Effective Concrete Strength within Slab-Column Joint

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ABSTRACT --American Concrete Institute has special provisions for determining the capacity of column when its concrete strength is greater than 1.4 times that of the floor system. Many researchers have observed that these code provisions are overly conservative for edge and corner columns, and overestimate the capacity of interior columns; and proposed new equations which are mostly empirical. In this study, equations derived from theory of elasticity are proposed for determining the effective concrete strength for sandwich, corner, edge and interior columns. Effective concrete strength values, determined using the proposed equations and the equations suggested by other researchers, are compared with the effective concrete strength values deduced from the test data. It is found that the proposed equations predict effective concrete strength values close to test data compared to the values obtained from American Concrete Institute's Code and also compare well with the results obtained from the equations proposed by other researchers.

Keywords: Concrete strength, Capacity of column, Column-floor system

I. INTRODUCTION

In last few decades, general construction practice for high-rise buildings is to use high strength concrete in columns and low strength concrete in intersecting floors. This difference in strength of two concretes affects the behavior of slab-column joint. There is a need to know an effective concrete strength (f'_{ce}) value for analysis of column as well as slab-column joint. American Concrete Institute (ACI) 318-11 provisions address this issue based on the ratio of column concrete strength (f'_{cc}) and floor (slab or beam) concrete strength (f'_{cs}) as under

If, $f'_{cc} / f'_{cs} \leq 1.4$, then

$$f'_{ce} = f'_{cc} \text{ (for calculating capacity of interior, edge and corner columns)} \quad (1)$$

When, $f'_{cc} / f'_{cs} > 1.4$, then

$$f'_{ce} = f'_{cs} \text{ (for calculating capacity of edge and corner columns)} \quad (2)$$

$$f'_{ce} = 0.75 f'_{cc} + 0.35 f'_{cs} \text{ (for calculating capacity of interior columns)} \quad (3)$$

ACI provisions are based on the experimental study of Bianchini et al.[2]. A considerable research studies have been carried out to investigate the effective concrete strength within a slab-column joint when there is significant difference in the concrete strengths of column and intersecting floors. Gamble and Klinar[3] tested six interior and six edge slab columns under axial compression and concluded that ACI code provisions overestimate the capacity of columns when ratio f'_{cc} / f'_{cs} is greater than 1.4. The authors proposed new equations for estimating effective concrete strength for interior and edge columns. Kayani[4] tested two edge and four sandwich column specimens. He concluded that ACI provisions overestimate the effective concrete strength of interior columns and developed alternative equations using mechanics of composite material approach for determining the effective concrete strength.

In another work by Shu and Hawkins[5], 54 sandwich column specimens were tested to study the effect of aspect ratio (thickness of slab (*h*) /width of column (*b*)) on effective concrete strength of slab-column joint. It was found that ACI code provisions are overly conservative for edge and corner columns, and are unsafe for interior columns in some cases. It was also noticed that f'_{ce} / f'_{cs} value for a given f'_{cc} / f'_{cs} increases linearly as ratio *h*/*b* decreases. They proposed new equation for calculating effective concrete strength of sandwich columns which depends on ratio *h*/*b*, f'_{cc} and f'_{cs}. Ospina and Alexander[6] tested 20 interior columns to investigate the effect of loaded slabs and aspect ratio, *h*/*b*, on the effective concrete strength of slab-column joint. They concluded that ACI code provisions are unsafe for interior columns when slab is loaded and f'_{ce} decreases with increase in slab loads and with increase in aspect ratio *h*/*b*. Lee and Mendis[7] tested six sandwich column specimens to study the effect of aspect ratio (*h*/*b*) and column shape on the effective concrete strength, f'_{ce}. They concluded that an increase in aspect ratio (*h*/*b*) reduces the load carrying capacity of columns and that the square columns give higher peak stress to slab concrete ratios as compared to rectangular columns. Shah et al.[8] also reported that f'_{ce} decreases with increase in *h*/*b* ratio and that ACI provisions are unsafe for interior columns. Interestingly, the study also reported that ACI code gives conservative prediction of effective concrete strength. Nine sandwich column specimens were tested to study the effect of floor thickness on the capacity of columns by Ahsan Ali[9]. The study reported that the f'_{ce} decreases with increase in *h*/*b* ratio and that ACI provisions are overly conservative for edge and corner columns for f'_{cc} / f'_{cs} greater than 1.4. He proposed new equations derived using mechanics of composite material approach for determining f'_{ce}. In all the studies mentioned above, it has been observed that ACI code provisions are overly conservative for edge and corner columns, and they overestimate the strength of interior columns.

