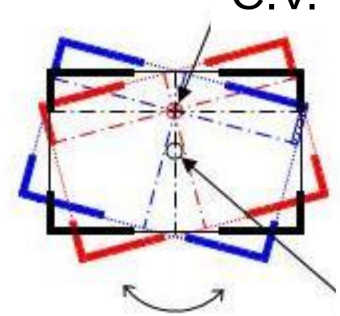
Japanese Building Standard Law
- Superstructure:「1st + 2nd」is required
- Foundation: Only「1st」is required.

Lessons from 1995 Kobe EQ

- Severe damage occurred to soft stories
  - Soft story needs strength/stiffness

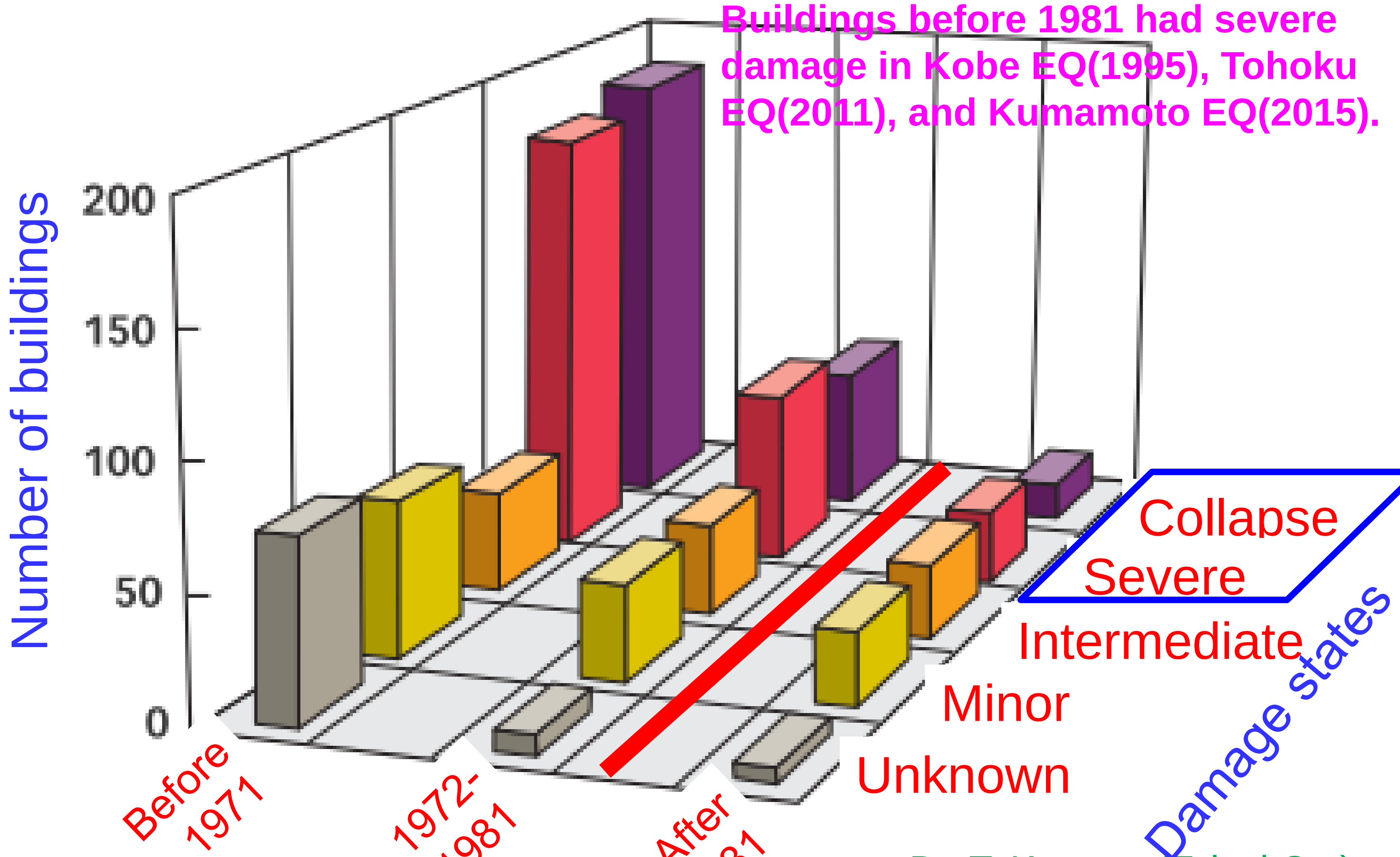


- Damage occurred due to torsion
  - Some members need large drift capacity



Lessons from 1995 Kobe Earthquake

Classification of damaged buildings from 1995 Kobe EQ

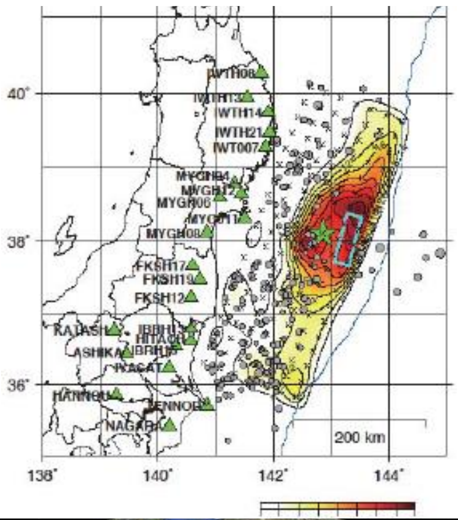


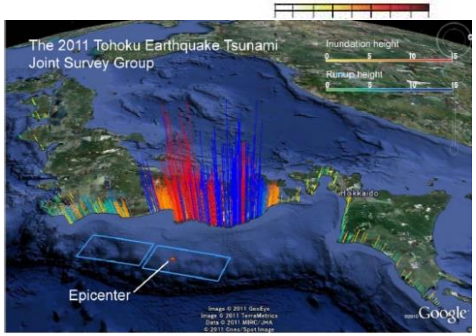
Dr. T. Komuro (Taisei Co.)

耐震補強講習会2012.11.27

Lessons from 2011 Tohoku EQ

Large scale EQ +Tsunami





Typical Damages

Courtesy: Dr. T. Mukai (BRI)

Lessons from 2011 Tohoku EQ

Resiliency can be severely hampered even from a single factor.

- RC non-structural walls
- Roof support at gymnasiums (schools for refugee camp)
- Concrete piles

Courtesy: Dr. T. Mukai (BRI)

Lessons from 2016 Kumamoto EQ

- Safety is still the most critical issue.

- The society wants to use its buildings continuously after EQ’s without losing any building functions.
  - Intermediate or severe damage to structural and non-structural elements cannot be accepted anymore.

Damage due to severe earthquakes

Resiliency of foundations

Damage to piles (2016 Kumamoto EQ)

Buildings following the current standard were demolished due to pile damage.

5-story apartment (1984)
Minor damage to superstructure
Demolished after evacuation

3-story municipal office (1980 +Retrofit 2012)
Intermediate damage to the superstructure
Demolished after a few months of use

Pile related code/events

1981 Building code
- Superstructure:
  - allowable +load carrying capacity
- Piles:
  - No regulations

1984 ASD(recommended)

1995 Kobe EQ. (safety check for severe EQ recommended)

2001 ASD (mandatory)
2017 M_n for some piles

Photo: Dr. T. Mukai (BRI)

Timber piles

Timber piles of Sagami river bridge was built in 1198. **(茅ケ崎市旧相模川橋脚)**
and found in 1924 after 1923 Kanto EQ.
https://japep.or.jp/history01/

Timber piles

Pine piles had supported an 8-story r/c building for 80 years.

東京駅前丸の内ビル（8 story）1923 - 2002

https://japep.or.jp/history01/

Steel piles

The first steel piles had a solid circular section used for a bridge in Osaka (1908). The section changed to H(wide flange) and hollow circular section.

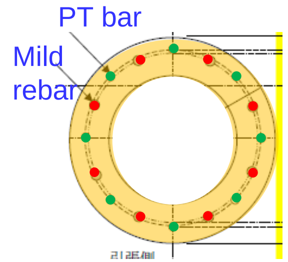
1908年大阪高麗橋の棒鋼杭が最初.その後，H形鋼杭から鋼管杭へ

https://japep.or.jp/history01/

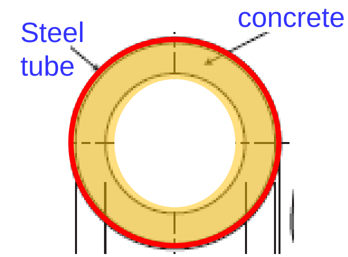
Typical concrete piles

- Precast concrete piles
  - PHC/PRC/CFST

    f'c=105MPa, Hollow section,
    D/ts=60～100, D=300～1200mm
    PT tendons (single wire), fy=1275MPa
    Mild long. rebars, fy≧345MPa
    Steel tube, fy=235MPa or 325MPa



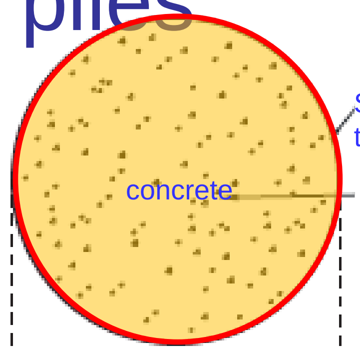
PHC / PRC pile



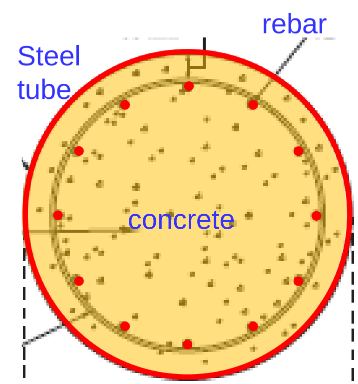
CFST pile

- Cast-in-place concrete piles
  - RC/CFST

    f'c=30－50MPa, Solid section,
    D/ts=100～200 , D=700～2500mm
    Mild long. rebars, fy ≧ 345MPa
    Steel tube, fy=235MPa or 325MPa



CFST pile



RC / RCFST pile

Different piles have different pile caps.

Precast concrete pile

Concrete piles

1910: On-site precast piles with square section

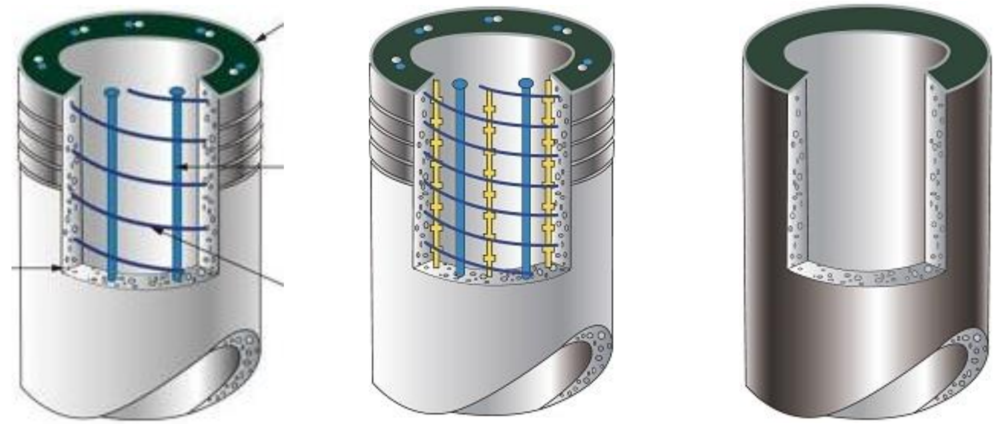
1934: Centrifugal r/c concrete piles

1967: Centrifugal prestressed concrete piles (Tokyo metro. expressway)

1970: Centrifugal prestressed high-strength concrete piles （PHC pile）

1980s:Precast CFST piles

https://japep.or.jp/history01/



PHC PRC CFST

Precast concrete piles

f’c=105MPa, Hollow section, D/ts=60～100, D=300～1200mm

PT tendons (single wire), fy=1275MPa

Mild rebars, fy≧345MPa

Steel tube, fy=235MPa or 325MPa

PHC piles (prestressed)

