Simulation of Cracking and Failure of Concrete Structures

V. Cervenka*, R. Eligehausen**

*Building Research Institute, Czech Technical University, Solinova 7, CS-16608 Praha 6, CSRR
**Institut für Werkstoffe im Bauwesen, Universität Stuttgart Pfaffenwaldring 4, D-7000 Stuttgart 80, Germany

ABSTRACT

The computer simulation of the cracking process in concrete structures is performed by means of the program system SBETA. The program is based on a nonlinear hypo-elastic constitutive model, which covers all important experimentally derived material properties, namely, cracking, nonlinear stress-strain law in compression, softenning in compression and tension, biaxial failure function, etc. The nonlinear fracture mechanics is included by means of the fictitious crack model and smeared crack approach. Two examples of computer simulation of concrete fracture are shown. In the first example the failure mode of a pull-out test is presented. In the second example, the process of the crack development and shear failure of a reinforced concrete beam is simulated.

KEYWORDS: finite element analysis, simulation, fracture, concrete, cracking, computer graphics

INTRODUCTION

The program system SBETA was recently developed in cooperation between Stuttgart University and the Technical University in Prague. It was designed for analysis of reinforced concrete structures in plane stress state with emphasis on capability to simulate the processes of crack growth and material failure. New numerical and graphical tools have been designed for presentation of strain localization in the smeared material environment. It is the purpose of this paper to illustrate the potentials of a numerical model which is based on standard FEM for the simulation of the cracking process. The paper is focused on the description of the material model and on the demonstration of results. The program system SBETA is documented in the report [1]. The techniques used for graphical postprocessing are treated in another paper of this proceedings [2]. Further applications are presented in Ref. [3],[4].

NUMERICAL MODEL

The numerical solution of the structural failure is based on a number of assumptions which approximate the real behavior. The approximations are required due to practical limits and sought effectivness of a solution. They are also inevitable because of our limited knowledge of the reality. Having this in mind the numerical model in the program SBETA was constructed with balanced approximations on all levels: structure, finite element, material model (see Fig.1). Details are treated in the report [1] and here we shall mention only the concept of the material model.

All important effects of the behavior of concrete are included. The constitutive relation is based on the hypo-elastic model. Its basic tools are nonlinear stress-strain law and biaxial failure function, Fig.2,3. Before cracking the material is isotropic and after cracking it is considered orthotropic. The cracks are therefore modelled by a smeared orthotropic material. Both, fixed and rotated cracks are implemented. The nonlinear fracture mechanics of the crack growth is implemented by means of the crack band theory, Bazant and Oh [7]. In this model the softening modulus E_t of the descending branch of the smeared material is derived from the fracture energy G_f (material property of the crack), Fig.4.

PULL-OUT TEST

An example taken out of the parameter study [4] is shown next. An anchoring element is embeded in a concrete block and is loaded by a tensile force. The goal of the study was to investigate the effect of the geometry (size and shape) on failure load, ductility and failure mode. The embedment length of the anchor is 50 mm, the span of the support is 200 mm and the thickness of the plate is 10 mm. The specimen is laterally constrained. The analysis was done with the rotated crack model. The final crack pattern after failure is shown in Fig.5, left. It corresponds to the stage of the last point on the descending branch of the load-displacement diagram, Fig.5, right. Note that the arch length method, which was employed as the nonlinear solution strategy, enabled to obtain a complete descending branch of the load-displacement diagram down to zero resistance.

The failure crack pattern can be observed from the strain localization in a narrow crack band. It is a matter of further investigation to compare this computer simulation with experimental results.

SHEAR TEST

This example shows the simulation of a shear failure of the reinforced concrete beam, which was tested experimentally by Leonhardt, Ref.[5]. The purpose of this simulation was to investigate the applicability of the program SBETA, which is based on the smeared crack approach, to the modelling of the shear failure mode. The post-processing provides variety of graphical representations including deformed shapes, principal stresses and principal strains (in three types of representation: vectors, isolines, isoareas), and crack patterns. Here we show mainly the last one, which is also most interesting for the fracturing process. (The other types of graphics are treated in the accompanying paper [2].)

The dimensions of the analyzed beam are as follows: cross section is 0.32x0.19m, spacing of supports is 1.95m. Two loading forces are applied near the centre of the span. The finite element mesh with boundary conditions and reinforcement scheme are shown in Fig.6. The beam has only horizontal bending reinforcement and no web reinforcement in the span. Some vertical reinforcement is provided in the parts exceeding the supports, which has no effect on the shear failure mechanism.

