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

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I-4

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

Prof. Dott. Ing. W. ZERNA, Dr. Ing. G. SCHNELLENBACH,
Dipl. Ing. K. SCHIMMELPFENNIG

Istitut Fuer Konstruktiven Ingenieurbau Ruhr-Universitaet Bochum

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. Furtermore 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

Schnitt im Zylinderbereich   Schnitt in der Bodenplatte

Prinzip der Ringvorspannung
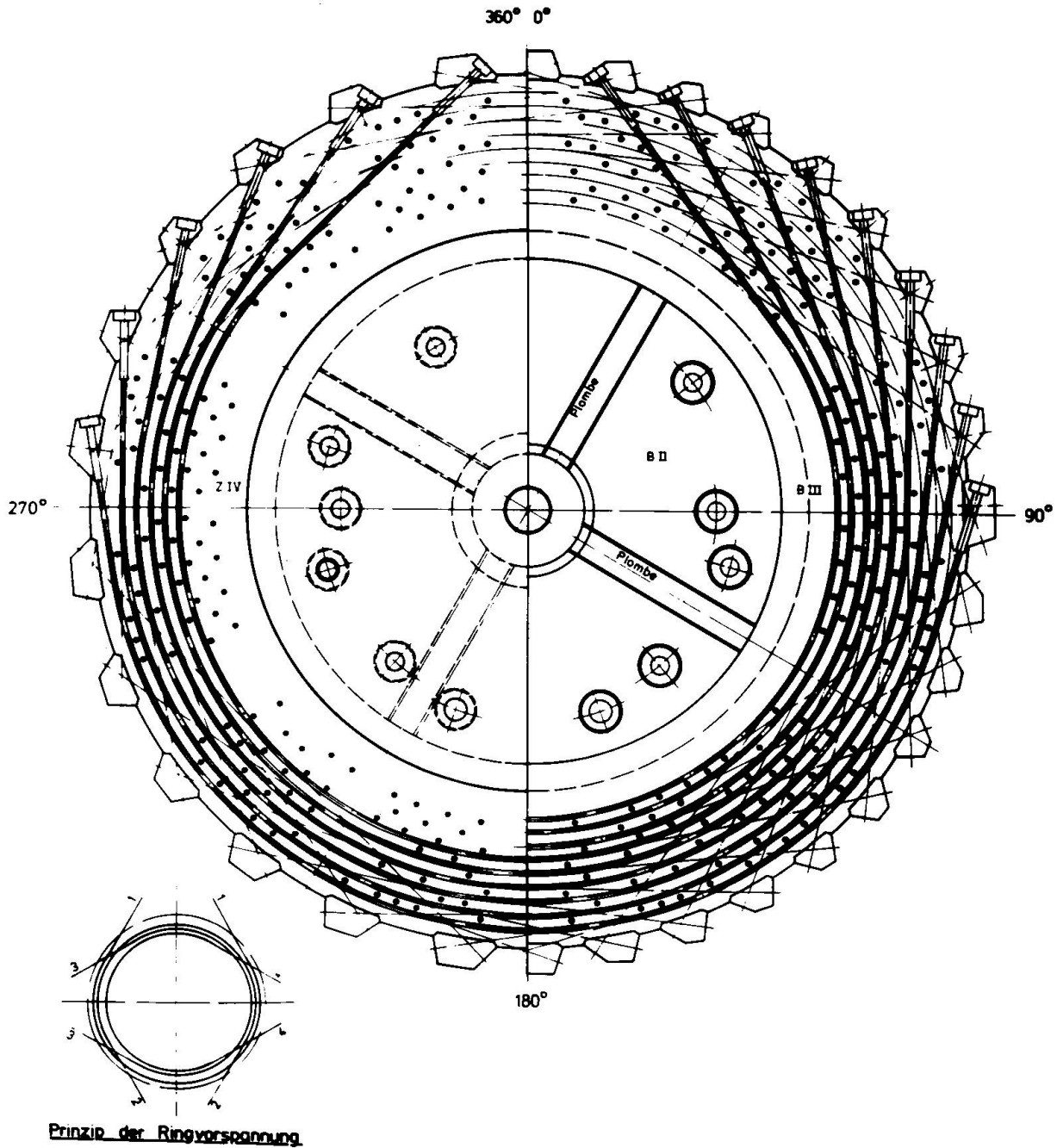
Bild 1.1   SBB - Lisenenvorspannung
                      PCRV Buttress prestressing system

25,90

29,26

6,91

Bühne 2

Wickelmaschine

Bühne 1
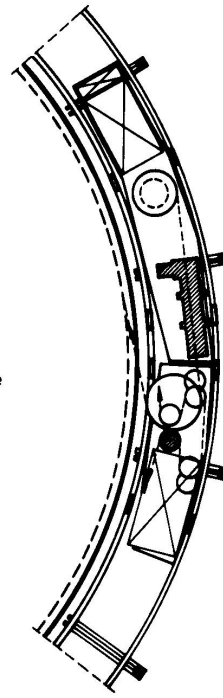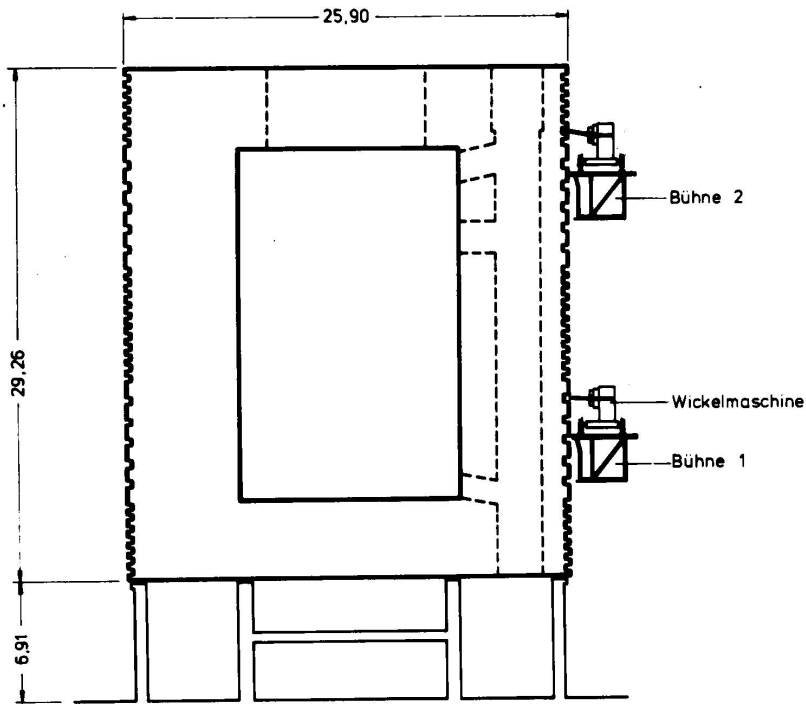
Übersicht

