PARAMETRIC STUDY ON LIGAMENT STRESSES IN MULTI-CAVITY PRESTRESSED CONCRETE REACTOR VESSELS (PCRV's)

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Summary

The work presented in this paper has been performed with regard to the PCRV for High Temperature Reactors (HTR). This reactor type is presently developed in the F.R.G. for electric power and process heat generating plants.
In the design of the PCRV the ligament stresses are an important layout criterion. An assessment of such stresses is useful to the correct dimensioning of the ligament widths without excessive analytical efforts.
A horizontal section at midheight level of the PCRV is modelled for numerical analyses. It is assumed that the behaviour of a 30^{o}-sector under prestressing and internal pressure loads is representative for the characteristics of the entire plane section.
For stress analysis purposes, the geometrical dimensions, as the diameter and location of pods, diameters of core and PCRV, are varied within reasonable limits.
The evaluation is made for significant ligament points, but for ligament zones as well, by indicating principle stresses.
The diagrams so received will permit a simple appraisal of ligament stresses to be expected within the cylindrical section originating from the load cases of internal pressure and prestressing, if the geometrical relations of a vessel are known as input data.
All calculations have been done assuming linear elastic material, neglecting creep, shrink and thermal effects. Initial prestress is governing the compressive ligament stresses. This parametric study facilities an appraisal of ligament stresses under late life conditions, too (assuming late life prestress values).

1. Introduction

The stress situations prevailing in prestressed concrete vessels are significantly influenced by the geometrical location of the cavities. Arranging of the same should therefore be effected so as to avoid unadmissible stress concentrations and achieve, as ever possible, a well-balanced spreading of stresses.

When designing vessels and appraising the geometrical proportions of the same, it proved relatively difficult to comprehend the ligament stresses occuring in between pods as well as the latter and the outside or inside edges, respectively of PCRV. Elementary calculation will generally furnish but results too much inaccurate, expensive finite elements analyses however, should be made but on account of geometrical proportions, as securely corresponding to reality as possible, in order to keep voluable iterative rectifications of the cavity locations and the PCRV's dimensions, on account of analyses results arrived at, limited to minimum.

For being enabled to appraise the ligament stresses to be expected, with a prestressing potential and an internal pressure taken for granted, as well as the ligament dimension assumed a series of finite elements analyses were performed on a circular slab model with the geometrical proportions varied within reasonable limits. For selected ligament points, the stresses were plotted in the form of curves.

When analyzing, importance was not so much attached to a calculation of utmost numerical exactness as to data proper both in magnitude and spreading. Stresses orginating from variations in temperature as well from shrinkage and creep have not been considered. The magnitude of the same however, is small, as a rule, taking e.g. the admissible compressive stress of the concrete as a value to be referred to, and can generally be confined by elementary appraisal. The influence of the three-dimensional action of stresses can, approximately be comprehended by ways of Poisson's ratio and usual stress transformation calculus.

For calculation purposes the steel plate lining of the cavaties has been neglected since the same, in view of large pods analysed in this case, do not have much influence to the load bearing characteristics, and with that to the ligament stresses, and its thickness varies, from design to design. Should it be desirable to consider the lining, too, its share in the membrane stresses can be arrived at from the gained pod brim deformation by a calculus with respect to the membrane force as unknown quantity. The bending share of such stresses is neglected, as a rule, even when establishing the definitive statical analyses for ligaments.

Past investigations proved that ligament stresses, and this particularly within the cylindrically shaped section of the PCRV, might become critical. This is why the study was made for the said section. Attention should be given also to the fact that - due to steep stress raises in the regions close to the three-dimensional bearing top and bottom slabs- the transferability of results gained with a two-dimensional model will have to be examined very thoroughly and again for every application.

The calculations were made for the stage of plane strain analyses.
For vessels sections where the plane stress analyses coming true, the results can be converted to said stage, according to the known formulare of mechanics.

2. Calculus execution

2.1 Geometrical marginal conditions

The geometrical marginal conditions that roughly apply to the conception of a HTR with ball cire and of standard capacity will be cited hereunder:

Diametre of the core cavity: abt. 13 through abt. 16 m
outer dia. of PCRV: abt. 38 through abt. 50 m
max. dia. of pods: upto abt. 6 m.

For the sake of limiting calculation large pods of 3 through 6 m dia. are considered only. For this very reason, the minimum ligament thickness between pods and PCRV brims is set equal to the pod radius. The distance in a circumferential direction is being assumed at 60°, as a reasonable figure with the pods considered. So also get information in the case of smaller distances, some calculations were made for a 40° pitch, too, that are of interest, above all, what concerns the radial stresses prevailing between cavities. Taking use of symmetrical properties, it is sufficient to consider a PCRV sector of 30° or 20°, respectively.

The geometrical conditions as well as the relations assumed can be seen from fig. 1. Fig. 2 will show the finite elements network being of interest what concerns the pitch and closeness of the elements.

