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변형율속도변화에 대한 철근콘크리트부재 설계인자의 민감성 연구

A Study on the Sensitivity of Reinforced Concrete Element Design Factors

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要 旨

변형율 속도를 고려할 수 있는 철근콘크리트부재 해석모델을 이용하여 서로 다른 설계인자를 가지는 철근콘크리트부재의 하중 재하속도에 따른 민감성을 연구하였다. 수행된 연구결과에서 정적하중에서부터 동적하중을 받는 부재의 압축거동 및 휨거동특성은 서로 상이함을 발견하였다. 본 논문에서는 또한 하중재하속도에 따른 철근콘크리트부재의 압축강도 및 휨강도를 계산할 수 있는 실용적인 설계공식을 제안하였다.

Abstract

A strain rate-dependent element model was used to study the loading rate-sensitivity of R/C beams and columns with different design factors. Conclusions were derived regarding the differences between the element axial/flexural performance under impulsive and quasi-static loads. Practical design formalas for predicting the loading rate-dependent axial and flexural strengths of R/C elements were also suggested.

1. INTRODUCTION

In general the compressive strength and stiffness of concrete and the yield strength of steel are observed to increase with increasing strain rate. As a result of the increases in material strength and stiffness the axial-flexural strengths and stiffnesses of reinforced concrete(R/C) elements also increase at higher loading rates. To have successful predictions of R/C elements behavior under different loading rates, the strain rate-sensitive constitutive models of steel and concrete were incroporated into the layer modeling technique for loading rate-dependent axial/flexural analysis of R/C beam-columns(1). The predictions of the analytical technique compared well with both quasi-static and dynamic test results on R/C elements.

In this paper the developed analytical technique(1) was used to study the loading rate sensitivity of R/C elements with different design factors including geometry, material properties of reinforcement configurations.

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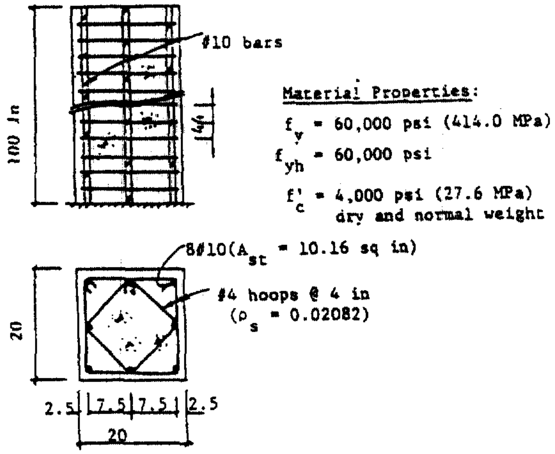
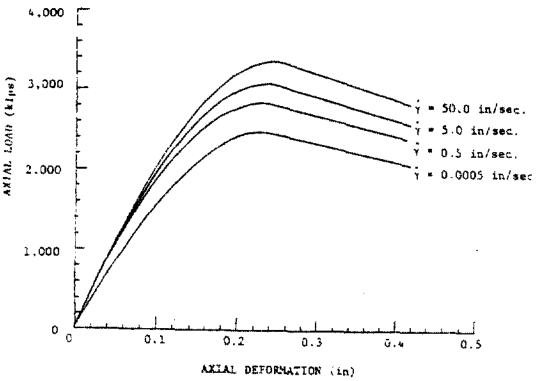
Two practical design formulas for calculating the loading rate-dependent axial and flexural strengths of R/C elements were also suggested.

2. THE SENSITIVITY OF R/C COLUMNS TO STRAIN RATE VARIATIONS

The effects of the variations in different material and geometric properties of R/C columns on the sensitivity of their axial behavior to strain rate variations are discussed in this section. The typical column shown in Fig. 1(a) was chosen as the "standard" column in this study, and the effects of the variations in different properties of this column on its strain rate-sensitivity were investigated by the developed analytical technique. Fig. 1(b) presents the axial load-displacement relationships of the standard column derived analytically at four different displacement rates(covering the range from quasi-static to impulsive loading rates). It is obvious in this figure that the axial strength and stiffness of the standard column increase with increasing rate of load application. At the highest loading rate, and increase of 30% in column axial strength over the quasi-static value is observed. The corresponding increase in column secant stiffness(measured at 45% of its peak axial strength) is also about 30%. The other observation in Fig. 1(b) is that with increasing loading rate, the deformation at peak axial load is slightly increased.



