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DEVELOPMENT AND APPLICATION OF A MATERIAL LAW FOR STEEL FIBRE REINFORCED CONCRETE WITH REGARD TO ITS USE FOR PCRVs

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1 INTRODUCTION

In the scope of a research activity, investigations on the applicability of steel fibre reinforced concrete (SFRC) for prestressed concrete reactor vessels (PCRVs) and on possible advantages concerning the safety and serviceability of PCRVs have been carried out. The main part of these investigations refered to the material description of SFRC. The development of a material law for SFRC including general multiaxial stress conditions was based on the evaluation of a lot of publications and on the results of experiments carried out by Hochtief company using an SFRC especially developed for PCRVs.

The derived material model of SFRC has been implemented in a computer program and tested by recalculating experiments with beam structures. Verifying analyses are necessary, since deriving such a material law only by theoretical considerations without including the feed-back of the obtained practical knowledge is impossible. At the end of the verification of the experimental results accompanied by some modifications being important for the correct consideration of the structural behaviour, well corresponding load-displacement curves and realistic crack propagations have been obtained.

Moreover this paper deals with some applications of the developed analysis method on structural parts of PCRVs – idealized models of whole PCRV top caps and detail models of the standtube area in the centre of a PCRV top cap. The results of these investigations are used to assess the obtainable advantages of the use of SFRC in PCRVs.

2 MECHANICAL MATERIAL PROPERTIES OF SFRC

2.1 Preliminary remarks

SFRC is a composite material, which can be idealized macroscopically as homogeneous and isotropic such as plain concrete. The objective of adding steel fibres to concrete is to improve its properties especially under tensile stresses. Thereto advantage is taken of the high tensile strength, the good interfacial bond properties, and the high stiffness of steel fibres.

The mechanical properties of SFRC are mostly influenced by the fibre content, aspect ratio, interfacial bond strength, and orientation of the fibres inside the matrix. Particularly with regard to the applicability of SFRC in PCRVs, a three-dimensional random orientation is assumed with respect to these thick-walled structures.

The essential difference between SFRC and plain concrete consists in the distinctly higher toughness of SFRC in compression and tension. Modulus of elasticity, Poisson's ratio, and uniaxial compressive strength are less influenced by addition of steel fibres, since the strength increasing influence of the steel fibres and the strength decreasing influence of the higher voids volume due to the worse workability nearly neutralize each other.

2.2 Behaviour under tensile stresses

The mechanical property of SFRC treated most of all in literature is its tensile strength, because SFRC is able to sustain tensile stresses of considerable size up to high tensile strains. Different authors have stated formulas for the calculation of the tensile cracking strength and the sustainable tensile stress after cracking. Using these 2 characteristic values, the load-displacement function of SFRC under tensile stress can be specified in a simplified way, the tensile stress after cracking being assumed to be constant and, thus, defining the horizontal branch of a trilinear curve, see Fig. 1. For a more realistic analysis of SFRC under tensile stress, load-displacement functions may be used, which take into account the gradual decrease of the capable tensile stress with increasing crack width. Such tensile stress crack width relationships have been derived from fibre pullout tests, which are documented in literature resp. have been carried out here by Hochtief, see Fig. 1.

2.3 Behaviour under compressive stresses with regard to multiaxial stress conditions

The substantial improvement of toughness of SFRC under compressive stress results from the lateral restraint by the steel fibres. This effect also leads to a considerable increase of the biaxial strength because of the addition of steel fibres to concrete, which is comparable to the increase caused by a small confining pressure in perpendicular direction. In Fig. 2 biaxial strength envelopes of SFRC compared with plain concrete have been plotted for different aspect ratios and volume fractions of the steel fibres. Whereas an increasing aspect ratio results in a considerable improvement of strength, the dependence on fibre content is of minor importance.

