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CURVATURE DUCTILITY DESIGN OF REINFORCED AND PRESTRESSED CONCRETE MEMBERS

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SUMMARY

Confining of concrete is one of most practical methods for enhancing the flexural ductility of concrete members. Main Purpose of this study is to propose the design procedure of confining reinforcement necessary to obtain the required section curvature. For this purpose, the stress-strain relationships of confined concrete were idealized by introducing the confining coefficient. The available limit of compressive strain necessary for calculating the maximum available section curvature was also given as a function of confining coefficient.

INTRODUCTION

In the seismic design of reinforced and prestressed concrete ductile frames, it is a matter of great importance to provide curvature ductility to each critical section of constituent members so as to satisfy the horizontal displacement ductility demand of the structure. Especially, the prestressed concrete flexural member shows relatively smaller section curvature ductility compared with ordinary reinforced concrete one, and thus the enhancing of section curvature ductility is quite important for it's successful use in seismic area. Similar problem exists in the reinforced concrete columns when they are subjected to heavy axial load. Past many researches indicate that the lateral confining of concrete is one of most practical methods for enhancing the curvature ductility of concrete members (Ref.1-5). In this study, basing on the idealized stress-strain relationships of confined concrete, design procedure of confining reinforcement necessary to provide the required ultimate section curvature in reinforced and prestressed concrete members is proposed. The idealization of stress-strain relationships of confined concrete were performed by using the authors' previous test results (Refs.6, 7). The curves are given in the formulae in which confining coefficient for evaluating the confining efficiency of lateral reinforcement is involved.

FLOW OF CURVATURE DUCTILITY DESIGN

Fig. 1 shows proposed curvature ductility design procedure in simple flow chart. First of all, ultimate strength design of member section is performed for given design earthquake load, where stress-strain curve of unconfined concrete is used in calculation for convenience. Then, section curvature, $\overline{\Phi}u$, necessary to absorb earthquake energy is determined in accordance with the seismic design code or the result of dynamic response analysis. After that, corresponding ultimate compressive fiber strain of concrete, $\overline{\varepsilon}u$, should be calculated, where idealized stress-strain relationships of confined concrete and of reinforcing steel shall be used. Stress-strain relationship of confined concrete is changed by the degree of lateral confining and exact curve can not be known at this stage because necessary amount of confining reinforcement is not yet determined. Therefore, roughly idealized stress-strain curve such as elastic perfectly plastic relationship, for instance, shall be applied to the calculation at this stage. After obtaining the ultimate compressive fiber strain of concrete, $\bar{\varepsilon}_u$, in corresponding to the necessary ultimate flexural curvature, $\bar{\Phi}_u$, the amount of confining reinforcement is designed so as to develop the required ultimate compressive fiber strain, $\bar{\varepsilon}_u$, in concrete. Relationship between the amount of confining reinforcement and the required ultimate compressive fiber strain is given hereafter. Design chart for obtaining the amount of confining reinforcement can be easily prepared as described afterward, and as a result, it is no need to follow design flow above for determining the necessary amount of confining reinforcement in practical design.

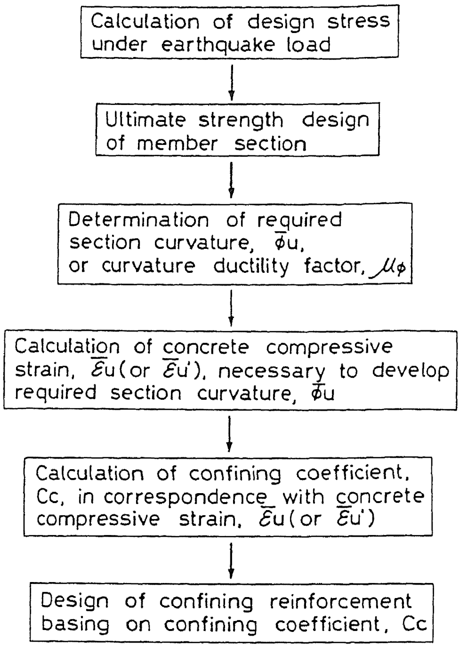


Fig.1 Flow of curvature ductility design

IDEALIZATION OF STRESS-STRAIN RELATIONSHIPS OF CONFINED CONCRETE

Fig. 2 shows proposed idealization of stress-strain curves both for unconfined and confined concrete (Curves OABC and OADEF). Points A and D represent the peak stresses in these curves. Points B and E are the strains at which mean stress in stress-strain curve becomes maximum. In this study, strains at Points B and E are defined as the available limit of compressive strain for unconfined and confined concrete, respectively. As describing hereafter, available limit of compressive strain at Point E is rather conservative in the use of calculation of ultimate curvature for confined member section, and thus, refined available limit of compressive strain is proposed at Point F for confined concrete, where the straight line extended from Point E attains at the stress level as same as that at Point B.