(a) standard column



(b) axial behavior

Fig. 1. Loading rate effects on the behavior of the standard .column.
(1 in = 25.4 mm : 1 kips = 0.445 KN)

The effects of loading rate variations on the column axial strength and secant stiffness are summarized, among other information, in Table 1. In this table, P_n and P_n' are the quasi-static and dynamic axial strengths, and K_r and K_r' are the quasi-static and dynamic secand axial stiffness, respectively. Table 1 also summarizes the strain axial effects on columns sinmilar to the standard column, except for the change in a single variable which could be confinement, concrete compressive strength, degree of saturation of concrete, or cross sectional shape. From the data presented in Table 1, it may be concluded that the variations in steel ratio, concrete compressive strength, confinement and cross sectional shape of columns do not significantly influence the column loading

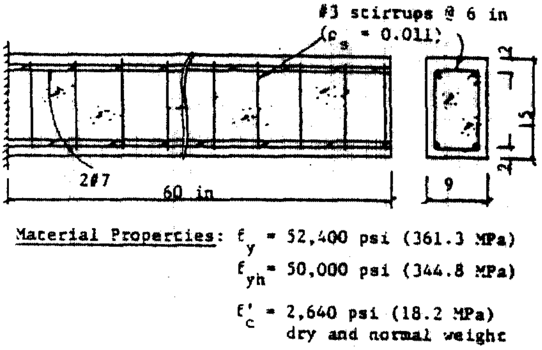
Table 1. Summary of the loading rate effects on the axial behavior of R/C columns.
(1 in = 25.4 mm : 1 kip = 0.445 KN)

SECTION	r (in/sec)	P_n'/P_n		K_r'/K_r
		refined analysis	practical eqn(2)	refined analysis
standard	0.5	1.16	1.16	1.22
	5.0	1.25	1.25	1.28
	50.0	1.36	1.35	1.31
low f_y(f_y = 40ksi)	0.5	1.18	1.17	1.23
	5.0	1.28	1.27	1.28
	50.0	1.40	1.39	1.37
high f_y(f_y = 80ksi)	0.5	1.12	1.13	1.23
	5.0	1.20	1.21	1.29
	50.0	1.31	1.30	1.32
low A_{st}(A_{st} = 8.0in^2)	0.5	1.16	1.16	1.23
	5.0	1.26	1.25	1.29
	50.0	1.37	1.37	1.32
high A_{st} (A_{st} = 12.48in^2)	0.5	1.15	1.15	1.22
	5.0	1.24	1.24	1.27
	50.0	1.35	1.34	1.30
low confinement (ρ_s = 0.0139)	0.5	1.14	1.16	1.23
	5.0	1.23	1.25	1.28
	50.0	1.35	1.35	1.31
high confinement (ρ_s = 0.4164)	0.5	1.17	1.16	1.23
	5.0	1.25	1.24	1.26
	50.0	1.37	1.35	1.31
low f_c'(f_c' = 3ksi)	0.5	1.16	1.15	1.21
	5.0	1.25	1.24	1.26
	50.0	1.36	1.34	1.29
high f_c'(f_c' = 6ksi)	0.5	1.15	1.16	1.24
	5.0	1.25	1.26	1.30
	50.0	1.37	1.37	1.33
saturated concrete	0.5	1.39	1.37	1.51
	5.0	1.69	1.65	1.78
	50.0	2.07	2.00	2.05
circular shape (D = 22.56 in)	0.5	1.23	1.16	1.15
	5.0	1.29	1.25	1.24
	50.0	1.31	1.35	1.36

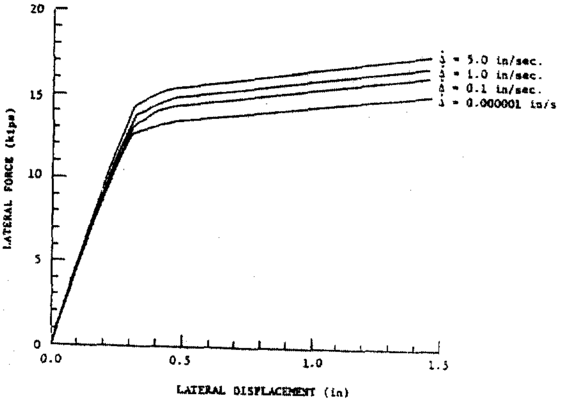
rate-sensitivity. There is, however, a slight increase in the loading rate-sensitivity of column axial strength with decreasing yield strength of steel. Both the axial strength and stiffness of the saturated concrete column are also observed to be far more loading rate-sensitive than those of dry concrete columns.

3. THE SNESITIVITY OF R/C BEAMS DUE TO STRAIN RATE VARIATIONS

In the studies on strain rate-sensitivity of the R/C beam flexural behavior, a typical R/C beam shown in Fig. 2(a) was chosen as the "standard" one. Fig. 2(b) shows the lateral load-displacement relationships of this beam derived analytically at four different displacement rates. The flexural strength, but not initial stiffness of the beam is observed to increase at higher loading rates.