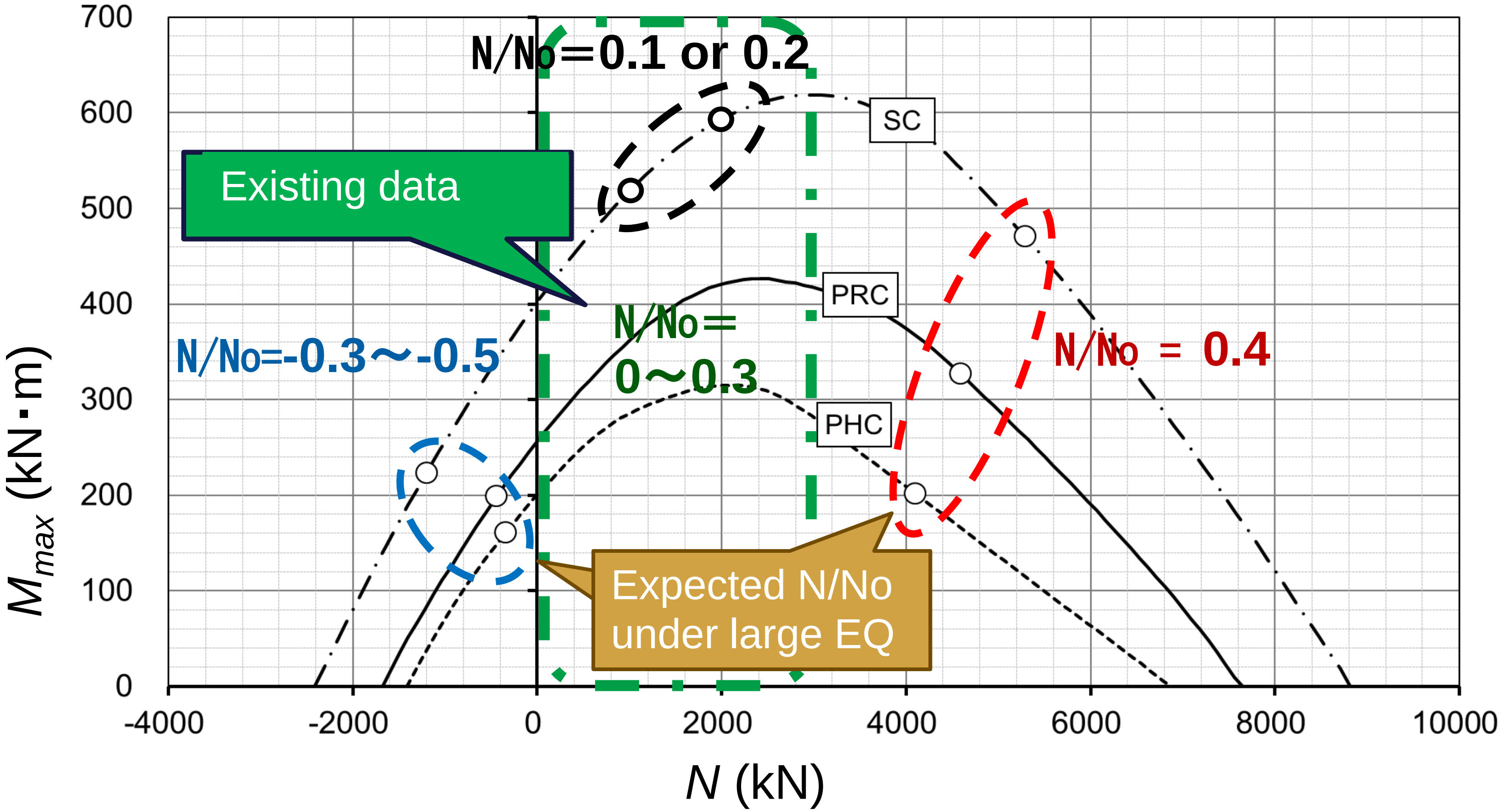
PRC piles (PHC + mild rebars)

Precast CFST piles (no rebars/tendons)

Flexural behavior of precast piles

Test variables

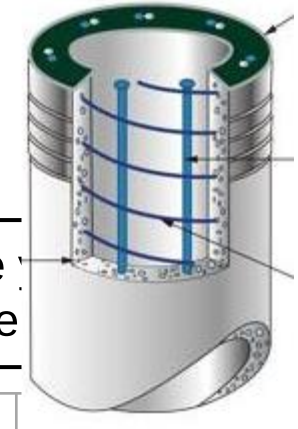
Type and N/No

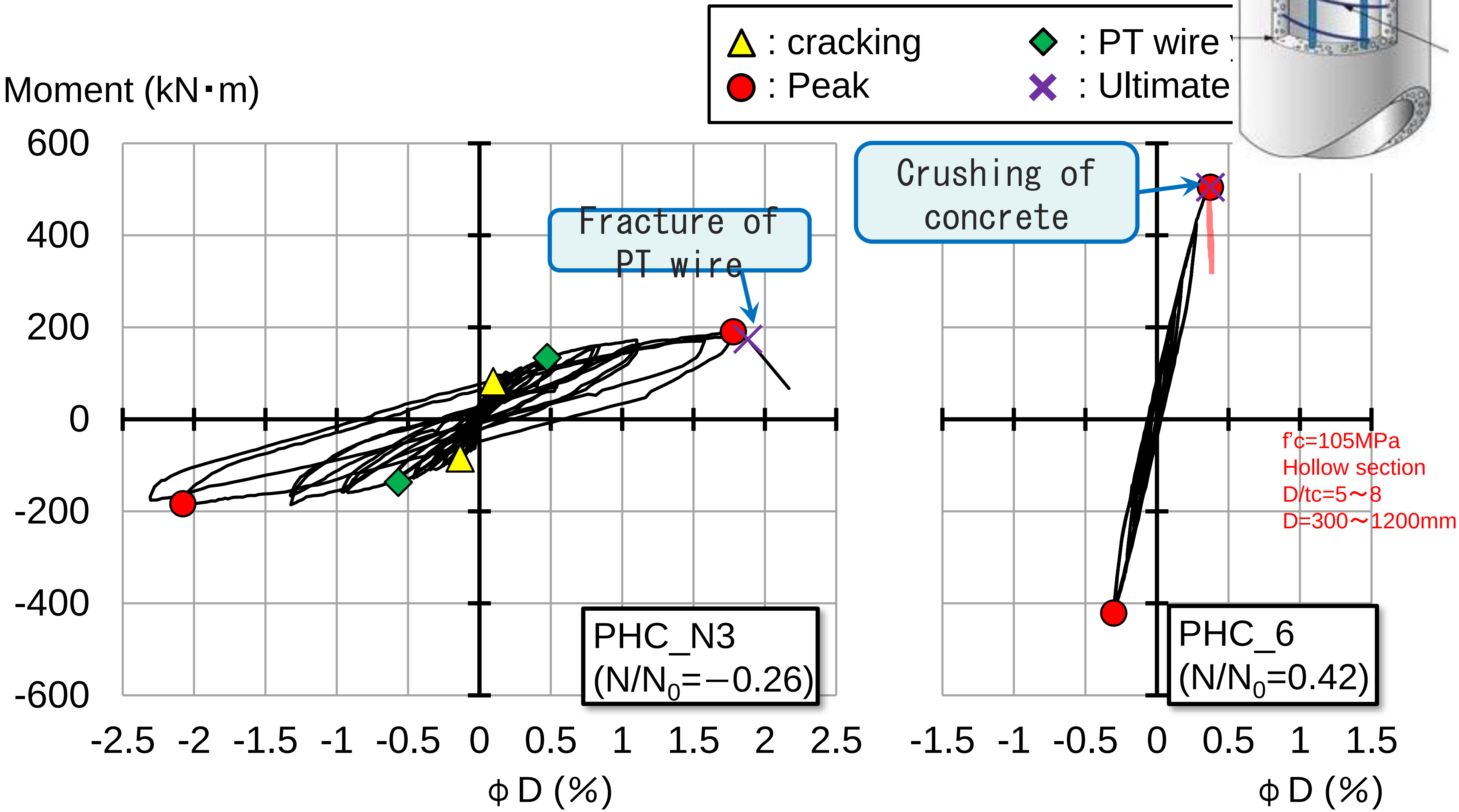


Bending behavior under tensile or high compressive force was examined.
M-φ was simulated with fiber analysis.

Loading system in BRI

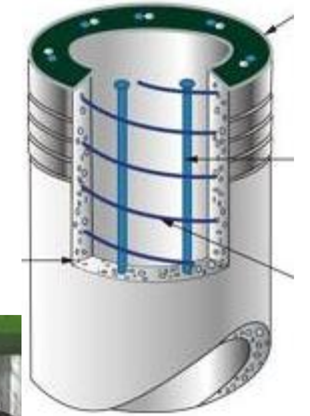
PHC (D=400mm)

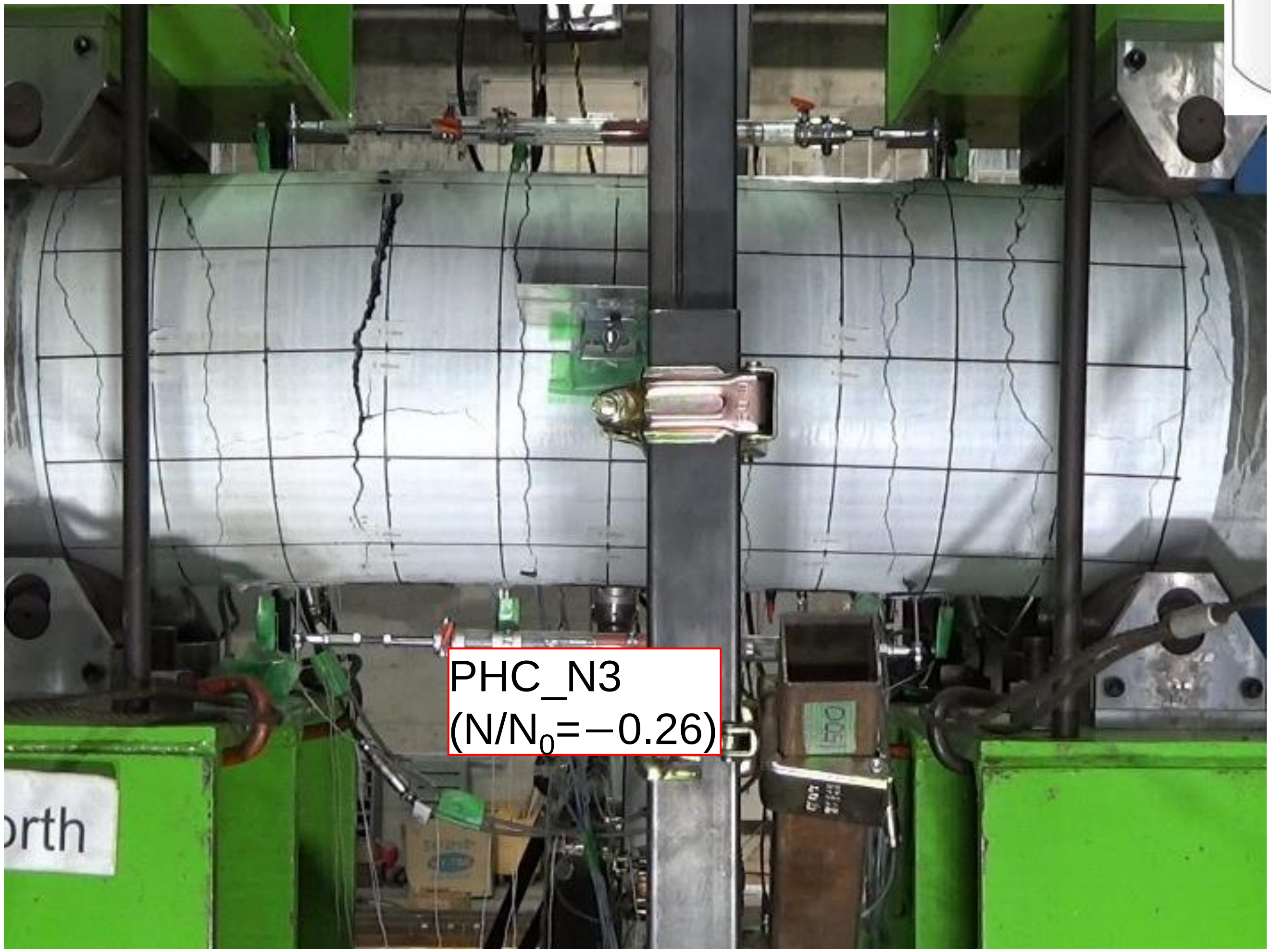



: cracking
: PT wire y
: Peak
: Ultimate
Moment (kN・m)
600
400
200
0
-200
-400
-600
Fracture of PT wire
Crushing of concrete
PHC_N3
(N/N$_0$=−0.26)
PHC_6
(N/N$_0$=0.42)
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
-1.5 -1 -0.5 0 0.5 1 1.5
φD (%)
φD (%)
f'c=105MPa
Hollow section
D/tc=5～8
D=300～1200mm

