Seismic Design of Urban Infrastructures
都市施設の耐震設計

(5-1) Strength and Ductility Capacity of RC Structural Members
⑸-1⑹ RC構造物の動的耐力・変形性能

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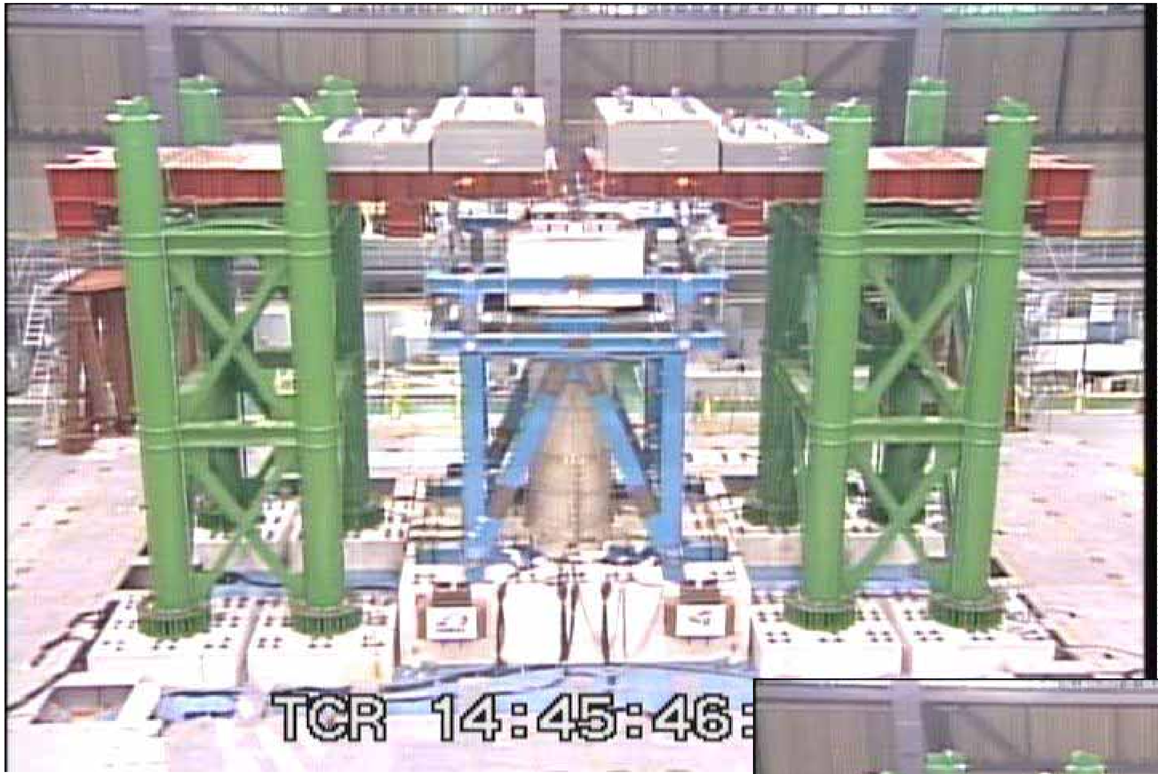
5.1 How Does Structure Suffer damage?



First Excitation

C1-1 Column
A typical column built in the 1970s

Second Excitation

First Excitation

Second Excitation

C1-2 Column
A typical column built in the 1970s

5 m from the base

3 m from the base

C1-5
Column
A typical column built after 1996

First excitation

Fifth excitation with added mass

The First

The second

The Third (added mass)

The fourth

The Fifth

C1-6 Column One of the next generation column

The first excitation

The sixth excitation

The first

The third
(added

The second

The sixth

The fourth

The fifth

5.2 Capacity ←→ Demand

Demand = Capability which is required to pose in a structural element or a structure
Capacity = Capability which is posed by a structural element or a structure

ディマンド = 構造部材あるいは構造物が持つべき性能
キャパシティー =構造部材あるいは構造物が有する性能

Ductility factor (Capacity)**じん性率 (キャパシティー)**

$$\mu \equiv \frac{u_u}{u_y}$$

Ductility factor (Response)**応答じん性率**

$$\mu_r \equiv \frac{u_{\max}}{u_y}$$

5.3 Strength and Ductility of Structural Members

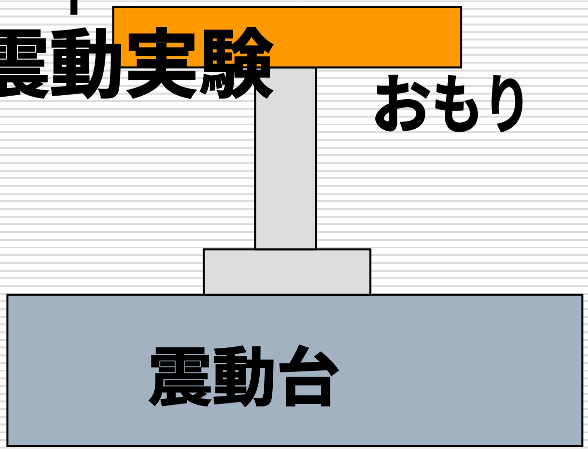
構造部材の耐力と変形性能

- ✓Strength **強度**：Flexural strength and shear strength
  曲げ強度、せん断強度等
- ✓Ductility capacity: Ductility factor
  変形性能：じん性率

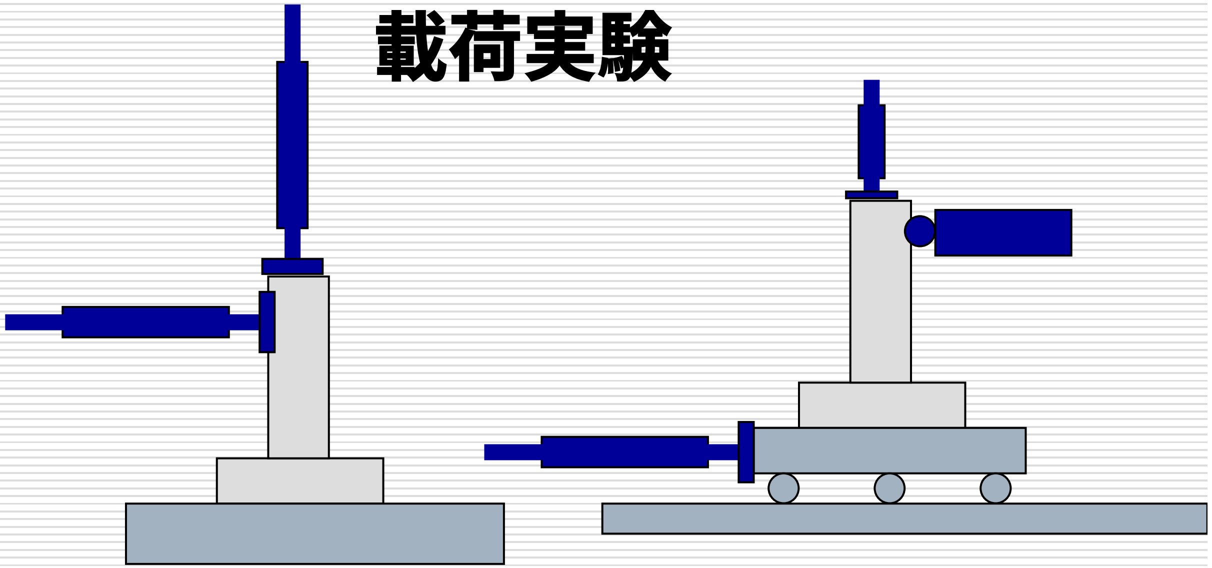
$$\mu \equiv \frac{u_u}{u_y}$$

5.4 How are strength and ductility capacity evaluated?

Shake table experiment
震動実験

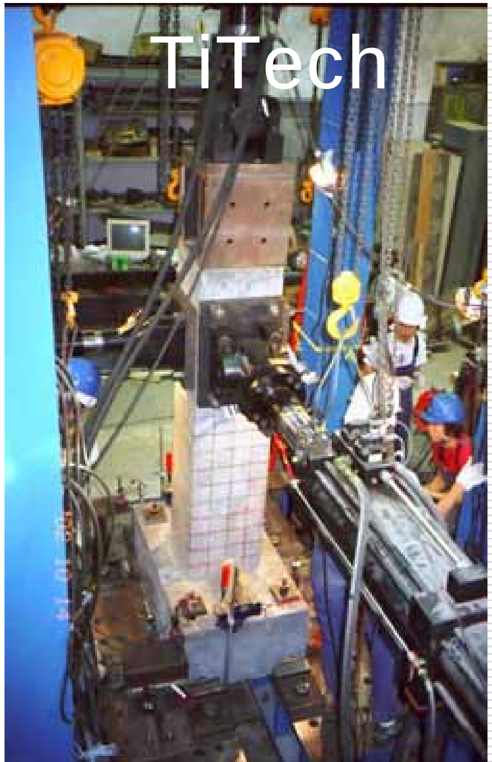


Loading Experiment
載荷実験



- ●実現象に近い
- ●地震動でも加震可能
- ●荷重制御なので、崩壊し始めたらいっきに崩壊
- ●高価

- ●荷重のP～Δ効果の影響を排除要
- ●正弦波による繰返し載荷
- ●ハイブリッド載荷（コンピュータ制御により、地震動を作用させた場合の応答を実験と解析の組み合わせで実施）


