Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 19 (1974)

Artikel: Construction and calculation of three-dimensional structures with particular reference to prestressed concrete reactor pressure vessels

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DOI: https://doi.org/10.5169/seals-17505

IABSE
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SEMINAR on:
«CONCRETE STRUCTURES SUBJECTED TO TRIAXIAL STRESSES»
17th-19th MAY, 1974 - ISMES - BERGAMO (ITALY)

Construction and Calculation of Three-Dimensional Structures with particular reference to Prestressed Concrete Reactor Pressure Vessels

Konstruktion und Berechnung Dreidimensionaler Bauwerke am Beispiel eines Spannbeton- Reaktordruckbehaelters

Construction et calcul de structures tridimensionnelles avec référence en particulier aux caissons en béton précontraint pour réacteurs nucléaires

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Preface

Load-bearing members of structures can be idealized in most cases by one dimensional or two dimensional systems (beams, arches, plates, shells). Hence, it was not necessary so far, to investigate the three dimensional state of stress and strain. Just in recent time, extremely loaded structures subjected to triaxial stresses get more and more important. Particularly, thick walled vessels are to be mentioned here, e.g. reactor pressure vessels for nuclear power plants. In various respects these vessels typify complicated three dimensional stress and strain problems, since considerably high static and possibly dynamic loads and elevated temperatures occur. If prestressed concrete is used, non-linear and time-dependent material behaviour further complicates the design work.

Thus, problems concerning prestressed concrete pressure vessels for nuclear power plants shall be discussed in the following which are the main object of investigations in the field of concrete structures subjected to triaxial stresses in the Federal Republic of Germany. Problems of construction, calculation of the states of stress and strain under service load conditions, and calculation of ultimate load behaviour will be considered.

1. Constructional Problems

1.1 General remarks

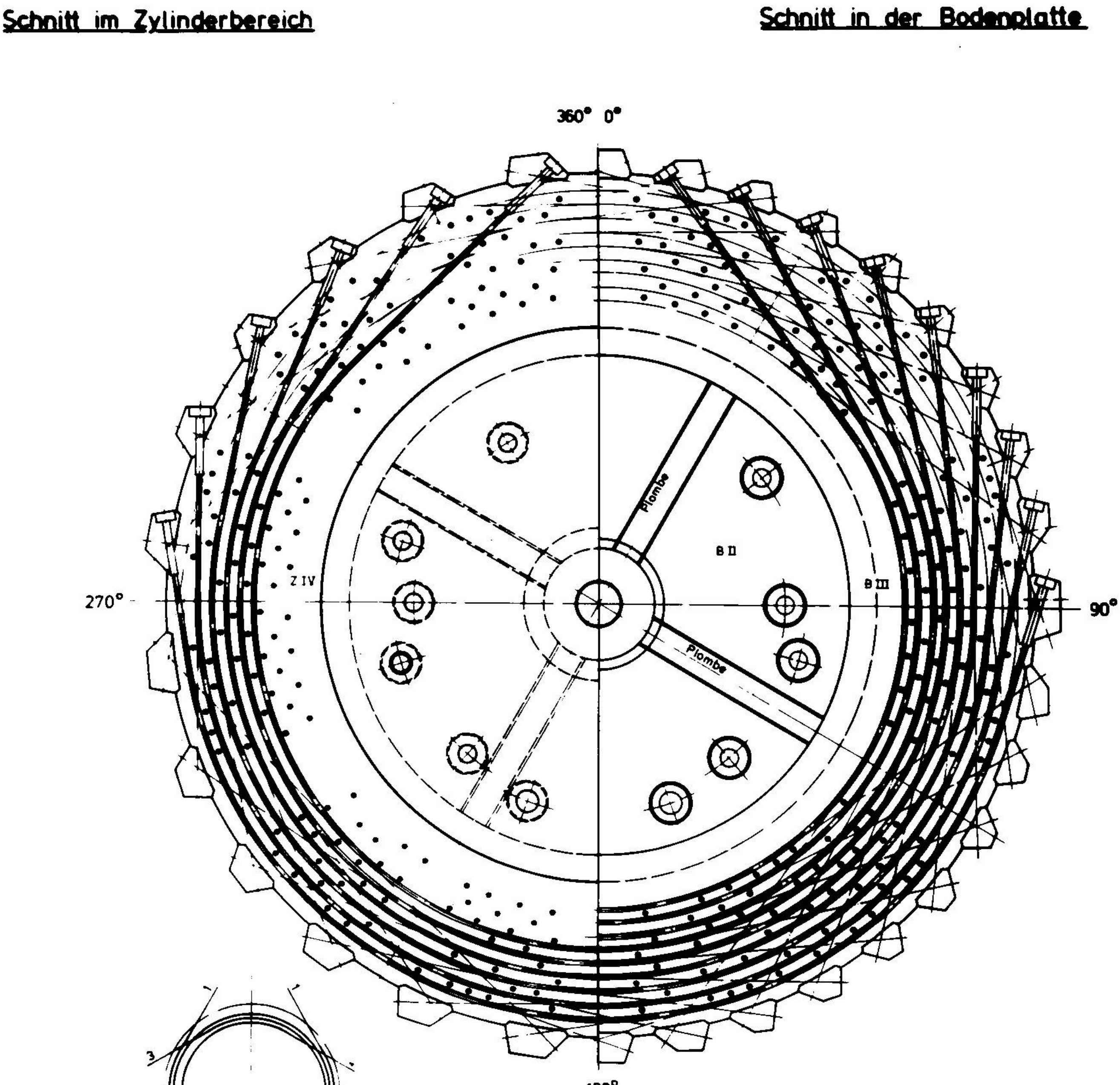
The first task in projecting a structure is the design of the construction, because it influences among other things the choice of the method of stress calculating and the choice of the erecting procedure. Thus, reflections on prestressed concrete pressure vessels shall be opened by discussing several important constructional problems.

Usually prestressed concrete reactor vessels are characterized by thick cylindrical walls and deep top and bottom closures. At numerous points walls and end slabs are penetrated by openings of various diameters. In order to withstand the internal pressure, above all the vessel must be tight against coolant. This is obtained by coating its inner surface with a steel liner.

Most important constructional problems are the technique of prestressing, the design of penetrations and inner haunches between end slabs and cylindrical wall, the performance of liner anchoring, as well as problems concerning construction joints and concrete casting process.

1.2 Prestressing

Prestressing is an essential element for a prestressed concrete pressure vessel. The prestressing system has to be appropriate and economical. In early reactor vessels, horizontal prestressing was performed by installing cables inside the wall and anchoring in buttresses, like conventional container design (Fig. 1.1). The difficulties of this procedure are obvious. Arranging of so many horizontal and vertical prestressing cables yields significant overlapping in the anchorage zones. During prestressing, reductions of prestressing force arise due to friction. These facts enlarge prestressing steel consumption. Furthermore the large number of anchoring elements needed is expensive. Hence, this method is uneconomic, additionally to its other disadvantages. For that reason, much effort was done to develop a circumferential prestressing suitable for structures like these. For that purpose, special wire-winding procedures were created, by which a number of wires can be tensioned simultaneously. In Fig. 1.2 a prestressing system using a wire-winding machine is shown. Here prestressing wires are wound into annular channels. In another system, well arranged wires are wound polygonally across guide borders used as intermediate anchoring simultaneonsly (Fig. 1.3). For vessels with smaller diameter, wire-winding technique is hardly applicable. For those cases, a system has been developed, where prestressing tendons are assembled on the vessel in a pretensioned state. Fig. 1.4 shows the principle of this technique. The concrete vessel is cast and hardened previously. Annular closed prestressing tendons are tensioned against a straining ring above or below the vessel an then moved into their final position in this tensioned state. There, prestressing forces are transmitted to



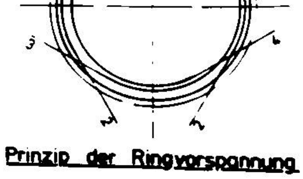
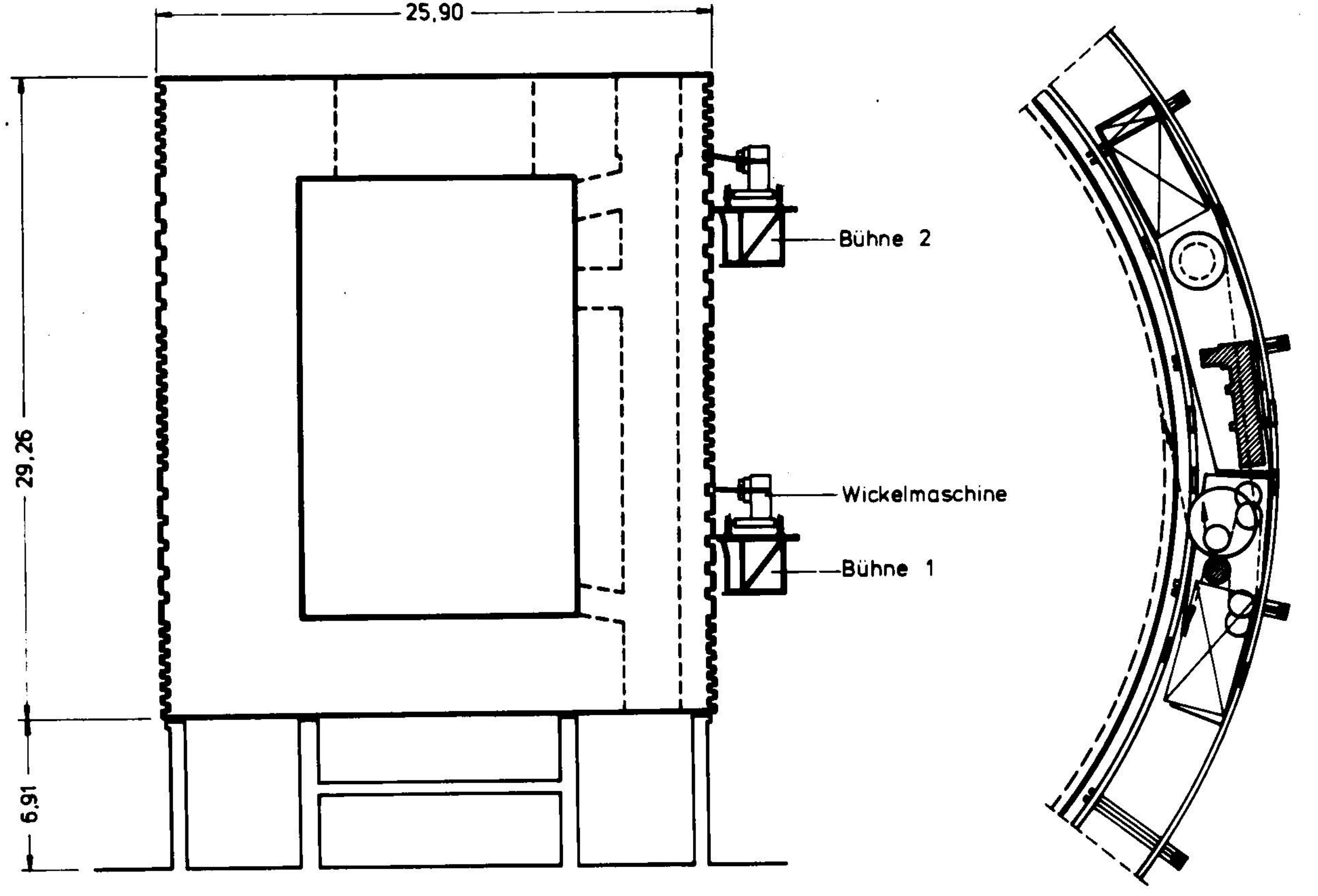


