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SIZE EFFECT ON THE CONCRETE COMPRESSION FAILURE LOAD

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Abstract
A numerical analysis was performed in order to check if the ultimate strain and stress capacity of compressed concrete columns is size independent what is currently used in design codes. The analysis was first performed for a series of eccentric compressed specimens of different sizes by the use of the 3D finite element program MASA which is based on the microplane material model. The numerical results were compared with experimental data. Furthermore, the size effect study of plain concrete columns for a broader size range was carried out. Both numerical and experimental results show almost no size effect on the nominal strength but an evident size effect on the deformational capacity exists.
Key words: Size effect, compression failure, numerical analysis.

1 Introduction

For a long time the ultimate strain and stress capacity in design codes for structures that fail in compression was assumed to be independent of the structure size (Eurocode 2, 1991; DIN, 1988). In order to check this, recently a number of theoretical and experimental studies have been performed (Bazant et al., 1994; Ozbolt, 1995; Meyer, 1996). According to the experimental results there is an indication that a size effect on the deformation capacity seems to exist and almost no size effect on the nominal strength (Meyer, 1996). This has also been shown by some recent theoretical studies (Ozbolt, 1995). To check this in more detail a numerical 3D fracture analysis for plain concrete specimens with different sizes loaded under eccentric compression has been carried out. The analysis has been performed using the 3D finite element program MASA (Ozbolt, 1998) that is based on the microplane material model.

Compared with experiments the numerical analysis has some evident advantages for the size effect analysis. For example, it is easy to carry out the analysis for large size specimen which is difficult to do in experiment; it is easy to use uniform material properties for a series of analysis, which is nearly impossible in experiment. These advantages of the numerical analysis are based on a reliable material model which should correctly simulate behavior of concrete. Recently the microplane model, which originally proposed by Taylor (1938) and developed by Bazant and his co-workers (Bazant & Prat, 1988; Ozbolt & Bazant, 1992), has been improved (Ozbolt et al., 1997). The numerical verification showed that the model performs well for concrete under compressive load (Li et al., 1998). In the present study the improved model is used.

In this paper, first, the experimental results performed by Meyer (1996) are simulated. The purpose is to further confirm the simulation capability of the material model and to check the size effect for plain concrete columns. Furthermore, a series of eccentric compression specimens of different sizes with the same material properties are calculated.

2 Numerical simulation of compression columns

The calculated specimens are the eccentric compression columns which aims to represent the compression zone of a beam under 4-point-bending loading. According to the experiments performed at Leipzig University (Meyer, 1996) three different geometries are considered for the analysis; small column with 40 cm high, middle column with 80 cm high and large column with 120 cm high. Although both plain and reinforced concrete specimens are tested in the experiments here only plain concrete specimens are simulated. The dimensions of the analysed specimens are shown in figure 1.

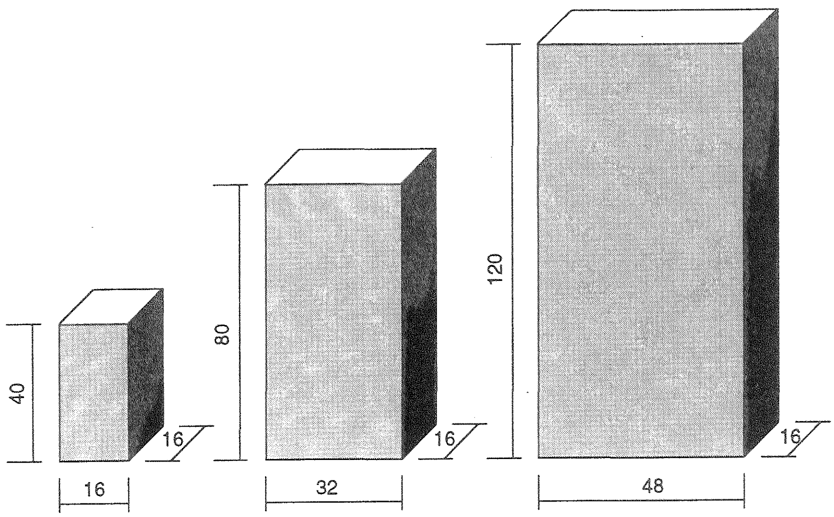

Fig. 1 Dimension of the experimental and numerical specimens (cm)

The numerical analysis was performed by the 3D special purpose FE computer program MASA. A typical finite element mesh for a middle size column is shown in figure 2. Due to the symmetry, only a half of the column is simulated. The simulated system includes the concrete column and the steel plates on the two ends of the column. Microplane model is used to simulate concrete material and the linear elastic model is used to simulate the steel plates. Loads were applied on one line of the up end of the steel plates with an eccentric distance $e = 0.1d$, here d is the length of the specimens. A fixed boundary condition at the correspondent line on the bottom is applied. Displacement control is used in order to obtain the full load-displacement curve. The steel plate is assumed to be a linear elastic material with Young's modulus $E = 2100000\,N/mm^2$ and Poisson's ratio $\nu = 0.3$. The concrete material parameters come directly from the experimental report (Meyer, 1996) and listed in table 1, in which E is Young's modulus, ν is Poisson's ratio, f_t is tension strength, f_c is compression strength and G_f is fracture energy.