The development of the failure process is shown in Fig.7. The sequences of the crack patterns show the process of the crack formation and localization of the main shear failure crack. The load-deflection diagram and the experimental crack pattern at failure are shown in the bottom right of Fig.7. The cracking process in the numerical model starts by formation of the crack process zone. In the process zone the tensile strength is reached and material exhibits strain softening. By increasing the loading the strain localizes only in some elements, Fig.8, left, in which full tension stress-free cracks are formed, while most of the other elements unload without creating macro-cracks, Fig.8, right. Following this observation only the open cracks are plotted in the final stages of failure. The method of graphical representation of this process by means of "crack filter" is described in paper [2].

CONCLUSION

The numerical studies performed with the program SBETA, which were partially described in this paper, indicated that the smeared crack approach can be succesfully used to simulate the fracture of concrete structures. In this approach the discrete cracks are approximated by crack bands in which strains are localized. The identification of the failure mode was made possible by specially developed post-processing procedure for crack localization.

ACKNOWLEDGEMENT

This investigation was carried out within the research cooperation agreement between the Institut für Werkstoffe im Bauwesen of the Stuttgart University and the Building Research Institute of the Czech Technical University. The sponsorship of both institutions is greatly appreciated.

References

[1] ČERVENKA, V., ELIGEHAUSEN, R., PUKL, R. - SBETA Computer Program For Nonlinear Finite Element Analysis of Concrete Structures, Part 1, Program Description, Part 2, User's Manual, Part 3, Examples of Applications, Institut für Werkstoffe im Bauwesen, Universität Stuttgart, 1989.

[2] ČERVENKA, V., ELIGEHAUSEN, R., PUKL, R. - Post-Processing Tools For Nonlinear FEM Analysis Of Concrete Fracture, STRUCENG & FEMCAD, Grenoble, 17-18.October, 1990.

[3] ČERVENKA, V., PUKL, R., ELIGEHAUSEN, R. - Computer Simulation Of Anchoring Technique In Reinforced Concrete Beams, Proc. Sec. Int. Conf. Computer Aided Analysis And Design Of Concrete Structures, Zell am See, Austria, 4th-6th April 1990, Ed. N.Bicanic,H.Mang, Pineridge Press.

[4] ČERVENKA, V., PUKL, R., ELIGEHAUSEN, R. - FEM Simulation Of Concrete Fracture, Conference 8 ECF Fracture Behavior And Design Of Materials And Structures, 1-3.October 1990, Torino, Italy.

[5] LEONHARDT, F., WALTHER, R. - Schubversuche an einfeldrigen Stahlbetonbalken mit und ohne Schubbewehrung, Deutscher Ausschuss fuer Stahlbeton, Heft 151, Berlin 1962.

[6] HILLERBORG, A., MODEER, M., PETERSSON, P.E. - Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement And Concrete Res., 6,1976, pp. 773-782.

[7] BAZANT, Z.P., OH, B.H. - Crack Band Theory for Fracture of Concrete, Mater. Struct. RILEM, Paris, France, 16, pp. 155-177.

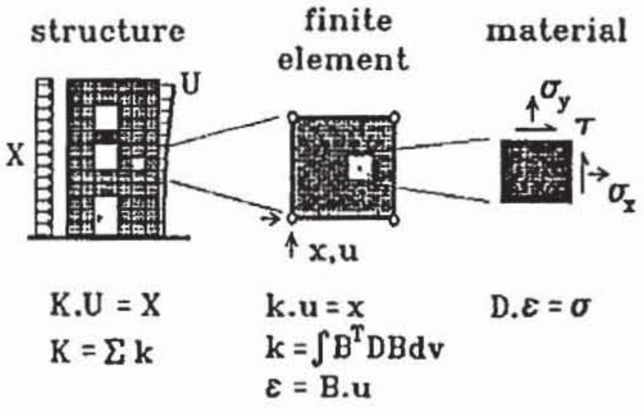


Fig.1 Structure of the finite element model.

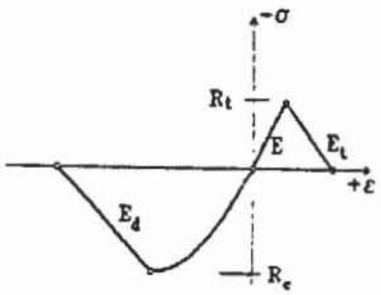


Fig.2 Effective stress-strain law.

