콘크리트 품질이 RC구조물의 신뢰성에 미치는 영향
Influence of Concrete Acceptance Strength Control on Reliability of RC Structures: Korean Practice

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ABSTRACT

This paper is designed to bring to the attention of the reader the situation that may constitute a threat to the safety of RC structures designed and constructed in Korea. This threat stems from the inadequate rules of the acceptance strength control of concrete. As a result in some cases probability of brittle failure can be very high and reliability becomes very low. The paper substantiates the above statements. Further investigations aimed at finding the measures to remedy the situation are recommended.

1. INTRODUCTION

Reliability of RC structures designed under the provisions of ACI Building Code [1] was investigated in several papers (e.g., [2-8]). For example, the implication of the analysis in the last paper [8] is that ACI Code 318-89 gives a uniform reliability. All component reliability indices vary from 3.2 to 4.2.

The aim of this paper is to show that in some cases probability of brittle failure is rather high, reliability is inadequate and reliability indices go well below 3.2. The analysis discloses that the rules of concrete acceptance strength control are responsible for low reliability levels. The first consideration is given to the conditions as they stand at present in Korea.

2. CONCRETE STRENGTH

The rules of the acceptance strength control of concrete in Korea [9] are very similar to those given in [1]. Under the provisions of [9] the concrete is considered acceptable if two criteria are met:

1) No single test strength shall be more than 15% below the specified compressive strength, f_c'.

2) The average of any three consecutive test results must equal or exceed the specified compressive strength, f_c'.

The second criterion implies that the minimum required average compressive strength of concrete is equal to the specified compressive strength, f_c'. Consider the concrete in a batch. Assume that random concrete strength $f_c'^*$ is normally distributed with mean value f_c' (sign * stands for random values). According to the second criterion, the concrete is accepted. In this batch the probability $P(f_c'^* > f_c')$ that actual concrete strength $f_c'^*$ exceeds f_c' is very low and equals 0.5. In Korean practice this exceedance probability appears to be much lower.

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As is shown in [10], the concrete in Korean practice can be classified in three categories: poor, medium and good with mean values of concrete strengths $0.65f'_c$, $0.73f'_c$ and $0.8f'_c$, respectively. Concrete strength is distributed lognormally with coefficient of variation 0.19. It is straightforward to show that in three above cases the probability that actual concrete strength $f'_c{}^*$ exceeds f'_c are 0.008, 0.039 and 0.16, respectively. These probabilities are very low and, as is shown below, substantially decrease the reliability of RC structures.

3. INITIAL DATA FOR ANALYSES

The influence of concrete strength control on the reliability of RC structures will be illustrated by the example of RC beams designed for flexure. Two failure modes related to moderately and over-reinforced beams will be considered. To distinguish between the modes the following limit-state function is used:

$$g_1 = \rho - \frac{0.85\beta_1 f'_c}{f_y}\frac{87000}{87000+f_y} \qquad (1)$$

Here ρ is reinforcement ratio; b_w, d, h are width, effective depth and height of beam cross section (in); f'_c, f_y are compressive strength of concrete, yield stress of steel (ksi); β_1 is the ratio of the depth of stressed block in the compression zone to the distance between the outside compression surface and the neutral axis (according to [1], $\beta_1 = 0.85$).

Condition $g_1 > 0$ holds for over-reinforcement. Otherwise (i.e., if $g_1 \le 0$) the beam is moderately reinforced.

The limit-state functions for moderately and over-reinforced beams are, respectively, as follows:

$$g_2 = B_f \rho f_y \left(1 - \frac{\rho f_y}{1.7 f'_c}\right) - M \qquad (2)$$

$$g_3 = B_f\left(\frac{1}{3}f'_c\right) - M \qquad (3)$$

Here B_f is a factor characterizing flexural model uncertainty; M is external bending moment.

