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Research

Mechanical Integrity of Copper Canister Lid and Cylinder

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SKI perspective

Background and purpose of the project

The integrity of the canister is an important factor for long-term safety of the repository for spent nuclear fuel. The mechanical integrity of the canister might be affected by different degradation mechanisms. Depending on different conditions i.e. loading intensity, loading mode and temperature etc, different degradation mechanisms can have a possible harmful effect on the mechanical integrity of the copper canister. The purpose of this project was to get an understanding of which degradation mechanism are most interesting, with regard to their harmful effect on the canister, by using simple calculation methods (FEM).

The calculations are made using the conditions in the repository and the canister design (presented by SKB) as boundary data.

Results

The most important conclusion is that in spite of the compression loads, the outer surface of the copper canister and the lid will be affected of tensile stresses. In presence of tensile stresses on the outer surface of the canister, stress corrosion cracking cannot be ignored and has to be taken care of in the canister lifetime calculations.

A sensitivity analysis is also performed to clarify the effect of design and creep parameters. Results of this analysis will be reported separately.

Effects on SKI work

The study will be a basis for coming SKI research projects and SKI reviews of SKB’s RD&D-programme.

Project information

Responsible for the project at SKI has been Behnaz Aghili.
SKI reference: 14.9-010574/01107.

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Research

Mechanical Integrity of Copper Canister Lid and Cylinder

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January 2002

Summary

This report compiles finite element analyses performed to ensure the structural integrity of canisters used for storing of nuclear fuel waste of type BWR. The report comprises analyses performed on the canister lid and cylinder casing in order to determine static and long-term strength of the structure. The analyses are originally performed by Gert Herdner, SKI and subsequently supplemented by Semcon.

Finite element analyses compiled in this report are listed under *Reference 1*.

The numerical finite element calculations on the canister complement analytical estimates [2] and are performed in order to identify areas that may be of interest when reviewing the integrity of the copper canister.

The report analyses the mechanical response of the lid and flange of the copper canister when subjected to loads caused by pressure from swelling bentonite and from ground water at a depth of 500 meter. The loads acting on the canister are somewhat uncertain and the cases investigated in this report are possible cases. Load cases analysed are:

- Pressure 15 MPa uniformly distributed on lid and 5 MPa uniformly distributed on cylinder.
- Pressure 5 MPa uniformly distributed on lid and 15 MPa uniformly distributed on cylinder.
- Pressure 20 MPa uniformly distributed on lid and cylinder.
- Side pressures 10 MPa and 20 MPa uniformly distributed on part of the cylinder.

Creep analyses are also performed in order to estimate the stresses that will arise when the canister is placed in the repository.

The analyses in this report are recreated from the original analyses but the models differ in geometry. Also, there is no information in the original reports on material data, time-independent as well as creep data, and analysis procedure. The data used in the recreated analyses are based on information from *References 2, 3, 6 and 7*.

The results presented in this report are based on the supplementary analyses. These results differ from the original results. Most likely this is due to differences in model geometry. The original results are appended to the report and are summarised for comparison with results from the supplementary analyses. Otherwise, these results are not further discussed.

Summary of results

For all load cases, high tensile stresses are found in the lid fillet between the planar part and the flange.

High tensile stresses are also found in the weld surface and on the outer side of the copper cylinder, in the region from the weld down to the level of the insert. Since these stresses appear on the outside of the canister, a damage tolerance analysis of this region should be performed.

Tensile stresses appearing on the bottom of the lid are not likely to cause initiation of defects. Due to the magnitude of the stresses, the region should however be assessed regarding growth of existing defects.

In a modified design, the lid is fitted in the copper cylinder with zero gap as opposed to the original design where there is a gap of 1 mm between the lid and cylinder. The peak tensile stresses caused by two critical load cases thus shift from the weld region to a region further down. Stresses in the order of magnitude of the yield strength do not appear until approximately 30 mm below the weld. This may be advantageous if the weld and the region in the vicinity of the weld are considered to be most critical as regards high tensile stresses.

Contents

Appendices

1 Introduction

The canister used for storing nuclear fuel waste of type BWR consists of an inner part (insert) of ductile cast iron and an outer part of copper. The copper canister is to provide a sealed barrier between the contents of the canister and the surroundings.

This report compiles finite element (FE) analyses performed to ensure the mechanical integrity of canisters used for storing of nuclear fuel waste. The objective is to determine static and long-term strength of the canister lid and flange. The original FE analyses are performed by Gert Herdner, SKI, and the supplementary performed analyses also presented in this report are based on these original analyses.

The FE calculations complement analytically performed estimates [2]. The analyses are performed in order to identify areas that may be of interest when reviewing the integrity of the copper canister.

The report analyses the mechanical integrity of the lid and flange of the copper canister for the load cases:

- Uniformly distributed outer pressure
- Different pressure for the upper part of the lid and for the copper cylinder
- Side pressure acting on a part of the cylindrical shell

Two designs, differing in initial gap distance between the copper lid and cylinder, are analysed. The analyses are initially performed on design 1, where the gap distance is 1 mm. Results from these analyses proved not acceptable why analyses also are performed on a design with zero gap between lid and cylinder. This design is more advantageous regarding high stresses in critical regions.

The recreated analyses in this report are performed on models that differ in geometry from the models used in the originally performed analyses. Geometrical dimensions were not determined at the time the original analyses were performed, and it is not possible to retrieve the data used for these analyses. Also, there is no information in the original reports on material data, time-independent as well as creep data, and analysis procedures. The data used in the recreated analyses are based on information from *References 3-6* and are outlined in subsequent sections.

2 Geometry

The region analysed is shown in *Figure 1*. For more details about the analysed design, see *References 2* and *6*.

The design of the copper canister was not definite and geometrical dimensions were not determined at the time the original analyses were performed. A preliminary design proposal of the canister was used and it is not possible to retrieve the data used. Estimates on dimensions, however, are shown in *Appendix A*.

Two designs, differing only in initial gap distance between the lid and copper cylinder, are evaluated.

The dimensions used for the supplementary analyses are based on data from *References 2-6* and are shown in *Figure 2*. The initial gap between lid and insert as well as the initial radial gap between the copper cylinder and the insert is 4 mm [2,6]. In design 1, the gap between the lid and the copper cylinder is initially 1 mm [2,6], while in design 2 there is zero initial gap between lid and cylinder.

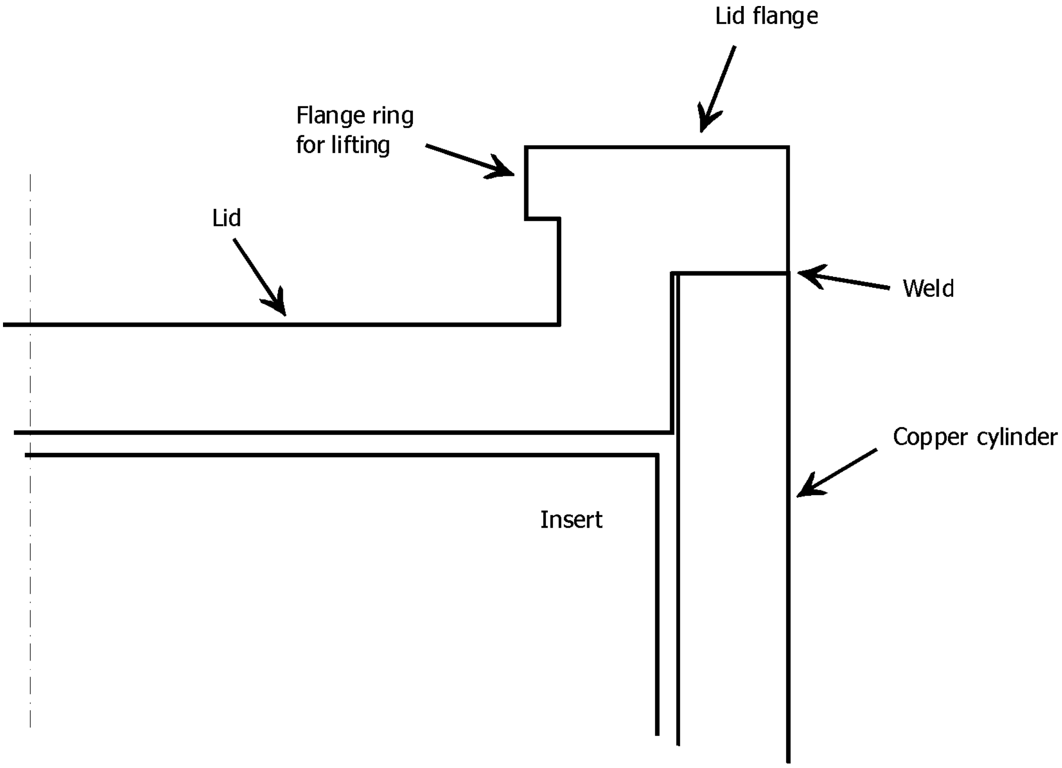


Figure 1 Analysis region of the copper canister lid and cylinder casing.

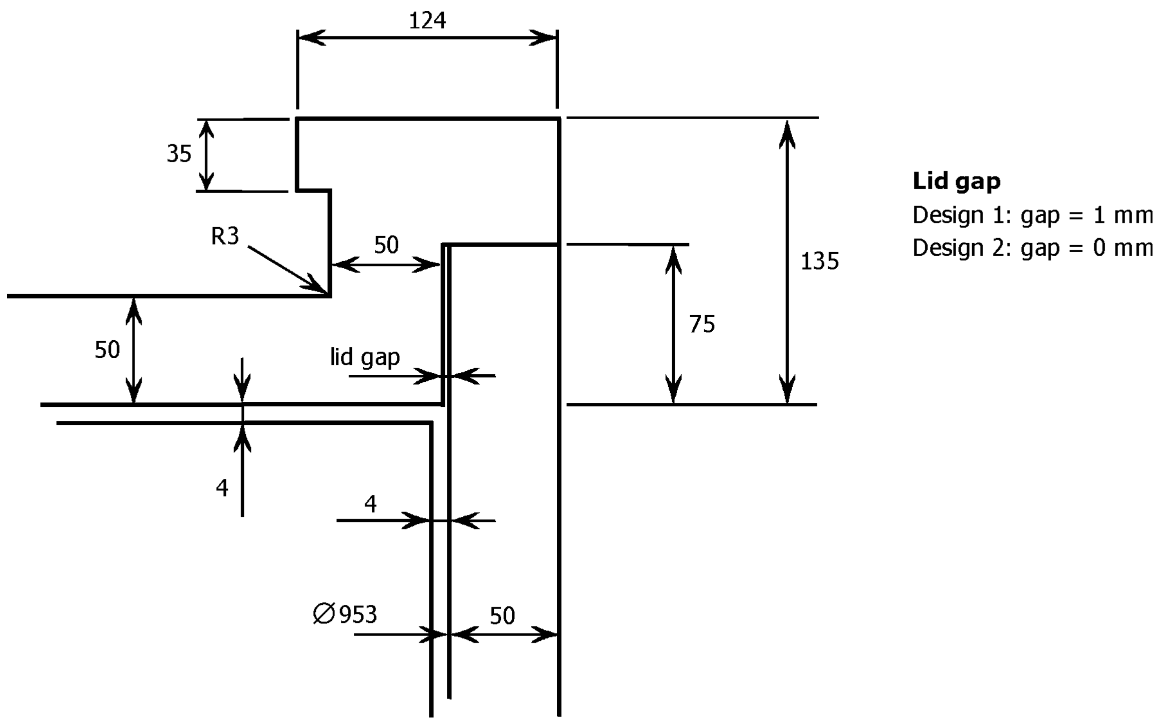


Figure 2 Dimensions used in the current FE analyses [2-6].

3 Material

3.1 Time-independent elastic-plastic properties

The material in the canister is copper with the following properties:

Young's modulus: $E = 114$ GPa
Poisson's ratio: $\nu = 0.35$
Yield strength: $\sigma_S = 50$MPa

The plastic properties are modelled using a bi-linear material model [2]. The plastic deformation is assumed to follow von Mises yield law and isotropic hardening. The plastic modulus is assumed to be 1/100 of the elastic Young's modulus, i.e.

$$E_p = E/100 = 114/100 = 1.14 \text{ GPa}$$

Figure 3 compares the stress-plastic strain relationship according to SKB TR 92-30 with the bi-linear stress-plastic strain relationship used in the current analysis. The difference between the two is small for plastic strains up to 10% or stresses up to 164 MPa [2].

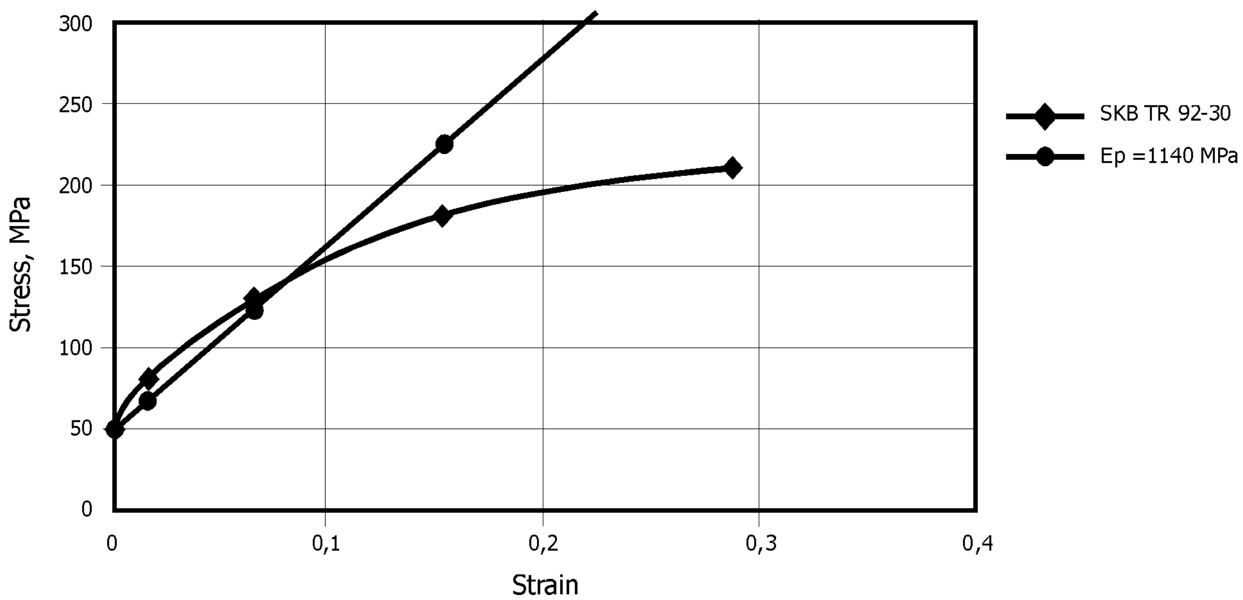


Figure 3 Comparison of the stress-plastic strain relationship according to SKB TR92-30 [8] and the bi-linear stress-plastic strain relationship used in this analysis [2].

3.2 Creep properties

According to *Reference 2*, the long-term creep properties for copper at 100°C are not well known. The longest creep tests that have been carried out are 19 900 hours, i.e. less than 2.5 years. Extrapolating the creep behaviour for time periods exceeding 100 years thus is not reliable and all predictions for times beyond 10 000 years are associated with great uncertainties. A listing of the estimates of secondary creep shows that the uncertainty is great [2].

Analyses performed in this report assumes a secondary creep rate of 1% for 100 years at a temperature of 100°C and a stress level of 100 MPa, and a linear stress dependency according to [2]:

$$\frac{d\varepsilon}{dt} = k \cdot \left(\frac{\sigma}{\sigma_0} \right)^n$$

where: $k=1 \cdot 10^{-4}$ 1/year
$\sigma_0=100$ MPa
$n=1$

4 Load cases

Loads analysed in this report are swelling pressure from the bentonite and hydrostatic pressure from the ground water.

The canister is placed in a hole in the bedrock, where it will be surrounded by a couple of decimetres of compacted bentonite clay. When the bentonite becomes saturated with water it expands and fills any gaps in the bentonite buffer. The bentonite will exert a pressure of maximum 10 MPa on both the bedrock and the canister [2,7].

This report assumes that the canister will be deposited at a depth of 500 m. The hydrostatic pressure caused by the ground water on the canister thus is 5 MPa.

An outline and discussion of possible loads are found in *Reference 2* and *7*. The loads acting on the canister are somewhat uncertain. The swelling pressure from the bentonite may vary substantially over time and, depending on how the watering of the bentonite is done, the swelling may induce uneven pressure on the canister. Possible load cases are handled in this report.

The analyses in this report consider three loading conditions:

- axisymmetric outer pressure that varies between lid and cylinder
- uniform outer pressure
- side pressure on part of the canister.

The load cases are listed in *Table 1*. Cases 1 to 3 are axisymmetric loads and case 4 is a side pressure applied on half of the cylinder casing. Regions A-C refer to axisymmetric regions and region D is symmetric in the *x-z* plane (about the *x-y* plane). Load cases will hereinafter be referred to by their load case number. Creep analyses are performed for load case 1 and for a side pressure (load case 4). In the latter case, the creep analysis is performed for a side pressure of 10 MPa.

Table 1 Load cases. See Figure 4 and 5 for reference regions A-D.

Load case		A Lid	B Lid flange top	C Lid outer flange and cylinder	D Lid outer flange and cylinder
1	Static/ creep 500 yrs	15 MPa	5 MPa	5 MPa	
2	Static	5 MPa	5 MPa	15 MPa	
3	Static	20 MPa	20 MPa	20 MPa	
4	Static Creep 1000 yrs				20 MPa 10 MPa

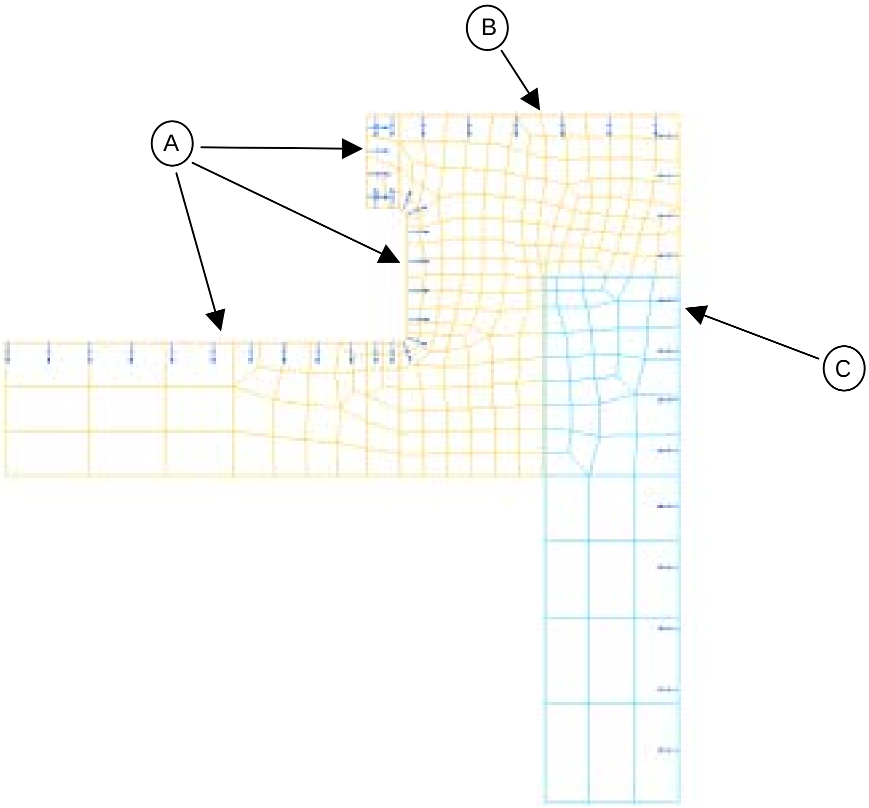


Figure 4 Outer pressure on lid and cylinder casing. Axisymmetric load cases.

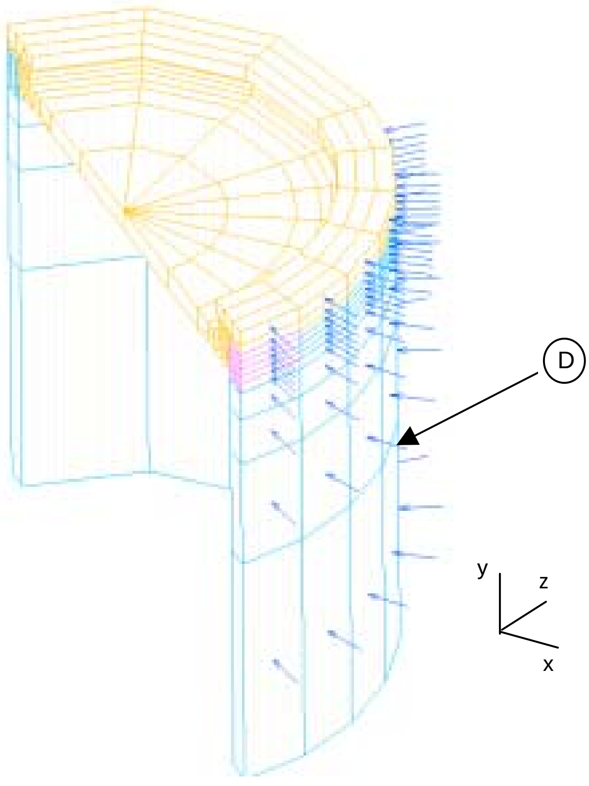


Figure 5 Outer pressure on lid and cylinder. Side load on half of the copper cylinder.

5 Design Criteria

Design criteria for the copper canister are referenced and discussed in *Reference 2* and *7*. Maximum principal stresses are of interest since initiation and growth of cracks (stress corrosion, stable and unstable crack growth) can take place in areas where tensile principal stresses are large. Damage tolerance analyses therefore should be performed in order to assess the risk for crack initiation and crack propagation. This is not done within the scope of this report. The creep strains are of interest since the creep ductility of copper in certain environments has proved to be low. Furthermore, deformations are of interest since large deformations may lead to thickness reductions of the canister causing the sealing margins for the copper canister to become to low [2,7].

6 Finite Element Analysis

6.1 Software

I-DEAS is used for modelling the geometry and for applying boundary conditions and loads. Abaqus is used for the finite element analyses. Post-processing of results is done using I-DEAS.

6.2 Finite element model

6.2.1 Model

The lid and cylinder casing are in the axisymmetric case modelled using axisymmetric solid elements (Abaqus type CAX4). *Figure 6 and 7* show the finite element (FE) model of design 1 and *Figure 8* shows the FE mesh of design 2. In the case where a side load is applied on part of the canister the canister is modelled using 3D brick elements (Abaqus type C3D8 and C3D6), see *Figure 9 and 10*.

The axisymmetric model of design 1 consists of 383 elements and 446 nodes, yielding a total of 1338 degrees of freedom. Corresponding figures for design 2 is 485 elements, 552 nodes and 1656 degrees of freedom.

The three-dimensional (3D) model is modelled using 681 elements and 913 nodes, yielding a total of 2739 degrees of freedom. Gap elements are red in *Figure 7 and 9*.

6.2.2 Contact

Contact between lid and insert and between lid and cylinder casing are modelled using GAP elements (Abaqus type GAPUNI).

Each GAP element is connected to a pair of nodes and is given a specified initial distance. During analysis, the relative displacement between the connected nodes will determine whether the nodes are in contact.

For design 1, the initial distance is specified to 1 mm. For design 2 the initial distance is 0 mm, i.e. there is no gap between the nodes.

Analyses performed on the design with zero gap between lid and cylinder considers friction between the contact areas. No friction, as assumed in analyses of design 1, may be overly conservative, particularly as regards tensile stresses in the weld surface region.

Friction between the copper lid and the insert and between copper cylinder and insert do not significantly affect the resulting stresses. In the calculations of design 2, the following friction coefficients are assumed, as they are considered conservative regarding stresses at the weld surface:

Copper – copper: $\mu_1 = 0.15$

Copper – cast iron: $\mu_2 = 0.3$

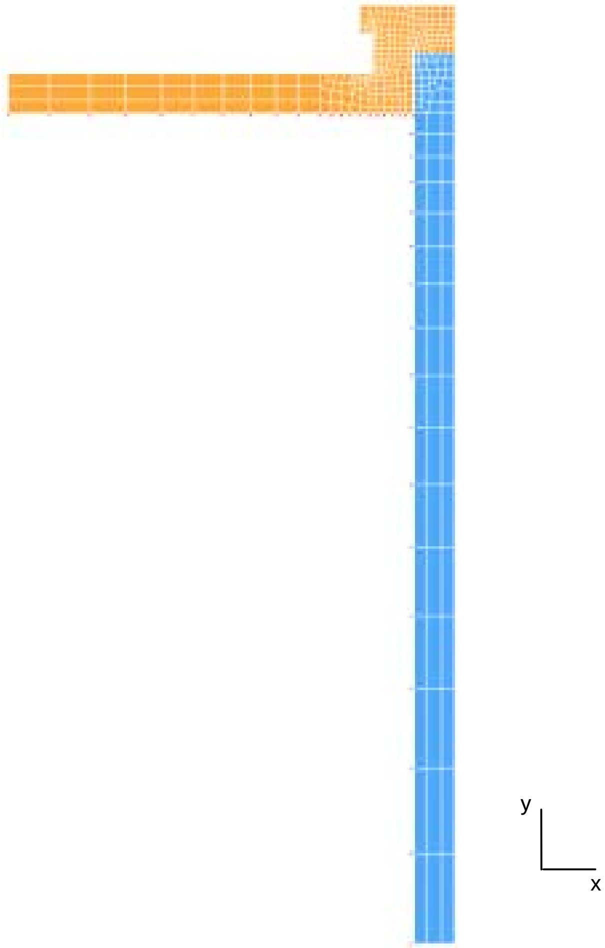


Figure 6 Axisymmetric FE model used in the axisymmetric analyses (load case 1-3).

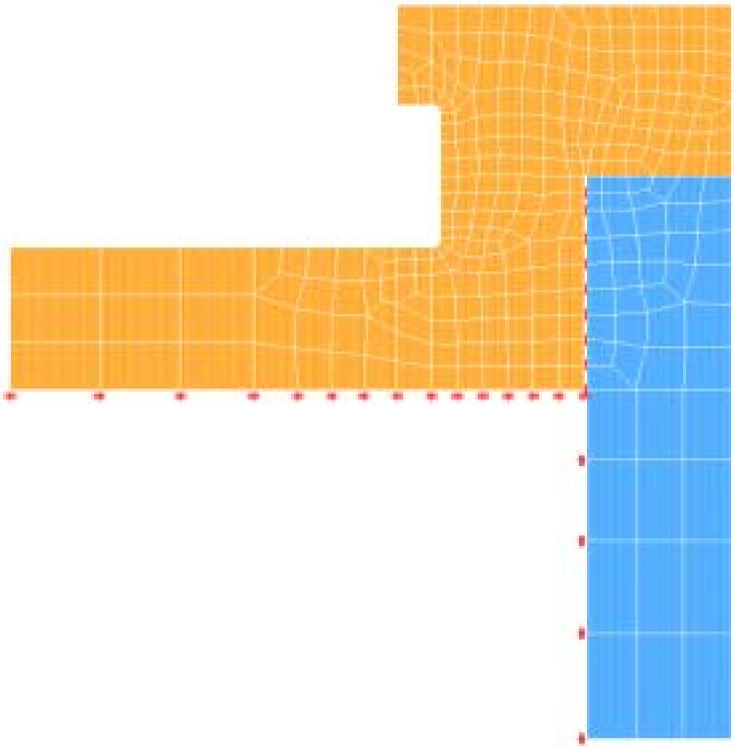


Figure 7 FE model in the transition region between lid and copper cylinder. Red elements are GAP contact elements.

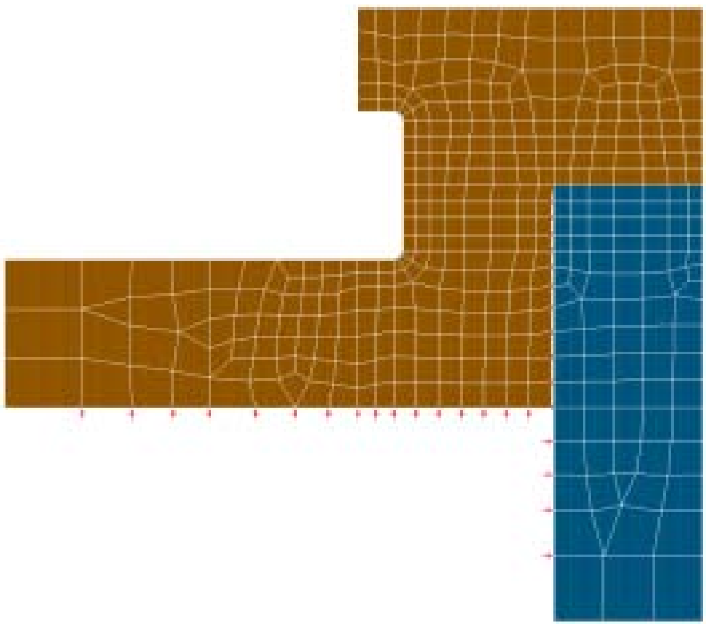


Figure 8 Local FE mesh of the design 2. The initial zero gap between lid and cylinder is specified in the GAP element property table.

