SLIPPAGE OF REINFORCEMENT IN BEAM-COLUMN JOINT OF REINFORCED CONCRETE FRAME

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SUMMARY

This paper presents a simplified relationship between a fixed end moment and an additional rotation due to the pull-out of beam reinforcing bars from the beam-column joint, based upon the experiments which placed emphasis on direct measurement of the pull-out. This relationship includes cyclic reversed loading and covers the stage at which the bar have yielded. Nonlinear analysis using this relationship was carried out into the one-bay two-story reinforced concrete frame, and a good agreement between analytical and experimental results was obtained.

INTRODUCTION

Many investigators have indicated and backed up with their experiments that the additional rotations caused by the pull-out of the reinforcing bars from th beam-column joints take a great part in total inelastic deformations of reinforced concrete multistory building frames subjected to strong earthquake motions (Ref. 1,2). Furthermore, a few of papers have been presented, in which analytical approaches on the load-displacement relationship of reinforced concrete beam-column subassemblages or frames are developed considering these additional rotations(Ref. 3,4,5).

In contrast with these detailed and rather phenomenalistic studies, authors present in this paper a simpler moment-additional rotation relationship, which is characterized bi-linear under monotonic loading and hard spring type under cyclic reversed loading, and is taken care to be easily applied to the nonlinear frame analysis. Various constants used in this formulation are of course determined based upon the beam-column subassemblages tests or pull-out tests of reinforced concrete prisms (Ref. 6,7).

FORMULATION OF ADDITIONAL ROTATION

Monotonic Loading

Neglecting the concrete strain along the bar in the joint, the slippage Δs at the beam-column interface is given as follows.

$$\Delta s = \int_0^{Ls} \varepsilon st(x)\, dx \qquad (1)$$

Ls represents the distance from the beam-column interface to the point at

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which the bar begins to slip as shown in Fig.1(a). Before bar yielding ($\varepsilon st \leq \varepsilon sy$), it is assumed that the bond stress τ in the joint is distributed uniformly and that its magnitude is proportional to the tensile strain εst at the beam-column interface; namely,

$$\tau = \tau av = \alpha \cdot \varepsilon st \qquad \text{where } \alpha = 27.3 \times 10^3 kgf/cm^2 \qquad (2)$$

The costant value α was determined from the authors' test results as shown in Fig.2. From the equilibrium of the bar axial force,

$$Ls = (\sigma st \cdot Ast)/(\Sigma\phi \cdot \tau av) = (Es \cdot D)/(4 \cdot \alpha) \qquad (3)$$

and then, $\Delta s = (Ls \cdot \varepsilon st)/2$ (4)

After bar yielding ($\varepsilon st > \varepsilon sy$), assuming that the bar stress-strain curve possesses no plastic flow and the strain-hardening immediately happens, the stess and strain distribution inthe joint may be thought as bi-linear as shown in Fig.1(b). Ly in Fig.1(b) represents the yield development length and was determined from the strain measurements of the bar in the joint by W.S.G. in T-form beam-column subassemblages tests (Ref.1), as shown in Fig.2,

$$\begin{aligned} &\text{for } 1 < \beta \leq 1.05 && Ly = 200\beta - 200 \text{ (cm)} \\ &\text{for } \beta > 1.05 && Ly = 50\beta - 42.5 \text{ (cm)} \end{aligned} \qquad (5)$$

where, $\beta = \sigma st / \sigma sy$
therefore, the value of bar pull-out from the joint can be calculated as follows.

$$\begin{aligned} \Delta s &= [\, Ls \cdot \varepsilon st + Ly \cdot (\varepsilon sy + \varepsilon st)]/2 \\ &= [(Ls + Ly)/Es + (\beta - 1) \cdot Ly/Esh]\, \sigma y/2 \end{aligned} \qquad (6)$$

Now, let's provide a certain limit for Ls and Ly so that these values do not happen to be thoughtlessly large. The upper limit length of slip region Lcs and that of the yield development region Lcy are defined as shown in Fig.4. For interior joint Lcy is the column depth and Lcs is column depth added a half of beam depth, and for exterior joint Lcy is the straight lead embedment length and Lcs is the straight lead embedment length added the circumference of bent up portion. And then, if Ls + Ly > Lcs or Ly > Lcy, Lcs or Lcy must be substituted for Ls or Ly in the equations (4) and (6).

