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6-4-11 DUCTILITY AND ITS EVALUATION OF REINFORCED CONCRETE STRUCTURAL MEMBERS

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SUMMARY

A review of research on ductility of reinforced concrete members and following discussions of ductility evaluation are briefly described. The review indicated that 1) common data base, 2) unified criteria of ductility and 3) analytical approaches would be essential to establish generalized methods for ductility evaluation. Several studies with analytical approaches proposed by the authors indicated that the ductility of columns, bridge piers and shear walls were reasonably evaluated using the proposed procedures.

INTRODUCTION

The concept of ductility is adopted in recent seismic design codes for reinforced concrete building and bridge structures. Hence, the design seismic forces are generally much less than the elastic response force induced by a major earthquake. However, it is not well understood, due to lack of information of ductility evaluation, that how much displacement the designed structure can actually undergo during a major earthquake. While a great deal of tests related to ductility of members have been conducted for many years. The ductility was evaluated in each test with own criterion, therefore, the existing test data have not yet been systematically reviewed. Thus, a review committee, chaired by the first author, was organized in the Japan Concrete Institute in 1985 aiming 1) to overview the state-of-the-arts of research in Japan on ductility, 2) to provide common data base, and 3) to conduct fundamental studies for ductility evaluation. This paper outelines the review and following studies on ductility evaluation for columns, bridge piers and shear walls based on several analytical approaches. Note that each study was conducted by each author from own viewpoint.

REVIEW OF RESEARCH ON DUCTILITY OF MEMBERS

Ductility of Members Ductility means the ability of a member to undergo several displacement reversals in the inelastic range while maintaining a substantial portion of the initial strength. In laboratory test of members the ductility was evaluated generally in terms of the ultimate displacement δu or the ratio μ of δu to yield diplacement δy (Fig.1(b)). Here, δu was the limit displacement to maintain substantial load Pu which might take either a load at crush of concrete, yielding or buckling of longitudinal reinforcement, or a factored maximum load αPmax. The yielding was determined based on calculation, measured strain or hysteresis curves. In most columns and shear walls, the load 0.80Pmax was taken as Pu while Py was taken in more cases of bridge piers. Thus, practically there was no unified method to determine these particular loads and displacements.

Factors to Control Ductility The ductility of columns subjected to high shear and axial force was strongly affected by axial compression. Figure 2(a) shows an example where the ductility fafctor μ clearly decreased with increase of axial compression. Similar trend was observed in Fig.2(b) for shear walls. The ultimate displacement Ru significantly decreased with increase of axial stress of boundary column induced by axial load and overturning moment. Another factor was the level of ultimate capacity of members. Figure 3(a) shows the case of columns reviewed in ref.4, where the ratio of flexural capacity to shear capacity was taken as the index. The shear capacity was calculated by an empirical equation. Although there was a wide scatter, the factor μ linearly reduced with decrease of shear capacity. The equation in the figure was proposed for the lower boundary of test results. Similar study was made for shear walls (ref.5, Fig.3(b)). The displacement Ru was clearly reduced with increase of flexural capcacity while it was increased corresponding to the shear capacity which was calculated as the ultimate strength determined by the strength of concrete struts (ref.6).

The effect of confined concrete was discussed in several tests. In case of wall-type wide columns laterally reinforced with different detailings (ref.7, Fig.4), the displacement ability was significantly improved with the restraint of compression bars by lateral reinforcement. The confinement was also investigated in uni-axial compression tests observing the enhanced strength of concrete. The strength increment normalized by the confining stress by fluid pressure (ref.11) is plotted in Fig.5 for the data of refs. 8, 10 togrther with those calculated by the equation of ref.9. Similar comparisons for all the available equations suggested to evaluate the unconfined portion within core concrete.

Ductility of bridge piers subjected to low level of axial force and of small amount of reinforcement was affected by the pull-out of embedded steel bars from foundation as well as by general factors to control flexural behavior. The rate and history of loading were minor factors while perpendicular forces in the two-directional lateral loading generally resulted in significant loss of ductility.