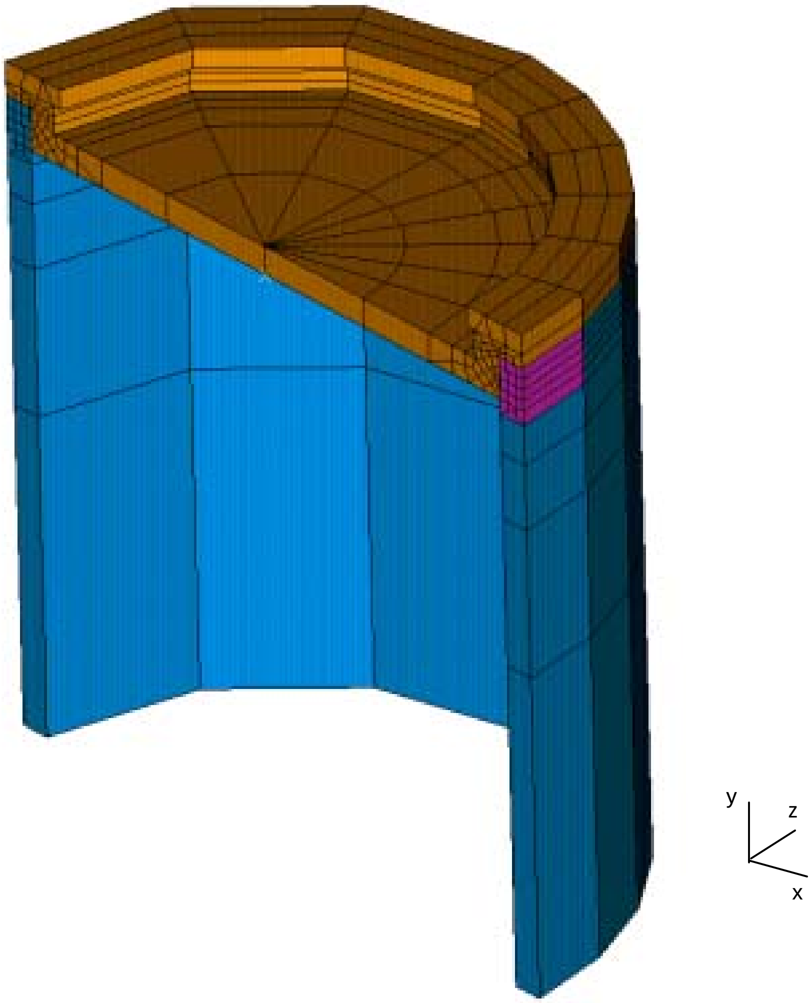


Figure 9 3D finite element model used in analysing a side load (load case 4).

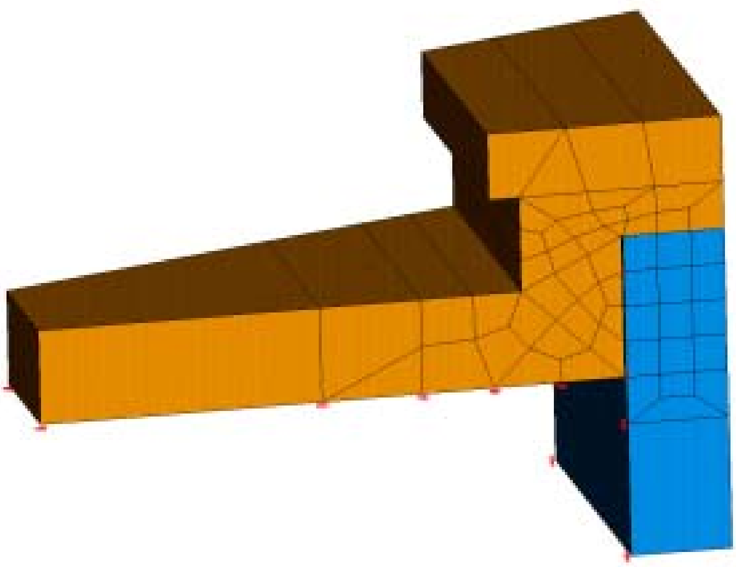


Figure 10   Local mesh in the 3D model.

6.2.3 Boundary conditions

Both the axisymmetric and the 3D finite element model are restrained not to translate in the tangential direction (*z*-direction in *Figure 6 and Figure 9*). In the first case due to axisymmetry and in the latter due to symmetry about the *x-y* plane. The bottom of the cylinder casing is restrained in axial translation.

To ensure that the stresses in the lid-cylinder transition region is undisturbed by applied boundary conditions, a sufficiently large part of the copper cylinder (1105 mm) is included in the model.

6.3 Analysis procedure

6.3.1 Static analysis

The static analyses consider elastic-plastic material behaviour. The behaviour is modelled with a bi-linear material model (see *Section 3.1*) where the plastic deformation is assumed to follow von Mises yield law and isotropic hardening. The analyses account for geometric non-linearity.

6.3.2 Creep analysis

In the creep analyses the load is applied in one step that considers the elastic-plastic behaviour of the material and geometric non-linearity. The load is kept at that level in the second step where the creep behaviour is analysed. Creep data according to *Section 3.2* is applied.

6.4 Limitations

The analyses in this report are recreated from the original analyses but the models differ in geometry. Also, there is no information in the original reports on material data, time-independent as well as creep data, and analysis procedure. The data used in the recreated analyses are based on information from *References 2, 3 and 6* and are outlined in preceding sections.

The models used in the analyses are quite coarse and the analyses are intended to give an estimate of areas that may cause problems regarding stresses and deformations that appear due to the various possible cases of external pressure.

7 Results

Results discussed in this section are based on the supplementary analyses performed on design 1 and 2. Regions specifically analysed are the lid fillet region, the weld between lid and casing and the outside of the cylinder casing from the weld down to the level of the insert. Regions are shown in *Figure 11*.

The results are summarised in *Section 7.1* and *Appendix A*. Referenced elements are shown in *Figure 11-13*. Details on results for each load case considered are presented in *Section 7.2* and *7.3*.

Result figures for design 1 are shown in *Appendix B-F* and for design 2 in *Appendix H*. Stresses, strains, contact force and displacements are shown in result plots from I-DEAS and result graphs as a function of applied load.

Results from the original finite element analyses are summarised and compared to results from the supplementary analyses in *Appendix A*. Original result figures are presented in *Appendix I*. Otherwise, these results are not further commented in this section.

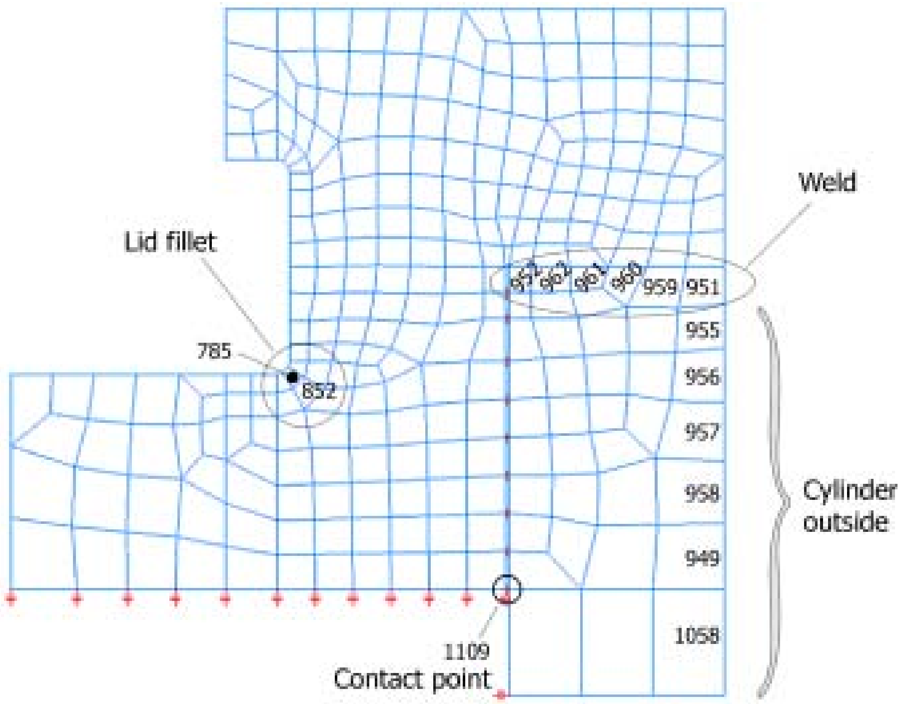


Figure 11 Elements in the lid/cylinder transition region for axisymmetric analyses (load cases 1-3). Design 1.

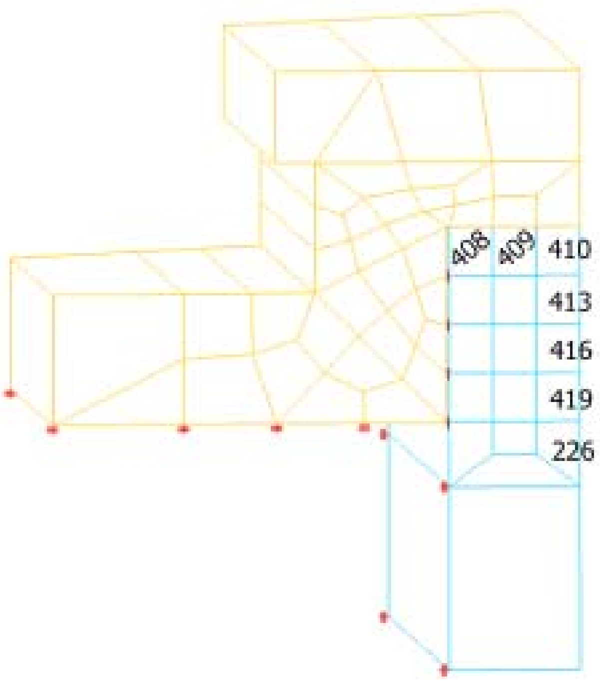


Figure 12 Elements in the lid/cylinder transition region for the 3D case (load case 4: side pressure).

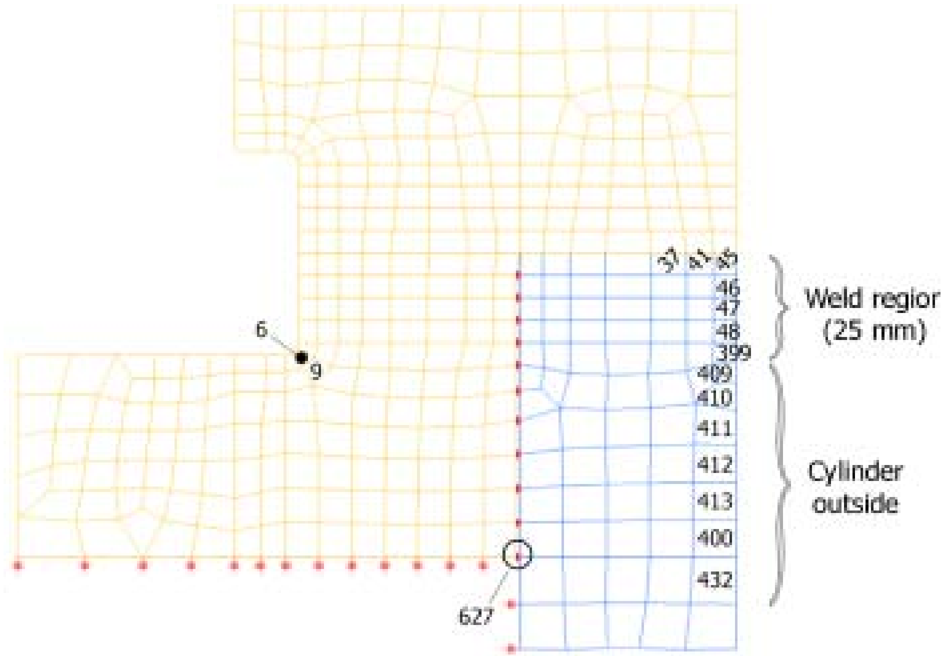


Figure 13 Design 2. Regions specifically analysed are the lid fillet, the weld region and the outside of the cylinder. The region referred to as the weld region includes the weld surface and root, and the region in the vicinity of the weld.

7.1 Summary of results

Resulting maximum stresses and strains for all load cases and both designs are summarised in *Table 2* and *Table 3*. Generally, the two designs differ regarding tensile stresses on the outside of the cylinder, in the region from the weld down to the level of the insert. In design 1, high tensile stresses are concentrated to the weld region while in design 2 the peak stresses appear further down, in a region closer to the level of the insert. The stress level is however not affected. Tensile stresses in the lid fillet are high and increase by approximately 10% from design 1 to design 2. Plastic strains and creep strains are in the same order of magnitude between the two designs.

For all load cases where pressure is applied on both lid and cylinder, high tensile stresses are found in the lid fillet region. Maximum principal stress is 100 MPa for design 1 and appears for load case 1 during loading at a load fraction of 0.2. For design 2, the maximum tensile stress is 113 MPa and appears for both load case1 and 2.

The stresses in the weld are mainly compressive. Tensile stresses appear in the weld surface and root where the maximum principal stress for design 1 is above the yield limit (load case 1 and 2). Design 2 shows lower stresses in this region; maximum tensile stress is 29 MPa. Stresses just above the yield limit appear approximately 30 mm further down along the copper cylinder. Maximum principal plastic strain caused by tensile stresses is in the order of 2.6%. Plastic strain on the inner side of the casing (element 952) is caused by compressive stresses.

On the outside of the cylinder casing, from the weld down to the level of the insert, high tensile stresses are for design 1 found (elements 951-1058) for several of the calculations. The high stresses are concentrated to a region close to the weld (element 951) and at the level of the insert (element 226). Maximum principal stress in the latter region is 71 MPa and appears for load case 4. For design 2 (elements 46-432) stresses just above 50 MPa are found for both analysed load cases. Strains in this region are negligible.

Plastic strains due to tensile stresses are less than 2.6%. Creep strains due to tensile stresses for the axisymmetric load cases are less than 2.8%. When a large side load is applied for a long period of time, the strain becomes in the order of 6%.

Table 2 Summary of resulting maximum tensile stresses and strains for analysed load cases. Supplementary analyses on design 1.

Load Case	Maximum principal stress (MPa)			Max strain (%)	
	Lid fillet Load case 1-3: Elements 785, 852	Weld surface *Load case 1-3:* Elements 959, 951 *Load case 4:* Element 409, 410	Cylinder outside *Load case 1-3:* Elements -1058 *Load case 4:* Elements 413-226	Plastic	Creep
1 static 15/5 MPa	100	52	55	2.4	
creep 500 yrs	51	4	2		2.8
2 static 5/15 MPa	85	53	53	(3*) 2.5	
3 static 20 MPa	96	48	52	(3.5*) 2.5	
4 static 20 MPa	<0	34 (root)	66	2.6	
creep 1000 yrs	<0	6 (root)	52		5.5
Maximum	100	53	66	2.6	5.5

* Strains are due to compressive stresses in the regions.

Table 3 Resulting maximum tensile stresses and strains for supplementary analyses on design 2. Results are summarised for a friction coefficient μ =0.15 between lid and copper cylinder.

Load Case	Maximum principal stress (MPa)			Max strain (%)	
	Lid fillet Elements 6, 9	Weld surface Elements 41, 45-46	Cylinder outside Elements 46-432	Plastic	Creep
1 static 15/5 MPa	113	15	55	3.5	
creep 500 yrs	51	5	5		2.5
2 static 5/15 MPa	113	29	45	3.2	
Maximum	113	29	55	3.5	2.5

7.2 Design 1

7.2.1 Axisymmetric load cases

Results for the axisymmetric loads are shown in *Appendix B-D*.

<u>Load case 1</u>

Result figures and graphs for load case 1 are shown in *Appendix B*.

Maximum principal stress in the lid fillet is 100 MPa and appears at a load fraction 0.2. The stresses remain relatively constant for increasing pressure. Max principal plastic strains are less than 2.4%.

For load case 1 there is no contact between the lid lower edge and casing to relieve the weld at the surface (element 951) why high tensile stresses are concentrated to this region.

Maximum principal stress at the weld surface is 52 MPa. Stresses in the weld are otherwise compressive. Strains are negligible.

Maximum principal stress on the cylinder outside is 55 MPa. Strains are negligible.

As an increasing part of the lid and the cylinder come into contact with the insert, tensile stresses appear in the lid. Maximum tensile stress in the lid bottom is approximately 90 MPa and at the inner side of the cylinder between 40 and 50 MPa.

Load case 2

Result figures and graphs for load case 2 are shown in *Appendix C*.

The lid lower edge and the copper cylinder come in contact at a load fraction 0.47 causing some of the load to be transferred at the contact point instead of the weld. As contact is established, the lid fillet and the weld will be relieved to some extent as seen in the result figures. Only the weld surface and root show tensile stresses.

The max principal stress in the lid fillet, approximately 85 MPa at load fraction 0.47, decreases with increasing load. At load fraction 0.85, the stresses have decreased to a level below the yield limit. Plastic strains at full load are negligible.

Weld maximum tensile stress, 53 MPa, appears at load fraction 0.5. Weld peak tensile stresses appear at the surface and decrease as the lid lower edge and the cylinder come in contact. Plastic strains appearing in element 952 are due to compressive stresses.

In the cylinder casing, except in the weld region, stresses are below the yield limit. Max principal plastic strains are negligible.

Tensile stresses due to bending in the lid bottom and at the inner side of the cylinder are lower than 45 MPa.

Stresses and plastic strains appearing in the contact region between the lid lower edge and the copper cylinder are not reliable. The contact is modelled as discrete points while contact actually is distributed over a continuous area. Thus, stresses and strains are likely to be lower than the ones appearing in this analysis.

Load case 3

Result figures and graphs for load case 3 are shown in *Appendix D*.

The lid lower edge and the copper cylinder come into contact at a load fraction 0.3.

The max principal stresses in the lid fillet, approximately 95 MPa, appear at a load fraction 0.1. The stresses decrease with increasing load. At load fraction 0.45, the stresses have decreased to a level below the yield limit. Plastic strains at full load are negligible.

Weld maximum tensile stress, below 50 MPa, appears at the weld surface. Max principal stresses initially increase with increasing load and are then kept at a relatively constant level. Plastic strains appearing in element 952 are due to high compressive stresses.

In the cylinder casing, max principal stresses are just below the yield limit. Stresses in the region below the weld (element 955 and 956) peak at approximately 53 MPa for a load fraction of 0.35. Max principal plastic strains are negligible at 15 MPa.

Bending stresses in the lid lower edge and at the inner side of the cylinder are approximately 50 MPa.

Creep

A creep analysis is performed for load case 1. Result figures and graphs for the analysis are shown in *Appendix E*.

During the initial loading, the lid lower edge and the cylinder casing do not come in contact, but after approximately 10 years of creep contact is established.

The initially high stresses in the lid fillet region are relaxed. In the fillet region the stresses decreases from initially 100 MPa to 55 MPa after 200 years and is then kept at a relatively constant level.

The stresses in the weld are compressive except on the outer surface. The tensile principal stresses in the weld in this region decreases from 55 MPa to approximately 5 MPa after 100 years and is then kept relatively constant.

The highest creep strains appear in this region. Maximum principal strain after 500 years is approximately 2.8%.

Tensile stresses due to bending in the lid bottom and at the inner side of the cylinder are also relaxed. The stress level is between 10 and 20 MPa.

7.2.2 Side load

Result figures and graphs for load case 4, side pressure, are shown in *Appendix E-F*.

Static load

Tensile stresses are initially high in the inner part of the weld; maximum principal stress is approximately 82 MPa, but decreases with increasing load. At a side pressure of 20 MPa, the tensile stresses have stagnated at approximately 12 MPa. Stresses at the weld surface are compressive.

At the outer side of the cylinder casing, stresses close to the weld (in elements 410 and 413) are compressive while stresses at the level of the lid lower edge are tensile. Max principal stresses in this region are relatively constant at approximately 66 MPa.

Bending stresses are high in the copper cylinder. Maximum von Mises stress is approximately 90 MPa.

Creep

A creep analysis is performed for a side load of 10 MPa. Result figures and graphs for the analysis are shown in *Appendix F*.

Max principal stresses increases to 47 MPa after 1000 years. Max principal creep strains after 1000 years are 5.5% in this region.

Max principal stresses in the outer side of the copper cylinder decreases slowly from initially 60 MPa to 53 MPa after 1000 years. The maximum tensile stresses appear at the level of the lid lower edge (element 410). Max principal creep strains after 1000 years are approximately 5%.

7.3 Design 2

For design 1, tensile stresses are unacceptably high in the weld surface region on the outside of the cylinder why this region is specifically evaluated in the modified design. Since load case 1 and 2 proved to be the cases causing the most severe tensile stresses, these cases are used in the analysis of design 2.

Design 2, with zero gap between copper lid and cylinder, is analysed in terms of both static loading and creep. Results are summarised in *Section 7.1* together with results for design 1. Result figures and graphs are shown in *Appendix H*.

The design shows better results regarding stresses in the weld region on the outside of the cylinder. Tensile stresses in the weld surface region and root are below the yield strength for both load cases. During static loading, the maximum tensile stress is less than 29 MPa, and after creep for 50 years, stresses on the weld surface are solely compressive. On the outside of the cylinder stresses in the magnitude of 50 MPa do not appear until approximately 30 mm below the weld.

A zero-gap fitting of the lid is however not advantageous regarding stresses in the lid fillet region. Stresses in this region are not relieved. Maximum principal stress increases with approximately 10% compared to design 1, to 113 MPa. Plastic strains are high, maximum principal strain on the surface is 3.5%

These calculations are performed assuming a friction coefficient 0.15 between copper lid and cylinder. The results are affected by the friction; a low coefficient yield conservative results regarding the weld surface. Regarding stresses in the lid fillet, a low friction coefficient is advantageous. The affect of different friction coefficients is shown in *Appendix H*.

8 Discussion

When the copper canister is subjected to the various cases of external pressure, the lid will partly come into contact with the insert causing tensile stresses in the lid bottom side. High tensile stresses appear on the lid bottom and the region with tensile stress increases with increasing load and time, as a larger part of the lid is pressed against the insert. As discussed in *Reference 6*, there is no known mechanism that will cause crack initiation on the inside of the canister; the material is assumed to be sufficiently ductile and defects from manufacturing cannot in absence of a corrosive environment propagate due to these stresses. *Reference 6* also suggests that a crack propagation assessment be done when crack growth data for the material is available.

The gap between the lid lower edge and the cylinder casing (element 1109 in *Figure 11*) closes with increasing load for most load cases. For load case 1 there is no contact during the initial loading, contact is established after approximately 10 years. As also discussed in *Reference 6*, contact between the lid and casing relieves the welded area, as some of the load will be transferred at the contact point. The external pressure on the canister causes axial compression of the copper cylinder. Additionally, as the lid deforms, bending stresses will appear in the cylinder casing. Tensile stresses appear on the outside of the cylinder in a region between the weld and the level of the lid lower edge. Maximum principal stress in this area is 66 MPa and appears at the level of the insert for a side load of 15 MPa. Maximum principal stress at the weld surface is 53 MPa. These stresses are relaxed during creep to 52 MPa (after 1000 years) and to 5 MPa (after 500 years), respectively. As discussed in *Reference 6*, manufacturing defects in this region may, due to the state of strain and due to exposure to a corrosive environment, initiate crack growth.

In design 2 the lid is fitted in the cylinder with zero gap in order to relieve the stresses in the welded region. The peak tensile stresses caused by load case 1 and 2 thus shift from the weld region to a region further down. Stresses in the vicinity of the weld thus become acceptable. This may be advantageous if the region at the level of the insert is considered less critical as regards high tensile stresses.

High principal stresses and strains appear in the lid fillet region. Peak tensile stress in this region is approximately 100 MPa and appears for load case 1. During creep, these stresses relax and after 200 years, the stresses are decreased to approximately 50 MPa. The high stresses and plastic strains as well as creep strains in this region suggest that a more detailed analysis of this region be performed. The radius of the fillet will affect the stresses and strains appearing. The axisymmetric model has a radius of 3 mm, while the 3D model have no radius modelled. In addition, as suggested in *Reference 6*, the region should be assessed regarding crack propagation.

Fitting the lid in the cylinder with zero gap yields higher stresses in the fillet region.

Uneven swelling of the bentonite is accounted for as a side load uniformly distributed along the height of the cylinder and lid flange. A possible case not considered in this report is an uneven distribution between the copper cylinder and the lid. *Reference 2* estimates shear stresses in the copper cylinder for a case where a shear load is applied to the lid. The shear stresses thus appearing suggest that a numerical analysis considering plastic deformation and creep be performed.

9 Conclusions

For all considered load cases high principal stresses appear on the outside of the copper cylinder in the region from the weld down to the level of the lid lower edge. As suggested in *Reference 6*, a damage tolerance analysis should be performed to assess this region.

In a design where the lid is fitted in the cylinder with no gap, the peak tensile stresses does not appear at the weld surface but further down. The level of maximum tensile stress is however not altered.

Tensile principal stresses also appear in the lid fillet region; particularly one load case causes high tensile stresses. The modification of the design does not significantly alter the resulting stresses. The state of strain in this region suggests that a more detailed analysis of this region be performed.

10 References

1 Result papers by Gert Herdner:

- Lock 15 MPa mantel 5 MPa elpl pålastning
- Lock 15 MPa mantel 5 MPa elpl krypning
- Lock 5 MPa mantel 15 MPa elpl pålastning
- Lock mantel 20 MPa elpl pålastning
- Sidobelastning El-pl 20 MPa
- Sidobelastning kryp, 1000 år

2 "Mechanical integrity of lid and cylindrical shell for the copper canister," PM, SKI.

3 C-G Andersson, *Test manufacturing of copper canisters with cast inserts*, TR-98-09, Swedish Nuclear Fuel and Waste Management Co, Stockholm, August 1998.

4 Drawing 00001-1111, Copper cylinder, BWR serial 1, rev 00, 970819.

5 Drawing 00001-31, Copper lid, BWR serial 1, rev 00, 970819.

6 "Creep stress analysis of the connection between the lid and the cylindrical shell of the canister," PM, SKI.

7 L Werme, *Design premises for canister for spent nuclear fuel*, TR-98-09, Swedish Nuclear Fuel and Waste Management Co, Stockholm, September 1998.

8 SKB TR92-30.

A Summary of current and original analyses

Table 4 and *Table 5* summarise and compare results from current (supplementary) and original analyses.

There are differences between the results and the most noticeable differences appear on the outer side of the copper cylinder, especially for load case 1. In order to make it easier to see and also to draw conclusions as to why these differences exist, stress plots from current and original analyses that also show deformations are presented side-by-side following the result tables.

As mentioned in *Section 6.4*, one obvious difference is the geometry. Other data (material properties) do most likely not differ[1] and thus are not likely to cause the differences in results. An effort to estimate the geometry used in the original analyses is made in *Figure 14*. The dimensions are based on the assumption that the cylinder wall thickness is 50 mm. *Figure 15* shows the geometry used in current analyses. As seen, there is one distinct difference in the geometry, namely the height of the lid flange. The original lid has a higher flange, resulting in a weaker flange. The current stiffer design have the effect that contact between the lid lower edge and the cylinder (contact point 1109) for static load cases is either not established or established at a higher load. The difference in stiffness is more obvious when studying the creep behaviour, see *Figure 17*. The consequence is that the weld surface and the region in the vicinity of the weld are not relieved to the same extent as in the original weaker geometry.

Another distinction is the lid fillet radius. The smaller lid fillet radius in current analyses yields higher local stresses in the fillet region.

[1] During the current analyses, possible alternative material data (in terms of yield strength and creep strain rate) have been used in an attempt to approach the original analyses as regards resulting stresses and strains and to interpret the differences in results. Conclusions from the analyses are that these alterations do not significantly affect the results, the behaviour of the model principally is the same.

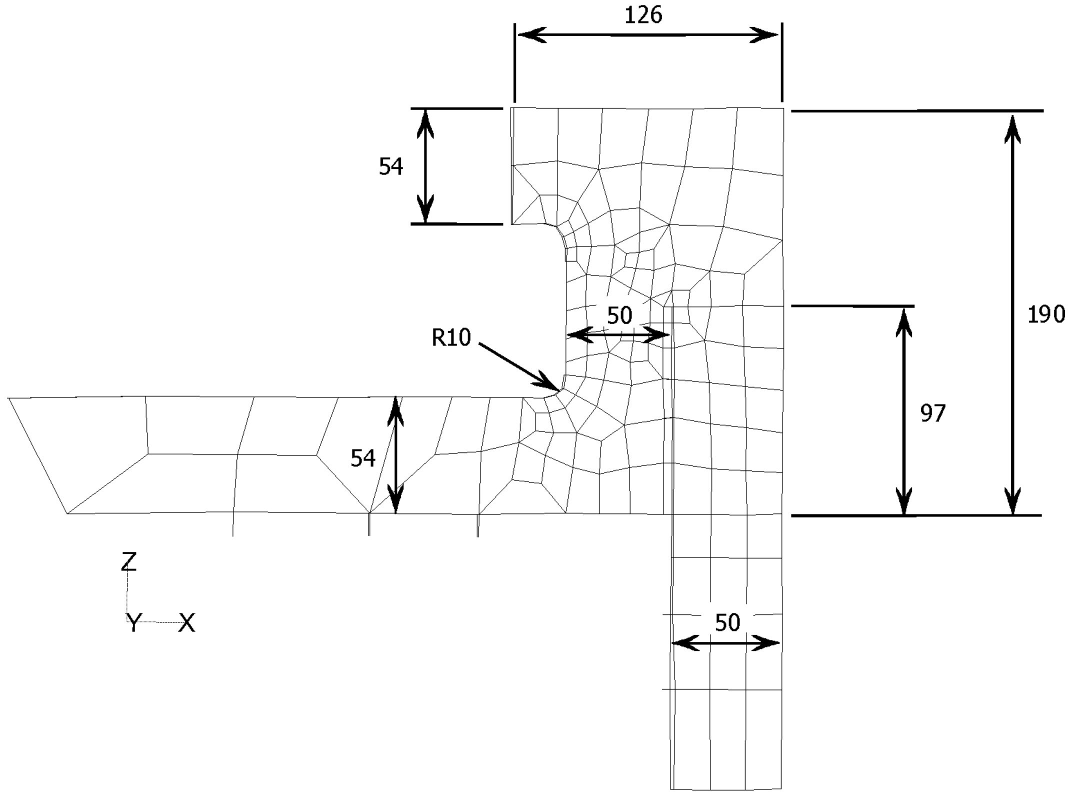


Figure 14 Geometry used in original analyses. Dimensions are measured assuming a copper cylinder thickness of 50 mm. Figures are approximate. (mm)

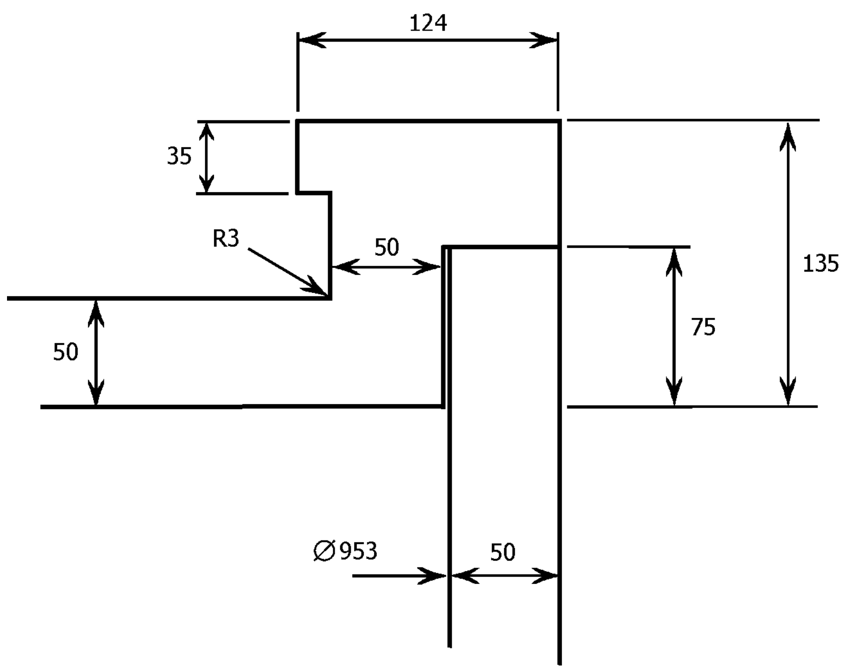


Figure 15 Geometry used in supplementary analyses. Dimensions are based on data from Reference 2-5 and 7. (mm)

Table 4 Summary of resulting maximum tensile stresses for analysed load cases. Comparison between current (supplementary) and original analyses. If no load fraction is specified, the stress appears at the final load.