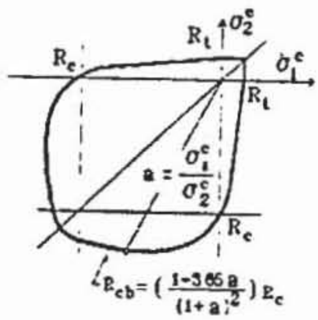


Fig.3 Biaxial failure function.

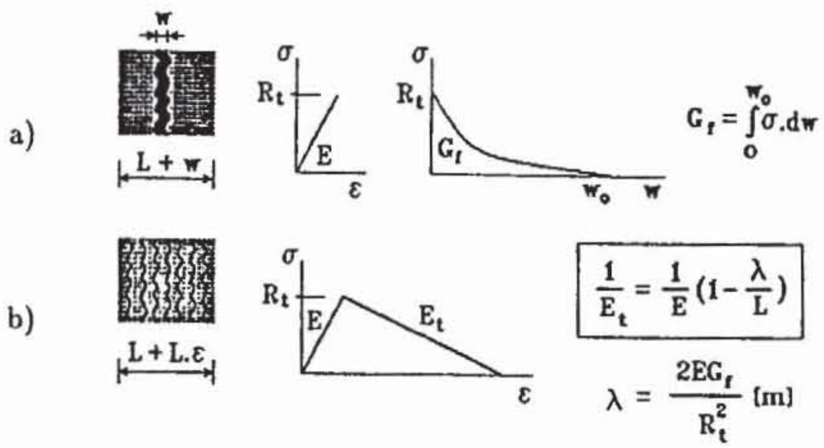
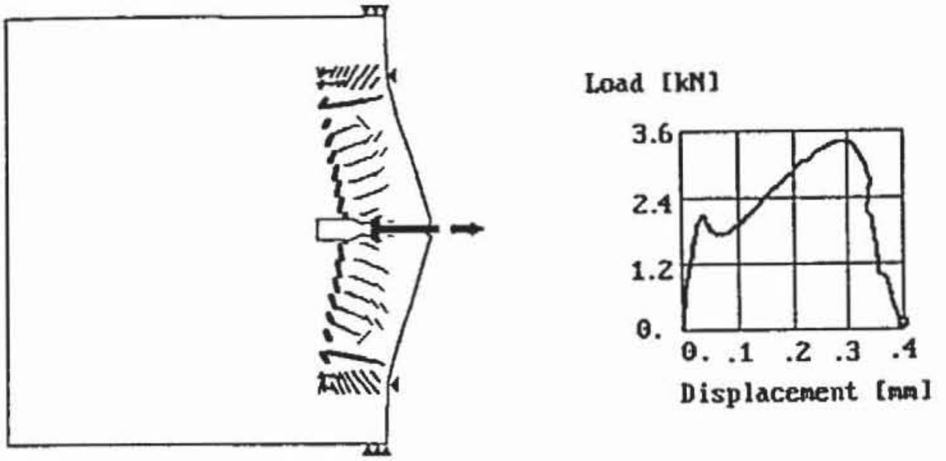
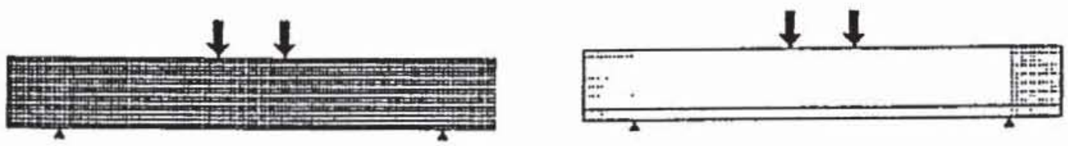


Fig.4 Smeared constitutive model for concrete in tension.
a) discrete crack (Hillerborg et al. [6])
b) smeared crack (Bazant and Oh [7])



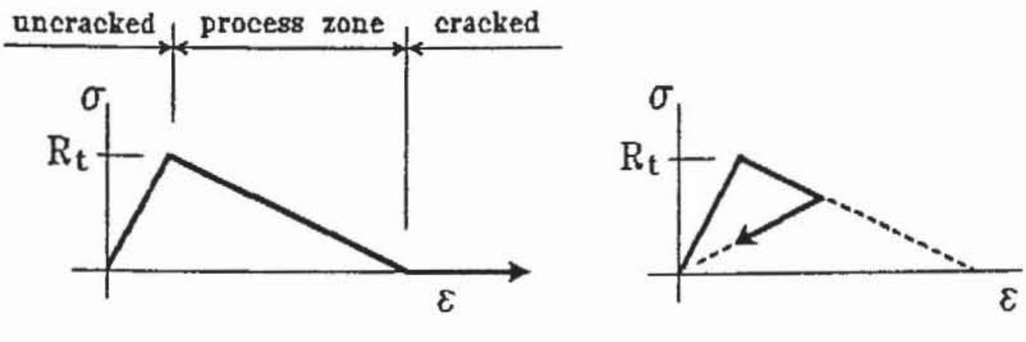
crack pattern load-displacement diagram

Fig.5 Failure mode of the pull-out specimen.



finite element mesh reinforcement

Fig.6 Finite element model of Leonhardt's beam.



crack opening crack closing

Fig.8 Strain localization.