Bild 1.1 SBB-Lisenenvorspannung
PCRV Buttress prestressing system



Übersicht

Draufsicht Wickelmaschine

Bild 1.2

SBB-Wickelvorspannung
PCRV Wire-winding prestressing system

the vessel by unloading the straining ring. This method of prestressing can also be carried out with immediate bond. In this case, each straining ring is loosened after the corresponding lifts have hardened (Fig. 1.5).

1.3 Structural problems due to local stresses

In the regions of penetrations, buttresses - if existing -, and inner haunches, local zones with stress concentrations arise. In these regions, besides high compressive stresses also significant tensile stresses can occur which practically cannot be compensated by prestressing. Regions like these with local stresses yield some special structural problems, caused particularly by an accumulation of bonded reinforcement. Fig. 1.6 demonstrates the reinforcing arrangement for buttresses. In Fig. 1.7 bonded reinforcement around the haunch between bottom closure and cylindrical wall can be seen. Most exceptional difficulties due to stress concentrations are to be solved in the standpipe region of the top slab and in zones around major penetrations. Substantial advantages with special regard to constructional problems could be gained by using steel fiber reinforced concrete. This is a new type of material which is today in the stage of development or testing, respectively. Its main characteristic is admixing short steel fibers (about 25 to 3o mm long and o,25 to o.4 mm in diameter) to a suitable concrete mix. This yields a quasi-homogeneous material with uniform strength qualities in all three dimensions. Particularly tensile strength of the concrete is increased. Fig. 1.8 outlines the increase of bending tensile strength in dependence of the quantity of steel fibers added. It is obvious that in regions where tensile stresses of a certain amount occur usual reinforcement can be avoided by using this special material. Fig. 1.9 shows the construction of the haunch between bottom slab and wall, if steel fiber reinforced concrete is used. In Fig. 1.1o a comparison between designs with conventional reinforced concrete and steel fiber reinforced concrete is pointed out for the zone around the pebble outlet penetration of a high temperature reactor.

1.4 Liner

The liner - i.e. the steel membrane at the inside surface of the vessel - acts as a gas-tight skin, that has to prevent leakage of the contained coolant through the concrete walls of the vessel. Its function as load carrying part is negligible in most regions of the vessel. The thickness of the membrane should be chosen as thin as possible in order to get minimal intermediate reactions between liner and concrete. On the other hand, requirements like necessity of producing a good quality weld and use of the liner as internal formwork of the concrete

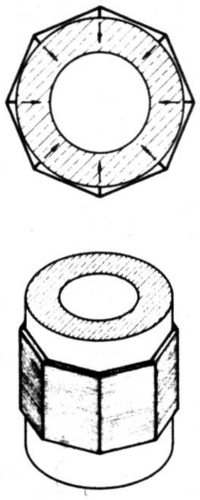


Bild 1.3 SBB - Prisma - Vorspannung
PCRV Prisma prestressing system

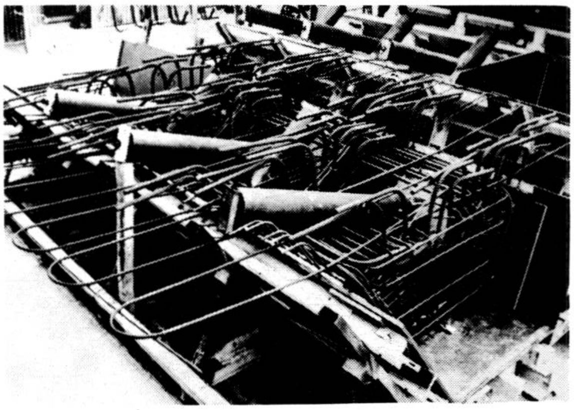


Bild 1.6 Bewehrung einer Fertigteillisene des THTR - Spannbetondruckbehälters
Precast buttress reinforcement of the THTR vessel

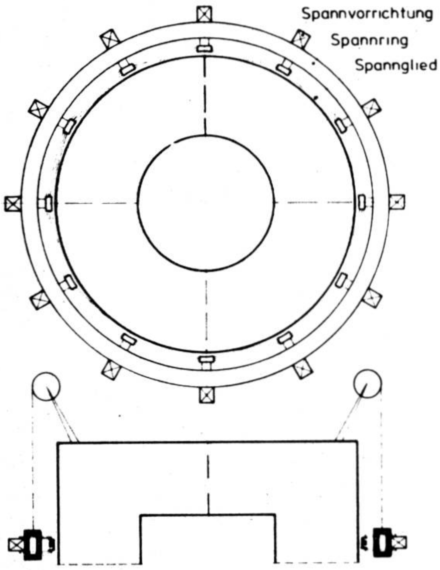


Bild 1.4
SBB - Ringvorspannung (mit Spannringen)
PCRV circumferential prestressing (with straining rings)

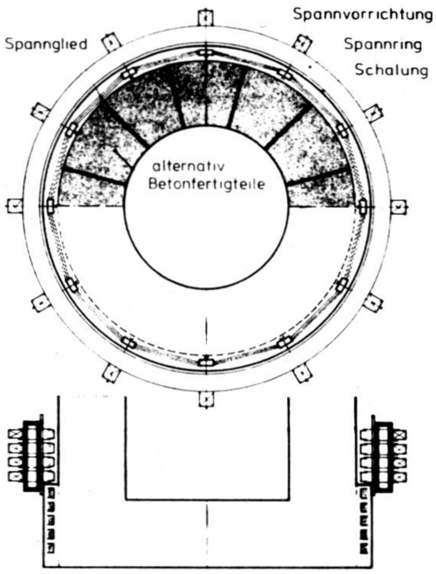


Bild 1.5 SBB - Ringvorspannung (mit Spannringen und sofortigem Verbund)
PCRV circumferential prestressing (with straining rings and immediate bond)

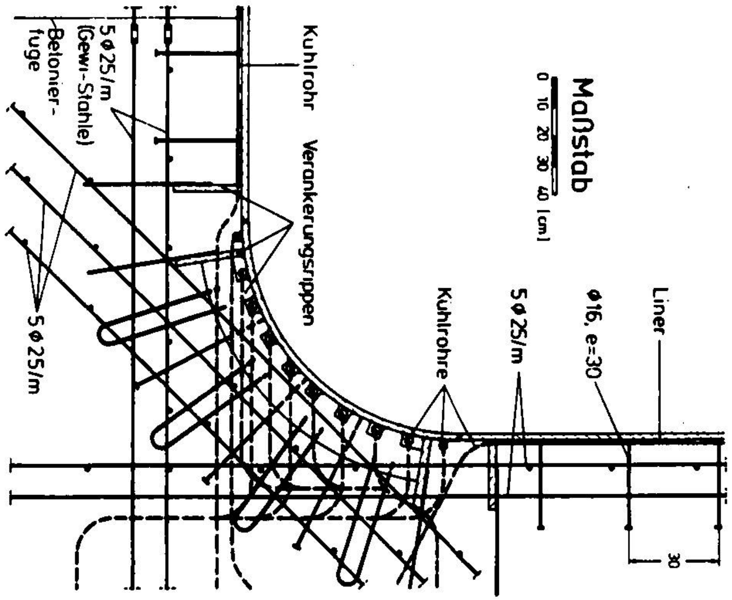


Bild 1.7 THTR-Spannbetonbehälter, untere Voute
THTR vessel, lower haunch

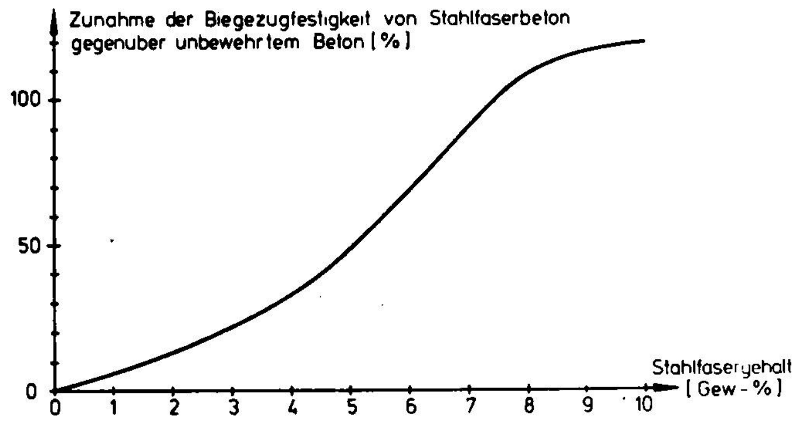


Bild 1.8 Zunahme der Biegezugfestigkeit von Stahlfaserbeton in Abhängigkeit vom Fasergehalt
Bending tensile strength increase of steel fiber reinforced concrete versus content of fibers