Load Case	Maximum principal stress (MPa)					
	Lid fillet		Weld surface		Cylinder outside	
	Current analyses *Load case 1-3:* Elements 785, 852	Original analyses *Load case 1-3:* Element 310, 311	Current analyses *Load case 1-3:* Element 951 *Load case 4:* 408-410	Original analyses *Load case 1-3:* Element 341 *Load case 4:* Element 362	Current analyses *Load case 1-3:* Elements 955-1058 *Load case 4:* Elements 413-226	Original analyses *Load case 1-3:* Element 344-366 *Load case 4:* Element 363-365
1 static 15/5 MPa	100	98	52	6	55	2
creep 500 yrs	51	80	4	6	2	2
2 static 5/15 MPa	85 (load 40%) 28	84 (load 47%) 37	53 (load 55%) 31	40 (load 40%) 18	53 (load 55%) 42 (load 100%)	41
3 static 20 MPa	96 (load 10%) 20	95 (load 10%) 28	48 (load 35%) 41	34 (load 32%) 9	52 (load 35%) 45	35 (load 32%) <0
4 static 20 MPa	<0	<0	Ò0 34 (root; load 15%) 81 (inside; load 15%)	<0 28 (root) 62 (inside)	71	69
creep 1000 yrs	<0	<0	<0 6 (root) 47 (inside)	<0 72 (root) 72 (inside)	52	80 (100 yrs) 60 (1000 yrs)
Maximum	100	98	53 34 (root) 81 (inside)	40 72 (root) 72 (inside)	71	80

Table 5 Summary of resulting maximum plastic strains for analysed load cases. Comparison between current and original analyses.

Load Case	Maximum principal strain (%)			
	Plastic		Creep	
	Current analyses	Original analyses	Current analyses	Original analyses
1 static 15/5 MPa	2.4 (fillet)	2.3 (fillet)		
creep 500 yrs			2.8 (fillet)	4 (lid fillet)
2 static 5/15 MPa	1.6 (weld inside)	1 (fillet/weld inside)		
3 static 20 MPa	3.5 (weld inside)	2 (fillet/weld inside)		
4 static 20 MPa	2.1 (cylinder outside) 2.6 (cylinder inside)	2.2 (cylinder outside)		
creep 1000 yrs			5.2 (cylinder outside) 5.5 (weld inside)	7.4 (cylinder outside)
Maximum	3.5 (weld inside)	2.3 (fillet)	5.5 (weld inside)	7.4 (cylinder outside)

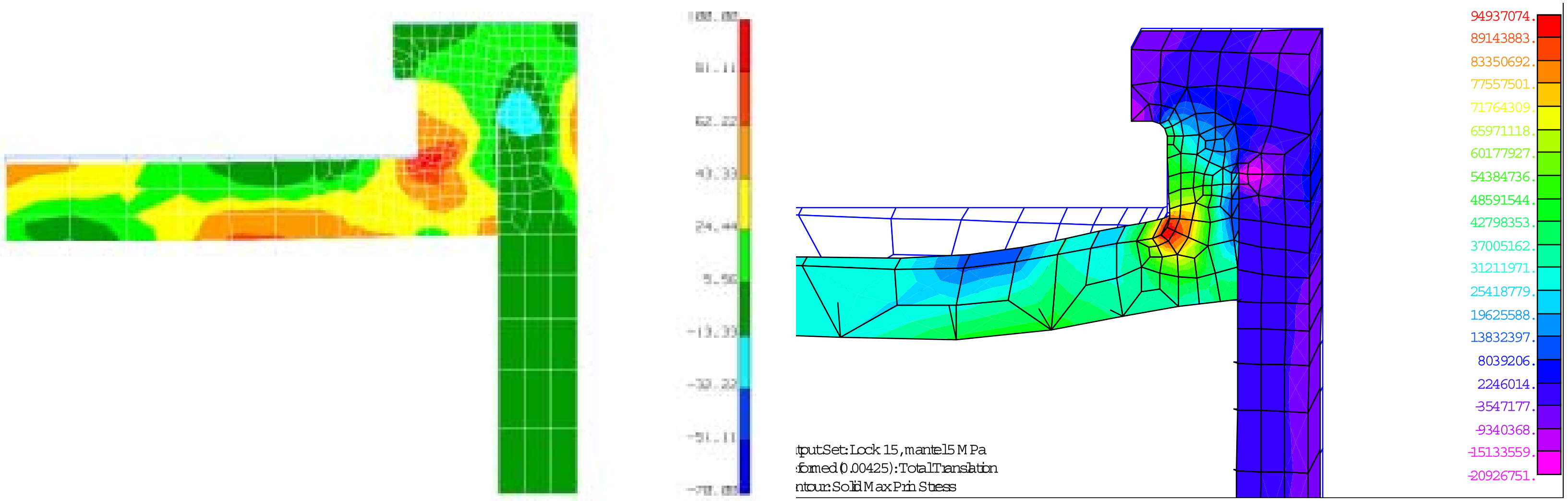


Figure 16 Max principal stresses. Load case 1. Current analysis on left (MPa) and original on right (Pa).

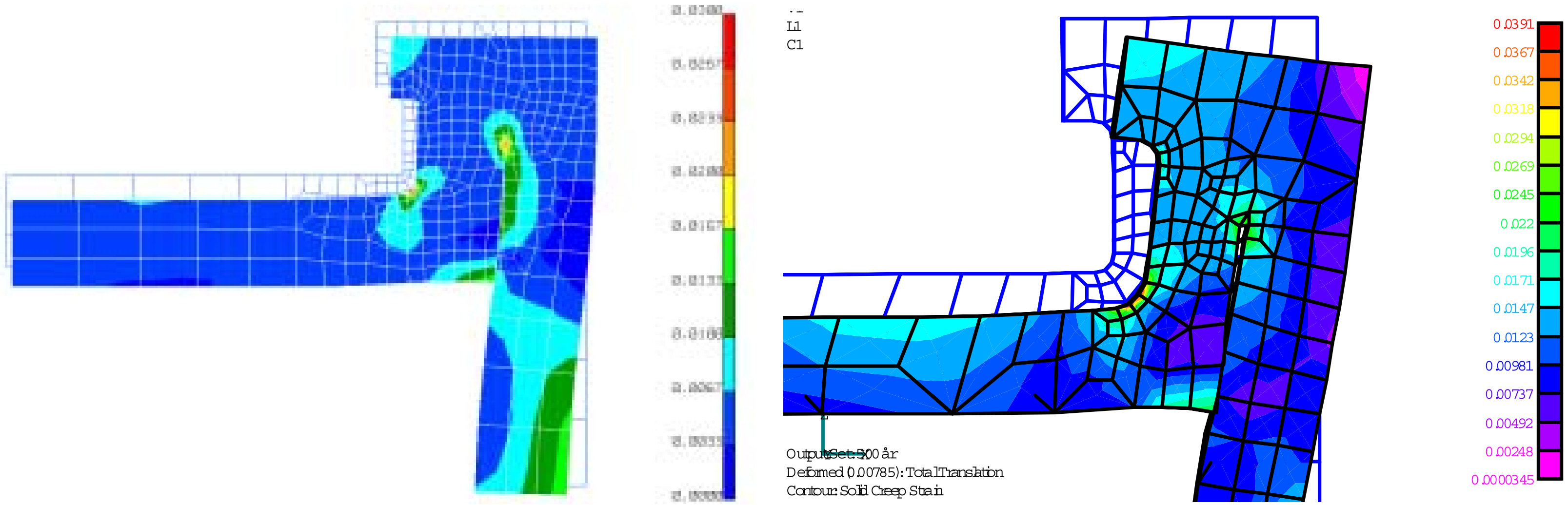


Figure 17 Creep strain. Load case 1, creep 500 years. Current analysis on left and original on right.

B Load case 1 — Lid 15 MPa, cylinder 5 MPa

B.1 Contact

There is no contact between the lid and cylinder casing during loading.

B.2 Stress

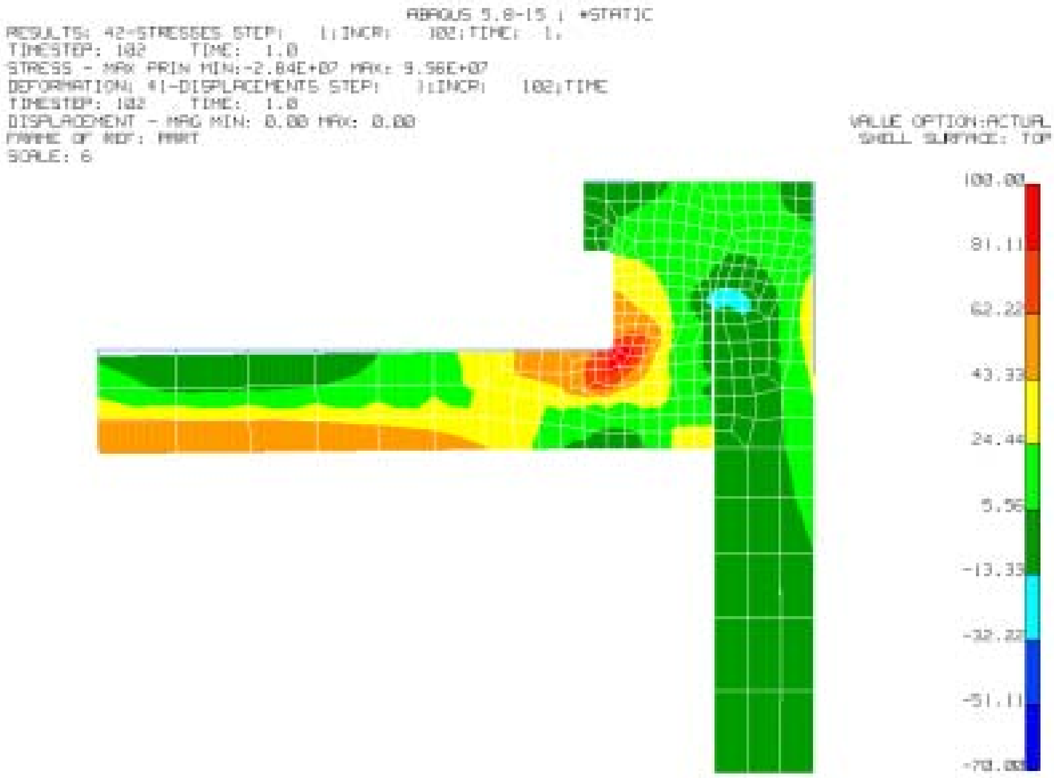


Figure 18 Max principal stress (MPa). Load case 1 at a load fraction of 0.2.

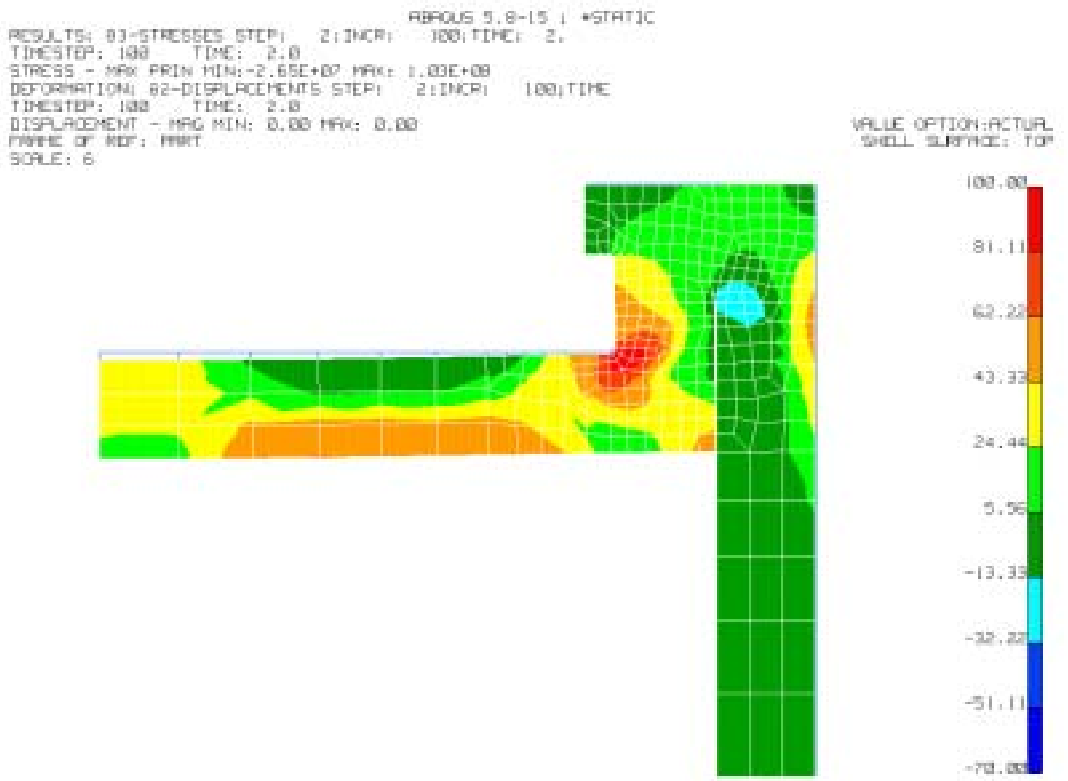


Figure 19 Max principal stresses (MPa). Load case 1 at a load fraction of 0.6.

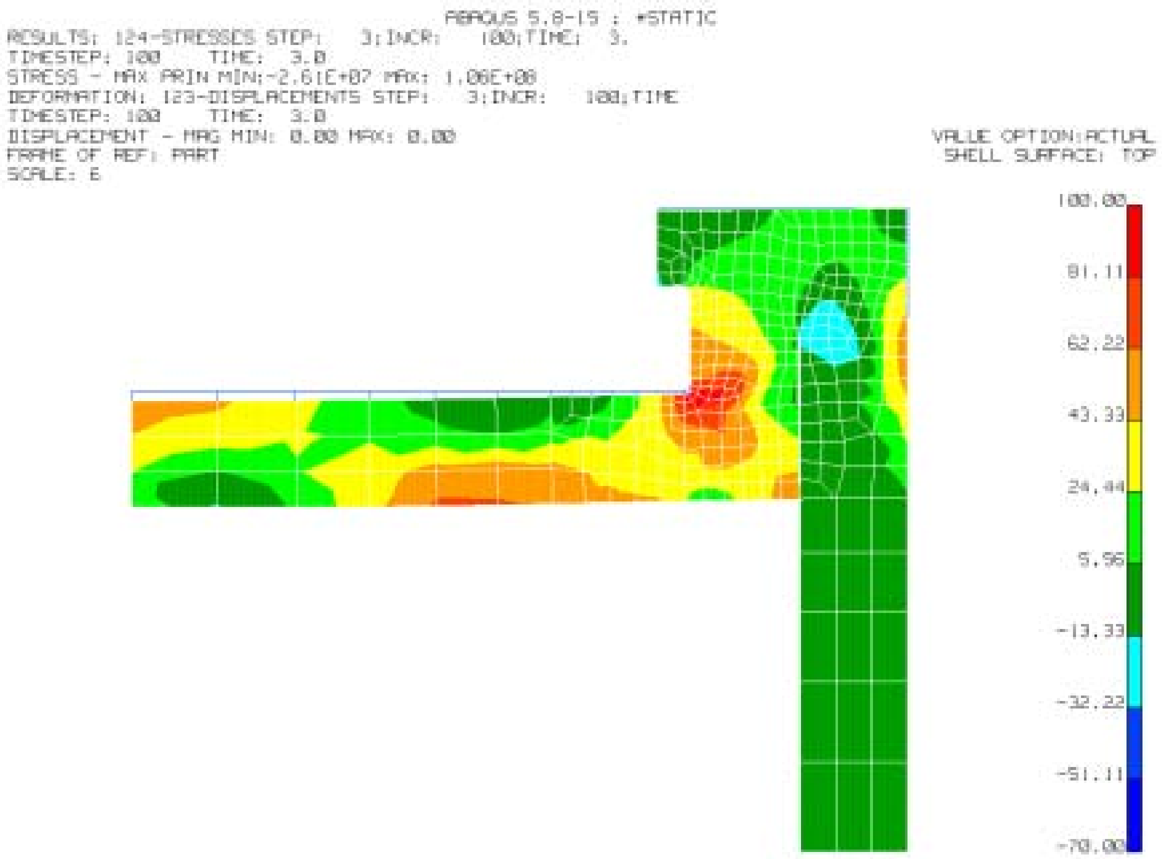


Figure 20 Max principal stress (MPa). Load case 1.

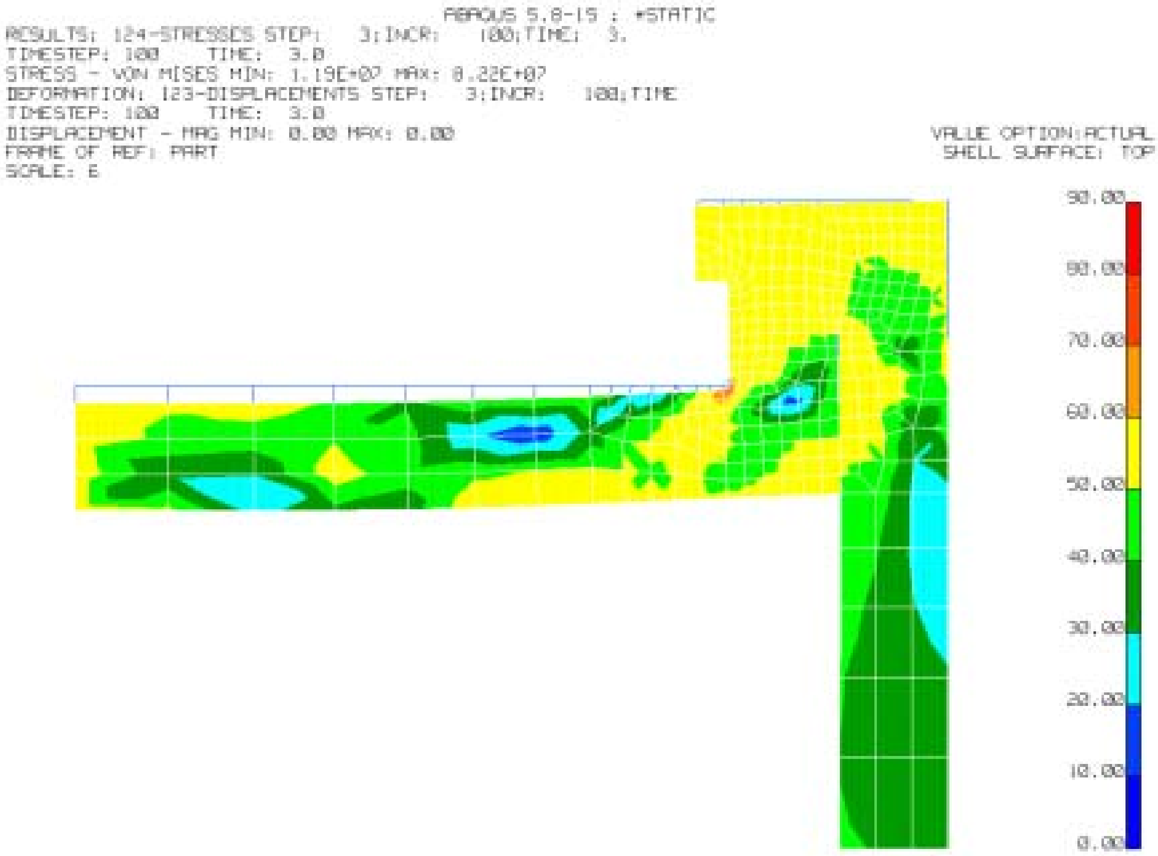


Figure 21 von Mises stress (MPa). Load case 1.

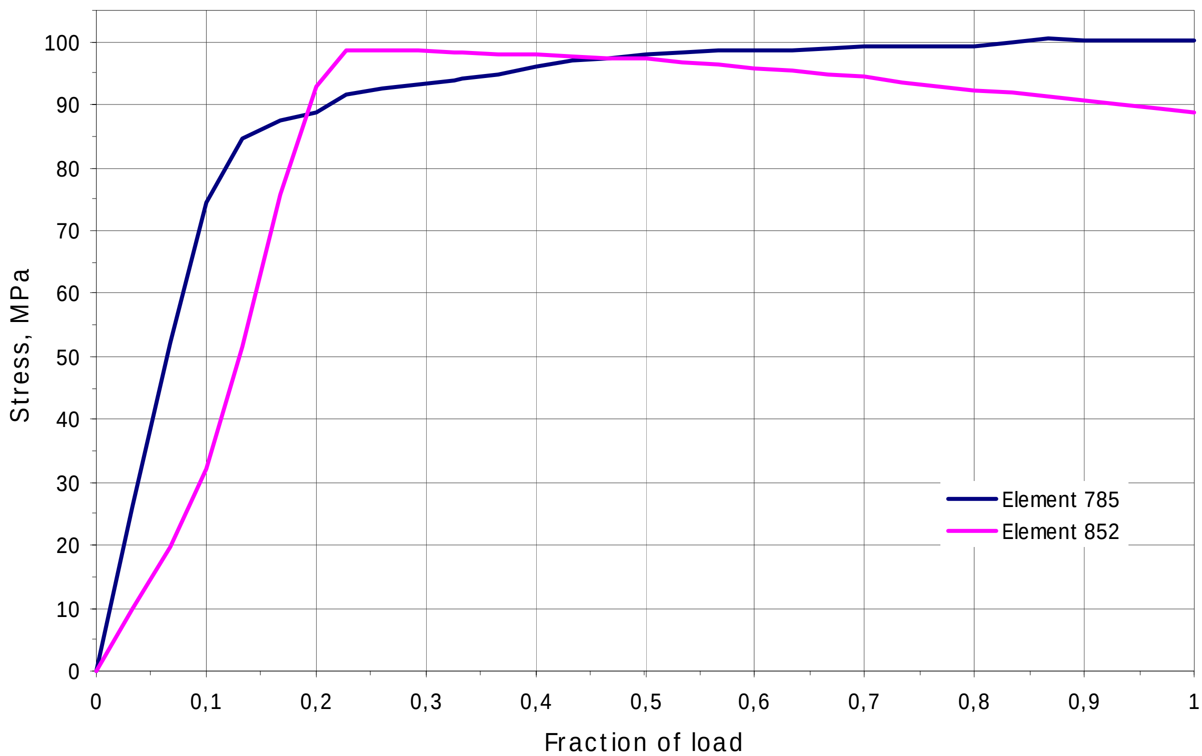


Figure 22 Max principal stresses in the lid fillet during loading. Load case 1.

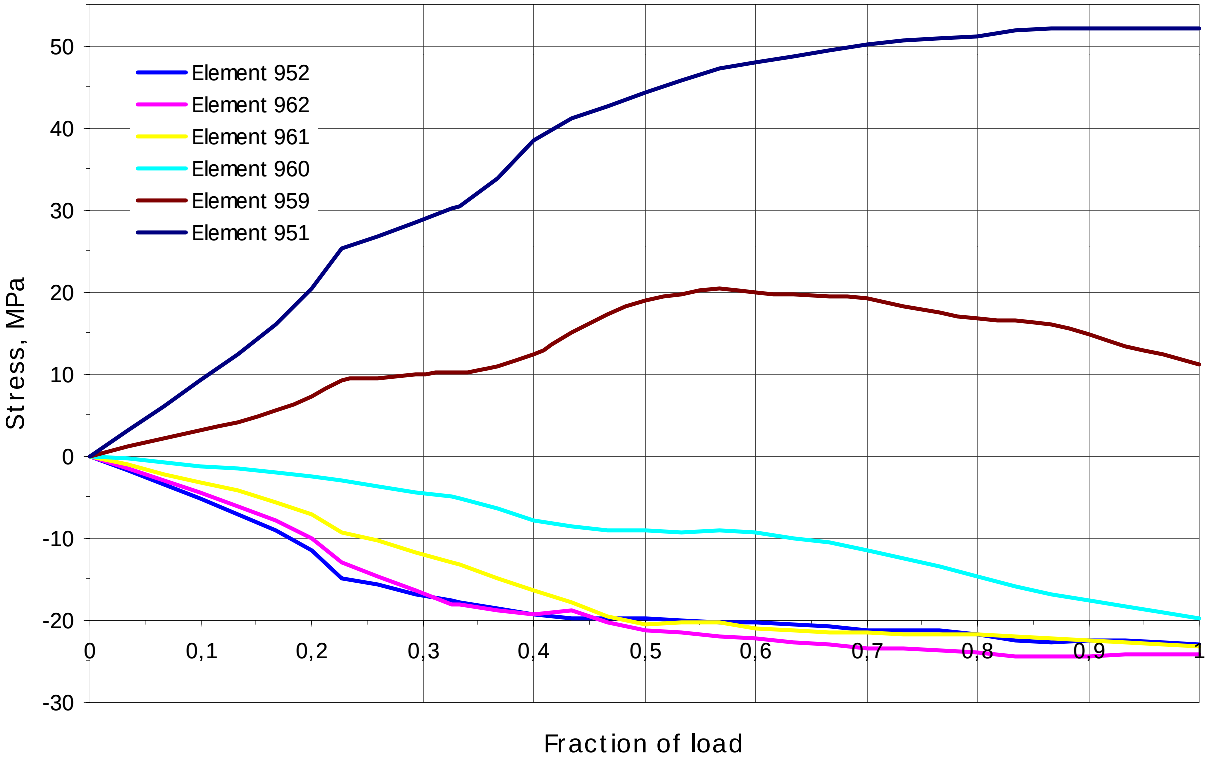


Figure 23 Max principal stress in weld during loading. Load case 1.

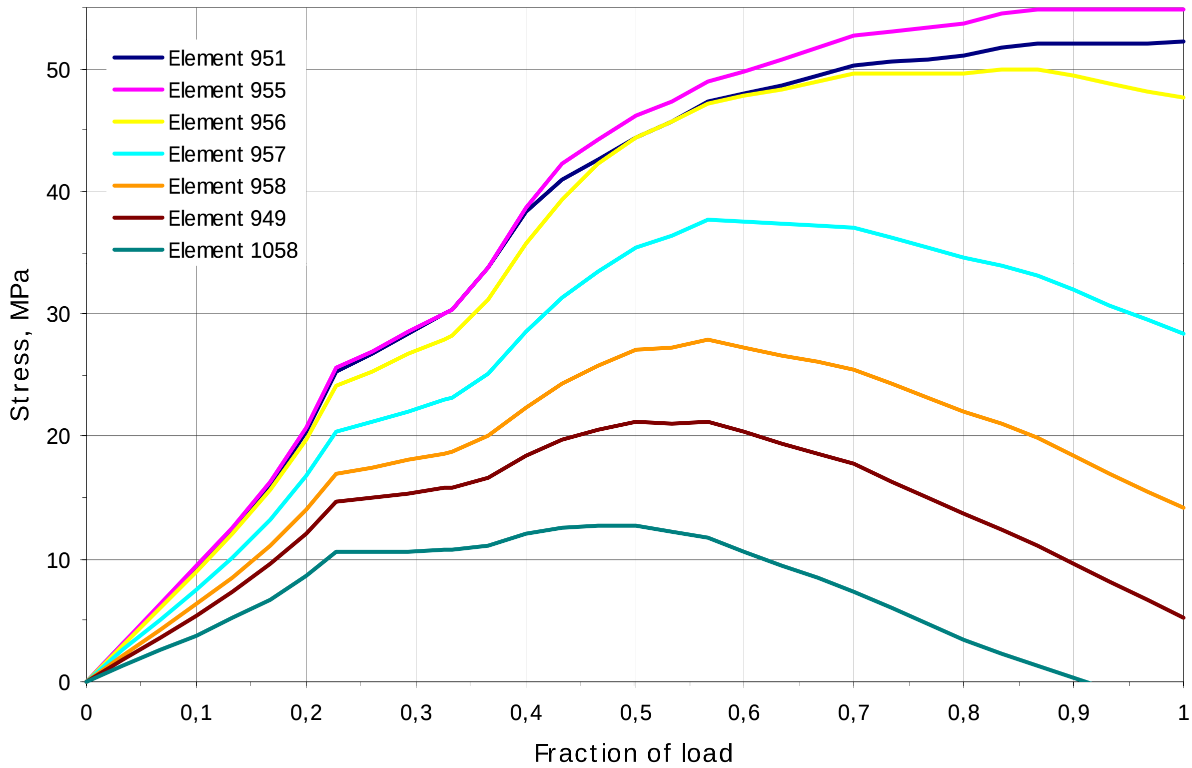


Figure 24 Max principal stress in cylinder during loading. Load case 1.