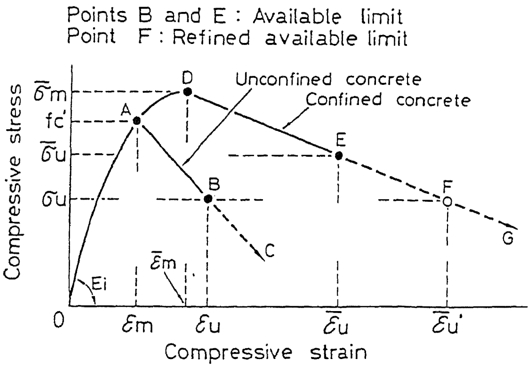


Fig.2 Idealization of stress-strain curves of confined and unconfined concrete

In the idealization, Curve OA is assumed as the parabola having the tangent modulus of Ei at the origin. Curve AD is also parabola but it has the vertex at Point D. For the strain softening regions after peak stress, straight lines of AB and DE are assumed both for unconfined and confined concretes. Thus, the idealized stress-strain relationships are given by following equations.

$$\text{Curve OA:} \quad \sigma_c = E_i \; \varepsilon_c + (f_c' - E_i \; \varepsilon_m)\left(\frac{\varepsilon_c}{\varepsilon_m}\right)^2 \qquad (1)$$

$$\text{Curve AB:} \quad \sigma_c = \frac{\varepsilon_c - \varepsilon_m}{\varepsilon_u - \varepsilon_m} (\sigma_u - f_c') + f_c' \qquad (2)$$

$$\text{Curve AD:} \quad \sigma_c = \left(\frac{\varepsilon_c - \bar{\varepsilon}_m}{\varepsilon_m - \bar{\varepsilon}_m}\right)^2 (f_c' - \bar{\sigma}_m) + \bar{\sigma}_m \qquad (3)$$

$$\text{Curve DEF:} \quad \sigma_c = \frac{\varepsilon_c - \bar{\varepsilon}_m}{\bar{\varepsilon}_u - \bar{\varepsilon}_m} (\bar{\sigma}_u - \bar{\sigma}_m) + \bar{\sigma}_m \qquad (4),$$

where, σ_c : Compressive stress (in MPa.), ε_c : Compressive strain.
E_i : Initial tangent modulus (in MPa.).
f_c' : Compressive strength of unconfined concrete (in MPa.).
ε_m and $\bar{\varepsilon}_m$: Strain at peak stress for unconfined and confined concrete.
ε_u and $\bar{\varepsilon}_u$: Available limit of compressive strain for unconfined and confined concrete.
σ_u and $\bar{\sigma}_u$: Stress levels at the strain of ε_u and $\bar{\varepsilon}_u$, respectively (in MPa.).

The values of σ_u and $\bar{\sigma}_u$ can be determined by applying the definition of available limit of compressive strain and the expressions are

$$\sigma_u = \frac{2 (A - f_c' \varepsilon_m)}{\varepsilon_u + \varepsilon_m} + f_c' \qquad (5)$$

$$\bar{\sigma}_u = \frac{2 (\bar{A} - \bar{\sigma}_m \bar{\varepsilon}_m)}{\bar{\varepsilon}_u + \bar{\varepsilon}_m} + \bar{\sigma}_m \qquad (6),$$

where, A and $\bar{A}$ are the areas of idealized stress-strain curves until the peak strain for unconfined and confined concrete, respectively.

According to the authors previous experimental study (Ref. 7), the value of Ei, m and u are given by following empirical formulae.

$$E_i = 22653\sqrt{f_c'/19.6} \qquad (7)$$

$$\varepsilon_m = 0.0013 (1 + f_c'/98.07) \qquad (8)$$

$$\varepsilon_u = 0.00413 (1 - f_c'/196.13) \qquad (9).$$

Also, the values of $\bar{\sigma}_m$, $\bar{\varepsilon}_m$ and $\bar{\varepsilon}_u$ were obtained by the authors basing on the test results on 19.4 x 19.4 x 40 cm square column specimens confined by various amounts of square confining reinforcement (Ref. 7). The test results cover 26.0 to 61.4 MPa. in compressive strength of unconfined concrete and 160 to 1353 MPa. in yield strength of confined reinforcement. Formulae obtained are as follows.

