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EVALUATION OF ULTIMATE DEFLECTION OF REINFORCED CONCRETE MEMBERS

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SUMMARY

Cyclic loading tests were carried out in order to obtain a reliable equation to estimate ductility. Based on the test results, effects of various variables on ductility were investigated one by one. The results were summarized to a series of equations to estimate ductility as a term of ductility factor. It was proved that the derived equations can essentially evaluate the effects of the valuables on ductility and can estimate the ductility factor with satisfactory accuracy, even a little modification may be needed on the effect of effective depth.

1. INTRODUCTION

In recent seismic resistant design of reinforced concrete structures, it becomes more important to evaluate ductility, that is, the ability to deform without a significant reduction of load carrying capacity, because such a design concept that the design earthquake load might be reduced depending upon the magnitude of ductility becomes more common. In many design specifications, however, rather empirical methods are adopted to evaluate ductility. This is because there has not been established any reliable method to evaluate ductility of a member subjected to earthquakes.

The investigation reported herein was conducted to meet the situation described above and to obtain a reliable equation, with such an accuracy that can be applied to the seismic resistant design of reinforced concrete members in ordinary civil engineering structures. That is, at first, the reversed cyclic loading tests were carried out on the specimens in which the influencing factors were varied individually, and the cracking patterns, deformation characteristics and failure characteristics were investigated in detail. Then, based on the results, problematic points in the previous studies [1], [2], [3], [4] were investigated, and the relations between each influencing factor and ductility were formulated to numerical equations. Finally, a series of equations to evaluate ductility, which contains all of the factors adopted in the loading tests, was formulated combining the above equations, and the reliability of the equations was evaluated using test results previously reported.

2. OUTLINE OF EXPERIMENTS

The reversed cyclic loading tests were carried out on specimens of a cantilever type shown in Fig.1. The variables of the tests were tensile reinforcement ratio (p_t), web reinforcement ratio (p_w), compressive strength of concrete (f_c'), shear span ratio (a/d), axial compressive stress(σ_0), maximum size of coarse aggregate G_{max} and the number of repetitions of cyclic loading (n). All specimens were designed so that the range of variations of the variables covered those of ordinary civil engineering structures. That is, p_t=0.59-1.66% ; p_w=0-0.24% ; a/d=2.5-6 ; σ_0 =0-30kg/cm^2 ; f_c'=128-565kg/cm2 ; G_{max}=5-25mm ; n=1-30.

In the experiments, the load was increased monotonously at first, controlling the actuator by the magnitude of the load until the yield load, and the measured displacement at the yield load was defined as the yield displacement B_y. The yield load is a calculated one by using the elastic theory and assuming the ratio of Young's modulus n=15, at which the stress in the main reinforcements reaches the actual yield point. After the load reached the yield load, the displacement of the integral multiples of the yield displacement were applied cyclically by controlling the actuator by the magnitude of displacement. The number of repetitions at a certain displacement was the predetermined one.

3. FORMULATION OF EFFECT OF VARIOUS FACTORS ON DUCTILITY OF REINFORCED CONCRETE MEMBERS

3.1 Index of ductility In this investigation, ductility factor, that is, the ratio of ultimate displacement to yield displacement, was adopted as a qualitative index of ductility of reinforced concrete members. In determining the ductility factor, the yield displacement was determined as described in 2 and the ultimate displacement was defined as the limit displacement at which the restoring force does not exceed 80% of the maximum value. The ultimate displacement should meet such condition that a severe damage including the diagonal cracks is observed from the external appearance and, at the same time, restoring force is greatly reduced. It was recognized that the ultimate displacements determined according above definition satisfied the conditions described above in all specimens tested.