B.3 Strain

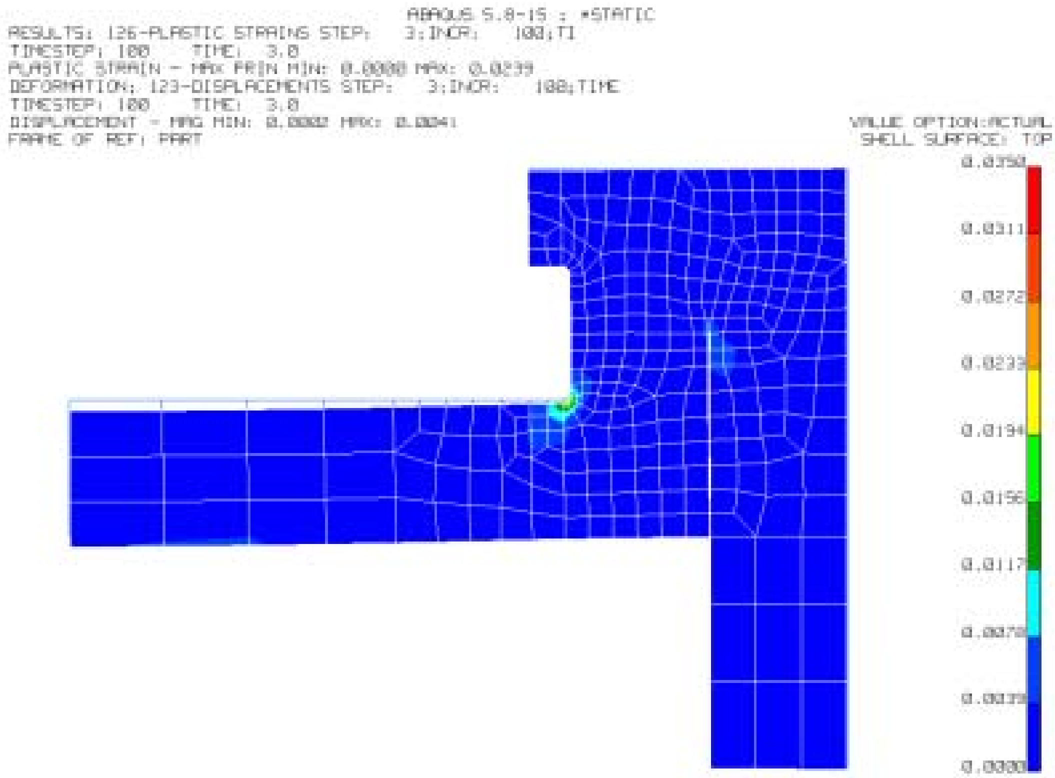


Figure 25 Max principal plastic strain. Load case 1.

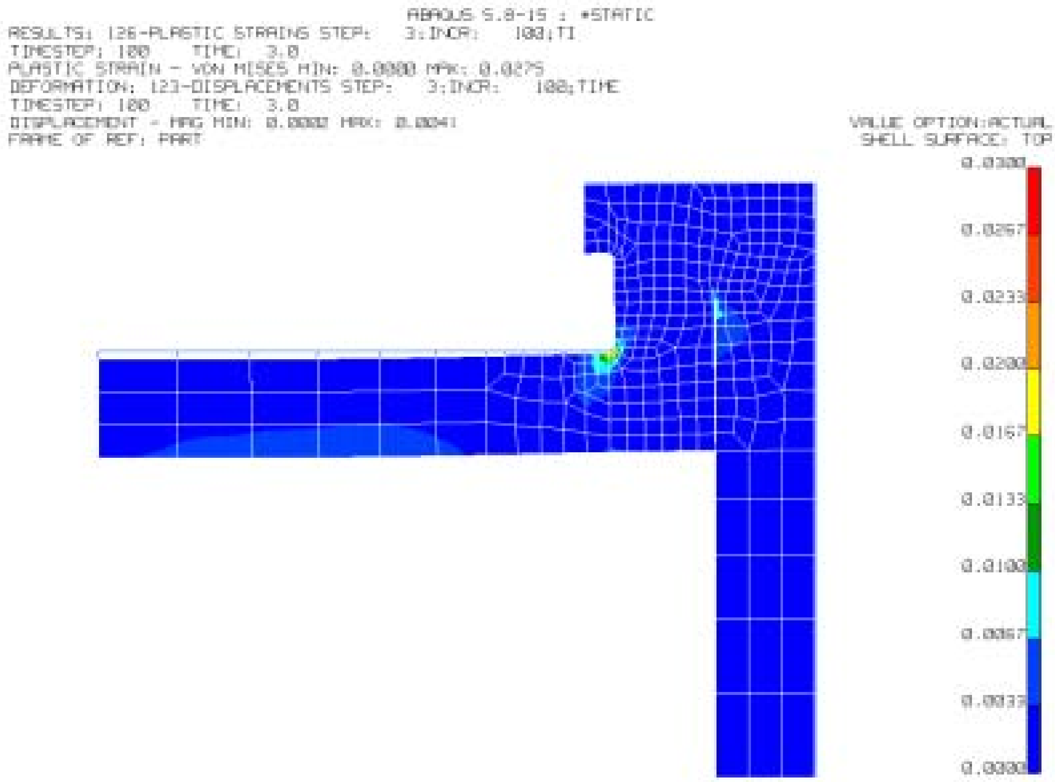


Figure 26 von Mises plastic strain. Load case 1.

C Load case 2 — Lid 5 MPa, cylinder 15 MPa

C.1 Contact

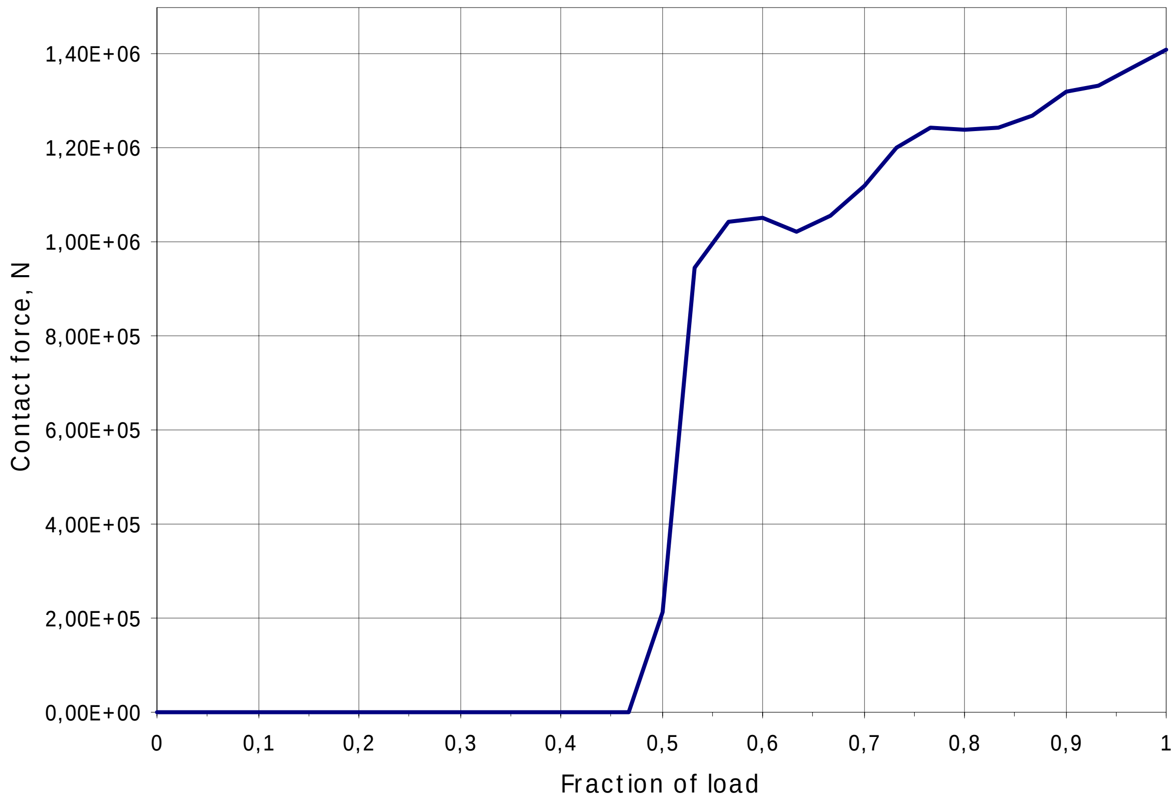


Figure 27 Contact force between the lid lower edge and cylinder casing (element 1109 as shown in Figure 11) during loading. Load case 2.

C.2 Stress

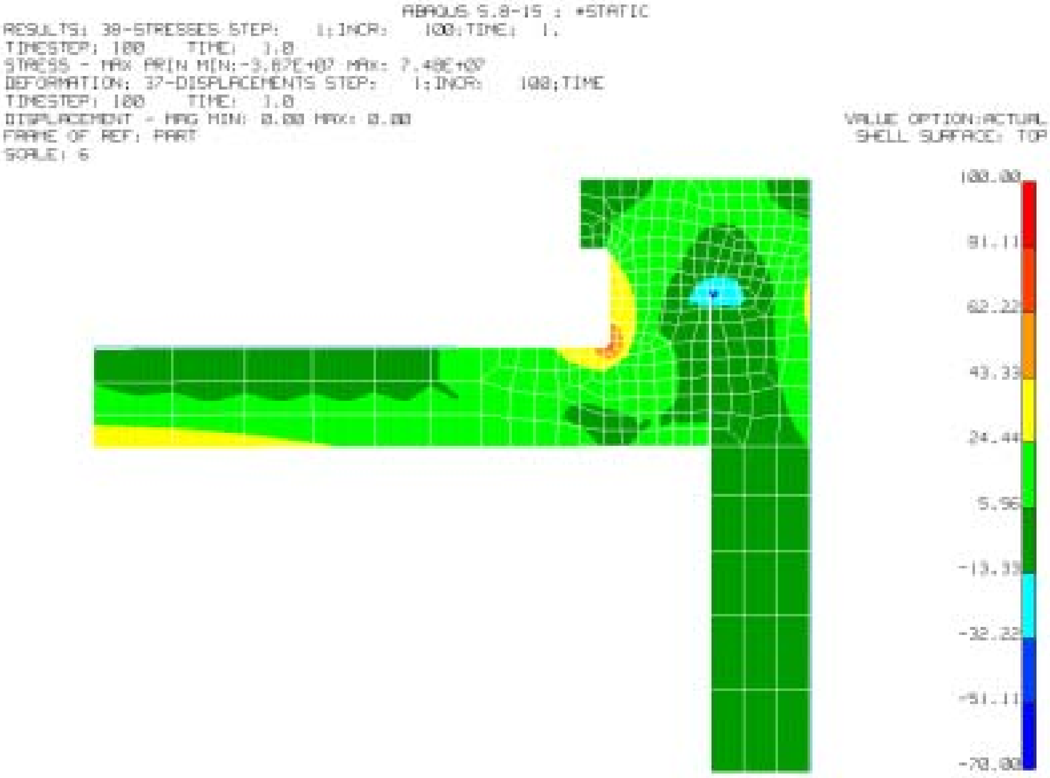


Figure 28 Max principal stress (MPa). Load case 2 at 20% of load.

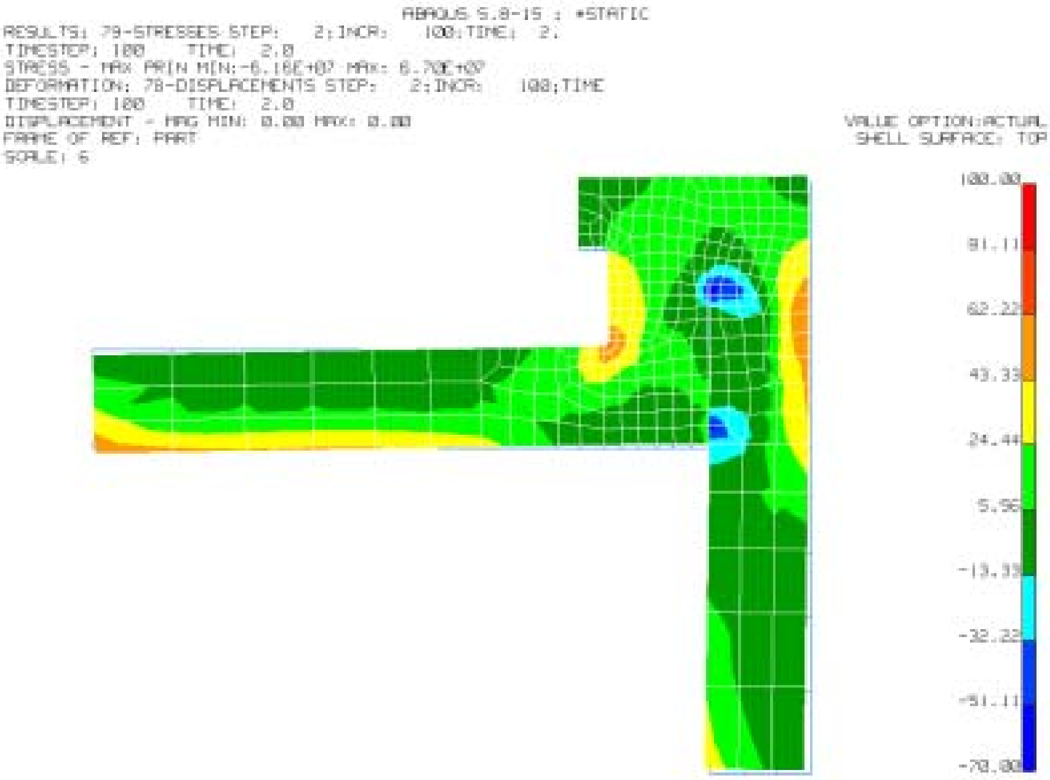


Figure 29 Max principal stress (MPa). Load case 2 at 60% of load.

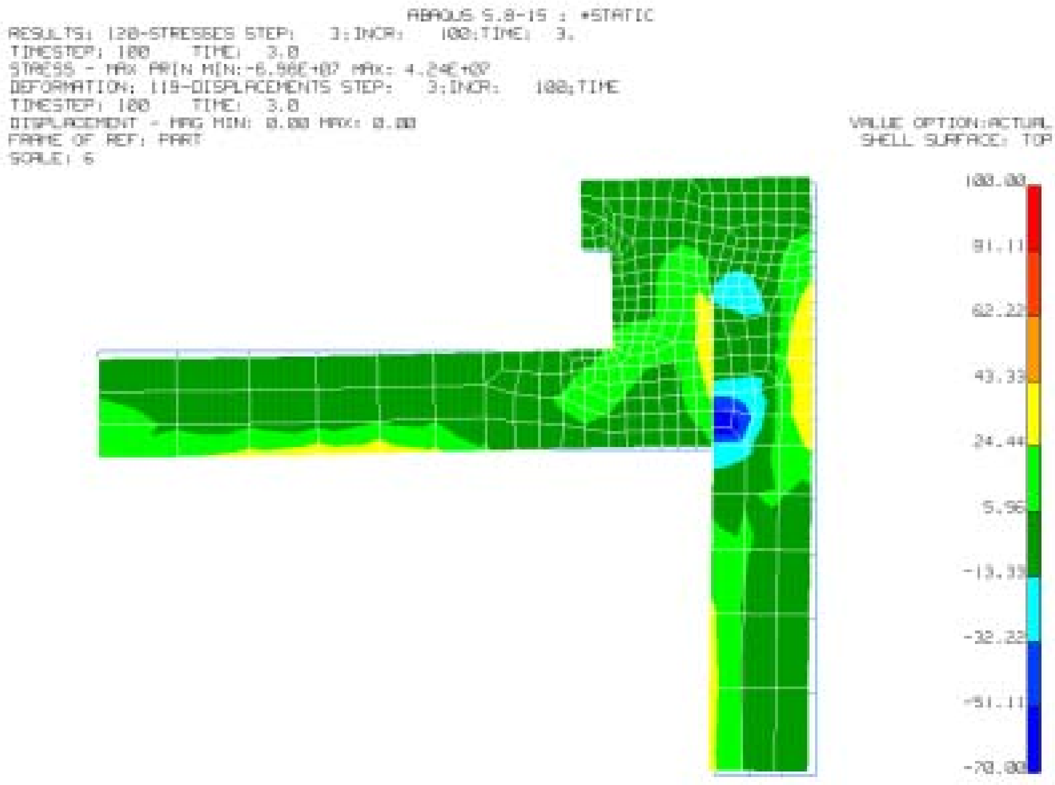


Figure 30 Max principal stress (MPa). Load case 2.

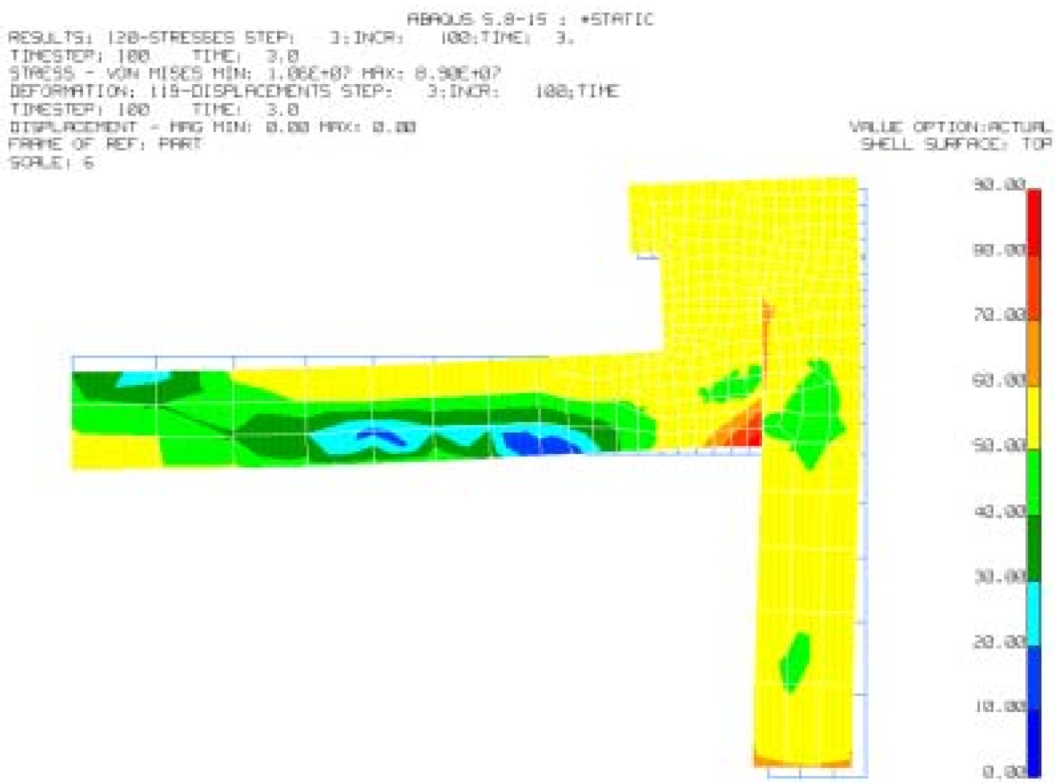


Figure 31 von Mises stress (MPa). Load case 2.

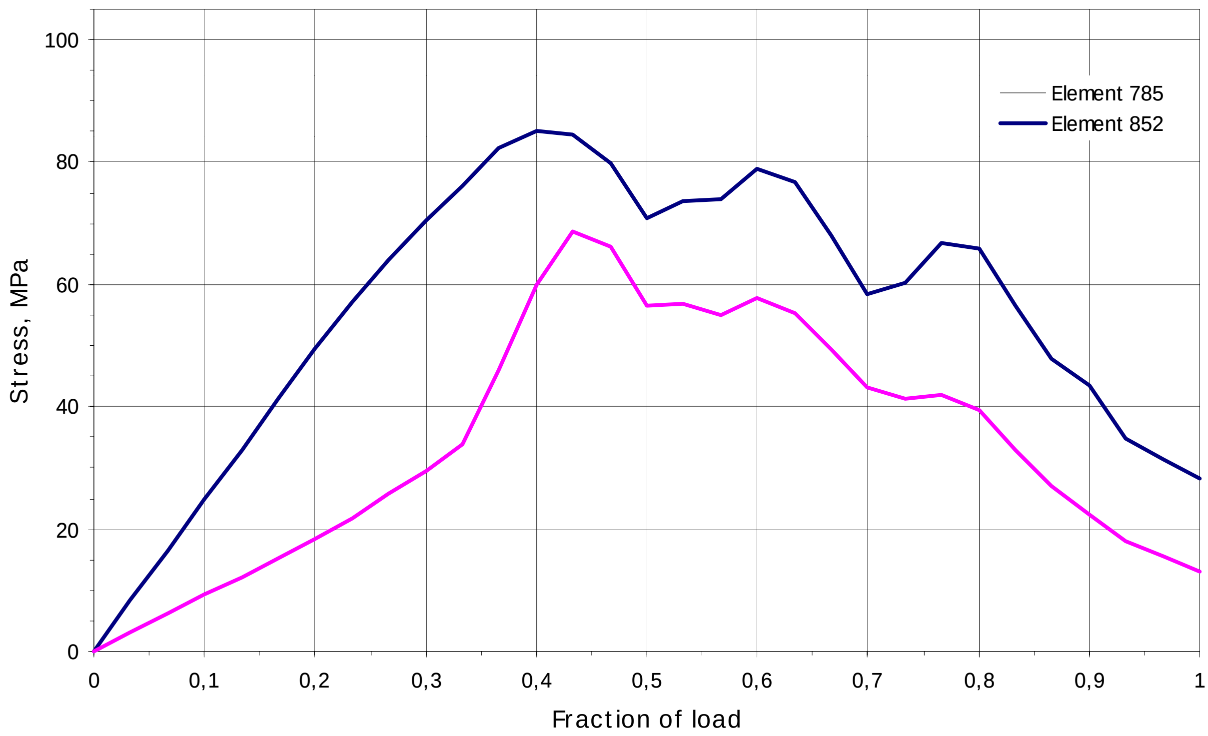


Figure 32 Max principal stress in lid fillet during loading. Load case 2.

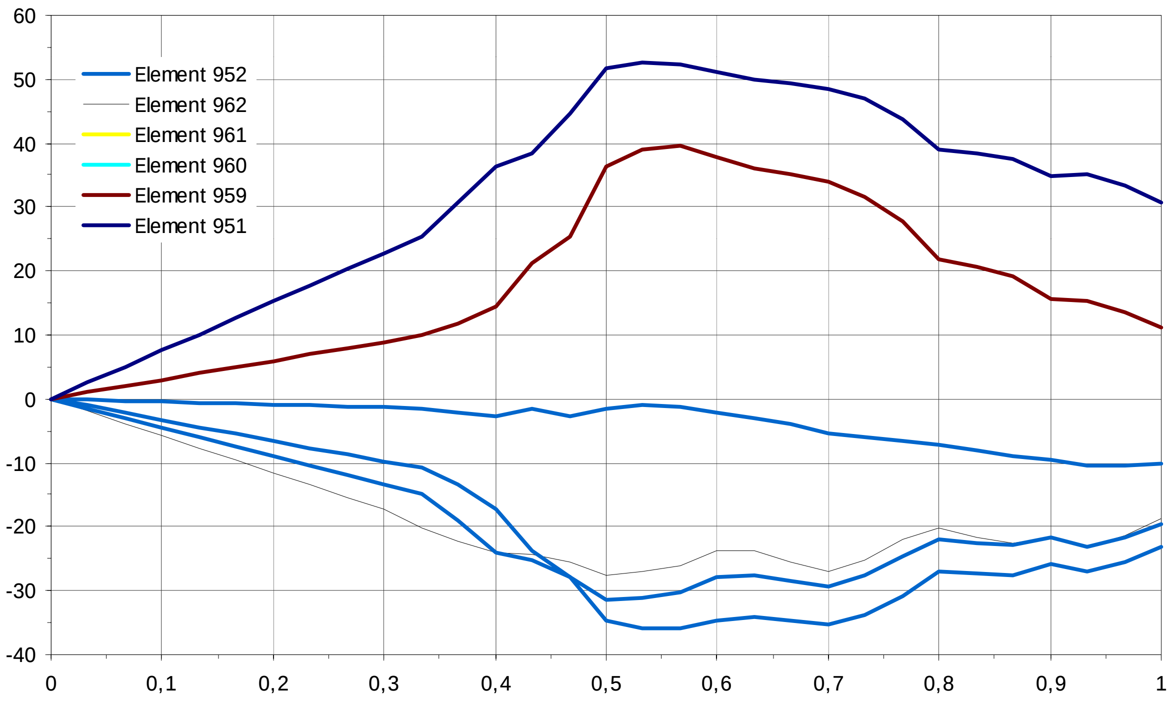


Figure 33 Max principal stress in weld during loading. Load case 2.

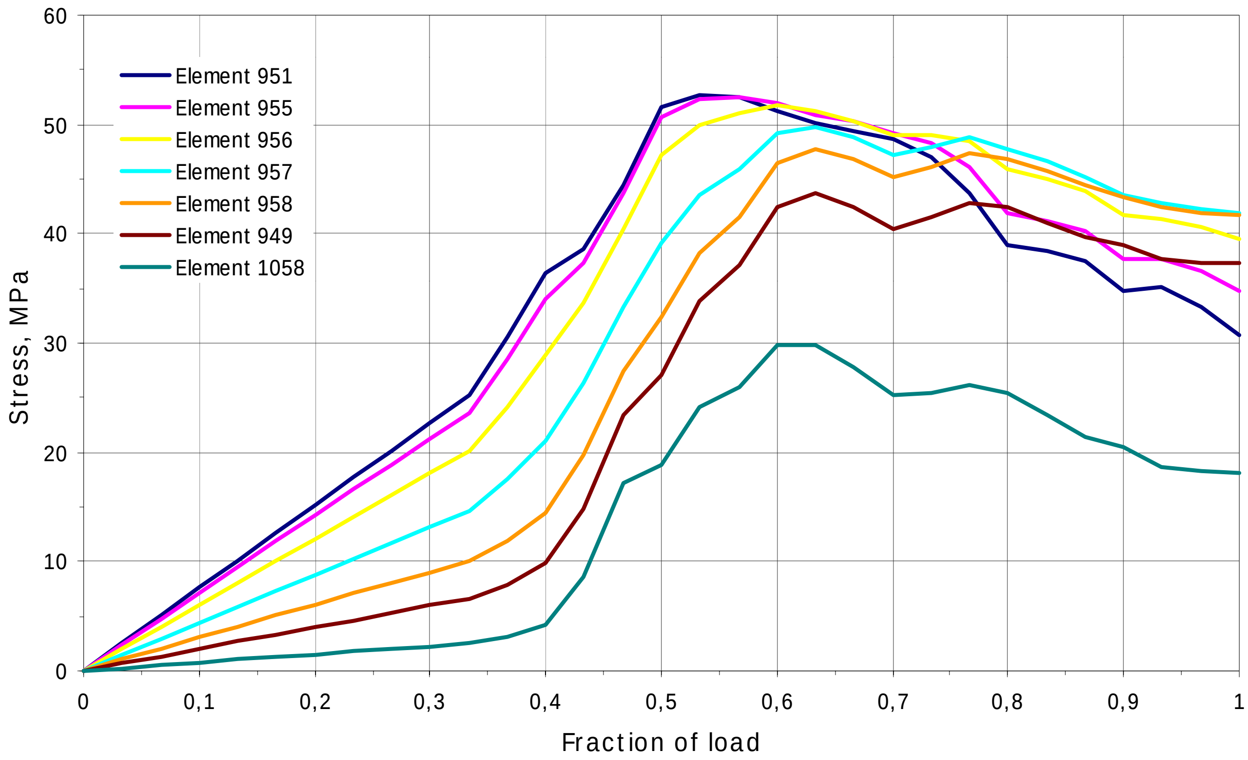


Figure 34 Max principal stress in casing during loading. Load case 2.

C.3 Strain

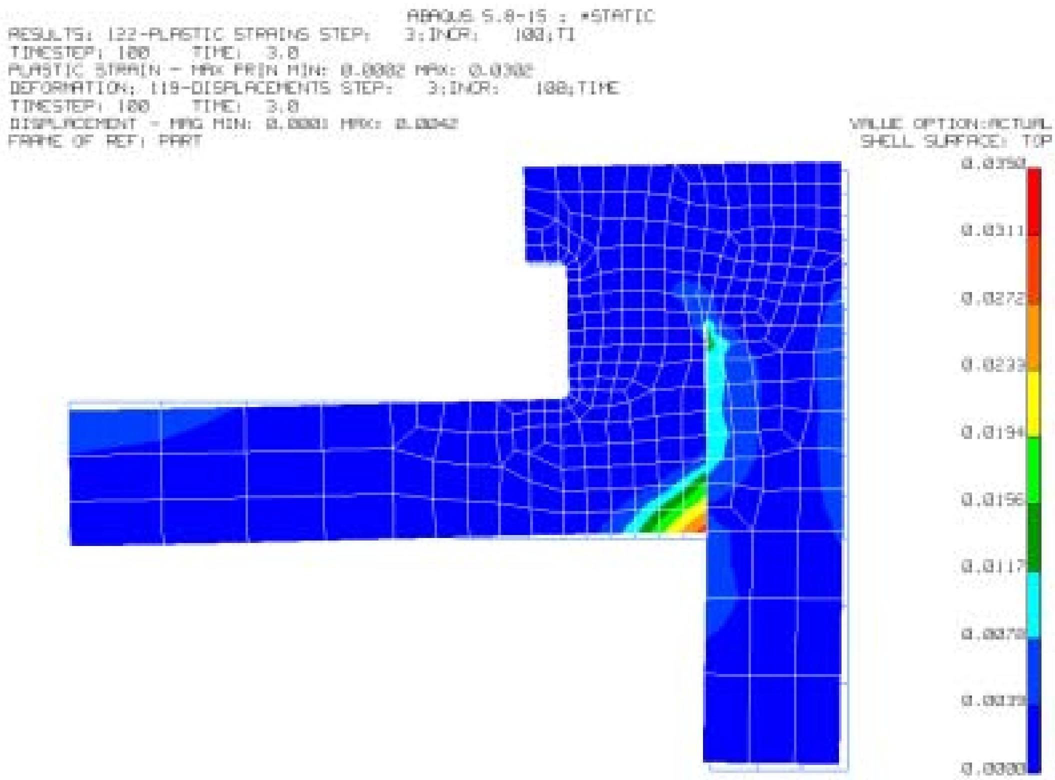


Figure 35 Max principal plastic strain. Load case 2.

