COMPUTER SIMULATION: SPLITTING TESTS OF CONCRETE THICK-WALLED RINGS

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ABSTRACT

Two non-linear program systems are used for a computer simulation of splitting failure of thick-walled concrete rings under internal radial pressure. Results of the numerical analyses for plane stress models, axisymmetrical model and 3D model are compared with available experimental data and empirical formulas. It is shown, that the behavior observed in experiments can be simulated using advanced material models, namely the nonlocal microplane model and SBETA material model based on the crack band theory. With increasing outer radius of the ring, a size effect can be observed.
Keywords: Splitting of concrete, Non-linear material models, Computer simulation, Finite element method, Fracture mechanics, Size effect

INTRODUCTION

The bond failure of deformed bars in reinforced concrete members is often caused by splitting of the concrete. A similar failure may occur in anchoring elements such as headed-, expansion- or undercut anchors installed close to an edge. Until now, mainly experimental studies exist [4], [11]. Only a few analytical or numerical investigations, usually based on simplified material models, have been performed [10]. In order to investigate this problem, authors have performed an extensive numerical study of the splitting failure of concrete rings under internal radial pressure.

NON-LINEAR CONSTITUTIVE MODELS AND COMPUTER PROGRAMS

The present computer simulation was made with two computer codes, which were recently developed in Stuttgart: the microplane programs and SBETA.

The microplane program system, developed by Ožbolt [3], contains two non-linear computer programs, one for solution of two-dimensional problems (including axial symmetry) and another one for solution of three-dimensional problems. Both programs are using the same microstructural constitutive relation based on the nonlocal microplane material model. In this model a new level of discretization is introduced within material in the form of a final number of microplanes. The material behavior is an integral response of all microplanes. For each microplane are defined the stress-strain relations by special exponential functions. Parameters of these functions should be given in input data as material constants.

A nonlocal concept of this model avoids stress concentrations and spurious mesh sensitivity. The nonlocal concept means, that the stress at a material point depends not only on the strain in the same point, but on the weighted average of strains in a certain representative volume. This volume is defined by a characteristic length, which should be given as an input parameter. The proposed value of the characteristic length is three times the maximum aggregate size. Isoparametric quadrilateral (in two-dimensional program) or brick (in three-dimensional program) finite elements with two or three Gaussian points in each direction are used to model the analysed specimen. The microplane programs use an exponential iteration algorithm for the solution of the non-linear equations.

Another program used for this computer simulation was the commercially available program SBETA, developed by Červenka et al. [6], [7], [8]. This non-linear finite element program for plane stress analysis is based on the smeared material approach and the crack band theory [2] for modeling of concrete cracking. The softening modulus, which describes concrete toughness, is related to the fracture energy parameter G_f, crack band width and tensile strength of concrete. The crack band width is related to the element size. The mesh sensitivity is significantly reduced. A four-node quadrilateral finite element composed of two four-node subtriangles with an exact stiffness integration is used. The non-linear solution is performed by the arch-length method, which enables analysis of the post-peak behavior.

NUMERICAL MODELS

The geometry of the rings, shown in Fig.1, and material properties are taken from the experimental investigation [4]. The inner radius of the rings was constant ($R_i = 9$ mm).

The thickness of the rings was 30 mm. The outer radius of the rings was varied: 50 mm, 100 mm, 150 mm, 365 mm and 625 mm. Experimental results are available only for the first three values of outer radius. The last two values of outer radius are used according to [11], but experimental results obtained in [11] cannot be used for comparison in this study because of the different material properties of the test specimens. A symmetrical quarter of the ring was analyzed in most cases. Fine and coarse meshes with the minimal element side in radial direction of about 2.7 mm and 5.2 mm were used to observe mesh sensitivity; results for both types of meshes are almost the same.