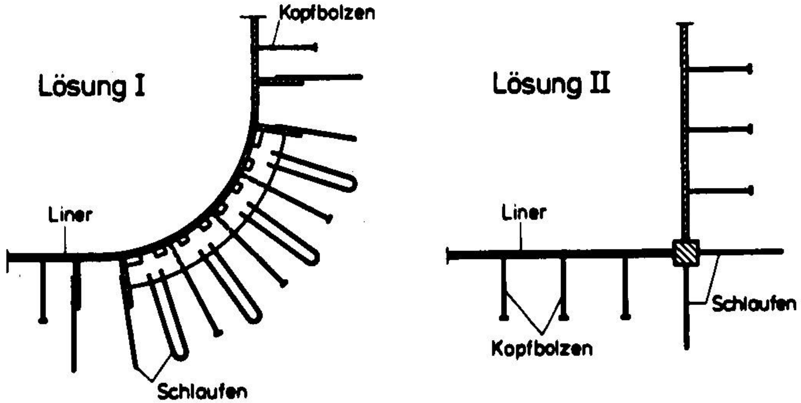


Bild 1.11 Linerübergang vom Boden zum Zylinder
Transition region between bottom and wall liner

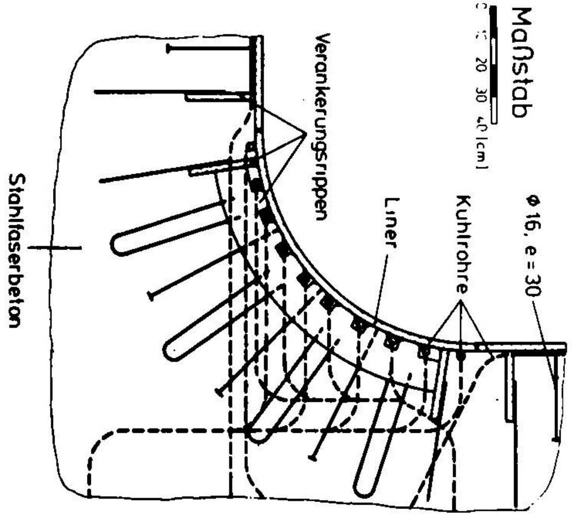


Bild 1.9 Voute eines Spannbetonbehälters bei Verwendung von Stahlfaserbeton
Haunch of a PCRV using steel fiber reinforced concrete

set certain limits for its minimum thickness. Additionally the liner has to be protected against buckling due to high compressive loads caused by vessel deformations or temperature restraints by a well balanced proportion of thickness to concrete anchoring. Thicknesses between 12 and 3o mm were found to be most suitable, where the thicker steel part rather concerns the flat top and bottom liners. For anchoring the liner in the concrete, butt welded stuts with diameters from 12 to 2o mm and distances from c. 18 to 3o cm are commonly used in the meantime. Generally, small relative displacements between liner and concrete are admissible. So, anchoring by bolts only - i.e. a junction by spring elements in principle - is sufficient. However, in the haunches between cylindrical wall and end slabs as well as in zones around penetrations, possibly an almost rigid joint can be necessary. Due to strong changing of stress or strain gradients high local forces have to be transfered between liner and concrete at these points. In Fig. 1.11 two construction alternatives are pointed out for the lower haunch,e.g. At first sight, the rounded version (solution I) seems to have certain advantages concerning the stress state within the vessel. But the liner has to be anchored in the concrete so as to fulfill its function even under these strongly changing load states in the haunch region. Hence, slipping of the liner from the cylinder or slab plane into the rounded region or vice versa has to be provided by strong ribs welded on the liner. This generally requires additional reinforcement which on the other hand cannot be easily arranged near the liner due to even these ribs. Moreover, feeding pipes for the liner cooling system must be installed in this zone, (Fig. 1.7). All this needs high accuracy and carefulness in constructing and reinforcing this detail of the structure. These problems get substantially more simple, if a construction like solution II in Fig. 1.11 is chosen. Reinforcement can be arranged much better, because there are no ribs.

1.5 Concrete Quality, concrete casting, construction joints

Mass concrete conditions and high demands on quality of prestressed concrete reactor vessels require carefulness in specifying the optimum concrete mix and fixing the lifts and bays for casting. Besides high compressive and tensile strength under ambient and elevated temperatures, it is of great importance that thermal expansion, shrinkage, creep, and elastic deformations are as low as possible. Creep deformations significantly influence the undesirable loss of force in the prestressing tendons. Furthermore, a high concrete density is required to give a good absorption of neutron and gamma rays. High thermal conductivity influences above all the dimensioning of the cooling system which

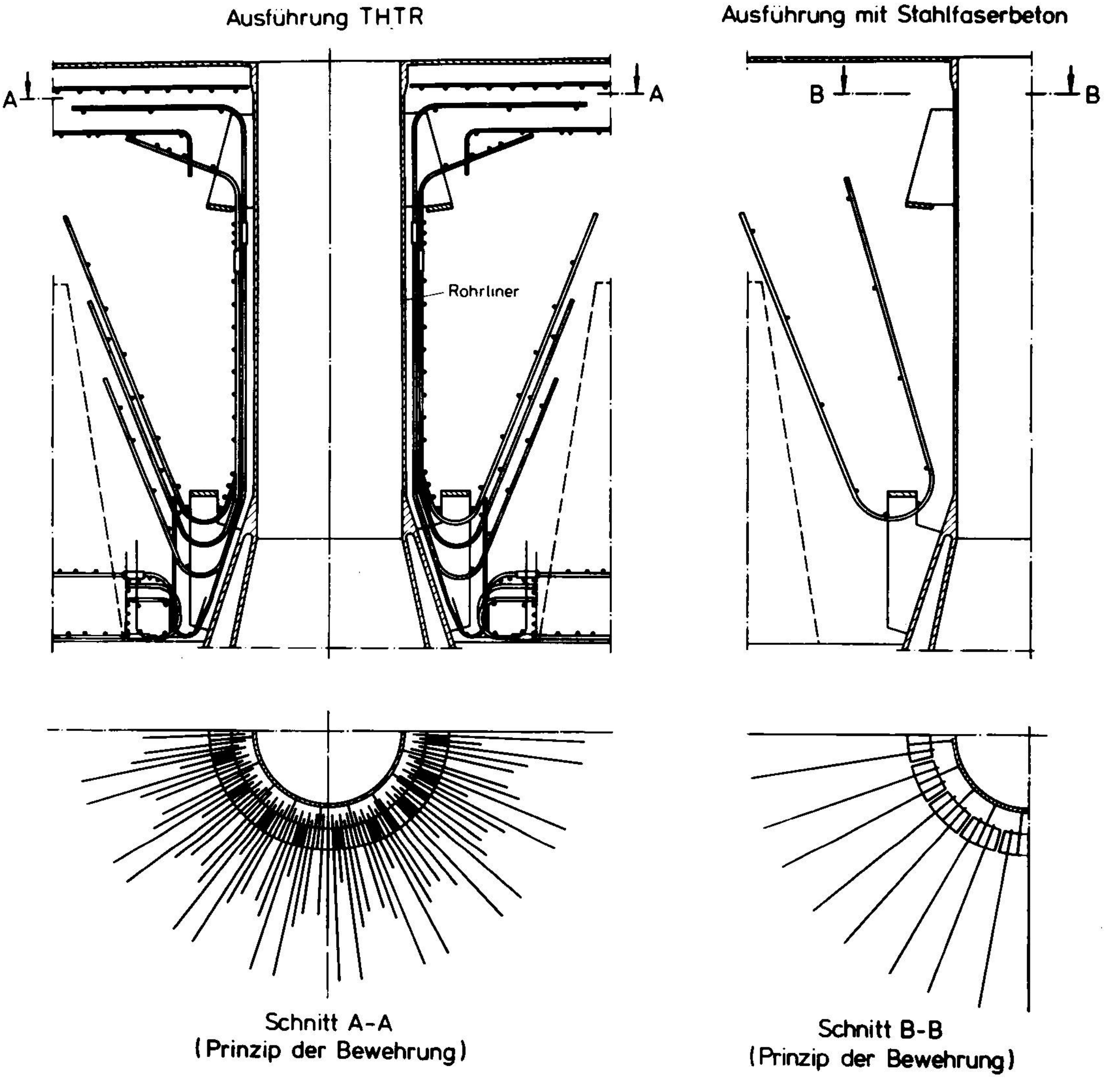


Bild 1.10 THTR-Spannbetonbehälter, Bewehrung um das Kugelabzugsrohr
THTR vessel, reinforcement near pebble outlet penetration

has to hold a provided temperature in the concrete. A reasonable choice of subdivisions in casting lifts and bays is important for quickly deducing hydratization heat. It has been found to be suitable to make casting lifts not deeper than 2 meters. Lifts are almost subdivided into several bays which are of some advantage for continuous progress of work, too. However, much more formwork is necessary then, and the well-known problems with vertical construction joints arise.

Designing a prestressed concrete pressure vessel yields altogether even more problems then mentioned here, for example the difficulties in concrete casting below the liner bottom in order to get a continuous supporting of the liner by concrete. But discussing all these special questions in detail would be beyond the scope of this report.

2. Experiences in the Application of Dynamic Relaxation

2.1 Introduction

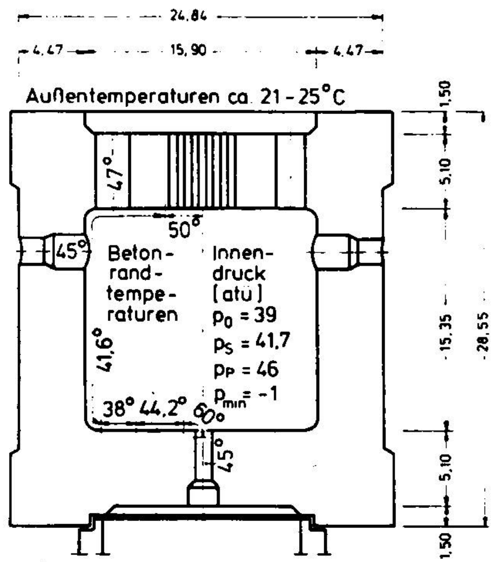
Prestressed concrete pressure vessels are three-dimensional structures, whose state of stress and strain is to be calculated three-dimensionally. These calculations have to take into account the complicated geometry of the vessel with large openings in the walls, the unhomogeneous and partly nonlinear behaviour of the material as well as the liner and the penetration liners with their influence on the vessel.

Fig. 2.1 shows the vessel of the THTR-nuclear power station as an example for such a structure. The inner surface of the vessel and the penetrations are covered with the mentioned liners. The high internal pressure of the vessel and its high temperature load require high prestressing. These are the essential loads compared with other loads like dead weight, installations etc.

The three-dimensional calculations of prestressed concrete pressure vessels are mainly done today by two methods. These are the finite element and the dynamic relaxation method. Both made important progress in the last years. For calculating three-dimensional or plane structures they seem to be of the same efficiency. For the THTR pressure vessel the dynamic relaxation mainly was preferred. This method was developped to the state of today in our institute. Because of these reasons it will be reported about the dynamic relaxation here.

