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Experimental and numerical study of eccentrically loaded normal and high strength RC columns

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Summary

This paper deals with an experimental investigation and numerical simulation of reinforced concrete columns. Verification of the proposed numerical model is carried out on the basis of unique experiments. Normal and high strength columns are studied together with confinement effects of transversal reinforcement. Special attention is paid to the character of a failure, ductility and post-peak behavior of columns. Three-dimensional computational model based on the microplane model for concrete was constructed and compared with experimental data. Results of numerical model showed good agreement and proved capabilities of the used material model.

Introduction

The ductility is a crucial part of the design of reinforced concrete structure subjected to some exceptional loading like earthquake. At this type of loading the overloaded regions are usually supposed to be in plastic state. This is true for bended elements like beams and girders but different situation is in columns. Columns are typically compressed elements loaded by high axial force with small eccentricity. The ductility of these elements is reduced and the post-peak behavior exhibits softening. This concerns both high and normal strength concretes. Since columns are common structural elements it is necessary to pay an attention to the post-peak behavior of such columns, because reduction of ductility can lead to the significant reduction of the overall load bearing capacity of the structure. The problem of the ductility is further complicated by the dependence on the amount of confinement, i.e. the amount of transversal reinforcement. The better understanding of concrete behavior in reinforced concrete structures such columns is needed and precise and verified models are required.

Methods

We decided to study the problem both experimentally and numerically. Eccentrically loaded reinforced concrete columns were chosen for this research. Combination of compression with small eccentricity produces relatively complicated triaxial stress state in the concrete which is longitudinally and transversally reinforced. One typical geometry with square cross section was chosen for all tested columns. The columns were reinforced with the same amount of longitudinal reinforcement and varied in the amount of lateral reinforcement (stirrups). Three different distances of stirrups were used. Two concrete grades (normal and high strength) were tested. Thus, the total number of studied cases was 6. The geometry of the column is shown in Figure 1.

Three dimensional finite element model for columns was constructed. As it was necessary to describe concrete behavior in its broad outline, some sophisticated material model

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which is capable to describe all important natural phenomena (such as tension and compression softening, path dependence, anisotropy and so on) had to be chosen. The microplane model M4 [3], [4] was our choice. The problem was solved using finite element package OOFEM [6] developed at the Department of Structural Mechanics, CTU Prague.

Experiments

Two grades of concrete, normal 30 MPa (N series) and high strength 70 MPa (H series), were selected. Common geometry for all columns was used. The longitudinal distance between stirrups at the middle part of columns varied: 50, 100 and 150 mm. The dimensions of specimens and their reinforcement is depicted in Figure 1.

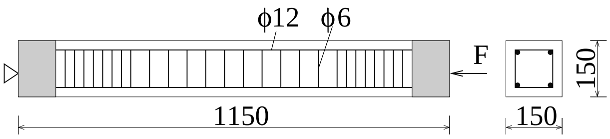

Figure 1: Geometry of specimens in mm (drawn in horizontal position).

Each series consisted of five identical specimens. The columns were loaded in uniaxial eccentric compression. The eccentricity of compressive load was 15 mm in all cases. Measured and observed experimental parameters were: overall axial force, midheight lateral deflection, strains measured over the whole length of column, strains measured at the ends of column, type and character of a failure.

Behavior of all series was very similar. Almost all specimens failed around the midheight. As an example, all specimens of normal strength series after the collapse can be seen in Figure 2 a . Their collapse was initiated by the concrete softening at the midheight, accompanied by the symmetric buckling of both reinforcing bars at the compressed side of the cross section. Bars always buckled between stirrups, as can be seen in Figure 2 b. Failure localized at the middle part of the column where a wedge-shaped pattern developed. The yield plateau in the force-deflection was very small and the load-bearing capacity decreased from the peak value. Loading diagrams plotted for overall axial force versus midheight lateral deflection are shown in Figure 3 for all series. Results show no significant influence of stirrups density on the peak values, i.e. strength and strain. However, in the post-peak region, this dependence occurs. The ductility characterized by the slope of force-deflection diagram increases as the distance between stirrups decreases.

Numerical simulation

A three-dimensional finite element model of specimens was developed. The microplane model M4 [3], [4] was chosen as a model for concrete due to its capability to describe many natural phenomena of this material like compression and tension softening, path dependence, development of anisotropy and others. It is a conceptually simple but computationally demanding triaxial model. The crucial aspect of a constitutive model of such kind is a proper fitting of material parameters. The microplane model constitutive relations are

(a) (b)

Figure 2: Experiments: (a) Series N10 after collapse. (b) Front view on the damaged zone at the midheight.

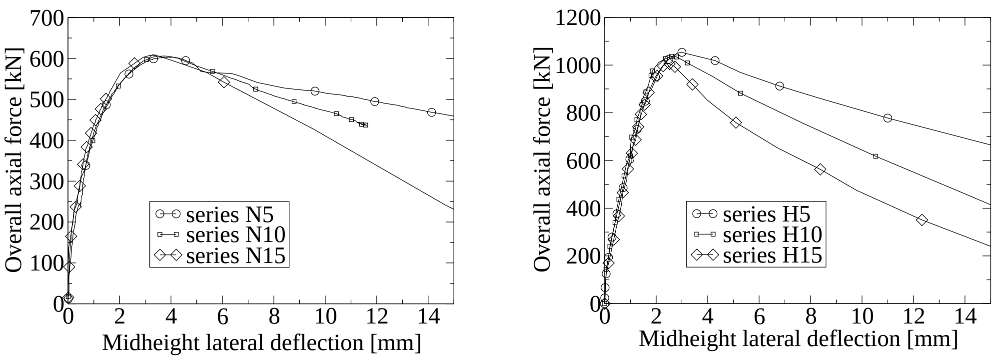

Figure 3: Experiments: Force vs. midheight lateral deflection diagrams of N (top) and H (bottom) series. Numbers 5, 10 and 15 stand for distance of stirrups in cm.

based on a set of parameters that have generally no direct physical meaning. By an optimal fitting of standard uniaxial compression tests on cylinders a set of material parameters for two concrete grades N and H were found. Always, the appropriate set of material parameters was used for computations of all specimens of N series and all of H series, respectively. The microplane model parameters for concrete are summarized in Table 1.