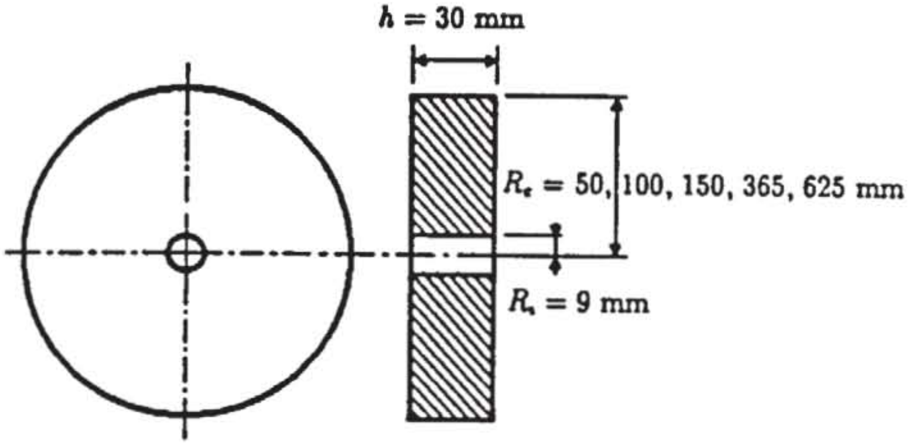

Fig.1 Geometry of the thick-walled concrete rings

Following material properties are given in [4]: Compressive cube strength f_c = 37.9 MPa, tensile strength f_t = 2.8 MPa, modulus of elasticity E = 28125 MPa, maximum aggregate size = 4 mm. These macroscopic material properties were used in SBETA analysis as input data. The material parameters of the microplane model were established from a correlation of the ring analysis with experiments [4] for the case of outer radius R_e = 100 mm, and for all three types of analysis (plane stress, axisymmetry, 3D). The same material parameters were used for the other values of outer radius R_e. A characteristic length of 12 mm was used in all cases. A study of the influence of the characteristic length for different types of analyses was performed. Results show, that the characteristic length influences the results differently in different types of analyses. In the splitting failure of the thick-walled concrete rings the influence of the characteristic length on the peak load in axisymmetrical and 3D models is relatively small; in plane stress model the peak internal pressure increases significantly with increasing characteristic length.

NUMERICAL RESULTS, COMPARISON WITH EXPERIMENTS AND WITH EMPIRICAL EQUATIONS

Table 1 contains a review of the peak values of internal pressure from analysis, experiments [4] and those calculated from the empirical formulas presented in [10]. Fig.2 shows the peak internal pressure as a function of the relative outer radius of the rings