Ductility Evaluation It was indicated that there was no general criterion to evaluate ductility. The energy dissipation was used as the index in few cases. The existing equations for ductility were generally followed by wide scatter due to the failure of concrete, in particular when they were applied to other data than their bases, because the equations were based on empirical approache alone.

DISCUSSIONS OF DUCTILITY EVALUATION

Ductility of Columns The ductility of selected columns in a series test of over 200 columns (ref.11) was studied and empirical equations for μ and Ru (Fig 6(b)) were proposed by S. Hayashi. The variables in the equation for μ were determined based on the flexural anaysis of concrete strain at the critical section. While the equation for Ru was derived assuming that a column displaced as a rigid body and the concrete strain at the critical section controlled Ru (Fig.6(c)). Figure 6(a) shows a good correlation of observed values of μ and Ru indicating that both were equivalent indices to evaluate ductility. Figs.6 (b) and (c) show good correlation between observed and calculated ductilities with acceptable error.

The confined concrete was studied by D. Kato using the most data of uni-axial compression tests. The enhanced strength of concrete and the strain at maximum load were evaluated by the proposed equations in Fig.7. The effective section area of core concrete, to be used to calculate the stress increment, was determined counting the unconfined portion of the core (ref.9). The calculation of stress increment referred to the study of ref.12, however, the confining stress was determined evaluating the role of lateral reinforcement to prevent buckling of main bars. The equation for the maximum strain was based on the proposal in ref.12. Although there were wide scatters, the trend of observed stress increment was well predicted while the strain was overestimated (Fig.7).

Ductility of Bridge Piers The existing empirical equations in refs. 13-16 to predict μ was studied by T. Endo using the same data base which included all the available data of bridge piers plus those of columns to have similar range of factors. It was indicated that each equation predicted μ with acceptable error within the recommended range of factors, however, it was subjected to a wide scatter for other data. Using the same data, empirical equations to predict both μ and Ru were derived from the regression analysis. Figure 8, however, shows very wide scatters to the obtained equations. It was presumed that the scatter would have been caused by different criterion of ductility in each test.

An approach to use a truss model in Fig.9(a) was studied for bridge piers by H. Mutsuyoshi. Here, lateral reinforcement, concrete between inclined cracks and shear resistance of concrete were replaced with elements of vertical tension, compression brace and another vertical tension, respectively. The stress-strain relation and the limit strain of concrete were assumed as shown in Fig.9(a). Figure 9(b) illustrates the influence of shear-span ratio on the ultimate displacement and the amount of tensile reinforcement on the ductility factor. The ultimate displacement was clearly decreased with decrease of shear-span ratio, while the trend of calculated ductility factor affected by the amount of tensile reinforcement was similar to that of test results.

Ductility of Shear Walls The ultimate displacement of shear walls was studied by T. Kabeyasawa with two approaches. The ratio of flexural and shear capacities in terms of $\nu m/\nu 0$ was used as the index in the first approach (Fig.10(a)). Where νm was the effectiveness coefficient for concrete strength to determine the required strength against the shear force developed at the full flexural capacity, and $\nu 0$ was the coefficient to determine the ultimate shear capacity. They were used for concrete struts in the model of truss and arch mechanisms. As shown in the figure, the displacement significantly increased with the increased margin of shear capacity. The lower boundary of test results were expressed with the equation in the figure. In the other approach, the calculated displacement as the sum of flexural and shear displacements were compared with test results. The flexuaral displacement was calculated using the neutral axis defined with a simple compression strut model in Fig.10(b) and the assumed limit strain of concrete at the critiacl sections of wall panel and boundary column. The shear displacement was based on the strain of the strut. Although there is a wide scatter, the caculation well grasps the trend of test results.

CONCLUDING REMARKS

Because of insufficient experience and lack of data, a great deal of work is yet to be done in the area of ductility evaluation. To estasblish methods for ductility evaluation of reinforced concrete structures, further discussions on 1) unified criteria of ductility in terms of appropriate indices, 2) theoretical approaches to investigate the factors and mechanism to control ductility, and 3) the effect of detailing of reinfircement on ductility, are needed.