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 concen-
trations are to be solved in the standpipe region
of the top slab and in zones around major penetra-
tions. 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 develop-
ment 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 in-
creased. 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 rein-
forcement 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 rein-
forced 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 sur-
face 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
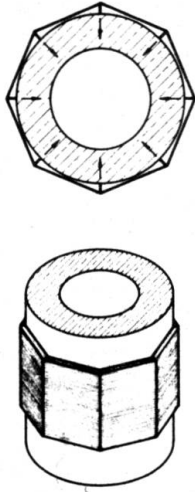
Bild 1.3   SBB - Prisma - Vorspannung
            PCRV Prisma prestressing system
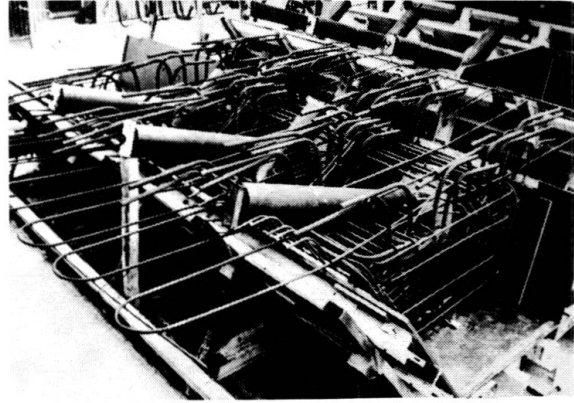
Bild 1.6   Bewehrung einer Fertigteillisene des
            THTR - Spannbetondruckbehälters
            Precast buttress reinforcement of the
            THTR vessel
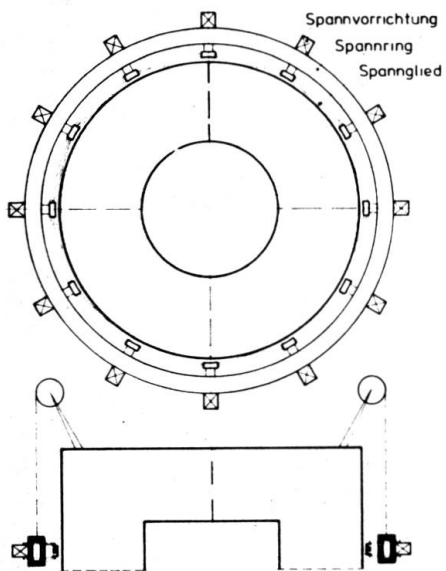
Bild 1.4
SBB - Ringvorspannung (mit Spannringen)
PCRV circumferential prestressing (with straining rings)
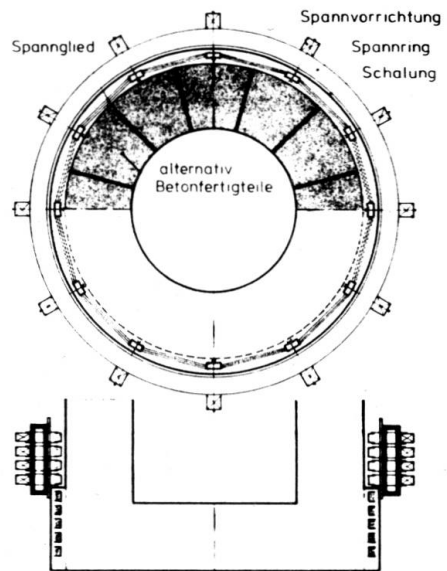
Bild 1.5   SBB - Ringvorspannung (mit Spannringen und
            sofortigem Verbund)
            PCRV circumferential prestressing (with
            straining rings and immediate bond)
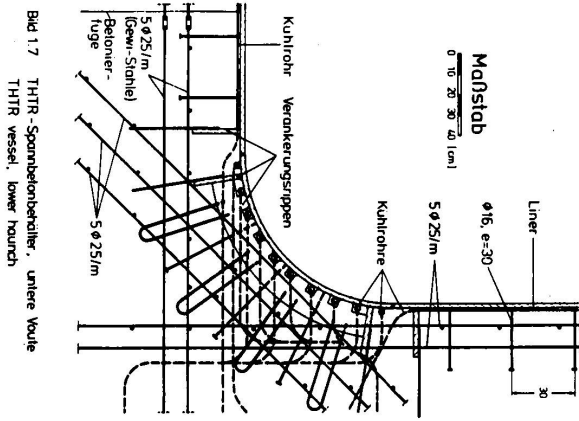
Bild 1.7 THTR-Spannbetonbehälter, untere Vaute
THTR vessel, lower haunch
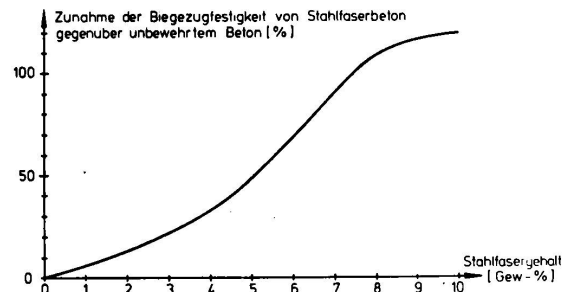
Bild 1.8 Zunahme der Biegezugfestigkeit von Stahlfaserbeton in Abhängigkeit vom Fasergehalt
Bending tensile strength increase of steel fiber reinforced concrete versus content of fibers
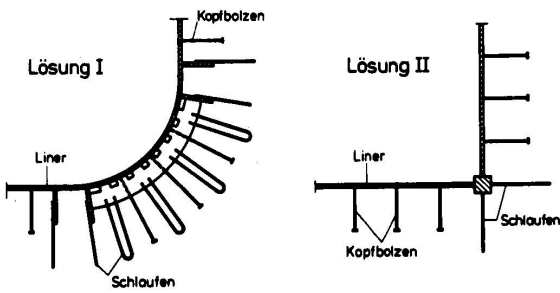
Bild 1.11 Linerübergang vom Boden zum Zylinder
Transition region between bottom and wall liner