II. RESEARCH SIGNIFICANCE

Many researchers have proposed empirical equations for estimating the effective concrete strength for calculating the capacity of columns, when concrete strength of columns is greater than 1.4 times that of intersecting floors. In this study, equations based on theory of elasticity approach are proposed for estimating the effective concrete strength within the slab-column joint. This study will help understand further the values of effective concrete strength within the slab-column joint. The equations proposed in this study are very simple and can be included in the design codes.

III. ANALYTICAL INVESTIGATIONS

Fig. 1 shows a sandwich column wherein column concrete strength is significantly higher than the slab concrete strength. Effective concrete strength within the slab-column joint could be determined using theory of elasticity as discussed in succeeding paragraphs.

A. State of triaxial compression of Slab-Column joint

Compressive strength of concrete (f'_{con}) confined by an active hydrostatic fluid pressure is based on the tests conducted by Richert et. Al [12] and can be estimated as

$$f'_{con} = f'_c + 4.1 f_l \quad (4)$$

where, f'_c is compressive strength of unconfined concrete and f_l is the lateral hydrostatic pressure applied to the concrete.

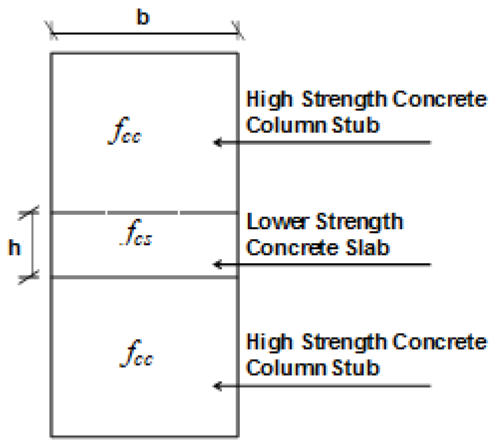


Fig.1-Sandwitch Column

The concrete in slab-column joint shown in Fig. 1 could also be assumed to be confined by the surrounding slab/beams and an effective concrete strength (f'_{ce}) within the slab-column joint may be assumed to be equal to:

$$f'_{ce} = f'_{cs} + 4.1 f_l \quad (5)$$

where, f_l is the lateral confining pressure on the joint.

B. Behavior of Sandwich Column under Compressive Load

Under compressive load '*P*', the joint concrete is expected to expand more than the column concrete. The lateral expansion of slab and column concretes, if stressed separately is

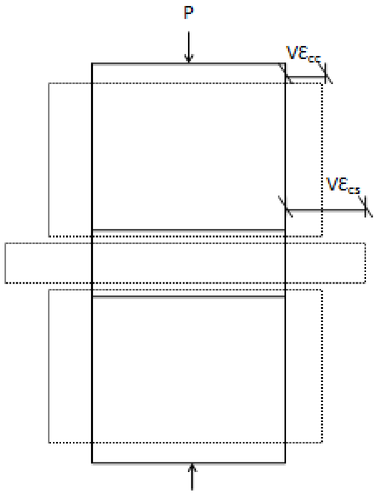


Fig.2-Lateral expansion of column and slab concrete

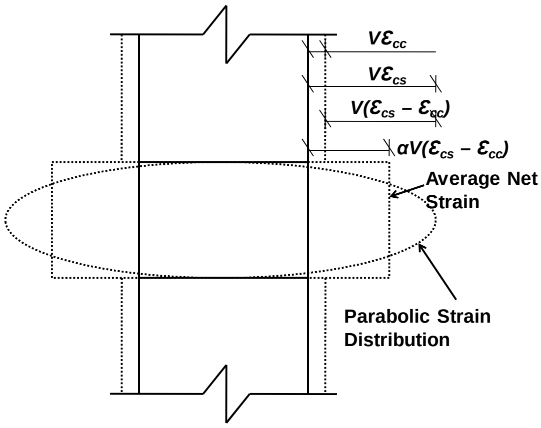


Fig.3-Parabolic and constant strain distribution of the joint concrete

shown in Fig.2. The transverse strains in slab and column concretes are $v\varepsilon_{cs}$ and $v\varepsilon_{cc}$, where v is the Poisson ratio, and ε_{cc} and ε_{cs} are longitudinal strains in column and slab concrete, respectively. The net strain ($\Delta\varepsilon$) at the slab-column joint interface at any point along the depth of slab may be deduced as

