Investigation of the Propagation of Pressurized Cracks in Prestressed Concrete Pressure Vessels

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Abstract

The hypothetical case of the propagation of pressurized cracks which presumes an untight liner is analysed for a PCRV of a High Temperature Reactor. A parameter study is carried out with a finite-element-model changing the degree of reinforcement and the value of the prestressing. The result is that the currently usual design of PCRV's is in the boundary region between propagating and non-propagating pressurized cracks, but it is slightly possible to stabilize the cracks by increasing the reinforcement and/or the prestressing level.

1. Introduction

Prestressed concrete pressure vessels are dimensioned in such a way that the resulting force in each section of the vessel under all operating conditions is a compressive stress. This ensures a stabilization of cracks with a tight liner. However, regions with tensile stresses, i.e. cracks, are present in the concrete, e.g. in the corners.

The liner is generally under compressive stresses during its life-time and thus leakage is extremely improbable. However, in order to also cover the case where the liner becomes untight, proof must be furnished that crack stabilization is maintained despite the resulting primary gas pressure load on the crack boundaries /1/, unless the pressure in the concrete is monitored by instrumentation. Irrespective of this, additional proof must be furnished that the primary gas pressure acts on postulated continuous cracks through the concrete vessel walls. For this purpose the internal pressure must be applied in horizontal and vertical crack areas. This evidence is decisive for designing the prestressing.

The problem of the propagation or stabilization of pressurized cracks has not been studied to date. In the study RS 447 'PCRV under hypothetical accident conditions' which was funded by the Minister of Research and Technology of the Federal Republic of Germany /2/ the problem has been dealt with in the form of parameter studies.

2. Model Studied

A rotationally symmetrical finite-element model with loads from prestressing and internal pressure was used as a basis (Fig. 1). The computations were implemented with the finite-element program SMART /3/. The criterion of Mohr-Coulomb with tensile cracking was used as the constitutive equation, with $\varphi = 56.08°$, $c = 7.01\ N/mm^2$ and $t = 3.5\ N/mm^2$ (tension cut-off).

3. Computation Results

Computations were carried out for different assumptions, on the one hand for non-reinforced and on the other hand for reinforced concrete. Very different behaviour was found, depending on the degree of reinforcement. If, for instance, only non-reinforced or weakly reinforced concrete is employed, no stabilization of the pressurized cracks is obtained at a design pressure of 50 bar, whereas the internal pressure can rise to 61.5 bar before unstable pressurized cracks occur, if a high proportion of reinforcement is included.

3.1 Non-Reinforced Concrete

Assuming an internal operating pressure of 50 bar and the design prestressing, the resulting cracks were computed by an elastic calculation. Cracks occur in the transitional area between top and wall as a result of the concrete tensile strength being exceeded. Keeping the internal pressure and prestressing load constant the internal pressure is applied to these cracks on the two crack borders and the resulting new crack configuration determined. Crack propagation is thus established which does not come to a standstill but leads to continuous cracks (Fig. 2). The cracks produced in the outer part of the vessel top are therefore not pressurized.

The relocation of stresses induced by the cracks and propagation of the cracks can, relative to elastic computation, be taken from the representations of the principle stresses (Fig. 3).

In spite of prestressing which is designed in accordance with the above mentioned assumptions to avoid pressurized cracks, there is no stabilization of the cracks if only the concrete tensile strength is assumed.

3.2 Reinforced Concrete

Since there is a strong reinforcement especially in the region near the core of a PCRV, the computations are too unfavourable if this is neglected. The influence of the reinforcement on propagation of the pressurized cracks has therefore been studied in further computations. A high reinforcement fraction of 4 % was assumed. In spite of the higher tensile strength, tensile cracking occurs initially at the same locations as in the case of non-reinforced concrete. If internal pressure is applied to these cracks then they remain stable.

The internal pressure was raised in increments of 0.5 bar in order to determine the internal pressure at which crack propagation must be expected. The cracks only continue to grow without stabilizing at an internal pressure of 61 bar.