D Load case 3 — Uniform pressure on canister

D.1 Contact

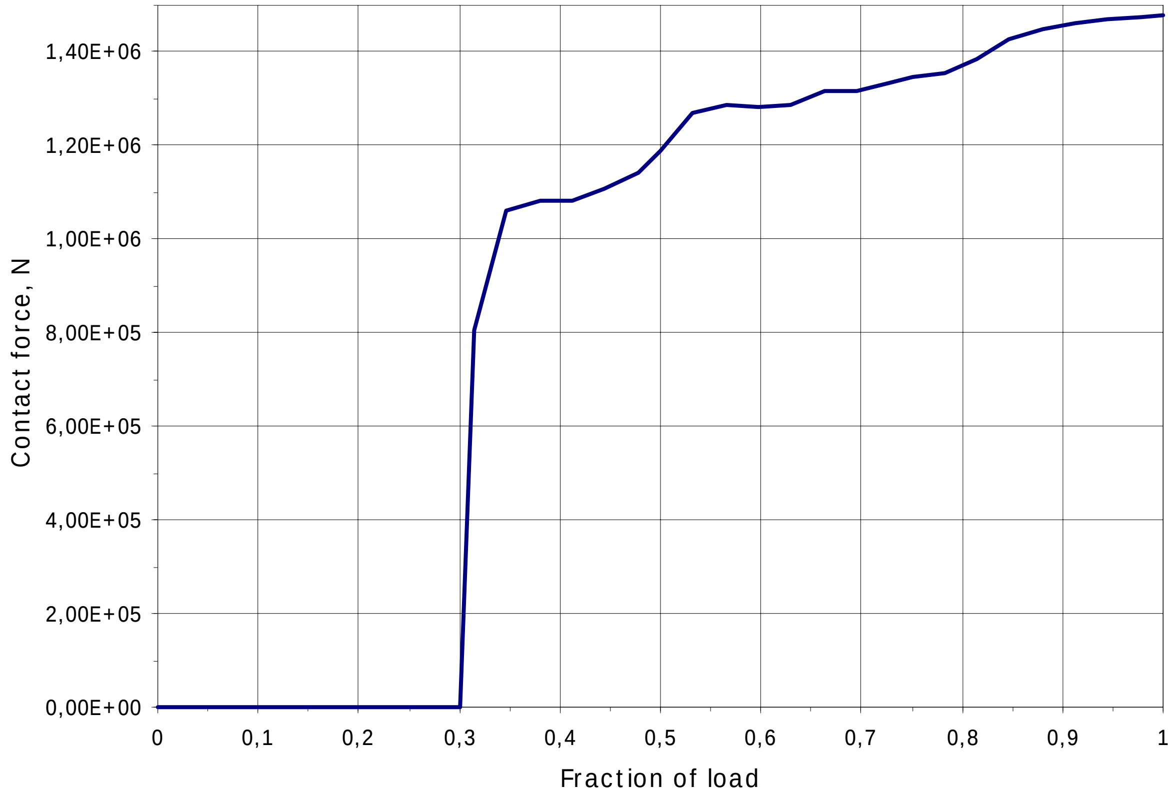


Figure 36 Contact force between the lid lower edge and cylinder casing (element 1109 as shown in Figure 11) during loading. Load case 3.

D.2 Stress

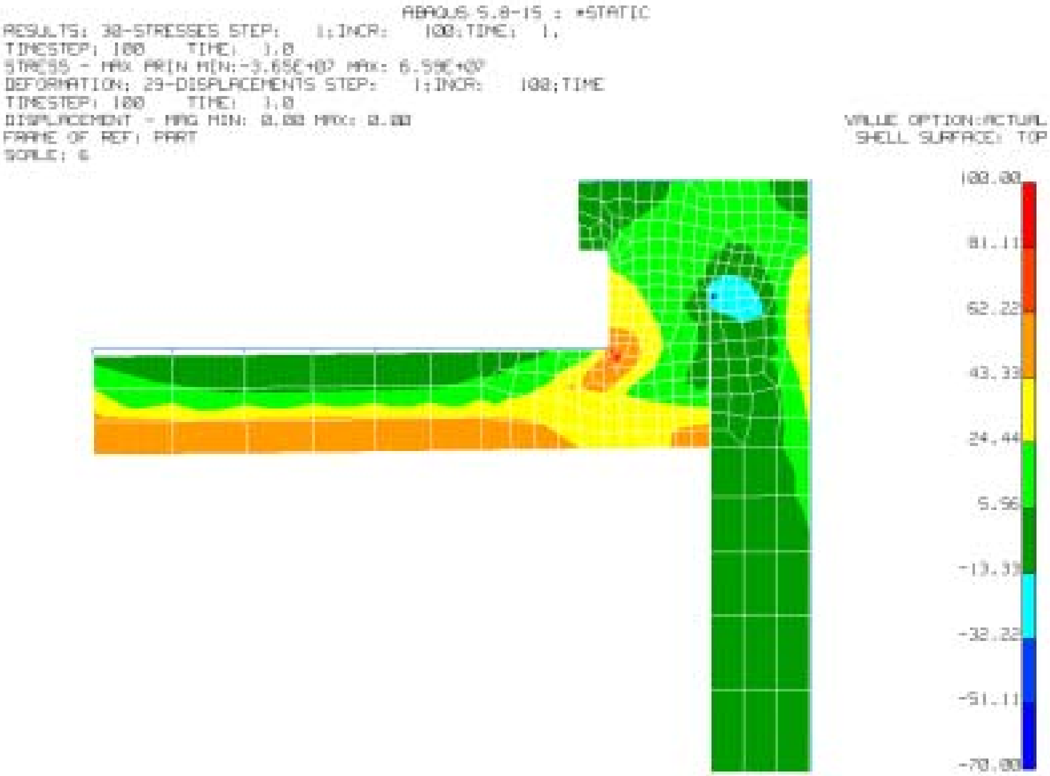


Figure 37 Max principal stress (MPa). Load case 3: uniform loading of 5 MPa.

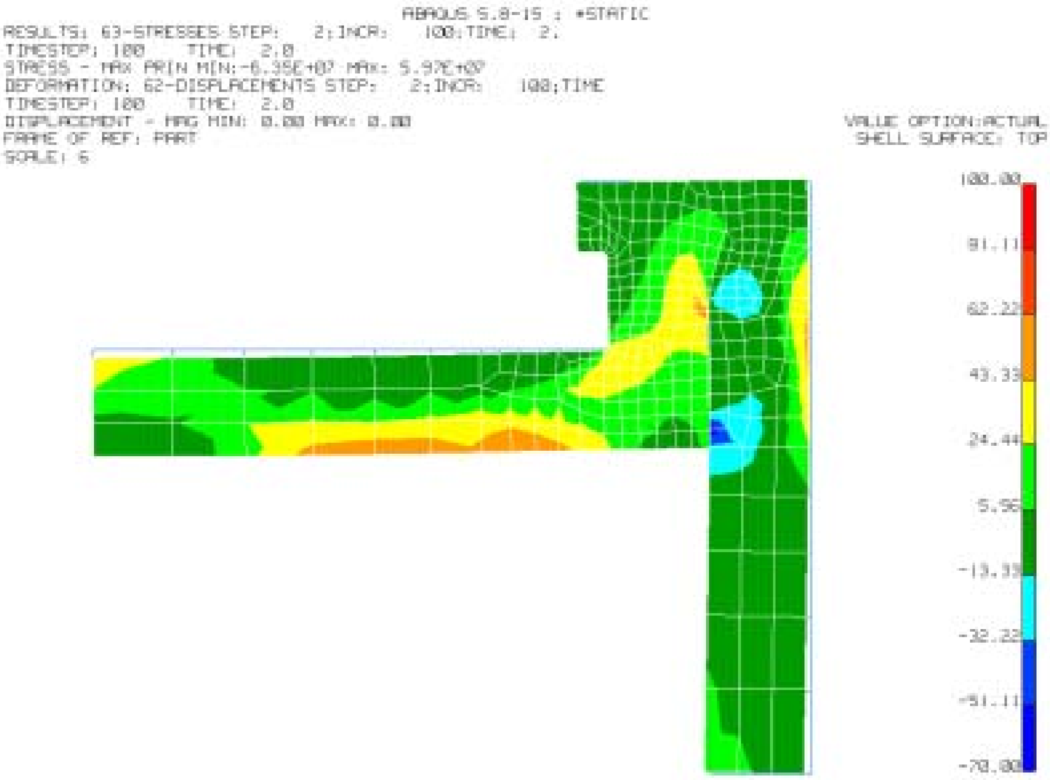


Figure 38 Max principal stress (MPa). Load case 3: uniform loading of 10 MPa.

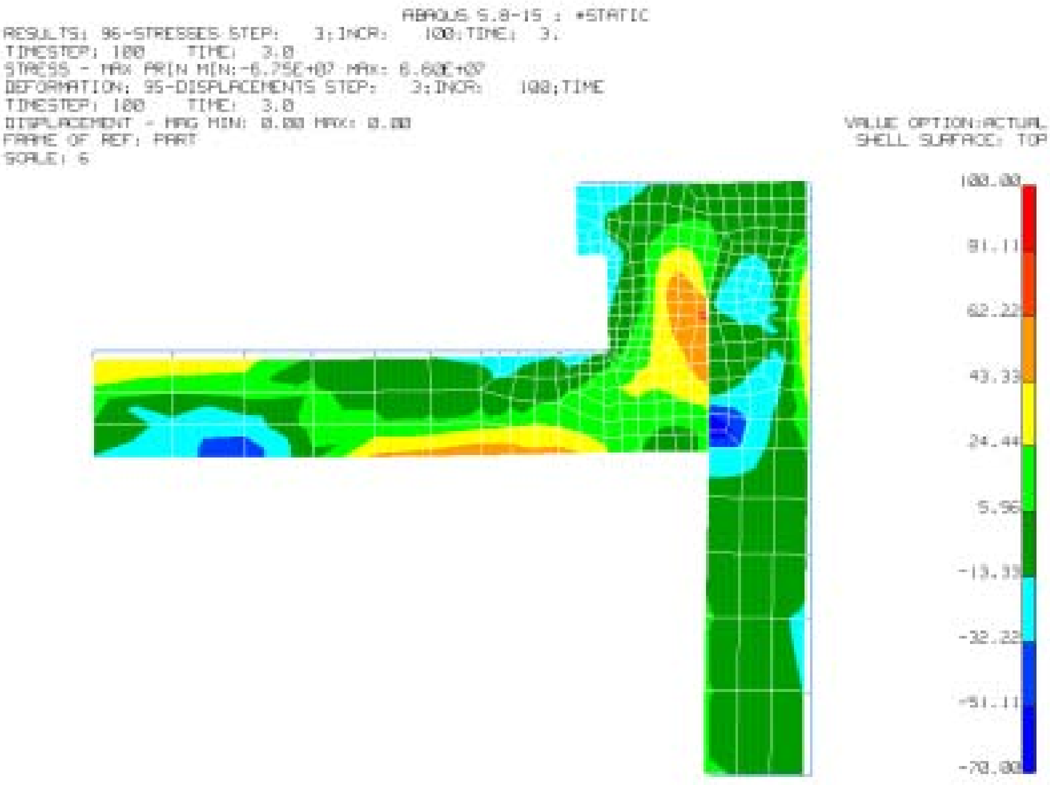


Figure 39 Max principal stress (MPa). Load case 3: uniform loading of 15 MPa.

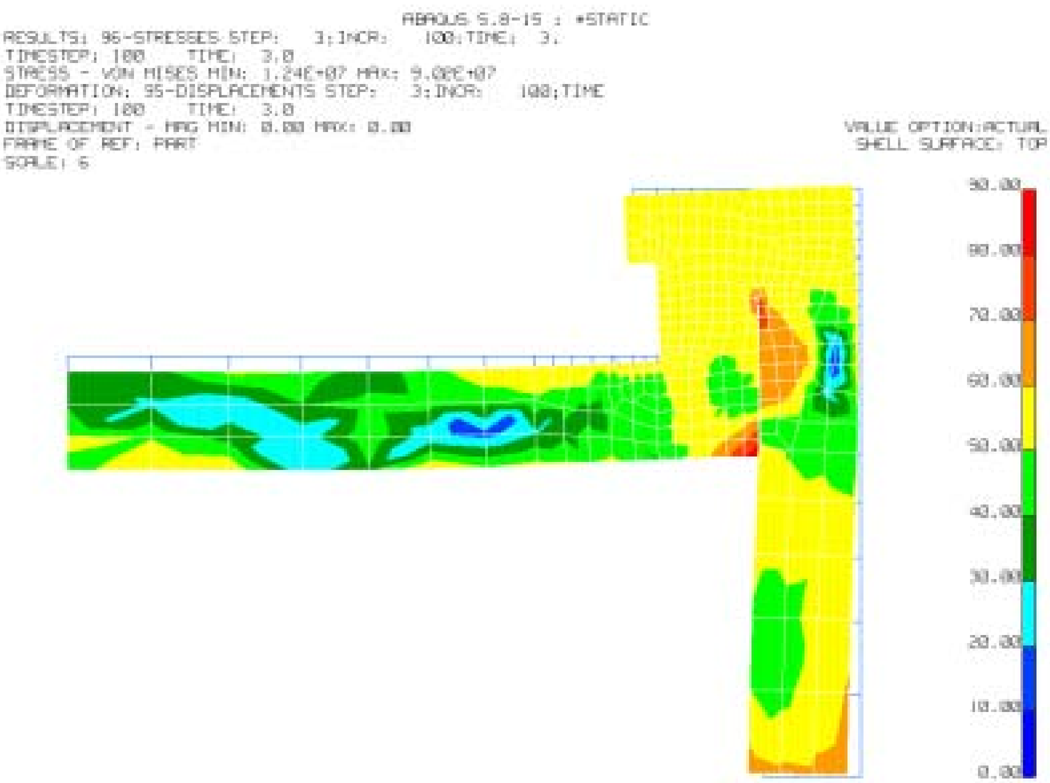


Figure 40 von Mises stress (MPa). Load case 3: uniform loading of 15 MPa.

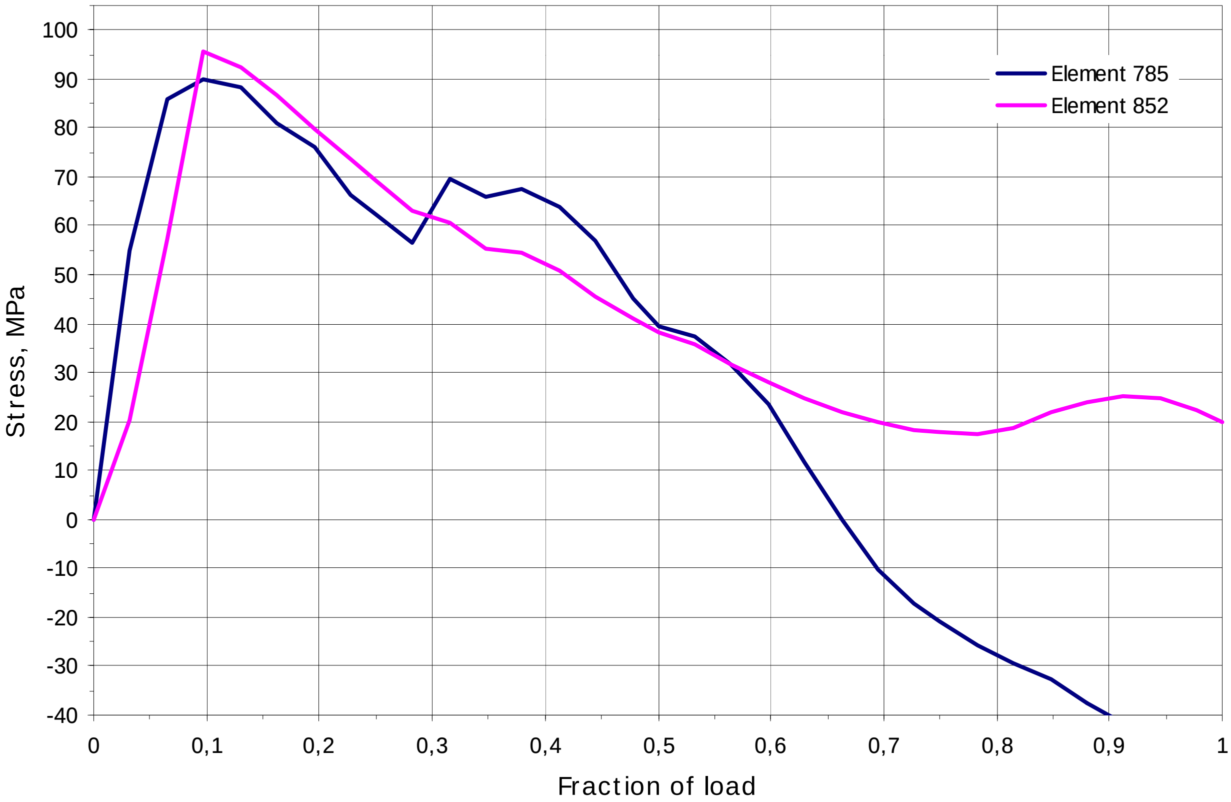


Figure 41 Max principal stress in lid fillet during loading. Load case 3.

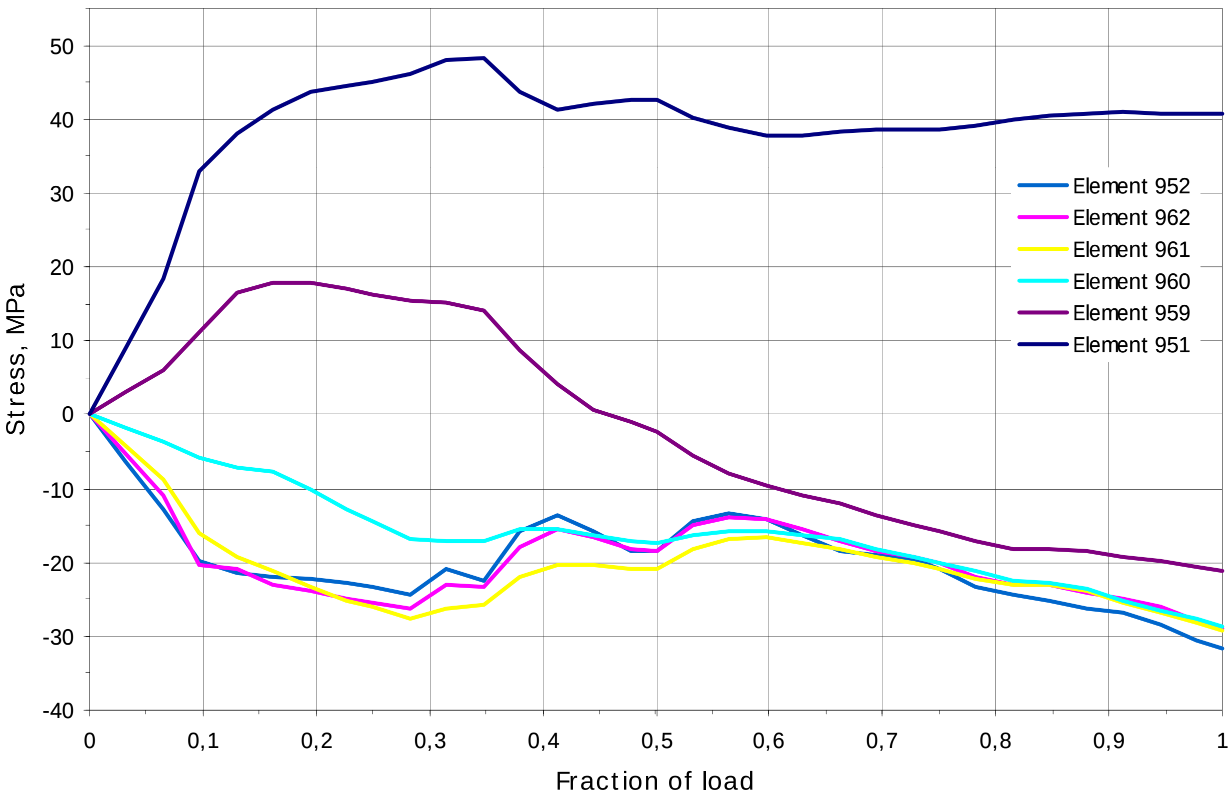


Figure 42 Max principal stress in weld during loading. Load case 3.

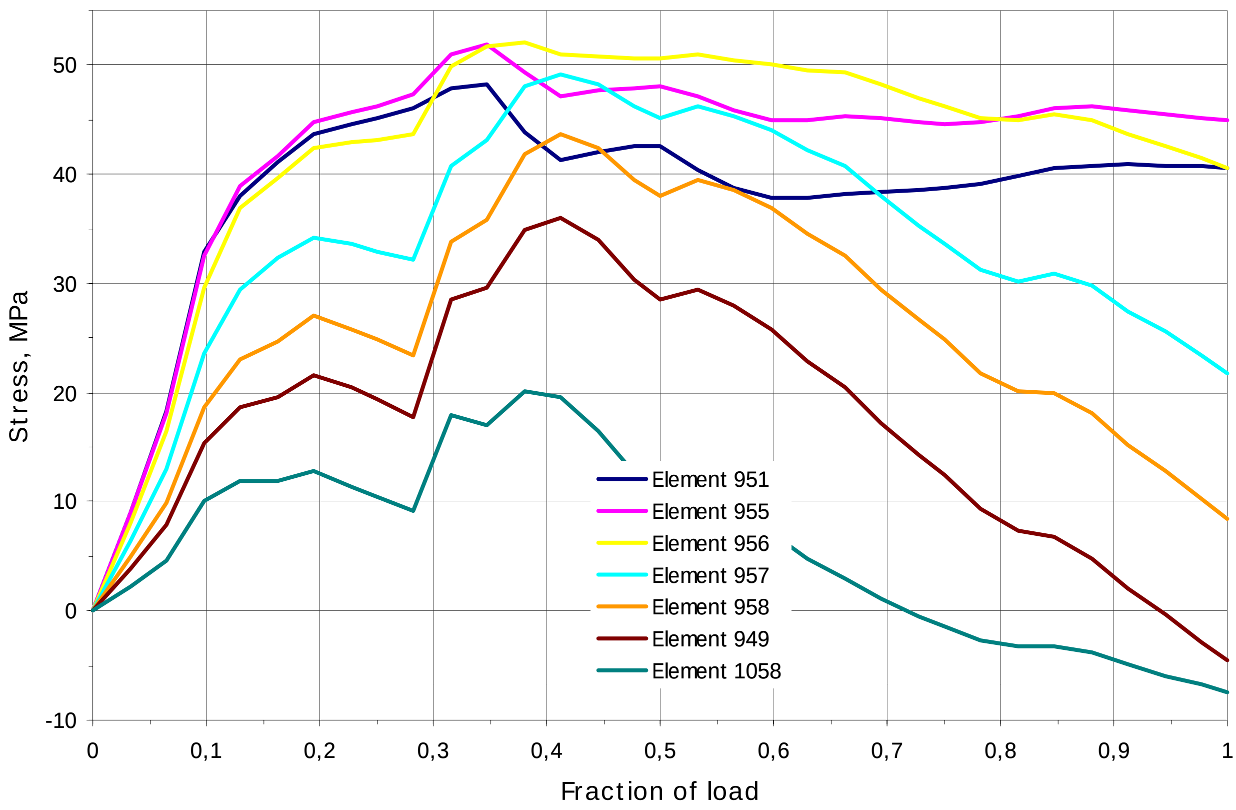


Figure 43 Max principal stress in casing during loading. Load case 3.

D.3 Strain

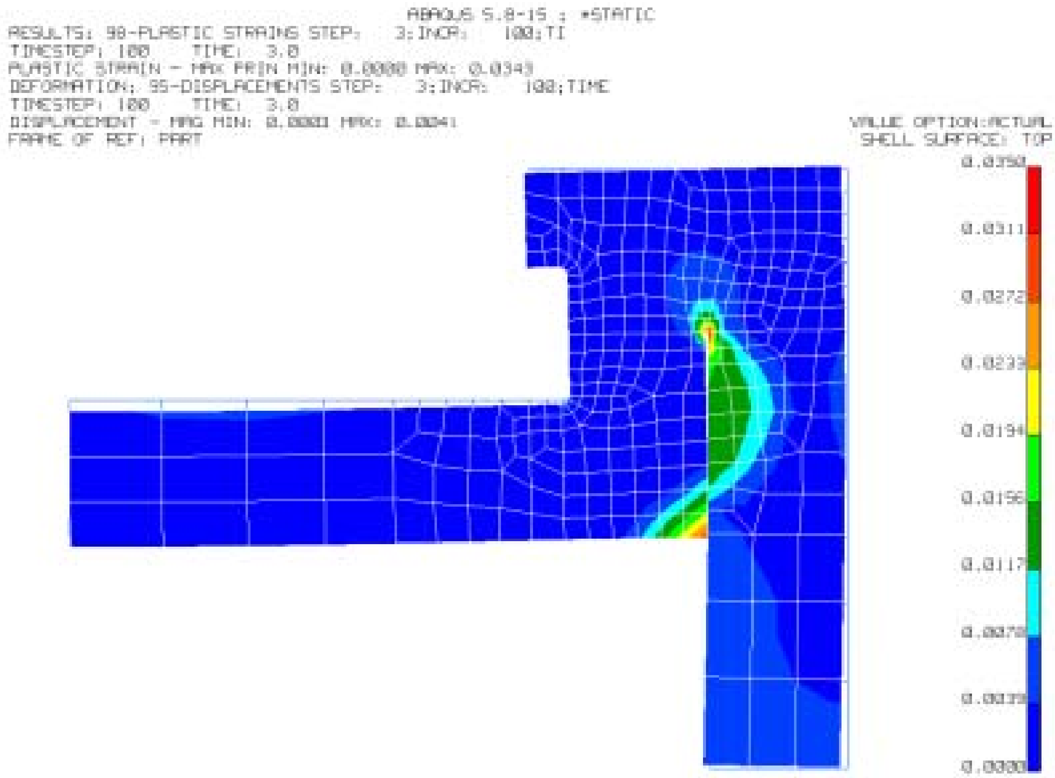


Figure 44 Max principal plastic strain. Load case 3: uniform loading of 15 MPa.

E Creep — Axisymmetric load

E.1 Contact

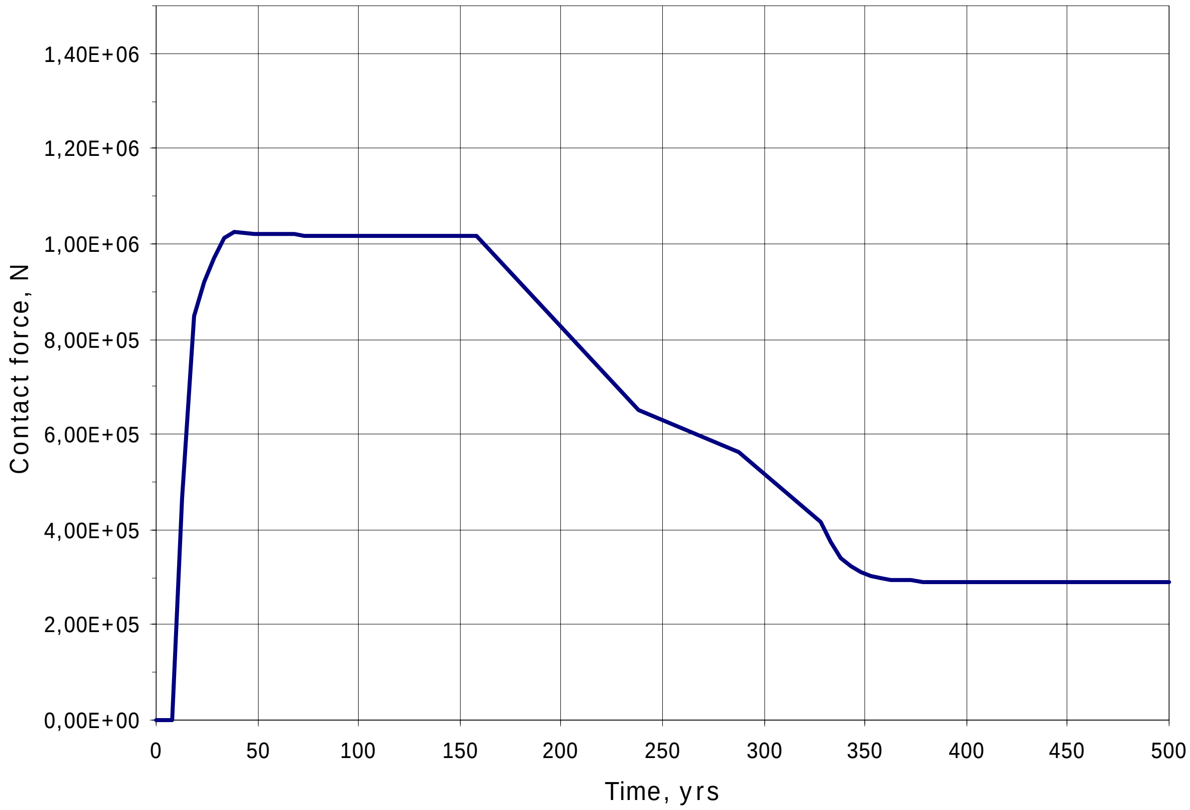


Figure 45 Contact force between the lid lower edge and cylinder casing (element 1109 as shown in Figure 11) during creep 500 years. Load case 1.