$$\Delta\varepsilon = v(\varepsilon_{cs} - \varepsilon_{cc}) \quad (6)$$

Actual distribution of strain through slab depth is likely to be parabolic instead of being abrupt due to net effect of two concretes. Since variation of strain through the depth of slab is difficult to ascertain, an equivalent constant strain value (ε_{ea}) can be conveniently assumed. This equivalent constant strain can be determined by ensuring that the areas of parabolic and constant strain distribution diagrams are same (Fig. 3).

Area of constant strain diagram = Area of parabolic strain diagram

$$\varepsilon_{av} \text{ x } h = \alpha v(\varepsilon_{cc} - \varepsilon_{cs}) \text{ x } h \quad (7)$$

where, α is a constant that depends on the degree of parabolic variation of strain in depth of slab. From Eq. (7):

$$\varepsilon_{av} = \alpha v(\varepsilon_{cs} - \varepsilon_{cc}) \quad (8)$$

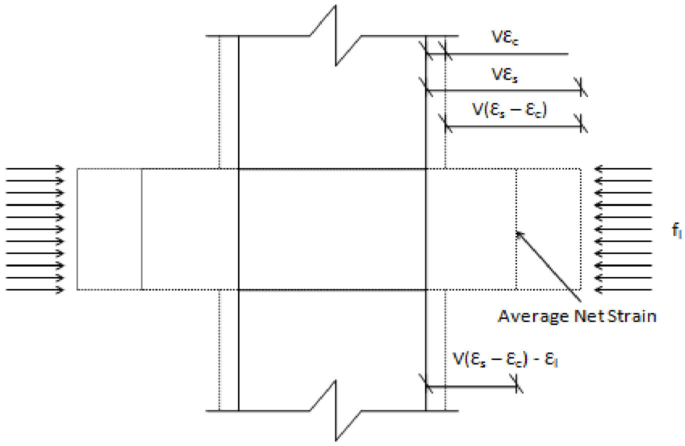


Fig.4-Idealized strain distribution of the joint concrete due to lateral confinement

As mentioned earlier, a state of triaxial compression can be assumed to exist in the slab-column joint. The idealized deformation of slab-column joint is shown in Fig.4. The lateral strain (ε_l) caused by lateral confining pressure (f_l) restricts the net transverse strain. Thus net strain in the slab (ε_{av}) can be written as

$$\varepsilon_{av} = \Delta\varepsilon - \varepsilon_l = \nu(\varepsilon_{cs} - \varepsilon_{cc}) - \varepsilon_l \tag{9}$$

Equating Eqs. (8) and (9)

$$1-\alpha = \frac{\varepsilon_l}{\upsilon(\varepsilon_{cs} - \varepsilon_{cc})} \tag{10}$$

As the load P approaches its ultimate value, the strain in slab concrete (ε_{cs}) can be assumed to have reached the expected limiting value of 0.003 provided there is no confinement, and strain in column concrete will have a lower value. It has been reported in almost all the previous studies that the effective strength of joint concrete decreases with increase in aspect ratio (h/b) because the increase in aspect ratio results into lesser lateral pressures. In this study, it is postulated that the maximum strain of slab concrete is inversely proportional to the root of aspect ratio. The data from available tests indicated better correlation with root of h/b. Therefore, the limiting strain value of slab concrete can be modified as

$$\varepsilon'_{cs} = \frac{0.003}{\sqrt{h/b}} \tag{11}$$

For ultimate conditions, Eq. (10) can be modified as:

$$1-\alpha = \frac{\varepsilon_l}{\upsilon(\varepsilon'_{cs} - \varepsilon_{cc})} \tag{12}$$

