Memorandum M-542

INITIAL IMPERFECTIONS OF SHELLS TESTED AT THE
DET NORSKE VERITAS RESEARCH LABORATORIES

by

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Delft - The Netherlands

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ACKNOWLEDGEMENT

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<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_r, A_s$</td>
<td>cross-sectional area of plate and stiffener (or ring)</td>
</tr>
<tr>
<td>$D_r$</td>
<td>$s_r E t^3/(12(1-\nu^2))$</td>
</tr>
<tr>
<td>$D_s$</td>
<td>$s_s E t^3/(12(1-\nu^2))$</td>
</tr>
<tr>
<td>$E$</td>
<td>Young's modulus</td>
</tr>
<tr>
<td>$e_r, e_s$</td>
<td>eccentricity of rings and stiffeners (from local centre of gravity to the middle of the shell plate)</td>
</tr>
<tr>
<td>$h_r, h_s$</td>
<td>height of ring and stiffener</td>
</tr>
<tr>
<td>$I_r, I_s$</td>
<td>moment of inertia about local centre of gravity for ring and stiffener</td>
</tr>
<tr>
<td>$L$</td>
<td>shell length</td>
</tr>
<tr>
<td>$NR$</td>
<td>number of data points in the axial direction</td>
</tr>
<tr>
<td>$NC$</td>
<td>number of data points in the circumferential direction</td>
</tr>
<tr>
<td>$R$</td>
<td>shell radius</td>
</tr>
<tr>
<td>$t$</td>
<td>shell thickness</td>
</tr>
<tr>
<td>$s_r, s_s$</td>
<td>spacing between ring and stiffeners</td>
</tr>
<tr>
<td>$\sigma_{col}$</td>
<td>column buckling stress for stiffeners</td>
</tr>
<tr>
<td>$\sigma_{equiv}$</td>
<td>smeared out stiffeners (increased thickness $t_{equiv}$) $0.6E t_{equiv}/R$</td>
</tr>
<tr>
<td>$\sigma_{cl}$</td>
<td>$0.6E t/R$, classical buckling stress</td>
</tr>
<tr>
<td>$\sigma_Z$</td>
<td>$(4\pi^2 E/12(1-\nu^2))(t/s_E)^2$</td>
</tr>
<tr>
<td>$\sigma_{teo}$</td>
<td>theoretical buckling stress, calculated by BOSOR, ref. 3, perfect geometry (no imperfections)</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>yield stress</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson's ratio</td>
</tr>
<tr>
<td>$\delta$</td>
<td>imperfection amplitude</td>
</tr>
</tbody>
</table>
SUMMARY

This report describes the process of data acquisition from tapes containing results of initial imperfections of axial stiffened and ring stiffened shells. The measurements were carried out at the Det Norske Veritas Research Laboratories in Oslo. The data have been recorded in binary form on magnetic tape using an A/D converter. The binary data of the initial imperfections are converted to the format of the Initial Imperfection Data Bank at the Delft University of Technology. Computer plots of the initial imperfections of the different shells are given when they are folded out. One can conclude that the shapes of the measured initial imperfections are clearly influenced by details of the shell construction.
1. INTRODUCTION

At the Department of Aerospace Engineering of the Delft University of Technology a research project is carried out on the influence of initial imperfections on the buckling loads of shells. Methods are examined to help the structural engineer to predict the buckling behaviour of shells considering the effect of the imperfection characteristics of the appropriate fabrication process. Recently, imperfection measurements of 35 circular cylindrical shells of different sizes are presented in the Initial Imperfection Data Bank (see ref. 1, 2).

At the Det Norske Veritas Research Laboratories imperfection measurements are done in connection with the development of the Moss Rosenberg self-supporting spherical LNG tanks (see ref. 3, 4). The main object of the experiments was to study the effect of imperfections on the elastic buckling strength of axial stiffened and ring stiffened shells.

The following shells were tested:
- Kvaerner models: 4 large axial stiffened and 1 ring stiffened cylindrical shell. Radius and shell thickness of the models are 1250 mm and 3 mm;
- Aker models: 4 large ring stiffened cylindrical shells. Radius and shell thickness of the models are 600 mm and 2.5 mm.

The imperfections are measured and have been recorded in binary form on magnetic tape using an 8 channel A/D converter.