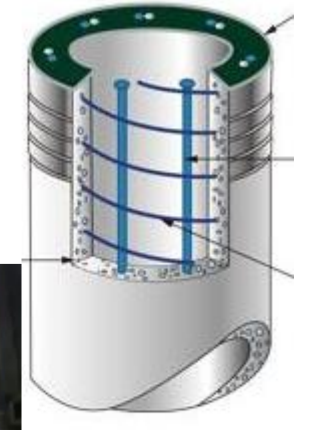
PHC (D=400mm)

$N/N_0=-0.26$

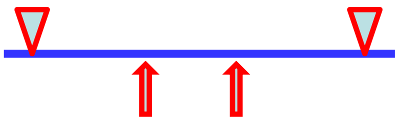


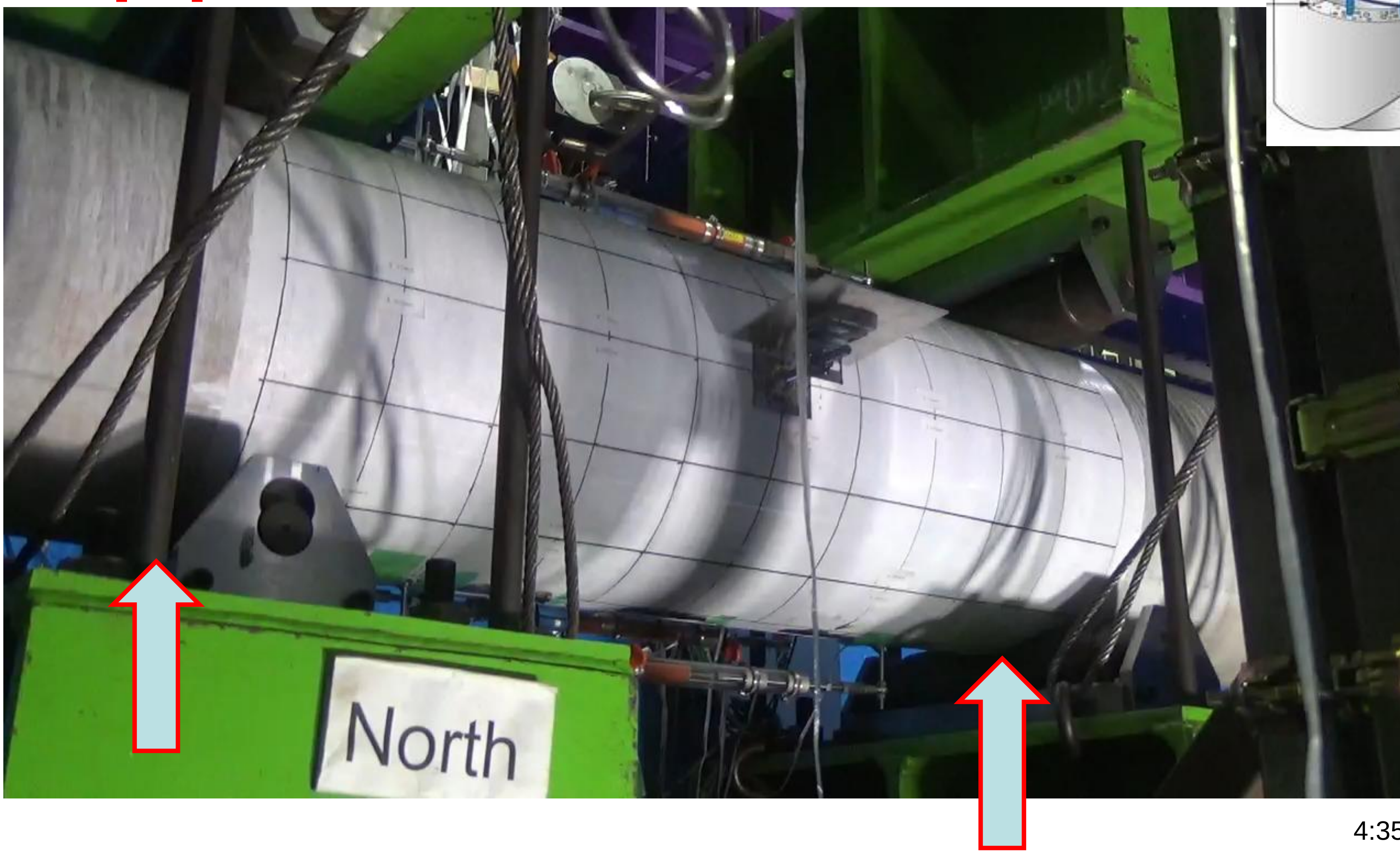


PHC (D=400mm)



N/No=0.42





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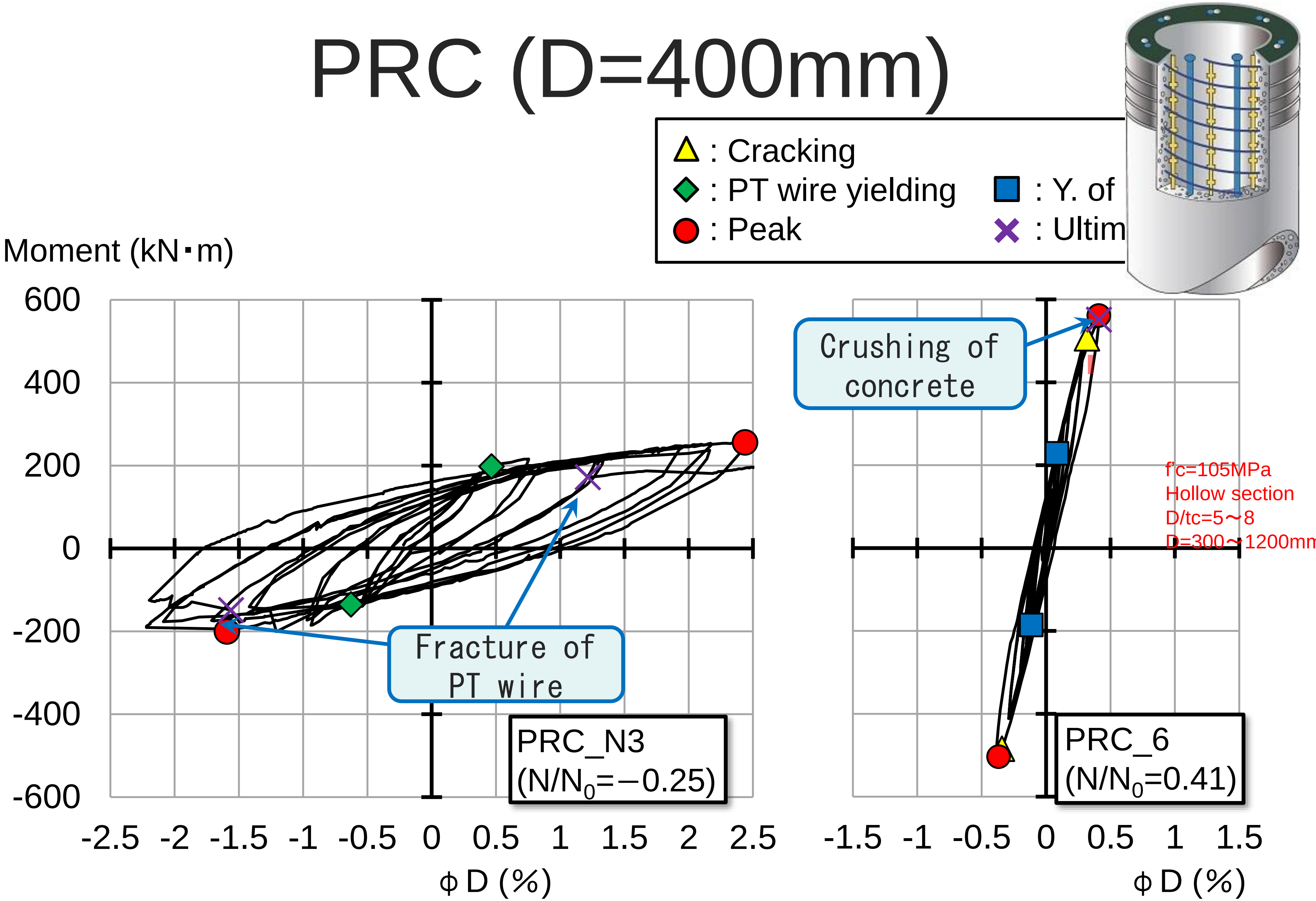
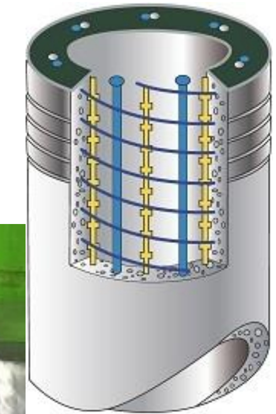
Sam Kono at Tokyo Tech

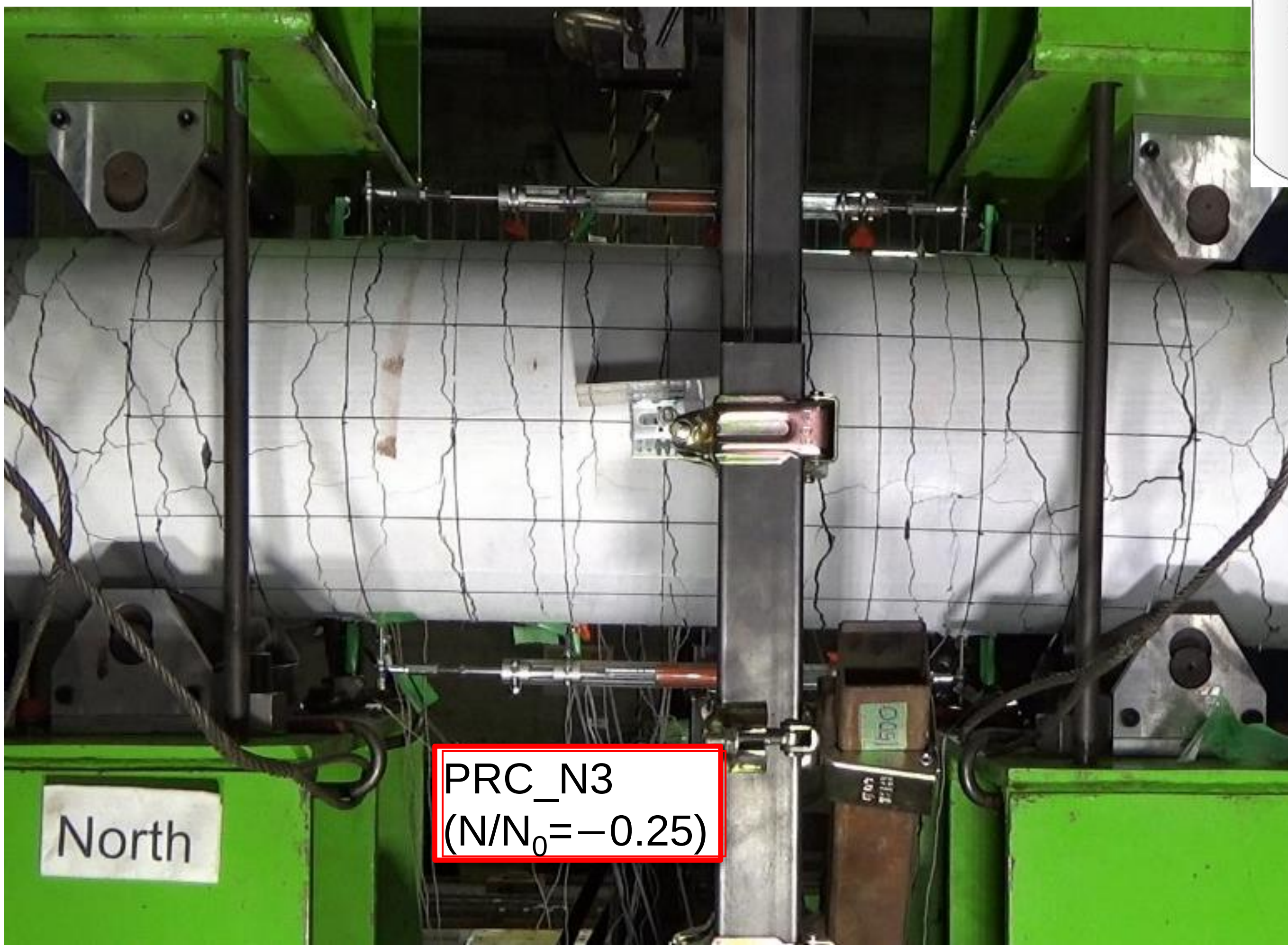
PRC (D=400mm)