The beam end moment M and the additional concentrated rotation θs due to bar pull-out are defined as follows;

$$M = \sigma st \cdot Ast \cdot g \qquad (7)$$

$$\theta s = \Delta s / g \qquad (8)$$

where, g represents the distance between top and bottom bars in the beam. Although the slip stiffness $Ks = M/\theta s$ is a constant value before bar yielding, Ks after bar yielding is not constant but a function of $\beta = \sigma st / \sigma sy$ clearly from equation (6). However, in order to simplify the troublesome calculation, the slip stiffness Ks after bar yielding is assumed to be the slope of the straight line which connect the point (θ_{sy}, My) and the point (θ_{s1}, M1), where the point (θ_{s1}, M1) was determined by Ly = Lcy in equation (5). Therefore,

$$K_{s1} = M_y / \theta_{sy} \qquad (\sigma_{st} \leq \sigma_{sy}) \qquad (9)$$

$$K_{s2} = (\beta_1 - 1)\, M_y / (\theta_s - \theta_{sy}) \qquad (\sigma_{st} > \sigma_{sy}) \qquad (10)$$

where, $1 = \sigma_{st1} / \sigma_{sy} = M_1/M_y$

Putting Esh/Es to γ and rearrangeing the above discussion, the following formulation are reduced.

for $L_s \leq L_{cs}$

$$K_{s1} = 2 \cdot \alpha\, \Sigma \phi\, g^2 \qquad (11)$$

$$K_{s2} = 2 \cdot (\beta_1 - 1) \cdot A_{st} \cdot E_s \cdot g^2 / [L_{cs} - L_{cy} + L_{cy}(\beta_1 - 0.98)] \qquad (L_{cy} + L_s > L_{cs}) \qquad (12)$$

$$K_{s2} = 2 \cdot (\beta_1 - 1) \cdot A_{st} \cdot E_s \cdot g^2 / [\gamma L_{cy} \cdot (\beta_1 - 0.98)] \qquad (L_{cy} + L_s \leq L_{cs}) \qquad (13)$$

for $L_s > L_{cs}$

$$K_{s1} = 2 \cdot A_{st} \cdot E_s \cdot g^2 / L_{cs} \qquad (14)$$

$$K_{s2} = 2 \cdot (\beta_1 - 1) \cdot A_{st} \cdot E_s \cdot g^2 / [-L_{cy} + L_{cy}(\beta_1 - 0.98)] \qquad (15)$$

<u>Cyclic Reversed Loading</u>

Fig.5 shows the outline of the reinforced concrete beam-column subassemblages test including the interior joint which have been carried out at Toyohashi University of Technology (Ref.8). The slippage at the beam-column interface was measured by the slip gage as shown in Fig.5. The obtained relationship of fixed-end moment and additional rotations are shown with dot dash lines in Fig.6. For full development length such as IJ40 [Fig.6(a)], the bond deterioration zone is limited to the neighborhood of column face and the pull-out due to inelastic strain accumulation is dominant. Only top and bottom bars resist against the external moment without any coorperation of concrete. These phenomena is characterized as a stable spindle type in the load-deflection curve. For short development length such as IJ20 [Fig.6 (b)], on the contrary, a large amount of slippages are noticed and the complete bar sliding throughout the joint occurred at low load stage after a number of high load cycles. These phenomena is characterized as a pinching type in load-deflection curve.

Considering the above test results, authors present a $M - \theta_s$ hysteretic model as shown in Fig.7, where "ρ_s" represents the degree of bond deterioration caused by cyclic load reversals. The ρ_s value may be thought to depend upon not only the development length of the beam bars in the joint but the degree of shear reinforcement in the joint, the existence of transversed beam, and number of loading cycles. Here, the following definition is adopted to the interior joint.

$$\text{for } Ls \leq C \qquad \rho s = 0 \tag{16}$$

$$\text{for } C < Ls \leq Lcs \qquad \rho s = 0.5\ (Ls-C)/(Lcs-C) \tag{17}$$

$$\text{for } Ls > Lcs \qquad \rho s = 0.5 \tag{18}$$

where, C represents the column depth. The calculated $M - \theta s$ hysteretic loop based upon this model are shown as solid lines in Fig.6.