E.2 Stress

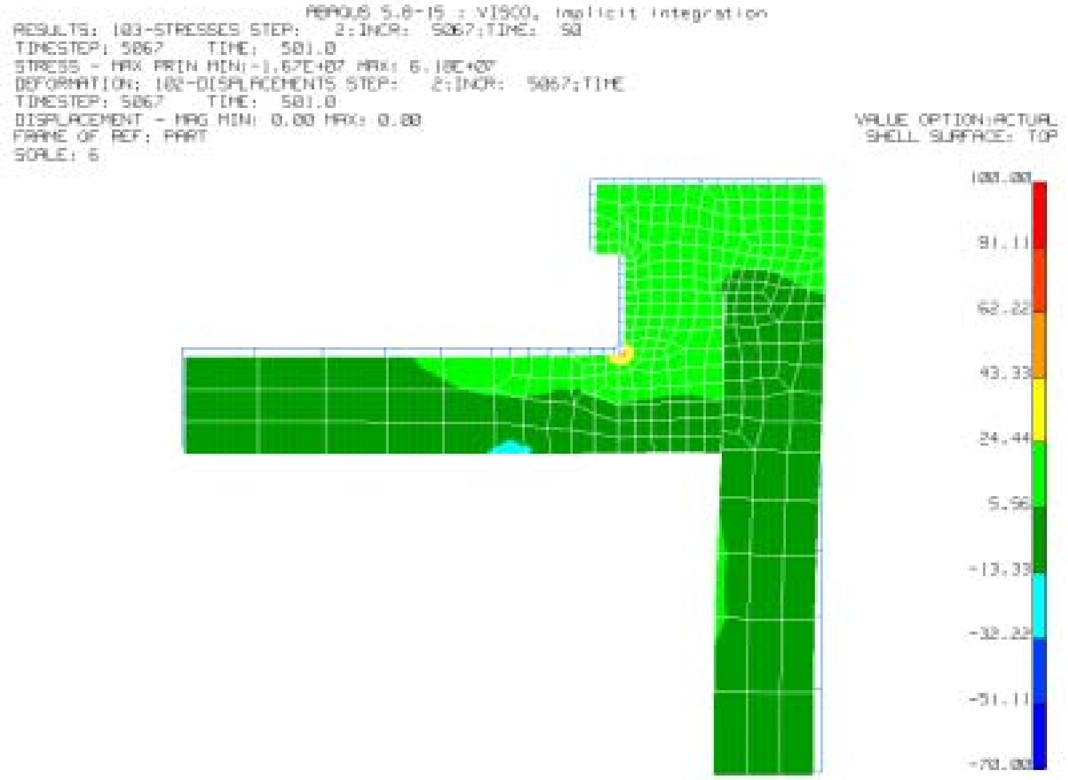


Figure 46 Max principal stress (MPa). Load case 1, creep 500 years.

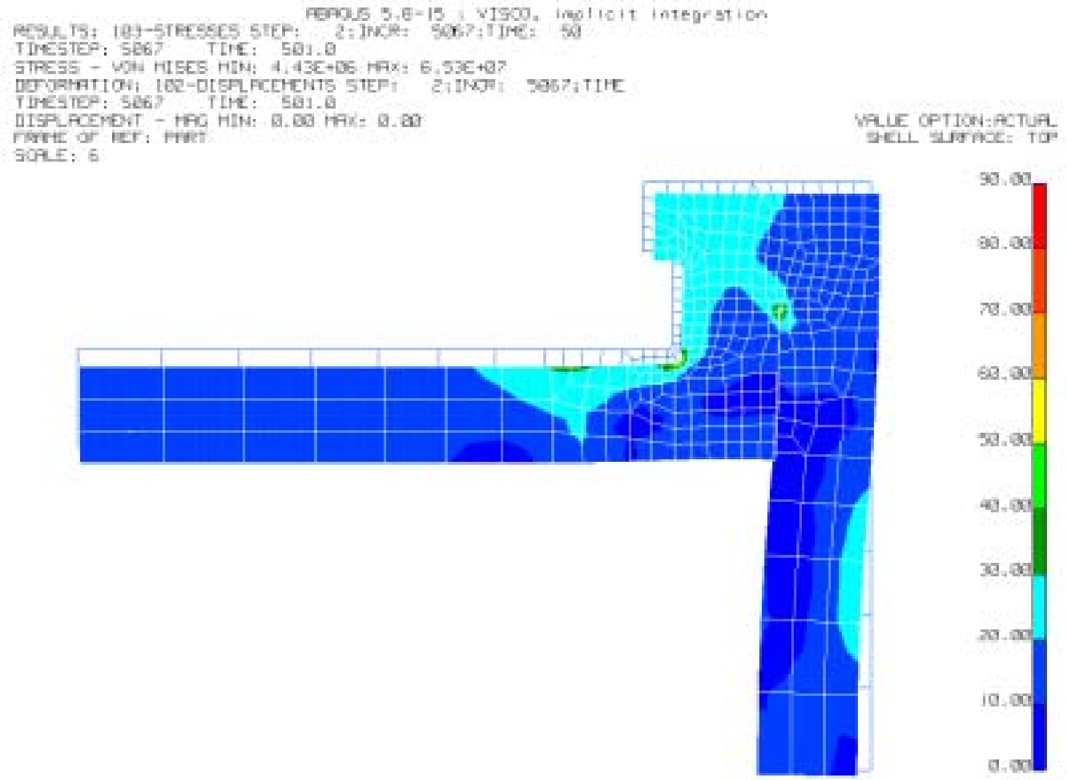


Figure 47 von Mises stress (MPa). Load case 1, creep 500 years.

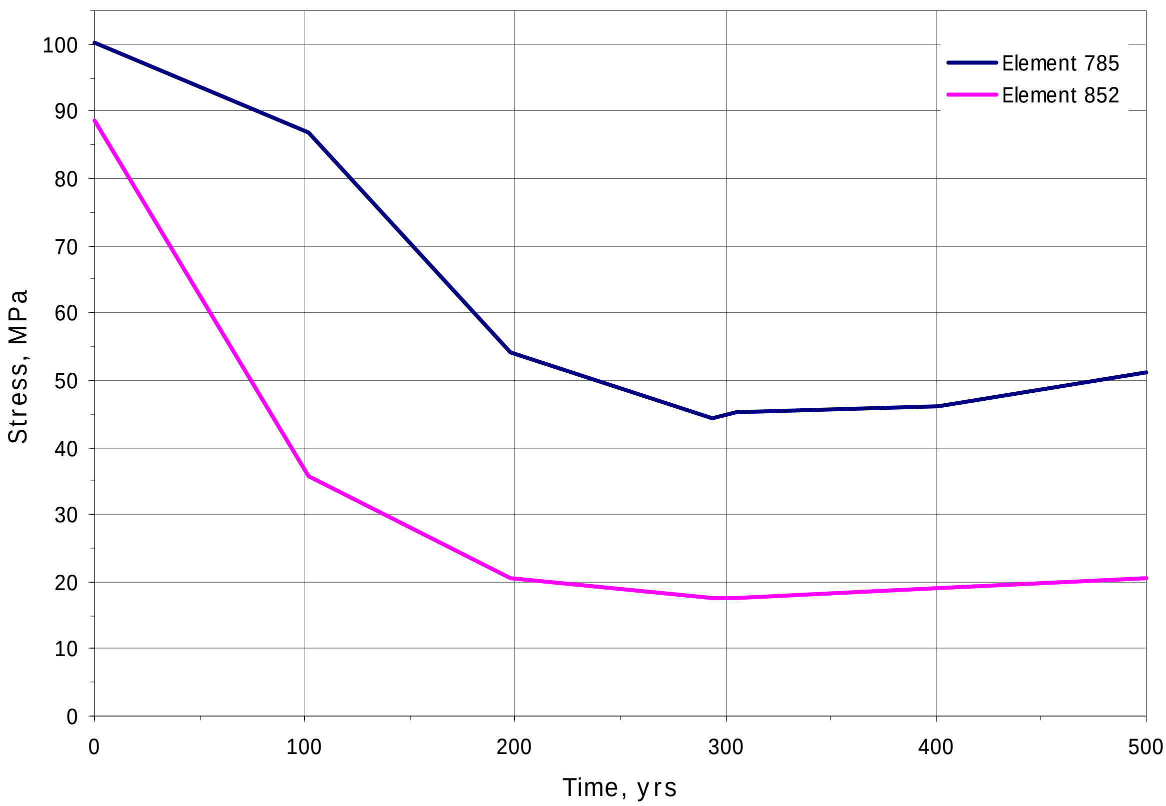


Figure 48 Max principal stress in lid fillet during creep 500 years. Load case 1.

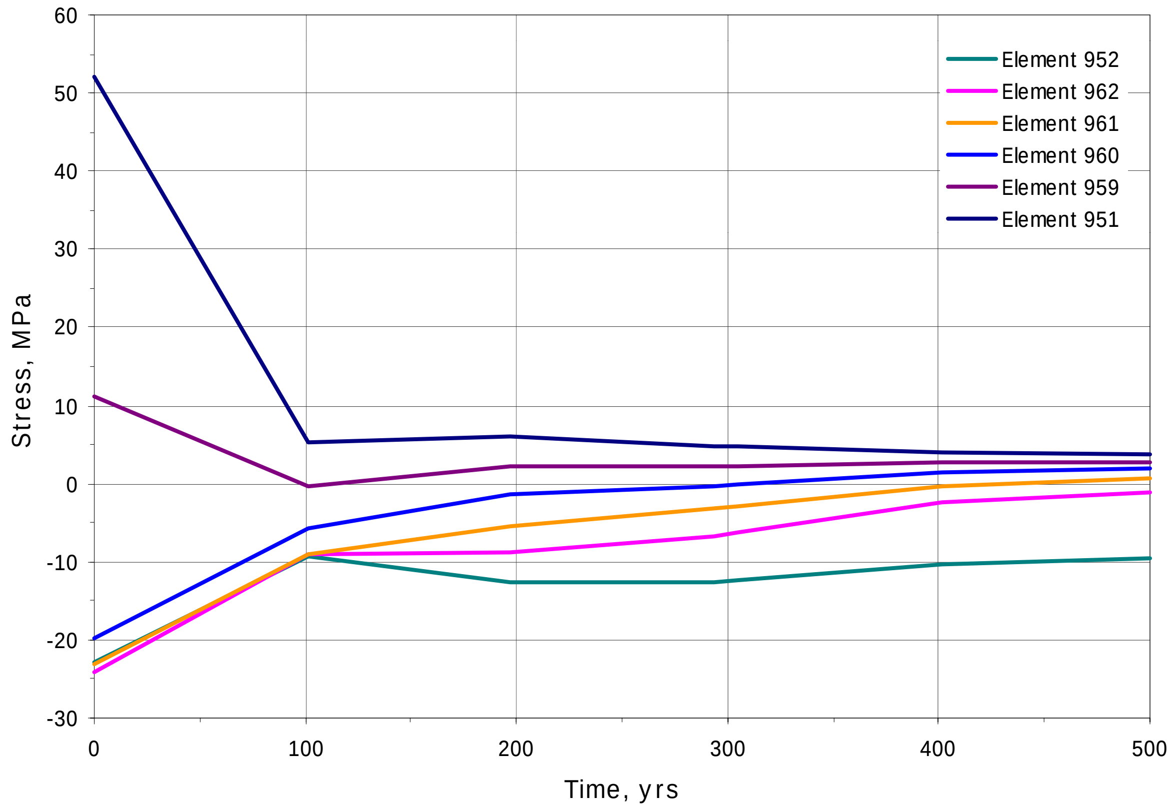


Figure 49 Max principal stress in weld during creep 500 years. Load case 1.

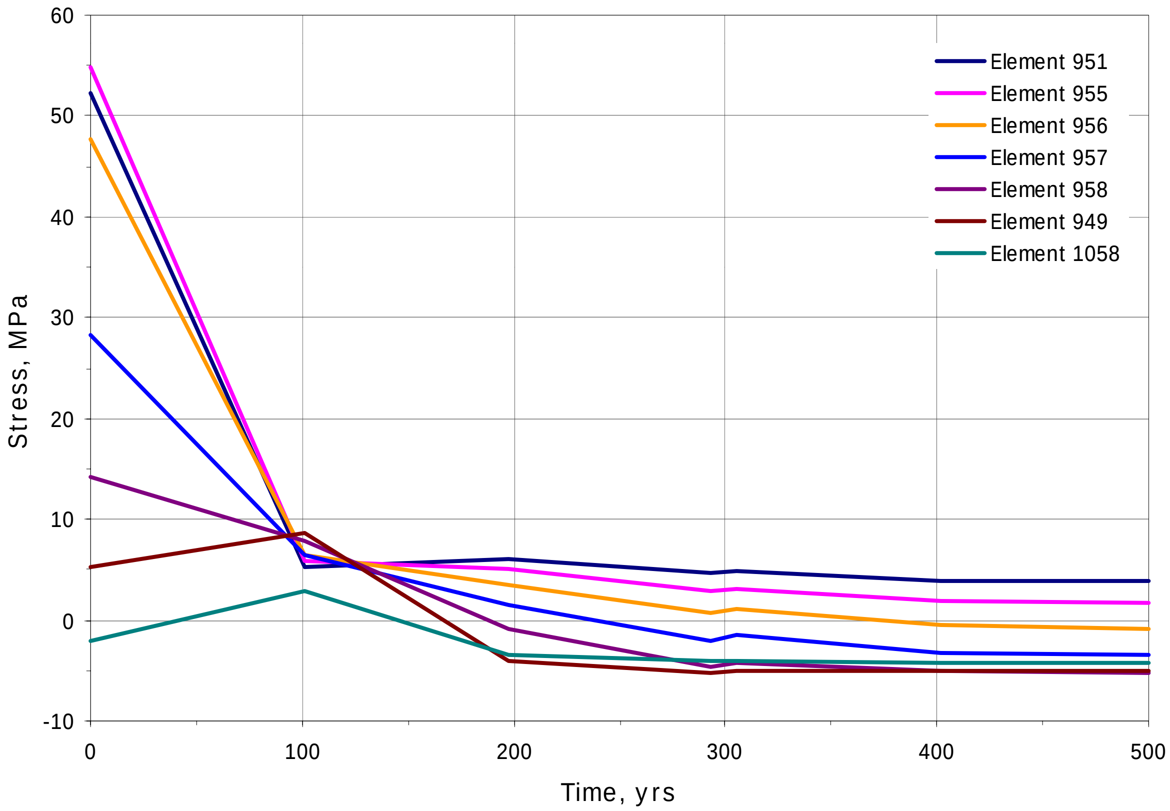


Figure 50 Max principal stress on outer side of copper cylinder during creep 500 years. Load case 1.

E.3 Strain

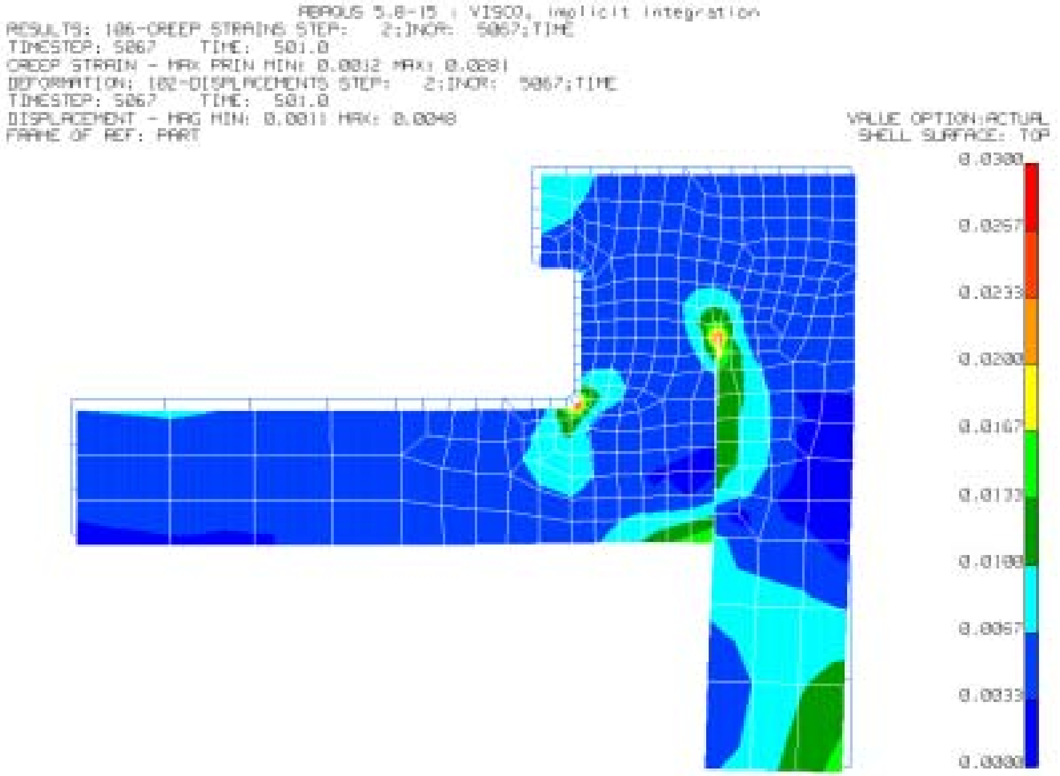


Figure 51 Max principal creep strains. Load case 1, creep 500 years.

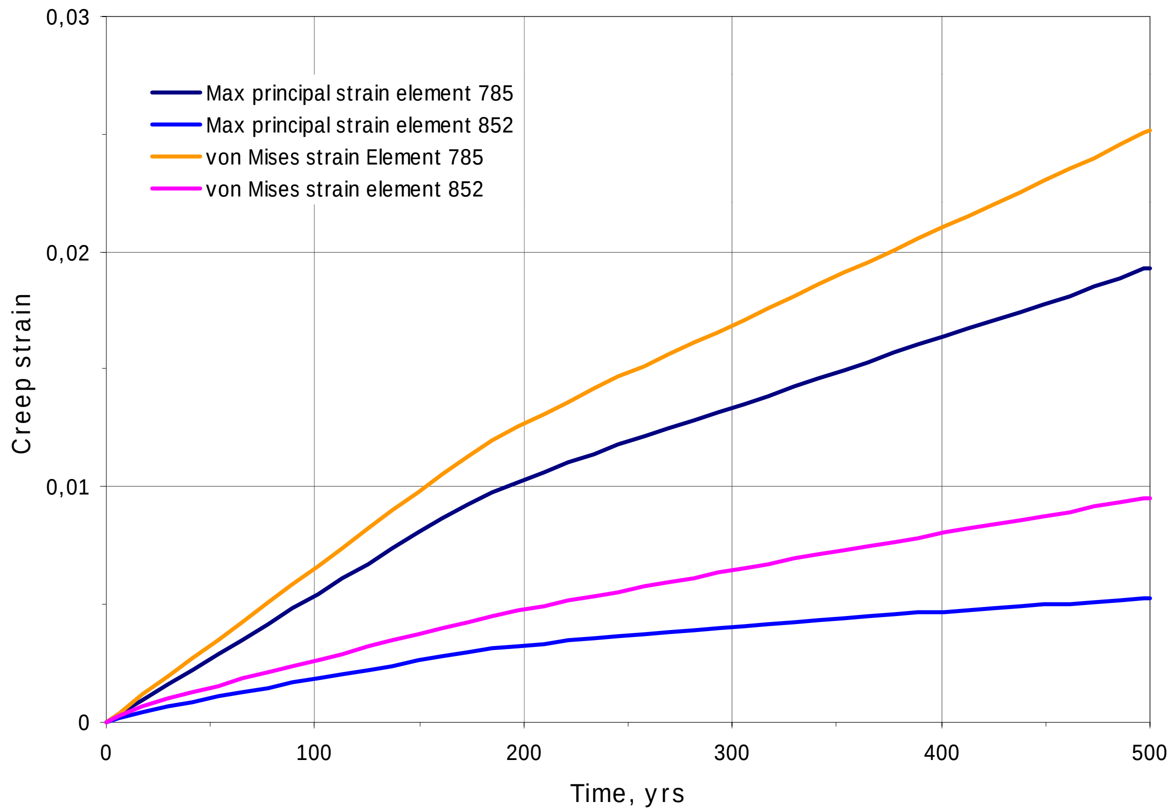


Figure 52 Creep strain in lid fillet during creep 500 years. Load case 1.

F Load case 4 — Side load

F.1 Stress

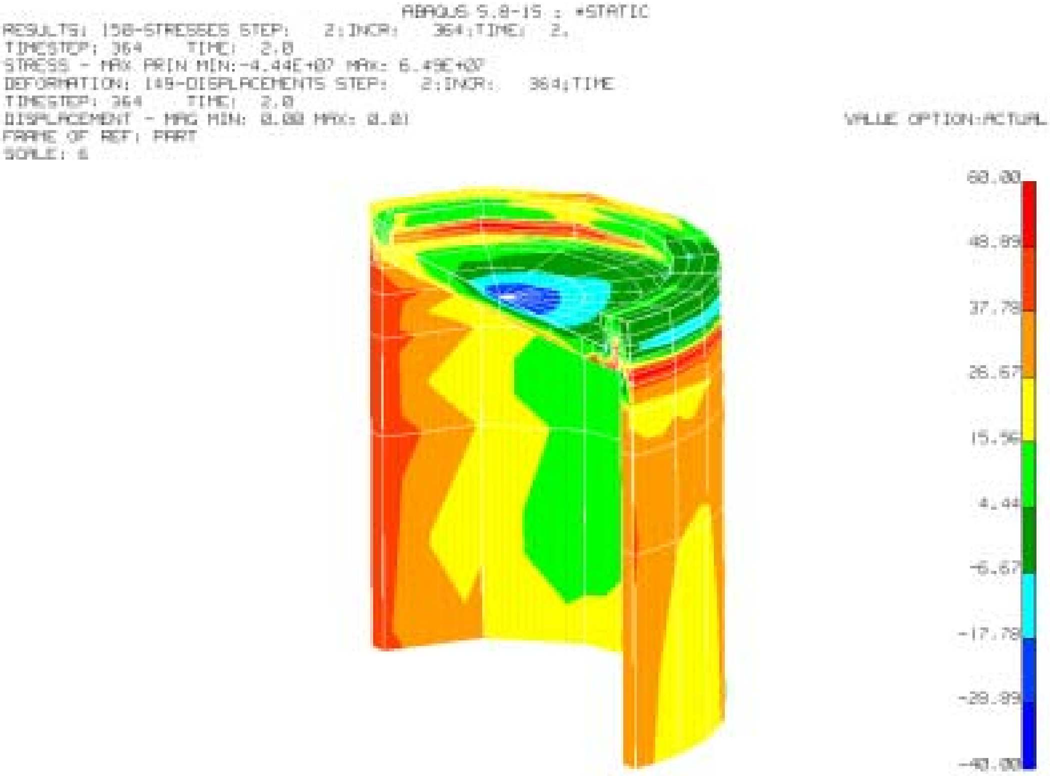


Figure 53 Max principal stress (MPa). Load case 4: side load of 20 MPa.

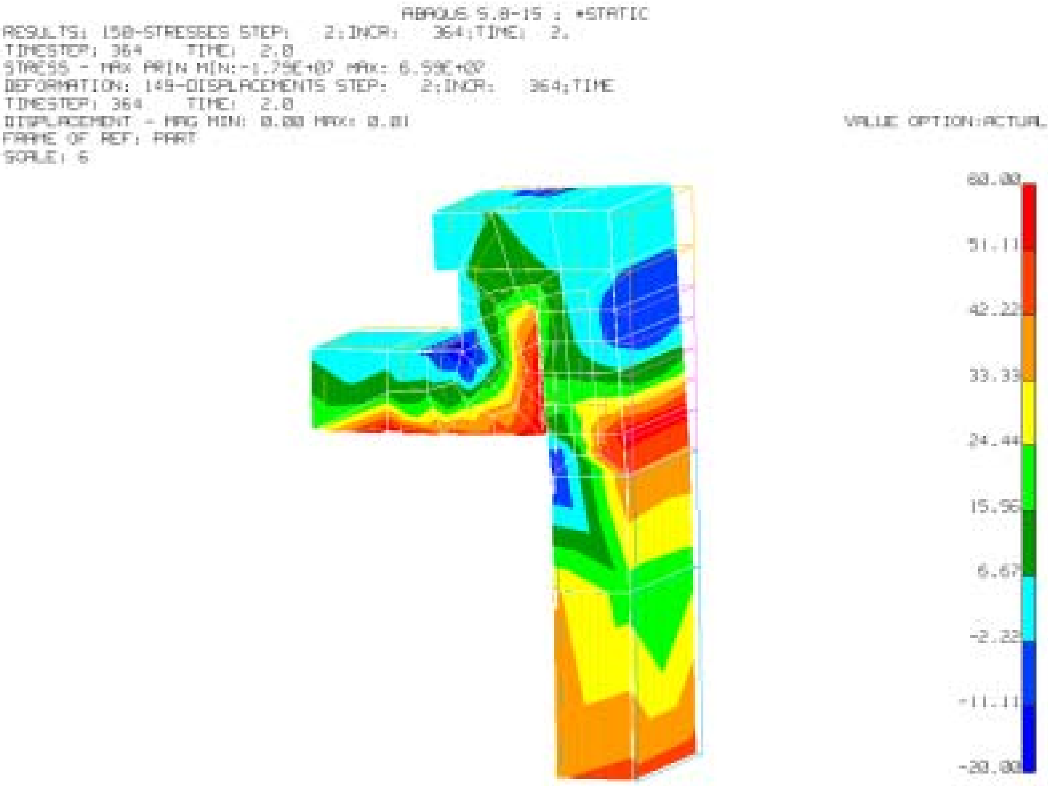


Figure 54 Max principal stress (MPa) in the lid/cylinder transition region. Load case 4: side load of 20 MPa.

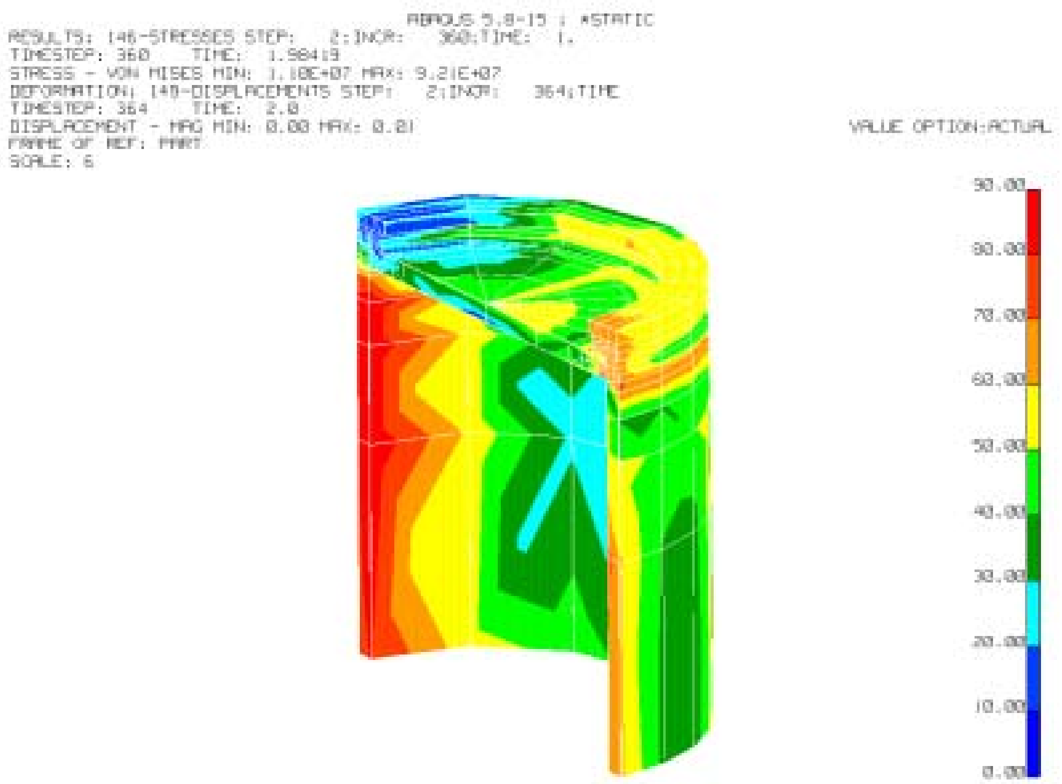


Figure 55 von Mises stress (MPa). Load case 4: side load of 20 MPa.

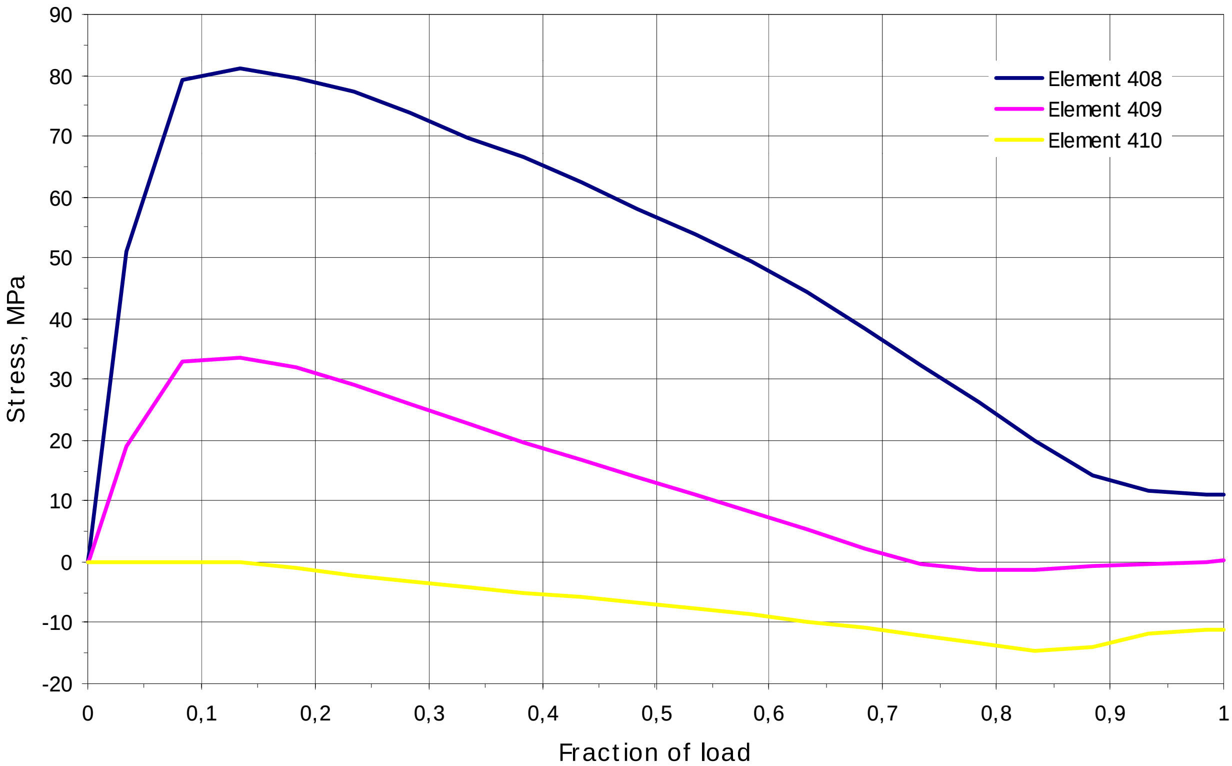


Figure 56 Max principal stress in weld during loading. Load case 4: side load of 20 MPa.