2.2 Description of the dynamic relaxation

For the calculation of prestressed concrete pressure vessels the restriction on infinitesimal deformations is sufficient. All nonlinear problems concerning the behaviour of the material can be reduced to linear step-by-step calculations if using numerical methods. Thereby the linear elasticity can be used for the behaviour of the material, too.



p_0 = Betriebsdruck p_P = Prüfdruck
p_S = Störfalldruck p_{min} = evakuierter Behälter

Temperatur- und Innendruckbelastung

Bild 2.1 THTR - Spannbetonbehälter, Geometrie und Belastung aus Reaktorbetrieb
THTR vessel, geometry and loads due to reactor service

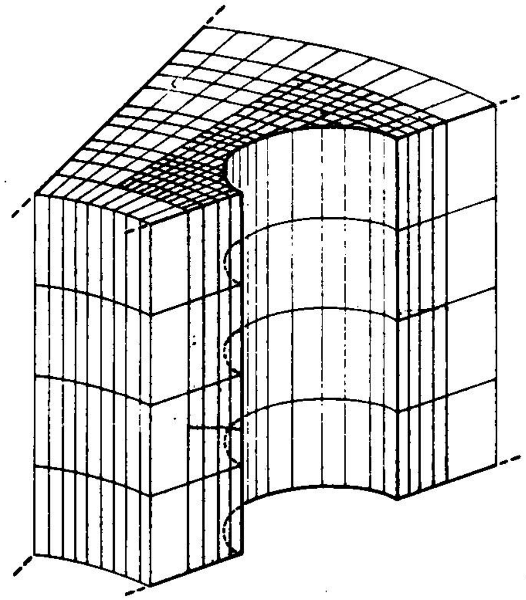


Bild 2.2 Dynamische Relaxation, Beispiel einer Rasterteilung
Dynamic relaxation, an example for a computing mesh

The basis of the dynamic relaxation in the case of the three-dimensional continuum is the system of differential equations, comprising the 3 dynamic equations of equilibrium and the 6 constitutive equations. At first it seems not to be suitable to introduce the time as fourth dimension into the calculation of static problems. But this leads to differential equations of hyperbolic form which are easy to solve with difference methods. For dynamic relaxation a special form of difference method is to be used, which solves the difference equations dependent on time. To get the static solution it is necessary to add damping terms, which are proportional to the velocity. By well chosen damping coefficients, only a short time is taken to lead the dynamic problem to the wanted static solution.
The solution of the initial value and boundary value problem begins from an arbitrary initial stress-strain-state of the structure, loaded by forces or enforced displacements at the boundaries or by the volume loads. Often an approximate stress-strain-state is known, from which the calculation can be started in order to get the solution in a shorter time. The boundary conditions are considered at every step of the iterative process of the numerical calculation. The stability and convergence of the numerical solution can be guaranteed by a simple criterion. Because it is not necessary to know the exact course of the vibration process, some simplifications are possible for the calculation. One of them is the possibility to store only the values of the last step of the iterative calculation. Only these values are necessary to get the values of the next iteration step. Because of this problems with thirty thousand or more unknows can be calculated only in the core storage of computers of middle size which are today available in universities or important companies everywhere. The needed storage for the calculation is smaller than for other numerical methods like finite elements etc. The basis of the dynamic relaxation is described in detail in literature for example /2.1/ and /2.1o/, so that the description of this method will not be continued here.

Similar to the calculation of stresses and deformations the state of temperature is computed by difference equations. The basis is the known differential equation of Fourier. The calculation here realistically describes the time dependant building up of the temperatures in the continuum. By that, stationary and unstationary states of temperature can be computed, vis. /2.5/. With the knowledge of the state of temperature and its time dependent variations in the vessel walls the calculations of stresses and deformations caused by thermal loads can be performed.

2.3 Calculation with dynamic relaxation

For numerical calculations with dynamic relaxation it is necessary, to devide the continuum or the pressure vessel into body elements corresponding to the finite differences. The width of the grid can be different so that in regions

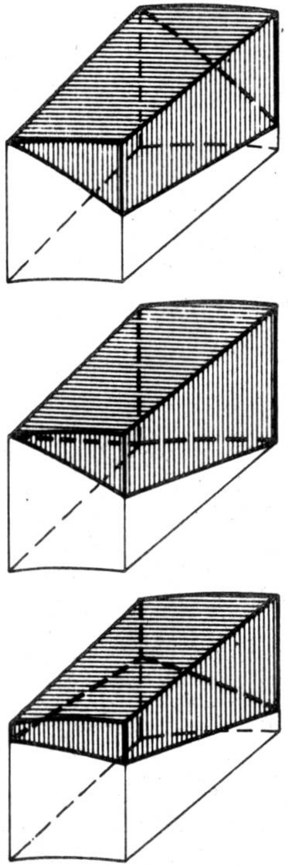


Bild 2.3 Dynamische Relaxation, Beispiele räumlicher Elementformen
Dynamic relaxation, examples for three-dimensional elements

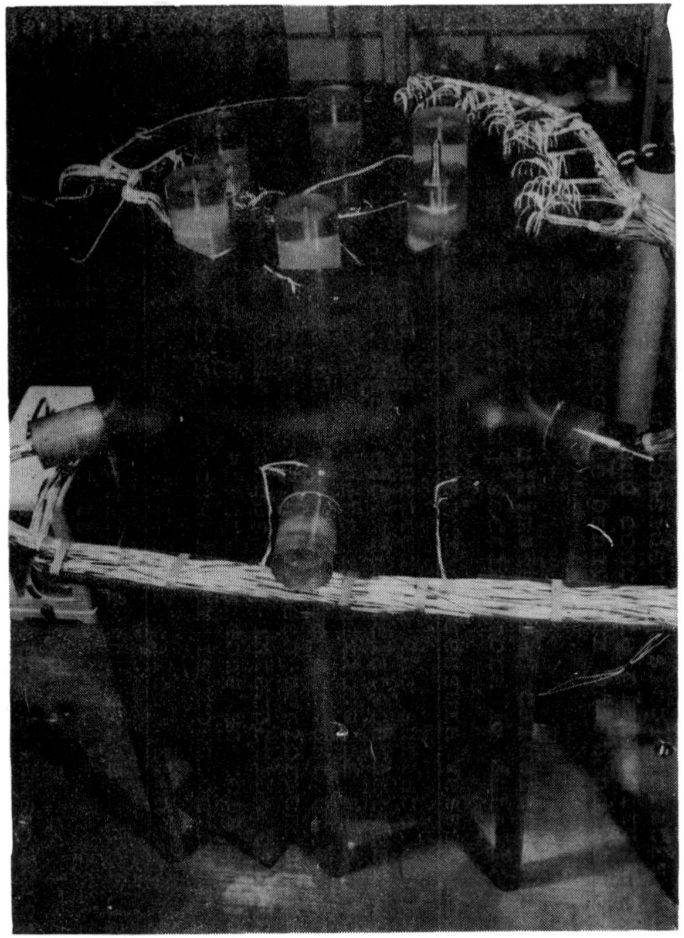


Bild 2.4 THTR-Gießharzmodell M 1:45
THTR 1:45 epoxy resin model

of local stress concentrations a grid with smaller differences is possible, vis. Fig. 2.2. In such a way the grid can be adjusted to the requirements of the structure. For other difference methods the difficulties due to the boundary conditions are well known, especially for boundaries not coinciding with the directions of the coordinates. The special kind of difference method used by dynamic relaxation and the special method of solving the differential equations of the elastic continuum simplify these problems considerably. Moreover any boundaries can be considered, vis. Fig. 2.3. In such a way it is possible to calculate the state of stress and deformation of any three-dimensional or two-dimensional structures. The computation itself is done by an iterative process, described earlier, the way that at different time steps stresses and displacements are calculated successively by the finite difference equations considering the boundary conditions. The calculation is finished, when the vibration is damped to the static solution.

The dynamic relaxation computer programs, set up in our institute, were tested by comparison with known results of special problems or by model experiments. Fig. 2.4 shows the epoxy-resin model of the THTR-vessel, scale about 1:45. At the inner and outer surfaces of the model and within the walls strain gauges had been arranged. For the installation of strain gauges inside the walls a special technic was develloped. Additionally meassurements of the deformations were done at the outer surface of the model. The model was loaded by internal pressure. The calculation of the vessel model and the results of the experiments showed a very good agreement. This comparison is possible for the elastic range of course. As an example of these comparisons Fig. 2.5 shows the tangential stresses at the upper surface of the vessel. Additionally the result of an axisymmetric calculation is plotted at the angle of 3o^{o}.

2.4 Application of the method to variable and non-linear material behaviour

More than usual structures, prestressed concrete pressure vessels have to be calculated with due regard to material behaviour of concrete. The higher concrete temperatures yield stronger creep, vis. Fig. 2.6. Shrinkage varies across the wall section depending among other things on temperature gradient and moisture content influenced by temperatures, vis. Fig. 2.7. Also other material properties are influenced by temperature more or less. Thus, material behaviour does not only depend on time, as commonly known, but on temperature, too.

