OVALITY OF THE STEEL LINING IN THE HAW TEST FIELD

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ABSTRACT

Investigations have been made into the deformation behaviour of the steel lining of the boreholes in the HAW test field, which is an underground experimental facility used for the investigation of the effects of storage of nuclear waste in salt formations. The HAW test field consists of two parallel galleries in an anticline type of salt formation. From each gallery four vertical boreholes have been drilled at equal distance. In two of these boreholes electrical heaters have been placed and in the remaining boreholes heat producing nuclear sources will be installed.

A lining of steel has been placed into the boreholes to guarantee the continuous retrievability of the radio-active canisters over the complete test period. During the experiments with the electrically heated holes, ovality of the cross section of the lining was measured. The results of the investigation into a possible cause of this type of deformation are presented in this report.

It was concluded that bending cannot be the cause of the ovality found in the lining. It is expected that the ovality is caused by pressure load variations in circumferential direction.
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LIST OF SYMBOLS

\( a \)  inner radius, mm
\( d \)  deflection of the centre line, mm
\( E \)  Young's modulus, MPa
\( h \)  wall thickness, mm
\( L \)  length, m
\( N \)  number of elements
\( p \)  pressure, MPa
\( r \)  radial coordinate, mm
\( \text{rotu} \)  rotation angle in radial direction, rad.
\( \text{rotv} \)  rotation angle in circumferential direction, rad.
\( \text{rotw} \)  rotation angle in axial direction, rad.
\( R \)  radius of curvature, m
\( u \)  radial displacement, mm
\( u/a \)  dimensionless radial displacement, ovality
\( t \)  time, days
\( v \)  circumferential displacement, mm
\( w \)  axial displacement, mm
\( z \)  axial coordinate, mm
\( \beta \)  rotation angle, rad.
\( \theta \)  circumferential coordinate, rad.
\( \nu \)  Poisson ratio
\( \kappa \)  curvature, m\(^{-1}\)

Subscripts

\( a \)  axial
\( c \)  circumferential
1 INTRODUCTION

A pilot-scale test will be performed in the Asse salt mine in Germany on the disposal of high level radio-active waste in salt formations. In the Asse salt mine the HAW experiment has been running since 1985. This experiment is performed by GSF (Gesellschaft für Strahlen- und Umwelt Forschung) and ECN (Netherlands Energy Research Foundation). The HAW test field consists of two large galleries between which a pillar is situated [1,2]. In the bottom of each of the galleries 4 vertical boreholes have been made (cf. Fig. 1).

In the boreholes a lining of steel has been placed to guarantee the continuous retrievability of the radio-active canisters over the complete test period (cf. Fig. 2). This implies that the lining has been designed with the objective to provide mechanical strength to sustain the thermally increased pressure load from the salt.

Understanding of the mechanical behaviour of the lining is of crucial importance to assure the retrievability of the radio-active canisters. During the experiments the occurrence of ovality of the cross section of the lining was observed. The results of the investigation into a possible cause of this type of deformation are presented in this report.

It is investigated whether observed ovality in a cross section of the lining might be caused by bending of the lining. As a first attempt the possible existence of analytical solutions for a semi-infinite pure elastic circular cylinder in constant bending has been investigated. Despite of the simplicity of the geometry and the loading conditions, attempts to find analytical solutions based on the shell theory according to Flügge [3] modified by Hoff [4] have not been successful. Therefore, the finite element method has been used to determine the resistance to bending. The lining has been modelled using shell elements. In Chapter 2 the finite element model is described and in Chapter 3 the results of the finite elements analyses are presented. In Chapter 4 some conclusions are drawn and recommendations are made.
Fig 1.2 The boreholes in the HAW test field.
2 THE FINITE ELEMENT ANALYSES

2.1 The Modelling Assumptions

The finite element analyses have been performed for the lining with the general purpose finite element code ANSYS 4.4a [5] as installed on the CONVEX 220S at ECN. The geometry of the lining in borehole A1 is presented in Table 1.