: Cracking
: PT wire yielding
: Peak
: Y. of
: Ultim
Moment (kN・m)
600
400
200
0
-200
-400
-600
Crushing of concrete
Fracture of PT wire
PRC_N3
(N/N0=−0.25)
PRC_6
(N/N0=0.41)
f'c=105MPa
Hollow section
D/tc=5～8
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
φD (%)
-1.5 -1 -0.5 0 0.5 1 1.5
φD (%)

PRC (D=400mm)

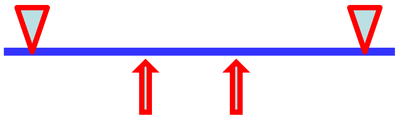
$N/N_0 = -0.25$

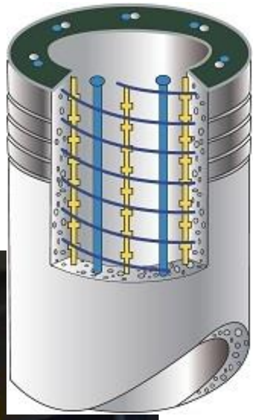


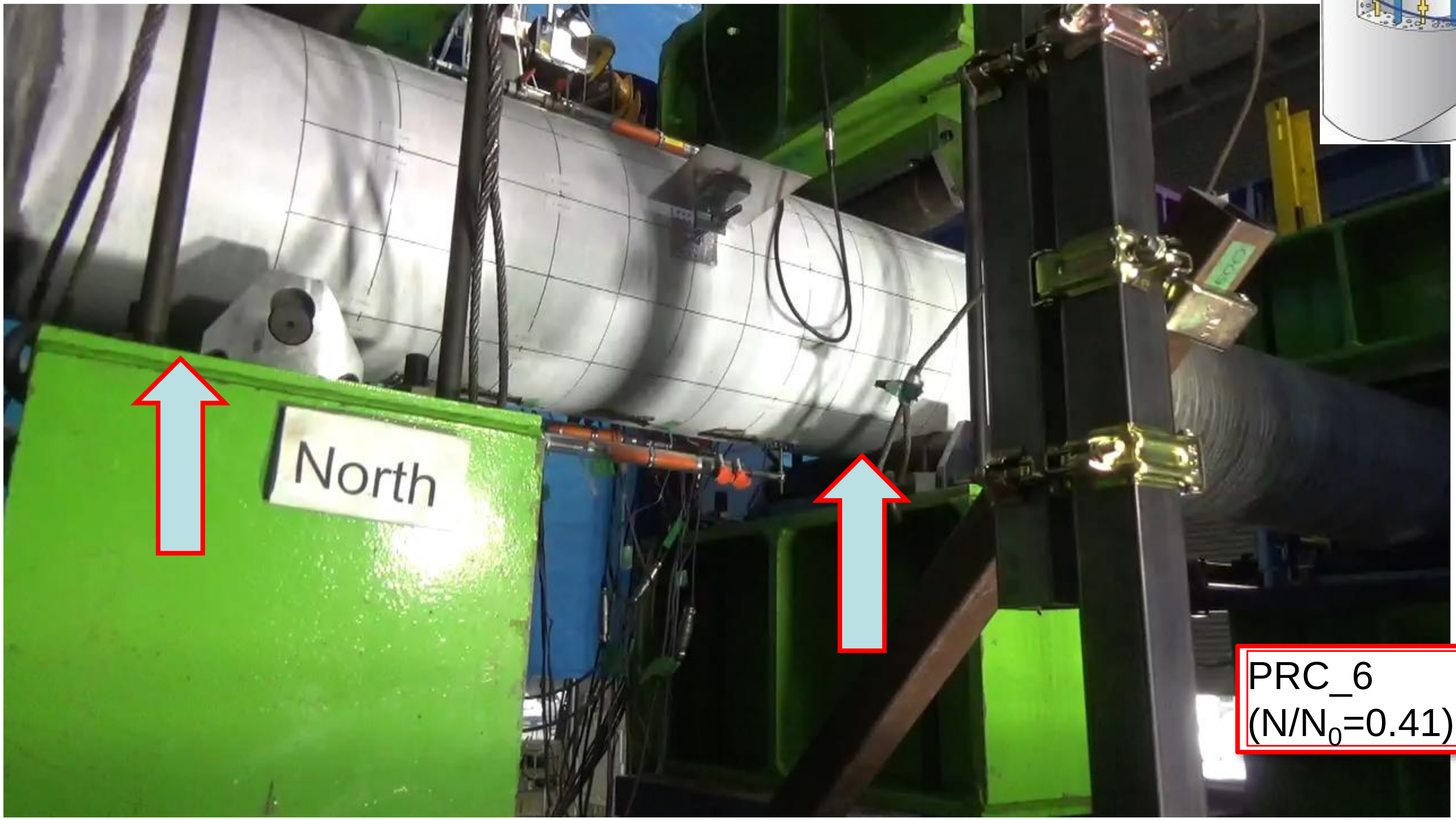


PRC (D=400mm)