where, $\varepsilon_l = f_l / E_s$, E_s is elastic modulus of floor concrete, $\varepsilon_{cc} = f'_{ce} / E_c$, and E_c is the elastic modulus of column concrete. The lateral pressure, f_l may be determined from Eq. (5) as under:

$$f_l = \frac{f'_{ce} - f'_{cs}}{4.1} \tag{13}$$

Eq. (12), after substituting values of ε_l, ε_{cc} and Eq. (13), becomes,

$$1-\alpha = \frac{f'_{ce} - f'_{cs}}{4.1\upsilon E_s(\varepsilon'_{cs} - f'_{ce}/E_c)} \tag{14}$$

Eq. (14) can be further simplified as,

$$\beta = \frac{f'_{ce} - f'_{cs}}{\varepsilon'_{cs} E_s - n f'_{ce}} \tag{15}$$

where, $\beta = 4.1\upsilon(1-\alpha)$ and $n = E_s / E_c$

If β is known, then the effective concrete strength (f'_{ce}) value may be obtained by rearranging Eq. (15) as under:

$$f'_{ce} = \frac{f'_{cs} + \beta \varepsilon'_{cs} E_s}{1 + \beta n} \tag{16}$$

Parameter β indirectly represents the parabolic distribution of the strain within the joint which depends on the joint confinement. β for interior, edge, corner and sandwich columns will be established through Eq. (15) using experimentally deduced values of f'_{ce} .

IV. DETERMINATION OF *Β* AND EXPERIMENTALLY DEDUCED VALUES OF f'_{ce}

As per ACI code, ultimate capacity of a column (P_0) under a concentric load may be calculated as:

$$P_0 = 0.85 f'_{cc}(A_g - A_{st}) + A_{st} f_y \tag{17}$$

where, f_y is the yield strength of steel, A_g is the area of cross-section and A_{st} is the area of steel reinforcement. When a floor of lower concrete strength intersects a column of higher concrete strength, the floor concrete strength (f'_{cs}) should be used in Eq. (17) instead of column concrete strength (f'_{cc}). However, due to restraint provided by column concrete, surrounding slab, etc., there will be an apparent increase in concrete strength above f'_{cs} , and therefore capacity of column through Eq. (17) may be calculated using an effective concrete strength (f'_{ce}) value as under:

$$P_0 = 0.85 f'_{ce}(A_g - A_{st}) + A_{st} f_y \tag{18}$$

Rearranging Eq (18), we get

$$f'_{ce} = \frac{P_0 - A_{st} f_y}{0.85(A_g - A_{st})} \tag{19}$$

Experimental values of f'_{ce} may be determined through Eq. (19) using P_t instead of P_o, where, P_t is the ultimate load capacity of the column found from the tests. The behavior of sandwich columns in tests is almost a representation of corner column behavior [4, 7]. Therefore, experimental values of f'_{ce} and β will be determined for three types (corner and sandwich, interior and edge) columns.

Available test data from previous studies (Bianchini et al.[2], Kayani[4], Shu & Hawkins[5], McHarg et al.[10], Shah et al.[8] and Lee et al.[11] for sandwich and corner columns; Bianchini et al.[2], Gamble & Klinar[3] and Kayani[4] for edge columns; Bianchini et al.[2], Gamble & Klinar[3], Ospina & Alexander[6], Shah et al.[8] and Lee et al.[7] for interior columns) was used for determining experimental values of f'_{ce} . These values of f'_{ce} for then used in Eq. (15) and following values of β were obtained:

Interior Columns: Mean value of β = 0.87, Standard Deviation (SD) = 0.55,
Co-efficient of Variation (COV) = 0.62

Edge Columns: Mean value of β = 0.25, SD = 0.15, COV = 0.61

Corner and Sandwich Columns: Mean value of β = 0.20, SD = 0.12, COV = 0.58

β for all categories of columns has a very high COV, therefore, using mean value of β in Eq. (16) for developing an expression for determining effective concrete strength (f'_{ce}) is not considered reasonable. Generally, in the design codes, the nominal values of design parameters are taken as one or two standard deviations above or below the mean value. A critical analysis of Eq. (16) reveals that use of a lower value of β in Eq. (16) will result into a lower value of effective concrete strength (f'_{ce}) and vice versa. Therefore, to be conservative, the value of β will be taken as one standard deviation below the mean value for all categories of columns as under:

β = 0.87 - 0.55 = 0.33 (for interior columns)
β = 0.25 - 0.15 = 0.10 (for edge columns)
β = 0.20 - 0.12 = 0.08 (for corner and sandwich columns)

V. EQUATIONS FOR DETERMINATION OF f'_{ce}

A. f'_{ce} for Interior Columns

For interior columns, using β = 0.33 in Eq. (15),

$$0.33 = \frac{f'_{ce} - f'_{cs}}{\varepsilon'_{cs} E_s - n f'_{ce}} \qquad (20)$$

On rearranging Eq. (20), we get

$$f'_{ce} = \frac{3 f'_{cs} + \varepsilon'_{cs} E_s}{3 + n} \qquad (21)$$

Eq. (21) may be further simplified as

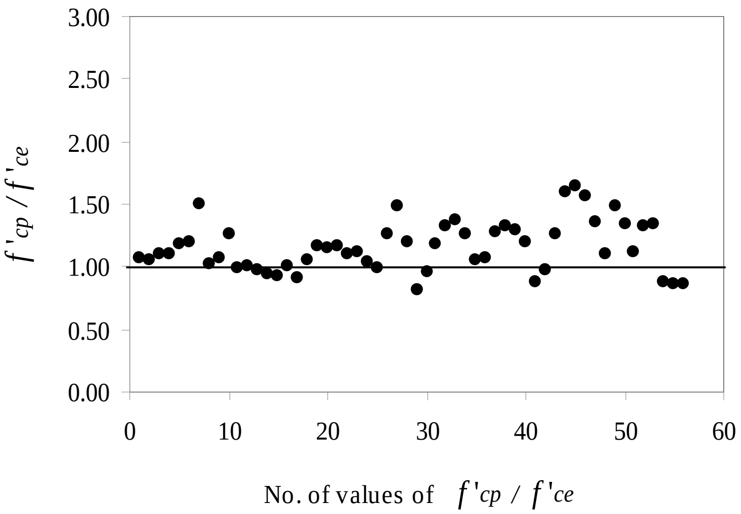
$$f'_{ce} = f'_{cs} + \frac{\varepsilon'_{cs} E_s}{3 + n} \qquad (22)$$

B. f'_{ce} for Edge and Corner & Sandwich Columns

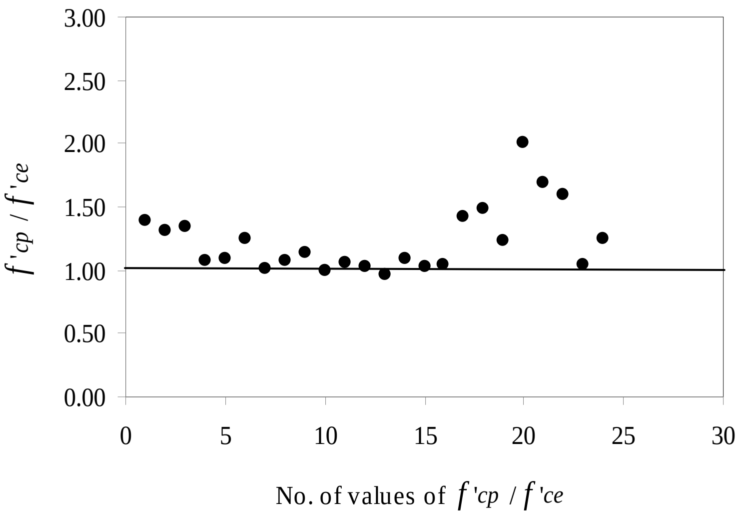
Using β = 0.10 (for edge columns) and β = 0.08 (for sandwich and corner columns) in Eq. (15) yields

$$f'_{ce} = f'_{cs} + \frac{\varepsilon'_{cs} E_s}{10 + n} \quad \text{(edge columns)} \qquad (23)$$