$$\bar{\sigma}_m = (1 + 50 C_c) f_c', \qquad \bar{\varepsilon}_m = (1 + 450 C_c) \varepsilon_m$$

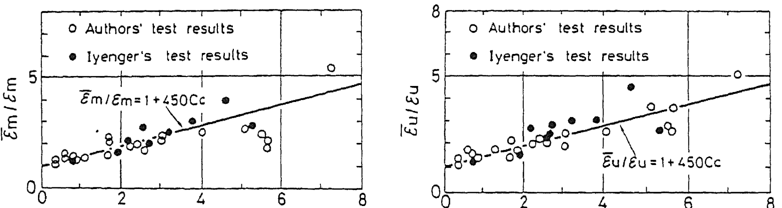
$$\bar{\varepsilon}_u = (1 + 450 C_c) \varepsilon_u \qquad (10),$$

where, Cc is the confining coefficient and is given by

$$C_c = 0.313 \; \rho_s \sqrt{\frac{f_y}{f_c'}} (1 - 0.5 \frac{S}{W}) \qquad (11).$$

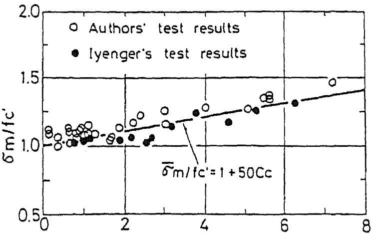
ρ_s : Volumetric ratio of confining reinforcement.
f_y : Yield strength of confining reinforcement in MPa.
S : Spacing of confining reinforcement in cm.
W : Minimum dimension of core concrete section in cm.

As a reference, comparison of Eq.(10) to the test results is shown in Fig.3.



Confining coefficient Cc ($\times 10^{-3}$)
(a) $\bar{\varepsilon}_m$-Cc relationships

Confining coefficient Cc ($\times 10^{-3}$)
(c) $\bar{\varepsilon}_u$-Cc relationships



Confining coefficient Cc ($\times 10^{-3}$)
(b) $\bar{\sigma}_m$-Cc relationships

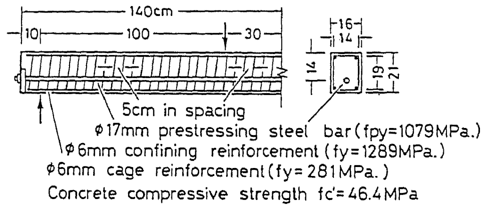
Fig.3 $\bar{\sigma}_m$ −, $\bar{\varepsilon}_m$ − and $\bar{\varepsilon}_u$ − Cc relationships obtained from experiments

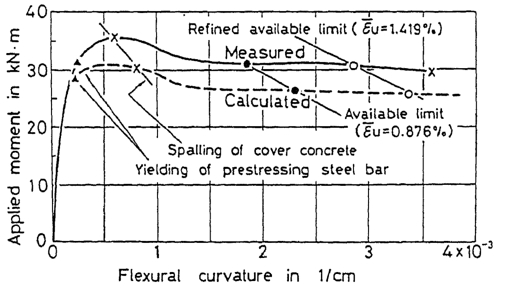
Refined available limit of compressive strain for confined concrete, $\bar{\varepsilon}_u'$, can be obtained by substituting the value of σ_u into σ_c in Eq. (4), that is,

$$\bar{\varepsilon}_u' = \frac{\sigma_u - \bar{\sigma}_m}{\bar{\sigma}_u - \bar{\sigma}_m}(\bar{\varepsilon}_u - \bar{\varepsilon}_m) + \bar{\varepsilon}_m \qquad (12).$$

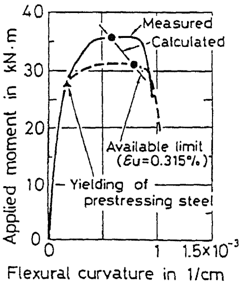
REFINING OF AVAILABLE LIMIT OF COMPRESSIVE STRAIN FOR CONFINED CONCRETE

For verifying the applicability of idealized stress-strain relationships of confined concrete, comparison of measured and calculated moment-curvature relationships was made on the prestressed concrete beams shown on top of Fig. 4.