TiTech


UCSD


NIST


UCB
C NORTH
C WEST


University of
Christchurch, NZ

E-Defense
Eディフェンス

5.5 How does a reinforced concrete column behave under a cyclic loading

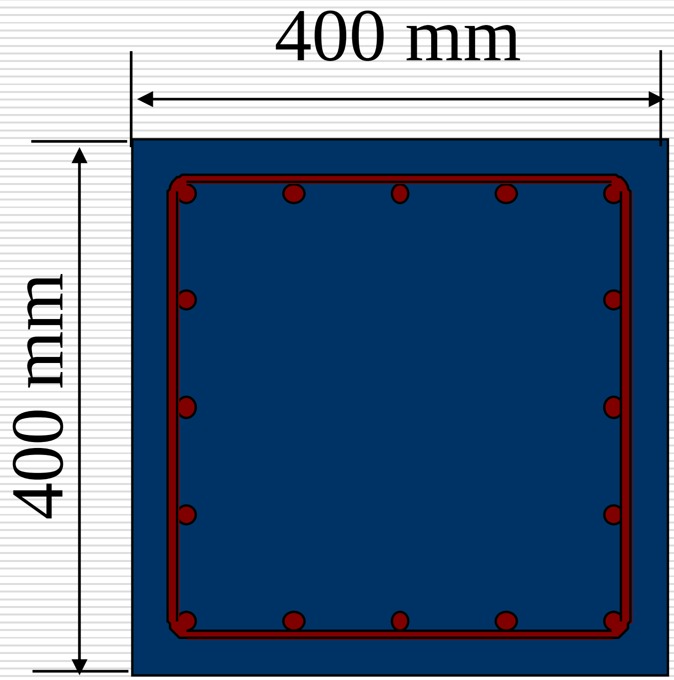
(1)Target column

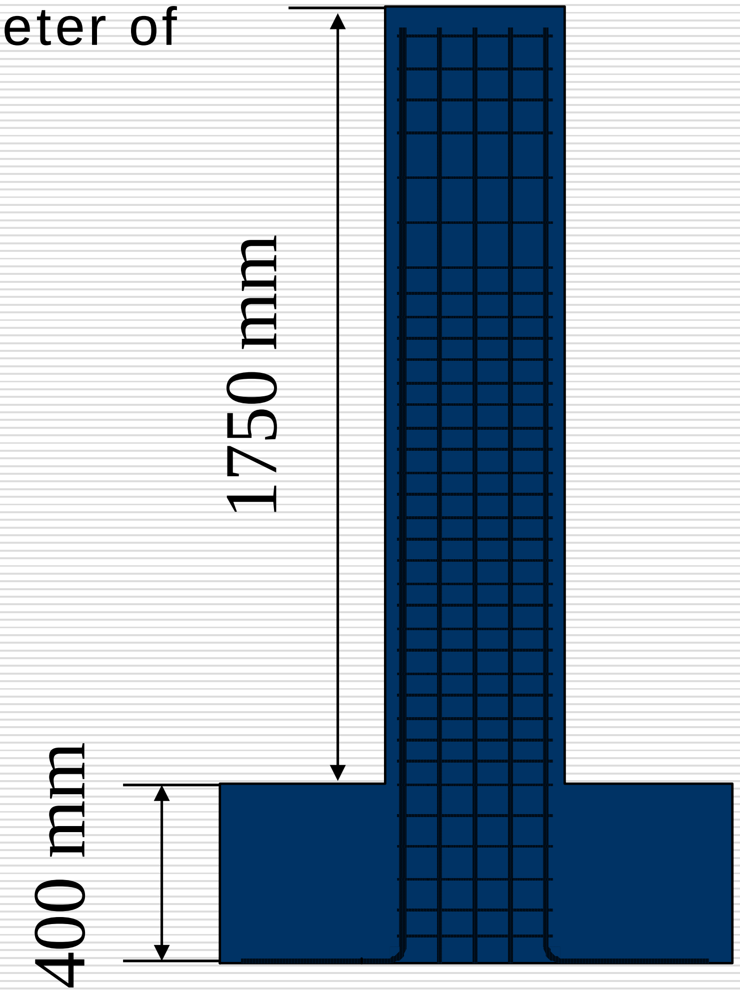
Axial reinforcements

D13(deformed bar with a diameter of 13mm)×16 bars

Tie reinforcements

D6 every 50mm interval

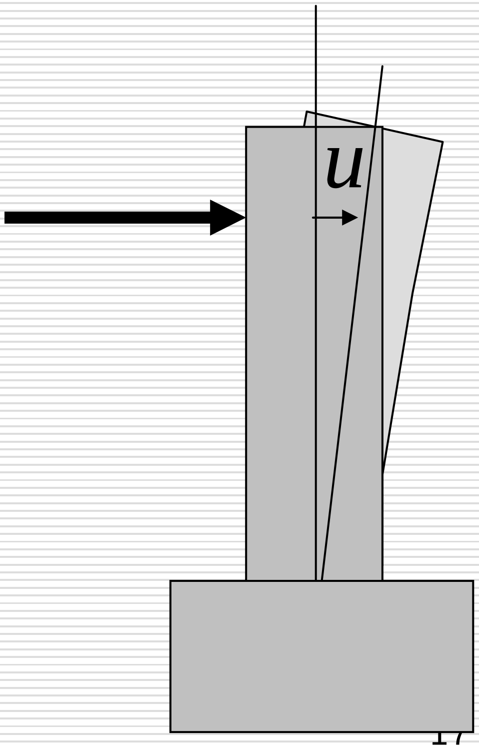




(2) Depending on loading parameters, we have different capacity in a cyclic loading

- Amplitude of loading
  - ✓N times yield displacement
  - ✓N times drift
  - ✓….
- Number of loading at each step

繰り返し載荷回数



  - ✓1
  - ✓3
  - ✓10
  - ✓…..
  - ✓Random
  - ✓Equivalent number?

(3) Various Contribution to the Lateral Displacement *u*

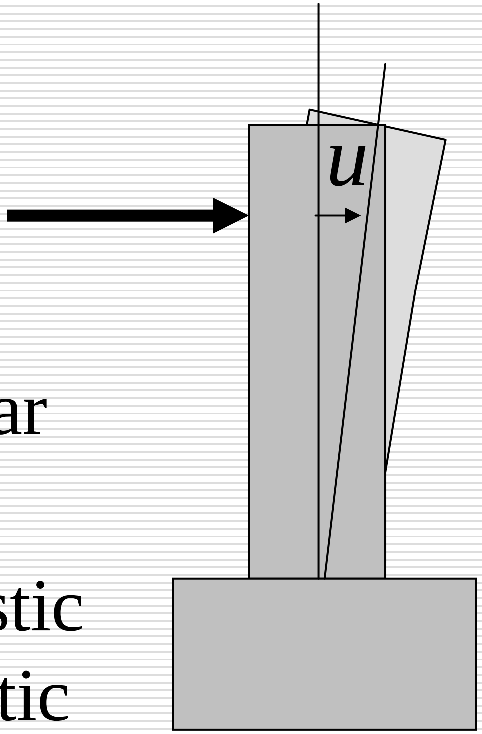
$$u = u_e + u_s + u_p + u_{dbf}$$

●Displacement resulted from the elastic deformation of the column **橋脚の弾性変形**

●Displacement resulted from the shear deformation of the column**せん断変形**

●Displacement resulted from the plastic deformation of the column at the plastic hinge**塑性ヒンジにおける塑性変形**

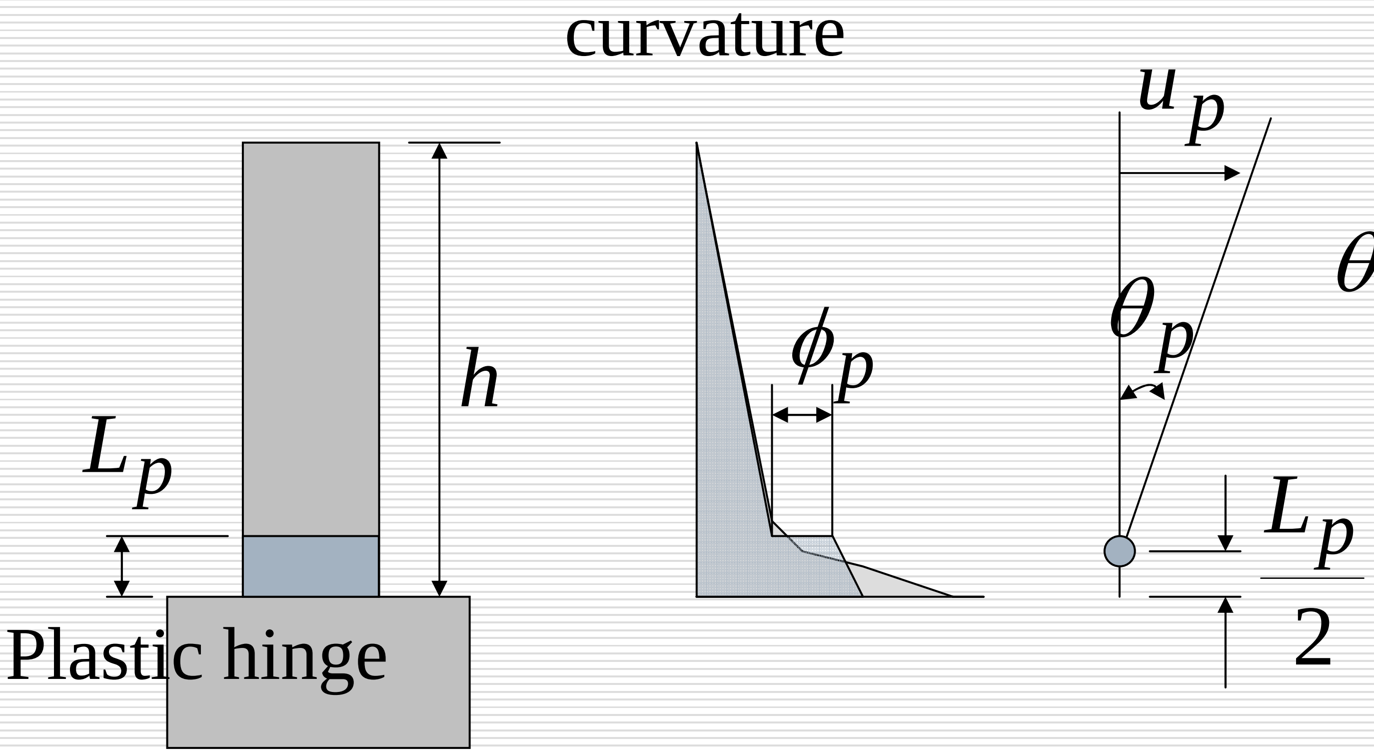
●Displacement resulted from the pull-out of rebars inside the footing **軸方向鉄筋の変形**, PLB effect



(5) Plastic Hinge 塑性ヒンジ

Plastic hinge is a virtual concept which make easy to evaluate displacement due to plastic deformation at the plastic hinge

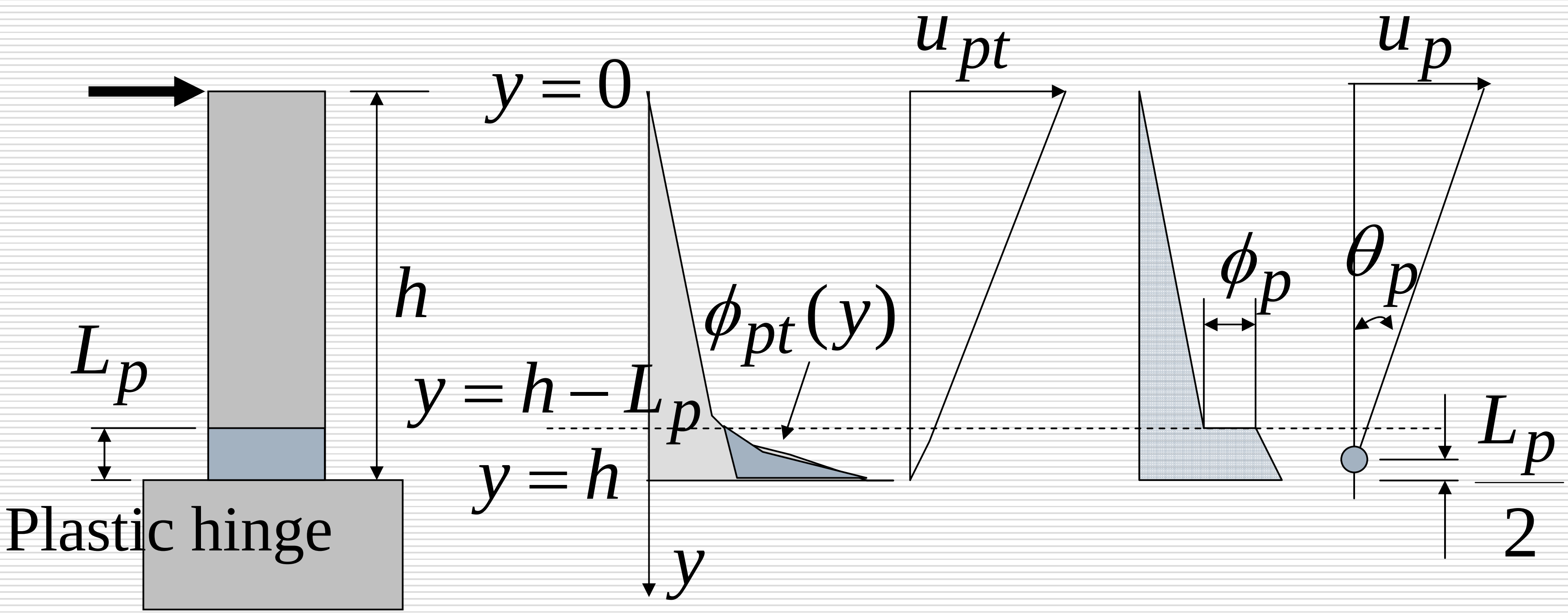
Averaged curvature at the plastic hinge ϕ_p



$$\theta_p = \phi_p L_p$$

$$u_p = \left(h - \frac{L_p}{2} \right) \cdot \theta_p = \left(h - \frac{L_p}{2} \right) \cdot \phi_p L_p$$

5) 塑性ヒンジ長 L_p と平均塑性曲率 ϕ_p の定義



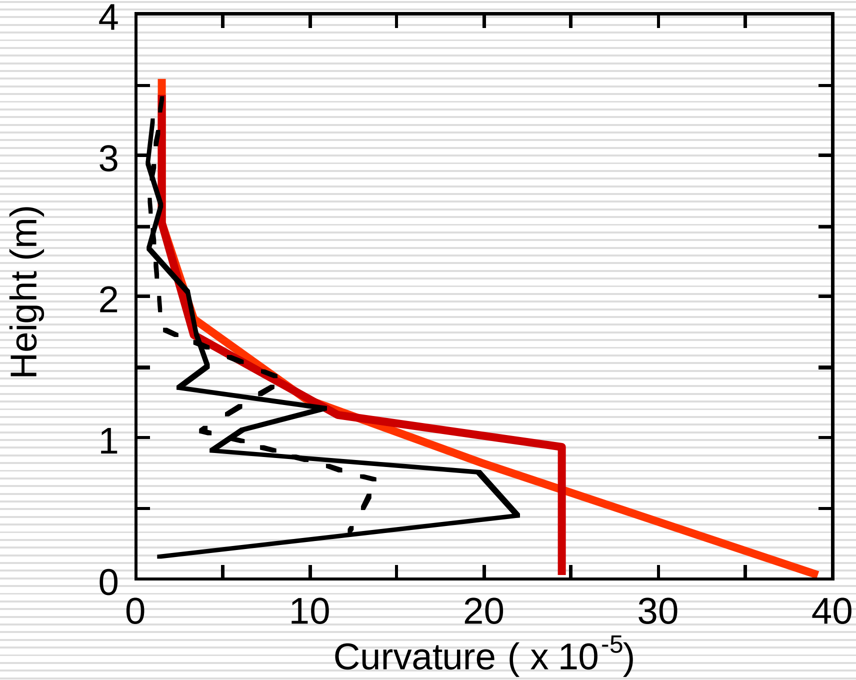
$$u_{pt} = \int_{h-L_p}^{h} \theta_{pt}(y)dy$$

$$= \int_{h-L_p}^{h} \phi_{pt}(y)\cdot y \cdot dy$$

$$u_p = \left(h - \frac{L_p}{2} \right) \cdot \phi_p L_p$$

The plastic hinge length L_p and the averaged curvature ϕ_p should be determined so that $u_p = u_{pt}$