Tensile strength of concrete is only small. In regions with local stresses or in the case of vessel design based on partial prestressing, tensile strength of concrete is exceeded. On the other hand, in local zones

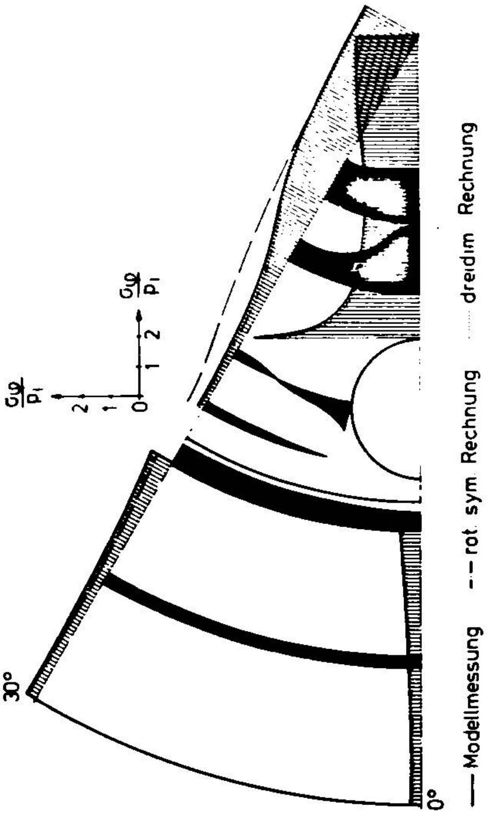
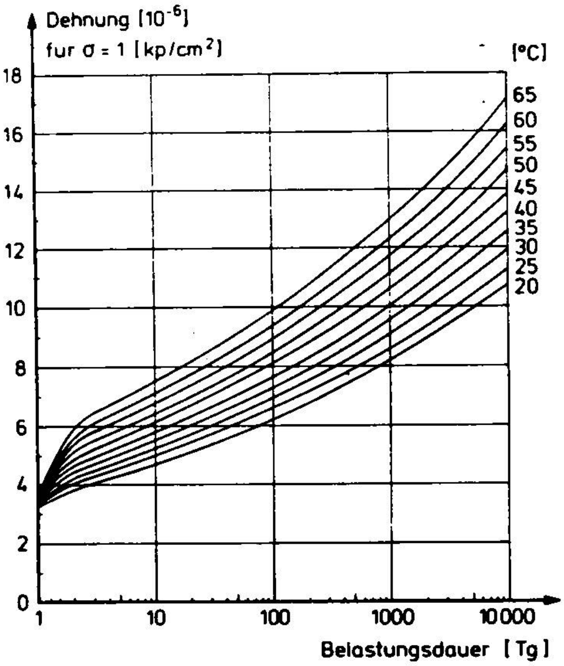
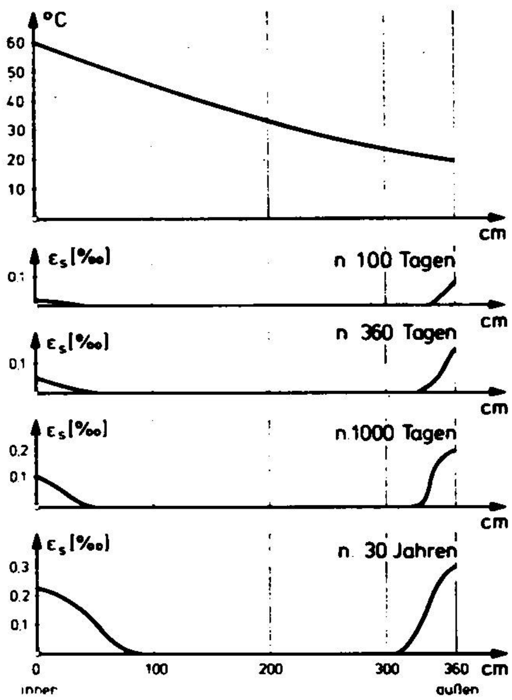


Bild 2.5 Vergleich von Messung am Gießharzmodell und Berechnung
Resin model measurements compared with calculations



$$\lg \varepsilon_{sp} = [1 - \frac{T}{25} \cdot 10^{-(t-t_{BA}+1)}] \cdot [0{,}46 + 0{,}0045 \cdot T + 0{,}12 \cdot \lg(t - t_{BA} + 1)]$$

Bild 2.6 Kriechfunktion eines typischen Behälterbetons
Creep function of a typical vessel concrete



Freies Schwindmaß über die Behälterwandung

Bild 2.7 Verteilung des Schwindens in der Behälterwand
Shrinkage distribution in the vessel wall

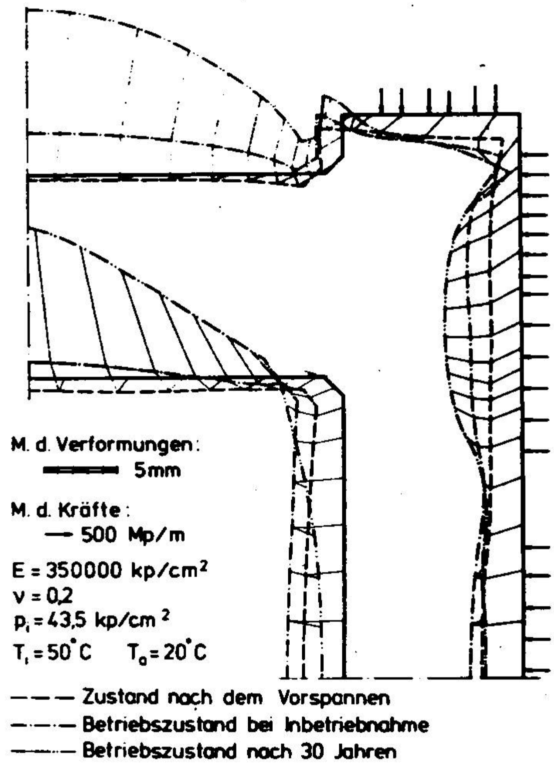


Bild 2.8 Einfluß des Betonkriechens auf die Behälterverformungen
Influence of concrete creep on vessel deformations

with high compressive stresses the limit may be exceeded, up to which linear-elastic concrete behaviour under short time load can be assumed. Computing problems are complicated due to variability and non-linearity of material behaviour, additionally to the requirement in calculating the three-dimensional state of stress and strain, which is a complex problem itself. For calculations like these, load history - i.e. the state of stress and strain imposed previously - is of great importance. Calculations assuming elastic material behaviour are no longer applicable on prestressed concrete reactor pressure vessels except for short time loadings.

Furthermore, the postulation to carry out an ultimate load calculation has to be mentioned here. For this analysis no methods are known from prestressed concrete structures, that could be transformed to the three-dimensional load carrying behaviour of the vessel.

Hence, dynamic relaxation was advanced in order to calculate three-dimensional structures with regard to inhomogeneous and non-linear material behaviour. Thereby, this method was found to be very efficient. In principle these calculations are reduced to step by step elastic calculations. Computations using an elasto-plastic material law were also performed already by non-linear equation systems, but this method is overcome by the solution with step by step elastic behaviour due to its expenditure. Dynamic relaxation is advantageous if used for stepwise elastic solutions, because during the iterative calculating process, that describes the formation of the state of stress and strain, the material law can be altered from one iteration step to the other.

The consideration of variability or non-linearity of material behaviour within the calculation is demonstrated by several examples.

2.4.1 <u>Creep of concrete</u>

Calculations are performed using the superposition method and direct methods as well. The great influence of creep can be seen in Fig. 2.8. Here, deformations of a prestressed concrete pressure vessel at beginning and end of vessel life are drawn up.

Another example is shown in Fig. 2.9, 2.1o and 2.11. This concerns a detail of a vessel wall. A small area is subjected to temperatures elevated up to 85^{o} C . This temperatures possibly can be caused by local failure of thermal insulation. In Fig. 2.9, elastic stresses are plotted. But these stresses cannot develop, since temperature stresses decrease already to some extent during the arising of the temperature field. In Fig, 2.1o, the quasi-stationary temperatures stresses after creep can be seen. If the reactor is shut down for a time, temperatures in this previously hot zone cool down to the temperatures existing in the region around. Because temperature stresses were already decreased largely, this yields an inverted temperature load in the region regarded. As creep recovery is essentially less than creep during first temperature increase, this unloading causes a

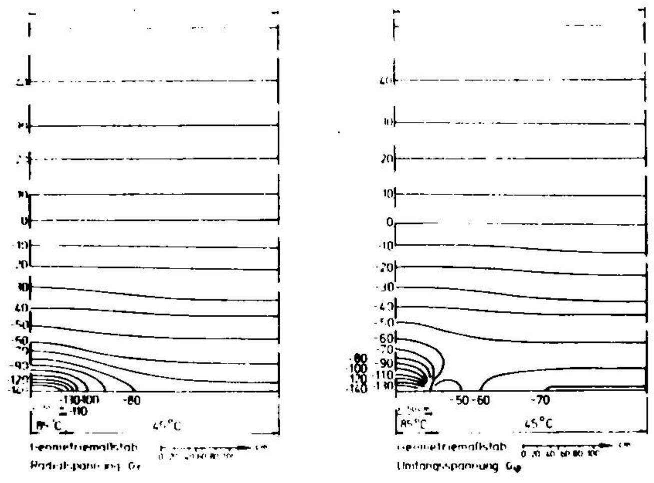


Bild 2.9 Heißer Bereich, elastische Temperaturspannungen
Hot spot, elastic temperature stresses

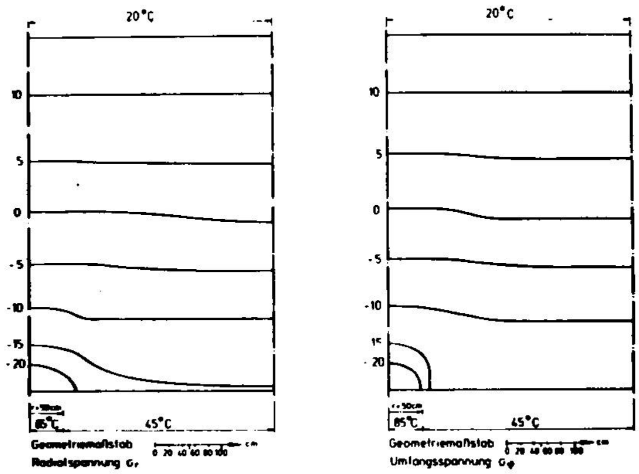


Bild 2.10 Heißer Bereich, Temperaturspannungen nach Kriechen
Hot spot, temperature stresses after creep

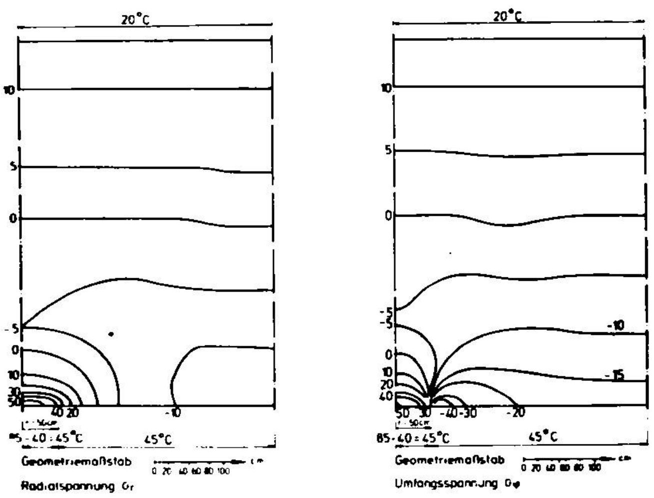


Bild 2.11 Heißer Bereich, Temperaturspannungen nach Kriechen und Abkühlung
Hot spot, temperature stresses after creep and cooling down

tension field , vis. Fig. 2.11. In the example shown here, these tensile stresses exceed tensile strength of concrete. That means, this region is in a cracked state.

