Effect of Specimen Sizes on Flexural Compressive Strength of Concrete
by Jin-Keun Kim, Seong-Tae Yi, and Jang-Ho Jay Kim

It is important to consider the effect of member length when estimating the ultimate strength of a concrete flexural member. It is also essential to evaluate the effect of neutral-axis depth on the flexural compressive strength of a beam. The current experimental data is still insufficient, however, for a proper evaluation. For all types of loading conditions, the trend is that the strength of a member tends to decrease when the member length and depth increase.

In this paper, the length and depth variations of a flexural compressive member have been studied experimentally. A series of C-shaped specimens subjected to axial compressive load and bending moment were tested. More specifically, four different length (h = 10, 20, 30, and 40 cm) and three different depth (c = 5, 10, and 20 cm) concrete specimens are tested to investigate the size effect of member length h and neutral axis depth c, respectively. The thickness of the specimens was kept constant where the size effect in out-of-plan direction is not considered. The test results are curve fitted using Levenberg-Marquardt’s least square method (LSM) to obtain parameters for the modified size effect law (MSEL) by Kim, Eo, and Park. The analysis results show that the effect of specimen length and depth on ultimate strength was apparent, but their effect on the ultimate strain was negligible. Finally, more general parameters for MSEL are suggested.

Keywords: compressive strength; flexural strength; load; specimen.

INTRODUCTION

Most concrete structural members experience combined loading conditions composed of compression, tension, moment, and shear. In the case of reinforced concrete members especially, the fundamental idea of concrete resisting compressive stress and steel resisting tensile stress is the basic foundation of reinforced concrete structural design. The fracture-mechanics-based formulation of size effect theory, however, has not been studied rigorously for compression-loaded members. The focus of this study is to further develop and clarify compressive size effect in quasibrittle materials. In this research, size effect of compression-loaded reinforced concrete specimens has been experimentally studied with C-shaped specimens.

It is a well-known fact that there is an effect of size differences in nominal strength of specimens made with quasibrittle materials.1-3 More specifically, the nominal strength of laboratory size specimens will differ from that of larger structural members used in the construction of real structures. The difference in the nominal strength is a direct consequence of energy release into a finite-size fracture process zone (damaged localized zone). In the early 1980s, it became clear that the size effect on the nominal strength of quasibrittle materials failing after large stable crack growth is caused principally by energy release3 and cannot be explained by Weibull-type statistics of random microdefects. Ever since then, the problem of size effect has received increasing attention.2-4 A description of such a size effect requires an energy analysis of fracture mechanics type.

Gonnerman5 experimentally showed that the ratio of the compressive failure stress to the compressive strength decreases as the specimen size increases. Bazant4 derived the size effect law (SEL) from the dimensional analysis and similitude arguments for geometrically similar structures of different sizes with initial crack considering the energy balance at crack propagation in concrete

\[
\sigma_N = \frac{P_u}{bD} = \frac{Bf'_c}{\lambda_c d_a} \left(1 + \frac{D}{\lambda_c d_a}\right)
\]

where \(\sigma_N\) is the nominal strength; \(P_u\) is the maximum load; \(b\) is the thickness of the specimen; \(D\) is the characteristic dimension; \(f'_c\) is the direct tensile strength of the concrete cylinder; \(d_a\) is the maximum aggregate size; and \(B\) and \(\lambda_c\) are the empirical constants.

Due to the fracture mechanics-based derivation of SEL, past research studies have focused more on pure tension and shear loading conditions than on compressive loading conditions. Only recently have studies9-12 on compressive loading based size effect become a focus of interest among researchers. Currently, researchers in the field accept the conclusion that the failure of concrete loaded in tension is caused by strain localization resulting in a finite size fracture process zone. In the last few years, many researchers13-15 have begun to realize that strain localization also occurs for concrete specimens loaded in compression. Unlike failure caused by pure tension loading, which usually takes place in a relatively narrow localized zone, compressive loading failure occurs within a larger damage zone. The compressive failure shows a similar failure mechanism as tensile failure. In both cases, the failure is caused by the distributed splitting cracks in the direction of member length as the lateral deformation increases during the failure progression. The compressive failure mechanism is more complex, however, than the tensile failure mechanism.