Distribution of Curvature at the Plastic Hinge Region



$$\int_0^h \varphi(y)\cdot y\cdot dy = const$$

塑性ヒンジ長
Plastic Hinge Length

Japan Road Association

$$L_P \approx 0.5W$$

W: Column width

Priestley, Seible and Calvi (1997)

$$L_P = 0.08H + 0.022 f_{ye} d_{bl} \geq 0.044 f_{ye} d_{bl}$$

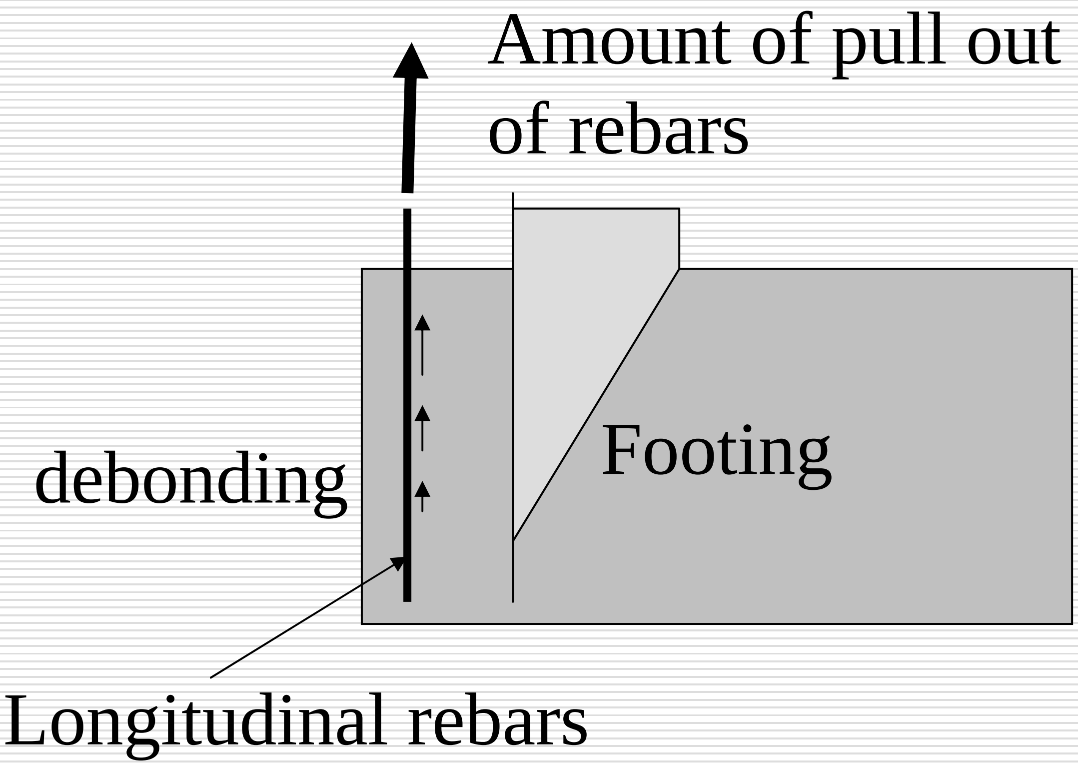
H :Column height (distance from the plastic hinge to the point of contra flexure)

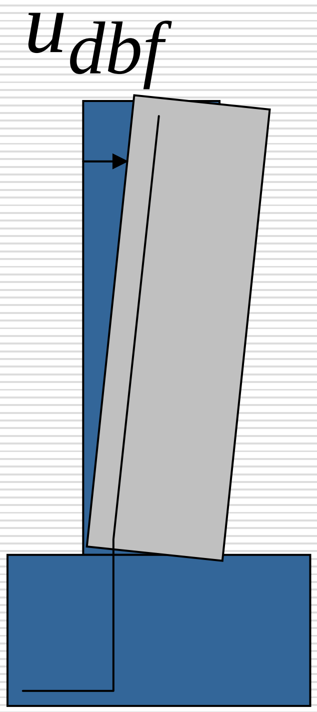
d_{bl} :diameter of axial bars

f_{ye} : design yielding strength of axial bars

6) フーチングからの鉄筋の抜け出しも橋脚の水平変位に寄与する

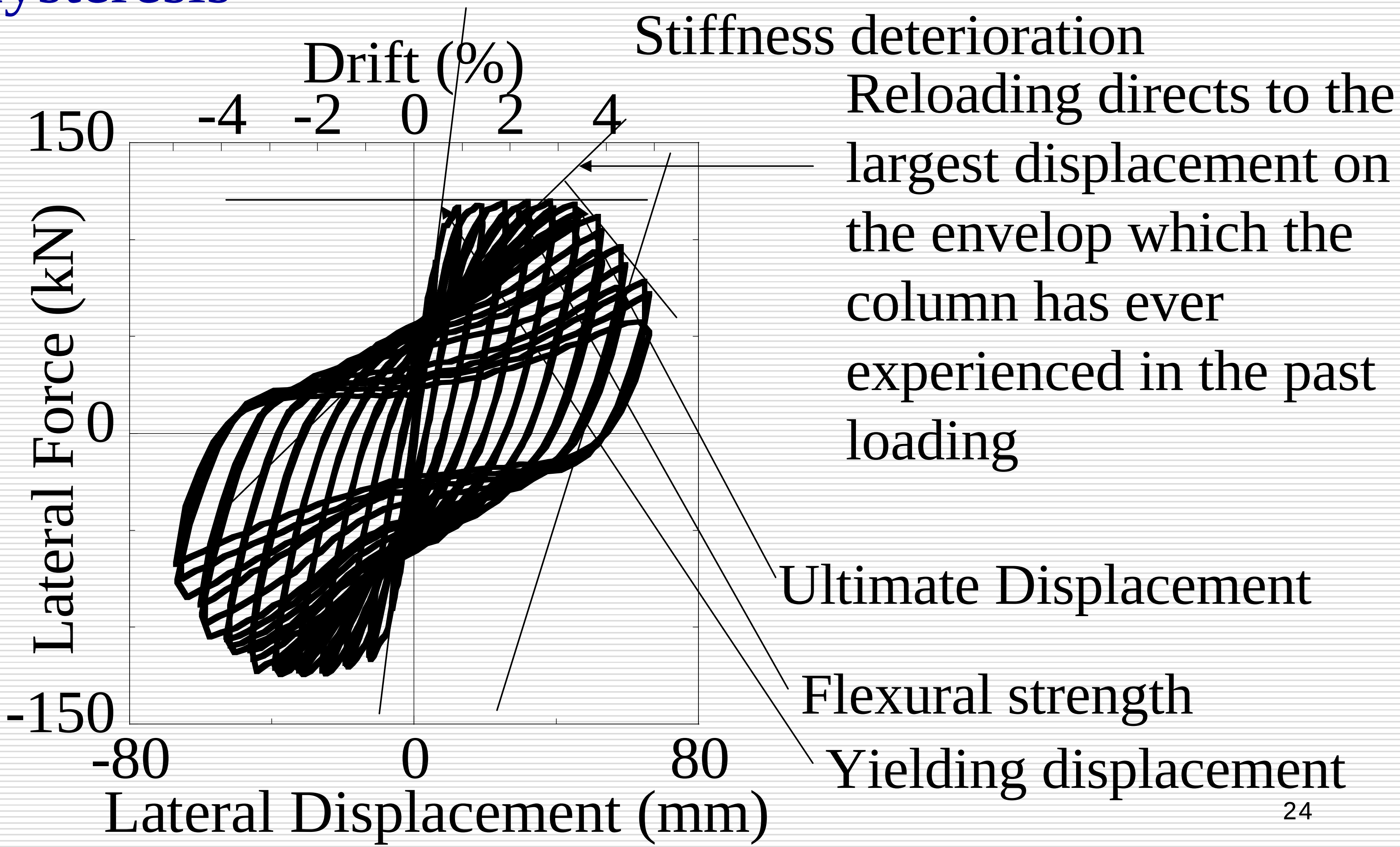
Lateral Displacement due to Pull out of Longitudinal Rebars in the Footing