The behaviour of SFRC under multiaxial stress conditions has been treated in literature only to a little extent. Fortunately, the behaviour under triaxial stress conditions with one of the principal stresses being tensile, which is seldom investigated even for plain concrete, is substantiated by test results at least to some extent. By comparison with 2 different definitions of failure envelopes of plain concrete in a compression-compression-tension octant in Fig. 3 it becomes obvious, that the capable tensile stress according to Ottosen under simultaneous action of compressive stresses overestimates the test results, the increase compared with Bremer (1972) being reasonable.

3 IMPLEMENTATION OF THE SFRC MATERIAL LAW IN THE COMPUTER PROGRAM

For the purpose of analysing experiments with beam structures, the material law of SFRC has been implemented in the computer program used. The aim of these test calculations was to check the suitability of the material law for predicting the mechanical behaviour of structures. The SFRC of the specimens had got 1 percent fibres by volume and an aspect ratio of 67.

For verifying the material law, 2 bending tensile tests have been used for comparing the different tensile stress crack width relationships from Fig. 1. The result was that the maximum load could be calculated with adequate accuracy also by use of the simple trilinear function A. Thereby the tensile strength after cracking proved to be the more important value than the tensile strength itself, if the strain behaviour in the cracked condition is of main interest.

In order to get more exact informations about the size of capable loads in the cracked condition, an improved tensile stress crack width relationship had to be used, which takes into account the decrease of the capable tensile stress with increasing crack width. The tensile stress crack width relationship C with 4 linear sections, derived from fibre pull out tests in literature, fulfils this requirement with good accuracy. But it had to be considered, that the ideal condition of fibres in the pullout test being anchored exactly with their half length l on both sides of the crack surfaces, does not exit in structures. Good results have been obtained assuming a fictitious length of l/4.

4 VERIFYING ANALYSES OF EXPERIMENTS WITH SFRC BEAMS

A first analysis of large flexural members (see Fig. 4) with unmodified application of the tensile stress crack width relationship, gained by calibration as mentioned before led to substantially higher capable loads than those from the experiments. The explanation of this difference has been found to be the dependence of the bending tensile strength on the stress gradient, which is also observed with plain concrete. In Fig. 5 the bending tensile strengths of tests with 150 mm high beams are compared with those of the 360 mm high flexural members from the experiments. They fit well to test results and derived functions for plain concrete (Borg 1990).

In order to consider this effect and moreover to eliminate an inaccuracy of the load versus deflection behaviour in the region of the maximum load, the analysis has been modified using the tensile stress crack width relationship D from Fig. 1, which has been developed on the basis of the Hochtief direct tension tests. As can be seen from Fig. 4, a well corresponding load-deflection curve and a plausible crack propagation have been gained.

The analysis of the shear stressed beams proved to be the distinctly more different problem than the analysis of the flexural members. This is caused by the load carrying capacity of the additional bar reinforcement and hence the failure mode of inclined cracks, which is a more complex mechanical system.

Firstly, instead of pursueing discrete cracks, as done with the flexural members, in this case "smeared" crack zones had to be introduced because of a finer crack pattern. This made necessary to define a parameter regarding the tensile stress crack width relationship, which allows the calculation of the crack widths from the strains of the cracked zones. Best results have been obtained here by relating the strains perpendicular to the crack direction to a length of approx. 0.7 m. Secondly, shear force transfer in cracked zones had to be regarded in detail, since it is important for the correct consideration of the maximum load carrying capacity of the structure. Thirdly, the contribution of SFRC to tension stiffening had to be taken into account by a suitable approach.

With appropriate assumptions concerning these influences, finally a good agreement of analysis and experiment has been achieved for the shear stressed beams. This applies also to the analysis of the additionally investigated beams made of reinforced concrete (RC), cf. Fig. 6.