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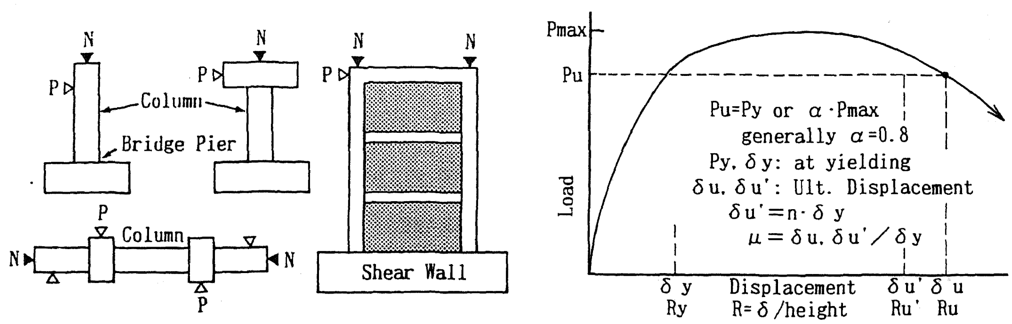
REFERENCE

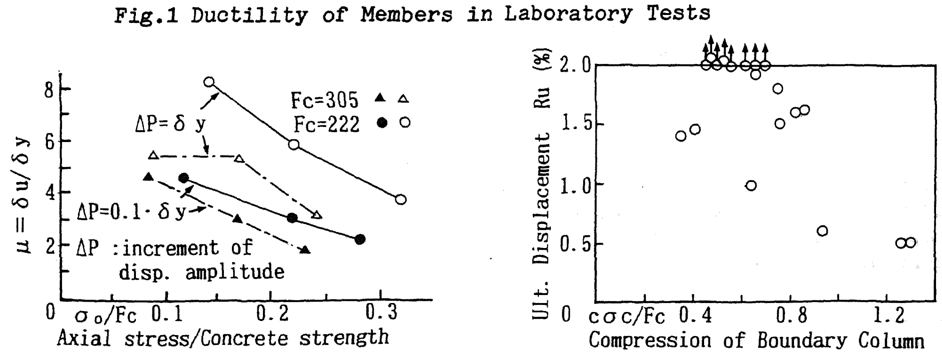
1. Japan Concrete Institute, Proceedings of the JCI Colloquium on Ductility of Concrete Structures and Its Evaluation, March 1988 (in Japanese)

2. Arakawa, T., et al, Evaluation of Deformational Behavior of R/C Columns under Cyclic Loadings, JCI 3rd Conference, 1981 (in Japanese)
3. Hiraishi, H., et al, Research on Seismic Performance of R/C High-Rise Frame Structure with Broad Columns -Part2-, Trans. of AIJ, 1986 (in apanese)
4. Arakawa, T., Relationship between Member Ductility and Amount of Lateral Reinforcement, Trans. of AIJ, 1977 (in Japanese)
5. Kabeyasawa, T., et al, Deformation Capacity of Reinforced Concrete Shear Walls, Transaction of Architectural Institute of Japan, 1986 (in Japanese)
6. Marti, P., Basic Tools of R/C Beam Deisign, ACI Journal, Jan.-Feb. 1985
7. Hiraishi, et al, Effect of Confinement in Comp. Zone on Ductility of Columns with Large Depth-to-Width Ratio, 7th Japan Earthquake Engng. Symposium, 1986
8. Muguruma, H., et al, Study on Improving the Flexural Deformation Capacity of Concrete by Using High Strength Hoop, JCI 1st Conference, 1979 (in Japanese)
9. Uzumeri, S. M., et al, Analysis Model for Concrete Confinement in Tied Columns, Journal of the Structural Division, ASCE, ST 12, December 1982
10. Moehle, J. P., et al, Confinement Effectiveness of Cross-ties in R/C, Journal of Structural Engineering, Proc., ASCE, Vol. 111, No.10, Oct. 1985
11. Richart, F. E., et. The Failure of Plain and Spirally R/C in Compression, Bull. No.190, Engng Experimental Station, Univ. of Ilinois, April 1929
12. Higashi, Y. and Hirosawa, M., Experimental Research on Ductility of R/C Short Columns under Cyclic Lateral Loads, IABSE Symposium, Quebec, 1974
13. Machida, A. and Mutsuyoshi, H., Evaluation of Ductility of reinforced Concrete Structures, 9th WCEE, Tokyo, Kyoto, 1988
14. Ishibashi, T., et al, Study on Deformation Capacity of R/C Bridge Piers Under Earthquake, Proceedings of JSCE No.390/V-8, Feb.1988 (in Japanese)
15. Higai, T., et al, Considerations on the Post-Yield Shear Failure Mechanism of R/C Members, 9th JCI Conference, 1987 (in Japanese)
16. Ohta, M., A Study on Earthquake Resistant Design for R/C Bridge Piers of Single Column Type, Public Works Res. Institute, Vol.153, 1980 (in Japanese)