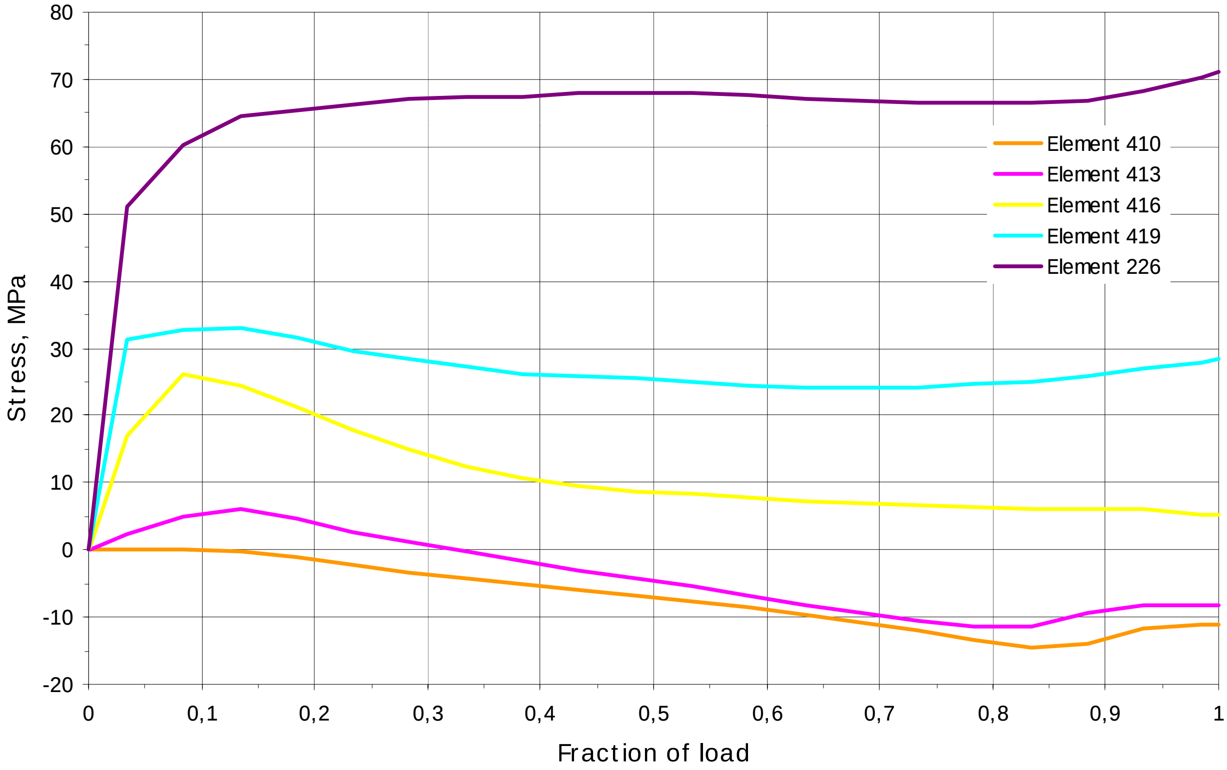


Figure 57 Max principal stress in casing during loading. Load case 4: side load of 20 MPa.

F.2 Strain

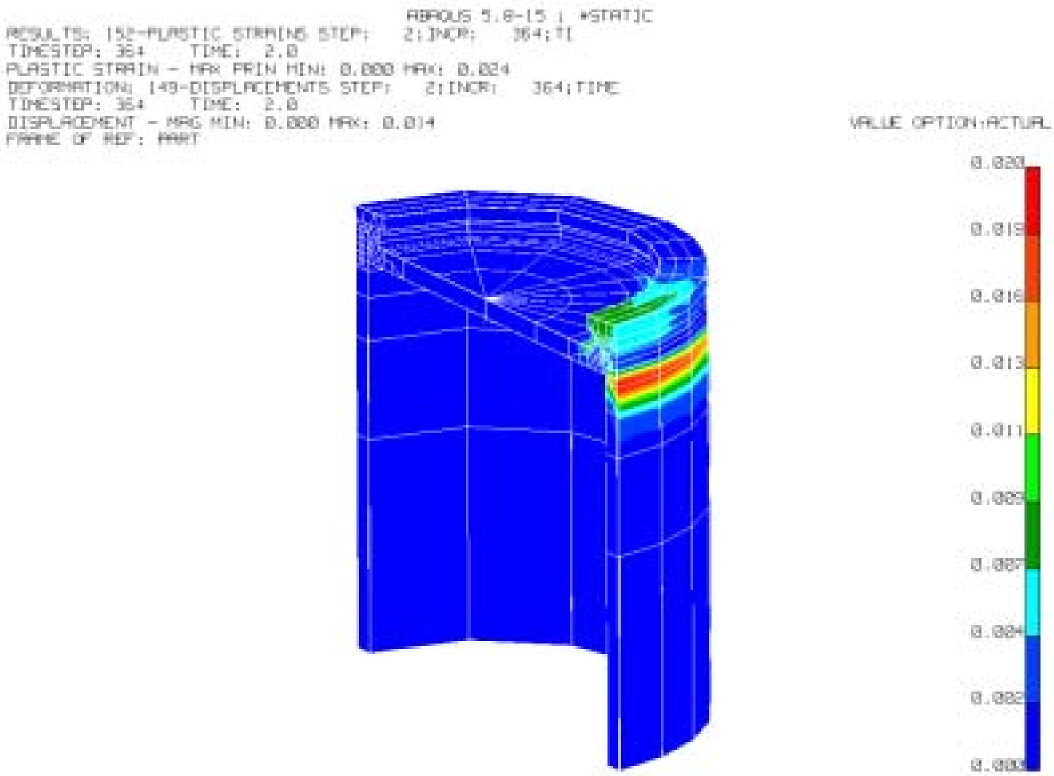


Figure 58 Max principal strain. Load case 4: side load 20 MPa.

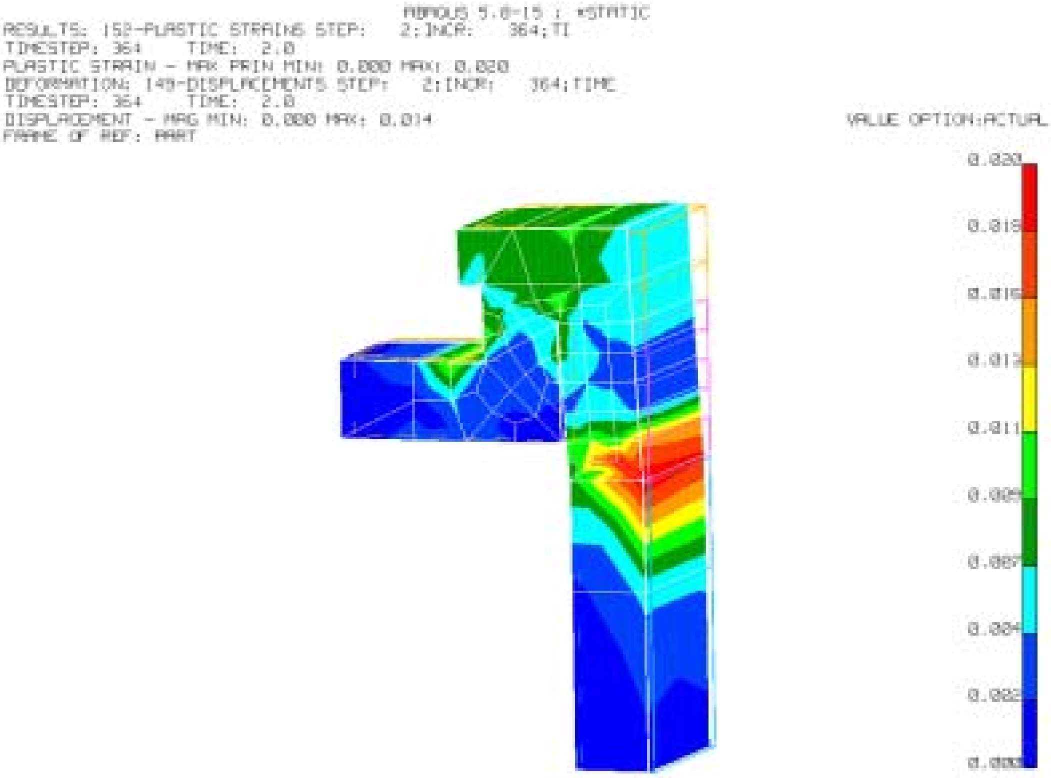


Figure 59 Max principal strain. Load case 4: side load 20 MPa.

F.3 Radial displacement

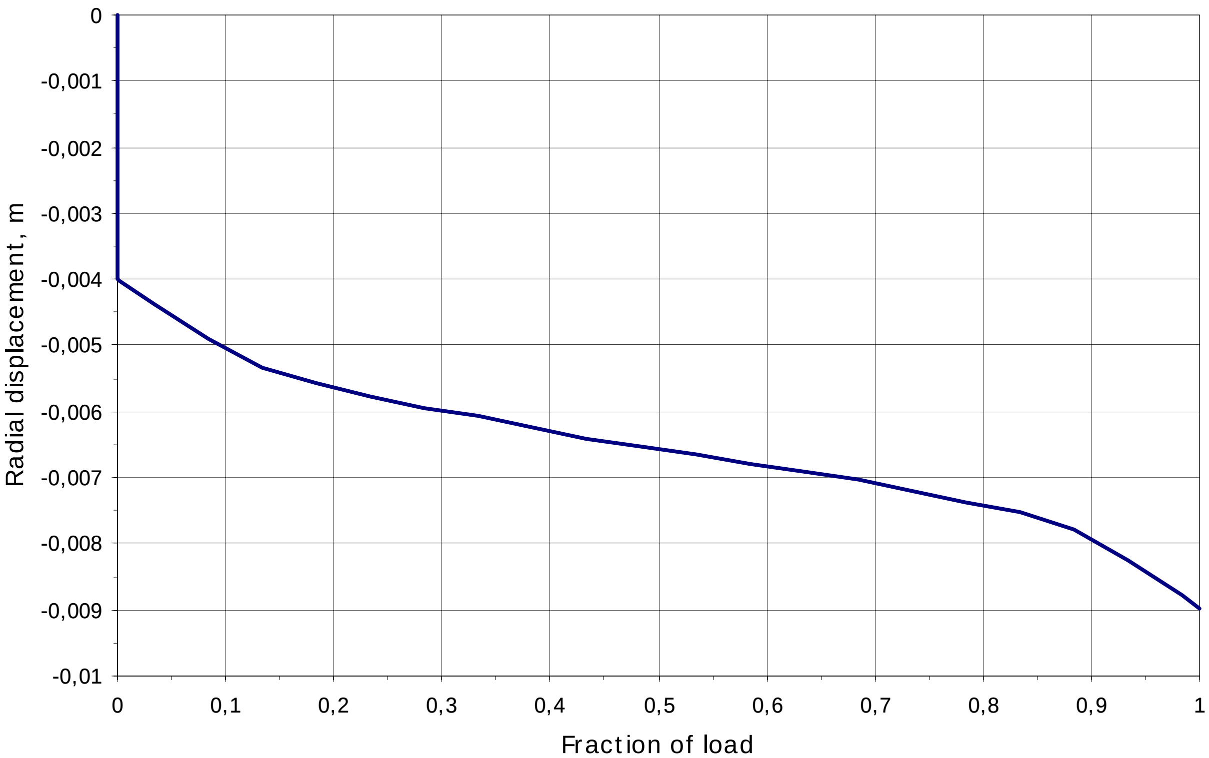


Figure 60 Radial displacement of lid centre node during loading. Load case 4: side load of 20 MPa.

G Creep — Side load 10 MPa

G.1 Stress

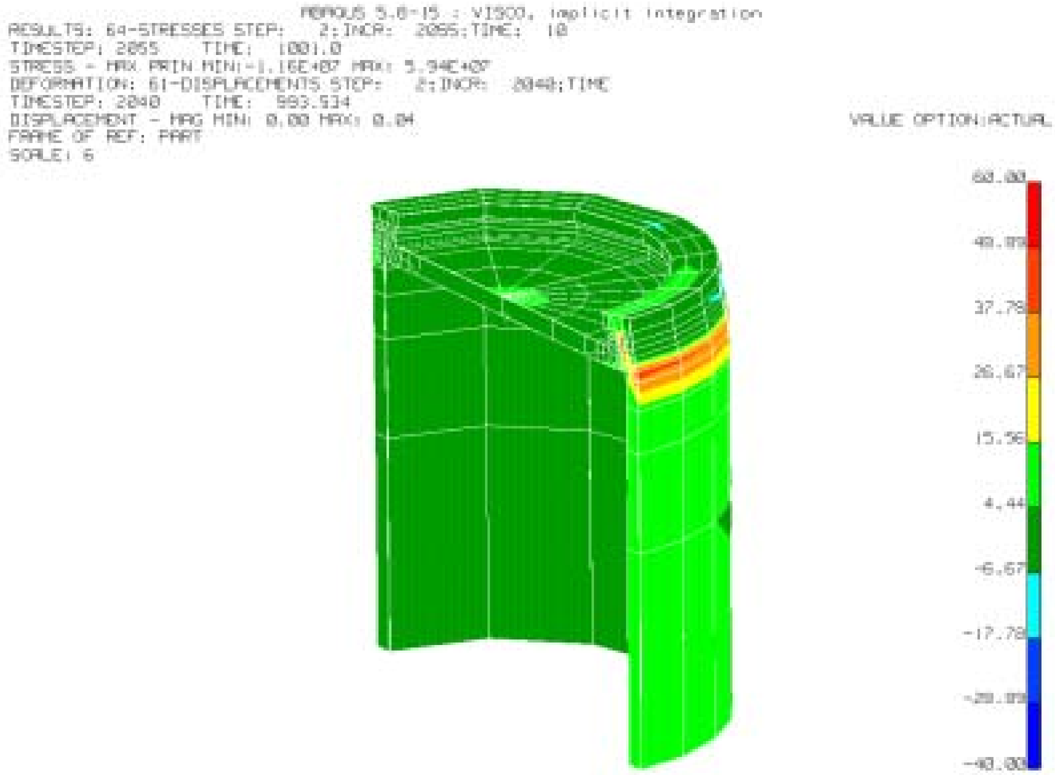


Figure 61 Max principal stress (MPa). Side load 10 MPa, creep 1000 years.

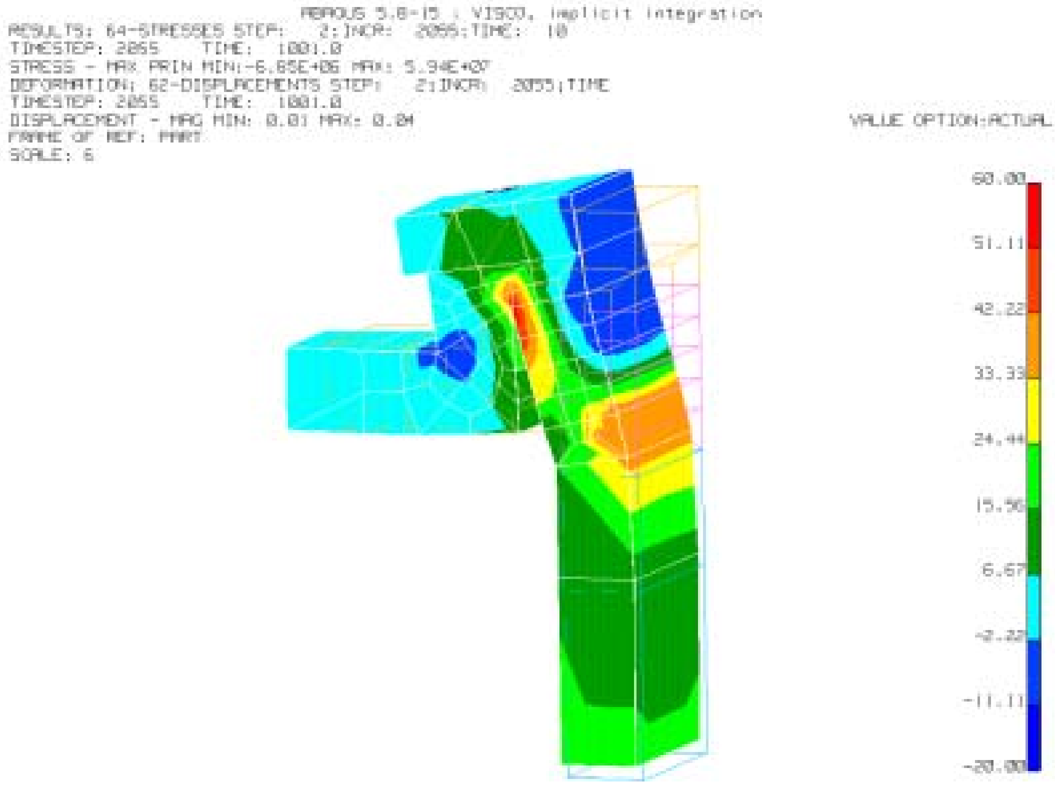


Figure 62 Max principal stress (MPa). Side load 10 MPa, creep 1000 years.

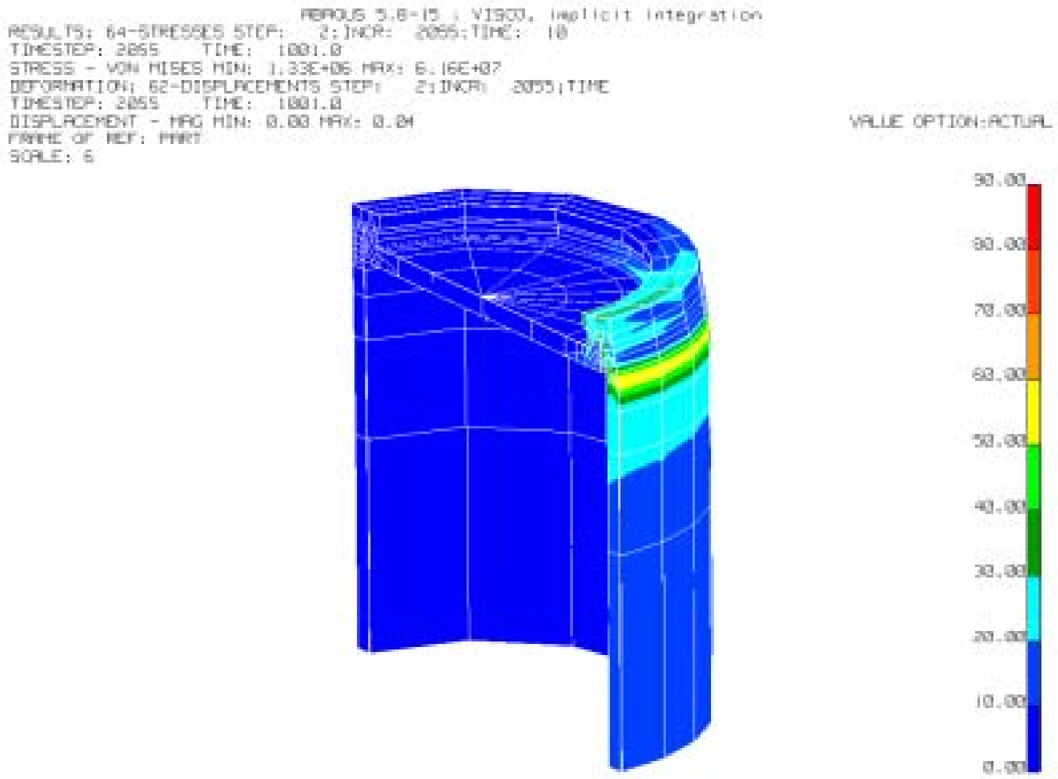


Figure 63 von Mises stress (MPa). Side load 10 MPa, creep 1000 years.

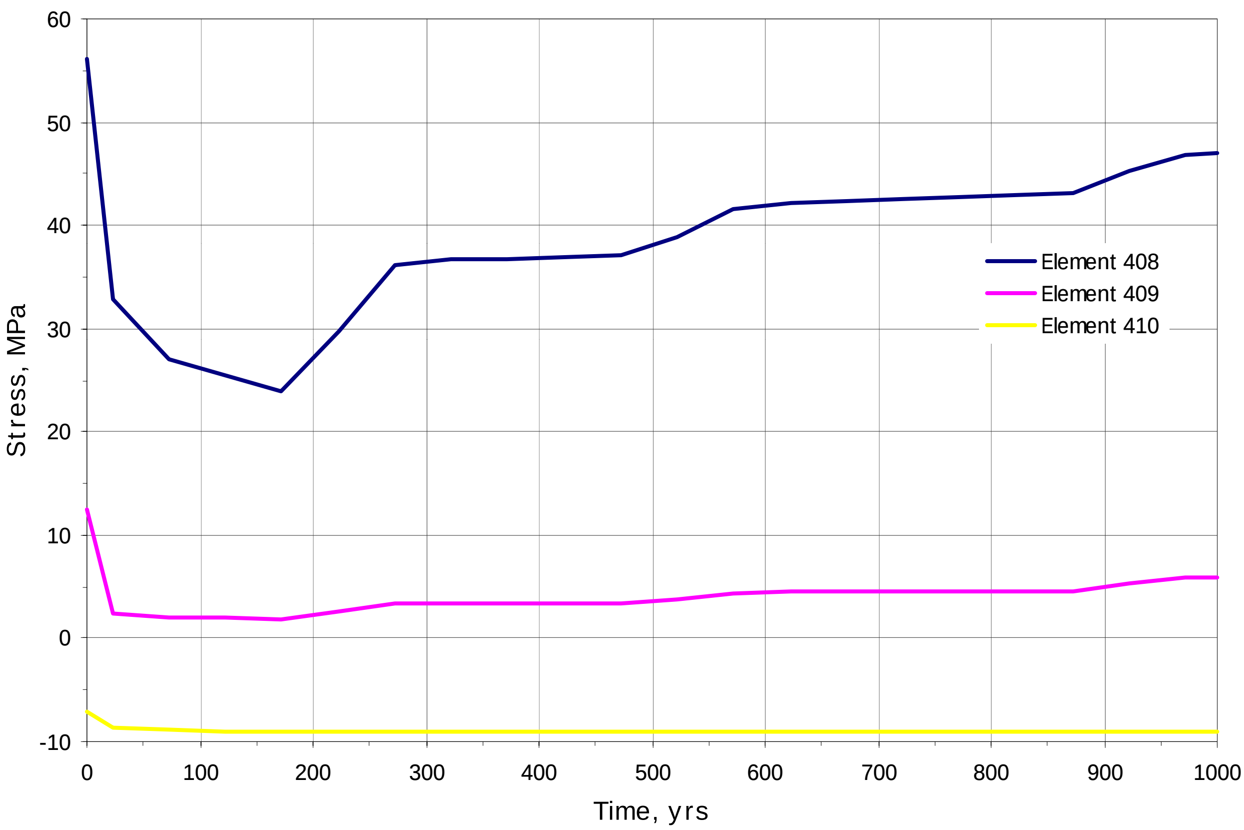


Figure 64 Max principal stress in weld region during creep for 1000 years. Load case 4.

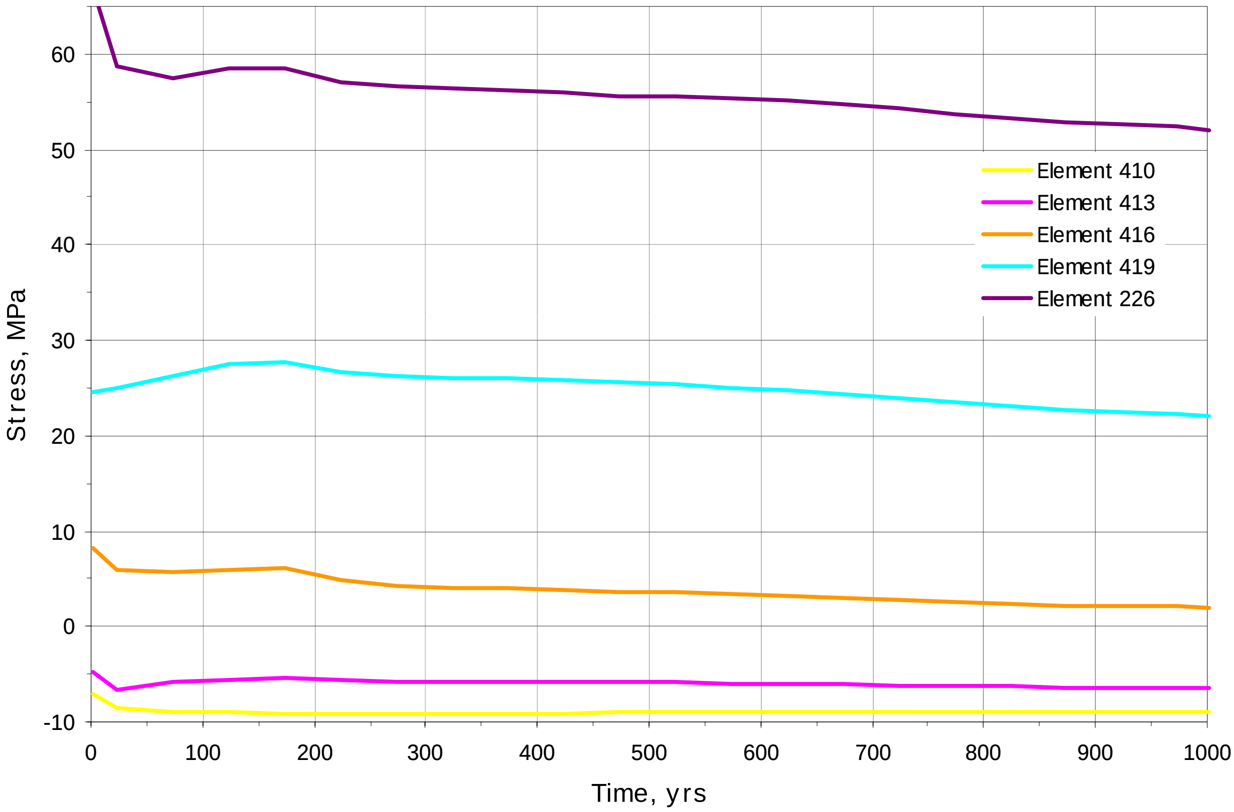


Figure 65 Max principal stress in casing during creep for 1000 years. Load case 4

G.2 Strain

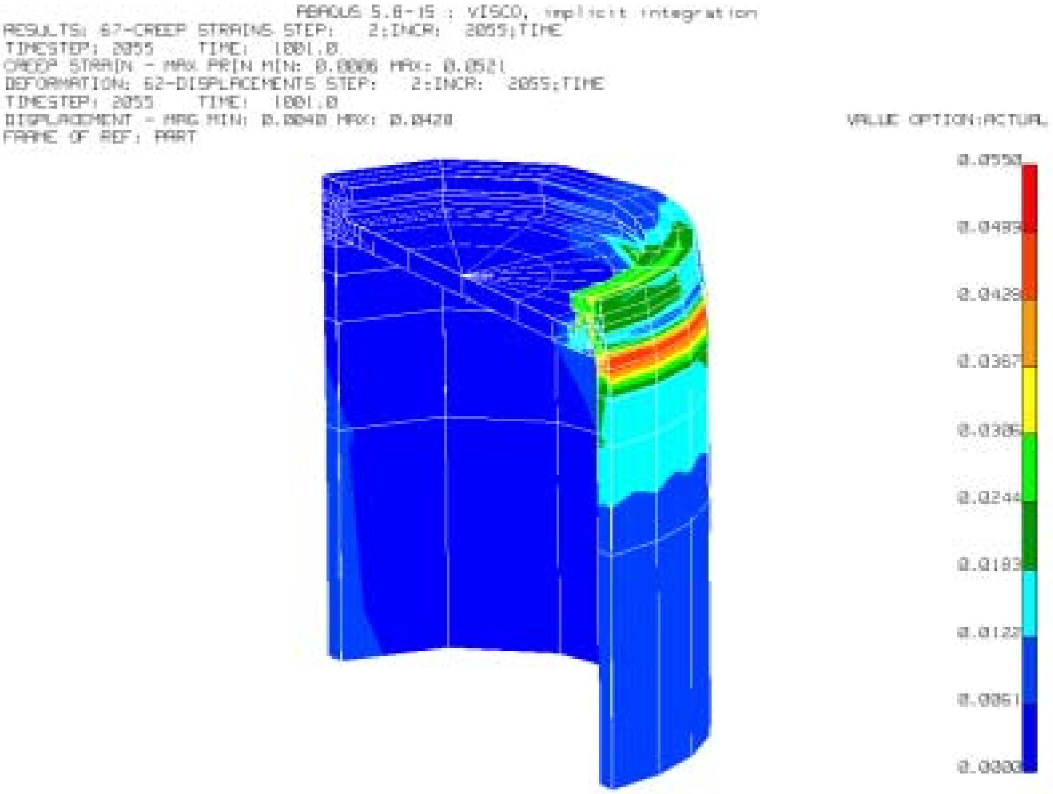


Figure 66 Max principal creep strain. Side load 10 MPa, creep 1000 years.