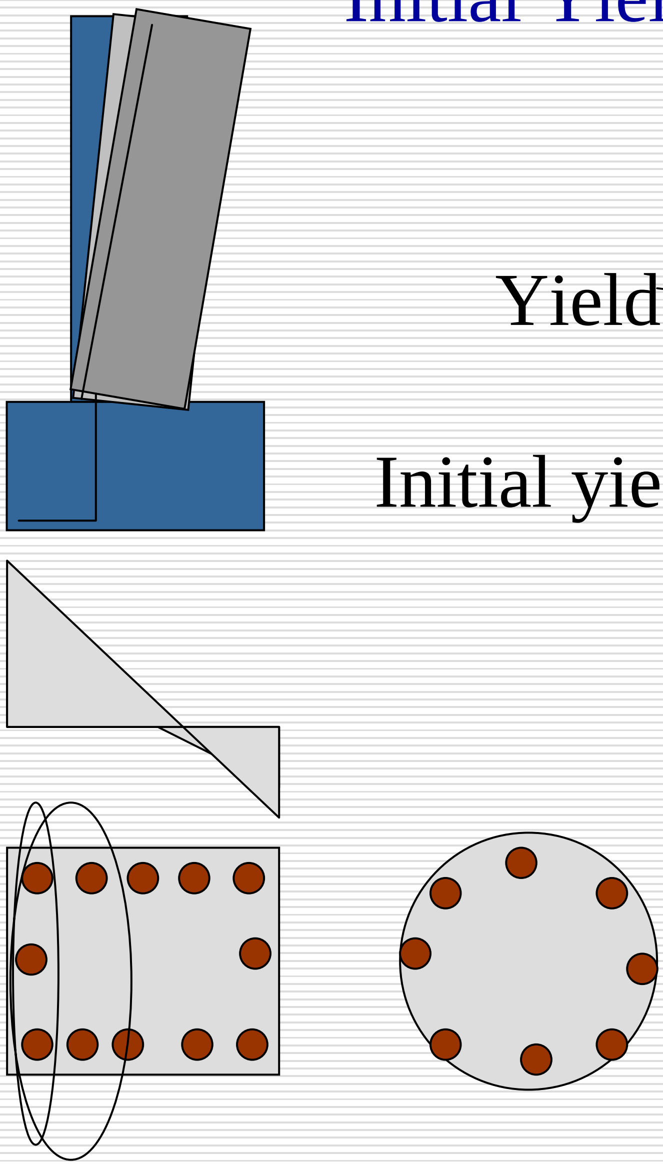
7) 荷重作用点における水平力～水平変位の履歴曲線

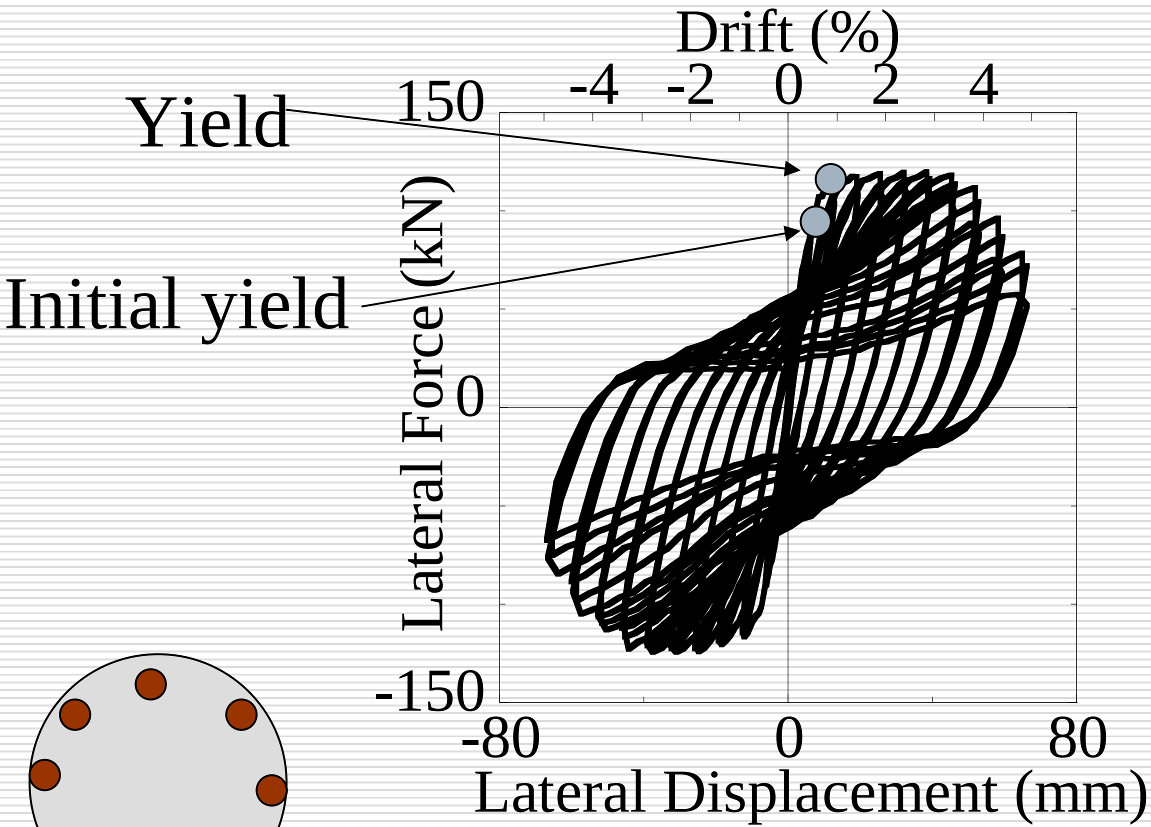
Lateral Force vs. Lateral Displacement Hysteresis



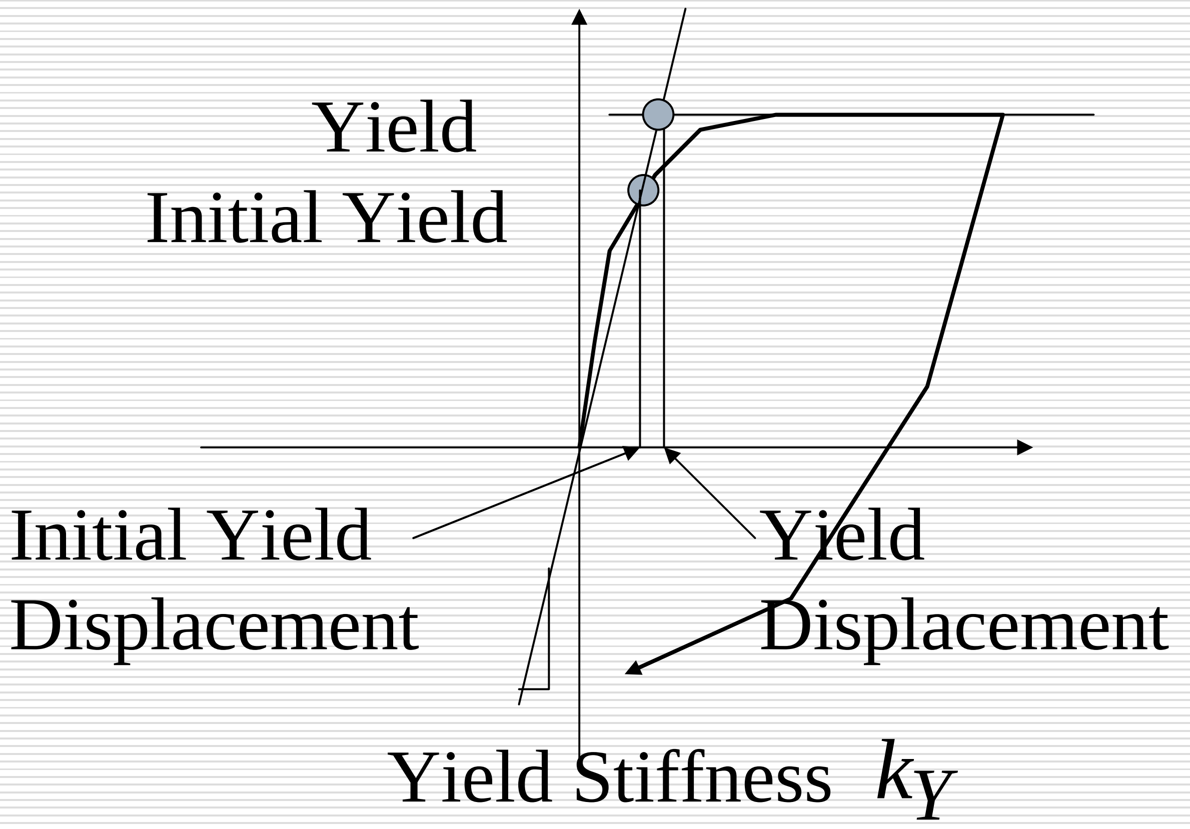
8) 初降伏と降伏

Initial Yield and Yield



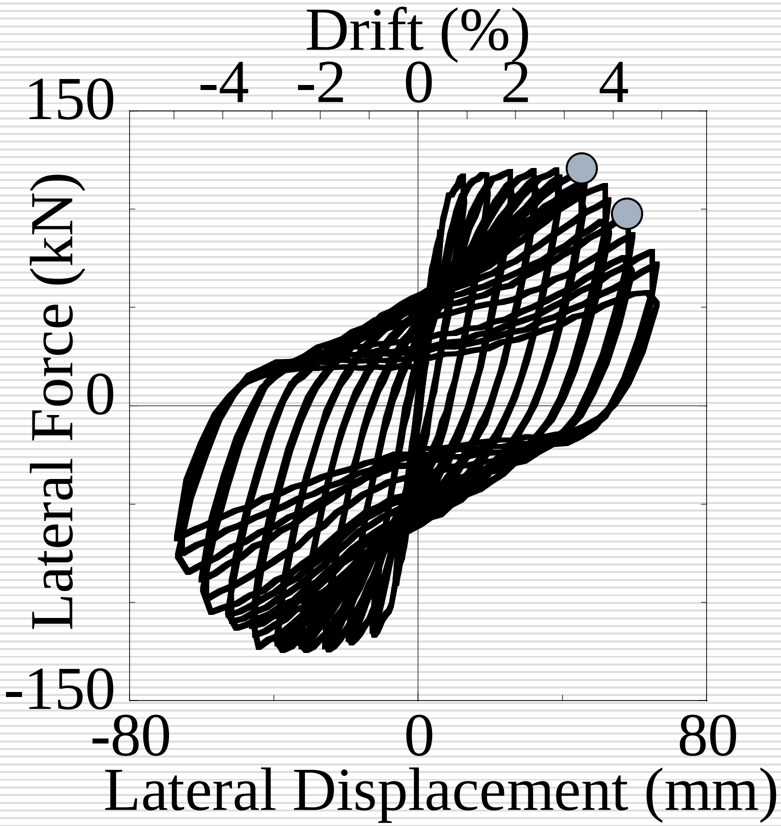


初降伏と降伏（続き）
Initial Yield and Yield (Continued)



It is convenient to define “yield displacement” in the bilinear or tri-linear idealization of the hysteresis

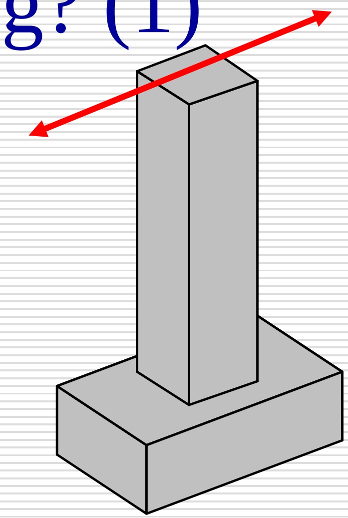
9) 終局状態の定義
9)Definition of Ultimate

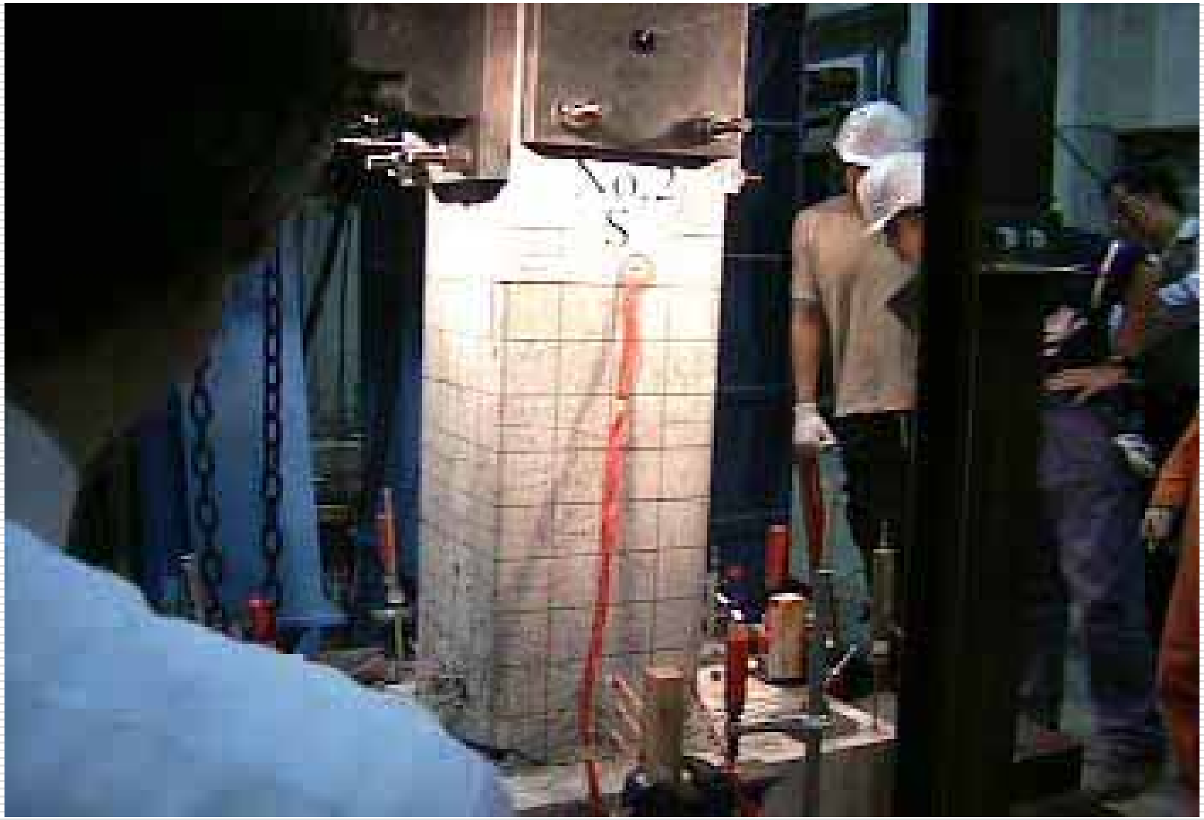


- Many definitions are used, and it depends on researchers and codes
- Major definitions are
  - ✓The point where restoring force starts to deteriorate
  - ✓The point where the restoring force has deteriorated to 80% of the strength
  - ✓The point where significant deterioration of restoring force starts to occur

10）載荷とともに橋脚の損傷はどのように進展するか? (1)

