構造体コンクリート強度の部位的変動に関する研究

山　田　和　夫

Study on Strength Distribution of Structral Concrete

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In this study, the strength distribution of structural concrete and the effect of heterogeneity of structural concrete on mechanical behavior, especially fracture mechanism, of reinforced concrete (RC) structure were investigated.

Main results are summarized as follows:

1) The distribution of concrete strength in column for casting height may be approximated by the equation of tri-linear type. The variation of concrete strengths between top and bottom of a column is about 26%.

2) The fracture processes of RC frame are affected by the difference of heterogeneity of structural concrete, such as strength variation of concrete.

3) In RC column which the bending moment of top is closer to that of bottom, the progression of damages at upper and lower portions of RC column change by the difference of heterogeneity of structural concrete.

1. INTRODUCTION

Strength of in-situ concrete is complicately affected by many factors, such as working way of mixing, placing and curing of concrete, or the sampling location of test specimens in structural members, and so on. Especially local strength of concrete cast in vertical members such as column and wall is remarkably varied with its casting height [1].

The effects of heterogeneity of structural concrete on the mechanical behaviors of reinforced concrete (RC) members or structures have been investigated previously by M. Yamada et al. [2], S. Morita et al. [3], Z. P. Bazant [4], L. H. Grant et al. [5] and S. A. Mirza et al. [6]. In these investigations, however, the concrete cast in the structural member has been regarded statistically as a homogeneous material, and the effects of variation of concrete strength owing to the casting height on the mechanical behaviors of RC structures have been unsolved.

In this study, the actual state of variation of concrete strength in structural members, and the effects of variation of compressive strength in structural members on the mechanical behaviors of RC structures were investigated, to evaluate the structural safety of RC structures.

2. CONCRETE STRENGTH IN STRUCTURAL MEMBERS

More than 1400 empirical data of compressive strength of in-situ concrete [1, 7, 8 and 9] were applied in the analysis. The state of strength distribution in concrete columns of different casting heights was shown in Fig. 1. The concrete strength in the upper portion of column becomes extremely weaker by the bleeding and the segregation, and that in the lower portion of column becomes stronger by the compaction [7]. Accordingly, these state of strength distribution in columns can be expressed more accurately by using tri-linear equation than linear equation, as shown by the soild line for the former and the broken line for the latter in Fig. 1, respectively. The concrete strength in upper and lower portions of columns were about 90 % and 116 % of the compressive strength in the middle portion of columns, respectively. The state of strength distri-

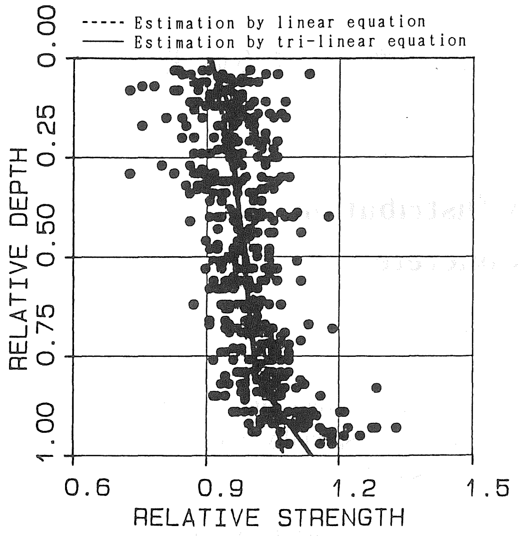


Fig 1 Variation of concrete strength in column

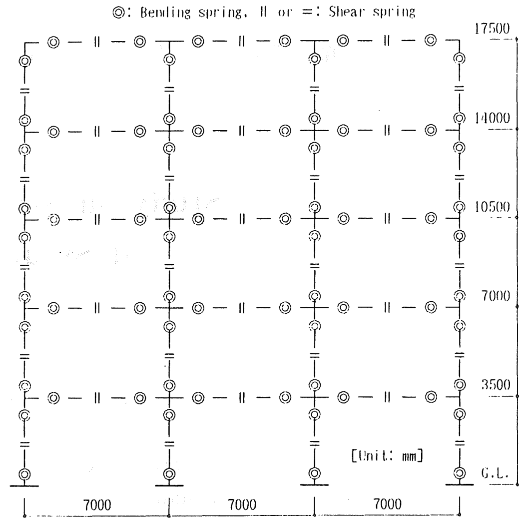


Fig 2 Model of RC frame

butions of walls and beams were also investigated by the same method. The relationship between local concrete strength in structural members and casting height of concrete are represented as follows:

1) Column

Linear expression:

RFC=0.176RDP+0.910,

Tri-linear expression:

RFC=0.373RDP+0.903 (Upper portion),
RFC=0.111RDP+0.993 (Middle portion),
RFC=0.715RDP+0.449 (Lower portion).