This report deals with the process of interpretation of the binary imperfection data of the tapes of DNV. The process consists of the following steps:
- conversion of the binary data to the format of the Initial Imperfection Data Bank. (see also ref. 5);
- graphical representation of the imperfections of the different shells; a computer program has been written to plot the imperfection data. The VS-FORTRAN program can be found in APPENDIX 1. The computer plots of this report are the same as the graphical representation given in ref. 3 and 4.

2. DESCRIPTION AND STORAGE OF THE IMPERFECTIONS

2.1. Test rig at Det Norske Veritas

The measurements of the initial imperfections have been carried out by using a test rig in which the shell was fixed (see fig. 1). The measuring device was mounted on a carriage, run manually in a machined rail around the shell, describing a reference cylinder of assumed perfect shape (see fig. 2). While moving the carriage, the imperfections were measured continuously with the displacement transducer. For a complete description of the process see ref. 3 and 4. The imperfections were stored in binary form with an A/D converter on 3 tapes: GROV01, GROV02 and GROV03. For the exact description of the binary data we refer to ref. 5.
2.2. Data acquisition

With help of the FORTRAN program written by van Baten (see ref. 5), all the 3 tapes could be analysed.
The binary data were converted to the format of the Initial Imperfection Data Bank with the help of this program.

The imperfections are stored in dataset VLST.DE TNOR.DA TA. Each member of this partitioned dataset contains the scaled imperfections of a shell. The data are stored in sequential order: 1000 equidistant intervals for each complete circumferential scan.
Characteristics of data set VLST.DE TNOR.DA TA:
- PARTITIONED ORGANISATION;
- RECFM = FB; BLKSIZE = 3200.
Imperfections of the Aker models can be found in the members A1 up to A4 (A1: Aker model no. 1).
Imperfections of the Kvaerner models are stored in the members K1 up to K5 (K1 Kvaerner model no. 1).
Every member contains NR x NC data points (NR and NC can be found in table 1 up to table 3).
For more information see APPENDIX I.
The axial positions of the measurement sections are also given in APPENDIX I.

3. INITIAL IMPERFECTIONS OF THE KVAERNER MODELS

3.1. Geometry of the models

The Kvaerner models consist of 4 large axial stiffened and 1 ring stiffened cylindrical shell (see fig. 3 and fig. 4). In table 1 and table 2 important characteristic parameters are given of the Kvaerner models. The data can be found in ref. 3.
The models were made of aluminium alloy. The stiffeners and rings are welded to the shell with staggered fillet weld with a welded length of 100 mm.

3.2. Kvaerner model no. 1

The geometry of the first Kvaerner model is shown in fig. 5.
The initial imperfections are measured at the sections shown in fig. 6.
Fig. 7 shows the initial imperfections when the shell is folded out.
At angle 258° 8/t is in the order of 2.6. At angle 95° the 8/t is in the order of 1.0.

3.3. Kvaerner model no. 2

Fig. 8 shows the geometry of Kvaerner model no. 2.
The initial imperfections are measured at the sections shown in fig. 9.
The distribution of the imperfections in the circumferential direction for the different sections are shown in fig. 10. The 8/t - values vary from 2.5 to 1.5.

3.4. Kvaerner model no. 3

The geometry of the model is shown in fig. 11.
The recorded imperfections are measured at the sections shown in fig. 12. The imperfections are shown in fig. 13. The recorded $\delta/t$ values are in the order of 1.4 - 1.9.

3.5. Kvaerner model no. 4

Fig. 14 shows the geometry and fig. 15 shows at which sections the imperfections are measured. Fig. 16 shows the imperfections when the shell is folded out. The recorded $\delta/t$ are up to about 2.0.

3.6. Kvaerner model no. 5

The geometry of the model is shown in fig. 17. The sections at which the imperfections are measured are shown in fig. 18. Fig. 19 shows the imperfections for different axial positions. The imperfections between the rings are very small ($\delta/t = 0.15$).

4. INITIAL IMPERFECTIONS OF THE AKER MODELS

4.1. Geometry of the models

The Aker models consist of 4 large ring stiffened cylindrical shells (see fig. 20). In table 3 important characteristic parameters are given of the Aker models. The data can be found in ref. 4. The models are made of aluminium alloy (AlZnMg) with a $\sigma_y$ of 4200 kp/cm$^2$. The rings are welded to the shell with staggered fillet weld with a welded length of 100 mm. The shell was rolled to correct radius and weld to a cylindrical shell. The models have not been heated. For more extensive information we refer to ref. 4.