2.4.2 Consideration of cracking

In order to estimate boundary strains and cracking at steel coated surfaces realistically, calculations with consideration of cracking are necessary. An economic design of bonded reinforcement can be gained only by calculations like these, too. Thus, procedures for taking account of crack development and reinforcement efficiency were developed based on dynamic relaxation using a fictive material law and assumption of single cracks as well. If distinct single cracks are considered, load carrying of bonded reinforcement is taken into account by special bars, where intermediate reactions act on the concrete as single, line, or volume forces according to respective conditions and bond assumptions. However, knowledge about bond is not yet so extensive as to be sufficient for an accurate calculation. In this field, experimental investigations are still necessary in order to derive laws for the calculation. That is why at present computations using a fictitious material law are preferred.

Both methods are generalized to such an extent that directions of crack propagation and direction of reinforcement can be arbitrarily chosen. Till now calculations were performed for the case of rotational symmetry. Fig. 2.12 shows an example of a calculation like this. It refers to the THTR vessel subjected to 1.6 operating pressure. The cracked regions are marked. Due to high circumferential prestressing of the vessel, cracks mainly occur in the r-z-plane at this pressure. Calculations for the general three-dimensional case are under work now.

2.4.3 Elasto-plastic calculation

As mentioned before, also in this case the iterative computation is carried out by use of stepwise constant elastic material coefficients, that are variable over the calculated region. Since the computation itself is similar to that one concerning cracking, it shall not be discussed in detail here.

2.4.4 Fracture analysis

Fracture analysis is possible by using integral description of the deformation behaviour of cracked zones, or by calculating structures with single cracks. Elasto-plastic behaviour of steel and concrete may be of importance, too. In this field, some research work is still necessary in order to get more detailed knowledge about material behaviour of reinforced concrete at different modes of fracture. With respect to computing technique, for example the dynamic relaxation is a suitable method in order to perform these calculations.

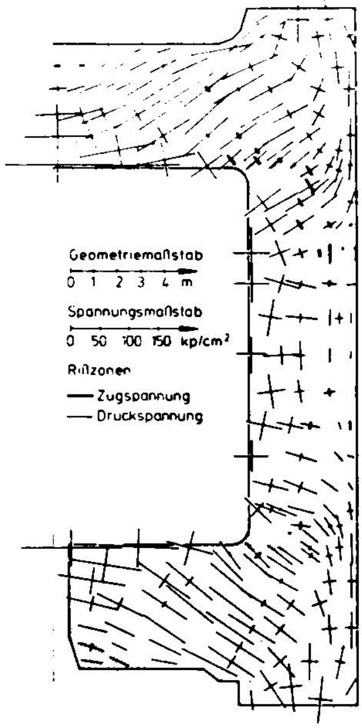
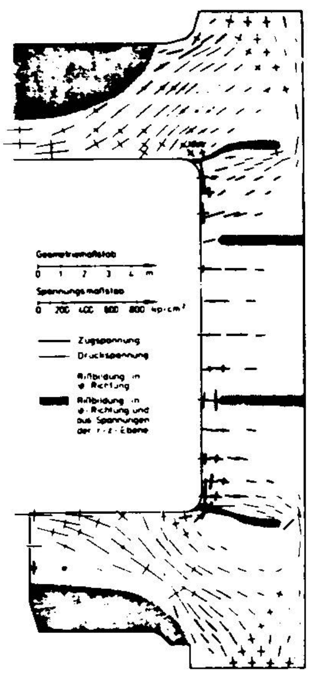


Bild 2.12 THTR-Behälter, Rißbildung bei 1,6-fachem Betriebsdruck
THTR vessel, crack propagation at 1.6 operating pressure



Hauptspannungen der r-z-Ebene bei $p = 2.8\,p_0$

Bild 2.13 THTR-Behalter, Nachweis des Grenzzustandes der Tragfahigkeit
THTR vessel, ultimate load analysis

Fig. 2.13 shows the THTR vessel subjected to 2.8 times operating pressure calculated in a still rather simplified way considering single cracks, dispersed crack regions, and concrete plasticity with presupposed laws for concrete behaviour and bond between concrete and steel.

How to improve ultimate load calculations is reported in the following section more in detail.

2.4.5 Interaction between the pressure vessel and its liner

The liner is connected to the surface of the concrete by studs, ribs etc. The relation between forces and deflections of these connexions is non-linear. The calculation of them has to take account of this non-linearity. Such calculations have been performed already for special cases to get the interaction between liner and concrete. Much effort is done in this field now. Moreover the buckling of the liner is considered by this research.

2.5 Further possibilities of calculation

The short description of the dynamic relaxation has shown the efficiency of this method with regard to the calculation of three- or two-dimensional structures. These calculations can be done with material laws, which are dependent on time, temperature, strain etc., including non-linear behaviour. As example the calculation of a prestressed concrete pressure vessel was described. The dynamic relaxation makes use of solving static problems by computing damped vibrations. It is obvious, that in the same way dynamic problems can be solved. With dynamic applications one would call this method the direct numeric integration of the equations of motion. The possibility of the direct integration was successfully used for calculating dynamic problems such as earthquake, or inpact forces for three- or twodimensional structures. This was done by taking into consideration cracking of concrete and elasto-plastic behaviour of the materials.

3. On calculations of ultimate load behaviour

3.1 Introduction

Ultimate load safety calculations for prestressed concrete pressure vessels for nuclear reactors (PCRV) up to this time always were performed using the method of kinematic rigid body mechanisms - in more or less refined mode, vis. [3.1] - and in most cases in connexion with large scale model tests. Since a long time it is desired to gain more generally valid methods herein, i.e. to formulate deformation and fracture processes in concrete structures when loaded up to the ultimate state using a general material law, which could be applied to three dimensional continua of any shape. Investigations in this field, that are done within the scope of the research work sponsored by the Bundesminister für Forschung und Technologie, shall be demonstrated by an example in this part of the report. The example presented here is chosen from the field of investigations on light water reactor vessels.

In the Danish AEC Research Establishment Risø, model tests for removable vessel top closures corresponding to the Nordic PCRV prototype were undertaken [3.2]. One of these models, called LM 3, and test results gained with it are object of the calculations mentioned here, which were performed to check material assumptions chosen. Fig. 3.1 shows the testing arrangement. The model acts as closure of a steel pressure vessel and is fastened by a supporting and sealing construction corresponding to the prototype. Special characteristics are:

- strong steel flange for supporting and sealing arrangement,
- bearing of the slab by 4o inclined struts,
- stiffening of the flange by 4o stiffening ribs,
- no bonded reinforcement.

3.2 Calculation fundamentals

The calculations were carried out on the basis of the dynamic relaxation method mentioned in section 2. The non-linear material behaviour of concrete and steel liner during increasing load was implied in the computing process as follows:

- Instead of continuous increase of load, single load steps were computed, here having distances of 4o kp/cm^2 . Refined scaling - in principle desirable - was renounced, because these were only testing calculations as a small part of more extensive parametric studies.
- Within each load level several computing steps are done, until changing of material behaviour has stabilized. For this, normally three computing steps were sufficient.

In each of these steps - from one load level to the next one as well as within the same load level - a new stress and deformation state is determined using the material parameters of the previous step. According to this new state, material coefficients are changed if necessary in compliance with distinct criteria. Thus, non-linear material behaviour is simulated by a number of steps, each of them with linear material behaviour.

For description of concrete characteristics the following facts are mainly taken into account:
- plastification based on the von Mises criterion with a certain modification for better fitting on concrete behaviour gained from experiments,
- crack propagation (In the case of cracking, material turns from the isotropic into orthotropic state.),
- fracture due to multiaxial compression (This means complete collapse of internal structure in the region regarded.).

Any occuring of fracture is determined by the general failure criterion for concrete subjected to multiaxial load, vis. /3.3/ e.g.

3.3 Example

Before results are discussed in detail, it should be mentioned that this report represents an instantaneous phase of current research work. That means that in some details investigations are still going on. But it can be said already that the present state seems not to be discouraging.

Two calculation procedures were carried out:
In the first one, the stiffening ribs were disregarded and the flange was assumed to have no bending stiffness, too. Hence the result will be conservative. In the second calculation the flange was set to be completely rigid in vertical direction due to the ribs. This is a more realistic, but somewhat optimistic approach.

First some results of the case without stiffening ribs shall be pointed out. Fig. 3.2 shows the propagation of tensile cracks with tangentially running crack areas. Cracked regions in dependence of pressure and crack directions are outlined. As to be seen in this figure, ample cracking starts in the central region of the upper side of the slab, while above the supporting zone only narrow cracks can be observed. Around 16o kp/cm^2 crack propagation decreases. But now, starting approximately in the middle between centerline and outer surface, inclined cracks propagate. In connexion herewith tangential vertical cracks arise above this zone at the upper surface at pressures about 2oo to 24o kp/cm^2. In the model test cracks like these were observed at circ. 25o kp/cm^2 - a remarkable accordance. In the following, cleavage fractures occur in the whole upper region of the slab, while downwards at half of slab radius a distinct weakening of the uncracked area is taking place. At this position ultimate failure occurs in the test at 37o kp/cm^2 . Up