2) Wall

Linear expression:

RFC=0.173RDP+0.902,

Tri-linear expression:

RFC=0.256RDP+0.886 (Upper portion),
RFC=0.260RDP+0.889 (Middle portion),
RFC=0.238RDP+0.841 (Lower portion).

3) Beam

Linear expression:

RFC=0.376RDP+0.891.

Where, REC: relative strength (each core strength/average of entire core strength),

RDP: relative depth (depth from the top surface/total depth).

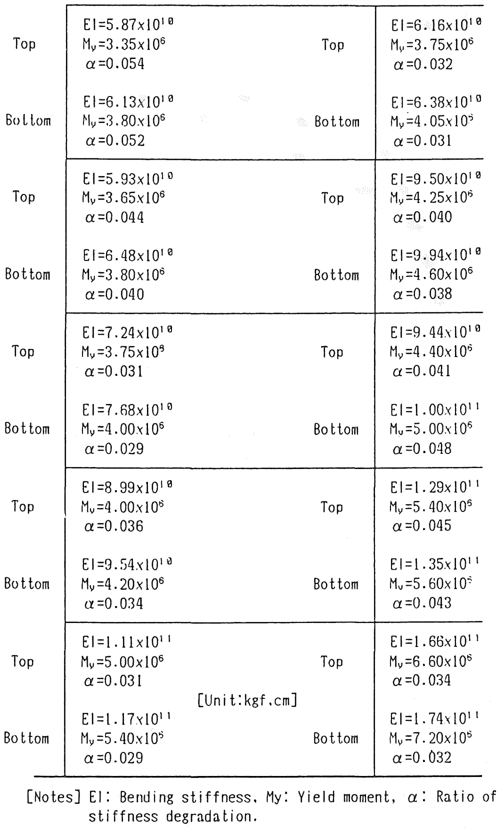
3. MECHANICAL BEHAVIOR OF RC FRAME

Effect of heterogeneity of structural concrete on the static and dynamic machanical behaviors of RC frames was examined applying two model frames with uniform and variable concrete strength in the structure.

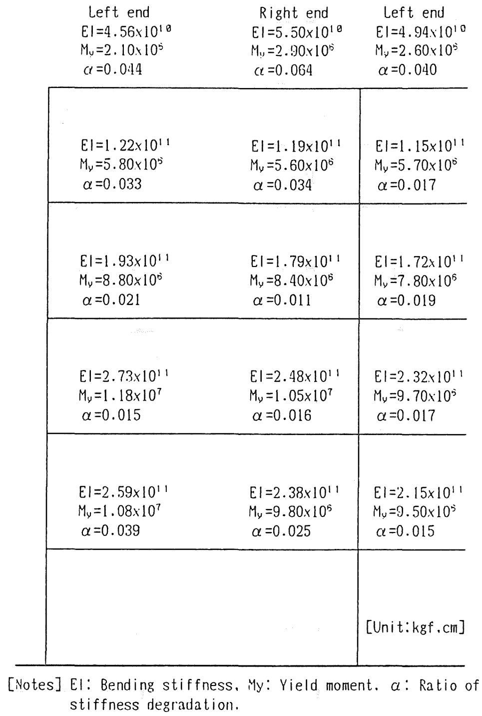
3. 1 ANALYTICAL MODEL

3·1·1 Constitutive Member

The RC frame with five stories and three spans as shown in Fig. 2 was used for the analysis. Assumed elastic first natural period of the RC frame was 0.35 sec. . The mechanical behavior of each structural member was characterized by two elastic-plastic bending springs set in both ends and one elastic shear spring set in the center of the member [10] . Longitudinal deformation of member was neglected, and it was assumed that the bending stiffness (EI) of middle element of the member was constant. The mechanical property of each bending spring was analyzed numerically by the layered element method [11] . Assumed average compressive strength of concrete was 210 kgf/cm². In the case of the RC frame having the concrete strength varied in the structure, the compressive strength of upper and lower portions of columns were 190 kgf/cm² and 245 kgf/cm² respectively, and the compressive strength of beams was 196 kgf/cm². The mechanical properties of each model springs used in the analysis



(a) Mechanical properties of bending springs in columns



(b) Mechanical properties of bending springs in beams

Fig 3 Mechanical properties of constitutive members (RC frame having variable concrete strength)

are shown in Figs. 3 (a) and (b).