ANALYTICAL CASE STUDY AND CONSIDERATION

Nonlinear frame analysis considering the slippage of the beam bar from the joint were performed on a one-bay two-story reinforced concrete frame of which horizontal loading tests were carried out by Ogura and Tanaka (Ref.9). Inelastic beam model proposed by Takizawa (Ref.10), which is characterized as "pseudo antisymmetric rotations" deduced not from the material constitutive equation but from the experimental results of beam or column members, was used to the beams and columns in this frame. Incremental moment-rotation relationship including additional rotation due to the slippage of the beam reinforcement at any member AB in the frame is as follows.

$$\begin{Bmatrix} d\theta_A \\ d\theta_B \end{Bmatrix} = \begin{bmatrix} f_{11} + 1/K_{sA}, & f_{12} \\ f_{21}, & f_{22} + 1/K_{sB} \end{bmatrix} \begin{Bmatrix} dM_A \\ dM_B \end{Bmatrix} \tag{19}$$

The dimension and reinforcing details of the specimens, and the analytical results are shown in Fig.8. Fig.8 (b) shows the horizontal load-deflection curve under monotonic loading. Analytical curves are decomposed to each component: (1) due to elasto-plastic flexural deformation of member in clear span (2) due to shear deformation of member in clear span (3) due to shear deformation in the joint (4) due to additional rotation caused by the slippage of the bars in the joint. It is clear from Fig.8(b) that the analytical curve remarkably steps up to experimental one only when the additional rotations are considered. Fig.8 (c) shows the load-deflection curve under cyclic reversed loading after yielding, in which ρs is assumed to be zero for lack of sufficient test data about exterior joints. Nevertheless, a good agreement between analytical and experimental results was obtained.

CONCLUSION

Assuming that the bar strain in the joint is linearly distributed and using the yield development length which was obtained from experiments, $M - \theta s$ relationship was formulated as bi-linear type under monotonic loading. And defining "bond deterioration facter" ρs, $M - \theta s$ hysteretic loop was formulated as hard spring type under reversed loading. Nonlinear frame analysis was performed into the two-story reinforced concrete frame and a good agreement between analytical and experimental results was obtained.

REFERENCE

1. Kaku,T. and S.Morita, " Bond Behavior of Beam Bars in the Joint of R.C. Frame," Annual Meeting of AIJ, Oct. 1978, pp.1777-1778
2. Soleimani,D., E.P.Popov and V.V.Bertero, " Hysteretic Behavior of R.C. Beam-Column Subassemblages," J. of ACI, Vol.76, No.11, Nov. 1979, pp. 1175-1195
3. Tada,T. and T.Takeda, "Analytical Study on Deformation Characteristics of Plastic Hinge at hte end of R.C. Member and Proccess of Bond Deterioration in neighboring Anchorage Zone," Prc. Kanto District Symp. of AIJ, 1980, pp.125-136
4. Noguchi,H., "Nonlinear Finite Element Analysis of R.C. Beam-Column Joint, " Introductory Reports, IABSE Symp. at Delft, June 1981, pp. 639-654
5. Ichinose,T., "Methods of Inelastic Analysis of R.C. Frames with Bond Slip," Transactions of AIJ, No.328, June 1983, pp.26-35.
6. Morita,S. and T.Kaku,"Pull-out of the Beam Bar from the Joint of R.C. Beam-Column Subassemblages," Annual Meeting of AIJ, Oct.1972,pp.1099-1100
7. Kaku,T., et al,"Experimental Study on the Bond Deterioration and Shear Deformation in R.C. Joint," Proc. Tohkai District Symp. of AIJ, Feb.1983, pp.153-156
8. Kaku,T., et al,"Bond Deterioration btween Concrete and Deformed Bar Including Post-Yielding," Transactions of JCI, Vol.4, pp.349-354
9. Ogura,K. and R.Tanaka,"Study on the Aseismic Ability of R.C. Frame with SD50 Steel Bar," Annual Meeting of AIJ, Sep.1980, pp.1653-1654
10. Takizawa,H.,"Notes on Some Basic Problem in Inelastic Analysis of Planar R/C Structures," Transactions of AIJ,No.240,Feb.1976,pp.51-61, No.241, Mar.1976, pp.65-76