4.2. Aker model no. 1

The geometry of the model is shown in fig. 21. The initial imperfections are measured at the sections shown in fig. 22. Fig. 23 shows the imperfections when the shell is folded out. The imperfections in the circumferential direction are considerable ($\delta/t$ is about 1.0). The vertical welds are assumed to be located at angles 75°, 165°, 255° and 345°.

4.3. Aker model no. 2

The geometry of the model is shown in fig. 24. Fig. 26 shows the imperfections at the sections shown in fig. 25. The imperfections in the circumferential direction are 0.6 times the plate thickness. The vertical welds are located at angles 40°, 130°, 225° and 310°.

4.4. Aker model no. 3

Fig. 27 shows the geometry of the model. The recorded imperfections are measured at the sections shown in fig. 28.
The imperfections are shown in fig. 29; they are very small.

4.5. Aker model no. 4

The geometry is shown in fig. 30. Fig. 32 shows the imperfections at the sections shown in fig. 31. The imperfections measured in the circumferential direction are equal to about half of the shell thickness. The vertical weld is assumed to be at angle 120°.

5. CONCLUSIONS

The conversion of the binary imperfection data into the format of the Initial Imperfection Data Bank was carried out successfully. Only minor differences can be found in the imperfection data comparing ref. 3 and ref. 4 with the figures presented in this report.

6. REFERENCES


Appendix I: Graphical representation of the imperfections

Purpose of the program

VS-PORTRAN program to plot initial imperfections of shells tested at the Det Norske Veritas Research Laboratories. Kvaerner and Aker models can be plotted. The imperfections are plotted with the scale used in ref. 3 and ref. 4.

Usage

The input data are in "free formatted" form (each data element should be separated by at least one blank or comma).

Card 1

R : radius of the shell (mm)
SL : shell length (mm)
T : wall thickness of the shell (mm)

Card 2

NCIRC : number of axial measurements sections
NS : number of axial ref. sections including end rings
NM : axial section number at which the measurements starts
NR : number of rings of the shell
NSCAN : number of points per circumferential scan (equal to 1001)

Card 3

PFACT : plotting scale factor (PFACT=1: 1 P.U. (plotting unit) = 1 inch)
XX : X position of down left corner of plotting frame (in plotting units)
YY : Y position of down left corner of plotting frame (in plotting units)
PUX : number of plotting units in X-direction
PUY : number of plotting units in Y-direction

Card 4

REF(i) (i=1, NTOT) (read from unit 8)
NTOT = NS + NR
NS axial positions of sections and NR axial ring positions (in mm)
Card 5

W(i) (i=1, NIMP) (read from unit 9)
NIMP = NCIRC * NSCAN
Normalized initial imperfections (+ outward; - inward)
Warning: the plotted imperfections are not normalized!

External files used by the program

Unit 8 : VLST.DETNOR2.DATA (**)
PARTITIONED ORGANIZATION (each shell 1 member)
RECFM = FB; LRECL = 80; BLKSIZE = 3200
Axial positions (mm) of sections and rings

Unit 9 : VLST.DETNOR.DATA (**)
PARTITIONED ORGANIZATION (each shell 1 member)
RECFM = FB; LRECL = 80; BLKSIZE = 3200
Normalized imperfections; for each axial station the data are stored in circumferential order.

Libraries used

The program uses the graphical CALCOMP package.

Storage

The source and JCL are stored in VLST.DETNOR2.CNTL (PLOTA LL)
After successful running of the program, the binary plotdata are stored in VLST.DETNOR2.PLOT(**).