Computations with 2 % reinforcement no longer showed any crack stabilization at an internal pressure of 50 bar. This means that only a high degree of reinforcement prevents the propagation of pressurized cracks.

The conditions resulting from precise modelling of the reinforcement present in the corner areas were studied in a further computation. For this purpose, reinforcement in these areas was simulated in detail in the model. Continuous cracks also resulted for 50 bar internal pressure.

Within the study RS 447 some investigations were done by Zerna, Schnellenbach and Partners. They varied the vertical prestressing and the reinforcement in the region of the expected crack formation at the inside corner.

The results of this parametric study are summarized in Fig. 4. The individual curves describe the crack length at which crack arrest occurs as a function of the vertical prestressing at a constant degree of reinforcement in each case.

The course of the curves indicates that this is a very sensitive system, i.e. even a slight reduction in reinforcement can already lead to a pronounced increase in crack depth. For considering hypothetical accident sequences, the studies conducted here provide evidence that the currently usual design of prestressed concrete vessels is in the boundary region between propagating and non-propagating pressurized cracks.

4. Conclusion

Pressurized cracks presuming a leak in the liner cover a hypothetical region, i.e. involving accidents with extremely low probabilities of occurrence. Proof of their stabilization required in the dimensioning guidelines /1/ is not achieved if only the strength of the non-reinforced concrete is considered, in spite of present prestressing designed in accordance with the pressure distribution usually assessed. Additional measures are therefore required, such as including a sufficiently high proportion of reinforcement and/or increased prestressing, which are slightly possible.

References

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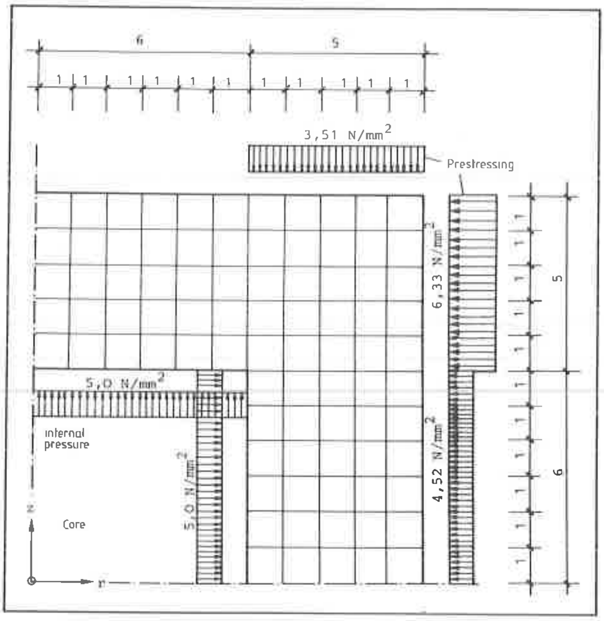

Fig. 1: Rotationally symmetrical finite element model with internal pressure and prestressing