10) How damage progress during loading? (1)





drift 4.0%

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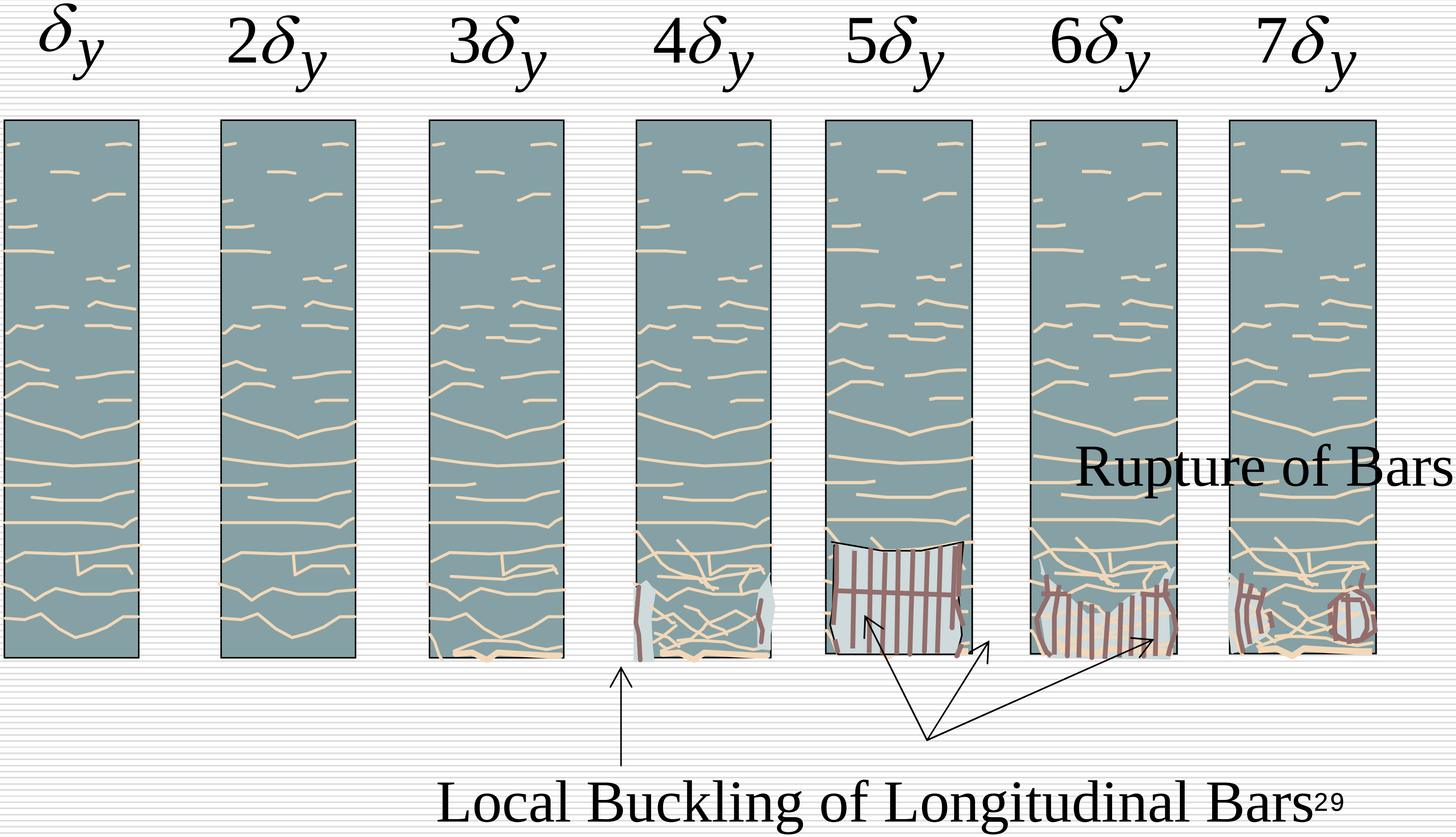
１０）載荷とともに橋脚の損傷はどのように進展するか? (2)

10) How damage progress during loading? (2)



11) どのように曲げ耐力は減少していくか?

11) How the flexural strength deteriorate?

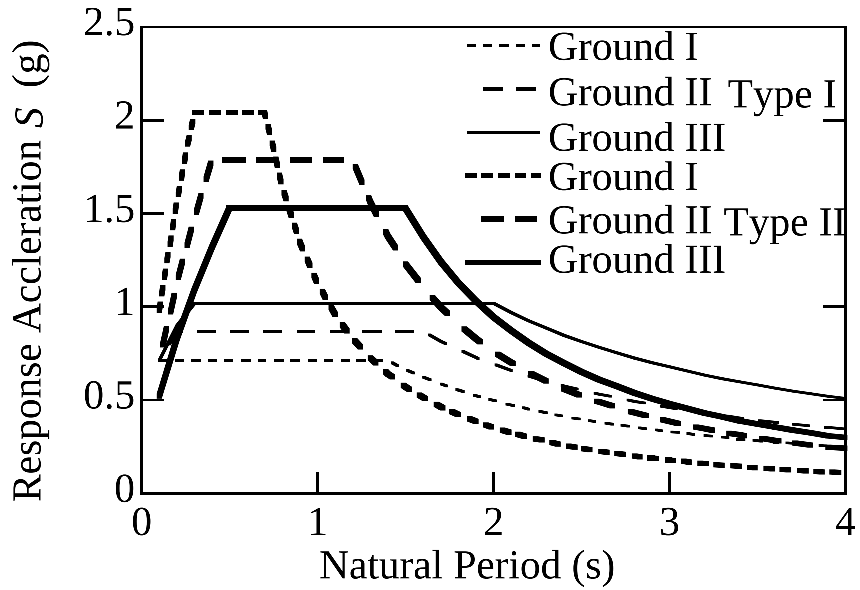
Flexural strength deteriorates when one or several of the followings occur

- Spalling-off of covering concrete and core concrete at the compression zone
- Loss of lateral confinement by ties
- Local buckling of longitudinal bars
- Rupture of longitudinal bars