<table>
<thead>
<tr>
<th>inner radius a in mm</th>
<th>thickness h in mm</th>
<th>length L in m</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>18</td>
<td>16.4</td>
</tr>
</tbody>
</table>

The lining is modelled by a cylindrical tube. For symmetry reasons only a quarter of the cylinder section has to be modelled. The model is created parametrically; this means that the tube length, the inner radius, the tube thickness, the number of elements in axial ($N_a$) and in circumferential ($N_c$) direction can be arbitrarily selected and that subsequently a finite element mesh is created. In appendix A an example of such a parametric input file is given and in Fig. 3 a schematic representation of a finite element mesh of the cylinder section is shown for 10 elements in circumferential direction and 5 elements in axial direction.

![Figure 3](image)

**Figure 3** Schematic description of the mesh ($N_a = 5$ and $N_c = 10$).

2.2 The Element Choice

The element type used is an elastic quadrilateral shell element. This element has four nodes and six degrees of freedom at each node (STIFF63 in the ANSYS 4.4a element-library). The large deflection option is included. For the load application a three-dimensional beam element (STIFF4) is used (see Section 2.4).

2.3 The Material Properties

The material behaviour is assumed to be linear elastic. $E = 2.1 \times 10^6$ MPa and $\nu = 0.3$ have been selected for Young's modulus and the Poisson ratio, respectively.
Figure 4  Schematic description of the geometry.

\[ \theta = \frac{2}{\pi} \sin \theta \]

\[ 2(1 - \cos \theta) \]

Figure 5  Description of the relationship between the radius of curvature \( R \), the deflection \( d \), and the arc length \( L \) of the centre line and the rotation angle \( \beta \).

\[ d = \frac{L}{2\beta} (1 - \cos \beta) \]

\[ \kappa = \frac{1}{R} = \frac{2\beta}{L} \]
2.4 The Boundary Conditions and Loading

In Fig. 4 a schematic representation of a cylinder section is given. Every point P(r,θ,z) in space has six degrees of freedom: the displacements u, v and w in radial, circumferential and axial direction, respectively, as well as the rotation angles along these directions denoted by rotu, rotv and rotw, respectively. The following boundary conditions are used along the symmetry planes OQB and ABC:

\[
\begin{align*}
\text{OQB:} & \quad w = 0, \text{rotu} = 0, \text{rotv} = 0 \\
\text{ABC:} & \quad v = 0, \text{rotu} = 0, \text{rotw} = 0
\end{align*}
\]  

(1)

The cylinder is considered to be loaded by a bending moment as to establish a constant radius of curvature of the centre line OE (cf. Fig. 5). This leads to an identical ovality of every cross section at a sufficient distance from the edges. This ovality is only dependent on the rotation angle β and the arc length L of the cylinder:

\[
κ = \frac{1}{R} = \frac{2β}{L}
\]

(2)

Accordingly, the ovality of the lining can be analyzed with any cylinder of identical cross section bent as to establish an identical radius of curvature of the centre line. The required length should only exceed the size of the zone influenced by edge effects. The rotation angle β₂ of a second cylinder with arc length L₂, selected as to establish an identical radius of curvature R, can be calculated as

\[
β₂ = β \frac{L₂}{L}
\]

(3)

For the load application two extra nodes E and F, connected by a beam element, have been introduced. The nodes in the cross section CDF are coupled to the node in E by constraint equations, the axial displacements w are coupled to the rotation angle β. The rotation angle β along EF is imposed and thus introduces a constant curvature in the centre line OE. It appeared that a small displacement component u' in the plane CDF was introduced (cf. Fig 6). This edge effect leads to an extra ovality and will damp out at a sufficient distance from the plane CDF.

For small rotation angles a linear approximation is justified, hence the radius of curvature R and the deflection d satisfy

\[
d = \frac{βL}{4} = \frac{L²}{8R}
\]

(4)

Table 2 shows a relationship between the lining and a geometry with identical radius of curvature.

<table>
<thead>
<tr>
<th>L in m</th>
<th>d in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.4</td>
<td>d</td>
</tr>
<tr>
<td>L₂</td>
<td>d(L₂/16.4)³</td>
</tr>
</tbody>
</table>
Figure 6  Displacement component $u'$ as a result of the load application.
3 THE RESULTS OF THE FINITE ELEMENT ANALYSES

Table 3 shows the eight finite element analyses that have been performed. Primarily, the influence of the loading level on the shape of the cross section has been investigated. An initial radius of curvature $R = 2500 \text{ m}$ has been selected and has been halved up to and including analysis 4 and has been divided by 10 in analysis 5. Secondly, the influence of the arc length $L$ on the deformation has been investigated (analyses 3 and 6).