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

7.
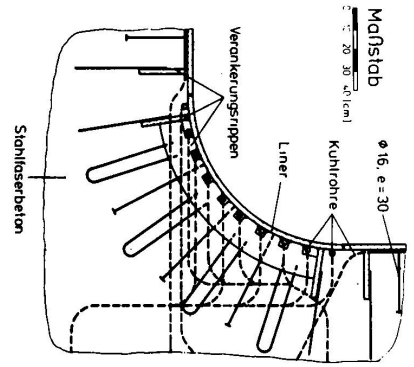
set certain limits for its minimum thickness.
Additionally the liner has to be protected against
buckling due to high compressive loads caused by
vessel deformations or temperature restraints by a
well balanced proportion of thickness to concrete
anchoring. Thicknesses between 12 and 3o mm were
found 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 mean-
time. 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 con-
crete 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

Ausführung THTR
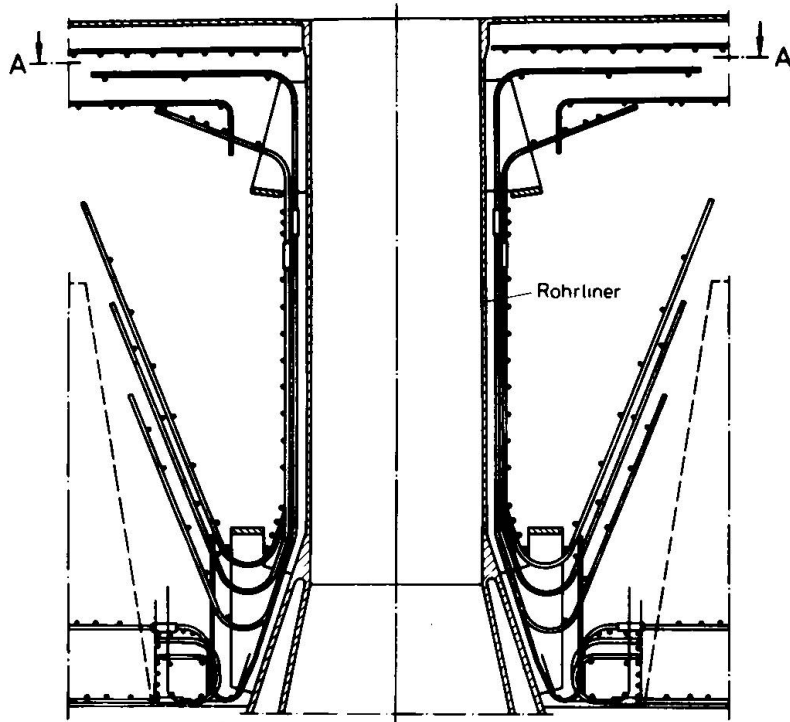
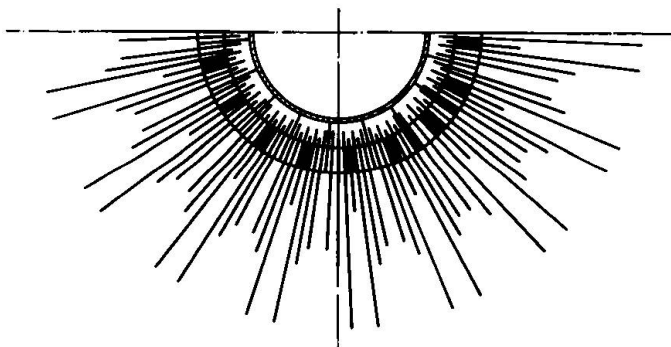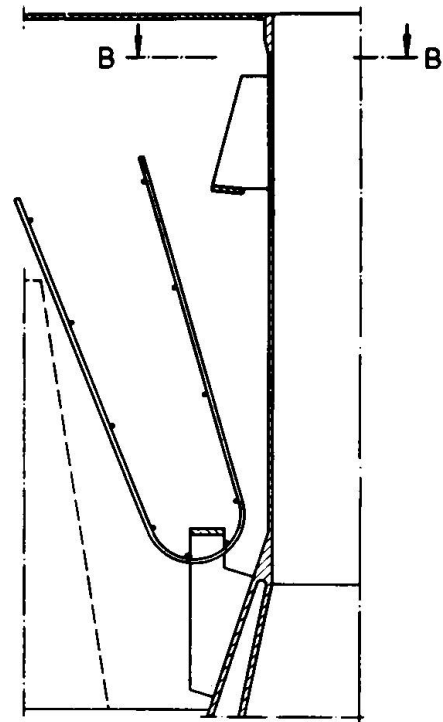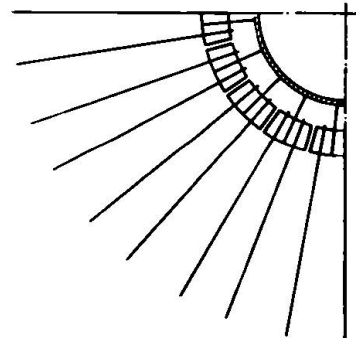Ausführung mit Stahlfaserbeton

Rohrliner

Schnitt A-A
(Prinzip der Bewehrung)

Schnitt B-B
(Prinzip der Bewehrung)

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-dimensio-
nal 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 sur-
face 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 prestres-
sing. 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. Be-
cause of these reasons it will be reported about the dyna-
mic 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.