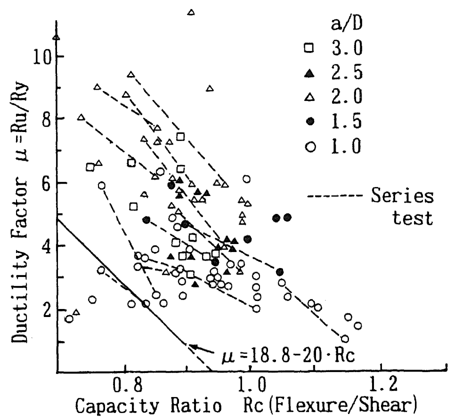
(a) Typical Test Members (b) Ultimate Displacement

Fig.1 Ductility of Members in Laboratory Tests

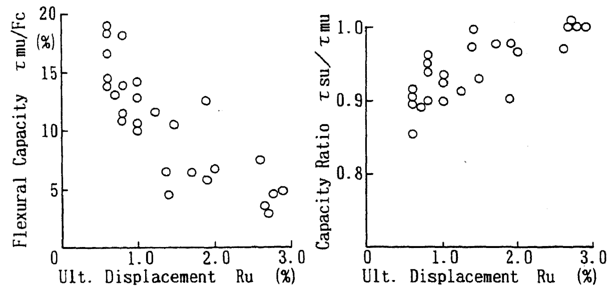


(a) Columns (Arakawa ref.2) (b) Shear Walls (Hiraishi ref.3)

Fig.2 Ductility vs Axial Compression



(a) Columns (Arakawa ref.4)



(b) Shear Walls (Kabeyasawa ref.5)

Fig.3 Ductility vs Capacity Level

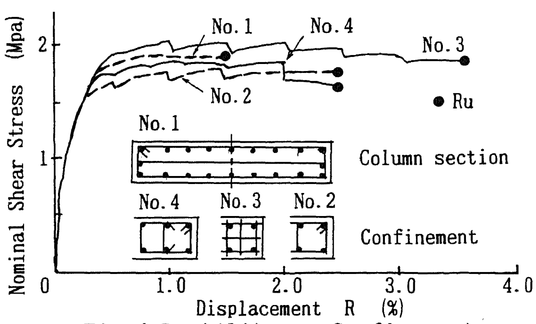


Fig.4 Ductility vs Confinement (Hiraishi et al ref.7)