3·1·2 Analytical Procedure on Static Problem

Analysis was done by using the step by step method under prepared external force increments. Working lateral force for the floor was approximated by the Ai-distribution. The increments of lateral forces were so controlled that the increment of lateral force of 5th story was 1 tf.

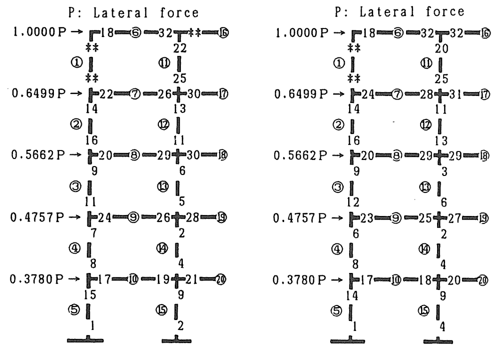
3·1·3 Analytical Procedure for Dynamic Problem

The earthquake ground motion of Elcentro NS-direction, whose maximum acceleration was adjusted to 500 gal, was applied for the analysis. The kinetic equation was solved by using the β-method of Newmark.

3. 2 ANALYTICAL RESULTS

3·2·1 Static Behavior

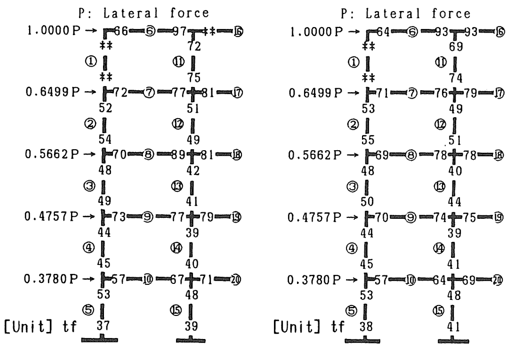
Fracture processes for two types of RC frame models are shown in Figs. 4 (a) and (b). The numerals in these figures indicate the forming orders of the plastic hinge of each member. It seems that the fracture process of the RC frame is affected by the state of heterogeneity of concrete in structural members. For instance, the forming orders of plastic hinges at the top and the bottom portions of No. 13 column were 6th and 5th, respectively, for the RC frame having the uniform concrete strength.But the forming orders of plastic hinges of No. 13 column having the variable concrete strength were 3rd and 6th, respectively. This may result from the damage of column being localized at the upper portion, because the con-



(a) RC frame having uniform concrete strength

(b) RC frame having variable concrete strength

Fig 4 Fracture process of RC frame



(a) RC frame having uniform concrete strength

(b) RC frame having variable concrete strength

Fig 5 Shear forces at yielding of each spring

crete strength of the upper portion of column is smaller than that of the lower portion. Similar tendency is also observed by No. 12 column. Furthermore, the forming order of plastic hinges at the bottom portion of No. 15 column changed from 2nd to 4th when the concrete strength in the member was varied.

Figs. 5 (a) and (b) show the values of lateral forced (P) applied on 5th floor at the time of yielding of each spring. It is shown in these figures that the values of lateral forces at yielding of each spring are affected by the heterogeneityof the

