COMPUTATIONAL MODEL OF REINFORCED CONCRETE COLUMNS AND ITS RELATIONSHIP WITH EXPERIMENTAL DATABASE

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This paper deals with the computational model of reinforced concrete (RC) structures, which is applied to the modeling of RC columns. The model is based on microplane model for concrete and nonlinear description of reinforcement. Material parameters are obtained by fitting of standard uniaxial compression tests. The computational model is used for simulation of conducted experiments. The applicability of the model and comparison of simulation with experiment is presented.

Key words: reinforced concrete structures; softening; post-peak behavior; finite element simulation; microplane model

1 Introduction

We have witnessed a strong progress in material modeling of concrete in the past decades. A lot of material models suitable for concrete based on plasticity, damage, smeared cracking or thermodynamics was developed. These 'classical' models are derived on the basis of macroscopic strain and stress tensors. Another approach is based on microscopic nontensorial formulation. Microplane model (Bažant et. al. ([1], [2], [3]) belongs between the second models' category. As it is widely known, concrete belongs to the group of so called 'quasi-brittle' materials. Its behavior is strongly influenced by a stress state to which it is exposed. This effect can be found in RC structures, where the brittleness or ductility of concrete is determined by outside constraints or by transversal reinforcement, which is the common case (e.g. Van Mier [11], Vonk [12]). Thus, modeling of RC structures involves both modeling of concrete and steel reinforcement, which cannot be ommited. In order to receive a realistic response, it is necessary to use some nonlinear triaxial material model for concrete. Moreover, for modeling of later stages of loading, one must take into account also the development of anisotropy within the material. This is done by the microplane model in a very intuitive manner, where all the inelastic processes are connected directly with the appropriate orientation and the final response is evaluated from all possible spatial orientations.

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2 Motivation for our research

Generally, the response of quasi-brittle materials depends on the loading and boundary conditions. They are characterized not only by the ultimate load and also by the dissipated energy, which is released during the post-peak process. Both the ultimate load and the post-peak behavior is dependent on confinement.

The question was, what is the situation in the post-peak regime of eccentrically compressed RC columns. We were interested in the presence or absence of a yield plateau in the post-peak diagram. Furthermore, if the descending branch occurs in the load-deflection diagram of the column loaded in compression similarly to plain concrete.

Present design practise is based on so called 'plastic limit analysis', which supposes perfectly ductile plastic hinges. This approach can be succesfully used for ductile structures loaded in bending. It was proved by further presented research, that the situation is different for structures with a significant axial load. Only a limited knowledge in this area can be found in the literature (similar experiments of RC columns but for smaller sizes were performed e.g. by Bažant [4] or for centric loading by Hollingworth [5]). The problem of softening hinges was studied also analytically by Jirásek [6].

We decided to investigate RC columns loaded in compression with small eccentricity. Details concerning conducted experiments can be found in Němeček [7]. The decision was made due to the following facts. RC columns are common structures, which are loaded in compression in the majority of cases. When eccentricity of load is small, structural failure of a column is initiated by compressive failure of concrete, not by yielding of steel. Finally, the failure can be readily observed, measured and also compared with the model simulation. The example of typical break-down of the column is shown in Fig. 1.

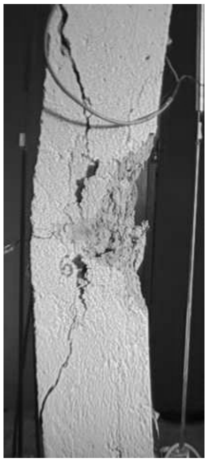


Figure 1: Typical break-down of the RC column.

3 Research strategy

The problem was studied experimentally and numerically. Experiments were conducted prior to numerical simulations. Several series of RC columns were investigated in order to study different phenomena and to build wide experimental database. But the work has been done with the knowledge of future modeling. This was a very important aspect, because it determined also the need of performing accompaning standard tests. These tests were the essetial source of information for calibration of the material model.

Computational model was based on finite element method. Material model for concrete was calibrated according to standard uniaxial compression tests on cylinders and then used for simulation. Following items were observed in experiments and compared with the simulation:

- ultimate load (maximum overall axial force),
- slope of the post-peak load-deflection diagram,
- place and size of the damage zone,
- strains at compressed and tension sides,
- strains at column's ends,
- lateral deflection.

For a succesful simulation of any kind of problem one must proceed following steps:

1. Construction of a computational model.
2. Acquirement of experimental results from standard test (uniaxial compression on cylinders in our case).
3. Calibration of material model from standard test (fitting of material parameters).
4. Simulation based on found parameters.
5. Verification of computational model by comparison with experiments.

4 Computational model

Finite element model was constructed for numerical simulation of experiments. The need of proper modeling of concrete in multiaxial stress state yielded in the use of microplane model M4 (Bažant et. al. ([1], [2], [3]). It was necessary to use structured mesh in order to keep the energy dissipation from each finite element constant, because a local formulation of this model was applied.