(a) standard beam



(b) flexural behavior of standard beam

Fig. 2. Loading rate effects on the flexural behavior of the standard beam.
(1 in = 25.4 mm : 1 kip = 0.445 KN)

The maximum increase in flexural strength is about 15% at the highest rate of lateral displacement application used in this study.

Table 2. summarizes the loading rate effects on the flexural strength of the standard R/C beam as well as those similar to the standard one except for the change in a single variable which could be steel yield strength, concrete compressive strength, the ratio of compression or tension steel, confinement, degree of concrete saturation, or the beam length. In this table, V and V′ are the quasi-static and dynamic values of lateral strength, respectively. From the data presented in Table 2, it can be concluded that R/C beams with lower yield strength steels and higher steel ratios are more sensitive to the variations in loading rate. Beams with saturated concrete are also more loading rate-sensitive than those with air-dried concrete. The variations in concrete compressive strength and confinement, element length, and cross sectional shape do not seem to influence the loading rate-sensitivity of the flexural behavior of R/C beams.

Table 2. Summary of the loading rate effects on the flexural behavior of R/C beams.
(1 in = 25.4 mm : 1 kip = 0.445 KN)

SECTION	Δ (in/sec)	V′/V refined analysis	V′/V practical eqn.(3)
standard	0.1 1.0 5.0	1.08 1.11 1.15	1.09 1.13 1.18
low f_y(f_y = 40ksi)	0.1 1.0 5.0	1.11 1.14 1.17	1.10 1.15 1.21
high f_y(f_y = 60ksi)	0.1 1.0 5.0	1.08 1.10 1.13	1.08 1.12 1.16
low A_s' (A_s' = 0.61in^2)	0.1 1.0 5.0	1.08 1.12 1.17	1.09 1.13 1.18
high A_s (A_s = 2.0in^2)	0.1 1.0 5.0	1.10 1.15 1.18	1.09 1.14 1.18
high confinement (ρ_s = 0.016)	0.1 1.0 5.0	1.07 1.10 1.15	1.09 1.13 1.18
high f_c'(f_c' = 6ksi)	0.1 1.0 5.0	1.07 1.12 1.15	1.09 1.13 1.17
saturated concrete	0.1 1.0 5.0	1.09 1.13 1.17	1.09 1.12 1.16
T-beam(flange width = 18in)	0.1 1.0 5.0	1.08 1.11 1.15	1.07 1.12 1.16
short beam (l = 40 in)	0.1 1.0 5.0	1.09 1.12 1.15	1.10 1.14 1.19

4. PRACTICAL DESIGN FORMULAS

The layer modeling technique developed in reference 1 for loading rate-sensitive axial/flexural analysis of R/C elements is not convenient for every day-use by designers.

This section illustrates two simple design techniques suggested for computing the axial and flexural strengths of R/C cross sections as functions of the applied deformation rates. The results of these simple techniques are also compared with those obtained from the more refined layer analysis procedures described earlier.

4. 1 Dynamic Axial Strength

ACI code⁽²⁾(318-83) suggests the following equation for calculating the nominal axial strength(P_n) of R/C columns :

$$P_n = 0.85 f_c' (A_g - A_{st}) + A_{st} f_y \qquad (1)$$

where

f_c' = standard(quasi-static) compressive strength of concrete(psi)

A_g = gross cross sectional area of concrete (in^2)

A_{st} = total area of longitudinal steel(in^2)

f_y = standard(quasi-static) yield strength of steel(psi)

The above equation has been based on the results of quasi-static tests. This equation can be modified as follow for calculating the column axial strength at high loading rates (P_n') :

$$P_n'=0.85f_c''(A_g-A_{st})+A_{st}f_y' \qquad (2)$$

where,

f_c'' = dynamic compressive strength of concrete(psi)

$$=\begin{cases} f_c'[1.48+0.160\,log_{10}\dot{\varepsilon}+0.0127(log_{10}\dot{\varepsilon})^2] \\ \quad \text{for air-dried concrete} \\ f_c'[2.54+0.580\,log_{10}\dot{\varepsilon}+0.0543(log_{10}\dot{\varepsilon})^2] \\ \quad \text{for saturated concrete} \end{cases}$$

f_y' = dynamic yield strength of steel(psi)

$$=f_y[-4.51\times10^{-6}f_y+1.46+(-9.20\times10^{-7}f_y+0.0927)log_{10}\dot{\varepsilon}]$$

$\dot{\varepsilon}$ = strain rate(1/sec) $\geq 10^{-5}$

Table 1 compares the ratios of dynamic to static compressive strengths obtained from the above equation with these obtained from the refined layer analysis procedure described earlier. The suggested simple approach is observed to compare well with the results of the refined analysis.