N/No=0.41

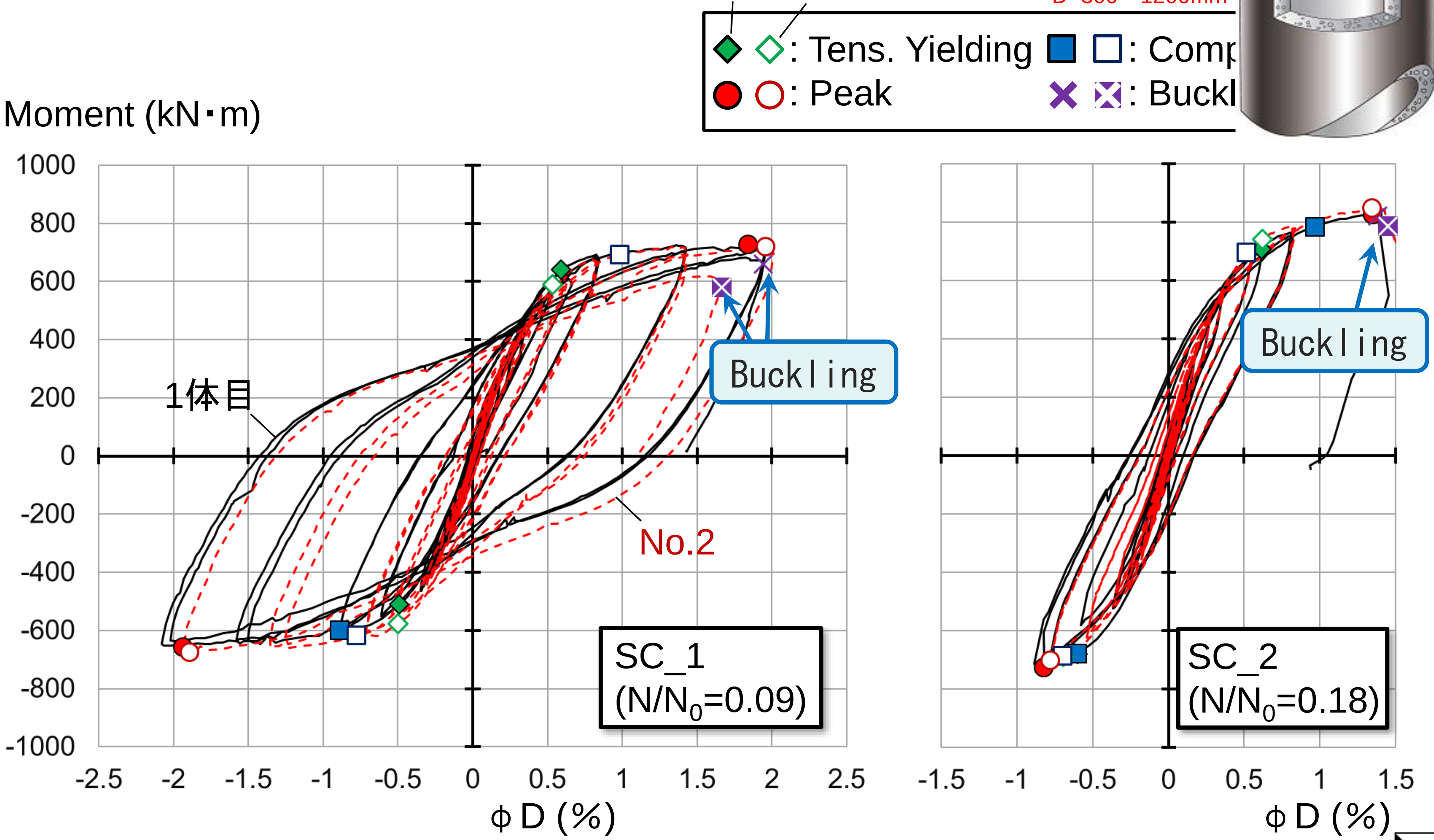






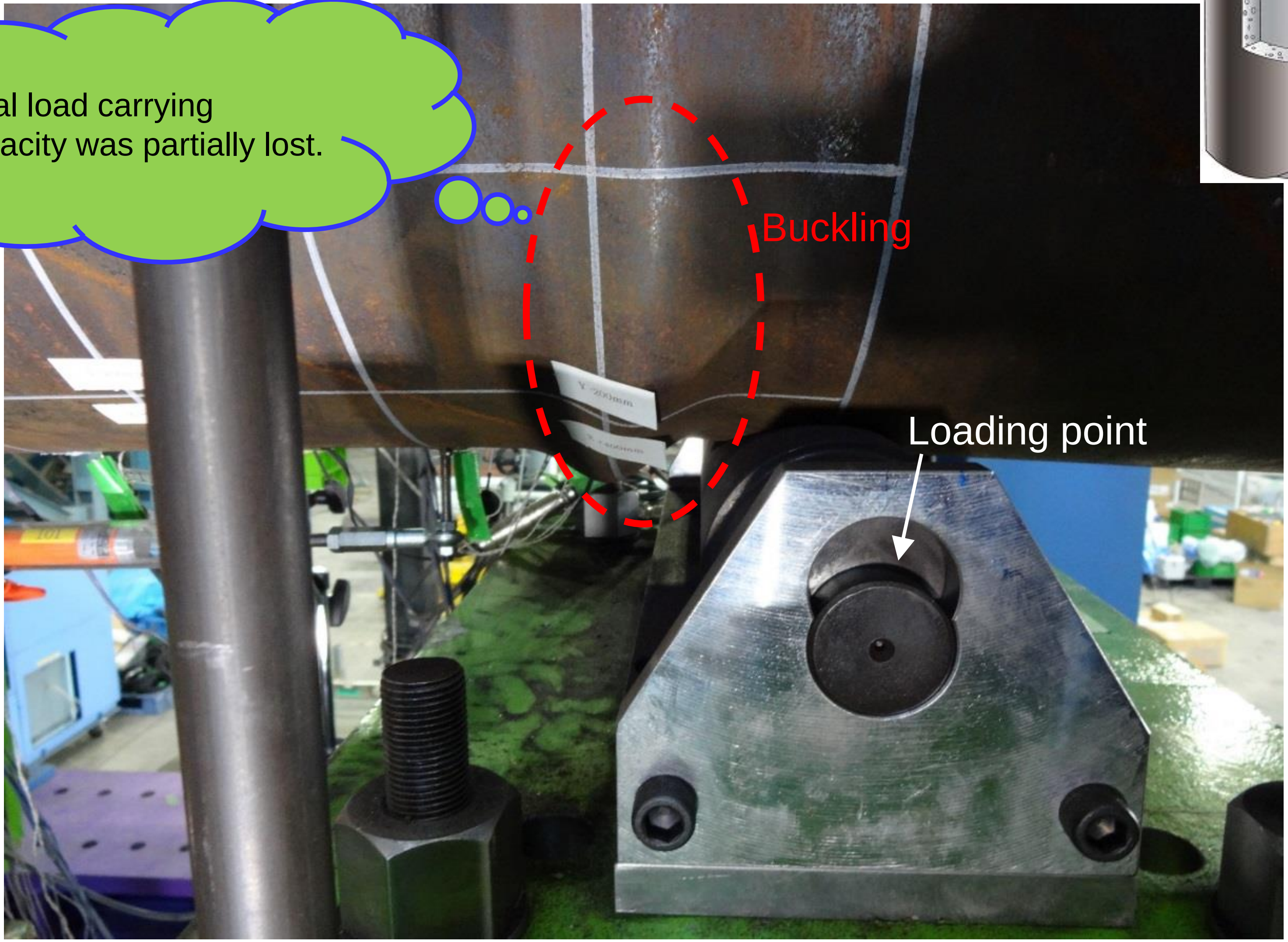
CFST piles

f'c=105MPa
Hollow section
D/ts=40～100
D=300～1200mm



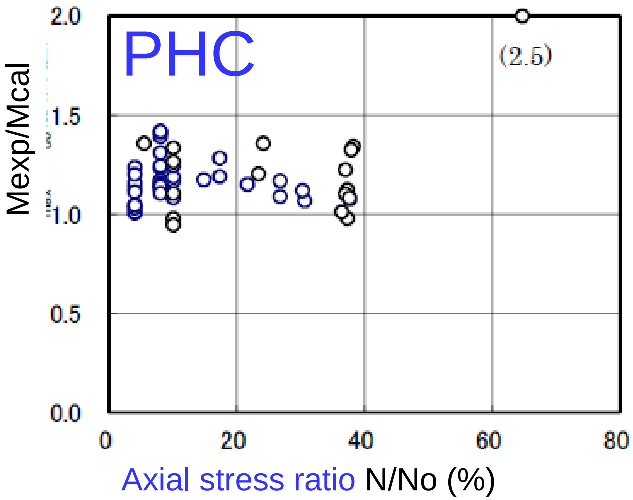
CFST piles

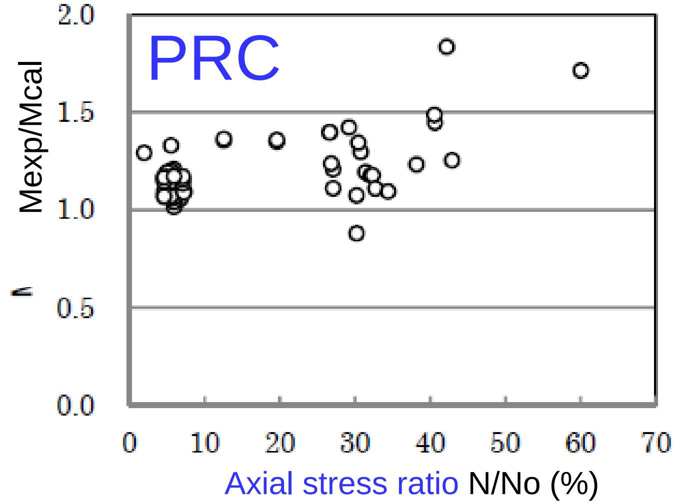
N/No=0.18



M_{max}/M_{cal} for PHC/PRC

M_{cal} is based on the section analysis. Concrete model is nearly linear till ε_{cu}=0.0026 .

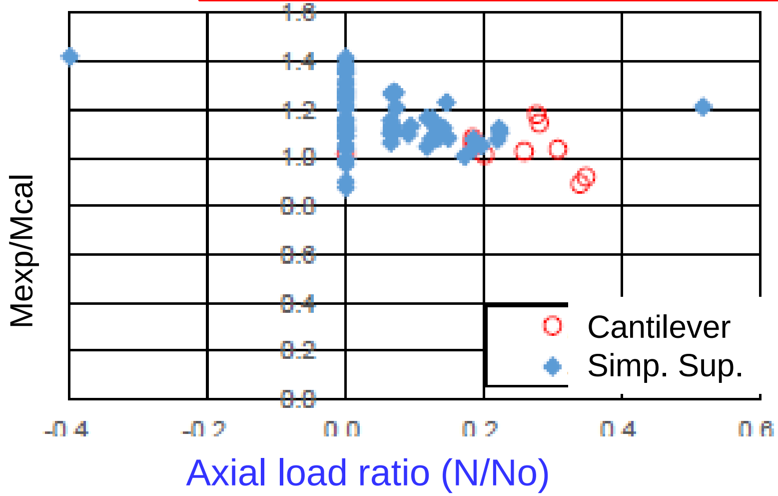


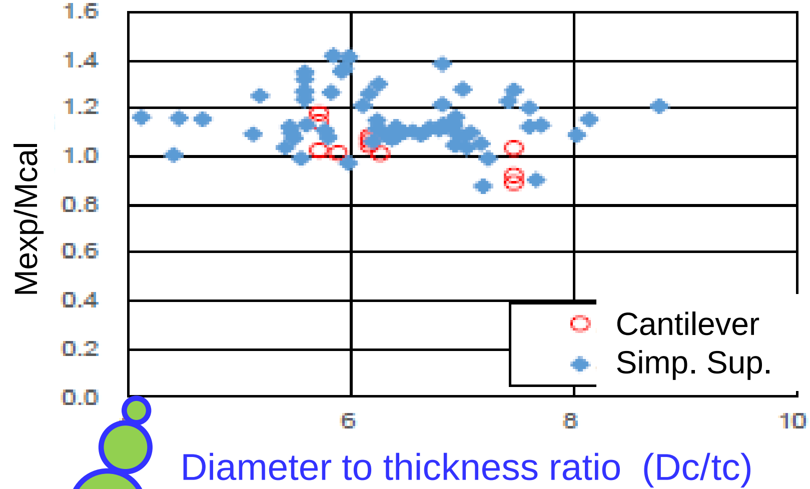


There should be penalties for scatter and brittle and/or explosive failure mode (complete loss of axial load carrying capacity).

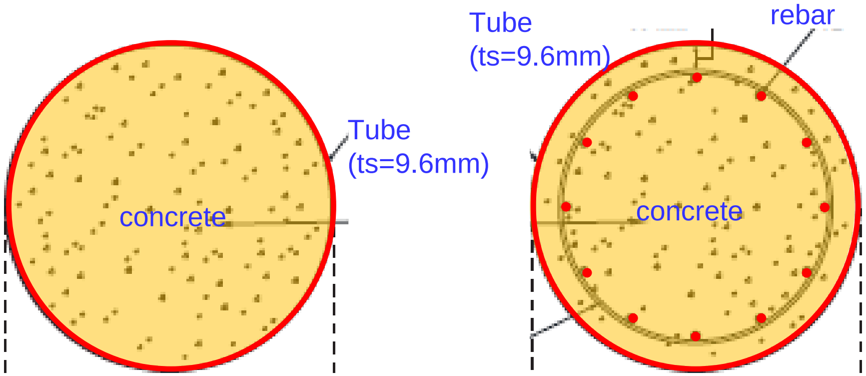
M_{max}/M_{cal} for precast CFST piles

M_{cal} is based on the section analysis. Concrete model is bilinear till ε_{cu}=0.004.



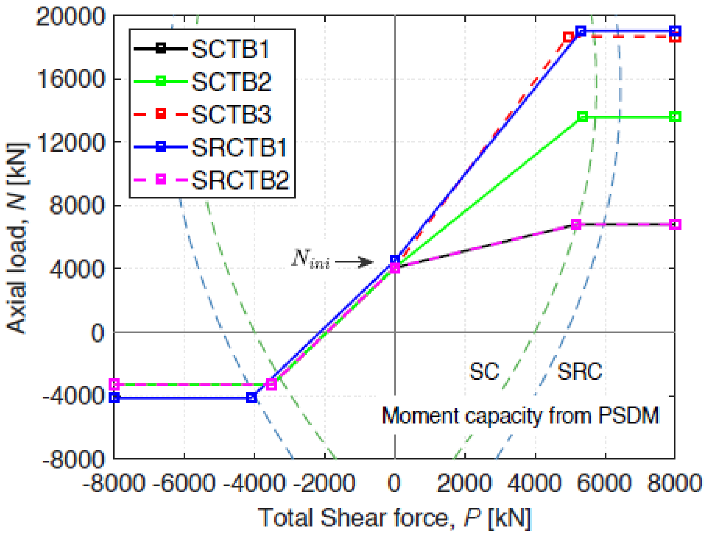


1. The limit strain ε_{cu}=0.004 should be revised.
2. There should be penalties for N/No and Dc/tc.
3. There should be some penalty for buckling of steel tube since axial load carrying capacity may be partially lost.



Cast-in-place CFST piles

f'c=30-40MPa, Solid section, D/ts=100～200, D=700～2700mm



Φ1200㎜ CFST pile

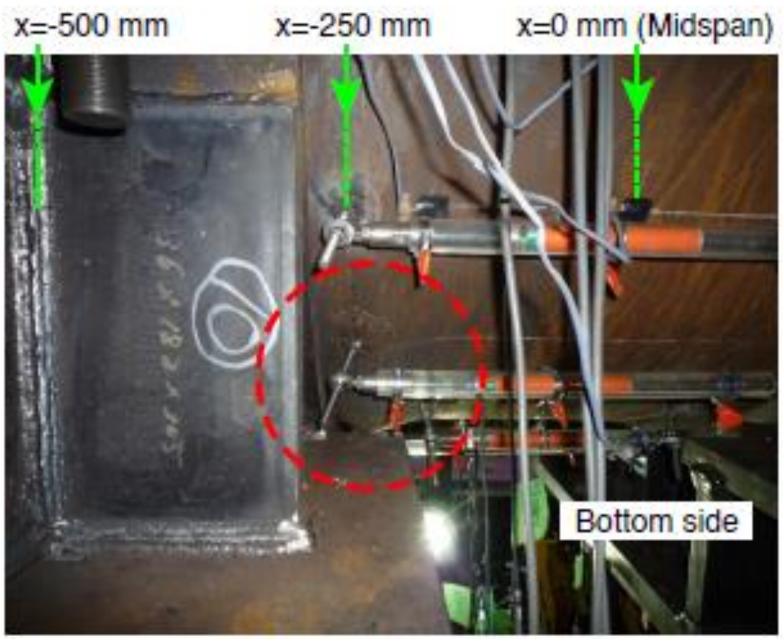
ts＝9.6㎜, f'c=30MPa,fy=430MPa

Specimen

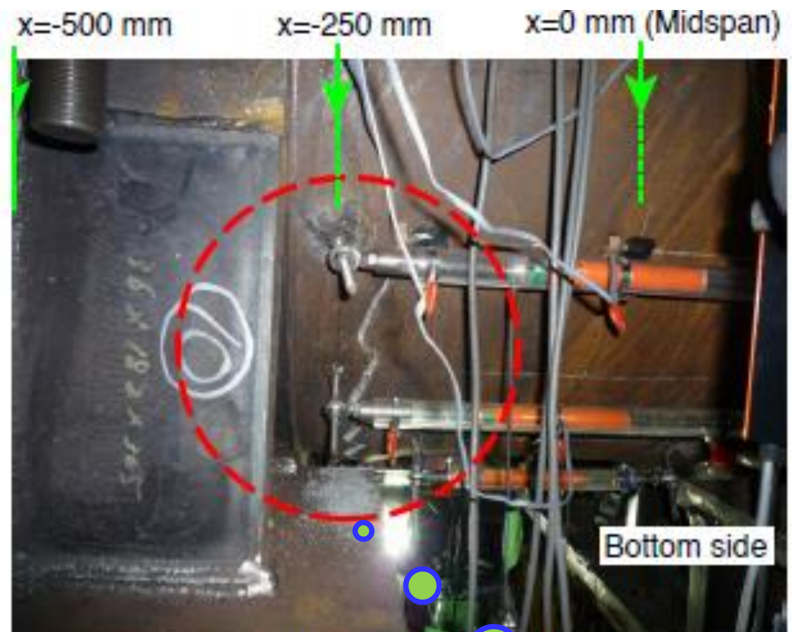
Internal ribs of steel tube（Φ＝1200mm）

Placing reinforcement cage in a steel tube

Cast-in-place CFST piles

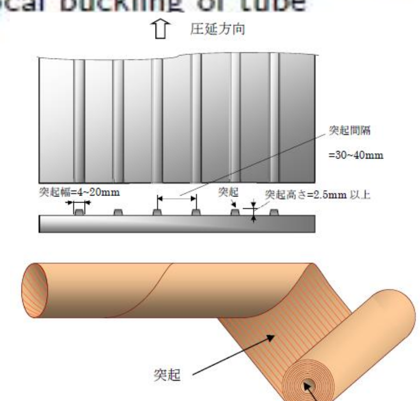


(a) Local buckling of tube

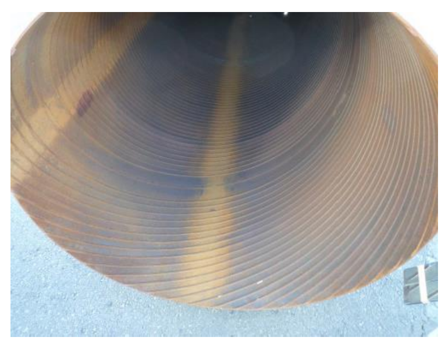


(b) Rupture of the tube

Rupture took place along the ribbed ridge after buckling.