In fig. 33 an example is given of the plotting of Aker model no. 1. Last but not least we will give a listing of the program (input data belong to Aker model no. 1).
LISTING OF THE PROGRAM

/ //VLSTP#1 JOB ('ACCTN',71),'NAME',TIME=(00,05),REGION=1500K,
/ MSGCLASS=A
/ JOBPARM Q=F,I
/**************************************************************************
/ *                    INPUT CARDS FOR AKER MODEL #1
/**************************************************************************
/ EXEC F77TCLG
/ FORT.SYSIN DD *
C----- PURPOSE
C-----
C PROGRAM TO PLOT INITIAL IMPERFECTIONS OF SHELLS
C TESTED AT THE DET NORSKE VERITAS RESEARCH LABORATORIES.
C KVAERN AND AKER MODELS CAN BE PLOTTED.
C-----
C INPUT DESCRIPTION : ALL INPUT IN FREE FORMATTED FORM
C-----
C CARD #1 : R,SL,T
C R : RADIUS OF THE SHELL (MM)
C SL : SHELL LENGTH (MM)
C T : WALL-THICKNESS OF THE SHELL (MM)
C CARD #2 : NCIRC,NS,NM,NR,NSCAN
C NCIRC : NUMBER OF AXIAL MEASUREMENT SECTIONS
C NS : NUMBER OF AXIAL REF. SECTIONS INCLUDING END-RINGS
C NM : AXIAL SECTION NUMBER AT WHICH THE MEASUREMENTS STARTS
C NR : NUMBER OF RINGS ( END-RINGS NOT INCLUDED )
C NSCAN : NUMBER OF POINTS PER CIRCUMFERENTIAL SCAN (1001)
C CARD #3 : PFACT,XX,YY,PUX,PUY
C PFACT : PLOTTING FACTOR ( PFACT = 1 MEANS 1 P.U. = 1 INCH )
C XX : X POSITION OF DOWN LEFT CORNER OF PLOT FRAME
C ( IN PLOTTING UNITS )
C YY : Y POSITION OF DOWN LEFT CORNER OF PLOT FRAME
C ( IN PLOTTING UNITS )
C PUX : NUMBER OF PLOTTING UNITS IN X-DIRECTION
C PUY : NUMBER OF PLOTTING UNITS IN Y-DIRECTION
C CARD #4 : REF(I), I=1,NTOT ( READ FROM UNIT 8 )
C NTOT = NS * NR
C REF(I) : NS AXIAL POSITIONS OF SECTIONS AND NR AXIAL RING
C POSITIONS
C CARD #5 : W(I), I=1,NIMP ( READ FROM UNIT 9 )
C NIMP = NCIRC * NSCAN
C W(I) : NORMALIZED IMPERFECTIONS (+ OUTWARD ; - INWARD )
SUBROUTINES CALLED BY THIS PROGRAM
PLOTS, FACTOR, CLIPY, PLOT, DASHP, AROHD, LASPLO
SUBROUTINES ARE FROM THE CALCOMP PACKAGE

COMMON BLOCKS USED BY THIS PROGRAM
NONE

EXTRA USER INFORMATION

COMPILER USED : VS - PORTRAN
STORAGE OF SOURCE : VLST.DETNOR2.CNTL(PLOTALL)
LAST UPDATE : OCTOBER 1985

START OF MAIN PROGRAM
DEclarations

DIMENSION W(26026),REF(50),PREF(50),PRING(50)
DIMENSION YYY(50),YARR(50)
DIMENSION X(1500),Y(1500),WW(1500)

READ INPUT

READ(5,*) R,SL,T
READ(5,*) NCIRC,NS,NM,NR,NSCAN
NTOT=NS + NR
NIMP= NCIRC * NSCAN
READ(5,*) PFACT,XX,YY,PUX,PUY
PPUY=PUY-1
READ(8,*) (REF(I),I=1,NTOT)
REWIND 8
READ(9,9000) (W(I), I=1,NIMP)
REWIND 9

OUTPUT

WRITE(6,*) 'R,SL,T'
WRITE(6,*) R,SL,T
WRITE(6,*) 'NCIRC,NS,NM,NR,NSCAN,NTOT,NIMP'
WRITE(6,*) NCIRC,NS,NM,NR,NSCAN,NTOT,NIMP
WRITE(6,*) 'REF(I)'
WRITE(6,*) (REF(I),I=1,NTOT)
WRITE(6,*) 'PFACT,XX,YY,PUX,PUY,PPUY'
WRITE(6,*) PFACT,XX,YY,PUX,PUY,PPUY