4. 2 Dynamic Flexural Strength

The ACI code⑵(318-83) flexural design procedure is based on simplified ultimate flexural strain and stress distributions at cross section shown in Fig. 3. It should be noticed that the tension steel area in this approach is assumed to be small enough(i.e. below balanced area) such that the tension steel yields at the ultimate flexural condition. In order to develop a simple procedure for computing the dynamic flexural strength of R/C beams, it was assumed that the absolute values of strain rate across the section are equal to the rate of straining at the extreme compression layer. This assumption leads to the following procedure for calculating the loading rate-sensitive flexural capacity of a doubly reinforced beam cross section :

(1) Assume a value for the depth of neutral axis(c in Fig. 3)

(2) Find steel stresses :

in compression, $f_{sc}=87000\dfrac{c-d'}{c}\leq f_y'$

in tension, f_y'

(3) Find the new value of c for the above steel stresses :

$a=(A_sf_y'-A_s'f_{sc})/(0.85\,f_c''\,b)$

$c=a/\beta_1$

where

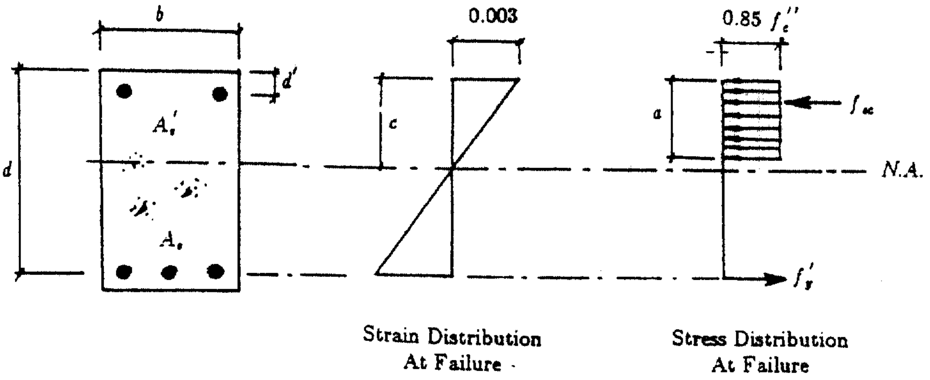


Fig. 3. Simplified flexural strain and stress distributions at failure.

$\beta_1 = 0.85 - 0.05(f_c' - 4000)/1000$,
but, $0.65 \leq \beta_1 \leq 0.85$

(4) Repeat from step (2) with the new value of c until the change in c is relatively small

(5) Find the strain rate-dependent flexural strength of the section :

$$M_n' = A_s f_y'(d-d') + 0.85 f_c'' a\, b(a/2 - d') \quad (3)$$

The value of strain rate at the extreme compressive layer($\dot{\varepsilon}$) used for calculating f_y' and f_c'' in the above equation should be obtained from the given rates of displacement application to the beam, using approximate analytical techniques.

The suggested procedure for calculating the loading rate-dependent flexural strength of R/C sections applied to all the beams used in the numerical study discussed earlier. The results are compared with the predictions of the layer modeling tenique in Table 2, and the comparison is observed to be quite satisfactory.

5. CONCLUSIONS

The refined(layer) and analytical method was used to preform a numerical study on the loading rate-sensitivity of the axial and flexural preformances of R/C elements. The results of this numerical study indicated that :

(1) Under typical impulsive loading rates, the axial strength and stiffness of typical R/C columns increase by about 30% over the corresponding quasi-static values.

(2) The flexural strength of typical R/C beam increases by about 15% at typical impulsive loading rates over the quasi-static values. The flexural stiffness of R/C beam is not much influenced by the loading rate variations.

(3) The loading rate-sensitivity of R/C column axial behavior increases with increasing degree of saturation of concrete. The variations in steel ratio, concrete compressive strength, confinement and cross sectional shape of columns do not significantly influence the column loading rate-sensitivity.

(4) The loading rate-sensitivity of R/C beam flexural behavior increases with decreasing steel yield strength and increasing steel ratio and concrete degree of saturation. The variations in concrete compressive strength, confinement, and element length and cross sectional shape do not significantly influence the loading rate-sensitivity of R/C beams in flexure.

(5) Practical design formulas were also suggested for calculating the axial and flexural strengths of R/C columns and beams as functions of the applied loading rates.

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