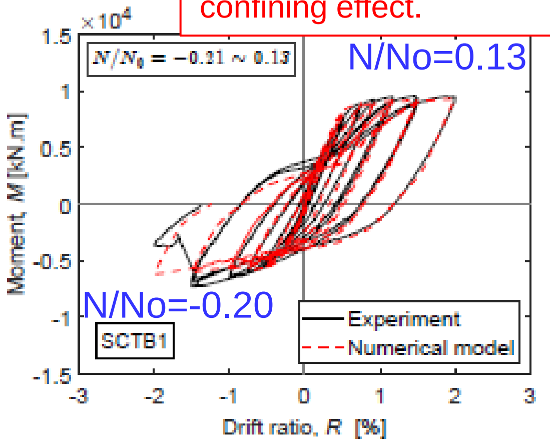
Fabrication of steel tube



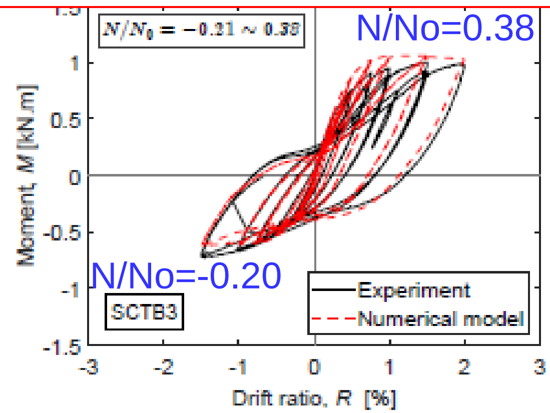
Internal view of tube

Cast-in-place CFST piles

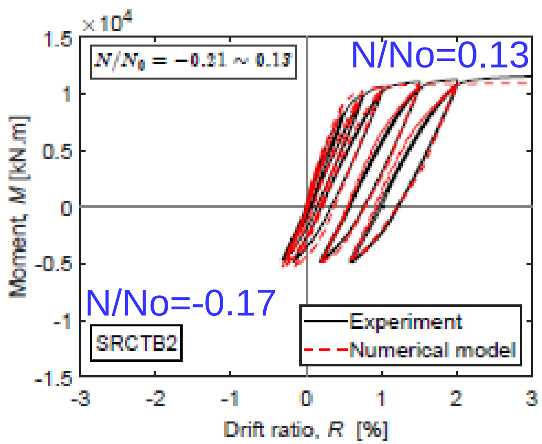
M_{cal} –R relation is based on a section analysis. Concrete model is basic one without confining effect.



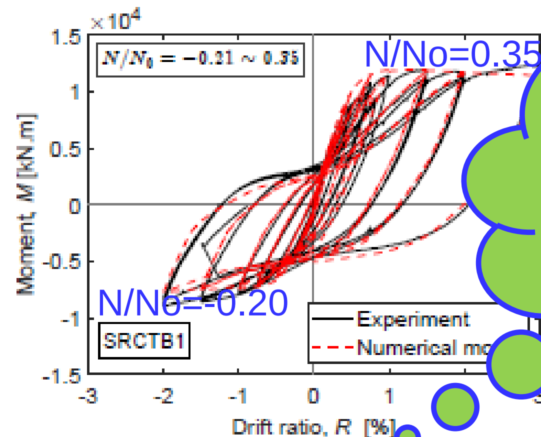
(a) SCTB1 (w/o rebars)



(b) SCTB3 (w/o rebars)



(d) SRCTB2 (w rebars)

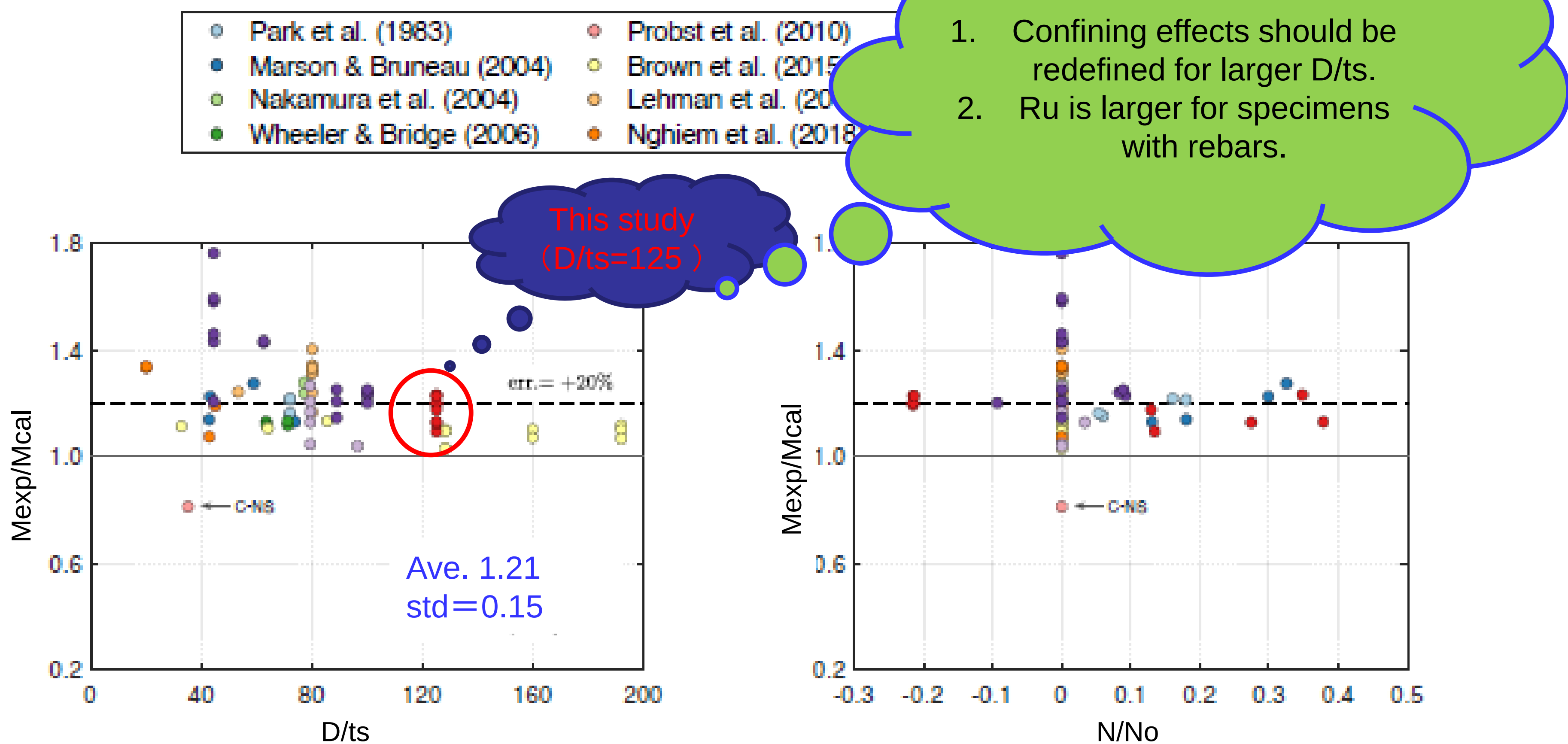


(c) SRCTB1 (w rebars)

1. Confining effects should be redefined for larger D/ts.
2. Ru is larger for specimens with rebars.

M_{max}/M_{cal} for Cast-in-place CFST

(1200mm≧D≧300mm)



Diameter to thickness ratio (D/ts)

Axial load ratio (N/No)

RC piles

(Φ800, pt=1.1%, pw=0.2%,)

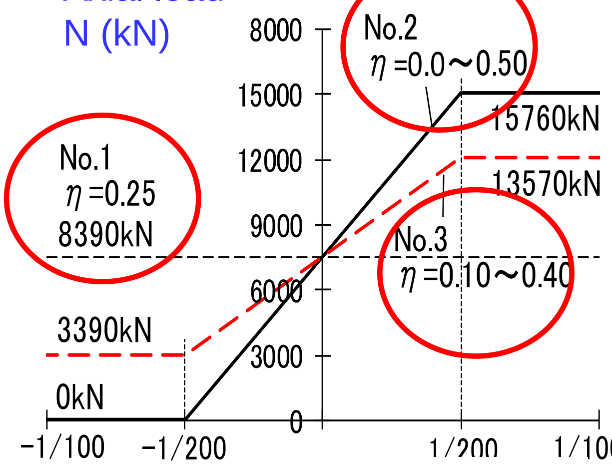
1. Behavior is sensitive to N/No.
2. There should be penalties for larger N/No and axial load-carrying capacity loss.

η=0.25

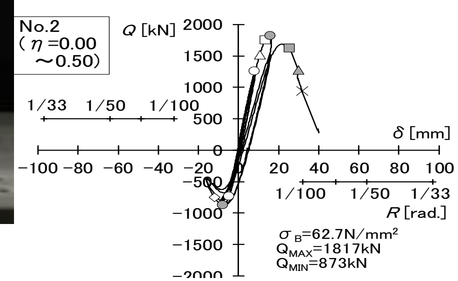
η=0〜0. 5

η=0.1〜0.4

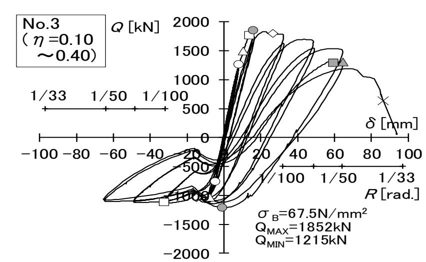
Axial load N (kN)



Drift ratio, R (rad)



η=0〜0. 5



η=0.1〜0.4

Data:Taisei Co.

Summary on Flexural behavior

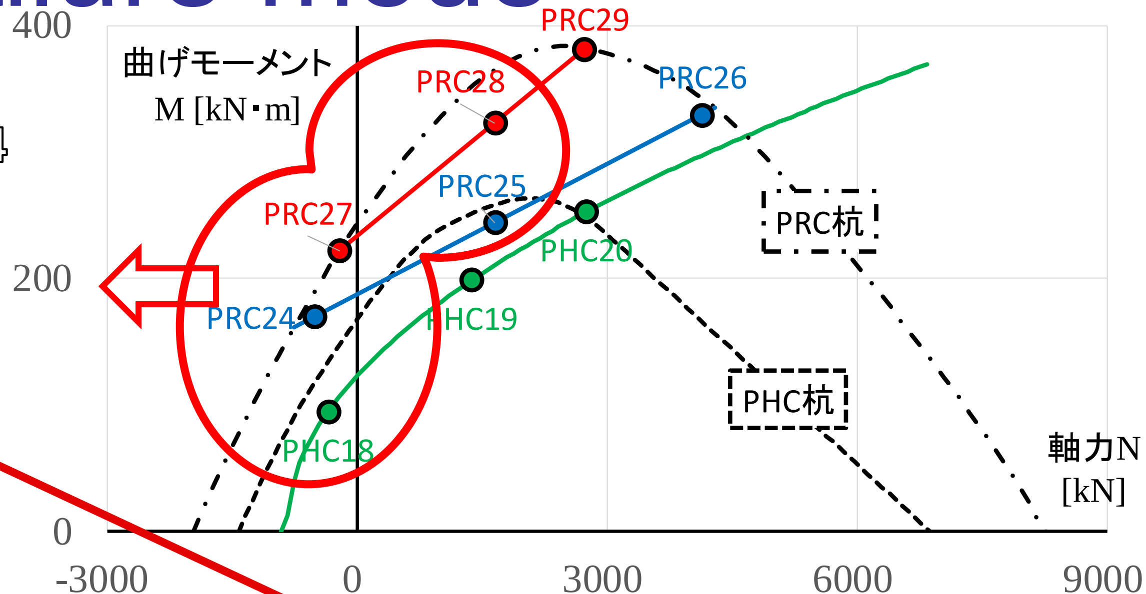
- PHC/PRC piles
  - The failure mode is extremely brittle and no inelastic deformation is expected.
  - They did NOT sustain axial load at the ultimate state.
- Precast/cast-in-place CFST piles
  - Failure is governed by buckling/fracture of steel tube.
  - Precast CFST piles did NOT sustain axial load at the ultimate state when $N/No \geqq 0.3$.
  - Cast-in-place CFST piles DID sustain axial load at the ultimate state.
- RC piles
  - Failure is governed by the crushing of concrete.
  - RC piles did NOT sustain axial load at the ultimate state when $N/N0 \geqq 0.4$.