Five random variables will be considered in the course of reliability analysis: yield strength of steel $f_y{}^*$, compressive strength of concrete $f'_c{}^*$, flexural model uncertainty $B_f{}^*$, external moments $M_1{}^*$ and $M_2{}^*$, produced by dead and live loads, respectively.

In all, 3 cases will be dealt with. For these cases nominal specified compressive strength of concrete is $f'_c = 3.0$ ksi, but in cases 1, 2, 3 poor, medium and good concrete with mean values 1.95, 2.19 and 2.40 ksi, respectively, will be considered. Concrete strength is distributed lognormally with c.o.v. = 0.19. Grade 40 reinforcing bars are used. Steel strength is distributed normally with mean value 42.3 ksi and c.o.v. = 0.12. Characteristics of concrete and steel strengths are taken from [10]. For all cases flexural model uncertainty $B_f{}^*$ is assumed normally distributed with mean value 1.1, c.o.v.=0.12 [8]. The description of random values $M_1{}^*$ and $M_2{}^*$ is given below.

4. PROBABILITY OF BRITTLE FAILURE

The beam is moderately reinforced if its reinforcement ratio satisfies the following conditions:

$$\rho_{min} \le \rho \le \rho_{max} \qquad (4)$$

where $\rho_{min} = 0.005$; $\rho_{max} = \frac{3}{4}\rho_b = 0.0278$ for $f_y = 40$ ksi; $f'_c = 3$ ksi. The balanced reinforcement ratio ρ_b is determined by the following formula:

$$\rho_b = \frac{0.85\beta_1 f'_c}{f_y}\frac{87000}{87000 + f_y} \qquad (5)$$

If material strengths are random values then the balanced reinforcement ratio ρ_b is a random value too. Let us denote it by ρ_b*. Using eqn (1) probabilities $P(\rho > \rho_b*) = P(g_1* > 0)$ and $P(\rho > \frac{3}{4}\rho_b* = \rho_{max}*)$ have been determined.

Probability $P(\rho > \rho_b*)$ is the probability that the beam initially designed as moderately reinforced with reinforcement ratio satisfying conditions (4) is actually over-reinforced. In much the same way probability $P(\rho > \frac{3}{4}\rho_b*)$ is the probability that the provisions of ACI Building Code for moderately reinforced beams are violated. Probabilities $P(\rho > \rho_b*)$ and $P(\rho > \frac{3}{4}\rho_b*)$ are determined for eleven ξ values: ξ = 0, 0.1, 0.2, ..., 1. The ξ values are associated with the reinforcement ratio ρ in the following way:

$$\xi = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \qquad (6)$$

Calculations were performed using three approaches:

1) Monte Carlo simulation with subsequent approximation of the results by Pearson's curves and numerical integration [11,12]; sample size was 5,000 (the description of this approach is given in more detail in section 5).

2) Crude Monte Carlo simulation with sample size 5,000.

3) Crude Monte Carlo simulation with sample size 15,000 (for some ρ values).

All results were in close agreement. They are presented in Tables 1, 2 for nine ξ values. As can be seen from the Tables, the probabilities $P(\rho > \rho_b*)$ and $P(\rho > \frac{3}{4}\rho_b*)$ are very high for high ρ values and gradually go down as the ρ values decrease.

Table 1. Probability $P(\rho > \rho_b*)$

Case	ξ								
No	0.0	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0.0000	0.0008	0.0316	0.1124	0.2446	0.4157	0.5785	0.7119	0.8191
2	0.0000	0.0002	0.0104	0.0464	0.1234	0.2432	0.3963	0.5506	0.6721
3	0.0000	0.0000	0.0035	0.0173	0.0618	0.1444	0.2571	0.3986	0.5410