Test data : ref. 8,10

Calculation : ref. 9

Δfcc : gained strength by confinement

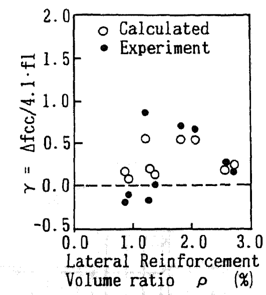
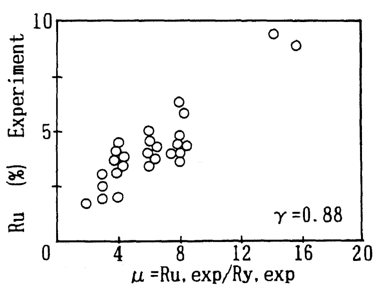


Fig.5 Effect of Confinement in Uni-axial Compression Tests



(a) Ru vs μ of Columns

$\mu\cdot cal = 0.93(1+1.29 Pw\cdot w\sigma y/\tau m) \times (1-4.35\cdot Pt\cdot s\sigma y/Fc) / (\eta_o+0.1) - 4.0(d/a)^2$

Pw, Pt : steel ratio

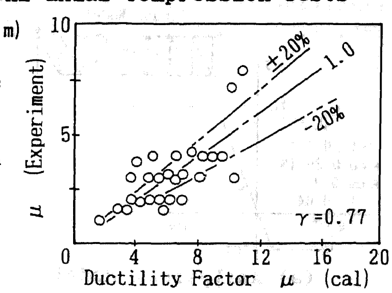
sσy, wσy : yield strength

τm : max. nominal shear stress

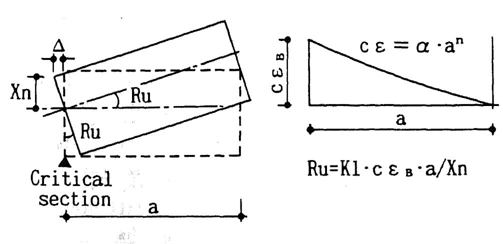
Fc : concrete strength

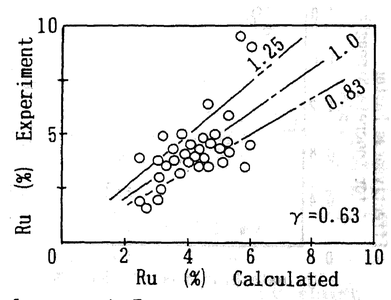
η_o : axial stress σ_o/Fc

a/d : shear span ratio



(b) Estimation of Ductility Factor μ





$Ru = 1.08a(2.61 Pw\cdot w\sigma y/Fc + 0.30)/Xn - 0.39$

(c) Estimation of Ultimate Displacement Ru

Fig.6 Ductility of Columns (Study by S. Hayashi)

$\Delta\sigma\ (cal) = 4.1 \cdot \sigma t$

$\Delta\sigma\ (exp) = (Pmax - Psteel - Pcover - Ai \cdot \sigma_0)/Ae - \sigma_0$

$\varepsilon max = 546 + 3.64 \cdot \sigma_0 + 150 \cdot \sigma t \quad (\mu)$

- σt : confining stress by lateral reinforcement
- Ae : confined area (ref. 9)
- Ai : unconfined area
- σ_0 : stress of plain concrete

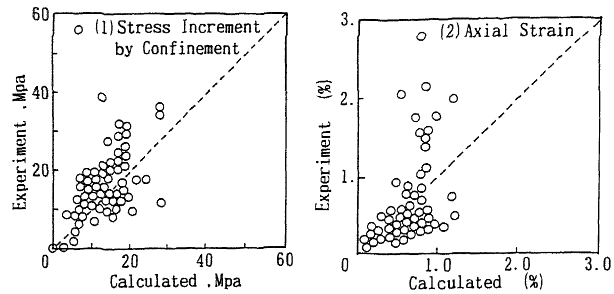


Fig.7 Confinement in Columns under Uni-axial Compression (Study by D. Kato)