3.2 Method to formulate the effects of various factors Two procedures were attempted to formulate the effects of various factors. The first one is to express the effects of various factors on ductility inclusively by the strength ratio, that is, the ratio of shear strength to flexural strength. However, it was indicated from the results that the inclusive expression is immoderate. This is because the effects of factors on ductility is slightly different from those on shear strength though both of ductility and shear strength are affected by almost same factors. Therefore, it was concluded that the effect of various factors must be investigated one by one. The second procedure is as follows. That is, the total displacement at the tip of specimen was resolved into several components such as displacement due to pulling out of reinforcement, displacement of the portion severely damaged with diagonal cracks, displacement of the portion slightly damaged with flexural cracks only and the displacement due to slip at the fixed end, or into flexural displacement and shear displacement, and ductility is evaluated by the displacement component chosen as governing the ultimate state. Although this procedure was considered essentially reasonable because it is intended to model the actual phenomena faithfully, it was impossible to determine such the displacement component. This is because the component is affected by various complicated factors and any special relations could not be found out between the component and combinations of governing factors. Therefore, it is interpreted that the displacement must be treated inclusively as the displacement at the tip of members of a cantilever type. Following the conclusions described above, the effects of each factor on ductility was formulated using the ductility factor based on the total displacement at the tip of specimens.

3.3 Formulation of effects of various factors In formulating the effects of various factors on ductility, the relations between the ductility factor and each factor were illustrated using the results in which only a single factor was varied keeping the other factors constant, and the equation was determined so that the best fit for the plots was obtained. In the illustrations, the ductility factor was expressed in terms of the ratio of the ductility factor for an arbitrary value of one factor to a particular value. The test results used to formulate the equations were forty six.

Figure 2, which shows the effect of main reinforcement ratio on ductility, is an example of the illustrations. From this figure, the following equation was derived.

$$\beta_t = \mu_t - 1 = (pt)^r - 1$$
$$r = 0.146/(a/d - 2.93) - 0.987$$

where, β_t is a coefficient which expresses the effect of p_t on the ductility factor, and equals to 0 when p_t = 1%; r is a constant depending on p_w and a/d.

Equations of same kind were derived for all the factors adopted in the investigation following the same procedure described above. It was found from the obtained equations that the strength ratio concept is not always reasonable to evaluate ductility. The results shown in Fig.3, which shows the relation between shear span ratio and the ductility factor, is a typical example. As can be recognized from Fig.3, the ductility factor became smaller for smaller the a/d. This coincides with the fact on shear strength previously recognized, that is, in the range of a/d > 3, the strength ratio is larger, the larger a/d is. However, it can be also recognized from Fig.3 that the degree of the increase of the ductility factor accompanied by the increase of a/d is smaller, the larger σ_0 . This fact could not be expressed by the strength ratio concept. The reason for this was revealed from the investigation on the relation between flexural and shear displacement, cracking patterns and so on. Another typical example is the effect of concrete strength fc' on ductility. As shown in Fig.4, f_c' has less effect on the ductility factor if web reinforcements were arranged, whereas, if no web reinforcements were arranged, f_c' has a rather significant effect on the ductility factor. As for f_c', therefore, the equation to formulate the ductility factor should be alternated, considering the existence of web reinforcement or not. This fact could not be included in the strength ratio concept.

<u>3.4 Proposal of equations to evaluate ductility</u> The following equation to evaluate the ductility is proposed in the form of total of coefficients which express the effect of each factor, taking into account of effects of all factors adopted. That is,

$$\mu_u = \beta_0(1 + \beta_t + \beta_w + \beta_c + \beta_N + \beta_a + \beta_n) \qquad (1)$$

where, μ_u:ductility factor (ultimate displacement/yield displacement)

$\beta_0 = 28.4/d + 2.03$, $\beta_t = (pt)^r - 1$, $r = -0.146/(a/d - 2.93) - 0.973$

$\beta_w = 2.70(p_w - 0.1)$, $\beta_N = 2.18(\sigma_0 + 10)^{-0.260} - 1$, $\beta_n = 1.26(n)^{-0.0990} - 1$

$\beta_c = 0.00170(f_c' - 300)$ $(p_w = 0\%)$, $\beta_c = 0$ $(p_w \neq 0\%)$

$\beta_a = (-0.0153\sigma_0 + 0.175)(a/d - 4.0)$ $(\sigma_0 \leq 11.4kg/cm^2)$

$\quad 0$ $(\sigma_0 > 11.4kg/cm^2)$

d:effective depth (cm), p_t:longitudinal reinforcement ratio (%), a/d:shear span ratio, f_c':compressive strength of concrete (kg/cm^2), p_w:web reinforcement raito (%), σ_0:axial compressive stress (kg/cm^2) n:number of repetitions of loading.