Außentemperaturen ca. 21–25°C

Beton-
rand-
tempe-
raturen

Innen-
druck
[atü]
$p_0 = 39$
$p_S = 41,7$
$p_P = 46$
$p_{min} = -1$
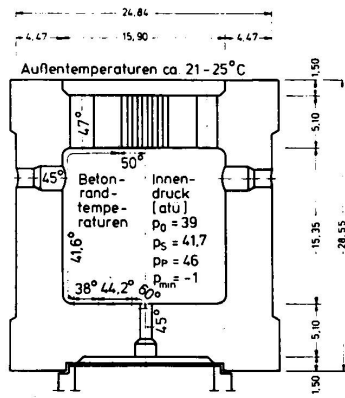
p_0 = Betriebsdruck p_P = Prüfdruck
p_S = Störfalldruck p_{min} = evakuierter Behälter

Temperatur- und Innendruckbelastung

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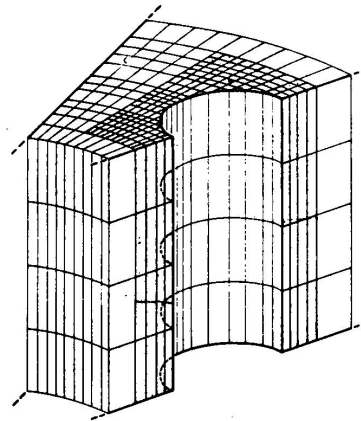THTR vessel, geometry and loads due to
reactor service

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 equilli-
brium and the 6 constitutive equations. At first it seems
not to be suitable to introduce the time as fourth dimen-
sion 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 dis-
placements 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 possibi-
lity 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 relaxa-
tion 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.
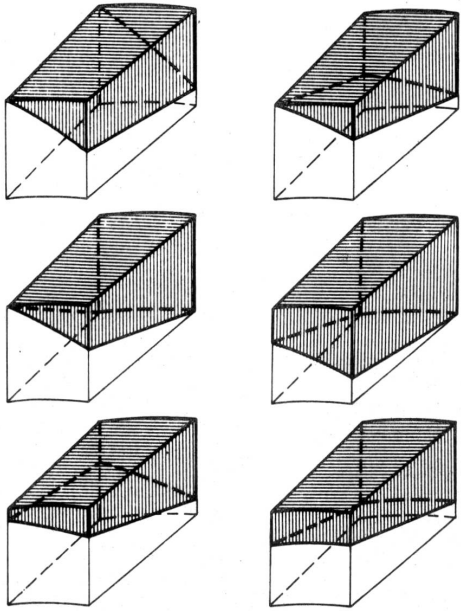The width of the grid can be different so that in regions

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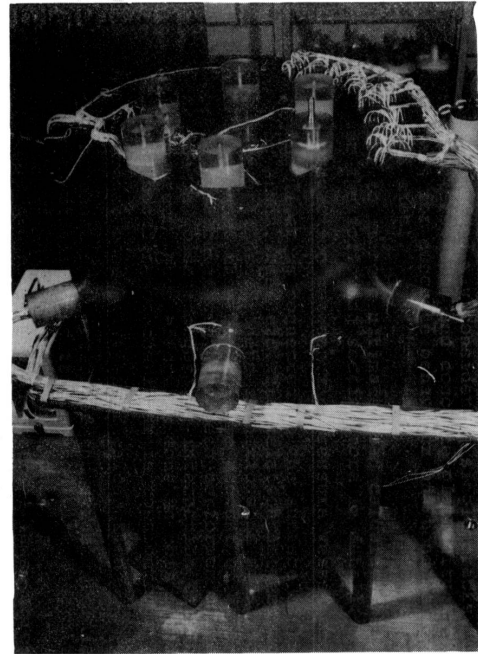dimensional elements

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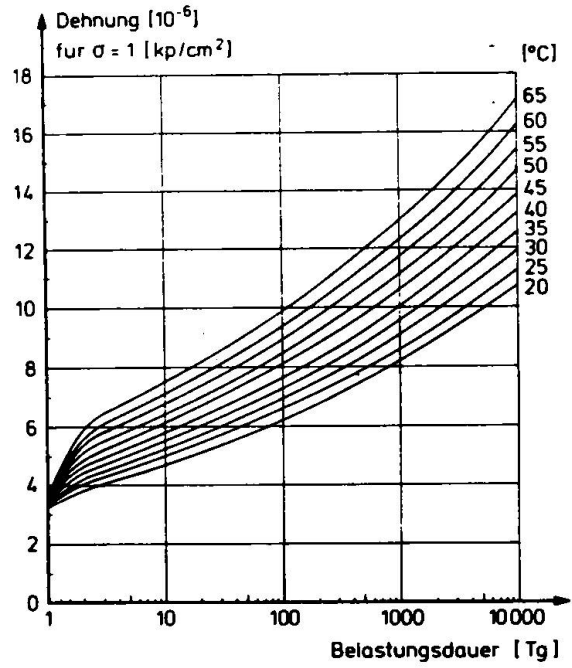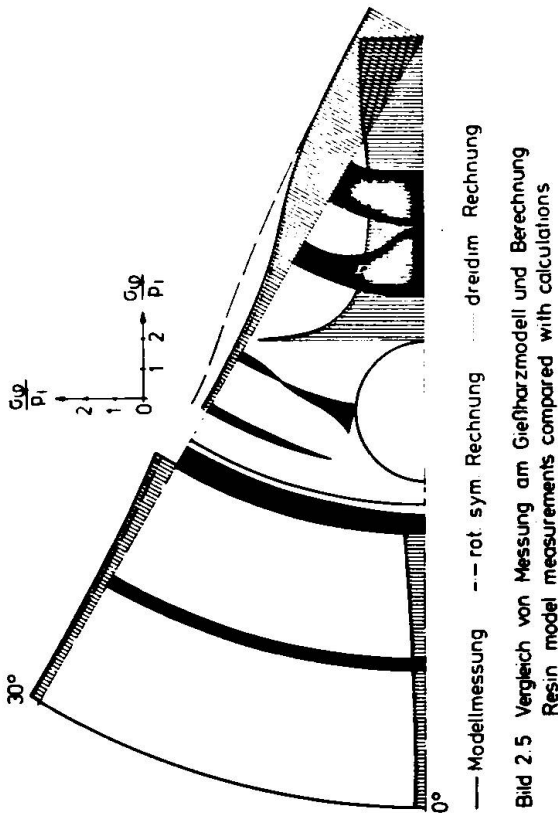THTR 1:45 epoxy resin model

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 difficul-
ties 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 con-
siderably. Moreover any boundaries can be considered,
vis. Fig. 2.3. In such a way it is possible to calcu-
late the state of stress and deformation of any three-
dimensional or two-dimensional structures. The computa-
tion 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 30°.