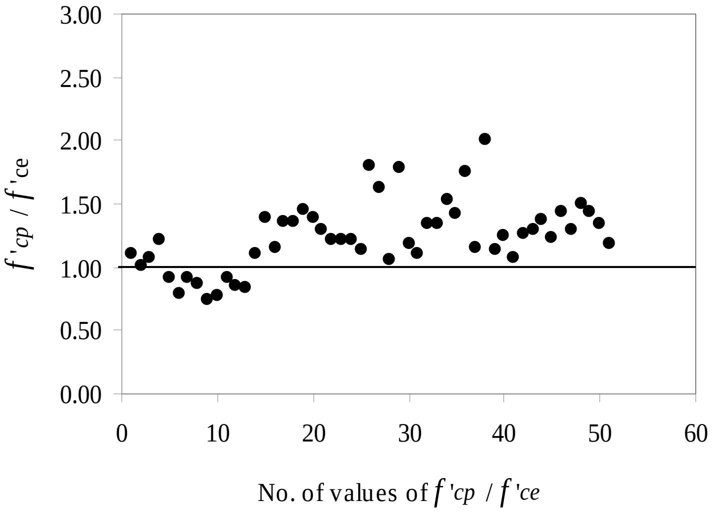
$$f'_{ce} = f'_{cs} + \frac{\varepsilon'_{cs} E_s}{12 + n} \quad \text{(corner and sandwich columns)} \qquad (24)$$



(a) Corner and sandwich columns



(b) Edge columns



(c) Interior Columns

Fig – 5: Ratio of apparent concrete strength (f'_{cp}) to effective concrete strength (f'_{ce}) for columns

VI. COMPARISON OF PREDICTIONS AND EXPERIMENTAL RESULTS

Accuracy of proposed equations is checked by comparing the predicted values of effective strength of concrete (f'_{ce}) with values of concrete strength (f'_{cp}) deduced from the test data (f'_{cp} will be referred herein as apparent concrete strength). Values of f'_{cp} were obtained by using P_t instead of P_o in Eq. (19), wherein, P_t is the ultimate axial load capacity of the column found from the tests. Available test data from previous studies (Bianchini et al.[2], Kayani[4], Shu & Hawkins[5], McHarg et al.[10], Shah et al.[8] and Lee et al.[11] for sandwich and corner columns; Bianchini et al.[2], Gamble & Klinar[3] and Kayani[4] for edge columns; Bianchini et al.[2], Gamble & Klinar[3], Ospina & Alexander[6], Shah et al.[8] and Lee et al.[11] for interior columns) was used for determining apparent concrete strength, f'_{cp}. Additionally, values of f'_{ce} obtained by using the equations proposed by other researchers are also compared to f'_{cp} in order to show the relative accuracy of the proposed equations.

The values of effective concrete strength (f'_{ce}) obtained from Eqs. (22), (23) and (24) are compared with the concrete strength (f'_{cp}) values deduced from test data. The ratio f'_{cp} / f'_{ce} obtained using equations proposed in this study is plotted in Fig. 5, a suitable correlation is found between the two which verifies the concept adopted in this study. Mean, standard deviation and COV of ratio f'_{cp} / f'_{ce} obtained using equations proposed in this and previous studies are shown in Table 1. For corner and sandwich columns the proposed equations gives relatively the best results. ACI 318 equations are over conservative as reported by the previous researchers and Shu & Hawkins equations are relatively unsafe. For edge columns, the proposed equations give comparable results, Kayani[4] and Shu & Hawkins[5] give relatively best results with lower COV and current ACI 318 equations are overly conservative. For interior columns, the proposed equation gives reasonable results. ACI 318 equations for interior columns are un-conservatives.

VII. CONCLUSIONS

A theory of elasticity based approach is proposed to predict effective concrete strength of concrete of a slab-column joint when a column of higher concrete strength intersects with floor of lower concrete strength. The predicted values of effective concrete strength are compared with the apparent concrete values deduced from test data and it is shown that the proposed equations give very reasonable results. The result of proposed equations are also compared with the ACI 318 provisions and with the results obtained from the equations proposed by other researchers, and it is shown that the proposed equations give comparable results. It is shown that ACI provisions are over conservative for the edge and corner columns and are unconservative for interior columns.

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