Shear behavior of precast piles

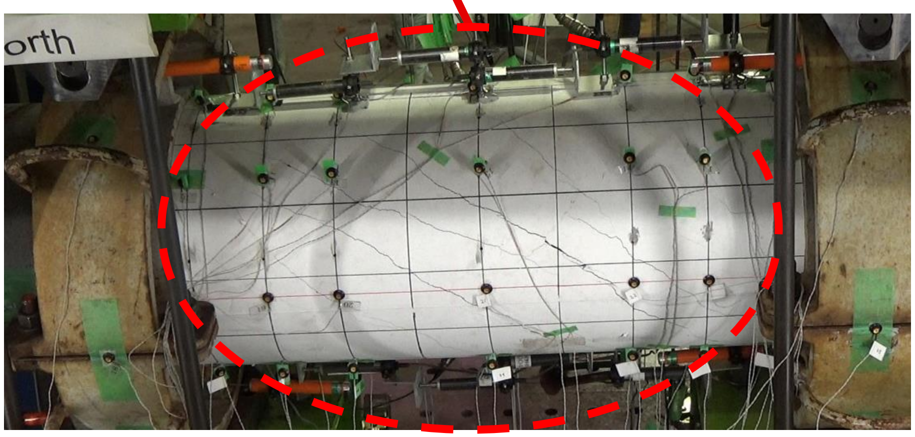
Failure mode

PRC27

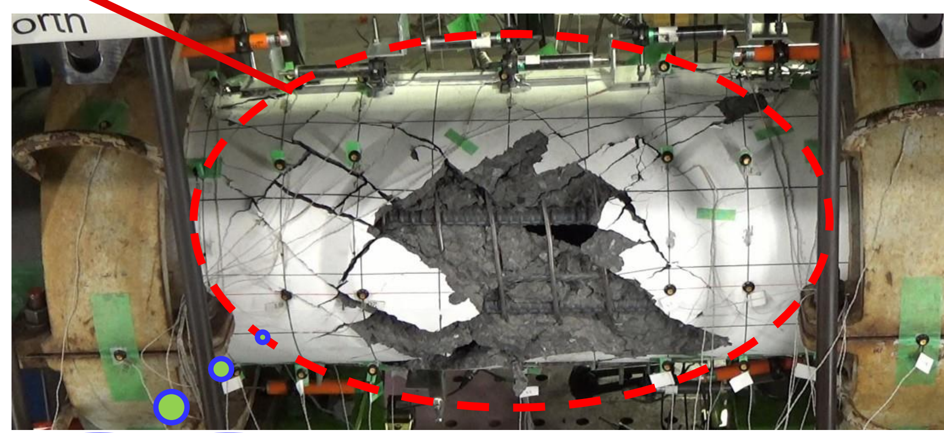
σ_0=-5.6MPa（Tensile） M/Qd=1.4



Diagonal cracks



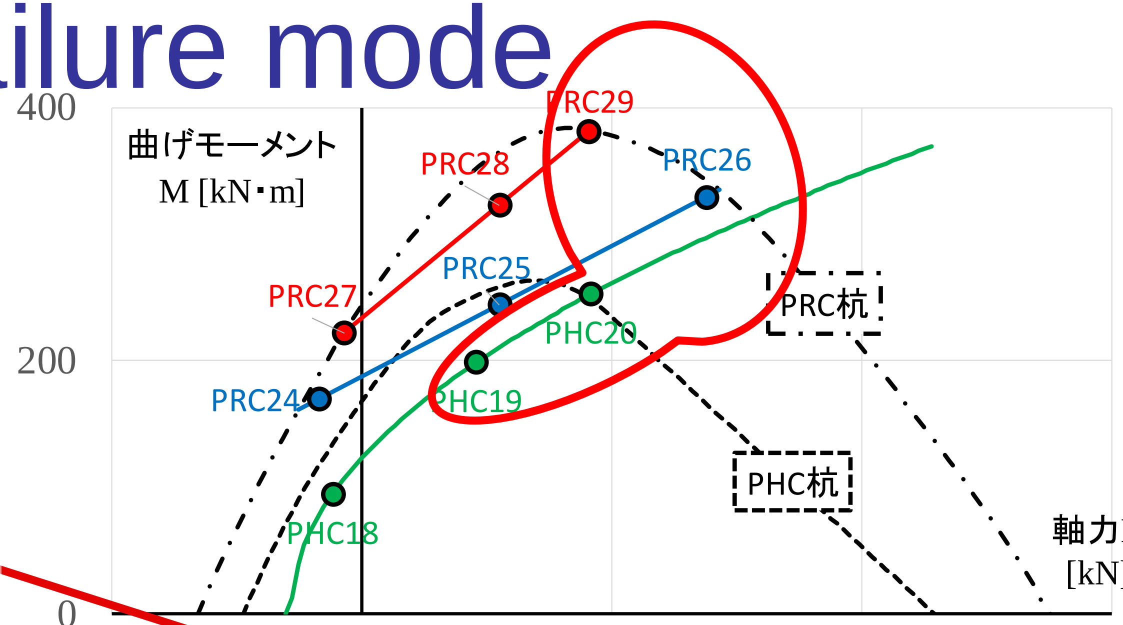
Peak



Ultimate

Axial load carrying capacity was somehow maintained.

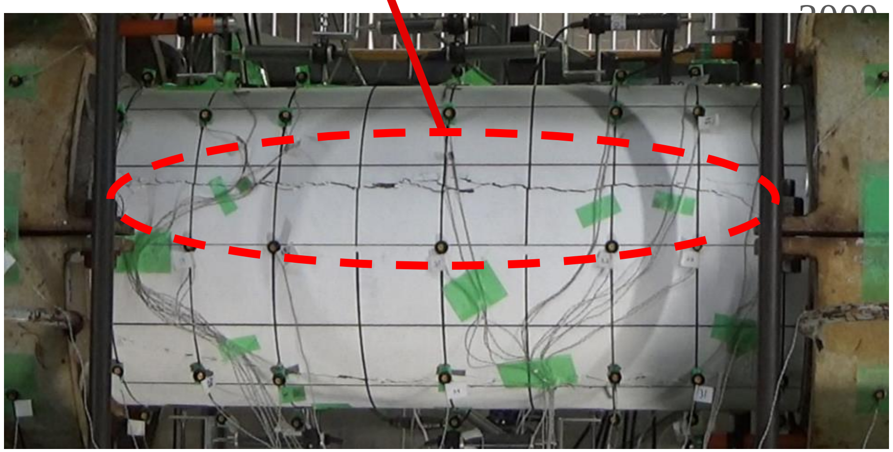
Failure mode



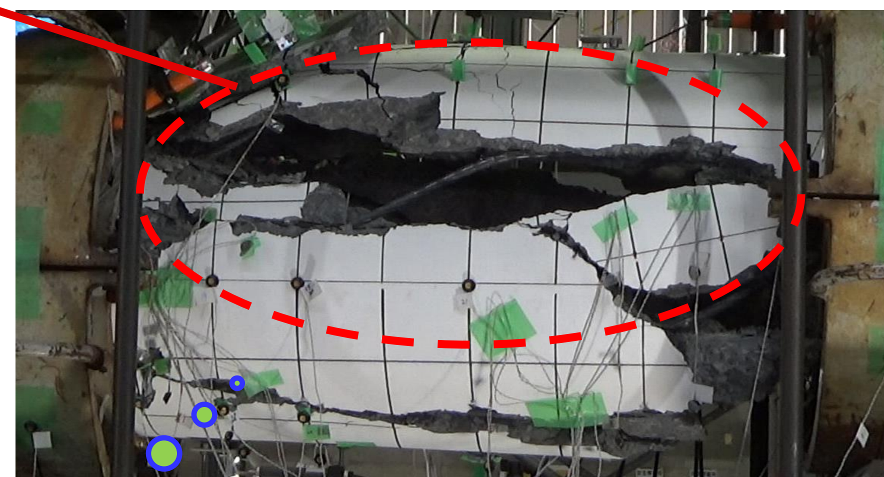
PHC20

σ_0=34MPa（Comp.） M/Qd=1.4

Axial splitting cracks



Peak



Ultimate

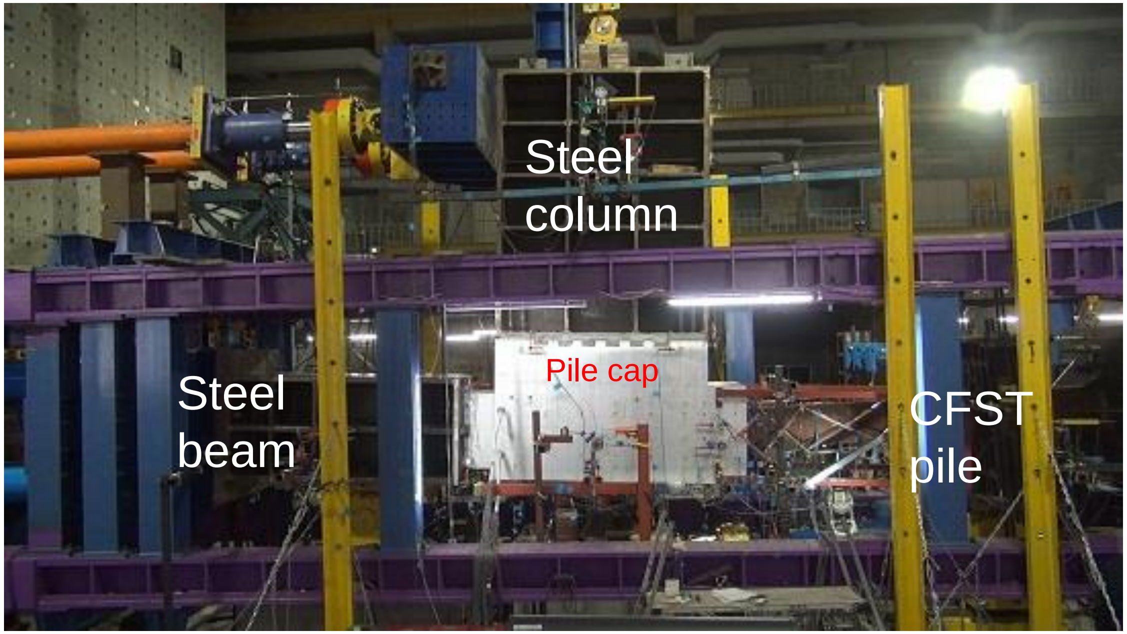
Axial load carrying capacity was completely lost.

Summary on shear behavior

Axial splitting cracking should be taken care of.

- PHC/PRC
  - The failure mode is brittle. Axial load carrying capacity was partially/completely lost.
- Precast/cast-in-place CFST
  - Shear failure takes place only for small M/Qd and large axial force.