Structured meshes were generated for all columns because only local formulation of the microplane model was used. It means that the energy dissipated from each element must be kept constant in order to receive mesh independent results. Thus, models consisted of the same size cubic elements in the middle part of the column where the microplane model was used. End parts of columns were modeled as elastic to save computational time. Reinforcement was modeled by 3D beam elements with both geometrical and material (J2 plasticity) nonlinearities in order to capture also yielding and buckling.

Table 1: Material parameters of concrete for N and H series.

	E	k_1	k_2	k_3	k_4	c_3	c_{20}
	MPa	nondimension. micrpln. model parameters					
N	33000.	0.000088	500.	15.	150.	4.	1.0
H	46039.	0.000140	500.	15.	150.	4.	0.4

The microplane model is very computationally demanding. The solution was based on nonlinear dynamic analysis - explicit integration [7], [8] with a special form of load time function to minimize inertia forces [9]. The problem was solved using the FE-code OOFEM [6] developed at the Dept. of Structural Mechanics at CTU Prague.

Results of the simulation

It was found that the model is capable of capturing all important features of RC-column behavior. It can give good prediction of the shape and size of the damage zone in concrete and buckling of steel (see Figure 4). The deformation and peak values of the loading diagram were captured well by the model. The computed loading diagrams are shown in Figure 5 where the overall axial force is plotted versus midheight lateral deflection for all series (see also corresponding experimental results in Figure 3). The character of a failure including the softening branch was in good agreement with experiments. It lacks yielding plateau as in experiments, however it does not follow the slope of the experimental curve in the post-peak region. The model gives less ductile response in this case. Probably, the reason for different results in post-peak behavior between simulation and experiments is that concrete-steel interaction was not taken into account. No bond of reinforcement was assumed. The reinforcement modeled by beam elements was connected only to nodes of corresponding finite element. The inaccurate fitting of the material parameters could be also a source of differences.

Conclusions

Behavior of six series of reinforced concrete columns was investigated. Two different grades of concrete (normal and high strength) and three different stirrups density were chosen. Columns were loaded in eccentric compression with small eccentricity. The problem was studied experimentally and numerically. Computational model based on the microplane model M4 for concrete was constructed and used for simulation of the problem. Major experimental and numerical results are as follows:

- Compression failure (crushing) accompanied by concrete softening and steel buck-

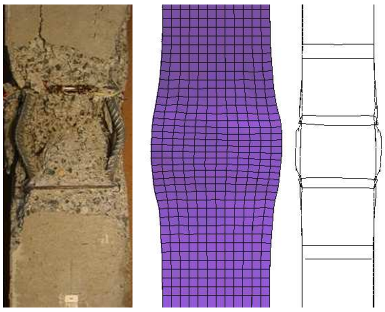

Figure 4: Comparison of experiment (left) and FE model. Damage zone with buckled reinforcement.

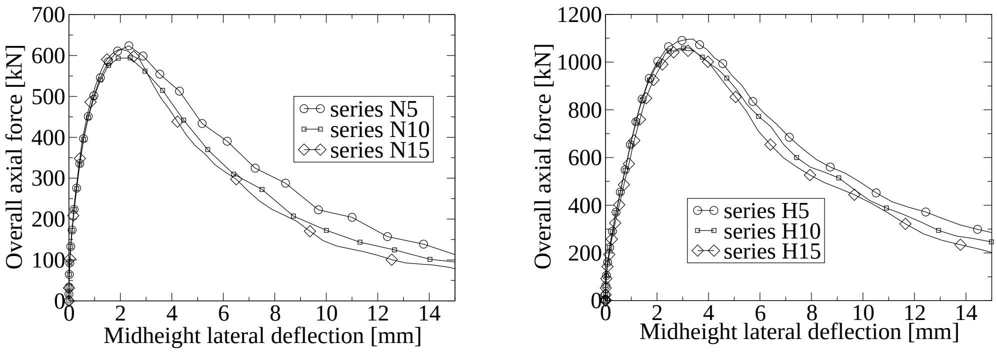

Figure 5: Simulation: Force vs. midheight lateral deflection diagrams of N (top) and H (bottom) series. Numbers 5, 10 and 15 stand for distance of stirrups in cm.

ling developed in columns.

- Failure of columns localized into the middle part, where a wedge-shape failure pattern developed in concrete together with buckling of reinforcement between stirrups.
- The influence of stirrups density on the column strength was negligible in the investigated cases (i.e. square cross section, stirrups density 50-150 mm).
- Significant influence of stirrups density was observed in the post-peak region. Post-peak is characterized by the lack of yield plateau and the slope of the descending branch depends on the density of stirrups. Ductility of columns increases as the distance between stirrups is smaller. This was observed for both normal and high strength concrete.
- The proposed computational model is able to well describe all observed parameters as the shape and size of the damage process zone, buckling of steel reinforcement, load capacity of the structure (peak values) and character of the post-peak behavior.

- Computational model gives less ductility in the post-peak region which might be caused by lacking of steel to concrete interaction in the model. The model should be improved in this feature.

Acknowledgements

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