2.2 Materials moduli

Young's modulus assumed:

$$E = 40\,000 \text{ MN/m}^2$$
$$v = 0{,}2$$

2.3 Dimensional Gauging

Using the nomenclature of fig. 1, the following dimensionless parameters are introduced:

$$\varkappa_1 = \frac{r_a}{r_i} \qquad (1)$$

$$\varkappa_2 = \frac{r_p}{r_a - r_i} \qquad (1)$$

$$\varkappa_3 = \frac{\varsigma - r_i}{r_a - r_i} \qquad 1$$

with the geometrical marginal conditions taken from paragraph 2.1 above, the variation range of the parameters is arrived at as follows:

$$\frac{38}{13} = 2{,}92 \leq \varkappa_1 \leq \frac{50}{16} = 3{,}13$$

assumed for the calculus: $\varkappa_1 = 3{,}0$

$$\frac{4}{50-16} = 0{,}118 \leq \frac{6}{38-13} = 0{,}24$$

assumed for the calculus: $\varkappa_2 = 0{,}155$

and $\varkappa_2 = 0{,}187$

Primary attention is given to $\varkappa_3$. Said parameter is incorporating the location of the pods within the PCRV wall, its variation effecting maximum stress alterations.
In the present investigation, the band width of $\varkappa_3$ was presupposed by:

$$0{,}3 \leq \varkappa_3 \leq 0{,}7$$

The majority of applications may be assumed to fit in between said limits.
The marginal values of $\varkappa_3$, i.e. 0 and 1, are of hypothetical significance only, since the same being applied, both the ligament thickness and the pod dimensions are becoming equal to 0, and the results arrived at will correspond to those of an undisturbed annular slab.

3. Handling curves

How to handle the curves will be shortly explained by the following example:

PCRV of:	40 m dia.	$r_a = 40$ m
	14 m core dia.	$r_i = 14$ m
	5 m pod-dia.	$r_p = 5$ m

Pod distance:	$\alpha = 60^{\circ}$
Ligament thickness, assumed:	6,0
Internal pressure:	$Pi_1 = Pi_2 = 9$ N/mm^2
Prestressing:	$V_o = 6{,}5$ N/mm^2

Hence:

$$\varkappa_1 = \frac{40}{14} = 2,86$$

$$\varkappa_2 = \frac{5}{40 - 14} = 0,19$$

$$c = 14 + 6 + 5 = 25$$

$$\varkappa_3 = \frac{25 - 14}{40 - 14} = 0,42$$

From the curves can be taken:

	Stress component	P_{i1} 9 N/mm^2	P_{i2} 9 N/mm^2	V 6.5 N/mm^2	Total amount of stress
FIG. 3	σ_{φ_1}	6.3	10.3	-18.1	-1.5
FIG. 4	σ_{φ_2}	10.0	11.2	-27.6	-6.4
FIG. 5	σ_{φ_3}	10.6	10.0	-21.8	-1.2
FIG. 6	σ_{φ_4}	3.1	0.5	-9.6	-6.0
FIG. 7	$\sigma_{\varphi m1}$	6.2	12.4	-19.6	-1.0
FIG. 8	$\sigma_{\varphi m2}$	5.1	4.1	-13.0	-3.8
FIG. 9	σ_{r5}	10.2	-7.2	-8.6	-5.6
FIG. 10	σ_{r6}	2.4	-1.1	-7.5	-6.2

ALL STRESSES [N/mm^2]

4. Comments on the results received

Due to the nature of the calculus and the graduation of the elements, respectively, peak stresses or sections showing steep stress rises occuring close to or at singular points (as e.g. edges of holes) are represented in a form only averaging the element dimensions. Within the targets given with this study, said form of representation is not admissible, should be considered, however. It has further to be remarked that peak stresses at singular points are but pure calculatory values that will practically not happen, due to the viscoelastical bearing characteristics of concrete or the occurence of statics II, respectively. When dimensioning, such consideration is generally taken into account by recommending reduction procedures, as e.g. at hole edges, that can not indeed be applied to the corresponding curve ordinates without further concern, due to the above mentioned reasons.
Evaluations performed for various cases show that the distance between pod and core, considering the load of primary prestressing, can easily

become critical, due to the compressive stresses of the concrete exceeding the admissible level. This also applies to the distance between the pod and the outer brim of the PCRV, where smaller ligament dimensions appear possible than for the inside. Investigations with the assumption of $\varkappa_3 > 0{,}7$ are demonstrating the growing influence of bending stresses. Late life load cases with a reduced level of prestressing are at less significance for the compressive stresses of the concrete, however, corresponding conditions prevailing, can entail tensile stresses necessiting steel reinforcement.

For cavities at distance from PCRV's outside of a pod diameter magnitude, the mean tangential compressive stresses in these ligaments caused by prestressing amount to the double value of the radial prestress, local peak stresses amounting up to three times the radial prestress. With ligaments narrowed further, conditions quickly turn to the unfavourable, and local tensile stresses may occur at pod brims, due to the increasing flexural stress components.

With a ligament width between the pod and core cavities of roughly the pod diameter, the mean compressive hoop stress due to prestress exceeds three times the prestress value, the peak stress amounts up to five times the radial prestress value.