Size effect of compressive failure is not as distinct as in tensile failure because the formation of microcracks in compressive failure is distributed in a wider region than in tensile failure.

Presently, most design codes for concrete structures do not consider the effect of size. Because quasibrittle materials...
such as concrete, rock, ice, ceramic, and composite materials fail by formation of cracks, size effect has to be implement-ed. In compressive failure of quasi-brittle materials, the size effect is quite apparent. Though the behavior of compressive failure has been studied extensively, the failure mechanism and its size effect have been insufficiently studied in comparison to the tensile failure mechanism. A few researchers, however, have continuously progressed the field (Kim, Yi, and Eo, \textsuperscript{16} Kim et al., \textsuperscript{17} Kim, Yi, and Yang, \textsuperscript{18} Baantand Xiang \textsuperscript{19}).

Reinforced concrete beams having different lengths with an equal cross-sectional area are shown in Fig. 1(a). Reinforced concrete beams having the same length and thickness with different depths are shown in Fig. 1(b). When evaluating the ultimate strength of a reinforced concrete beam member, the effect of member length is usually not taken into account. In other words, if reinforced concrete beam properties such as compressive strength, longitudinal reinforcement ratio, and geometric section dimensions are equivalent, the flexural strength of the beams with different specimen lengths shall be equal. The effect of neutral-axis depth on flexural compressive strength of beams is also important. The experimental data currently available for proper analyses of size effect, however, is lacking at best. From the few available experimental data, it is apparent that the flexural strength decreases as specimen length or depth increase. This phenomenon of reduction in strength dependent on specimen size is called reduction phenomenon.

For experiments on concrete beams (Fig. 1) subjected to flexural loads, the length or depth effect cannot be evaluated systematically due to the change in the location of the neutral axis of the cross section as member sizes, reinforcement ratios, applied loading increments, and loading point locations vary. To resolve these problems, a series of experiments for C-shaped concrete specimens (Fig. 2) subjected to axial load and bending moment are performed following the test procedure of Hognestad, Hanson, and McHenry \textsuperscript{21} Kaar, Hanson, and Capell, \textsuperscript{22} and Swartz et al. \textsuperscript{23} The position of neutral axis \( c \) is kept fixed by continuously monitoring strains on one surface of the C-shaped specimen and adjusting the eccentricity of the applied force so that the strains on the neutral surface remain zero.

The purpose of this paper is to experimentally investigate the relationship between the flexural compressive strength of a reinforced concrete beam and its length and depth. For an unreinforced concrete beam or a concrete beam with less than minimal reinforcement required, the beam fails catastrophically in tension as cracks initiate. Therefore, for beams with this type of failure, size effect is different from beams with reinforcements greater than the minimal required reinforcement in the code. Thus, this study can only be applied to beams that contain a reinforcement ratio more than the minimal required flexural reinforcement defined in the code, but less than the maximum, or so-called 75\% of balanced reinforcement.

**RESEARCH SIGNIFICANCE**

Reduction phenomenon on flexural compressive strength with different lengths or depths for the reinforced concrete beams is an important topic. Currently, appropriate analytical or experimental techniques of understanding this phenomenon are not available. The research described herein was conducted to investigate the length and depth effect of the flexural compressive strength of flexural concrete members. Analytical equations that predict the size effect of flexural compressive strength are proposed based on the experimental data obtained from the compression tests of C-shaped specimens with various lengths and depths. More generalized parameters for modified size effect law (MSEL) are also suggested.

**TEST SPECIMENS AND EXPERIMENTAL PROCEDURE**

**Main test variable**

The shape of specimens and the test procedures used were similar to those of Hognestad, Hanson, and McHenry \textsuperscript{21} Kaar, Hanson, and Capell, \textsuperscript{22} and Swartz et al. \textsuperscript{23} Specimen length-depth ratios of 1:1, 2:1, 3:1, and 4:1 are used to study the effect of length where a constant depth \((c = 10 \text{ cm})\) was maintained and specimen lengths were varied from 10 to 20...
Specimen length-depth ratios of 1:1, 2:1, and 4:1 are used to study the effect of depth where a constant height \( h = 20 \text{ cm} \) was maintained and specimen depths were varied from 5 to 10 to 20 cm (Fig. 2(b)). The thickness of all specimens was kept constant \( b = 12.5 \text{ cm} \) to eliminate the out-of-plan size effect. The specimen thickness \( b \) is chosen to allow stable failure. The average concrete compressive strengths for the length and depth size effect were 58 and 55 MPa, respectively.