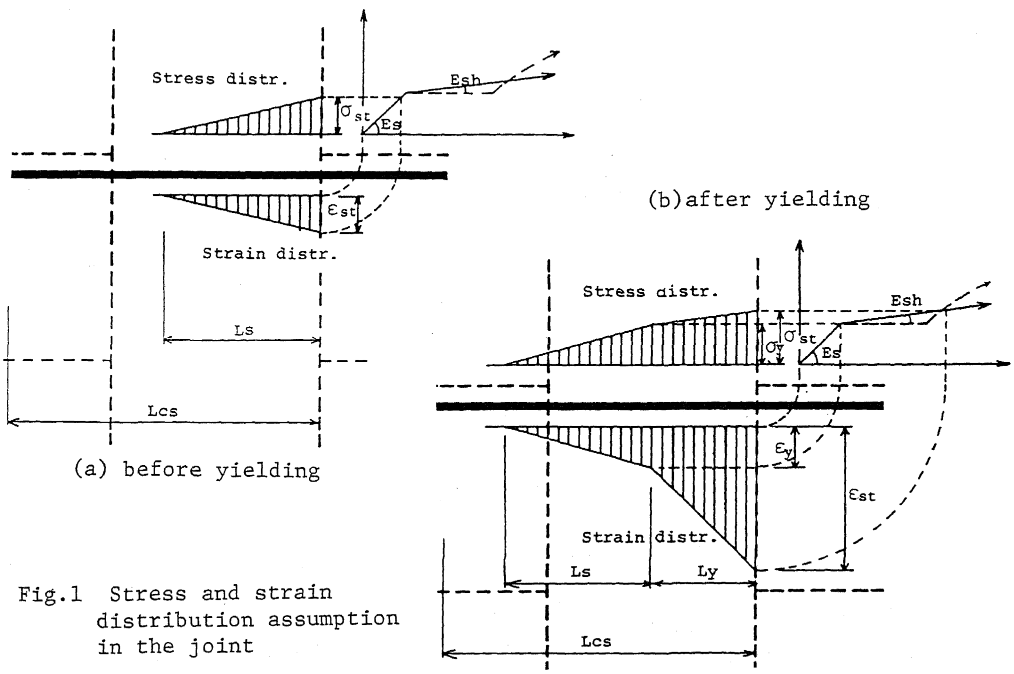


Fig.1 Stress and strain distribution assumption in the joint

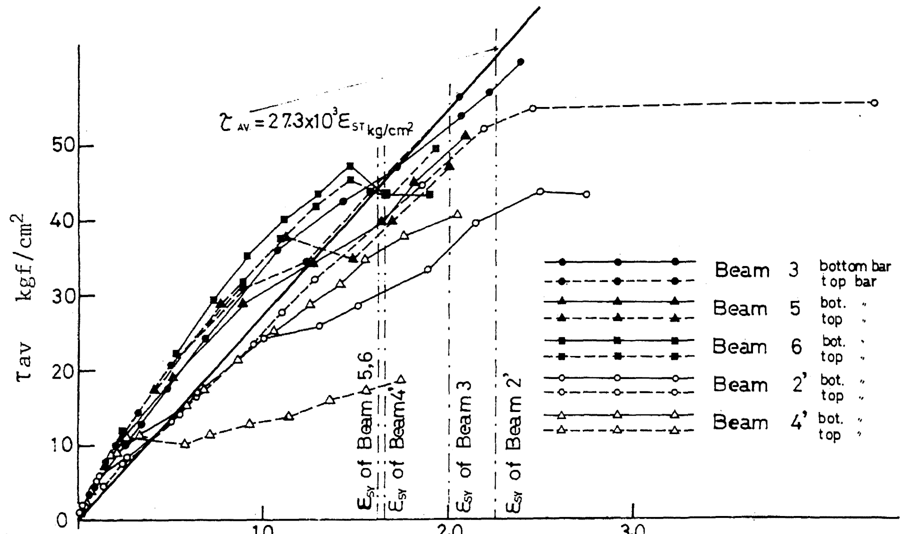


Fig.2 τ_{av} - ε_{st} Relationship (Ref.6)

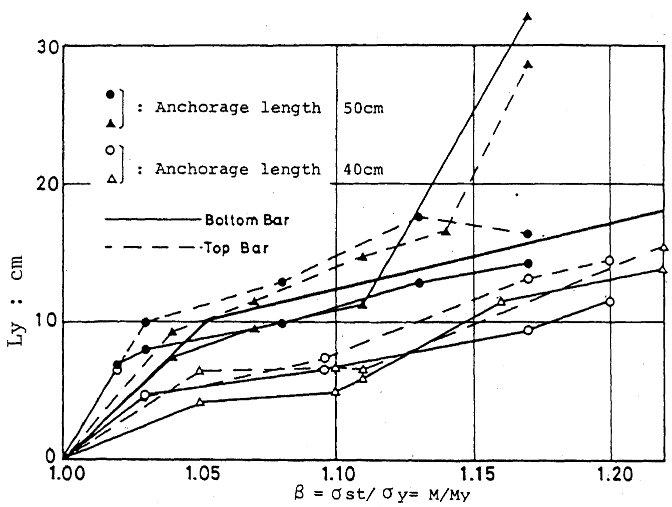


Fig.3 Yield development length in the joint from the test results (Ref.6)