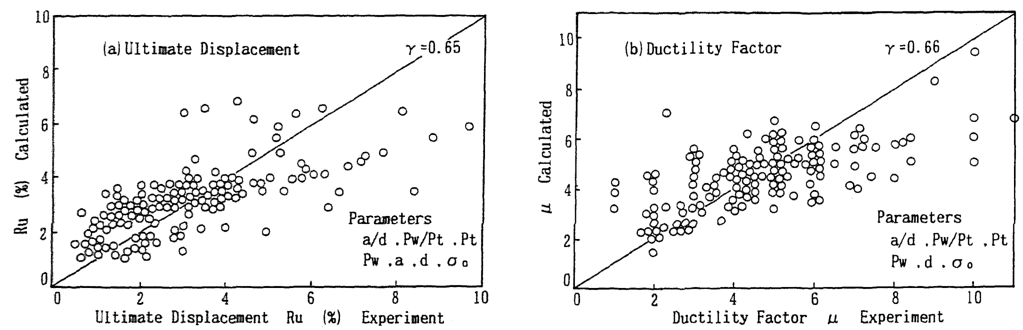
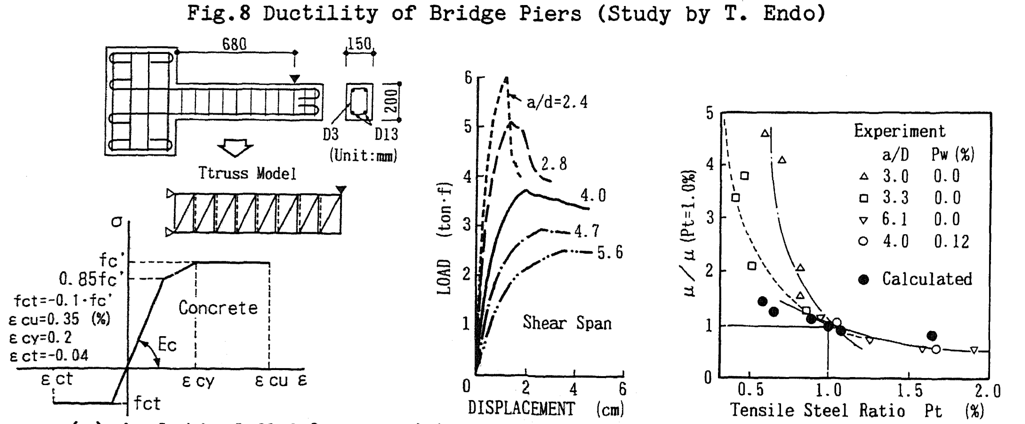
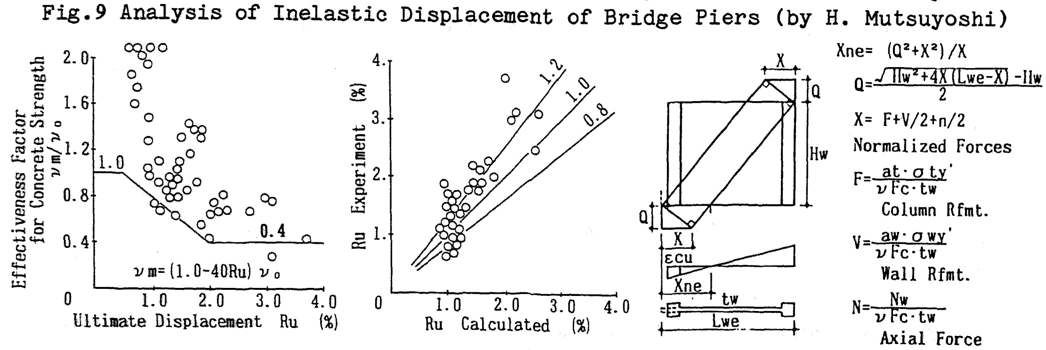


Fig.8 Ductility of Bridge Piers (Study by T. Endo)



(a) Analytical Model **(b) Calculated Displacement and Ductility Factor**

Fig.9 Analysis of Inelastic Displacement of Bridge Piers (by H. Mutsuyoshi)



(a) νm/ν0 vs Ru **(b) Estimation of Ultimate Displacement Ru**

Fig.10 Ductility of Shear Walls (Study by T. Kabeyasawa)