### Mixture proportions

The concrete mixture proportions selected for the C-shaped and 28-day compressive strength cylinder specimens are listed in Table 1. Type I portland cement was used. Maximum aggregate size \( d_a \) was 13 mm and a high-range water-reducing admixture and vibrator were used to improve workability and consolidation of concrete.

All beam specimens and test cylinders were removed from the mold after 24 h and were wet-cured (specimens for length effect) and dry-cured (specimens for depth effect) in a curing room for 28 days until the testing date. Concrete compressive strength \( f_c' \), splitting tensile strength \( f_{ct} \), and elastic modulus \( E_c \) were determined based on an average result of three identical \( 610 \times 20 \text{ cm} \) cylinders from the same batch. Table 2 tabulates the experimental data of \( f_c' \), \( f_{ct} \), and \( E_c \) of the concrete cylinders where concrete from the same batch was used to cast C-shaped specimens for length and depth size effect tests. It is important to note that the cylinder and C-shaped specimens for length and depth size effect tests were performed approximately 28 days after casting.

### Details of test specimens

The dimensions, shape, and loading point locations of C-shaped specimens used in the experiments are shown in Fig. 2.

### Table 1—Concrete mixture proportions

<table>
<thead>
<tr>
<th>( w/c ), %</th>
<th>( s/a ), %</th>
<th>Unit weight, kg/m(^3)</th>
<th>S.P.</th>
<th></th>
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<tr>
<td>37</td>
<td>40</td>
<td>178</td>
<td>480</td>
<td>676</td>
</tr>
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</table>

\( w/c \) - Water-cement ratio.
\( s/a \) - Sand/(sand+gravel).
\( d_a \) - Maximum aggregate size of 13 mm.
S.P. - Superplasticizer (high-range water-reducing admixture), ratio of cement weight.

### Table 2—Physical properties of concrete

<table>
<thead>
<tr>
<th></th>
<th>( f_c' ), MPa</th>
<th>( f_{ct} ), MPa</th>
<th>( E_c ), MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length effect</td>
<td>58.0</td>
<td>6.0</td>
<td>( 3.04 \times 10^4 )</td>
</tr>
<tr>
<td>Depth effect</td>
<td>55.0</td>
<td>5.0</td>
<td>( 3.10 \times 10^4 )</td>
</tr>
</tbody>
</table>
The inner vertical thick solid lines of the hollow circle in Fig. 2 represent the locations where strain gages are attached to the sides of specimens. Three specimens per specimen size are prepared because they are the minimum data points required for the data curve fitting. The midheight of C-shaped specimens, which is the critical section under compression, was not reinforced. Flexural and shear reinforcements were inserted at both ends of the specimen to eliminate the undesired premature shear failure at the two end sections and enforce failure in the midheight of the specimen. During testing, strains were measured up to failure at midheight of specimen by 12 strain gages. Two liner variable displacement transducers (LVDTs) were used to monitor the horizontal displacement at midheight. This information was used to adjust the load lever arm distances \( a_1 \) and \( a_2 \) in calculation of bending moments.

**Test procedure**

Displacement-controlled load application is used. Strain increments measured on the midheight of specimen were \( 50 \times 10^{-6} \text{ mm/mm} \) for all sizes in the elastic region. Near the peak stress and postpeak regions, however, the strain increments were gradually reduced to enforce a consistent failure in the specimens of equal size. The major axial compressive load \( P_1 \), shown in Fig. 2, was applied using a universal testing machine (UTM) with a capacity of 2500 kN using a displacement control method. The minor load \( P_2 \), also shown in Fig. 2, was applied using a hand-operated hydraulic jack of 200 kN capacity.