CHANGE SIGN OF IMPERFECTIONS

DO 10 I=1,NIMP
     W(I)=W(I)
10 CONTINUE
CALCULATION OF PREF AND PRING

PREF(I) : SCALED REF(I) : AXIAL POSITIONS OF SECTIONS
PRING(I) : SCALED AXIAL RING POSITIONS

DO 20 I = 1, NS
   PREF(I) = REF(I) / SL
20 CONTINUE
DO 30 I = 1, NR
   PRING(I) = REF(NS + I) / SL
30 CONTINUE
WRITE(6, *) 'PREF(I)'
WRITE(6, *) (PREF(I), I = 1, NS)
WRITE(6, *) 'PRING(I)'
WRITE(6, *) (PRING(I), I = 1, NR)

PLOTTING OF FRAME

CALL PLOTS(1, 15)
CALL FACTOR(PFACT)
CALL CLIPY(1)
CALL PLOT(XX, YY, 3)
CALL PLOT(XX + PUX, YY, 2)
CALL PLOT(XX + PUX, YY + PUY, 2)
CALL PLOT(XX, YY + PUY, 2)
CALL PLOT(XX, YY, 2)

PLOTTING OF --- DASHED LINES ---

VERTICAL

DO 40 I = 1, 3
   DX = (PUX / 4.) * I
   CALL PLOT(XX + DX, YY, 3)
   CALL DASHP(XX + DX, YY + PUY, 0.1)
40 CONTINUE

HORIZONTAL

DO 50 I = 1, NS
   YYY(I) = YY + 0.5 + PREF(I) * PPUY
   CALL PLOT(XX, YYY(I), 3)
   CALL DASHP(XX + PUX, YYY(I), 0.1)
50 CONTINUE

ARROWS --> FOR RING POSITIONS OF THE SHELL

DO 60 I = 1, NR
   YARR(I) = YY + 0.5 + PRING(I) * PPUY
   CALL AROHD(XX - 0.5, YARR(I), XX, YARR(I), 0.3, 0., 11)
60 CONTINUE

PLOTTING OF IMPERFECTIONS

MULTIPLICATION OF NORMALIZED W(I) WITH T/4 TO GET SCALE USED IN D.N.V. REPORTS.

T4 = T/4.
DO 70 I = 1, NIMP
   W(I) = T4 * W(I)
70 CONTINUE
X-COORDINATES X(I)

X(I) = 0.E+00 + XX

DDX = PUX / (NSCAN-1)

DO 80 I=2,NSCAN

X(I) = X(I-1) + DDX

80 CONTINUE

Y-COORDINATES Y(I) AND PLOTTING THEM (STARTING AT SECTION # NM)

DO 90 I=1,NCIRC

DO 100 J=1,NSCAN

WW(J) = W((I-1) * NSCAN + J)

Y(J) = YY + 0.5 + PPUY + WW(J)

100 CONTINUE

CALL PLOT(X(1),Y(1),3)

DO 110 K=2,NSCAN

CALL PLOT(X(K),Y(K),2)

110 CONTINUE

90 CONTINUE

END PLOTTING

CALL LASPLO

STOP

FORMAT(6E12.5)

END

//LIKED.SYSLIB DD
//                    DD
//                    DD DSN=SYS2.PLOTLIBF,DISP=SHR
//GO.FT08F001 DD DSN=VLST.DETNOR2.DATA(A1),DISP=SHR
//GO.FT09F001 DD DSN=VLST.DETNOR.DATA(A1),DISP=SHR
//GO.PILODS DD DSN=VLST.DETNOR2.PLOT(A1),DISP=SHR

/************ INPUT DATA FOR AKER MODEL NO. 1 *******************/
//GO.SYSIN DD *
600 960. 2.5
14 16 2 5 1001
0.787 2. 2. 9. 12.

//
Table 1. Geometry and characteristic parameters for Kvaerner models no's 1, 2, 3, and 4