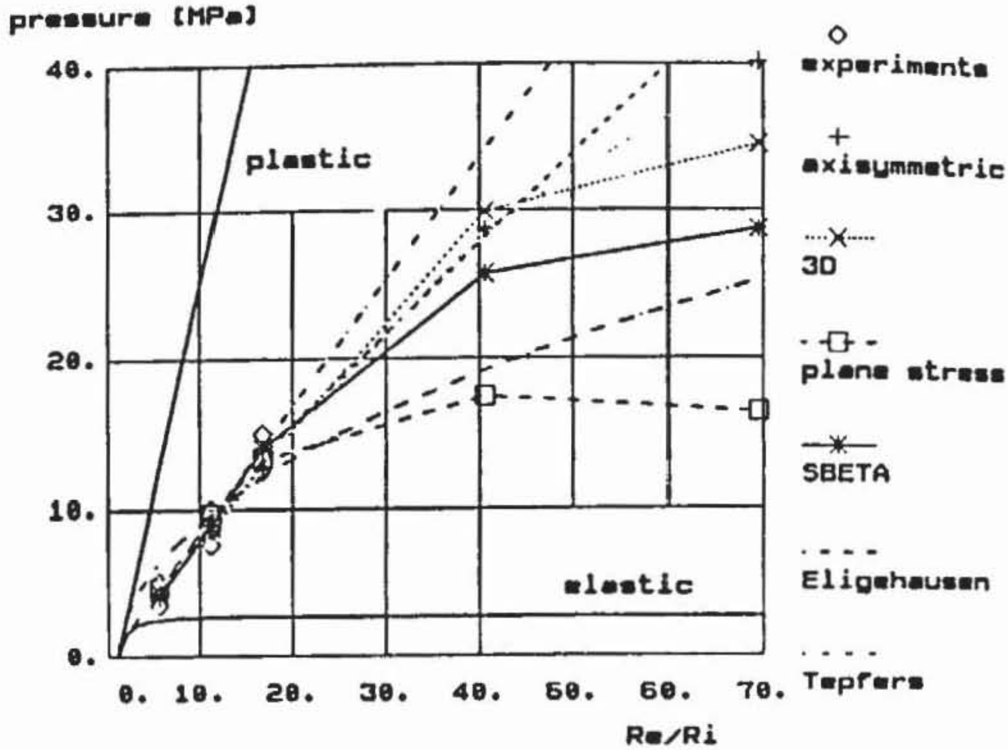

Fig.2 Peak values of internal radial pressure

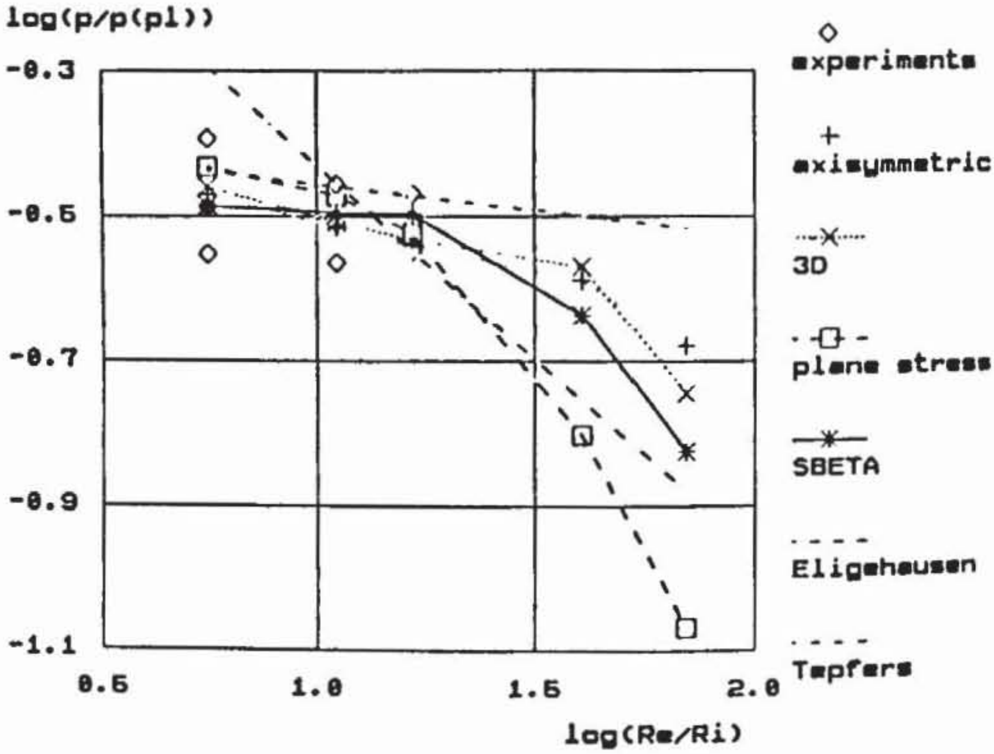

Fig.3 Relative peak pressures in logarithmic scale

(ratio R_e/R_i). In Fig.3 the peak internal pressure related to the value valid for plastic analysis is plotted as a function of the relative outer radius in double logarithmic scale. A size effect can be observed from the results obtained by computer simulation. The nature of this size effect observed from Fig.3 is similar to the size effect law proposed by Bažant [1].

TABLE 1

Peak values of internal radial pressure						
Pressure p [MPa]						
outer radius R_e	[mm]	50.	100.	150.	365.	625.
ratio $r = \frac{R_e}{R_i}$		5.56	11.11	16.67	40.56	69.44
experiments [4]	serie 1	3.58	7.73	12.43	-	-
	serie 2	4.17	8.79	13.55	-	-
	serie 3	5.18	9.91	14.92	-	-
experiments	mean	4.31	8.81	13.63	-	-
microplane	plane stress	4.73	9.59	13.17	17.43	16.38
	axisymmetric	4.34	8.68	12.66	28.61	40.17
	3D	4.44	8.80	12.91	29.89	34.53
SBETA	plane stress	4.18	9.05	13.97	25.66	28.68
elastic	$f_t.\frac{r^2-1}{r^2+1}$	2.62	2.76	2.78	2.80	2.80
Tepfers [12]	$c_1.f_t.r$	4.68	9.35	14.03	34.12	58.42
Eligehausen [9]	$c_2.f_t.\sqrt{r}-1$	6.51	9.69	12.07	19.18	25.22
plastic	$f_t.(r-1)$	12.77	28.31	43.88	110.77	191.63

CONCLUSIONS

Computer simulation of the splitting failure of concrete rings was performed by two finite element codes, namely, the microplane system and SBETA. With suitable material parameters the behavior observed in experiments can be succesfully simulated using computer material models. Deviations of numerical results from the mean experimental values did not exceed the scatter of the experiments. With increasing outer radius of the ring, a size effect in simulated results can be observed.

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