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

More than usual structures, prestressed concrete pres-
sure 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 con-
crete 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

— Modellmessung — — rot sym Rechnung ····· dreidim Rechnung

$\dfrac{G \cdot \varphi}{p_i}$

30°   0°

Dehnung $[10^{-6}]$
für $\sigma = 1\ [kp/cm^2]$ [°C]

18
16   65
14   60
12   55
10   50
8   45
6   40
4   35
2   30
0   25
                                                              20

1   10   100   1000   10000

Belastungsdauer [Tg]

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

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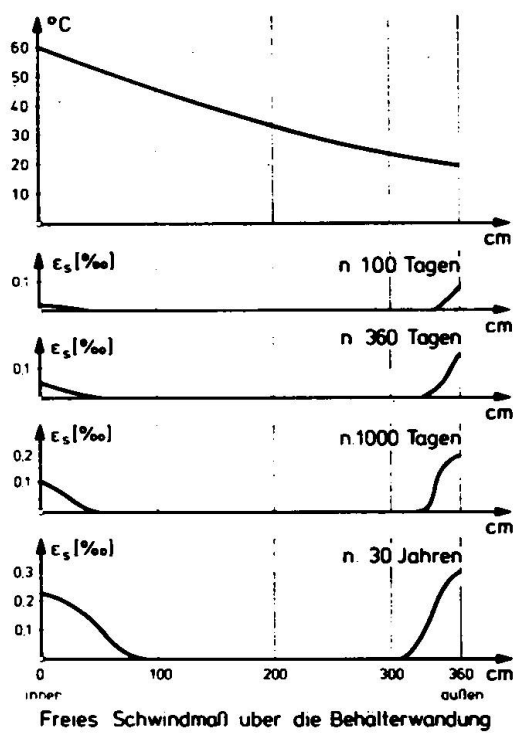Creep function of a typical vessel concrete

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°C
60
50
40
30
20
10
                                              cm

ε_s [‰]   n 100 Tagen
0.1
                                              cm

ε_s [‰]   n 360 Tagen
0.1
                                              cm

ε_s [‰]   n 1000 Tagen
0.2
0.1
                                              cm

ε_s [‰]   n. 30 Jahren
0.3
0.2
0.1

0   100   200   300   360 cm
inner   außen

Freies Schwindmaß über die Behälterwandung

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

M. d. Verformungen:
━━━━ 5mm

M. d. Kräfte:
→ 500 Mp/m

E = 350000 kp/cm²
ν = 0,2
p_i = 43,5 kp/cm²
T_i = 50°C T_a = 20°C

— — — Zustand nach dem Vorspannen
— ·— Betriebszustand bei Inbetriebnahme
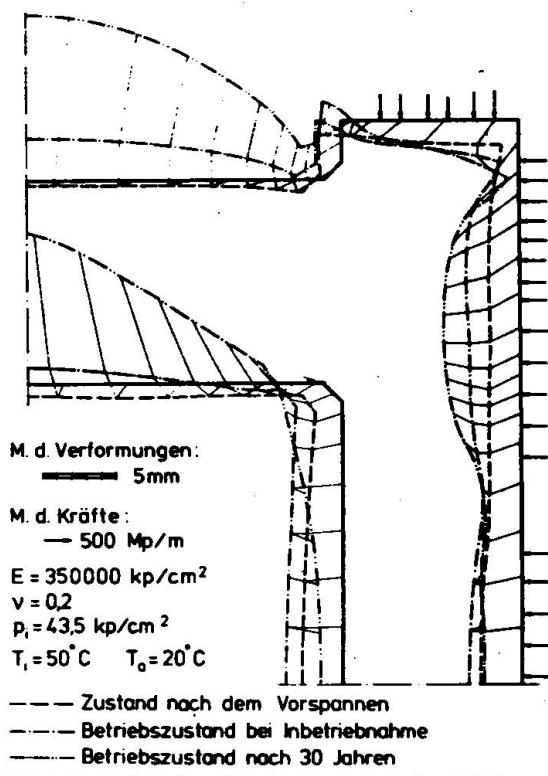———— Betriebszustand nach 30 Jahren

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 calcula-
tions 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 cal-
culate 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 forma-
tion 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 Creep of concrete

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 subjec-
ted to temperatures elevated up to 85° C . This temperatures
possibly can be caused by local failure of thermal insula-
tion. 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
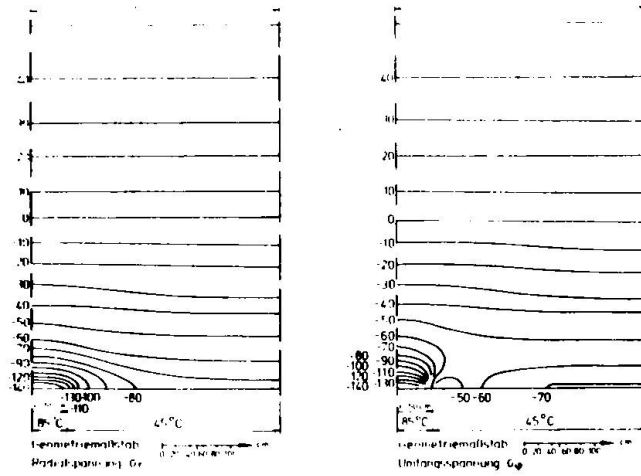during first temperature increase, this unloading causes a

Bild 2 9   Heißer Bereich, elastische Temperaturspannungen
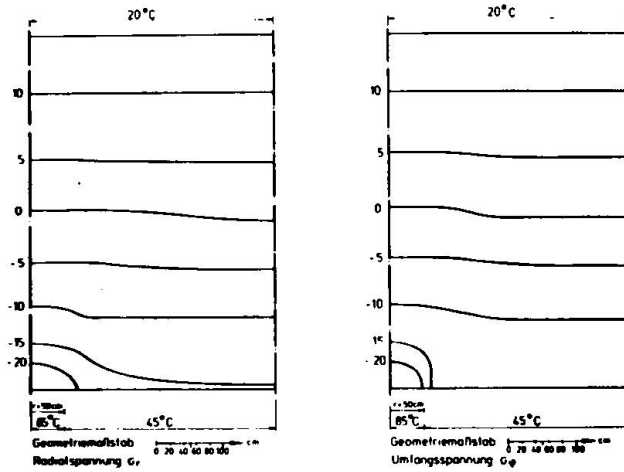Hot spot, elastic temperature stresses