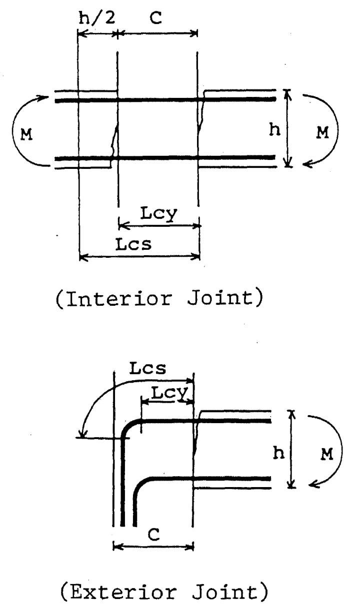
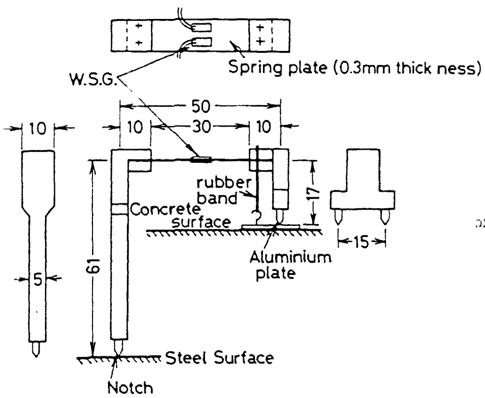
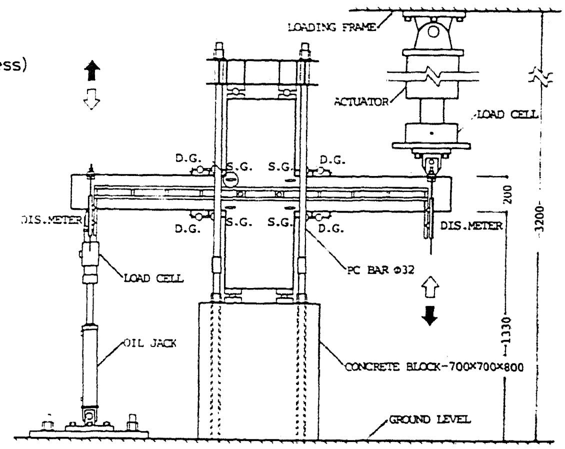


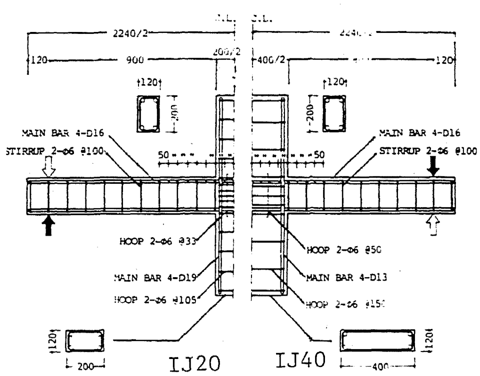
Fig.4 Definition of Lcs and Lcy



(a) Detail of slip gage



(b) Loading and measurement system



(c) Details of reinforcement

Fig.5 Outline of interior beam-column subassemblages tests (Ref.7) Unit: mm

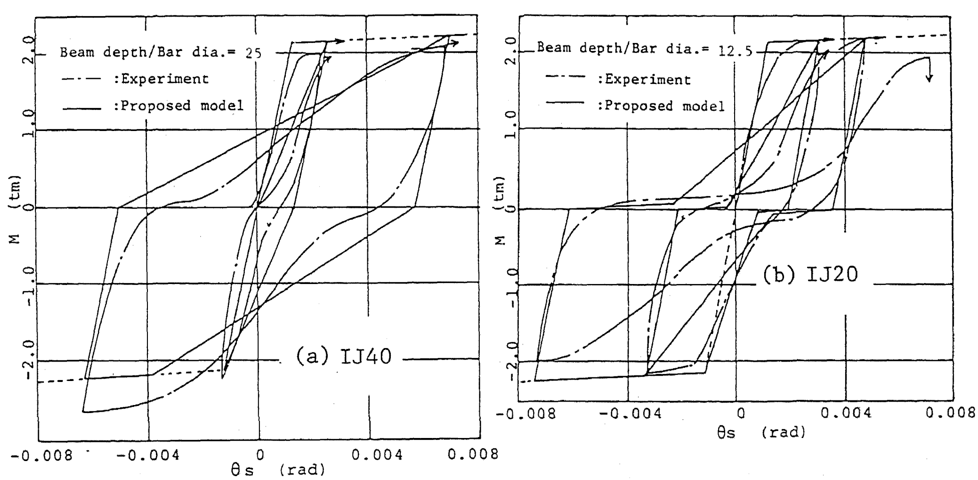


Fig.6 Moment - additional rotation relationship (Ref.7)