<table>
<thead>
<tr>
<th>KVAERNER MODEL NO.:</th>
<th>1</th>
<th>2 and 3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR x NC</td>
<td>15x1001</td>
<td>17x1001</td>
<td>17x1001</td>
</tr>
<tr>
<td>Shell thickness t (mm)</td>
<td>3.5</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Number of axial stiffeners</td>
<td>80</td>
<td>85</td>
<td>60</td>
</tr>
<tr>
<td>Stiffener spacing $s_g$ (mm)</td>
<td>109.1</td>
<td>92.4</td>
<td>132.7</td>
</tr>
<tr>
<td>Stiffener size, $h_{sgxt}$ (mm)</td>
<td>21.8x3.5</td>
<td>18.8x3.0</td>
<td>21.8x3.0</td>
</tr>
<tr>
<td>$A_g/s_g\cdot t$</td>
<td>0.20</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>$EI_g/s_g\cdot D_g$</td>
<td>7.8</td>
<td>7.3</td>
<td>7.8</td>
</tr>
<tr>
<td>$e_g/t$</td>
<td>3.6</td>
<td>3.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Internal radius (mm)</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
</tr>
<tr>
<td>R/t</td>
<td>360</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>Shell length L (mm)</td>
<td>1334</td>
<td>1264</td>
<td>1264</td>
</tr>
<tr>
<td>$\sigma_{col}$ (Kp/cm²)</td>
<td>500</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>$\sigma_{eqv}$ (Kp/cm²)</td>
<td>1450</td>
<td>1250</td>
<td>1200</td>
</tr>
<tr>
<td>$\sigma_\lambda$ (Kp/cm²)</td>
<td>2680</td>
<td>2640</td>
<td>1320</td>
</tr>
<tr>
<td>$\sigma_{teo}$ (Kp/cm²)</td>
<td>2400</td>
<td>2100</td>
<td>2200</td>
</tr>
<tr>
<td>Numer of $2\pi$ waves around model</td>
<td>13</td>
<td>13</td>
<td>13</td>
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</tbody>
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Table 2. Geometry and characteristic parameters for Kvaerner model 5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR x NC</td>
<td>26x1001</td>
</tr>
<tr>
<td>Shell thickness t (mm)</td>
<td>3.0</td>
</tr>
<tr>
<td>Radius R (mm)</td>
<td>1250</td>
</tr>
<tr>
<td>Shell length L (mm)</td>
<td>1120</td>
</tr>
<tr>
<td>Number of ring frames</td>
<td>9</td>
</tr>
<tr>
<td>$s_r$, spacing between rings (mm)</td>
<td>123</td>
</tr>
<tr>
<td>$s_s$ / $R_t$</td>
<td>2.0</td>
</tr>
<tr>
<td>$A_r$ / $s_r$ . $t$</td>
<td>0.20</td>
</tr>
<tr>
<td>$E I_r$ / $D_r$ . $s_r$</td>
<td>13.0</td>
</tr>
<tr>
<td>$e_r$ / $t$</td>
<td>4.6</td>
</tr>
<tr>
<td>Rings, $h_r xt$ (mm)</td>
<td>25x3</td>
</tr>
<tr>
<td>$\sigma_{c_L}$ (Kp/cm²)</td>
<td>1035</td>
</tr>
<tr>
<td>$\sigma_{teo}$ (Kp/cm²)</td>
<td>1220</td>
</tr>
</tbody>
</table>
Table 3. Geometry and characteristic parameters for the Aker models

<table>
<thead>
<tr>
<th>AKER MODEL NO:</th>
<th>1 and 2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR x NC</td>
<td>{ model1: 14x1001 }</td>
<td>20x1001</td>
<td>19x1001</td>
</tr>
<tr>
<td>Radius, R (mm)</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Shell thickness t (mm)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Shell length L (mm)</td>
<td>960</td>
<td>960</td>
<td>960</td>
</tr>
<tr>
<td>Number of rings</td>
<td>5</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>( s_r ), spacing between rings (mm)</td>
<td>200</td>
<td>133</td>
<td>266</td>
</tr>
<tr>
<td>( s_r / R_t )</td>
<td>5.16</td>
<td>3.44</td>
<td>6.87</td>
</tr>
<tr>
<td>Rings, ( h_r \times t ) (mm)</td>
<td>26x2.5</td>
<td>29x2.5</td>
<td>31x2.5</td>
</tr>
<tr>
<td>( A_r / s_r \times t )</td>
<td>0.13</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>( e_r / t )</td>
<td>5.7</td>
<td>6.3</td>
<td>6.7</td>
</tr>
<tr>
<td>( EI_r / D_r \times s_r )</td>
<td>12.8</td>
<td>26.7</td>
<td>16.3</td>
</tr>
<tr>
<td>R/t</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>( \sigma_{cl} ) (KPa/cm²)</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Number of 2\pi waves (minimum buckling load)</td>
<td>18</td>
<td>21</td>
<td>16</td>
</tr>
</tbody>
</table>
Fig. 1. Test rig used at Det Norske Veritas.
Fig. 2. Mapping of initial imperfections.
Fig. 3. Axial stiffened Kvaerner model.
Fig. 4. Ring stiffened Kvaerner model.
Fig. 5. Geometry of Kvaerner model no. 1.
Fig. 6. Measurement sections of Kvaerner model no. 1.
INITIAL IMPERFECTIONS OF KVAERNER MODEL NO. 1

Position of rings, see fig. 6.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 6.