This equation is formally such that only the main effect of each factor is taken up and the interactions are neglected. However, the equations were determined in such a manner that each coefficient β included the interactions, and so, the interactions are not neglected though the form shown above is adopted. The coefficient β_0 in the equation was introduced to express the effect of effective depth d, which was not taken into account. In determining β_0, β_0 were calculated by substituting experimentally obtained ductility factors and calculated coefficients β_t-β_n into the equations, and the relation between the calculated β_0 and d was illustrated (see Fig.5). It is recognized from Fig.5 that the relation between $\beta 0$ and 1/d was almost linear except in the case of G_{max} = 5mm. Based on this fact, the relation between them was formulated by the method of least squares. The result is,

$$\beta_0 = 28.4/d + 2.03$$

4. EVALUATION OF PROPOSED EQUATIONS

The preciseness of the proposed equations were calibrated as follows. At first, the relations between every influencing factor and the ratio of the experimental ductility factors to the calculated ones were investigated. As a result, it was concluded that the equations were properly evaluating the effects of various influencing factors on the ductility except the case of p_w = 0%. In the case of p_w= 0%, it could be hardly drawn the same conclusions as the other factors because the scatterings of the ratio of the experimental values to the calculated ones were relatively wide. This may be caused by the fact that no interaction between a/d and p_w were taken into account, in formulating the equations.

As a next step, the equations were evaluated using the data by other researchers [1], [2], [5], [6], which were not used in the formulation. That is, The ductility factors obtained by the data were compared with the ones calculated by the proposed equations. The result was as shown in Fig.6. According to this figure, it is recognized that the calculated values agreed well with the experimental ones. The average of the ratios of experimental values to the calculated ones for all specimens was 1.01 and the coefficient of variation was 16.5%. These values also indicate the equations give proper results. However, it was found from further investigations that the equations give unsafe side estimates for members of larger effective depth.

5. CONCLUSIONS

The investigations were carried out to make clear ductility of reinforced concrete members, which is very important to evaluate earthquake resisting capacity of the structures, and the equations to evaluate ductility were proposed, based on cracking patterns and displacement characteristics of specimens subjected to reversed cyclic loadings and adopting the ductility factor as an index of ductility. Within the limits of the investigations, the followings can be concluded.

(1) A method, in which equations to estimate the ductility factor are formulated by resolving the displacements of members into several components and extracting the component which govern the ultimate state of the member, will not give a fruitful result although this method is superior in its concept per se. This is because which and how each component arouse the ultimate state is governed by only a little change of various influencing factors.

(2) There have been many examples of a method to estimate the ultimate displacement using the relation between the ductility factor and the ratio of shear

strength to flexural strength, in which the effects of many factors are expressed inclusively by the ratio. To obtain a precise equation to estimate the ductility factor, the degrees of effects of various factors on the ratio should be nearly equal to the effects on the ductility factor. However, it was found that the above requirement was not necessarily satisfied. The typical examples are the effects of shear span ratio and compressive strength of concrete. Therefore, it is essentially improper to express the effects of various factors inclusively by the strength ratio though it could be allowed if used as an approximation. In order to obtain a precise equation to estimate the ductility factor based on actual phenomena, it is concluded to be proper to investigate the effects of each factor one by one and to formulate equation based on the results.

(3) The displacement at the tip of specimens of a cantilever type was adopted as the target function, following the facts described in (1), and the relations between the ductility factor and each influencing factor were formulated one by one, following the facts described in (2) and using data obtained from in this investigation and previous ones. The results were summarized to a series of equations to estimate the ductility factor. These equations include, as influencing factors, tensile reinforcement ratio, web reinforcement ratio, shear span ratio, axial stress, concrete strength, maximum size of coarse aggregate and number of repetitions of loading. From the result, it was recognized that the effects of various factors were essentially successfully taken into account in the equations though a little modification was needed in the effect of effective depth, which were out of range of data used to formulate the equations.