Table 3. The finite element analyses that have been performed. $N_c = 14$, $N_n = 50$ for $L = 20$, and $N_n = 20$ for $L = 8$.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$L$ in m</th>
<th>$h$ in mm</th>
<th>$R$ in m</th>
<th>$d$ in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>18</td>
<td>2500.00</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>18</td>
<td>1250.00</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>18</td>
<td>625.00</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>18</td>
<td>312.50</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>18</td>
<td>31.25</td>
<td>1600</td>
</tr>
<tr>
<td>6</td>
<td>8°</td>
<td>18</td>
<td>625.00</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>9°</td>
<td>2500.00</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>4.5°</td>
<td>2500.00</td>
<td>20</td>
</tr>
</tbody>
</table>

*1) Influence of the arc length $L$
*2) Influence of the wall thickness $h$

In the following ovality is defined by the ratio of the radial displacement $u$ at $\theta = 90^\circ$ and the inner radius $a$. Fig. 7 shows the ovality $u/a$ cast as a function of the axial coordinate $z$. Theoretically, the ovality should be independent of the axial coordinate $z$. However, an edge effect is caused by the cross section where the load is applied, and the ovality at the symmetry planes OQB and the ovality at the cross section ECF are opposite in sign and unequal in magnitude. This edge effect damps out and at increasing loading levels ($R = 31.25 \text{ m}$) the ovality appears to be constant at distances more than 3 m away from the edge. The ovality at the symmetry plane OQB is presented in Fig. 8. A nonlinear relationship between the ovality and the curvature is clear.

In Fig. 9 a model with 8 m of length was compared with the longer model used in analysis 3. A radius of curvature $R = 625 \text{ m}$ has been applied. It appears that for this curvature the both models give the same ovality.

The influence of the wall thickness has also been investigated for an imposed radius of curvature $R = 2500 \text{ m}$ (analyses 1, 7 and 8). In Fig. 10 it appears that even when the thickness of the tube is reduced to 25% of the original thickness, the ovality remains smaller than $3 \times 10^4$ (0.03%).

It appeared that 1010 days after the heaters were started ovality of at least $1.43 \times 10^3$ was measured in borehole B1 [6]. To predict a value of $1.43 \times 10^3$ for the ovality with a calculation model the lining would have to be bent as to establish a radius of curvature $R = 64.51 \text{ m}$, as follows directly from Fig. 8. According to (4), this would result in a deflection $d = 0.52 \text{ m}$ for the centre line of the lining. Furthermore, the wall thickness of borehole B1 is 25 mm so a cylinder section with $h = 25 \text{ mm}$ would have to be bent even more than the current calculation model. Consequently, it is unlikely that the ovality as measured in a cross section can be explained by bending of the lining.
Figure 7  
Vlalitv of  
oller for various radii of curvature.

Figure 8  
Influence of curvature on the ovality at the symmetry plane.
Figure 9 Influence of the tube length on the ovality of the cylinder.

Figure 10 Influence of the wall thickness on the ovality of the cylinder.
4 CONCLUSIONS AND RECOMMENDATIONS

Finite element calculations have been made to analyze a possible cause of ovality in a cross section of the lining in the boreholes in the HAW test field. The lining has been considered to be loaded by a bending moment as to establish a constant radius of curvature of the centre line. The following conclusions can be drawn:

- The calculation model was long enough to successfully analyze the ovality of the lining. The size of the zone influenced by the edge effects was smaller than 4 m in all load cases considered.

- The relationship between the ovality and curvature is nonlinear.

- It is unlikely that the ovality in a cross section of borehole B1, as derived from the experimental data, can be explained by bending of the lining.