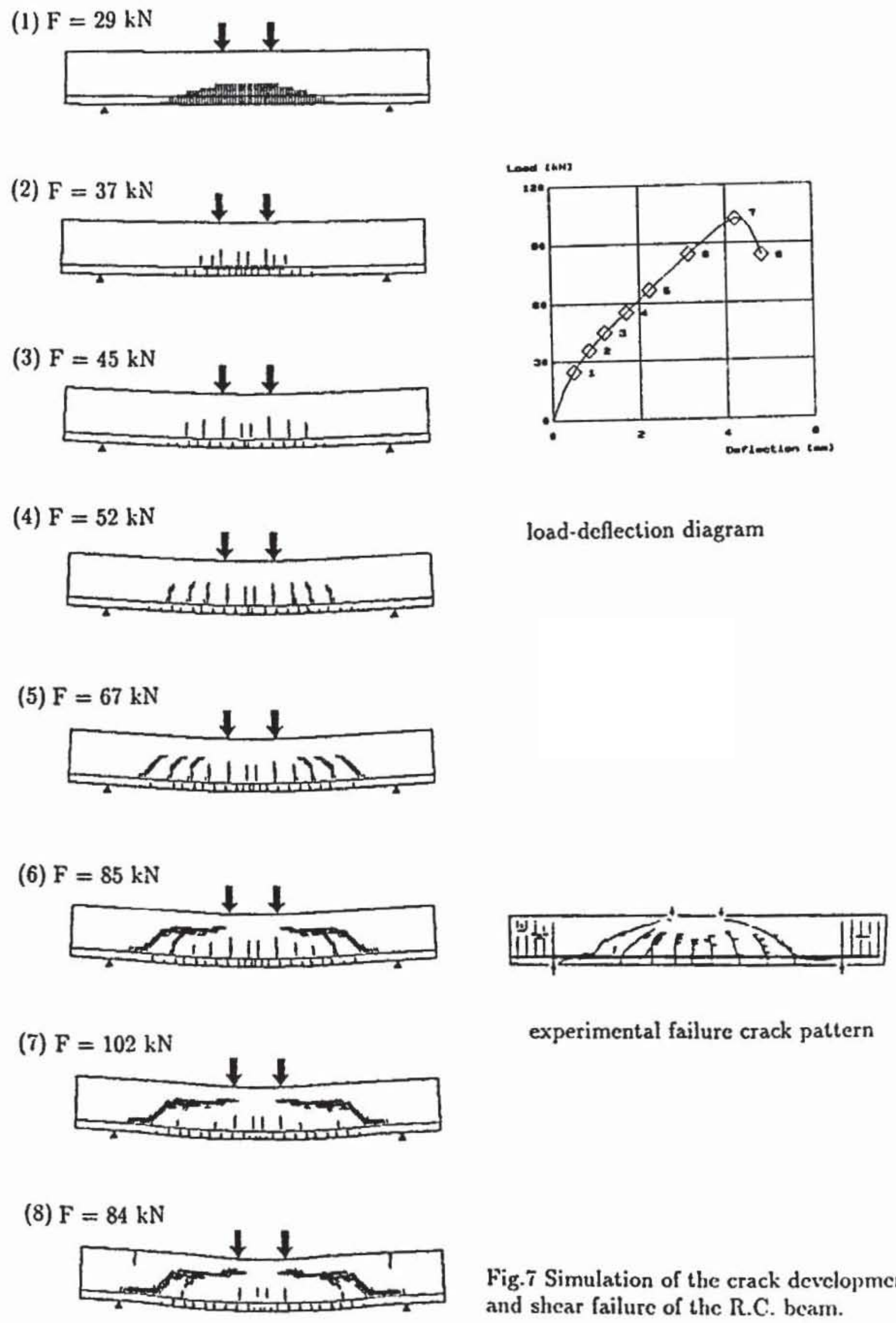


Fig.7 Simulation of the crack development and shear failure of the R.C. beam.