Table 2. Probability $P(\rho > \frac{3}{4}\rho_b*)$

Case	ξ								
No	0.0	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0.0000	0.0116	0.2541	0.4844	0.6811	0.8226	0.9078	0.9529	0.9756
2	0.0000	0.0032	0.1306	0.3002	0.5078	0.6793	0.8196	0.8902	0.9428
3	0.0000	0.0001	0.0663	0.1888	0.3614	0.5553	0.6948	0.8137	0.8858

To take an example, for the poor concrete (case 1) for ξ = 1 the probabilities $P(\rho > \rho_b*)$ and $P(\rho > \frac{3}{4}\rho_b*)$ are 0.8191 and 0.9756, respectively, and for the good concrete (case 3) these probabilities are 0.5410 and 0.8858, respectively. The probability of brittle failure is fairly high even for relatively low ρ

values: for example, $P(\rho > \rho_b^*)$ ranges from 0.0173 (case 3) to 0.1124 (case 1) for ξ = 0.5, $\rho = \rho_{min} + 0.5(\rho_{max} - \rho_{min})$.

The reason for this phenomenon is quite apparent. As indicated above, the probability that concrete strength will fall below f_c' equals 0.992 (case 1) to 0.84 (case 3). From physical considerations as well as from eqn (1) one can see that the probability of over-reinforcement increases as concrete strength decreases. In view of high probability of low concrete strength values the probability of over-reinforcement is high. Thus, the rules of the acceptance concrete strength control exert a detrimental effect on the probability of brittle failure.

5. RELIABILITY OF BEAMS

When evaluating the reliability of beams in all 3 cases live-to-dead load ratio is assumed to be 3.0. The initial data for calculations were prepared in the following way.

1. Specify reinforcement ratio ρ satisfying conditions (4).
2. Determine the nominal moment capacity of the beam M_n. Assume that the factorized external moment M_f equals ϕM_n (ϕ is a strength reduction factor, $\phi = 0.9$ [11]).
3. Take $M_1 = M_f/6.5$; $M_2 = 3M_1$, where M_1 and M_2 are unfactored moments produced by dead and live loads, respectively. The coefficient 6.5 is easily obtained from two following equations:

$$1.4M_1 + 1.7M_2 = M_f; \quad M_2 = 3M_1 \qquad (7)$$

Here 1.4 and 1.7 are load factors for dead and live loads, respectively.

4. According to [10], assume that $1.05M_1$, $1.038M_2$ are mean values of the random moments M_1^* and M_2^* produced by dead and live loads, respectively. Assume that M_1^* is normally distributed with c.o.v. = 0.10 and M_2^* fits a type 1 extreme value distribution with c.o.v. = 0.24.
5. In eqns. (2), (3) assume that $M = M_1^* + M_2^*$; $f_y = f_y^*$; $f_c' = f_c'^*$; $B_f = B_f^*$ and that all random variables are mutually statistically independent.

Perform calculations in the following order.

1. Using Monte Carlo simulation obtain a set of realizations of random variables $f_y^*, f_c'^*, B_f^*, M_1^*, M_2^*$.
2. Check condition (1) to determine whether the beam is moderately or over-reinforced.
3. Choose the corresponding limit-state function among (2), (3) and calculate its value g.
4. Perform steps 1 to 3 m times. As a result obtain m values $g_1, \dots, g_m$.
5. Fit an appropriate Pearson's curve $y(z)$ to describe probability density functions of g values.
6. Calculate the reliability of the beam R by numerical integration:

$$R = \int_0^{\infty} y(z)dz \qquad (8)$$

All calculations were performed with sample size m = 5,000 and for some cases were checked by crude Monte Carlo simulation with sample size 15,000. Reliabilities obtained by the two methods were in close agreement.