5 APPLICATIONS ON STRUCTURAL PARTS OF PCRVs

In order to assess whether the use of SFRC is advantangeous also for the high shear stressed areas of PCRV top caps, 2 nonlinear mechanical analyses of a simplified top cap model loaded by increasing internal pressure have been carried out, one for a PCRV of plain concrete without consideration of any reinforcement and another for a PCRV, whose top cap is made of SFRC up to a diameter embracing the shear stressed area. Important load steps are the beginning of the inclined cracking, which starts at an internal pressure of 32.5 N/mm^2 in the concrete model and of 35.5 N/mm^2 in the SFRC model, and the failure due to crushing in the concrete model at 57.5 N/mm^2 and in the SFRC model at 60.0 N/mm^2. The differences are small, because both variants ultimately result in a failure by destruction of the texture in the shear stressed area. And this behaviour is controlled by the compressive strengths of the materials, which have been supposed to be 70 N/mm^2 for SFRC and 65 N/mm^2 for plain concrete. Since the influence of steel fibres on compressive strength is small, these investigations have not shown any benefit from the use of SFRC in shear areas of PCRV top caps.

The use of SFRC in the standtube area in the centre of a PCRV top cap would be profitable, if the difficult arrangement of reinforcement in the narrow space between the standtubes could be avoided by this. For the purpose of analysing the upper centre of a top cap, which is in tension under high internal pressure, an annullar plate with a central hole for the tube has been chosen as model of a detail of the top cap, which is representative for the whole standtube area, see Fig. 7. Due to the missing tensile force transfer between tubes and concrete resp. SFRC, the inclusion of the tube itself in the model could be omitted. This annular plate – for comparison consisting of SFRC and of RC – has been analysed strain controlled for a tensile stress at the external diameter. For the application of the tensile stress crack width relationship of SFRC, a specific crack pattern between the tubes to be expected because of geometric reasons has been assumed.

The radial stresses at the external diameter of the model, which are equal to the radial stresses at the external diameter of the complete standtube area, as a function of the integral radial strains of the standtube area, are considerably different for SFRC and RC, see Fig. 7. Up to 0.6 ‰ radial strain, the capable SFRC stress is higher than the RC stress. Considering that the expected maximum surface strains in the limit state of ultimate load do not exceed 0.5 ‰, SFRC is at least equivalent to RC. Regarding the distinctly lower effort of fabrication, SFRC should be prefered for the standtube area.

6 CONCLUSION

By deriving tensile stress crack width relationships for SFRC under multiaxial stress states accompanied by suitable calibration analyses it has been made possible to calculate the mechanical behaviour even of SFRC structures with complex load carrying conditions.

The application to PCRVs, which was subject of the research program, has not shown any advantage in the use of SFRC for the top cap areas under high shear stress. Only for the upper part of the top cap centre, which is in tension under elevated internal pressure, the use of SFRC is worth mentioning because of the difficulties concerning the arrangement of reinforcement in the concrete between the tubes. So, economics – concerning the erection – and improvement of liner anchoring discussed by Oberpichler (1993) may be the prevailing reasons for the use of SFRC in PCRV design. Although there is no indication that this application could be realized in the near future, the design tools described in this paper, nevertheless, might be useful also fo other design tasks taking benefit of the specific properties of SFRC.

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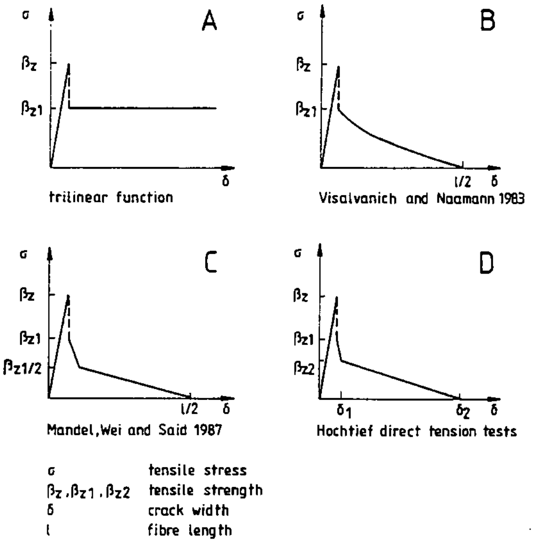