Bild 2 10   Heißer Bereich, Temperaturspannungen nach Kriechen
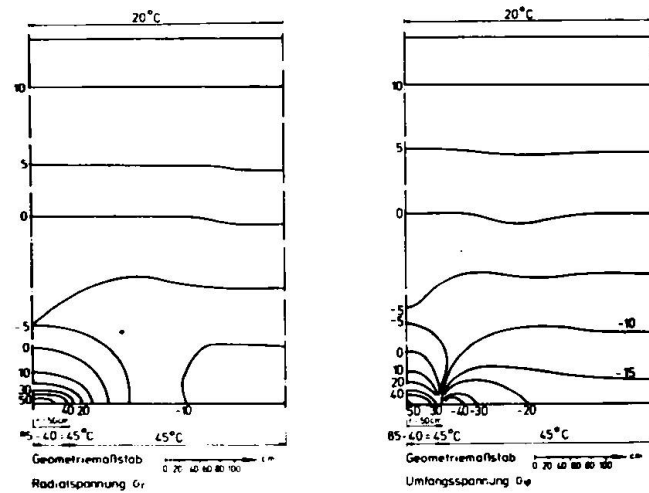Hot spot, temperature stresses after creep

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 rein-
forcement can be arbitrarily chosen. Till now calcula-
tions were performed for the case of rotational sym-
metry. 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 descrip-
tion 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
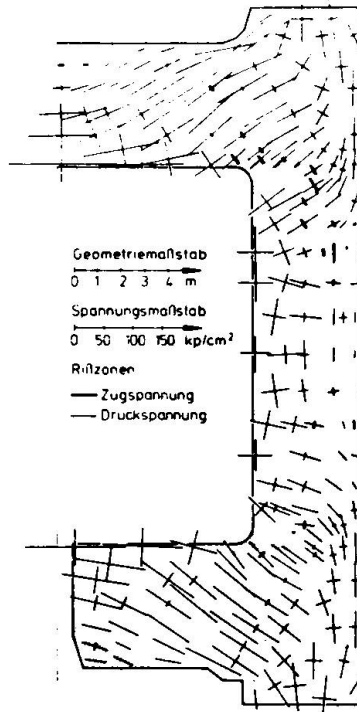suitable method in order to perform these calculations.
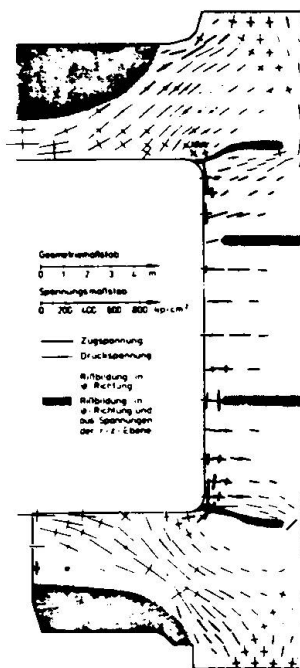
Bild 2.12 THTR - Behälter, Rißbildung bei 1.6-fachem
Betriebsdruck
THTR vessel, crack propagation at 1.6
operating pressure

Hauptspannungen der r-z-Ebene bei p=2.8 po

Bild 2.13 THTR - Behälter, Nachweis des Grenzzustandes
der Tragfähigkeit
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 con-
crete 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. $\sqrt{3.1}$ - 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 con-
crete 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 For-
schung 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 $\sqrt{3.2}$. One of these
models, called LM 3, and test results gained with it are
object of the calculations mentioned here, which were per-
formed 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 arrange-
  ment,
- 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 pro-
cess 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. $\sqrt{3.3\_}$ 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 $160 \ kp/cm^2$ 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 200 to $240 \ kp/cm^2$. In the model test cracks like these were observed at circ. $250 \ kp/cm^2$ – 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 $370 \ kp/cm^2$. Up
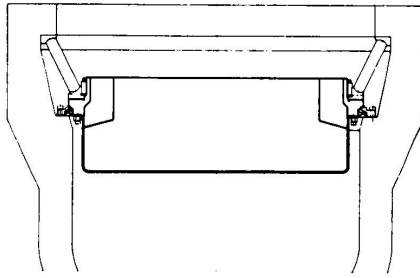
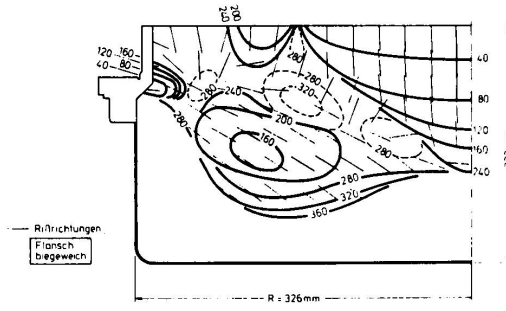Bild 3.1   Versuchsanordnung
Test arrangement

Bild 3.2   Bereiche mit Tangentialrissen bis p = 360 kp/cm²
Crack patterns, tangential cracks up to p = 360 kp/cm²

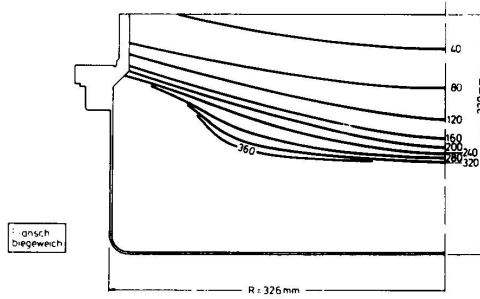

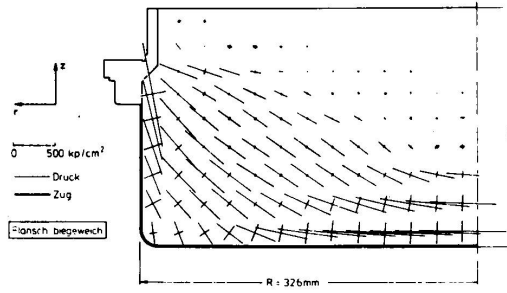Bild 3.3   Bereiche mit Radialrissen
Crack patterns, radial cracks