The testing procedure was as follows:

1. An increment of load \( P_1 \) was applied;
2. \( P_1 \) was maintained while incrementally applying Load \( P_2 \) and monitoring the strain value from the attached strain gages on the tension face;
3. On reaching zero strain value (on the average), the load \( P_2 \) was maintained, while \( P_1 \) was further increased; and
4. This procedure was repeated until the specimen failed.

**ANALYSIS OF TEST RESULTS**

**Test results**

Test results for length and depth effect are shown in Table 3 and 4, respectively. Also, the numbering of the specimen (that is, L-I-1) and experimental data are tabulated in Table 3 and 4. The specimens for length and depth effect are assigned with L and D in the specimen names, respectively. Also, the roman numerals I, II, III, and IV represent the size of the specimens with I being the smallest and increasing accordingly. The Arabic numbers 1, 2, and 3 are the three specimens tested for each specimen size. \( P_{cu} \), \( \varepsilon_{cu} \), and \( \delta \) represent the added load value of \( P_1 \) and \( P_2 \), ultimate strain at failure, and displacement at center of specimens at failure, correspondingly. The added load value \( P_{cu} \) is used to calculate nominal flexural compressive strength at failure \( \sigma_{cu} \) as \( P_{cu} / bd \).

Eleven specimens and eight specimens for length and depth effect, respectively, were tested successfully where the stable failure occurred in the middle section of specimens in compressive mode with spalling preceding the failure. The failure shapes were similar to the flexural compression failure of beams under two-point loading, regardless of specimen sizes. It is important to note that the test data of the specimen numbers L-I-3 and D-III-1 are excluded from the data analysis due to undesired failures at two end sections and the rod that applies load \( P_2 \), respectively.

**Length and depth effect of flexural compressive strength**

Kim and Eo,24 and Kim, Eo, and Park25 proposed MSEL by adding the size-independent strength \( \sigma_{\text{ant}} (\text{= } \sigma_{f} \text{)} \) to SEL, which was originally proposed by Ba ant19-20 and Ba ant and Xiang.9 Because this study deals with compressive failure mechanism, the failure strength \( f' \) used in MSEL must be substituted by the compressive strength \( f'_c \) in the new model equation for the prediction of compression-loaded size effect. As an application of this law, a set of experiments has been performed on C-shaped specimens subjected to flexural compressive force and cylindrical specimens subjected to uniaxial compressive force.16-18

Because the crack distribution of axial compressive specimens is wider than flexural compressive specimens and the strain gradients of both cases are different, the size effect of axial compressive specimens is less visible than in flexural compressive specimens. The shapes of strain gradients are rectangular and triangular distributions for axial and flexural compressive specimens, respectively. To show the difference of strain gradients in axial and flexural compressive specimens, the experiments of length and depth effect were performed. Additionally, for the depth effect experiment, the authors predicted that the specimens with smaller value of \( c \) will show a greater strength because cracks will be concentrated in a finite area.

Markeset and Hillerborg26 and Markeset27 experimentally showed that the postpeak energy per unit area is independent
of the specimen length when the slenderness is greater than approximately 2.50 for concrete cylinders. Jansen and Shah also experimentally showed that prepeak energy per unit cross-sectional area increases proportionally with specimen length and postpeak energy per unit cross-sectional area does not change with specimen length for lengths greater than 20.0 cm in concrete cylinders. In this study, it was concluded that flexural compressive strength does not change for specimens having a length greater than 30.0 cm for C-shaped reinforced concrete specimens, as shown in Fig. 3.

The modified size effect equation proposed by Kim and Eo and Kim, Eo, and Park was used as the basic equation for the regression analysis of the experimental results of both length and depth size effect. The predicted depth size effect equation was given as

$$\sigma_N(c) = \frac{B f'_c}{\sqrt{1 + \frac{c}{l_o} \lambda(c)}} + \alpha f'_c$$

(2)

where the function $\lambda(c)$ represents the size of fracture process zone with a strain gradient; $l_o$ is the width of crack band that is empirically known to be related to the maximum aggregate size (that is, $l_o = \lambda_o d_o$) in which $\lambda_o$ is an approximate constant between values of 2.0 and 3.0\(^{16,18}\); and $B$ and $\alpha$ are empirical constants of MSEL calculated as 0.70 and 0.47,\(^{18}\) respectively. In the regression analyses, $\lambda_o$ was chosen as 2.0 where $l_o = 2.0 \times d_o = 2.6$ cm.