Since bending is not the cause of the ovality found in borehole B1, there must be another cause. A possible cause could be a variation in the radial pressure along the circumference as will be outlined in the following. In [1] it is stated that when there is full contact between salt and lining and axial interaction is ignored, the following relationship between the radial pressure change \( p \) and the maximum radial displacement \( u \) exists at any time \( t \):

\[
p(t, \theta) = u(t) \frac{3Eh^3}{8a^4} \cos^2 \theta - 1232.16 \frac{u(t)}{a} \cos 2\theta \tag{5}
\]

This means that if a lower bound of \( 1.43 \times 10^3 \) for the ovality in borehole B1 is assumed to be caused by pressure changes in circumferential direction, a pressure variation of \( 2p = 3.52 \) MPa would have to be present, a value that could very well be possible. Therefore, the ovality of the lining caused by potential pressure load variations in circumferential direction of the lining should be the subject of future studies.
REFERENCES

[1] Prij, J.:  


APPENDICES

Appendix A An Input File of the Parametric Finite Element Model

```
/COM
/COM
R = .219
T = .018
L = 10
NA = 50
NR = 14
DL=L/NA
RANG=.004
/COM
ISHA=0
/COM
/PREP7
/VIEW,1,1,1,1
/TITLE, INFINITE STRAIGHT TUBE S
/COM
KAN,0
KAY,6,1
CNVR,,0.000001
ET,1,63,,ISHA
R,1,T
ET,2,4
/COM
MP,EX,1,2100000
MP,NUXY, 1,0.3
MP,EX,2,1
/COM
/COM
/COM
CLOCAL,11,1
N,1,R,,
N,NR+1,R,180
FILL,1,NR+1,NR-1,2,1
NGEN,NA+1,NR+1,1,NR+1,1,,DL
E,1,NR+2,NR+3,2
EGEN,NR,1,1
EGEN,NA,NR+1,1,NR,1
MAT,2
TYPE,2
R,2,1,1,1,1
N,(NR+1)*(NA+1)+1,, 1
N,(NR+1)*(NA+1)+2,R/2,,L
E,,(NR+1)*(NA+1)+1,,((NR+1)*(NA+1)
/COM
D,1,UX,
/COM
CSYS,0
NSEL,Z,0
```

- Initialize geometry (length in m)
- Inner radius of the steel tube
- Thickness of the steel tube
- Half the length of the steel tube
- Number of elements in axial direction
- Number of elements in radial direction
- Length of element in axial direction
- Rotation angle for load application
- Initialize parameters
- No extra displacements shapes
- Entering the preprocessor

- Static analysis
- Large deflection analysis
- Tolerance criterion for large displacements
- Elastic quadrilateral shell element
- Input of the thickness
- Three-dimensional elastic beam
- Material properties
- Young's modulus
- Poisson ratio
- Stiffness for beam element (STIFF3)

Geometry definition

Define cylindrical coordinate system

Fixing the geometry to the world

Symmetry boundary conditions
D,ALL,UZ,0
D,ALL,ROTX,0
D,ALL,ROTY,0
NSELY,0
D,ALL,UY,0
D,ALL,ROTX,0
D,ALL,ROTY,0
NAULL
D,(NR+1)*(NA+1)+1,ROTY,RANG
/COM
NSELZ,L
NUSEL,NODE,(NR+1)*(NA+1)+2
CERIG,(NR+1)*(NA+1)-1,ALL
*SET,K,1
:STRT
*IF,K,GT,NR+1,:END
CEDELE,1+((K-1)*6),2+((K-1)*6)
CEDELE,4+((K-1)*6),6+((K-1)*6)
*SET,K,K+1
*GO,:STRT
:END
CECOMPR
NAULL
ITER,-10,1,1
AFWRITE,,1

* Load application
* Coupled degrees of freedom

* Definition of master and slave

* Deleting some constraint equations
* Deleting some constraint equations
Appendix B  Magnetic Tape

The analysis files are stored on a 9 track 6250 BPI tape, created with the BACKUP-utility on the CONVEX. The VSN number of the tape is 1726 and the tape has no password. The name of each file includes all the necessary information about the contents. All the results of the analyses are stored on the directories HAW. For example:

<table>
<thead>
<tr>
<th>Files</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>/analysis1/comfile</td>
<td>command include file</td>
</tr>
<tr>
<td>/analysis1/start</td>
<td>jobfile</td>
</tr>
<tr>
<td>/analysis1/file12.dat</td>
<td>postfile</td>
</tr>
</tbody>
</table>