12) 載荷履歴が曲げ損傷型橋脚の耐力劣化に及ぼす影響

12) Effect of Loading Type on the Deterioration of Flexure-Dominant Columns

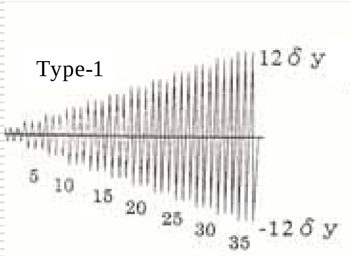
Safety Evaluation GM

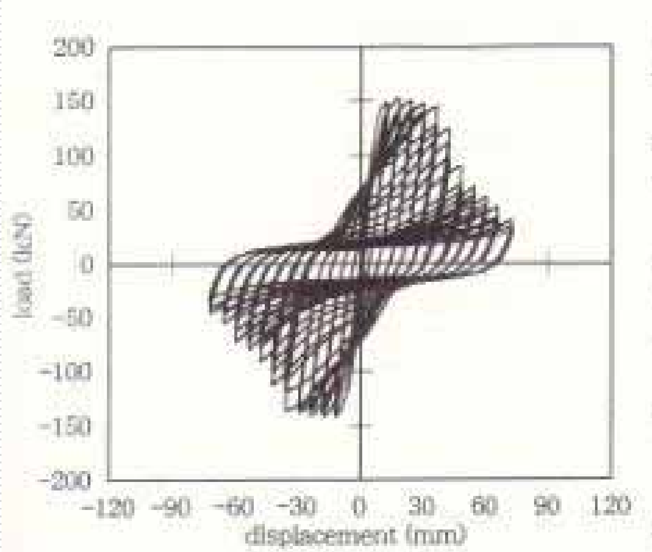


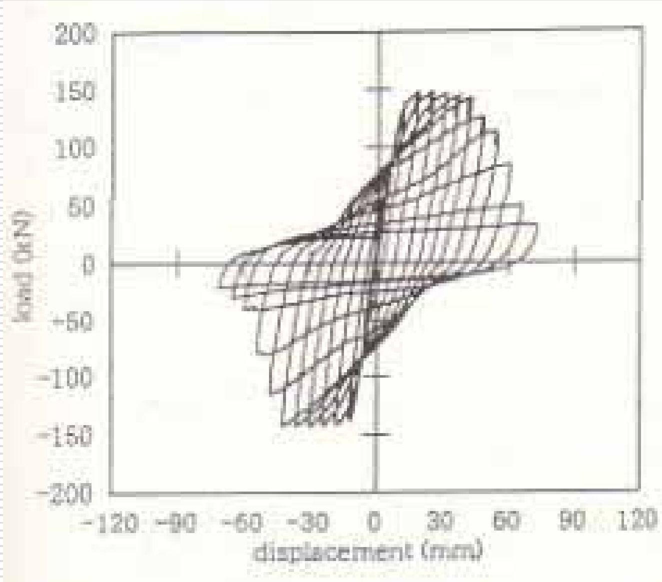
Type II GMs

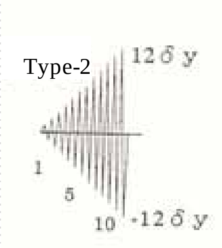
Type I GMs

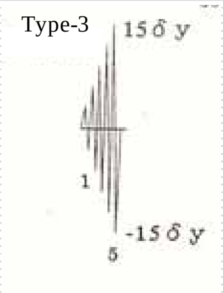
(1) Effect of Number of Loading Cycles

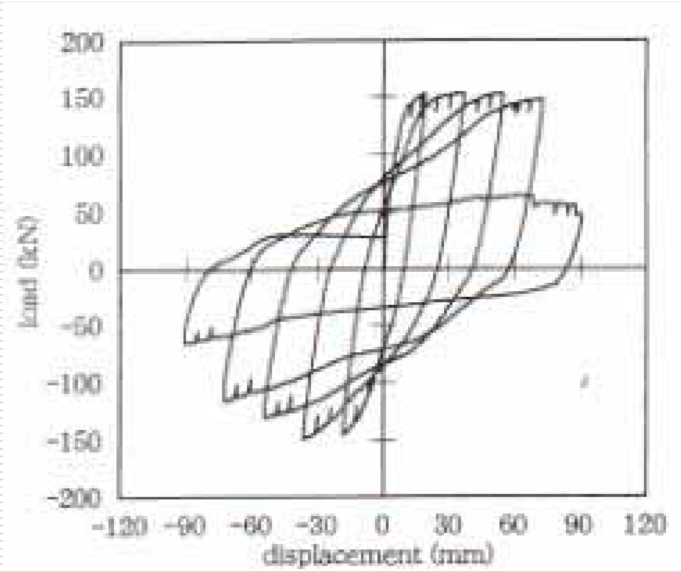




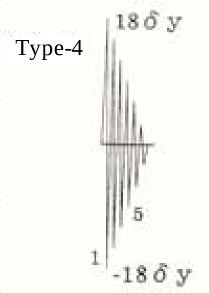


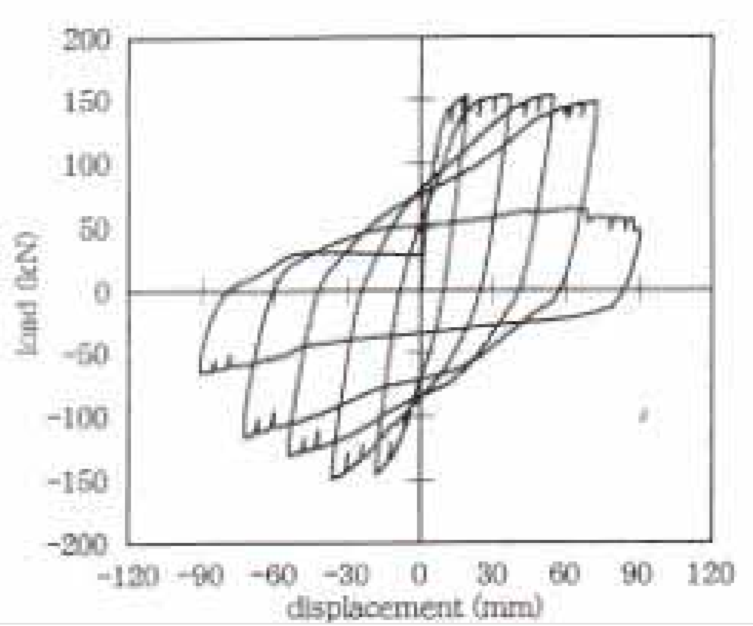


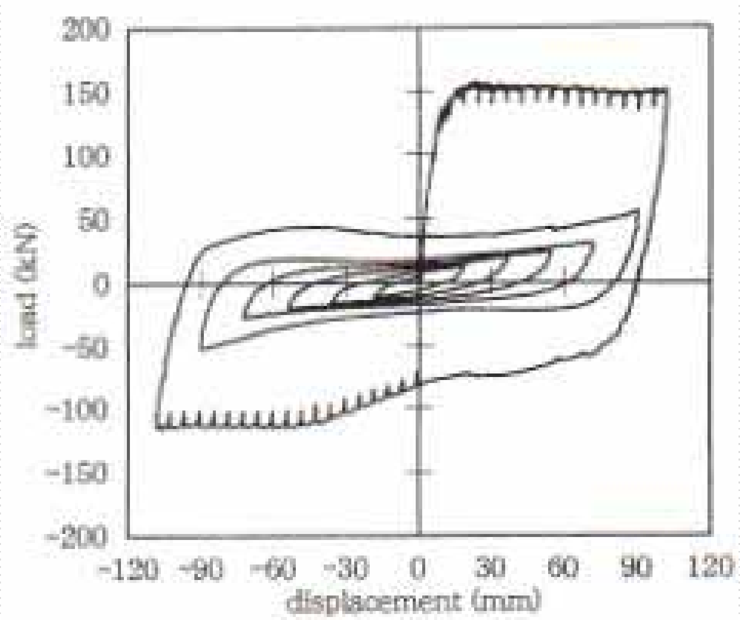




(2) Effect of Loading History



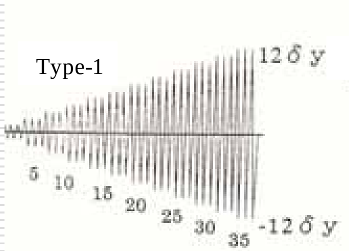


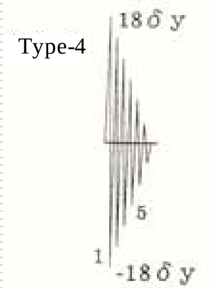


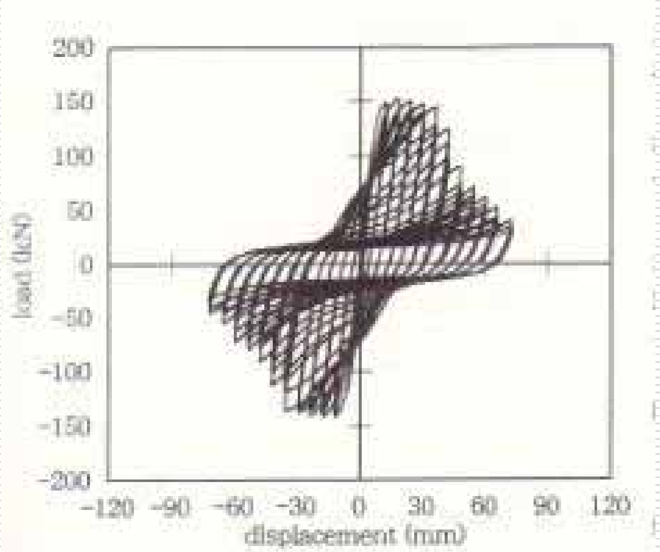
(3) Effect of Loading History & Number of Loading Cycles (continued)

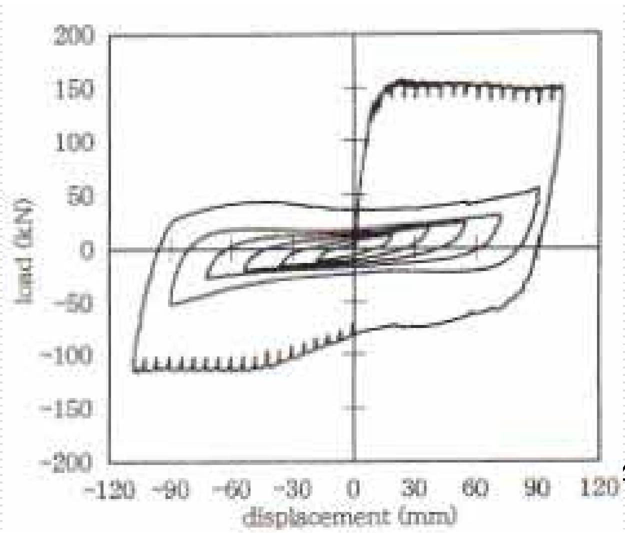
Type I GMs

Type II GMs





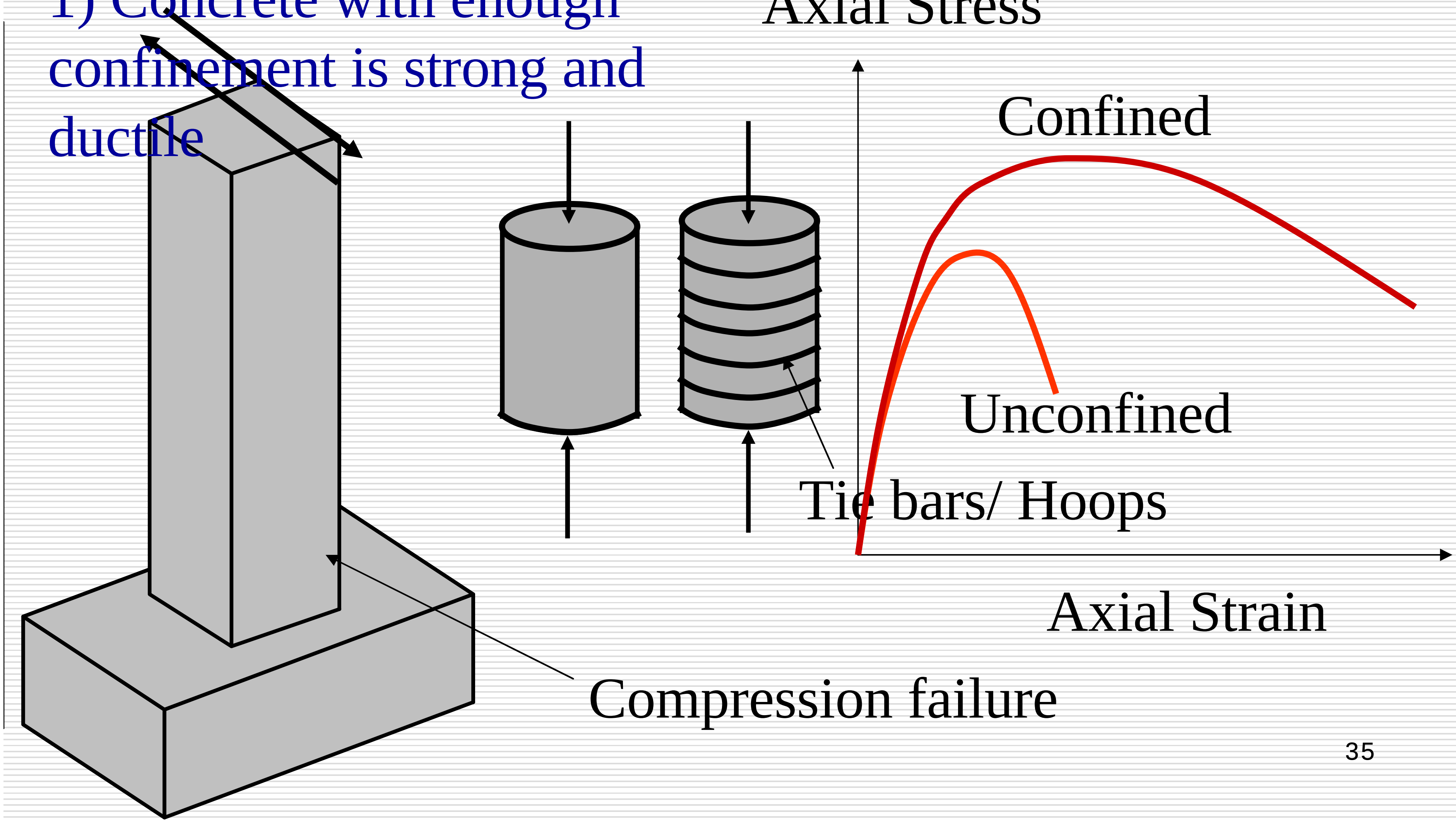




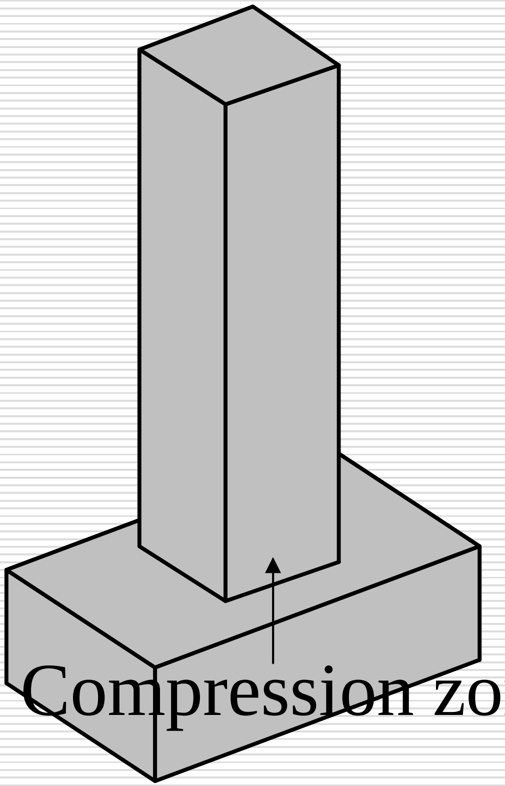
4．3　横拘束効果とその定式化

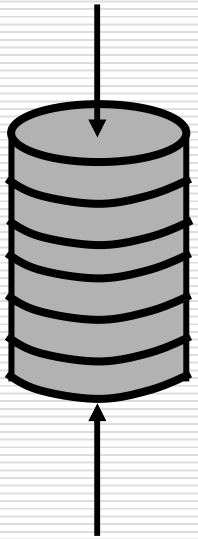
4.3 Effect of Lateral Confinement of Concrete and Its Formulation

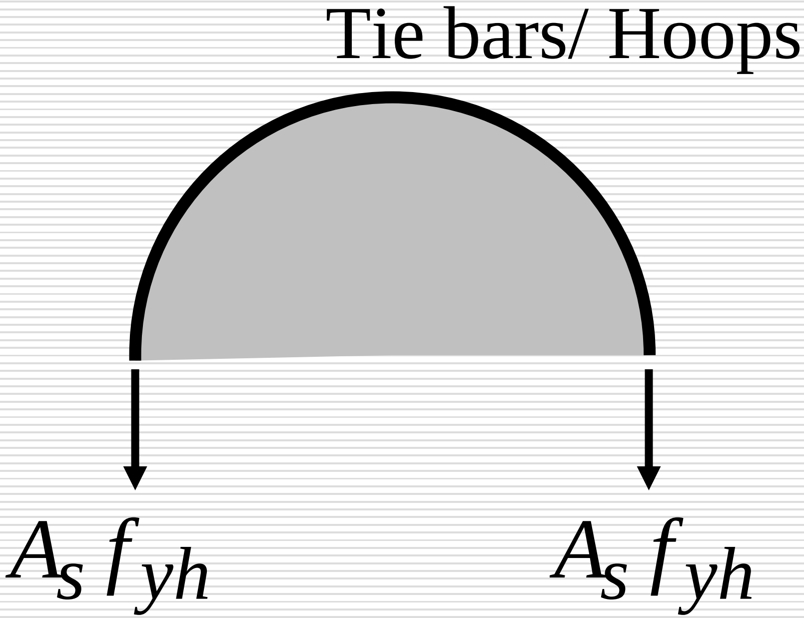
1) Concrete with enough confinement is strong and ductile



2) Stress and Failure Mechanism in the Compression Zone of Column are not the same with those of Cylinder







The matter is not so simple!!