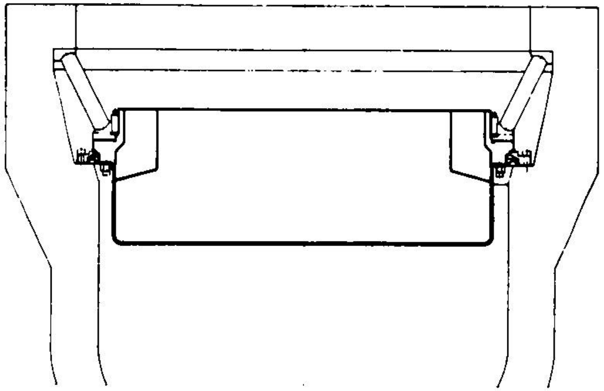


Bild 3.1 Versuchsanordnung
Test arrangement

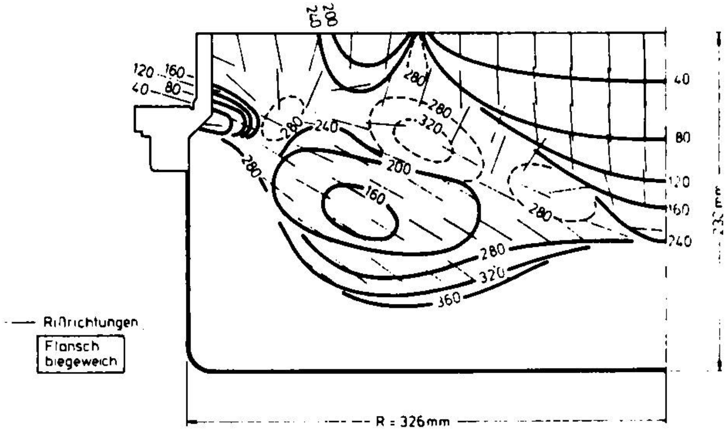


Bild 3.2 Bereiche mit Tangentialrissen bis $p = 360\ kp/cm^2$
Crack patterns, tangential cracks up to $p = 360\ kp/cm^2$

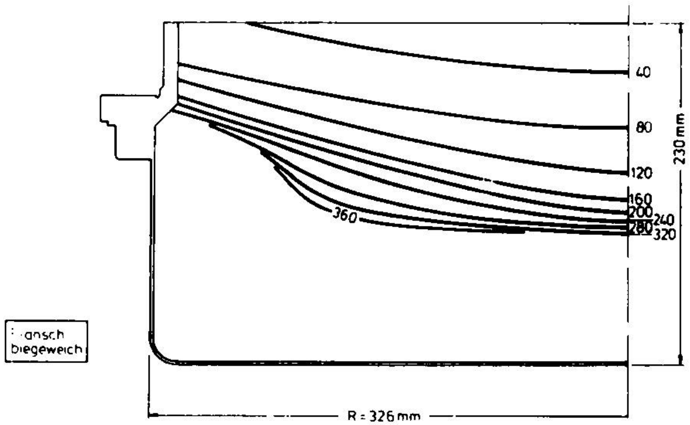


Bild 3.3 Bereiche mit Radialrissen
Crack patterns, radial cracks

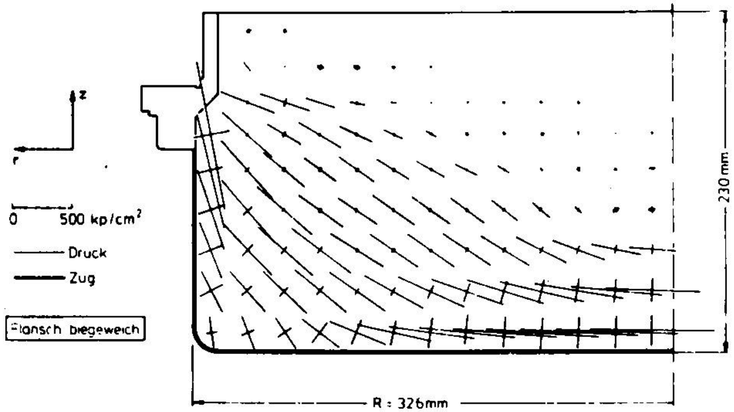


Bild 3.4 Hauptspannungen in der r-z-Ebene bei $p = 280\ kp/cm^2$
Principal stresses in the r-z-plane at $p = 280\ kp/cm^2$

to now it has not been possible to simulate this final phase in the calculation satisfying, but efforts on this subject will go on.

Fig. 3.3 shows the patterns for radially running cracks. It can be seen, that already at 8o kp/cm^2 pressure the whole upper surface of the closure is cracked. But at higher pressures expansion of crack regions decreases. This shows also, that no bending failure can be expected here. Rather an unmistakable pressure dome developes. This fact can also be recognized in Fig. 3.4, where principal stresses in the r-z-plane at a pressure of 28o kp/cm^2 as an example are plotted. The whole upper region does in fact not participate in the load carrying function of the slab.

The following figures show corresponding drawings for the second calculation with stiffened flange. In Fig. 3.5 it can be noticed, that tangentially cracked regions in the slab center remain smaller than in the former example. Here however, the inclined crackes continuously run forward from the supporting zone into the midst of the closure, until at 32o kp/cm^2 the two crack regions are joining. In this case too, ab about half the outer radius, the weakest point developes at which finally ultimate failure occurs. There is no fundamental difference in radial cracking between both calculations (Fig. 3.6), merely the crack regions are somewhat smaller due to the stiffer system. Fig. 3.7 outlines the formation of a pressure dome in this example too. (The remaining principal tensile stresses result from stress redistributions after cracking, because in tensile cracks, if not too wide opened, shear forces still can be transfered. Secundary effects like these will be further investigated.)

In the following some deformations shall be pointed out as a comparison between calculations and model testing. First of all the vertical displacement at slab center (Fig. 3.8): The dash-and-dot lines describe the results of the calculation with weak flange, the continuous lines of that one with stiffened flange respectively. Both curves fit the results of measurement quite well. As expected, the first calculation is somewhat conservative, the second one unconservative. Caused by a comparatively rough computing mesh and rough load step subdivision the resulting curves are not always exactly continuous. This could be compensated by suitable refinements.

Further on, comparisons with measured concrete strains shall be presented. Fig. 3.9 represents strain in the apex of the pressure dome. There is a good accordance of test results with the calculation of the weaker system, while fitting of the other calculated curve is not as good. Nevertheless also this one is rather satisfying, particularly since there are several influences on measurement such as load cycles and time effects

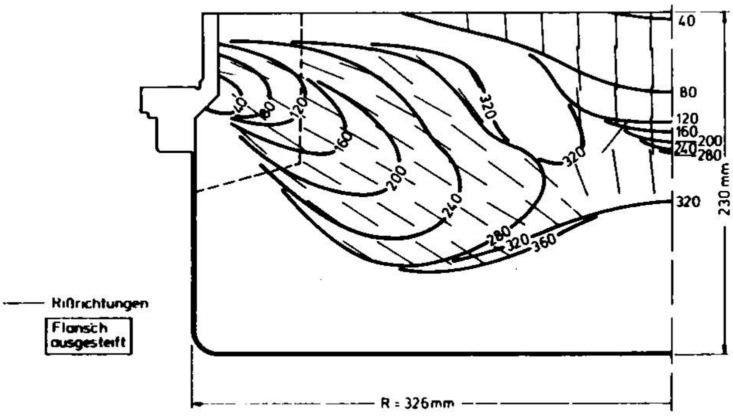


Bild 3.5 Bereiche mit Tangentialrissen bis $p = 360$ kp/cm²
Crack patterns, tangential cracks up to $p = 360$ kp/cm²

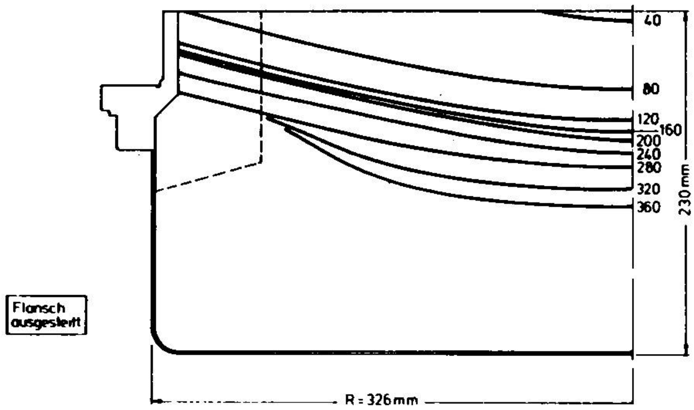


Bild 3.6 Bereiche mit Radialrissen
Crack patterns, radial cracks

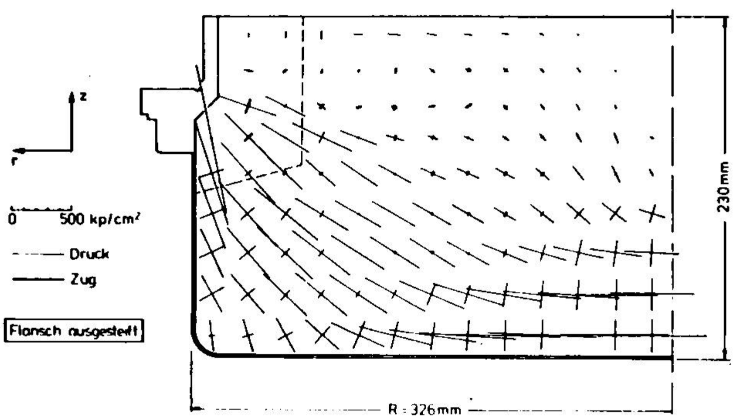


Bild 3.7 Hauptspannungen in der r-z-Ebene bei $p = 280$ kp/cm²
Principal stresses in the r-z-plane at $p = 280$ kp/cm²

that can modify test results. A confrontation of measurement and computation in the region of neutral fiber at the centerline (Fig. 3.1o) shows basically similar behaviour. Quantitative differences may be caused by the mentioned roughness of calculation, but also by local material conditions and consequently doubtful statement of testing. However trying to get much better accordance in details like these is not so necessary in the author's opinion. Finally in Fig. 3.11 tangential strains at about half radius and about midheight of the closure are compared. Also here qualitative accordance can be recognized. Whether reasons for quantitative differences are more in calculation or more in model testing again cannot be estimated.

3.4 Conclusion

All things considered, this comparison shows that there seems to be a good chance to simulate in the way described non-linear behaviour of concrete in three demensional continua of any shape when loaded up to failure. As mentioned earlier, there are still some minor problems to be solved. But in a measurable space of time, surely it will be possible to perform ultimate load investigations for PCRV by theoretical methods only.