The deformations were measured in the experiments for all three different size specimens. In order to examine the strain localisation effect the vertical deformations at both tension and compression sides of the specimens were recorded by measurements over a shorter (about 50% of the height of the specimen) and a longer (about 90% of the height of

Table 1. Concrete material properties

Specimens	Small size	Middle size	Large size
$E\ (N/mm^2)$	29000	32000	31500
ν	0.18	0.18	0.18
$f_t\ (N/mm^2)$	2.7	3.1	2.9
$f_c\ (N/mm^2)$	33.9	40.1	37.8
$G_f\ (N/m)$	87.4	92.8	85

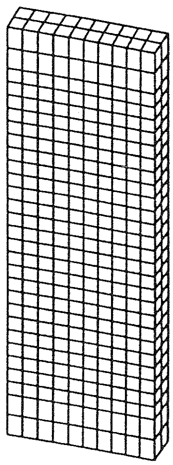

Fig. 2 Finite element mesh

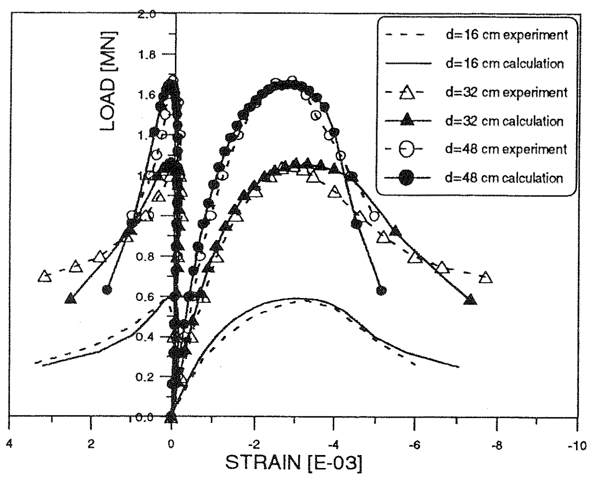

Fig. 3 Experimental and numerical results

specimen) length. In this study only the results with a longer measuring length are considered. The average load-strain curves of longer length for three different sizes, both from experiments and calculations, are shown in figure 3. From this figure we can see that the numerical results agree well with the correspondent experimental results. This confirms again that the simulation capability of the improved microplane model performs well for compression failure of concrete structures. The maximum loads for both experiments and calculations are listed in table 2, in which P_P^E is experimental results and P_P^C is numerical data. An error estimation is performed and shown in the same table. From this table we can see again that the numerical results are agree well with the experimental ones. The final deformed meshes of three different size specimen are shown in figure 4, in which we can clearly see the damage localization zone.

Table 2. Experimental and numerical maximum loads

Specimens	P_P^E (MN)	P_P^C (MN)	P_P^C / P_P^E
Small size	0.58	0.59	1.02
Middle size	1.25	1.26	1.01
Large size	1.67	1.65	0.988