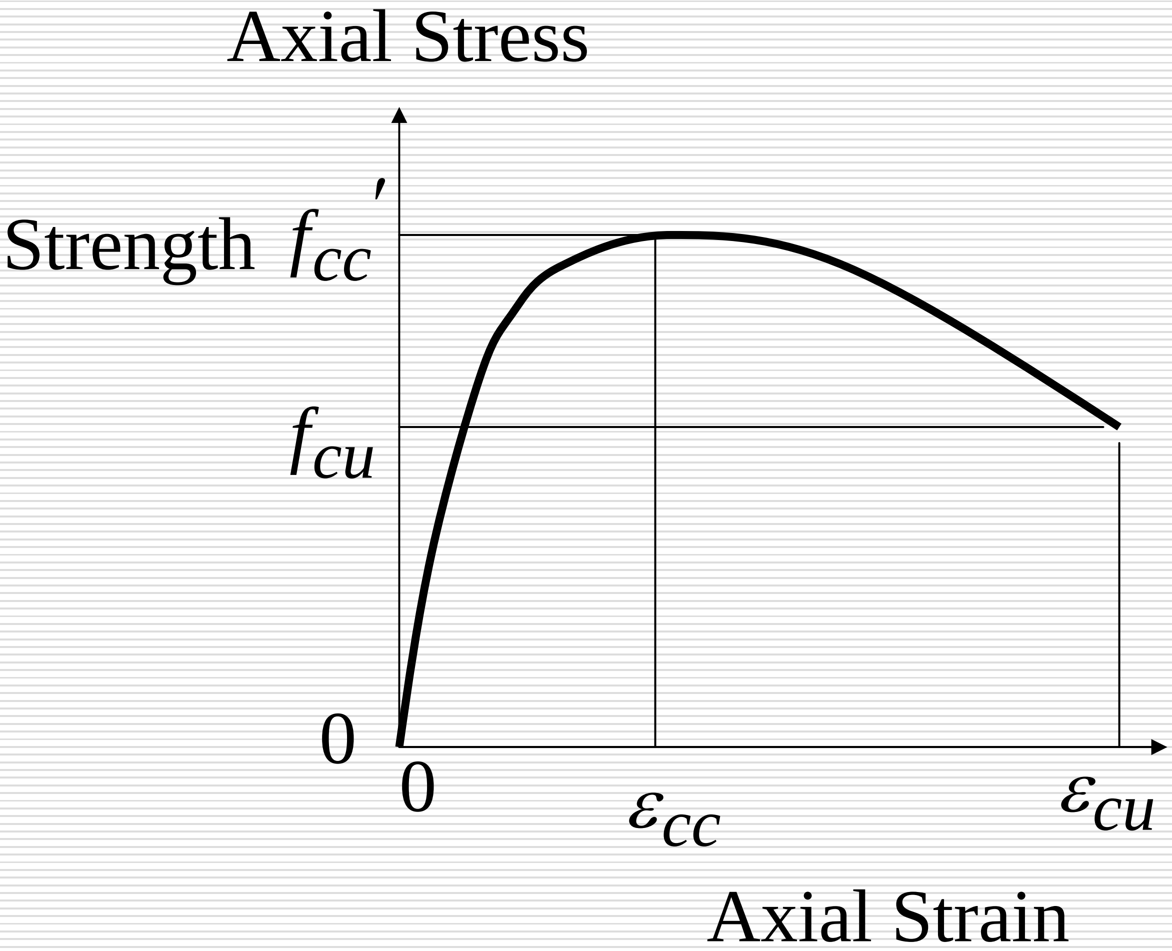
3) Empirical equations based on unilateral compression tests

- Park, R., Kent, D.C. & Sampson, R.A., 1972
- Mander, J. Priestley, N.M.J. and Park, R., 1988
- Sheikh, S.A. & Uzumeri, 1980
- Muguruma, Watanabe and others, 1980
- ….
- Hoshikuma, Kawashima, Nagaya & Taylor, 1997
- Sakai, J. & Kawashima, 2002
- ….

4) コンクリートの横拘束の定式化

4) Formulation of Lateral Confinement of Concrete

Four parameters required to define a confinement model



f_{cc}'

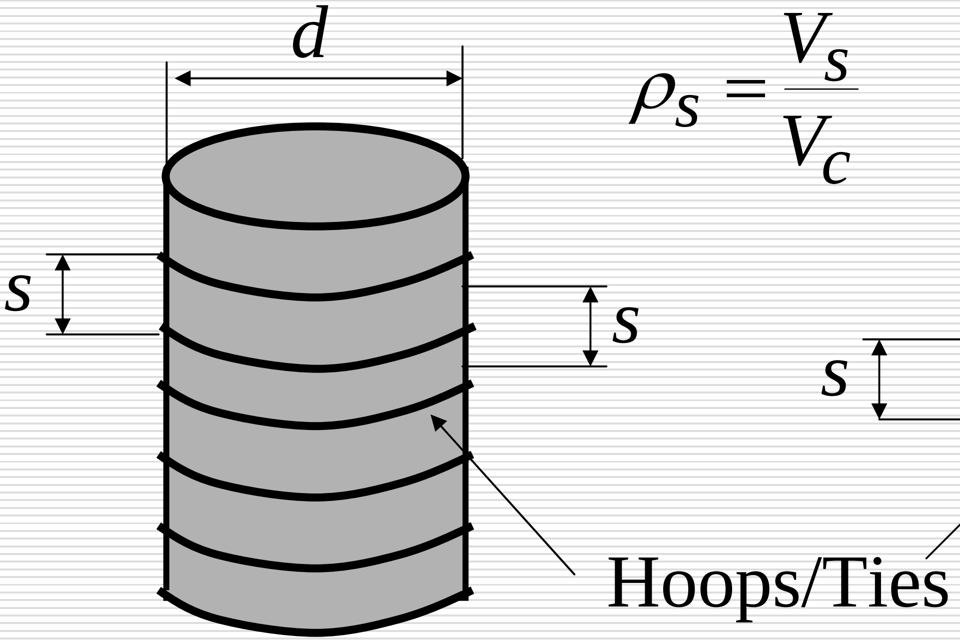
ε_{cc}

f_{cu}

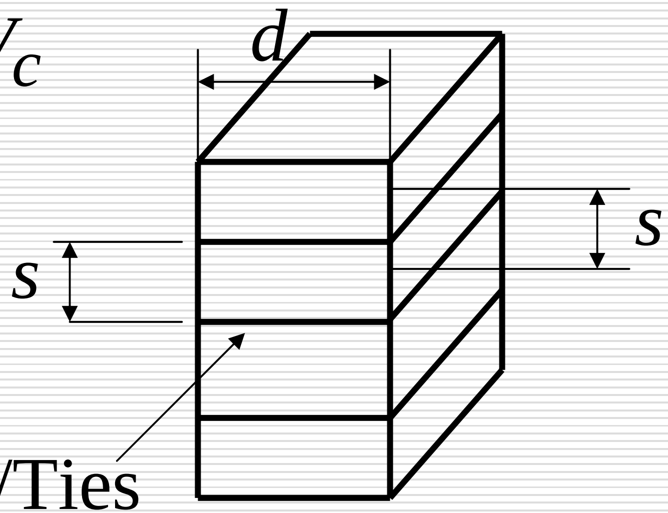
ε_{cu}

5) 帯鉄筋 (体積) 比

5) Volumetric Tie Reinforcement Ratio



$$\rho_s = \frac{V_s}{V_c}$$



$$\rho_s = \frac{\pi d A_s}{s \pi d^2 / 4} = \frac{4A_s}{sd}$$

$$\rho_s = \frac{4dA_s}{d^2 s} = \frac{4A_s}{sd}$$

6) 初期の頃の定式化

6) Formulation at the early days

コンクリート強度は横拘束（静水圧）f_{lc} に比例することは古くから知られていた

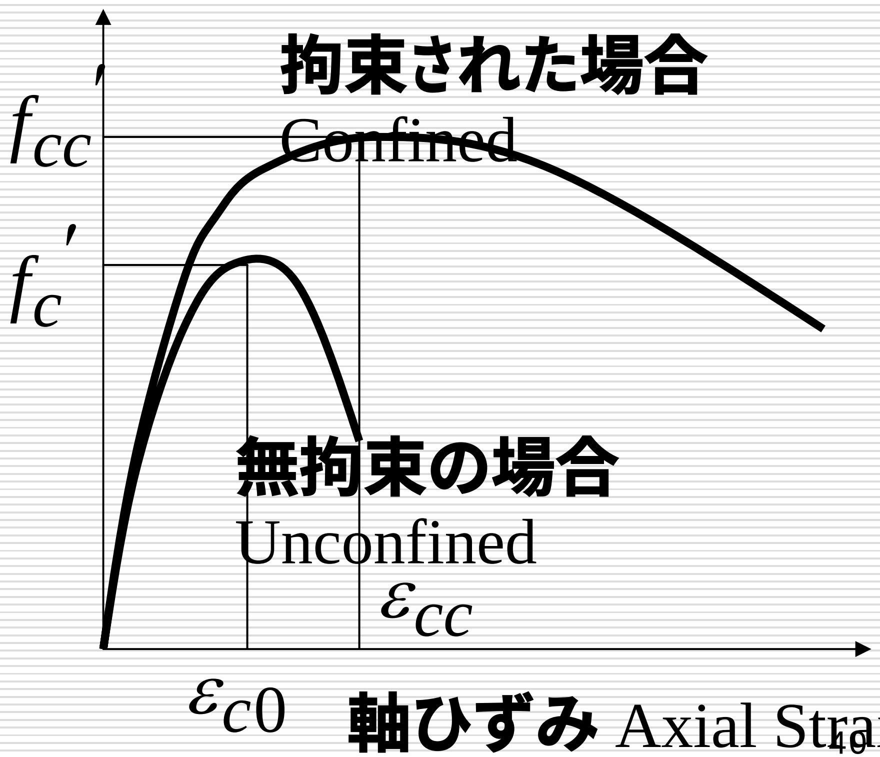
$$f_{cc}' = f_c' + \alpha \cdot f_{lc}$$

Richardt, F.E.,
Brandezuberg, A.
& Brown, 1929

$$\alpha = 4.1$$

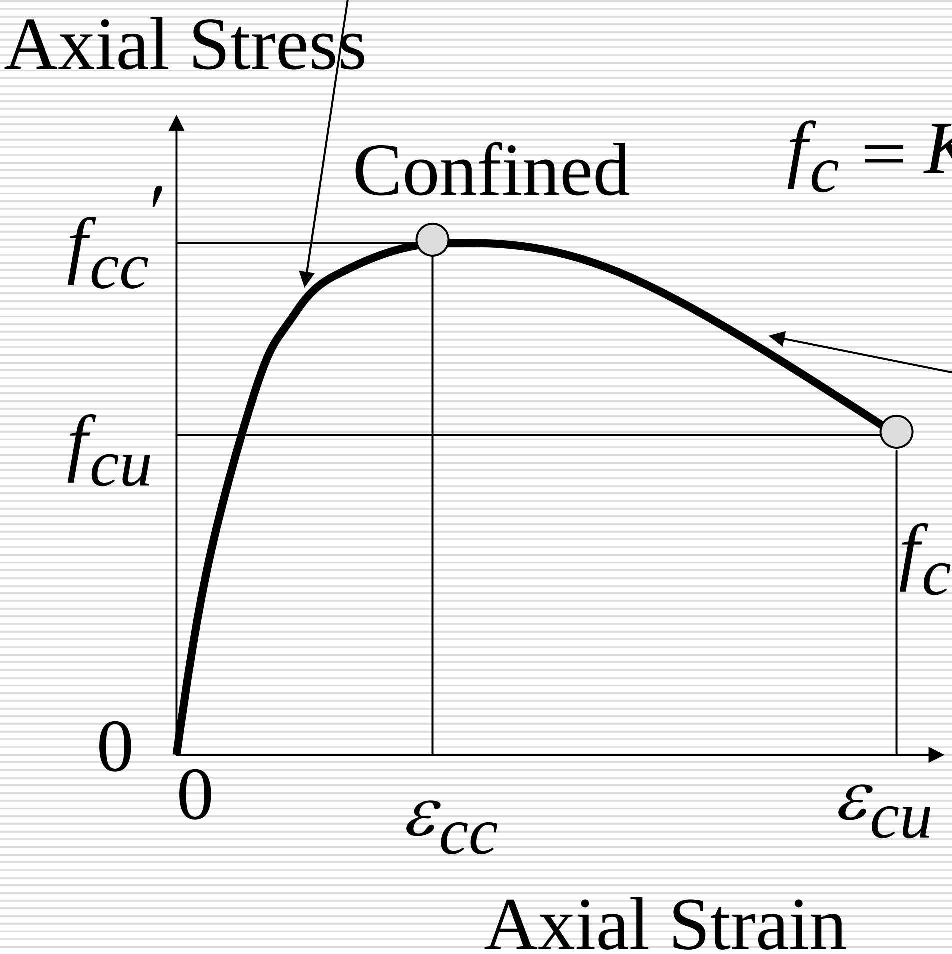
$$\varepsilon_{cc} = \varepsilon_{c0} + \beta \cdot \frac{f_{lc}}{f_c'}$$

軸応力 Axial Stress



軸ひずみ Axial Strain

7) Formulation by Kent and Park (1971)



応力上昇域

$$f_c = Kf_{cc}\left\{\frac{2\varepsilon_c}{0.002K} - \left(\frac{\varepsilon_c}{0.002K}\right)^2\right\}$$