Due to the microcrack concentration at the failure zone that intensifies the strain gradient, the size effect becomes distinct. More specifically, if the value of $c$ increases, then the strain gradient and size effect decrease. Therefore, it is assumed that the size of $c$ is inversely proportional to the value of $\lambda(c)$. For the case of length-dependent size effect, the MSEL equation is similar to Eq. (2) except that the depth variable $c$ will be replaced by the length variable $h$, where $\lambda(c)$ is then substituted with $\lambda(h)$.

To obtain an analytical equation that predicts the flexural compressive strength of C-shaped specimens for length effect at failure, MSEL is used. Then, least square method (LSM) regression analyses\(^{29,30}\) are performed on the results of the 11 test data for length effect. Equation (3) is obtained from the analyses and the results are graphed and shown in Fig. 3.

$$\sigma_N(h) = \frac{0.70 f'_c}{\sqrt{1 + \frac{h}{2.6 \lambda_o \left( \frac{h}{h} \right)^{0.37}}}} + 0.47 f'_c \ (h/c \leq 3.0) \quad (3a)$$

$$\sigma_N(h) = 0.75 f'_c \ (h/c \geq 3.0) \quad (3b)$$

where nominal flexural compressive strength $\sigma_N$ and uniaxial compressive strength $f'_c$ are in MPa; and length of the C-shaped specimen $h$ is in cm. If the ratio of length to depth $h/c$ is greater than or equal to 3.0, then this ratio $h/c$ shall be 3.0.

To develop an equation for depth effect, LSM regression analyses are also performed on the eight results from the depth effect series. All techniques and notations are the same as for length effect. Equation (4) is obtained from the analyses and the results are graphically shown in Fig. 4.

$$\sigma_N(c) = \frac{0.70 f'_c}{\sqrt{1 + \frac{c}{2.6 \left( \frac{h}{1.59 \frac{c}{h}} \right)^{0.53}}}} + 0.47 f'_c \quad (4)$$

where the depth of C-shaped specimen $c$ is in cm. Figure 3 shows the value $\sigma_N(h)/f'_c$ as a function of the length-depth ratio $(h/c)$, and Fig. 4 shows the value $\sigma_N(c)/f'_c$ as a function of the depth $c$. The hollow circular data points and the thick solid line in Fig. 3 and 4 represent experimental data and analytical results from Eq. (3) and (4), respectively. Figure 3 indicates a strong length-dependent size effect. Equation (3) shows a good agreement with the experimental results. For a
length-depth ratio greater than 3.0, the failure strength approaches a constant value of 0.75. Figure 4 shows a distinct depth-dependent size effect when normalized with the compressive strength \( f'_c \). Equation (4) shows a reasonable agreement between the theoretical results and the experimental results.

Figure 5 and 6 are the plots of \( \log(\sigma_N/Bf'_c) \) versus \( \log(h/h_o) \) and \( \log(c/c_o) \) for the individual test results for length and depth effects, respectively. In Fig. 5 and 6, the hollow circular data points, the thick solid line, the curved thin solid line, the horizontal thin solid line, and the inclined thin solid line represent the experimental data, the results from Eq. (3) (or Eq. (4)), SEL, strength criterion, and linear elastic fracture mechanics (LEFM), correspondingly. This size effect plot represents a transition from the strength criterion (elastic or plastic limit analysis) characterized by a horizontal asymptote, to a straight line with slope -0.5, representing LEFM. The intersection of the two asymptotes corresponds to \( h = h_o \) (or \( c = c_o \)) and is called the transitional size.

The test results in Fig. 5 and 6 show that: 1) the failure exhibits a significant size effect; and 2) the size effect represents a gradual transition with increasing size from the strength criterion to LEFM as described by SEL. These conclusions can be implemented in all design situations and safety evaluations where a large traction-free crack can grow in a stable manner prior to failure. These conclusions are especially important for extrapolation of small-scale laboratory tests to real structures. The strength theory, which does not account for size effect, is inadequate for these applications.