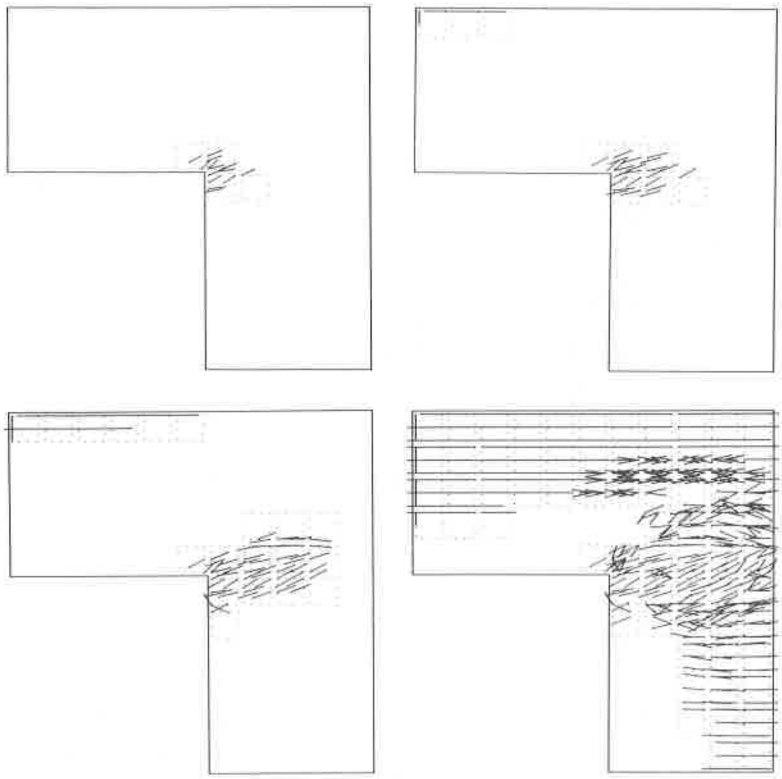

Fig. 2: Crack propagation at constant pressure and prestressing for non-reinforced concrete

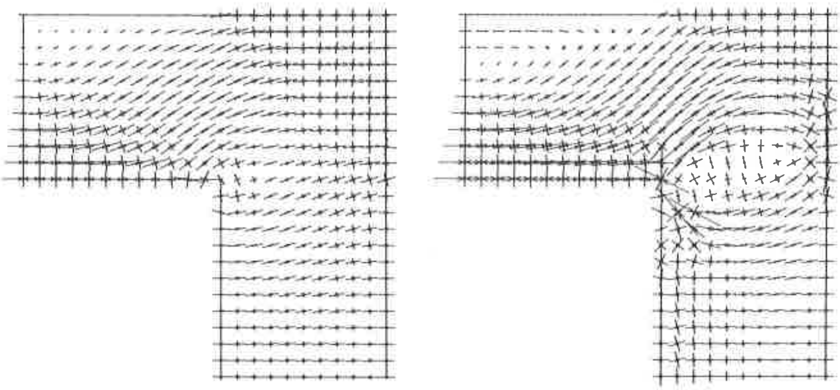

Fig. 3: Principal stresses for the elastic (a) and the fully cracked state (b)

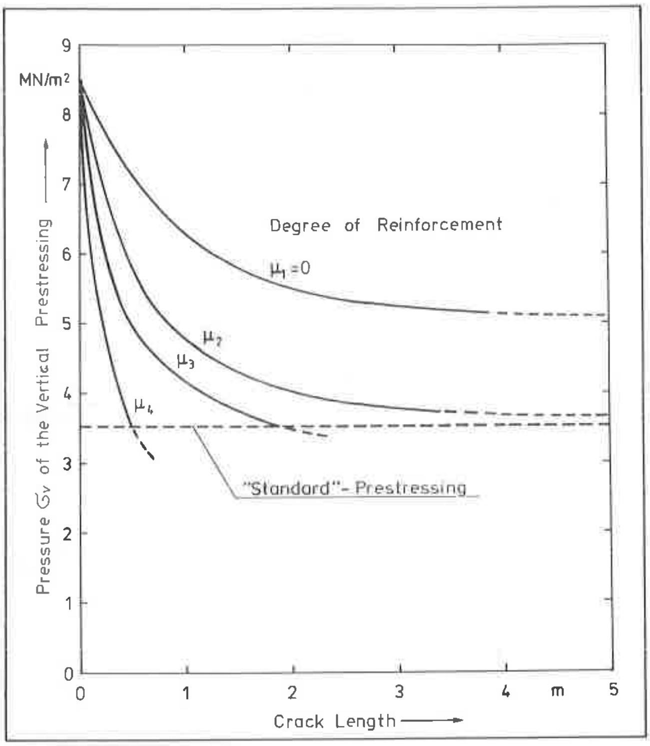

Fig. 4: Crack length as a function of the degree of reinforcement and the vertical prestressing