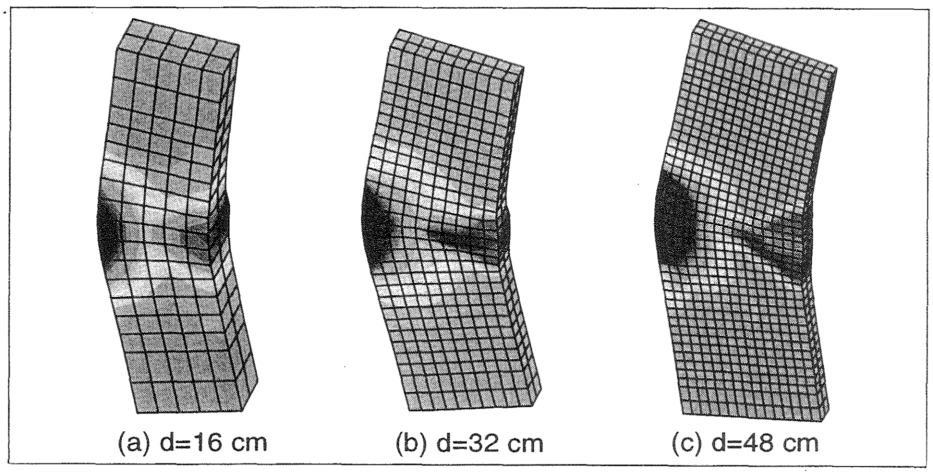

Fig. 4 Numerical results

3 Size effect analysis

In the size effect analysis two aspects are considered, namely ultimate strain capacity and load bearing capacity. According to design codes the ultimate strain of concrete is defined as the strain reached at the maximum load bearing capacity of the concrete compression zone. In this study the determination of the ultimate strain ε_{cu} is taken based on this idea. The ratio α_v between the capacity of the eccentrically loaded compression zone and the full compression capacity of the centrically loaded compression zone is used to determine the load bearing capacity of the concrete compression zone. α_v is calculated as follows:

$$\alpha_v = \frac{F_c}{f_c b d_e} \tag{1}$$

in which, F_c is the maximum load, f_c is the compression strength, b is the width of the specimen and d_e is the effective compression zone which can be determined by the following equation,

$$d_e = d\left|\frac{\varepsilon_c}{\varepsilon_c - \varepsilon_t}\right| \tag{2}$$

in which d is the original length of compression zone, ε_c is the maximum compression strain in the cross section and ε_t is the maximum tension strain in the cross section.

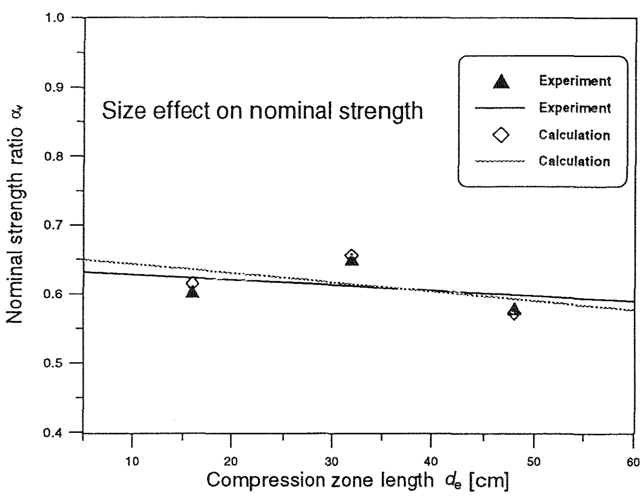

Fig. 5 Size effect on nominal strength

The loading capacity ratio α_v and the ultimate strain ε_{cu} obtained from both experiments and numerical analyses for plain concrete prisms versus

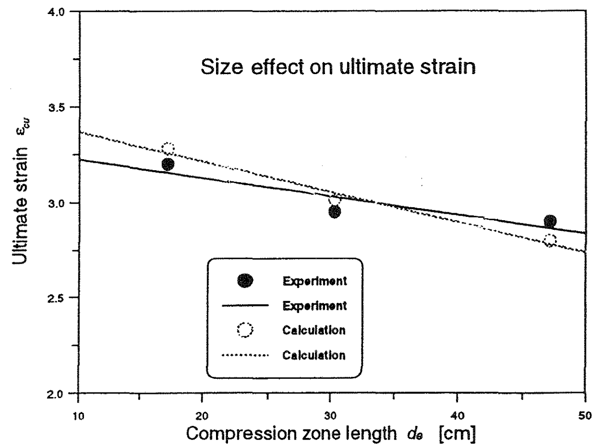

Fig. 6 Size effect on ultimate strain

the effective compression zone length d_e are plotted in figure 5 and figure 6, respectively. A linear regression is performed for these data and the regression lines are shown in the same figures. From figure 5 we can see that the regression lines for both experiments and calculations are quite flat. This means that almost no size effect on the nominal strength of plain concrete compression columns. On the contrary, the deformation capacity (see figure 6) seems to be influenced by a size effect. In figure 6 the regression lines shows a decreasing tendency with increase of the specimen size. This means that the deformation capacity is not size independent as assumed in current design codes.