According to Fig. 5 and 6, the data points are concentrated in a region where the value of \( \log(h/h_o) \) (or \( \log(c/c_o) \)) is lower than 0.0. From these results, it was acknowledged that the size effect would not have been clearly revealed if the size range were less than 1:4. The present size range of 1:4 appears to be approximately the minimum for being able to clearly demonstrate the size effect. Because of inevitable scatter, it would be desirable in the future to test specimens of broader size ranges.

**Generalization of size effect law for C-shaped specimens**

Equation (5) was obtained from LSM regression analysis of 19 new experimental data and 20 previous data, \(^{18} \) of which the \( h/c \) value was a constant value of 2.0.

\[
\sigma_N(c, h) = \frac{0.70f'_c}{\sqrt{1 + \frac{c}{2.6}(0.77\left(\frac{h}{c}\right)^{0.56} - 0.13)}} + 0.47f'_c
\]  

(5)

where if \( h/c \geq 3.0 \), \( h/c \) shall be 3.0, and notations are the same as in Eq. (3) and (4). If \( h/c \) is 2.0, then the value of \( \lambda(h/c) \) will be 1.0, and Eq. (5) will be same as Eq. (1) presented in Reference 18.

In Fig. 7, the thick solid line represents the analytical results obtained using Eq. (5) and the hollow circular data points represent the experimental data. The figure shows that Eq. (5) agrees with the experimental results quite well. Thus, flexural compressive strength of a beam specimen for various length and depth can be calculated by inputting \( c, h \), and \( f'_c \) into Eq. (5).

**Other observations**

**Ultimate strain**—It is generally acknowledged that the ultimate strain of concrete ranges between 0.003 and 0.004, based on many experimental results from beams with rectangular cross section subjected to flexural compressive load. Similar results were also obtained in this study for both length and depth size effect cases. In Fig. 8, the thick dashed line represents the ultimate strain of 0.003 suggested by ACI Code and the hollow circular data points represent the test results. It was observed that the ultimate strain of every specimen is greater than 0.003, which is similar to the research results reported by Hognessdad, Hanson, and McHenry, Kaar, Hanson, and Capell, Nedderman, and Corley. Although there is a minute scattering of data points for larger specimens, the difference is insignificant.

![Fig. 5—Experimental length effect of C-shaped specimens compared with SEL.](image)

![Fig. 6—Experimental depth effect of C-shaped specimens compared with SEL.](image)
Load-displacement curve—Figure 9 shows the relationship between load $P_u (= P_1 + P_2)$ and the measured horizontal displacement at the middle section of C-shaped specimens from LVDT for length and depth effect, respectively. The results from the length dependent size effect experiments show that the load $P_u$ decreases and the displacement increases with the increase in the specimen length. The loads $P_u$ for Specimen III and IV, however, are similar. For the depth-dependent size effect experiments, the results show that the load $P_u$ increases and the displacement decreases with the increase in the specimen depth. In these figures, the relationship between applied load and horizontal displacement shows a slight nonlinearity at larger loading stages due to the stress distribution in C-shaped specimen varying from linear to nonlinear.

Stress and strain relationship—Stress values on compressed face $f_c$ obtained from LSM regression analyses using a cubic equation $f_c = A_1 + A_2 \varepsilon_c + A_3 \varepsilon_c^2 + A_4 \varepsilon_c^3$ for length and depth effect of C-shaped specimens are plotted against strain values on compressed face $\varepsilon_c$ in Fig. 10(a) and (b), respectively. LSM regression analysis was performed on the data points obtained from the experiments based on satisfying force and moment equilibrium around the neutral-axis of the cross section. In other words, to perform LSM regression, the values of force, moment, and extreme compression fiber strain $\varepsilon_c$ at every load step are required. LSM regression method minimizes the sum of squares of $m$ nonlinear functions $f_i$ of $n$-dimensional vector $x$ (column matrix), which is expressed as

$$\sum_{i=1}^{m} f_i^2(x) = \text{minimum}.$$  

The coefficients $A_1, A_2, A_3,$ and $A_4$ are also determined. It is assumed that the established $f_c$ and $\varepsilon_c$ relationship is valid for all layers in the section. Thus, a compressive stress can be determined from this relationship using the measured strain values.