Bild 3.4   Hauptspannungen in der r-z-Ebene bei p = 280 kp/cm²
Principal stresses in the r-z-plane at p = 280 kp/cm²

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 expec-
ted 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 for-
ward 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 princi-
pal 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 measure-
ment 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 al-
ways 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 satis-
fying, particularly since there are several influences
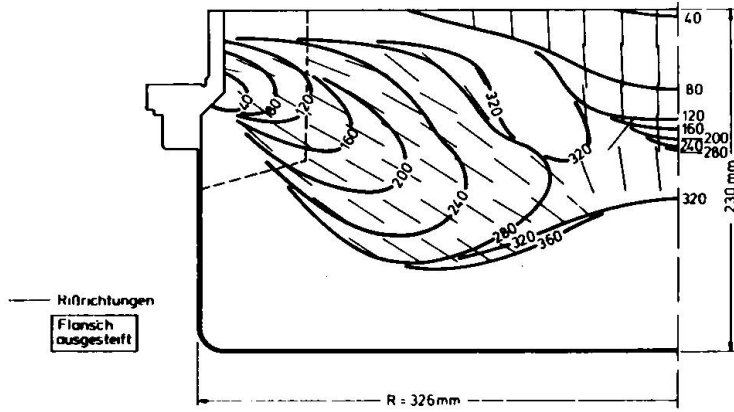on measurement such as load cycles and time effects

25.

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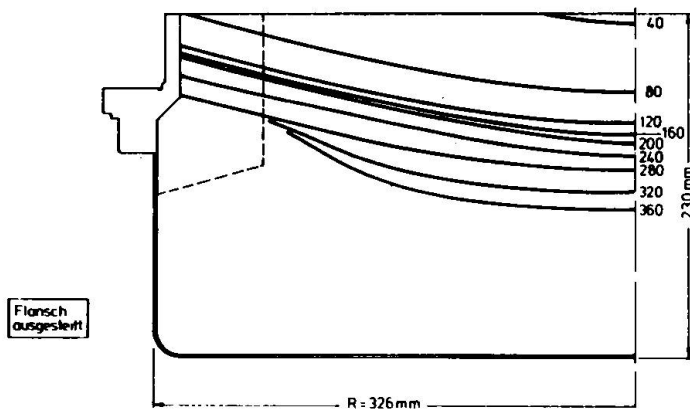

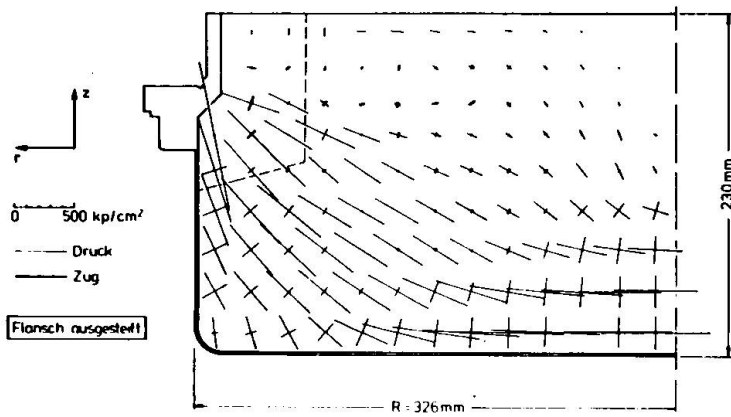Bild 3.6   Bereiche mit Radialrissen
Crack patterns, radial cracks