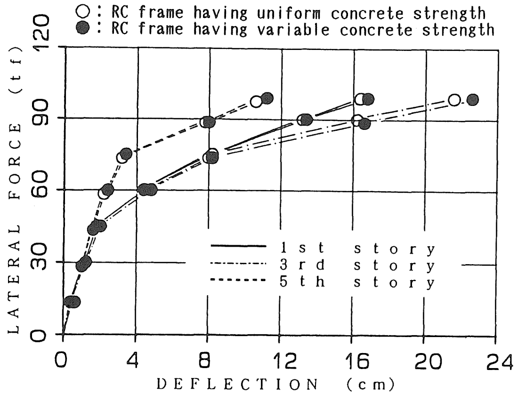


Fig 6 Relationship between shear force and storey deflection

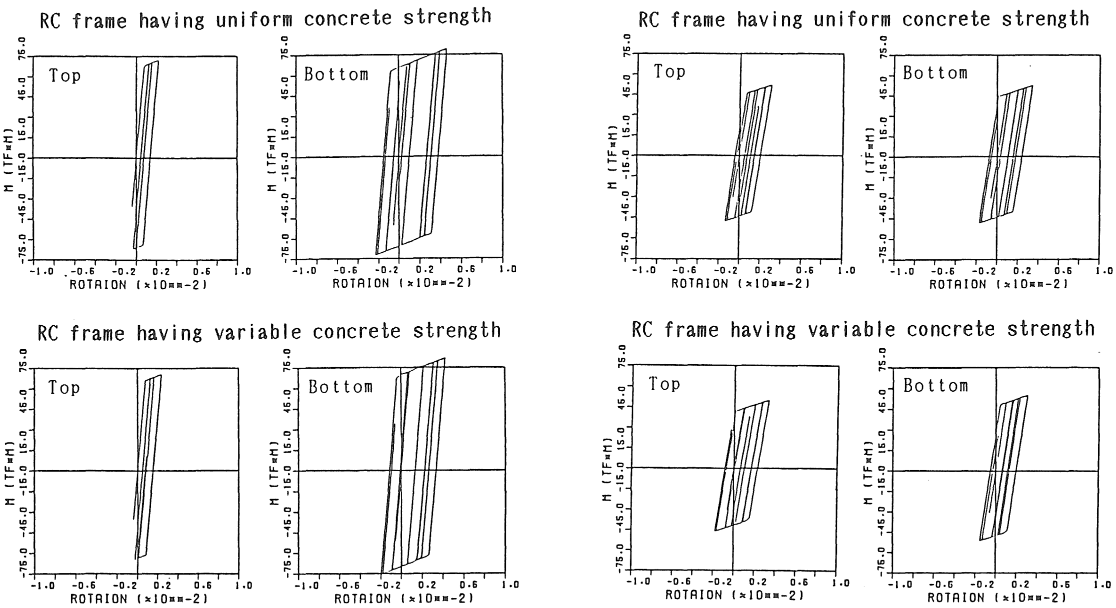
structural concrete, in addition to the fracture process of the RC frame mentioned above. For example, the value of P at yielding of the bottom end of No. 13 column was 41 tf in the case of the RC frame having the uniform concrete strength, but was 44 tf in the case of the RC frame having the un-uniform concrete strength. The values of P at yielding of beams generally decrease with the increase of variation of concrete strength in the structural member.

Fig. 6 ahows the relationship between lateral force applied on 5th floor (P) and storey deflection (d). It seems that the relationships between P and d and the maximum bearing capacity of the RC frame are hardly affected by the heterogeneity of structural concrete, except for the behaviors in large deflection range.

3·2·2 Dynamic Behavior

Fig. 7 (a) show the dynamic responses of model bending springs set in both ends of No. 15 column. It seems from this figure that the maximum rotation angles of the bending spring set in the top and the bottom ends of No.15 column in the RC frame having the distribution of variable concrete strength increase and increase by about 10 % than that of the RC frame having the uniform concrete strength. It seems that the state of damage progression of the RC frame is delocalized by the heterogeneity of structural concrete, for the RC column which the bending moment at the bottom is rather large in comparison with that at the top.

Fig. 7 (b) show the dynamic responses of model bending springs set in both ends of No. 13



(a) Responses of No. 13 column

(b) Responses of No. 15 column

Fig 7 Responses of bending springs

column. It is found in this figure that the maximum rotation angle of bending spring at the bottom end of column increases by about 10 % than that of bending spring at the top end of column in the case of the RC frame having the uniform concrete strength. On the other hand, in the case of the RC frame having the distribution of variable concrete strength in the member, the maximum rotation angle of bending spring at the top end of column conversely increases by about 5 % than that of bending spring at the bottom end of column. Accordingly, it is suggested that, in the RC column which the working bending moment at the top is closer to that at the bottom, the progressing order of damages of the upper and lower portions of RC columns may be turn over by the difference of heterogeneity of structural concrete.

4. CONCLUSIONS

Actual state of strength distribution of structural concrete and the effect of heterogeneity of structural concrete on mechanical behavior of structure, especially fracture mechanism, of a RC structure were investigated in the present study. Results are summarized briefly as follows:

1) Actual distribution of concrete strength in column can be approximated by the following equations of tri-linear type:

RFC = 0.373RDP+0.903 (Upper portion),

RFC = 0.111RDP+0.993 (Middle portion),

RFC = 0.715RDP+0.449 (Lower portion),

And the variation of concrete strength between the top and the bottom of a column is about 26 %.

2) The fracture processes of RC frame are affected by the heterogeneity of structural concrete.

3) The order of progression of damages at upper and lower portions of RC columns change by the state of heterogeneity of structural concrete, for the RC column which the bending moment of the top is closer to that of the bottom.

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