For longitudinal reinforcement geometrically nonlinear beam elements were used to capture buckling of steel. FE-mesh is shown in Fig. 2. Reinforcement was characterized by an elastoplastic behavior with an isotropic hardening. Details concerning FE-mesh can be found in Tab. 1.

The crucial point in material modeling using as complex constitutive model as microplane involves very precise calibration of the model, i.e. it is necessary to obtain material parameters by fitting of some standard tests. Uniaxial compression tests on cylinders were used for this purpose as it was mentioned above.

Although, we solved static loading, nonlinear dynamic analysis (explicit integration) was used. The reasons were following. Microplane model is computationally extremally demanding model. The latest version of this model gives no direct formulation of tangential stiffness matrix and the only way is to use initial elastic stiffness matrix through the whole computation, which yields very poor convergence, of course. Thus, nonlinear

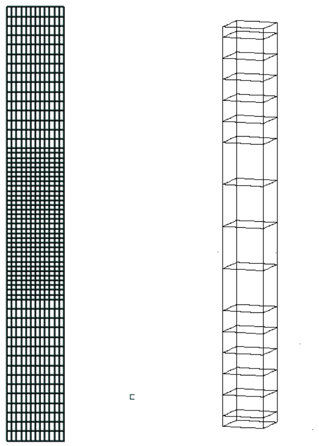

(a) (b)

Figure 2: FE-mesh. (a) elements, (b) embedded reinforcement.

dofs	nodes	brick elements (elastic)	brick elements (M4)	nonlinear beams	truss beams
33159	10647	4320	4608	216	456

Table 1: Description of FE-model.

static analysis became computationally forbidden (see Patzák et. al. [10]). The problem was solved using FE-code OOFEM (Patzák [8], [9]) developed at the Dept. of Structural Mechanics at CTU Prague.

5 Results of the simulation

It was found that the model is capable to capture all important features of RC-column behavior. It can give good prediction of the shape and size of the damage zone in concrete (see Fig. 4), load bearing capacity of the column and the buckling of steel. Results of the simulation are in good agreement with experiments in all above features. Moreover, the model describes the descending branch also very satisfactorily. The comparison of simulation with the experimental results is shown in Fig. 3, where the overall axial force is plotted versus midheight lateral deflection. Good correlation with test data was achieved.

6 Conclusions

Eccentrically loaded RC columns were investigated experimentally and simulated numerically. The main purpose of the investigation was the the study of the post-peak behavior of the columns. Computational model based on the microplane model for concrete was constructed and used for simulation of the problem. The material parameters of constitutive models were obtained from standard tests and used for computation. The major experimental and numerical results are as follows:

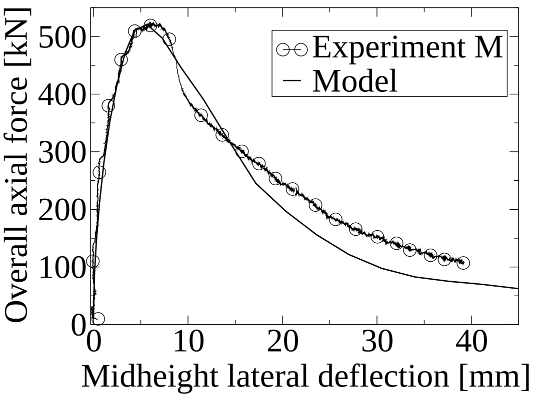
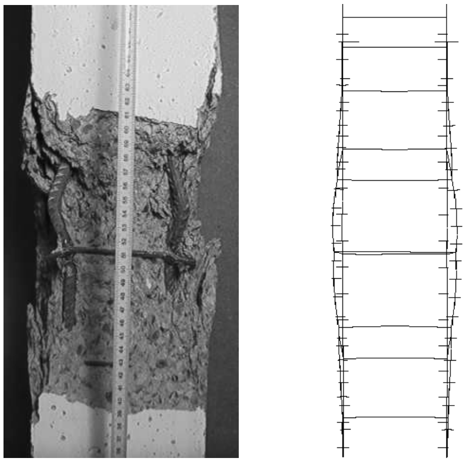


Figure 3: Simulation: Force-lateral deflection diagram.



(a) (b)

Figure 4: Damage zone with buckled reinforcement: (a) experiment, (b) model.

- Failure of columns localized into the middle part, where a wedge-shape failure pattern developed in concrete together with buckling of reinforcement between stirrups.
- Post-peak behavior of eccentrically loaded RC columns is characterized by the lack of yield plateau. In contrary to plastic (ductile) behavior, steep descending branch occurs after the peak.
- The proposed computational model is able to well describe all observed parameters as a shape and size of the damage process zone, buckling of steel reinforcement, load capacity of the structure and post-peak behavior.

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