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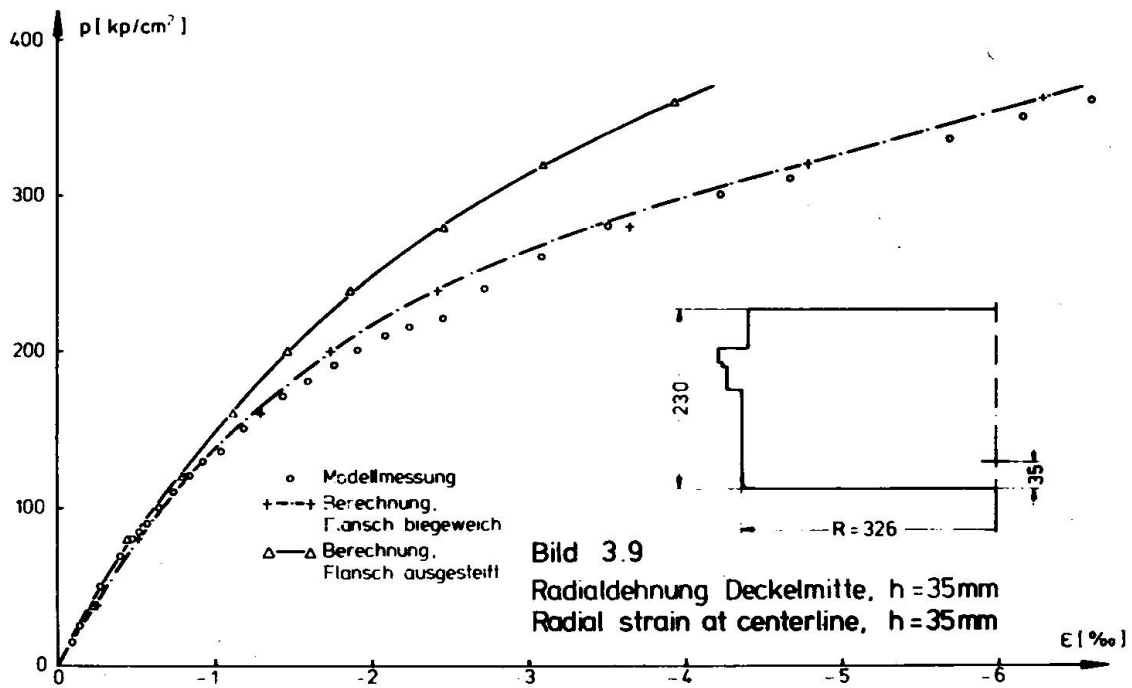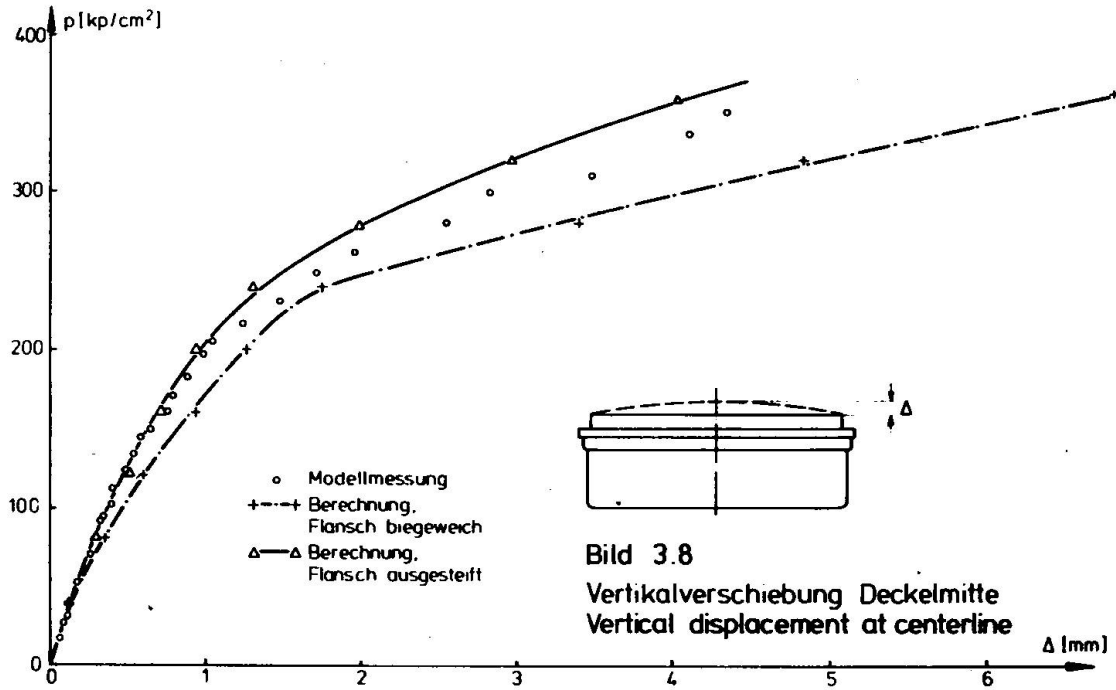Principal stresses in the r-z-plane at p = 280 kp/cm²

that can modify test results. A confrontation of measure-
ment and computation in the region of neutral fiber at
the centerline (Fig. 3.1o) shows basically similar behavi-
our. 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 compa-
red. Also here qualitative accordance can be recognized.
Whether reasons for quantitative differences are more in
calculation or more in model testing again cannot be
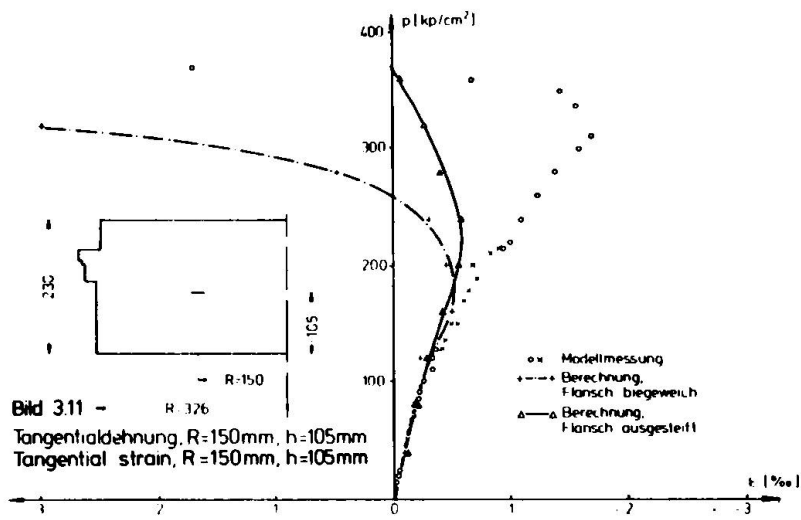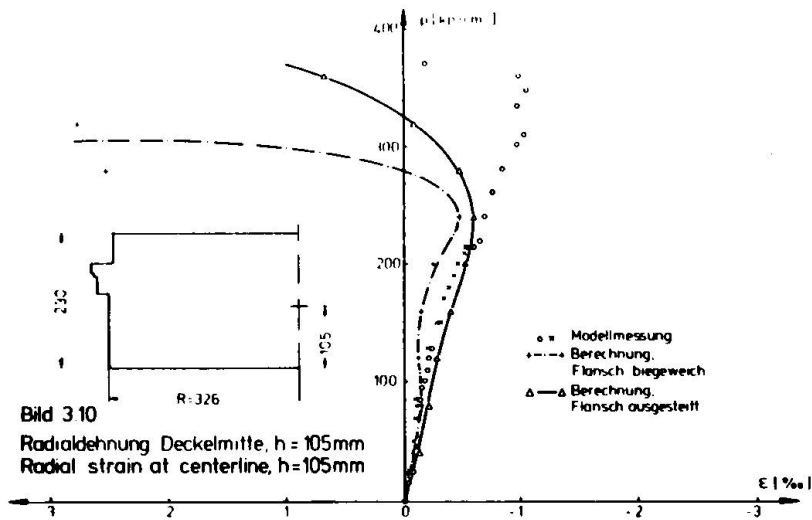estimated.

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

28.

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paper H 1/3

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

30.

/3.1/ K. SCHIMMELPFENNIG, V. HANSSON: Untersuchungen zur
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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 dif
férentes 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' étanchéi-
té, la compositions et le coulage du béton. On traite la calcul tridi
mensionel du caisson, avec considération particulière pour la mé-
thode de la relaxation dinamique. En particulier, on souligne com-
ment tenir compte de: conditions géométriques complexes; varia-
tions en fonction de l' espace et du temps et non-linéarité des pro-
priétés 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.

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