Shear/Flexure at connection

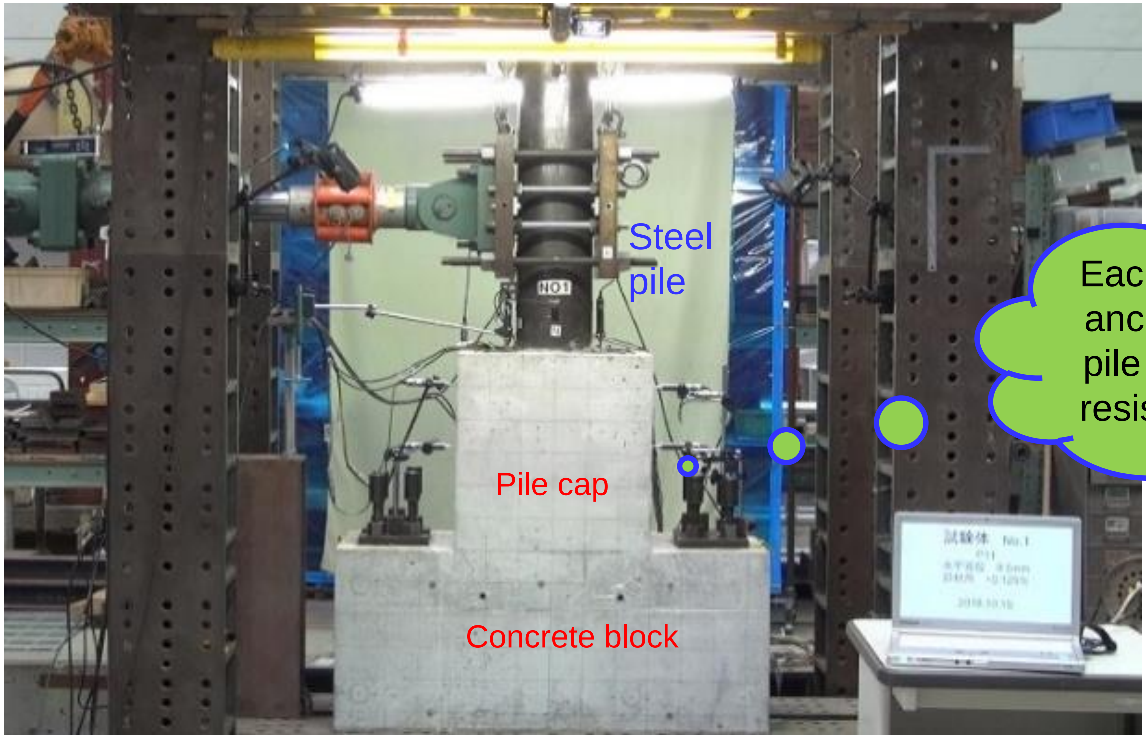


Column-beam-pile connection (tested in sideways)
(large scale)

Column-beam-pile connection
(smaller scale)

We need to take care of various failure modes.

Flexure at pile cap



Pile and pile cap (inverted specimen)

Each pile has its own anchorage type. The pile cap has different resisting mechanism.

Conclusions

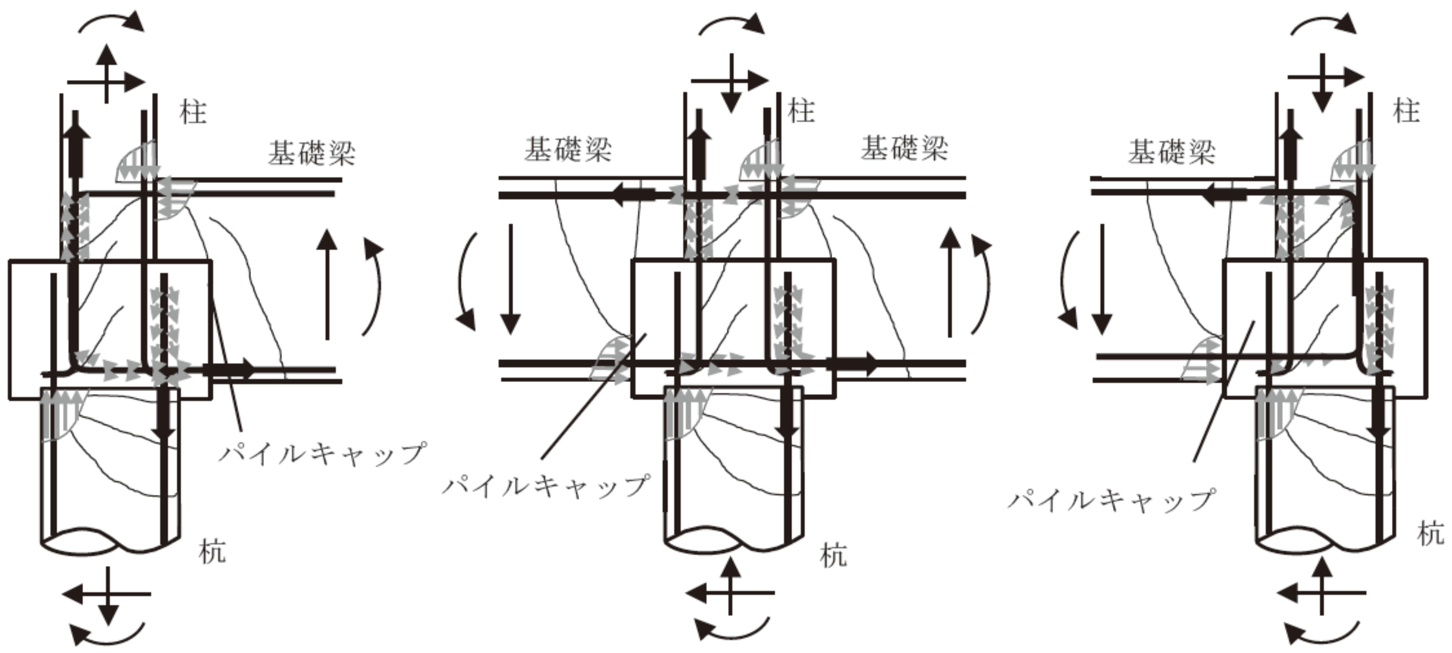
- Series of tests have been conducted to study flexure and shear behavior.
  - for pile caps
  - for piles
    - precast spun concrete piles PHC/PRC/CFST
    - cast-in-place reinforced concrete piles
    - cast-in-place CFST piles
- Design procedures for flexure and shear have been assessed/revised and some of them are reflected in 2022 AIJ guidelines for foundation members.

Pile type	Design issue	2017 AIJ guidelines	Test
RC (cast-in-place)	・Mmax and Vmax ・Ru	・N/No -0.05～1/3 ・Ru = 1/100	→ -0.1～0.6 → Ru for axial load carrying limit
CFST (cast-in-place)	・Mmax ・Ru ・D/ts	・N/No -0.07～0.15 ・Eq. has not been not confirmed ・D/ts<100	→ -0.3～0.55 → Eq. is shown → D/ts<133
PHC	・Mmax and Vmax	・N/No 0～0.3	→ -0.05～0.4
PRC	・Mmax and Vmax ・Ru	・N/No 0～0.05 ・Eq. has not been not confirmed	→ -0.25～0.4 → Ru for axial load carrying limit
SC	・Mmax ・Ru	・no description ・no description	→ N/No=-0.1～0.5 → Eq. is shown

Chap. 9: Pile cap for cast-in-place rc piles
（場所打ち鉄筋コンクリート杭のパイルキャップ）

p.300,304

9.1 Scope



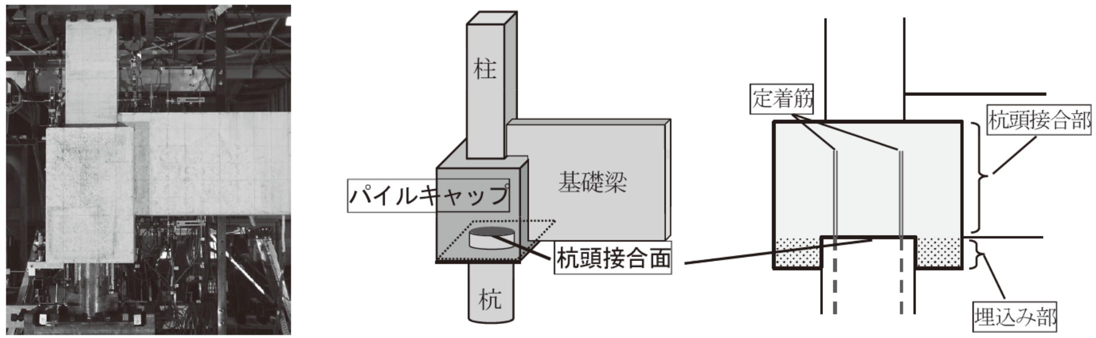
(a) Opening T
(b) Criss-cross
(c) Closing T

Stress conditions of pile cap

Chap. 9: Pile cap for precast concrete piles
（既製杭のパイルキャップ）

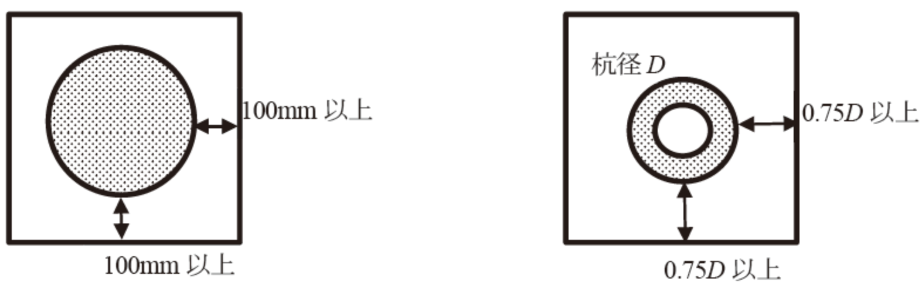
p.327,330

10.1 Scope



（a）パイルキャップ全体写真　（b）パイルキャップ周辺部材　（c）パイルキャップ内構成図

解説図10.1　パイルキャップの適用範囲



（a）場所打ち杭の場合　（b）既製杭の場合

解説図10.5　パイルキャップ内における杭の位置関係

Chap. 11: Foundation beams
（基礎梁）

11.1 Scope

Rebar ratio, curtailment, anchorage

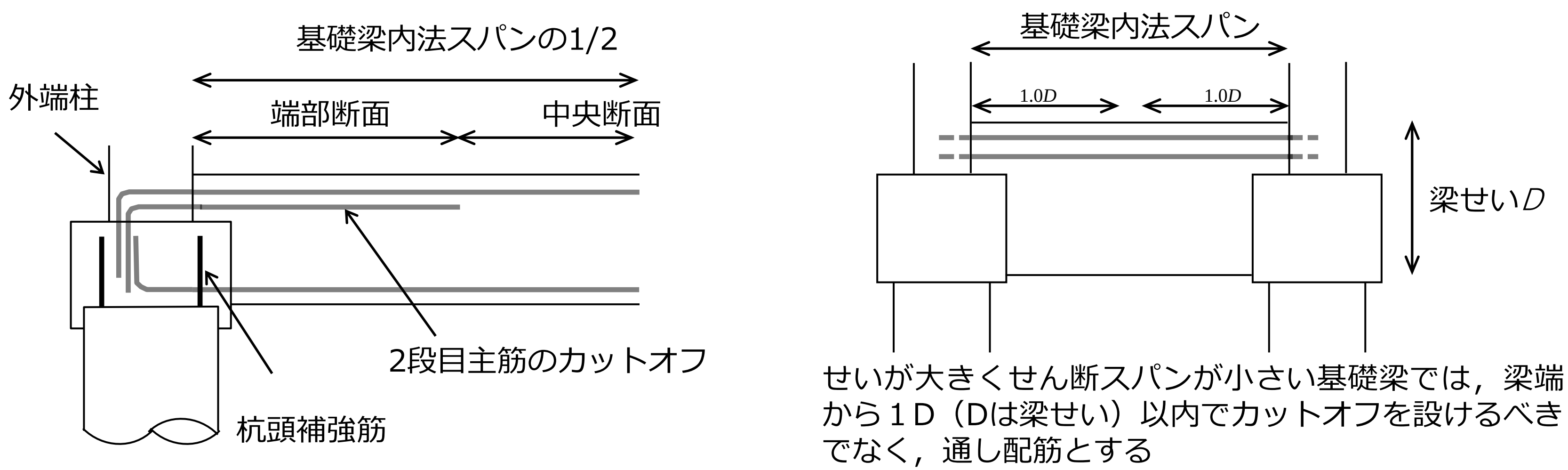


Fig 11.2　Curtailment of long. rebars of foundation beams

Thank you.