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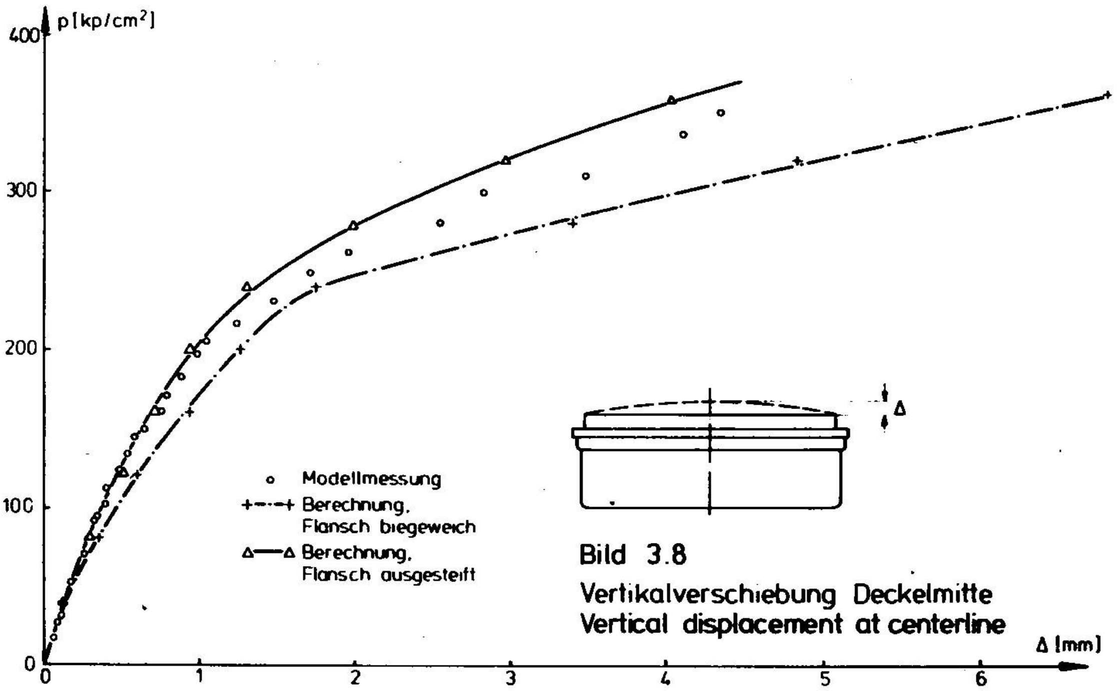

Bild 3.8
Vertikalverschiebung Deckelmitte
Vertical displacement at centerline

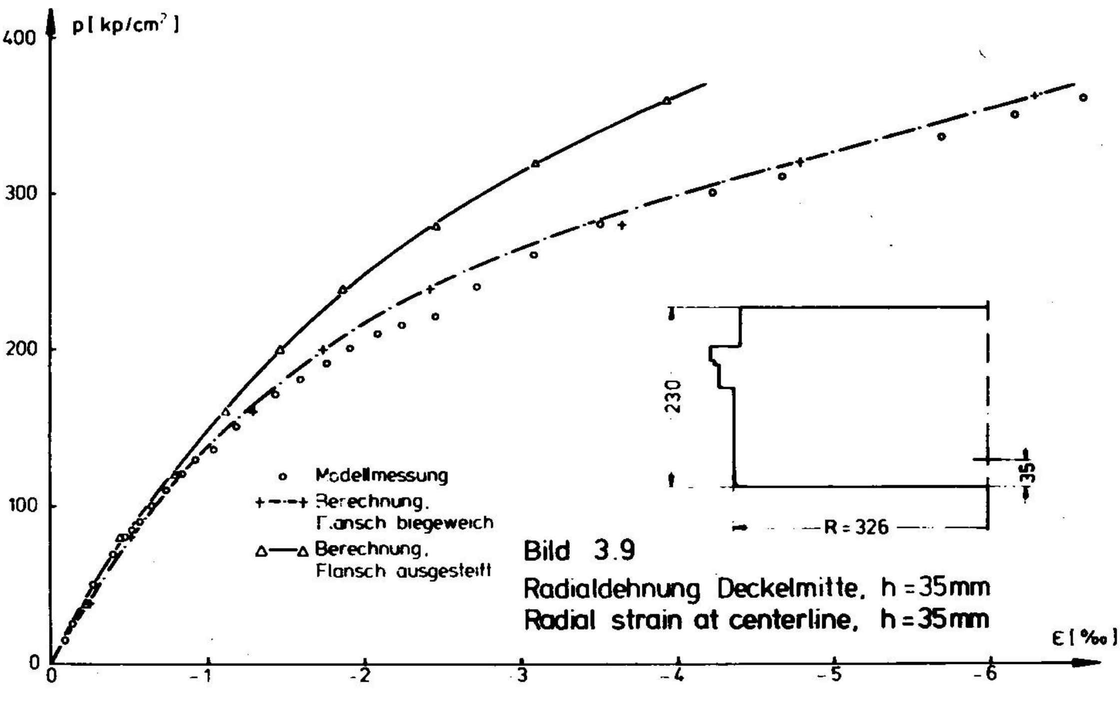

Bild 3.9
Radialdehnung Deckelmitte, h = 35mm
Radial strain at centerline, h = 35mm

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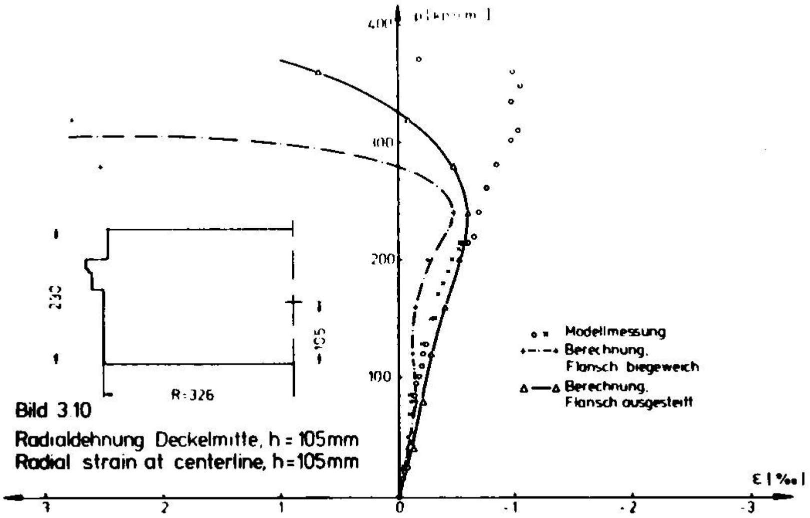

Bild 3.10
Radialdehnung Deckelmitte, h = 105mm
Radial strain at centerline, h=105mm

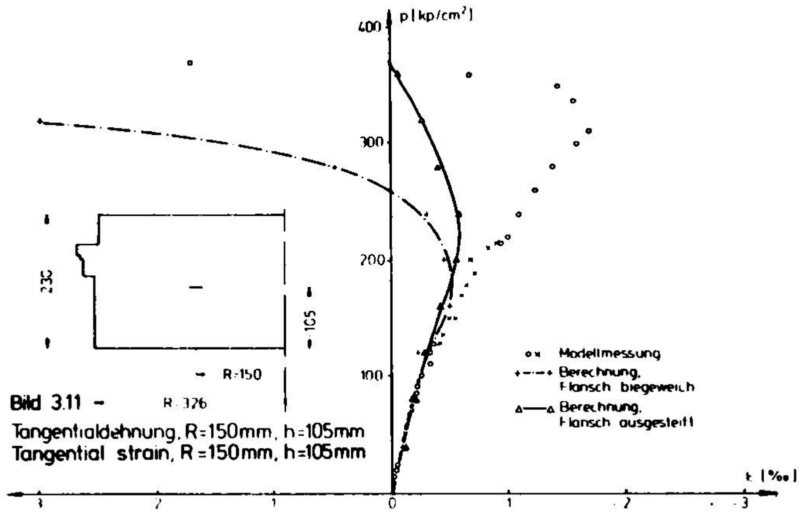

Bild 3.11
Tangentialdehnung, R=150mm, h=105mm
Tangential strain, R=150mm, h=105mm

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Résumé

Le calcul et la construction de structures en béton soumises à des contraintes triaxiales on eu un progrès significatif par les caissons en béton précontraint pour réacteurs nucléaires. Ce rapport veut donner un panorama du travail de recherche dans ce domaine, soit du point de vue du calcul que de la construction. On a considéré différentes techniques de précompression du caisson, concentrations locales de contraintes et les requises conséquentes pour le projet et la réalisation, problèmes qui concernent la "peau" d' étanchéité, la compositions et le coulage du béton. On traite la calcul tridimensionel du caisson, avec considération particulière pour la méthode de la relaxation dinamique. En particulier, on souligne comment tenir compte de: conditions géométriques complexes; variations en fonction de l' espace et du temps et non-linéarité des propriétés des matériaux; influence des variations de température.

Summary

Calculation and construction of concrete structures subjected to triaxial stresses was significantly advanced by erecting prestressed concrete pressure vessels for nuclear power plants. This report shall give a survey of research work in this field, that includes problems of calculation and problems of construction as well. Different vessel prestressing techniques, local stresses and resulting requirements on design and manufacture, problems concerning the liner, as well as concrete mix and concrete casting demands are discussed. Three-dimensional calculation of prestressed concrete pressure vessels is reported with particular consideration of the dynamic relaxation method. Especially it is pointed out how to take account of complicated geometry conditions, of space and time dependent variations and non-linearity of material properties and of the influence of variable temperatures. Finally, the present state of investigations on ultimate load behaviour of concrete structures subjected to triaxial stresses is outlined. For this, ultimate load calculation results of removable closures for light-water reactor vessels are presented.

Übersicht

Die Berechnung und Konstruktion von Betonbauwerken mit dreidimensionaler Beanspruchung erhielt mit dem Bau von Spannbeton-Druckbehältern für Kernkraftwerke wesentliche Impulse. Dieser Beitrag soll über Erfahrungen und Forschungsarbeiten auf diesem Gebiet, die sowohl Probleme der Berechnung als auch der Konstruktion betreffen, einen Überblick geben. Behandelt werden Möglichkeiten der Behältervorspannung, örtliche Störungszonen und ihre Anforderungen an Konstruktion und Ausführung, Probleme im Zusammenhang mit dem Liner sowie Fragen der Betonzusammensetzung und des Betoniervorganges. Über die dreidimensionale Berechnung von Spannbetonbehältern wird am Beispiel des Verfahrens der Dynamischen Relaxation berichtet. Insbesondere werden Möglichkeiten der Berücksichtigung geometrischer Besonderheiten, des örtlich und zeitlich veränderlichen sowie des nichtlinearen Materialverhaltens und des Einflusses unterschiedlicher Temperaturen aufgezeigt. Schließlich wird über den derzeitigen Stand von Untersuchungen zum Bruchverhalten dreidimensional beanspruchter Betonkonstruktionen gesprochen. Dazu werden Ergebnisse von Bruchberechnungen beweglicher Deckel für Leichtwasser-Reaktordruckbehälter vorgestellt.