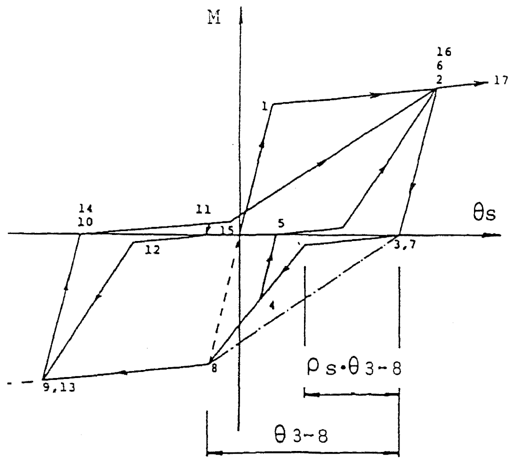
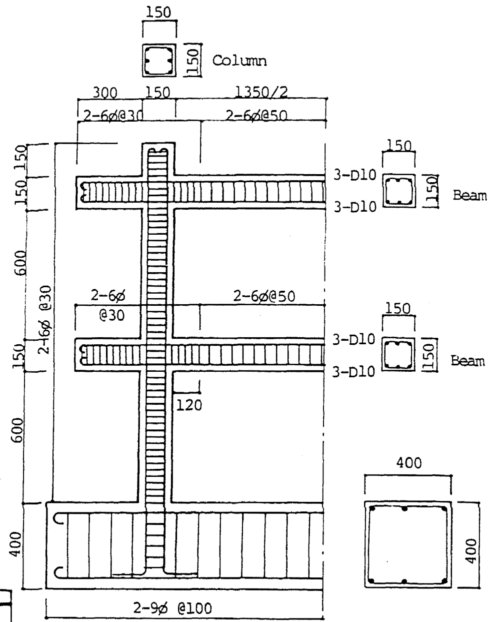
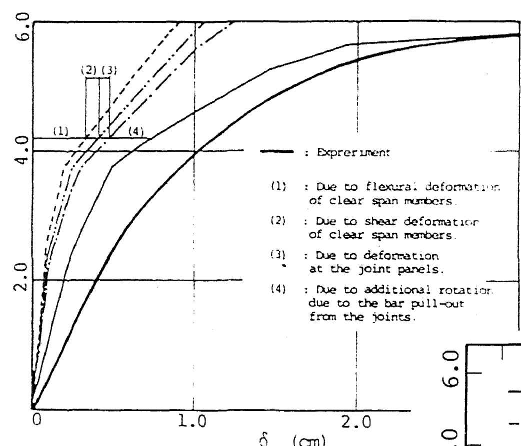


Fig.7 Hysteretic model under cyclic reversed loading



(a) Reinforcment detail of analized frame (Ref.9)
Unit: mm



(b) Load-displacement relation under monotonic loading

(c) Load-displacement relation under reversed loading

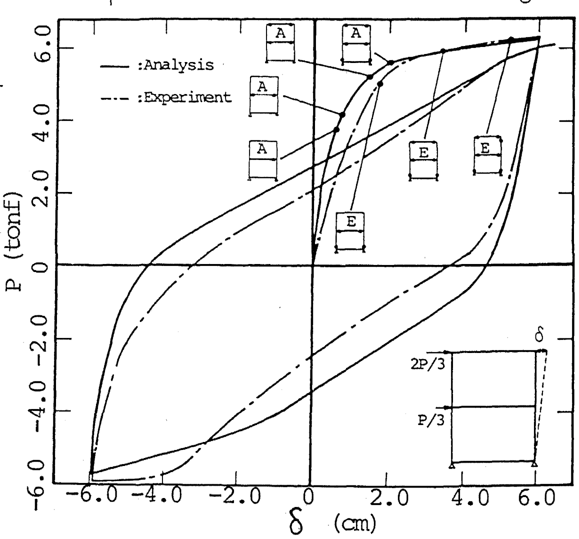


Fig.8 Comparison of analysis and experiment for R.C. one-bay two-story frame