The distribution of radial stress components due to prestress is characterized by a drop to zero at the pod brim. When superimposing the loads due to prestress and to internal pressure, the distribution of the stresses will be smoothed, due to the fact that the minima are roughly coinciding with the maxima, however, extreme values with equal sign do not.

Due to rectified space, deformation diagrams as e.g. required for considering pipe liners could not be comprised here; the same, however, can be received from the author.

5. References

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Fig 1

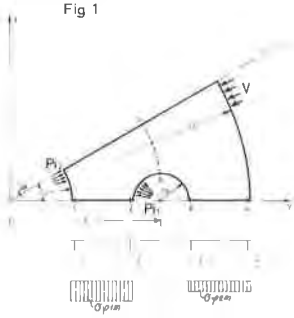

Fig 2

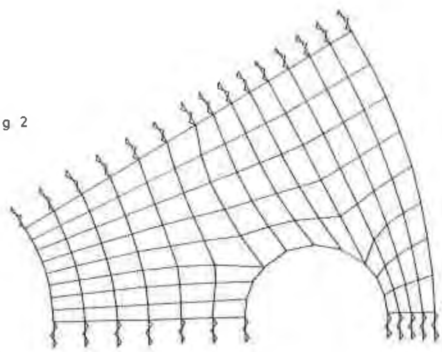

Fig 3

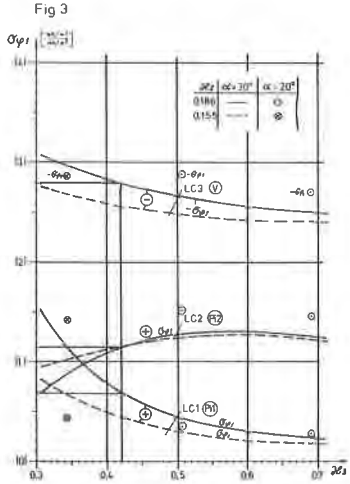

Fig 4

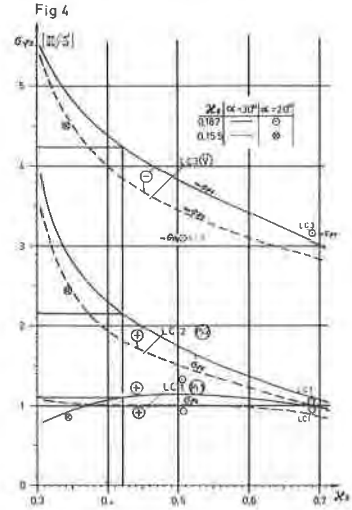

Fig 5

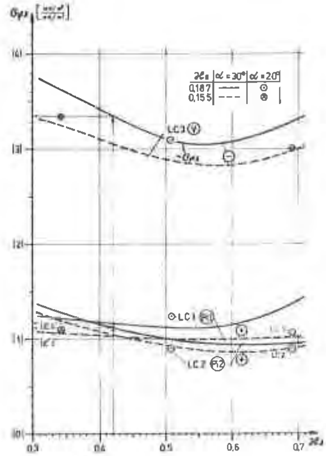

Fig 6

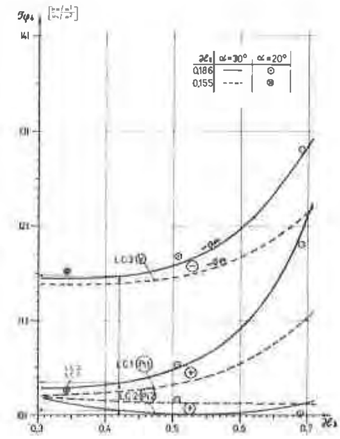

Fig 7

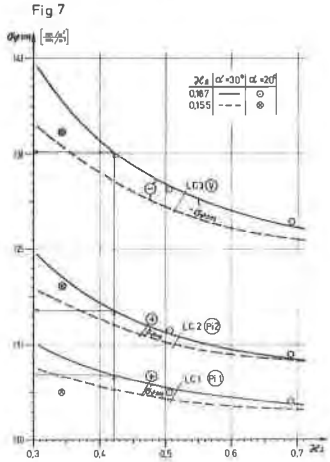

Fig 8

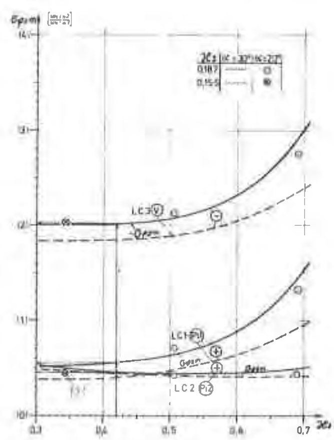

Fig 9

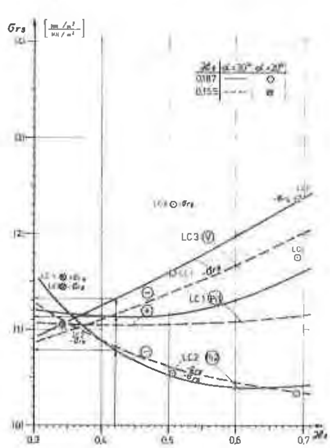

Fig 10