ACKNOWLEDGMENT

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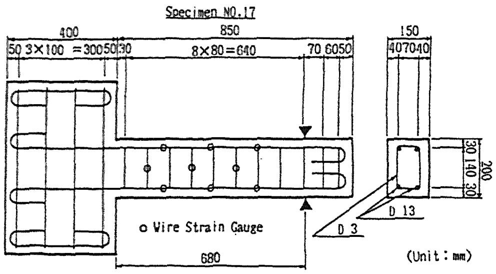

Fig.1 Dimensions of Specimens

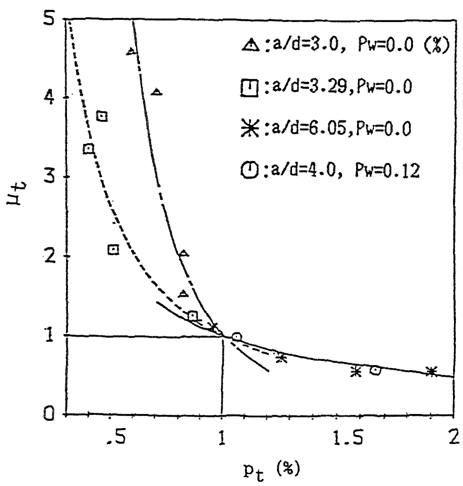

Fig.2 Relation between p_t and μ_t

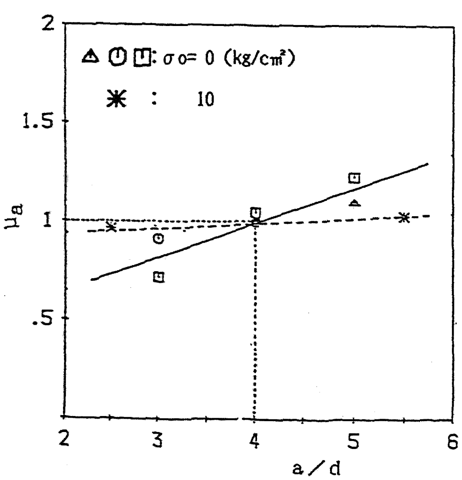

Fig.3 Relation between a/d and μ_a

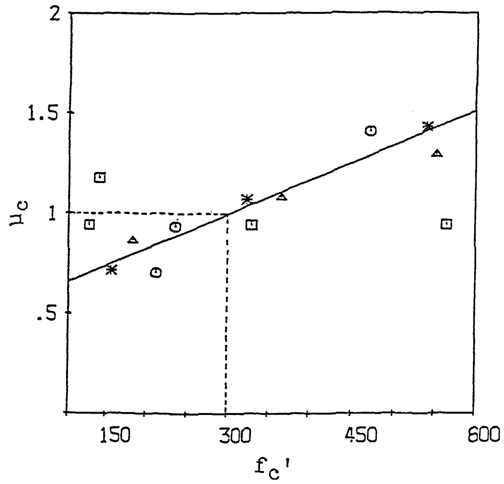

Fig.4 Relation between f_c' and μ_c

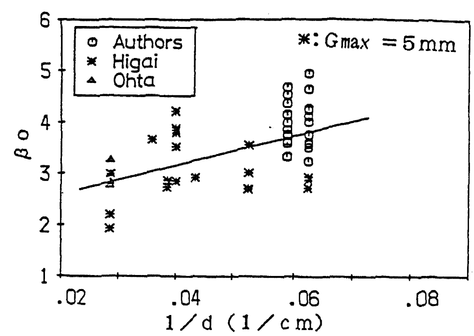

Fig.5 Relation between β_0 and 1/d

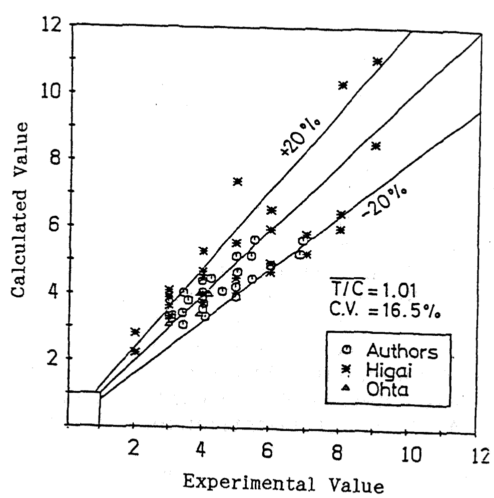

Fig.6 Evaluation of Proposed Equations.