Figure 1. Qualitative description of the used tensile stress crack width relationships

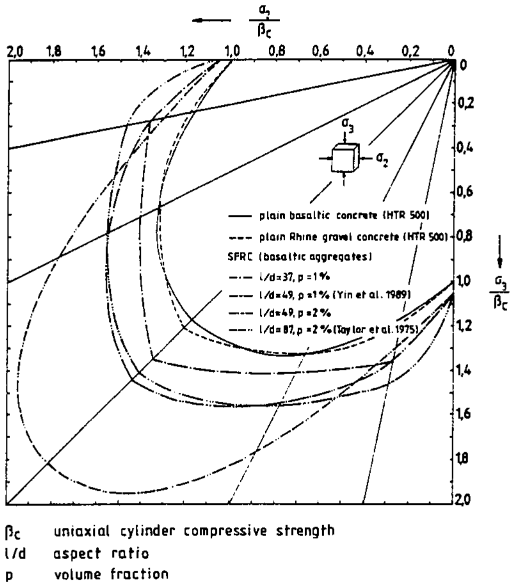

Figure 2. Biaxial compressive strength envelopes of plain concrete and SFRC with basaltic aggregates

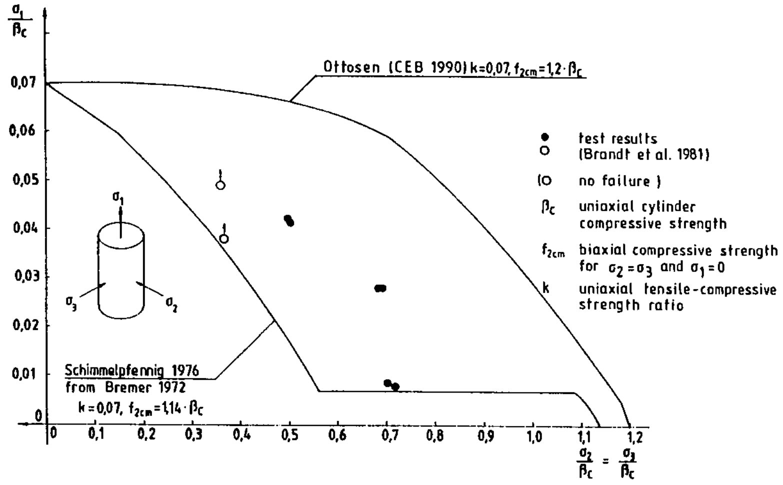

Figure 3. Strength results from triaxial tests of SFRC specimens under compression-compression-tension loading in comparison with failure envelopes of plain concrete

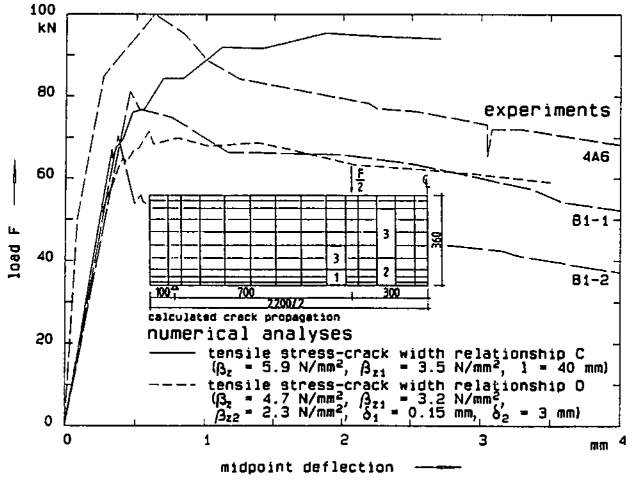

Figure 4. Load versus midpoint deflection of the SFRC beams without additional reinforcement

