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

(5-2) Strength and Ductility Capacity of RC Structural Members (5-2)RC構造物の動的耐力・変形性能

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### 10) 星隈、川島他による定式化 10) Formulation by Hoshikuma and Kawashima et al (1996)

### Loading Concrete Cylinders using 30MN Compression Machine at the Public Works Research Institute





### Unilateral Loading Tests to Evaluate An Empirical Confinement Model



Hoshikuma, J., Kawashima, K., Nagaya, K. & Taylor, A., 1997 (Proc. ASCE, ST 123, 1997) (**道路橋示方書**、Design Specifications of Highway Bridges, JRA, 1996 & 2002)



$$f_{c} = 0 \quad \text{at } \varepsilon_{c} = 0$$

$$\frac{df_{c}}{d\varepsilon_{c}} = E_{c} \quad \text{at } \varepsilon_{c} = 0$$

$$f_{c} = f_{cc} \quad \text{at } \varepsilon_{c} = \varepsilon_{cc}$$

$$\frac{df_{c}}{d\varepsilon_{c}} = 0 \quad \text{at } \varepsilon_{c} = \varepsilon_{cc}$$

### Formulation of Ascending Branch

Kent & Park

 $f_{c} = f_{cc} \left\{ \frac{2\varepsilon_{c}}{\varepsilon_{cc}} - \left(\frac{\varepsilon_{c}}{\varepsilon_{cc}}\right)^{2} \right\}$ 

Initial stiffness

 $\left(\frac{df_c}{d\varepsilon_c}\right)_{\varepsilon_c=0} = \frac{2f_{cc}}{\varepsilon_{cc}}$ 



In the Kent & Park equation, the initial stiffness depends on the tie reinforcement ratio, however the test results show that it is independent of the tie reinforcement ratio

 $f_c = C_1 \varepsilon_c^{\ n} + C_2 \varepsilon_c + C_3$ 

# Formulation by Hoshikuma, J., Kawashima, K. et al (1997)

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$$f_{c} = \begin{cases} E_{c}\varepsilon_{c} \left\{ 1 - \frac{1}{n} \left(\frac{\varepsilon_{c}}{\varepsilon_{cc}}\right)^{n-1} \right\} & \text{Ascending branch} \\ f_{cc} - E_{des}(\varepsilon_{c} - \varepsilon_{cc}) & \text{Descending branch} \end{cases}$$



$$n = \frac{E_c \varepsilon_{cc}}{E_c \varepsilon_{cc} - f_{cc}},$$
  
$$f_{cc} = f_c' + 3.8 \cdot \alpha \cdot \rho_s \cdot f_{yh}$$
  
$$E_{des} = 11.2 \frac{f_c}{\rho_s \cdot f_{yh}}$$

# Formulation by Hoshikuma, J. and Kawashima, K. et al (1997)



### Applicability of the Empirical Model



11) **除荷および再載荷履歴の定式化** 11) Formulation of Unloading & reloading paths

Uniaxial Loading Test on Concrete Cylinders









# Full Unloading & Reloading Paths (continued)

where

$$\widetilde{f} = \frac{f_c}{f_{ul,n}}$$
$$\widetilde{\varepsilon} = \frac{\varepsilon_c - \varepsilon_{pl,n}}{\varepsilon_{ul} - \varepsilon_{pl,n}}$$

$$E_{rl} = \frac{f_{ul,n+1} - 0.1 f_{ul,n}}{0.8(\varepsilon_{ul} - \varepsilon_{pl,n})}$$



#### 繰り返し載荷の影響 Full Unloadings & Full Reloadings Deterioration rate of the stress at an unloading strain $\sigma_{ul,1}$ $\sigma_{ul.n+1}$ $\sigma_{ul,2}$ $\sigma_{uln}$ $\sigma_{ul,3}$ Stress Deterioration rate of plastic $\varepsilon_{pl,2}$ strains after fully unloaded $\varepsilon_{pl,1} \ \varepsilon_{pl,3}$ $\varepsilon_{ul}$ $\gamma_n = \frac{\varepsilon_{ul} - \varepsilon_{pl.n}}{\varepsilon_{ul} - \varepsilon_{pl.n-1}}$ Strain





$$\rho_{s} = 0.67\%$$



Mander, Priestley & Park (1988)











# Interlocking Column



Great Contribution of New Zealand for the Development of Interlocking Spiral Columns



#### University of Canterbury



# Implementation of Interlocking Spiral Columns in USA

#### Retrofit after 1994 Northridge EQ



### Cyclic Loading Test on Interlocking Spiral Columns



# Courtesy of Tokyu Construction







## **Rectangular Hollow Section**



## Verification on the Effectiveness of Lateral Confinement on Bridge Columns

NO.3 B

....

Public Works Research Institut

10m

## Pre-1995 Kobe Earthquake Column





4.5 曲げ非線形性のモデル化 4.5 Idealization of Flexural Hysteretic Behavior

### 1) Available methods

- Finite Element Analysis Many unknowns, and limited for simple structures
- Fiber Element Analysis Practical constitutive models are required for concrete and reinforcing bars
- Empirical Constitutive Model
  - ✓ Practical, widely used
  - Still good empirical models which take account of bilateral bending and variation of axial force are not available





4) ファイバー要素解析法
4) Fiber Element Analysis
(1) Feature of FEA



• Account for hysteretic behavior of structural members, such as reinforced concrete column and steel columns

•Easy to introduce constitutive laws of structural materials

• Much less computer time than the standard FEM

• Extensively used in seismic design of bridges 34







 $\sigma_s(x)$  Stress of longitudinal rebars at the distance of x from the center of the column

 $\sigma_c(x)$  Stress of concrete fiber at the distance of x from the center of the column



 $\mathcal{E}_{c} + \phi \cdot x$ 

•X

 $\mathcal{E} =$ 

 $\mathcal{E}$ 

$$N = \int \sigma_s(x) dA + \int \sigma_c(x) dA$$

 $M = \int \sigma_s(x) \cdot x dA + \int \sigma_c(x) \cdot x dA$ 

(6) Appropriate Idealization of Hysteresis of Confined Concrete and Reinforcing Bars



### (7) Pushover Analysis

Increase *F* in one direction to compute moment vs. curvature relation or the lateral force F vs. lateral displacement at the loading point







# Evaluation of Moment vs. Curvature Relation (continued)



Lateral displacement of a column

$$u = \int_0^h \theta dy = \int_0^h \int_0^h \phi(y) dy dy$$