(a) Confined beam



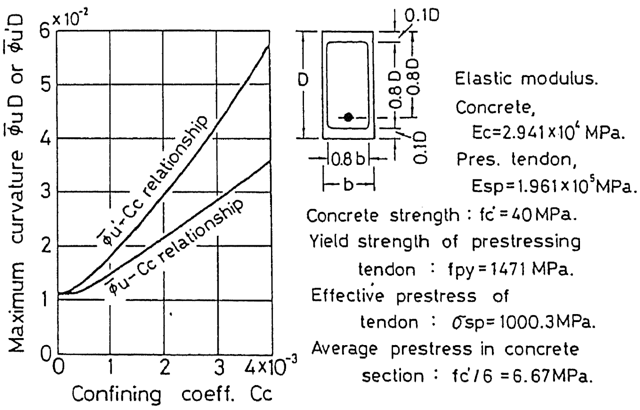
(b) Unconfined beam

Fig.4 Comparison between measured and calculated moment curvature relationships of prestressed concrete beams

Typical results for confined and corresponding unconfined beams are shown in Figs. 4(a) and 4(b), respectively. Rather good agreement between measured and calculated moment-curvature relationships can be obtained both for confined and unconfined beams. The curvature indicated by solid circle is available limit of curvature, $\bar{\Phi}u$, which corresponds to the concrete compressive fiber strain of $\bar{\varepsilon}u$. As can be seen from Fig. 4(a), the confined beam behaves in very stable manner beyond the available limit indicated by solid circle. And thus, it gives too conservative calculation result on ultimate available curvature when the strain, $\bar{\varepsilon}u$, at maximum mean stress in stress-strain curve idealized for confined concrete is defined as the ultimate compressive strain. On the contrary, the curvature, $\bar{\Phi}u'$, indicated by white circle corresponds to the refined available limit of compressive fiber strain, $\bar{\varepsilon}u'$, and is quite close to the measured ultimate curvature. Therefore, it is reasonable that the curvature, $\bar{\Phi}u'$, obtained from the refined available limit of compressive strain , $\bar{\varepsilon}u'$, shall be regarded as the ultimate section curvature, and the confining reinforcement necessary to develop the required ultimate section curvature shall be designed basing on this value. Relationship between the refined available limit of compressive strain, $\bar{\varepsilon}u'$, and the confining coefficient, Cc, can be obtained by substituting the second equation of Eq.(10) into Eq.(12). The expression is omitted in this paper.

CURVATURE DUCTILITY DESIGN CHART

Curvature ductility design chart can be prepared by using the formulae of idealized stress-strain curves for confined and unconfined concrete given in this study. The chart is given as the relationships between confining coefficient Cc and ultimate curvature, $\bar{\Phi}u'$. As a reference, the design chart for the prestressed concrete rectangular section having b x D in gross sectional dimension and 0.8b x 0.8D in core sectional dimension is shown in Fig. 5, where properties of materials and others necessary in calculation are given at the right-hand side of the



Elastic modulus.
Concrete,
$E_c = 2.941\times 10^4$ MPa.
Pres. tendon,
$E_{sp} = 1.961\times 10^5$ MPa.
Concrete strength : $f_c' = 40$ MPa.
Yield strength of prestressing tendon : $f_{py} = 1471$ MPa.
Effective prestress of tendon : $\sigma_{sp} = 1000.3$ MPa.
Average prestress in concrete section : $f_c'/6 = 6.67$ MPa.

Fig.5 Curvature ductility design chart

figure. After finding the necessary value of confining coefficient, Cc, in corresponding to required ultimate curvature, $\bar{\Phi}u'$, the amount of confining reinforcement is obtained from Eq. (11).

CONCLUSIONS

From this study, followings can be concluded.

(1) Curvature ductility design procedure to be applied to both reinforced and prestressed concrete members are proposed basing on the idealized stress-strain curves for confined concrete.

(2) In the idealization of stress-strain curves, confining coefficient, Cc, is introduced for evaluating the confining efficiency of lateral reinforcement.

(3) The moment-curvature relationship calculated by using idealized stress-strain curve of confined concrete agreed fairy well with measured one.

(4) Refined available limit of compressive strain, $\overline{\varepsilon}u'$, is also proposed in the idealized stress-strain curve of confined concrete. The ultimate curvature, $\overline{\phi}u'$, calculated from refined available limit of compressive strain, $\overline{\varepsilon}u'$, showed good agreement with that obtained from beam test.

(5) As a reference, practical design chart for obtaining the amount of confining reinforcement necessary to develop the required ultimate curvature is shown for a rectangular prestressed concrete beam.

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