Also, the thick solid lines in these figures are the uniaxial compressive stress-strain curves obtained from standard concrete cylinder tests. Maximum stress value and the corresponding strain value of C-shaped specimen show a significant increase as the specimen length or depth decreases. For length effect, the maximum stress value and the corresponding strain value of specimen size I is largest when compared to the other specimen sizes. Maximum stresses and corresponding strains of C-shaped specimens, however, are relatively similar for specimen sizes III and IV in Fig. 10(a). The reason for this trend is that flexural compressive strength does not change for specimens having a ratio of length-depth greater than 3.0. For depth size effect, the maximum stress value and the corresponding strain value of specimen size I is largest when compared to the other specimen sizes.
These figures show that there is a brittle failure when concrete with higher strength is used. To capture the descending branch of the stress-strain curve, the experiment should be performed using concrete with lower strength. Also, the figures show that a stress-strain relationship for concrete in flexural compression may be different from that of a uniaxial compressive strength of cylinders, especially in the descending branch.

CONCLUSIONS

A series of compression tests for 19 C-shaped concrete specimens and cylinders cast from the same batch were performed to evaluate the length and depth effects on the flexural compressive strength of flexural members. From the test results and analyses, the following conclusions are drawn.

1. Length effect is apparent (that is, the flexural compressive strength at failure decreases as the specimen length increases). Depth effect is also distinct. New parameter values of MSEL are suggested to better predict the reduction phenomena of the strength. More general parameter values are also suggested using the previous data;

2. For the stress-strain relationship, the length and depth effect is also apparent. For specimens with a length-depth ratio greater than 3.0, however, the length effect of flexural compressive strengths is insignificant. It would be desirable in the future, however, to test specimens of broader size ranges;

3. Ultimate strains for both cases range between 0.003 and 0.004. They are similar to general test results for beams and are greater than the value of 0.003 suggested by ACI Code; and
4. The results suggest that the current strength criteria based design practice should be reviewed.

ACKNOWLEDGMENTS
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CONVERSION FACTORS

100 mm = 3.94 in.
1 kN = 0.225 kips
1 MPa = 145 psi
1 kN-m = 0.738 kip-ft

NOTATION

\( a_1 \) = distance from neutral surface to center of member
\( a_2 \) = distance from neutral surface to center of rod
\( A_{12} A_{3} A_{4} \) = coefficients of cubic equation \( f_c = A_1 + A_2 x + A_3 x^2 + A_4 x^3 \)
\( b \) = thickness of specimen
\( B \) = empirical constant
\( c \) = depth of C-shaped specimen
\( c_{w h} \) = constant depending on both fracture process zone size and specimen geometry
\( d_{p} \) = maximum aggregate size
\( D \) = characteristic dimension
\( E_c \) = elastic modulus of concrete
\( f_{c} \) = stress in concrete
\( f_{c}^t \) = uniaxial compressive strength of standard concrete cylinder
\( f_{i} \) = splitting tensile strength of concrete cylinder
\( f_{r} \) = functions defining residuals between measured and calculated values
\( f_{t}^c \) = direct tensile strength of concrete cylinder
\( h \) = length of C-shaped specimen
\( l_{cb} \) = width of crack band (= \( 2.5 d_{a} \))
\( P_1 \) = major load
\( P_2 \) = minor load
\( P_u \) = maximum load, or ultimate axial load = \( P_1 + P_2 \)
\( r \) = correlation coefficient
\( s \) = standard deviation
\( x \) = vector of unknown variables
\( \alpha \) = empirical constant
\( \delta \) = lateral displacement at center of specimens at failure
\( \sigma_c \) = strain in concrete
\( \sigma_{cu} \) = ultimate strain in concrete
\( \lambda_0 \) = approximate constant (= 2.0)
\( \sigma_0 \) = size independent stress (= \( \sigma_0^f \))
\( \sigma_N \) = nominal flexural compressive strength at failure (= \( P_u/b h c \))

REFERENCES


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