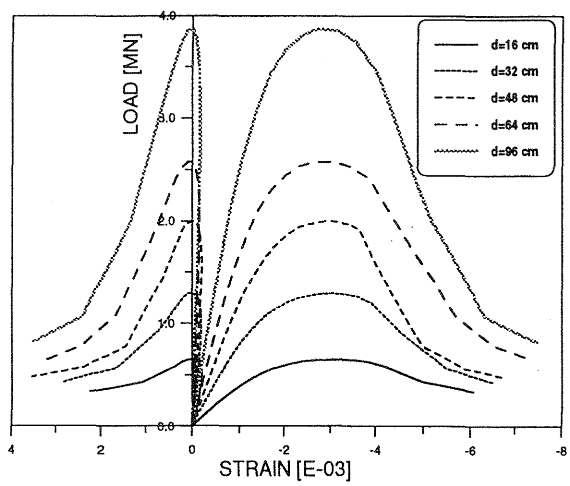

Fig. 7 Load-strain curves for specimens with constant material properties

It is worth to mention that there are two drawbacks in the above size effect analysis. The first one is that the maximum length of the considered specimens is 48 cm. It seems that this dimension is not large enough for a size effect analysis. Secondly, the material properties of three different size specimens are not uniform, e.g. the relative error among compression strengths is about 20%. Evidently this will influence the objectivity of the size effect analysis. In order to remedy these drawbacks and to check the size effect in more detail, a series of eccentric compression specimens with uniform material properties are calculated. The length of the specimens range from 16 cm to 96 cm. The selected material properties are Young's modulus $E = 31000\ N/mm^2$, Poisson's ratio $\nu = 0.18$, compression strength $f_c = 37.7\ N/mm^2$, tensile strength $f_t = 2.95\ N/mm^2$ and fracture energy $G_f = 95\ N/m$. The calculated load-strain curves for all of the specimens are shown in figure 7. From this figure we can see that the maximum load increases and the ductility decreases with increase of the specimen size. A size effect analysis is carried out by the same way as described above. The load capacity ratio α_v and the ultimate strain ε_{cu} versus the effective compression zone length d_e are plotted in figure 8 and figure 9. Linear regressions are performed and the regression lines are shown in the correspondent figures. These two figures show again that almost no size effect on nominal strength and an evident size effect on the deformation capacity exists.

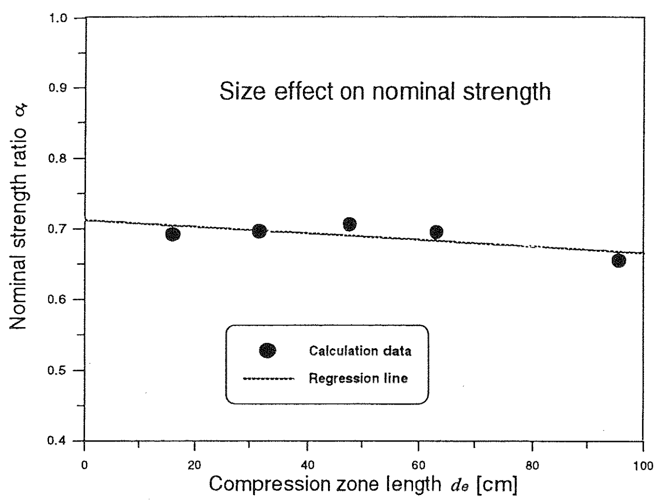

Fig. 8 Size effect on the nominal strength for specimens with constant material properties

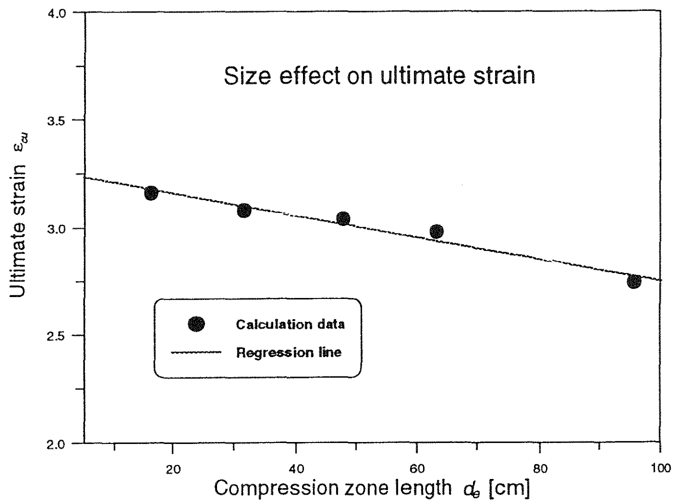

Fig. 9 Size effect on ultimate strain for specimens with constant material properties

4 Concluding remarks

In the present study the numerical simulation of eccentrically compressed specimens of different sizes was performed. The numerical results agree well with the test results. Furthermore, more detailed size effect study was carried out for the specimens of extended sizes and with constant material properties. Both experimental and numerical results show almost no size effect on the nominal strength of the compression load but a size effect on the deformational capacity exists. When the specimen size increases the nominal strength is approximately constant, however, the deformational capacity decreases. This size effect on the deformational capacity of compressed structural members should be taken into account in design codes.

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