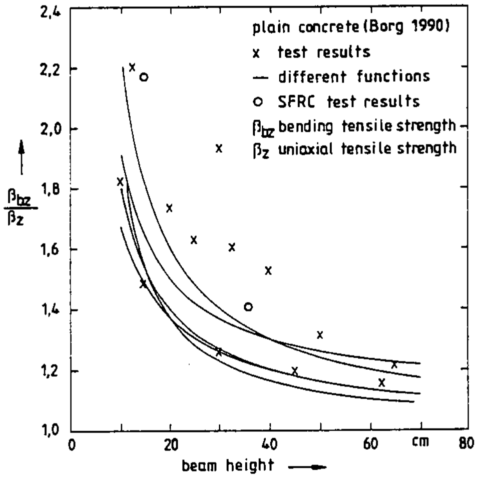

Figure 5. Normalized bending tensile strength versus beam height for SFRC and plain concrete

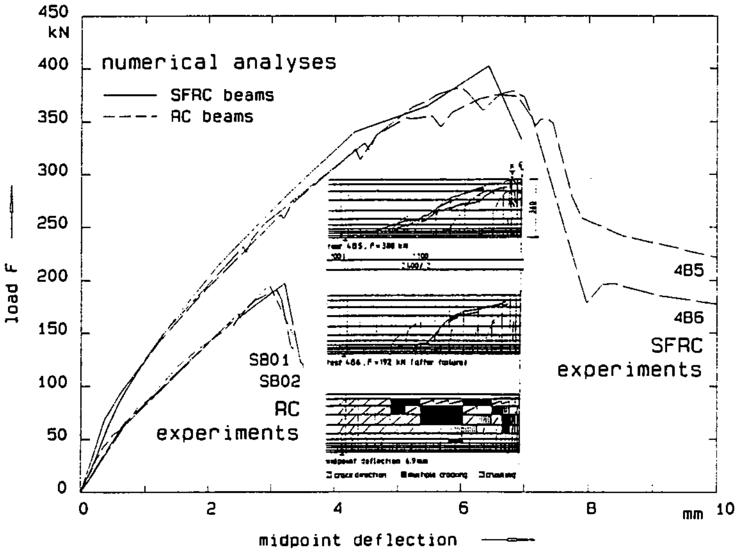

Figure 6. Load versus midpoint deflection of the beams with an additional reinforcement of 5 bars with 20 mm diameter

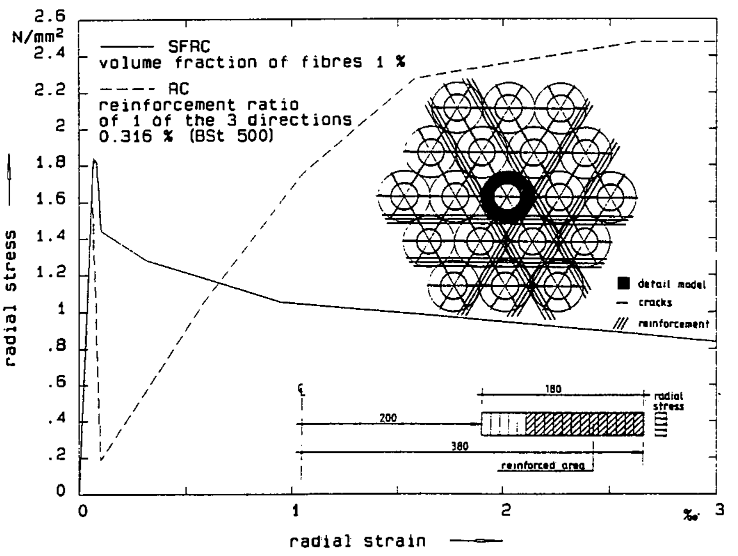

Figure 7. Comparison of the stress-strain behaviour of SFRC and RC in the standtube area of a PCRV top cap