Calculation results are presented in Fig 1. Here the reliability indices β are plotted vs. ξ. The obtained results are in complete agreement with the values of probabilities $P(\rho > \rho_{max}^*)$ discussed above. As ξ increases from 0 to 1, the probability $P(\rho > \rho_{max}^*)$ increases as well (see Table 1). As a result in the course of Monte Carlo simulation in increasing number of cases limit-state function (3) is used and this

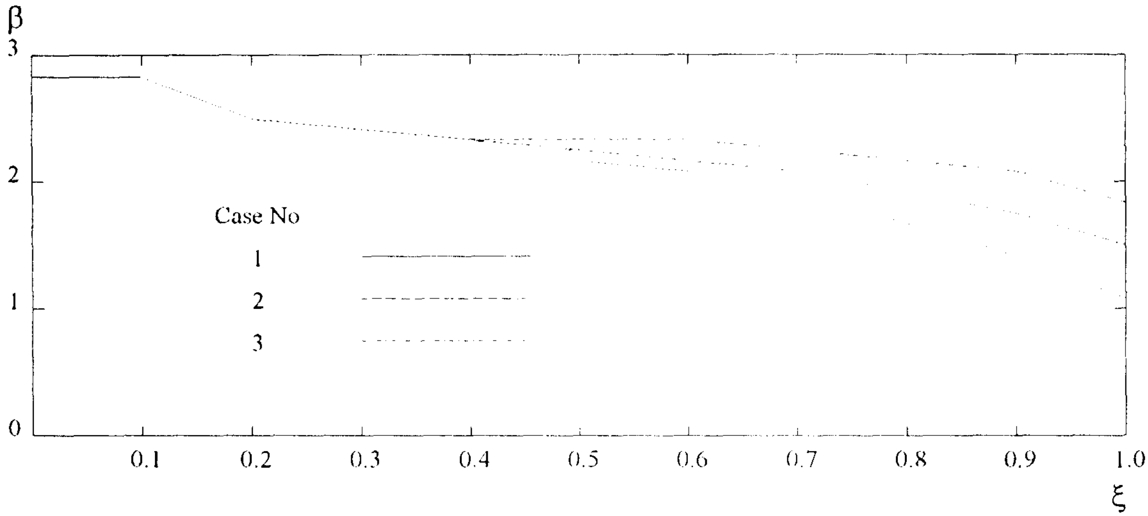

Fig. 1. Flexural reliability index β vs. relative reinforcement ratio ξ

function gives lower g values in comparison with limit-state function (2). For $\xi = 1$ ($\rho = \rho_{max}$) reliability index β drops to the lowest level: β = 1.1 for case 1 and β = 1.9 for case 3. Thus, the rules of concrete acceptance strength control exert a detrimental effect on the reliability of RC structures.

6. CONCLUSION

The rules of the acceptance control of concrete used in Korea are inadequate and in some cases can substantially impair the reliability of RC structures. The matters can be straightened out by the following measures.

Specified compressive strength of concrete f'_c should be defined with a certain exceedance probability. Then the rules of the acceptance control of concrete can be changed in such a way as to satisfy this definition. In this case the minimum average required compressive strength of concrete will, of course, exceed f'_c.

By these means the cases with inadequate reliability are eliminated. However, excessive reliability can appear in some cases. In such an event a material combination factor [11] can be introduced to regulate reliability.

The material combination factor is an additional partial safety factor. It is similar to load factors. It takes into account low probabilities of simultaneously low values of strength of several materials. By comparison, load factors take into account low probabilities of simultaneously high values of several loads. With the material combination factor a uniform reliability can be achieved. A similar approach has been already used in Russia [13, 14].

Comprehensive investigations must be carried out. Their aims are:

(i) to reveal design cases with inadequate reliabilities (for flexure, compression, torsion, etc.);

(ii) to check cases of prestressed concrete;

(iii) to establish target reliabilities for all above cases and to choose the target reliability to be used for the rules of the acceptance strength control of concrete;

(iv) to develop new rules for the acceptance strength control of concrete using this target reliability;

(v) to calculate numerical values of the material combination factor to achieve the target reliability in all cases.

The investigation will result in safe and economical design of RC structures.

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