応力下降域

$$f_c = Kf_{c0}\{1 - Z(\varepsilon_c - 0.002K)\}$$

8) Formulation by John Mander, Nigel Priestley & Robert Park, 1988

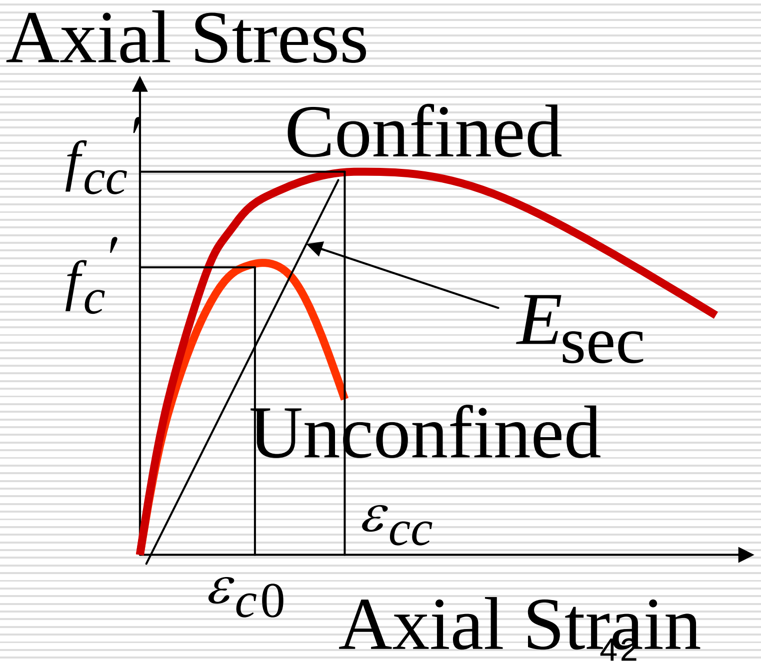
$$f_c = \frac{f_{cc}' x r}{r - 1 + x^r}$$

$$f_{cc}' = f_c' \left(2.254\sqrt{1 + \frac{7.94 f_l'}{f_c'}} - \frac{2 f_l'}{f_c'} - 1.254\right)$$

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}}$$

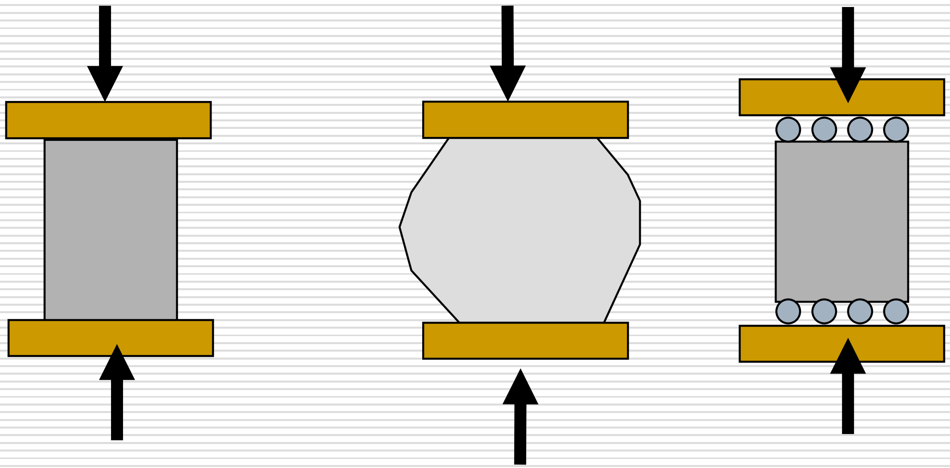
$$\varepsilon_{cc} = 0.002\left\{1 + 5\left(\frac{f_{cc}'}{f_c'} - 1\right)\right\}$$

$$r = \frac{E_c}{E_c - E_{sec}}$$

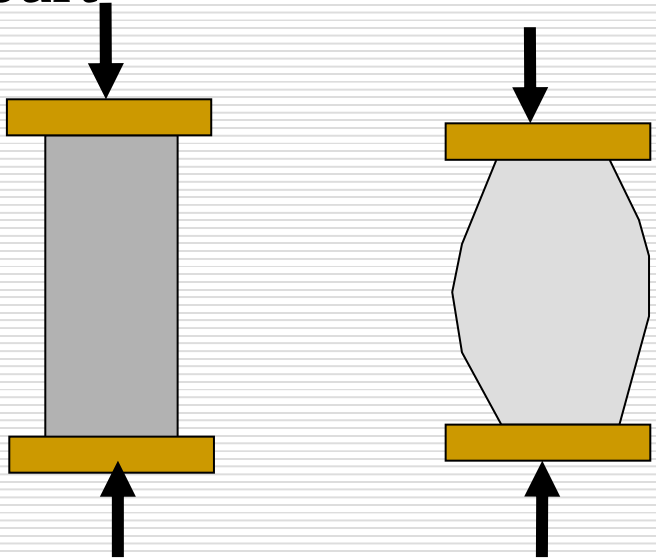


9) Important points which should be noticed

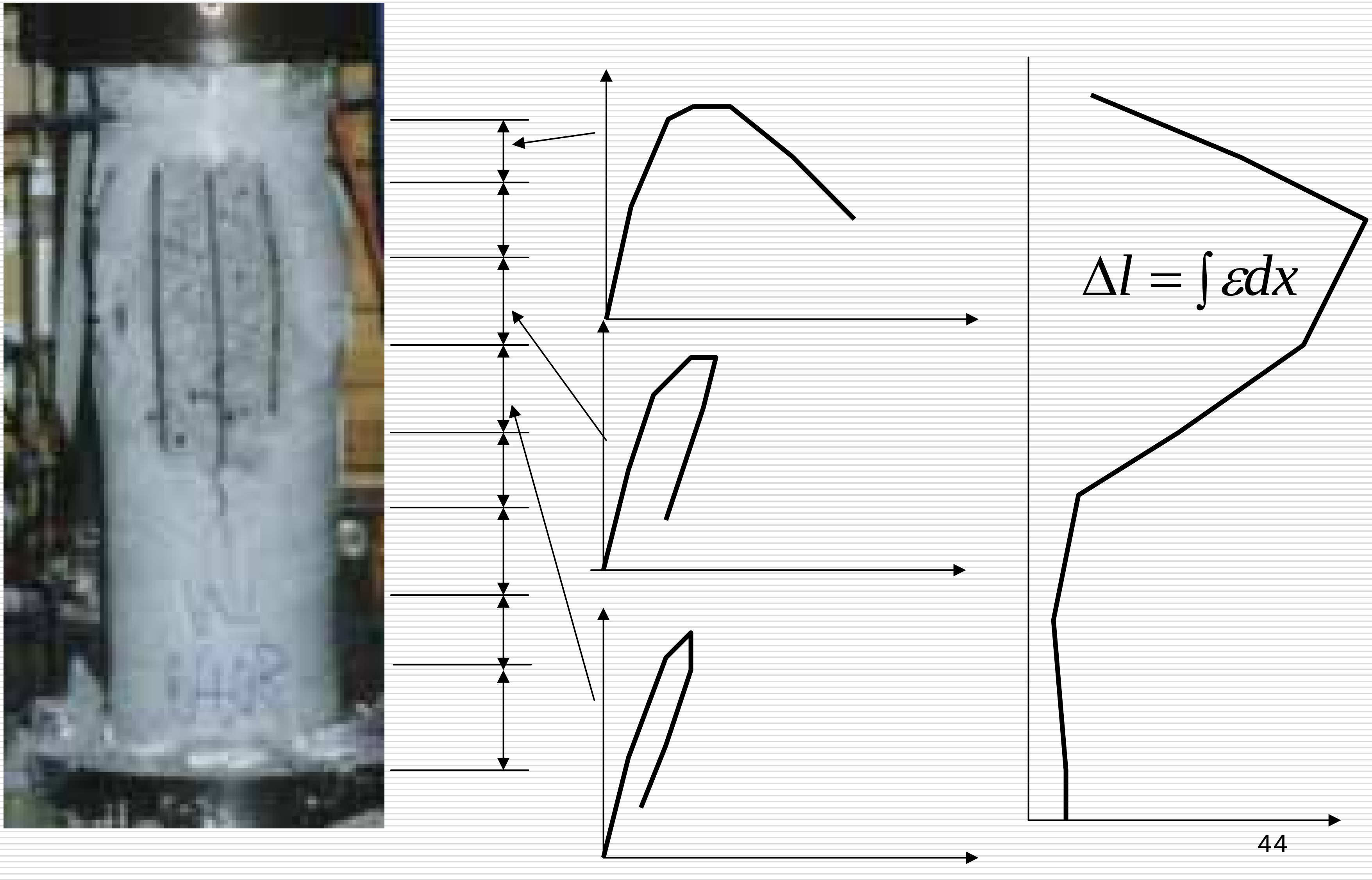
(1) Effect of Friction at the Top & Bottom of the Cylinder



If the cylinder is high, the effect of friction is less at the center part



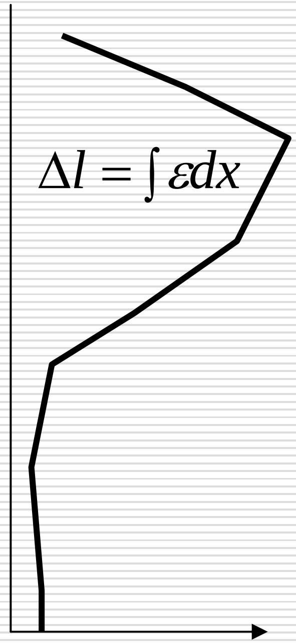
Strain along the Height



(2) 平均ひずみか局所ひずみか？
(2) Averaged strain vs. Peak strain

- Average axial strain within a certain height increases as the height decreases

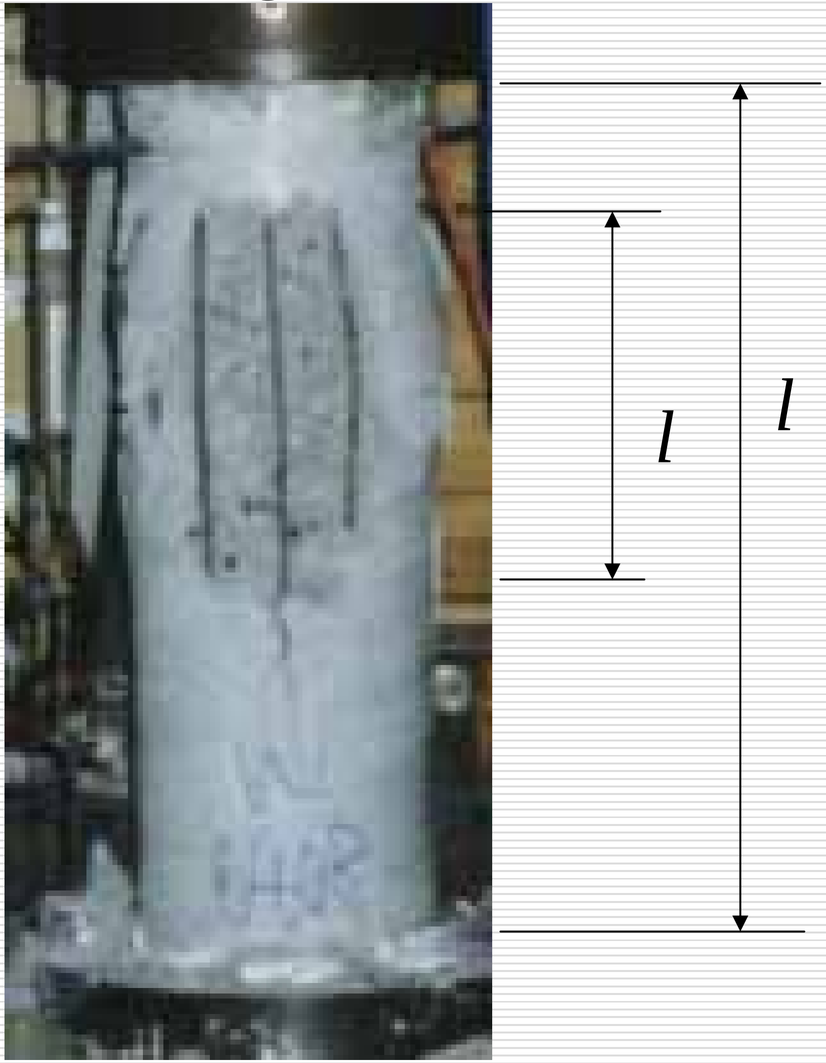
$$\varepsilon_{c,average} < \varepsilon_c$$



- How can we know the location where extensive failure occurs prior to the test?

How should we measure the vertical strain?

Failure of concrete does not occur uniformly along the cylinder height



Axial concrete strain

$$\varepsilon_c = \frac{\Delta l}{l}$$

- Where should we measure the strain?
- How should l be decided?

We have to use the existing constitutive models by knowing that all of them provide only approximate results

- By knowing the various approximation involved in the constitutive model, we have to use the model in analysis. Any models developed from unilateral loading experiments to cylinders are only approximate.

- Calibration of the validity of constitutive models based on an approximate loading experiment for structural components concerned is required. In other word, we can use the constitutive models under the conditions that they are calibrated.