Scale on imperfections measured from ref. surface

Fig. 7. Kvaerner model no. 1.
Fig. 8. Geometry of Kvaerner model no. 2.
SECTIONS WHERE THE INITIAL GEOMETRY WAS MEASURED
KVÆRNER MODEL NO. 2

Fig. 9. Measurement sections of Kvaerner model no. 2.
INITIAL IMPERFECTIONS OF KVAERNER MODEL NO. 2

Position of rings, see fig. 9.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 9.

Scale on imperfections measured from ref. surface

Fig. 10. Kvaerner model no. 2.
Fig. 11. Geometry of Kvaerner model no. 3.
Fig. 12. Measurement sections of Kvaerner model no. 3.
INITIAL IMPERFECTIONS OF KVAERNER MODEL NO. 3.

Position of rings, see fig. 12.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 12.

Scale on imperfections measured from ref. surface

Fig. 13. Kvaerner model no. 3.
Fig. 14. Geometry of Kvaerner model no. 4.
Sections where the initial geometry was measured
Kvaerner model No. 4

Fig. 15. Measurement sections of Kvaerner model no. 4.
INITIAL IMPERFECTIONS OF KVAERNER MODEL NO. 4.

Position of rings, see fig. 15.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 15.

Scale on imperfections measured from ref. surface

Fig. 16. Kvaerner model no. 4.
Fig. 17. Geometry of Kvaerner model no. 5.
Fig. 18. Measurement sections of Kvaerner model no. 5.
INITIAL IMPERFECTIONS OF KVAERNER MODEL NO. 5.

Position of rings, see fig. 18.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 18.

Scale on imperfections measured from ref. surface

Fig. 19. Kvaerner model no. 5.
Fig. 20. Ring stiffened Aker model.
Fig. 22. Measurement sections of Aker model no. 1.
INITIAL IMPERFECTIONS OF ÅKER MODEL NO. 1.

Position of rings, see fig. 22.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 22.

Scale on imperfections measured from ref. surface

Fig. 23. Åker model no. 1.
Fig. 24. Geometry of Aker model no. 2.
SECTIONS WHERE THE INITIAL GEOMETRY HAS BEEN MEASURED, AKER MODEL No. 2

Fig. 25. Measurement sections of Aker model no. 2.
INITIAL IMPERFECTIONS OF AKER MODEL NO. 2.

Position of rings, see fig. 25.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 25.

Scale on imperfections measured from ref. surface

Fig. 26. Aker model no. 2.
Fig. 27. Geometry of Aker model no. 3.
Fig. 28. Measurement sections of Aker model no. 3.
INITIAL IMPERFECTIONS OF AKER MODEL NO. 3.

Position of rings, see fig. 28.
Ref. surface (perfect shape) for this section
The number refers to section number in fig. 28.

Scale on imperfections measured from ref. surface

Fig. 29. Aker model no. 3.
Fig. 30. Geometry of Aker model no. 4.
SECTIONS WHERE THE INITIAL GEOMETRY HAS BEEN MEASURED, AKER MODEL NO. 4.

Fig. 31. Measurement sections of Aker model no. 4.
INITIAL IMPERFECTIONS OF AKER MODEL NO. 4.

Position of rings, see fig. 31.

Ref. surface (perfect shape) for this section
The number refers to section number in fig. 31.

Scale on imperfections measured from ref. surface

Fig. 32. Aker model no. 4.
Fig. 33. Plotting of imperfections of Aker model no.

R = 600 mm; SL = 960 mm; T = 2.5 mm
NCIRC = 14; NS = 16; NM = 2; NR = 5; NSCAN = 1001
PFAC = 0.787; XX = 2.; YY = 2.; PUX = 9.; PUY = 12.