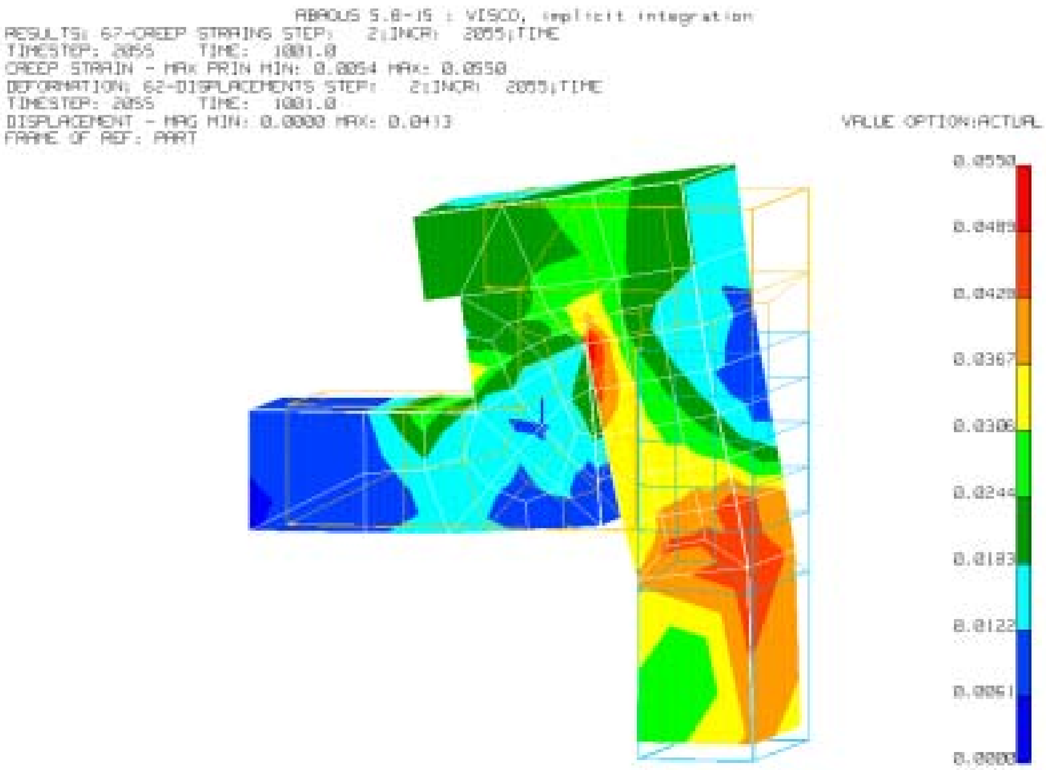


Figure 67 Max principal creep strain. Side load 10 MPa, creep 1000 years.

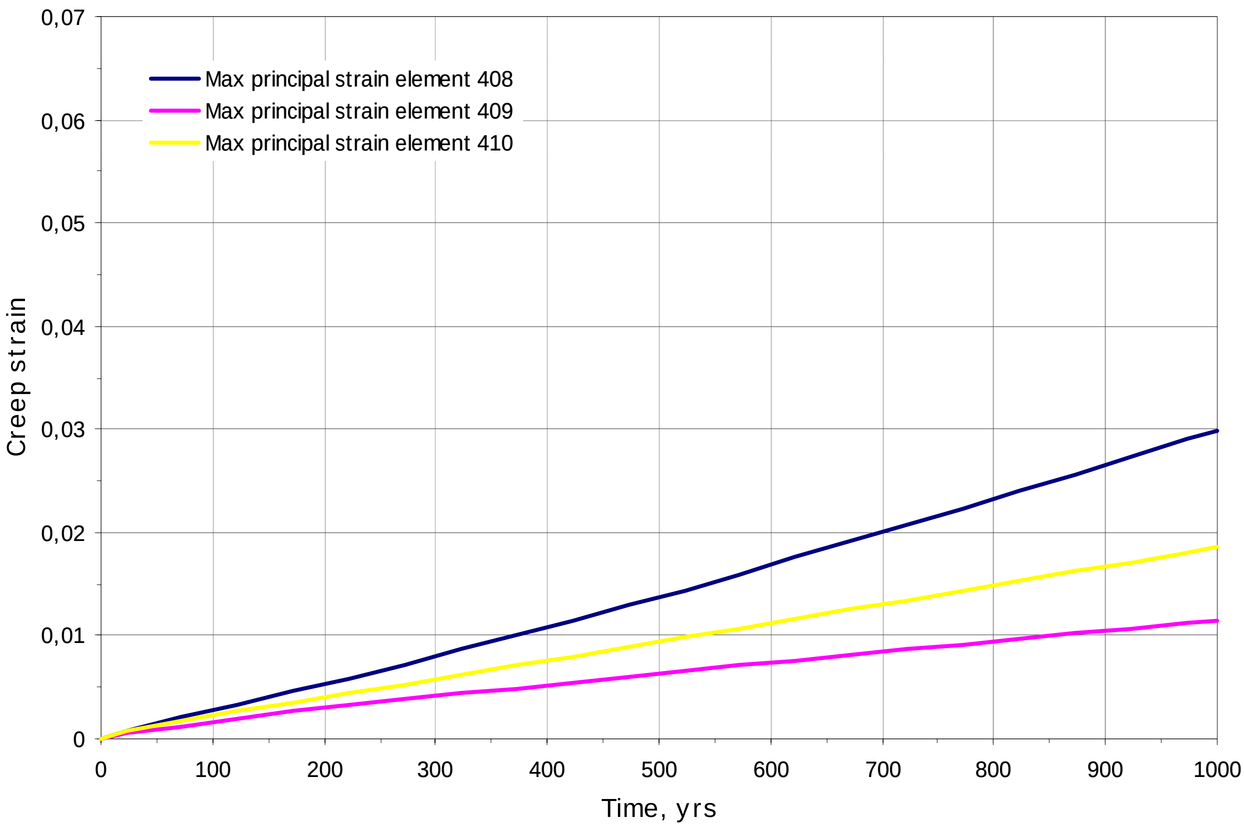


Figure 68 Max principal creep strain in weld during creep for 1000 years. Load case 4.

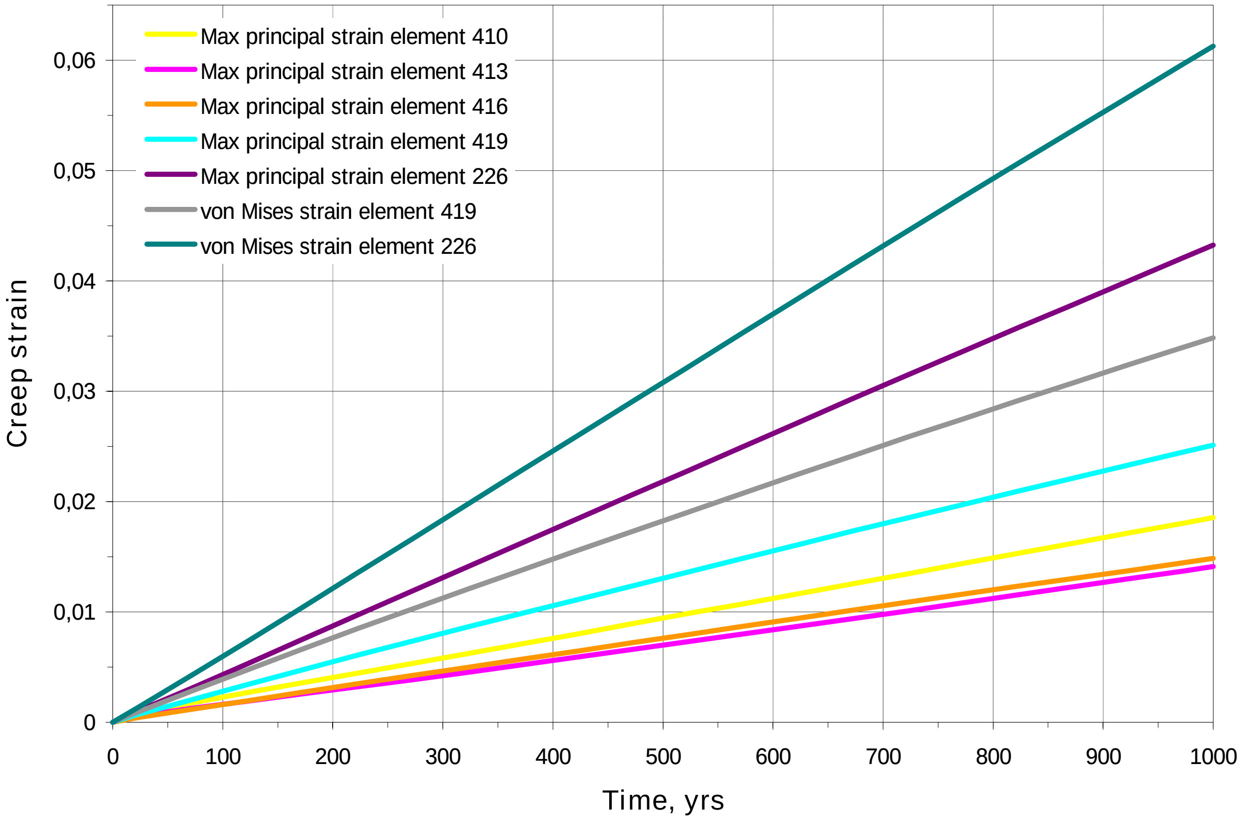


Figure 69 Max principal creep strain and von Mises creep strain in casing during creep for 1000 years. Load case 4.

G.3 Radial displacement

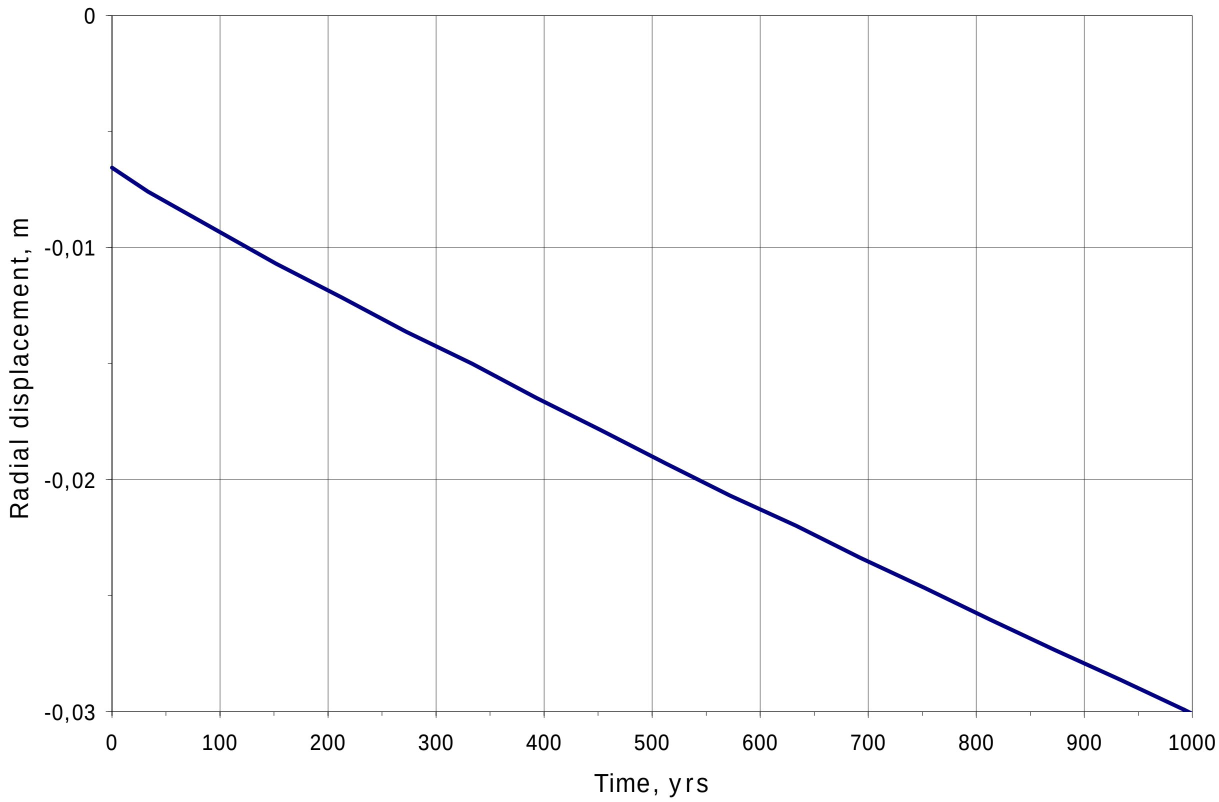


Figure 70 Radial displacement of lid centre node during creep 1000 years. Load case 4: side load 10 MPa.

H Design 2

H.1 Static analysis — Load case 1 and 2

H.1.1 Contact

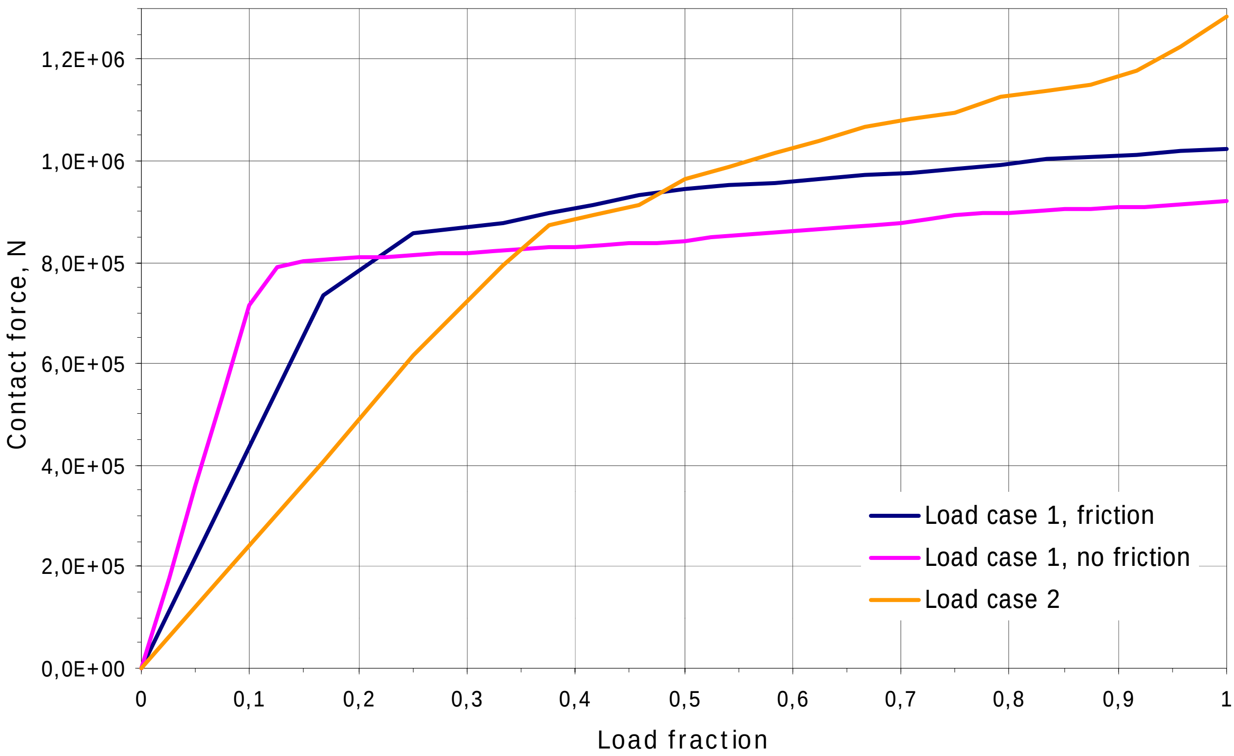


Figure 71 Contact force (N) between the lid lower edge and cylinder casing (element 627 as shown in Figure 13) during loading. Load case 1 and 2. Contact for load case 1 is shown for a case where the friction coefficient μ=0.15 between lid and copper cylinder and for a case with no friction. For load case 2 μ=0.15 between lid and cylinder.

H.1.2 Stress

Stress plots are shown for load case 1 and 2, for load levels 20%, 60% and full load. Results (figures and graphs) are shown for a friction coefficient μ=0.15 between copper lid and cylinder. For load case 1, result figures are also shown for additional friction coefficients to depict the influence of sliding friction between lid and cylinder on the stress level.

Note that the scale on stress plots is linear between –20 MPa and 50 MPa only. Red areas indicate regions with stresses above 50 MPa.

Load case 1, μ =0.15 between lid and cylinder

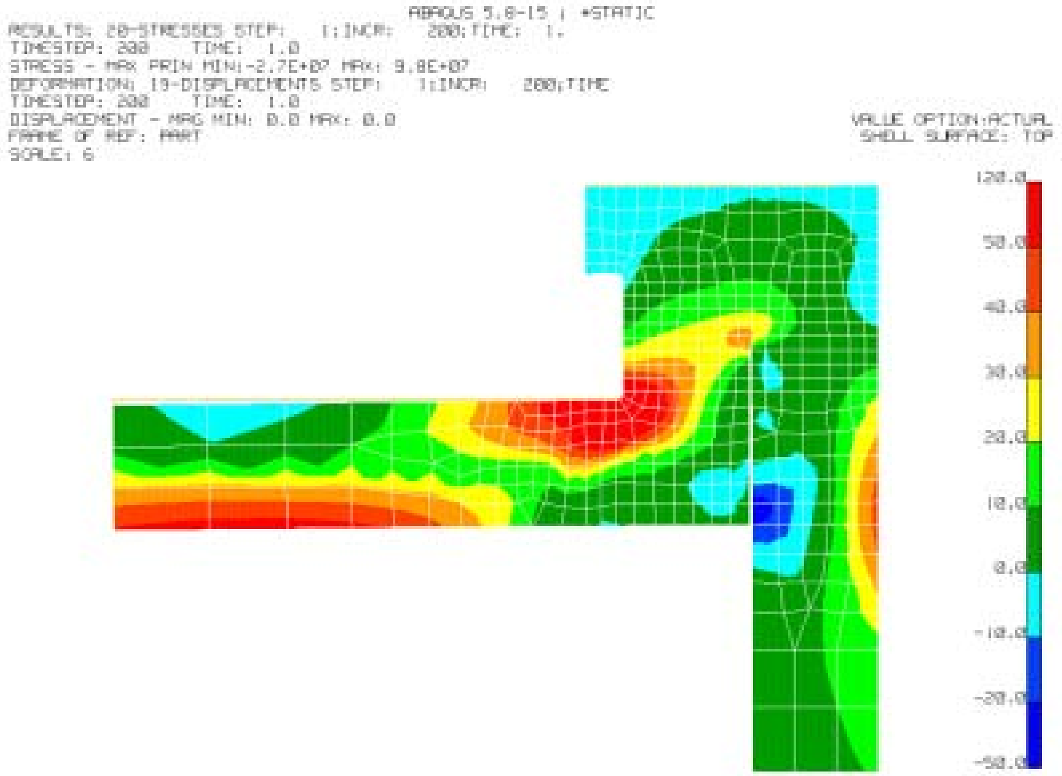


Figure 72 Max principal stress (MPa). Load case 1 at a load fraction of 0.2.

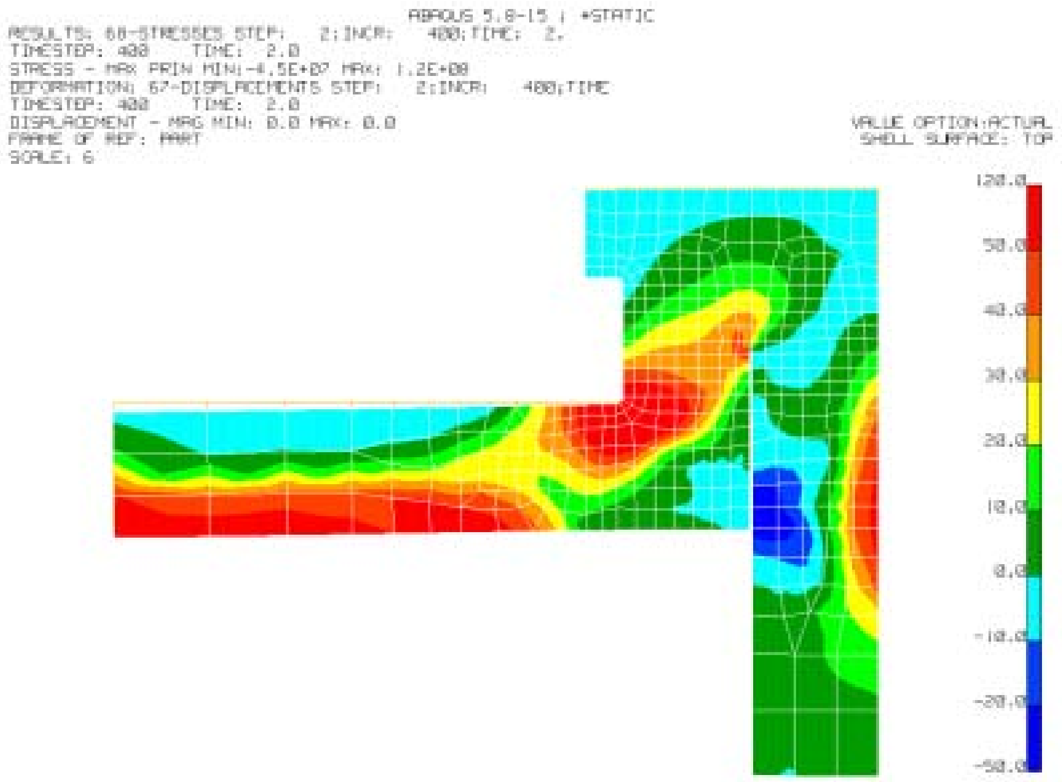


Figure 73 Maximum principal stress (MPa). Load case 1 at a load fraction of 0.6.

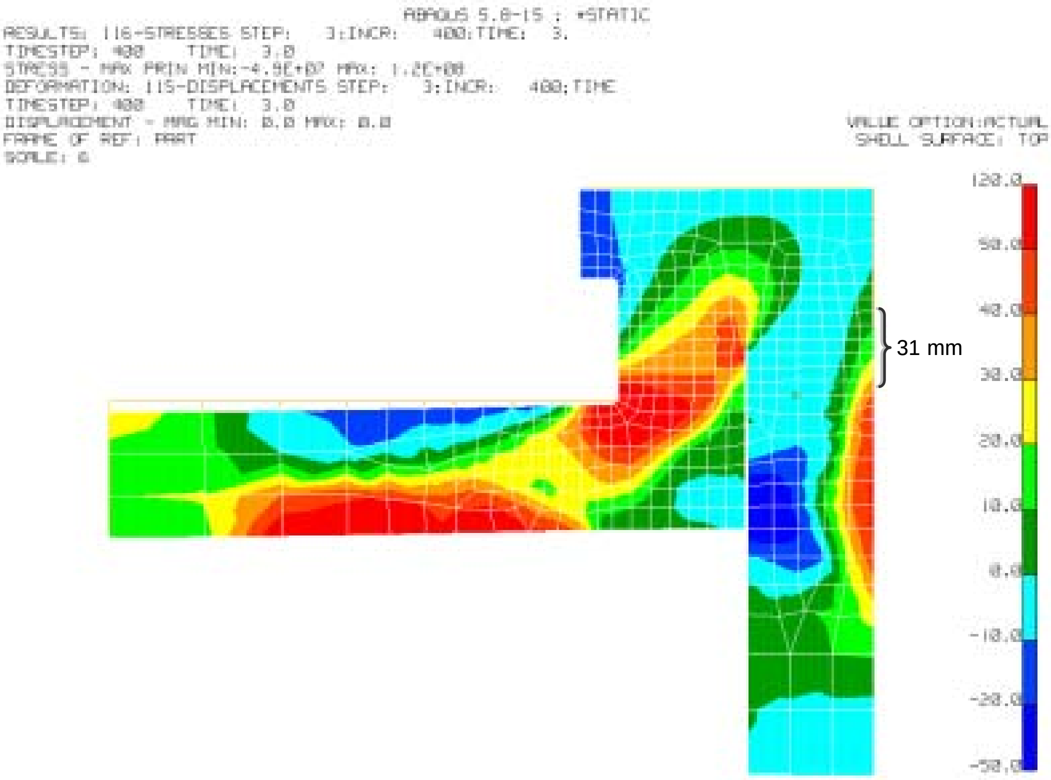


Figure 74 Maximum principal stress (MPa). Load case 1.

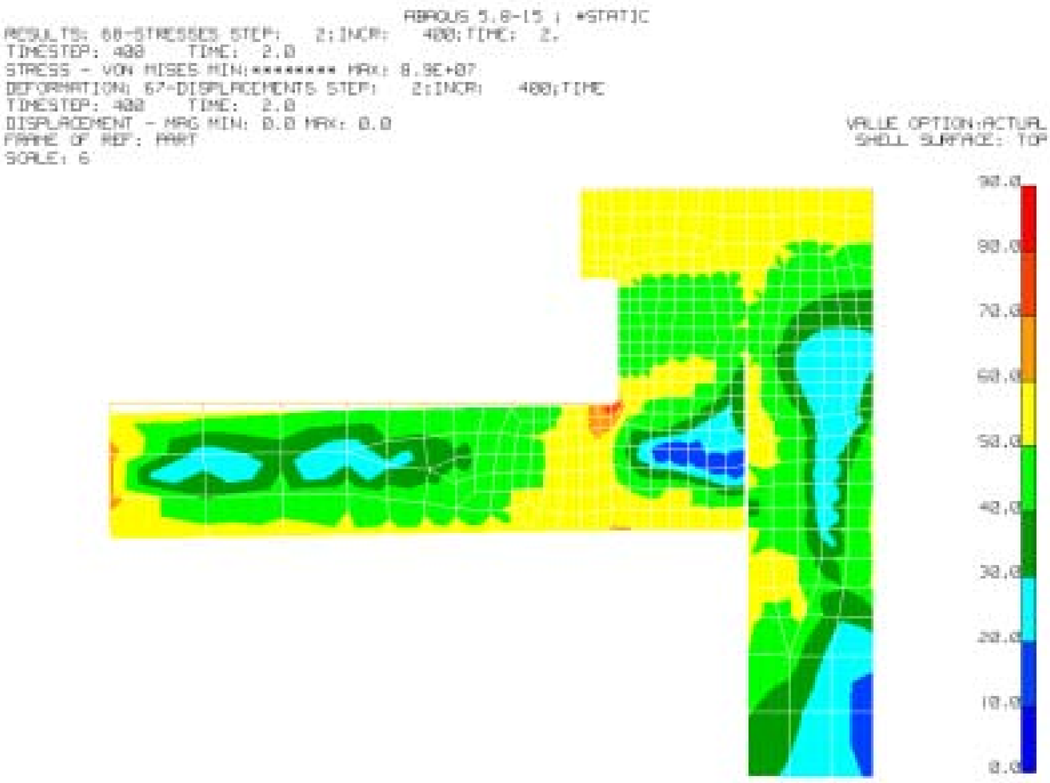


Figure 75 von Mises stress (MPa). Load case 1.

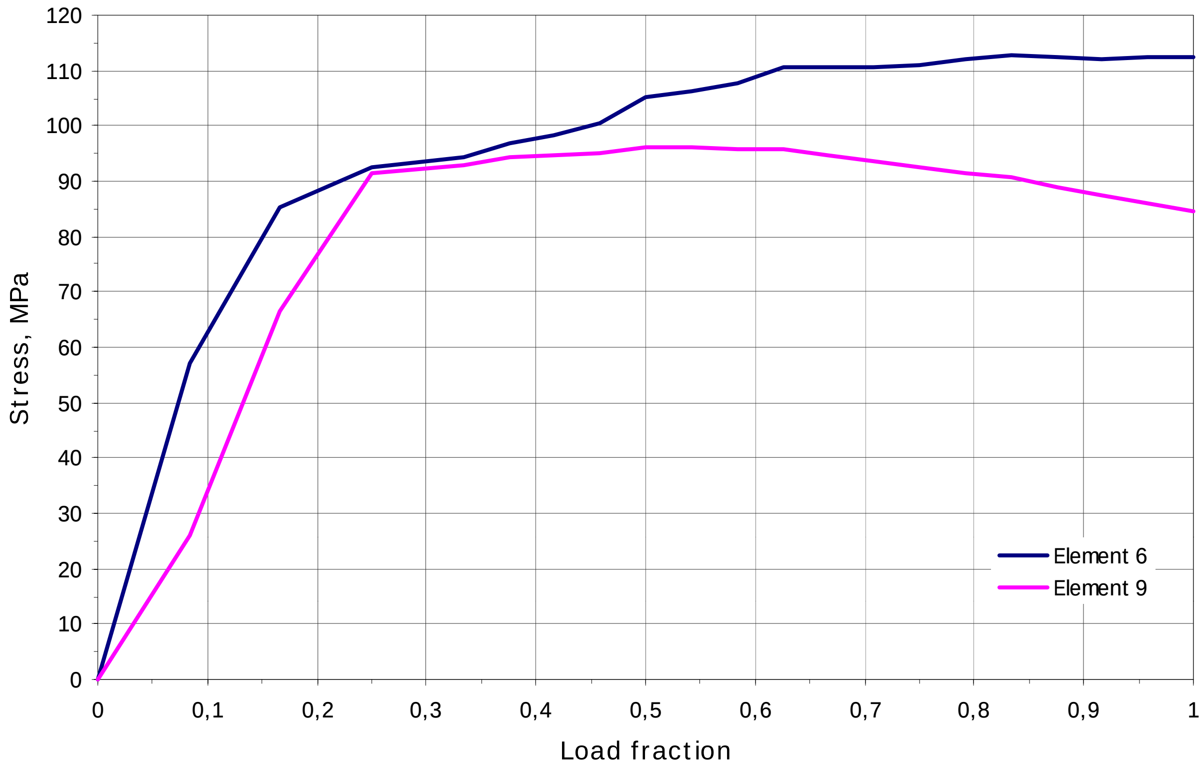


Figure 76 Maximum principal stresses in lid fillet during loading. Load case 1.

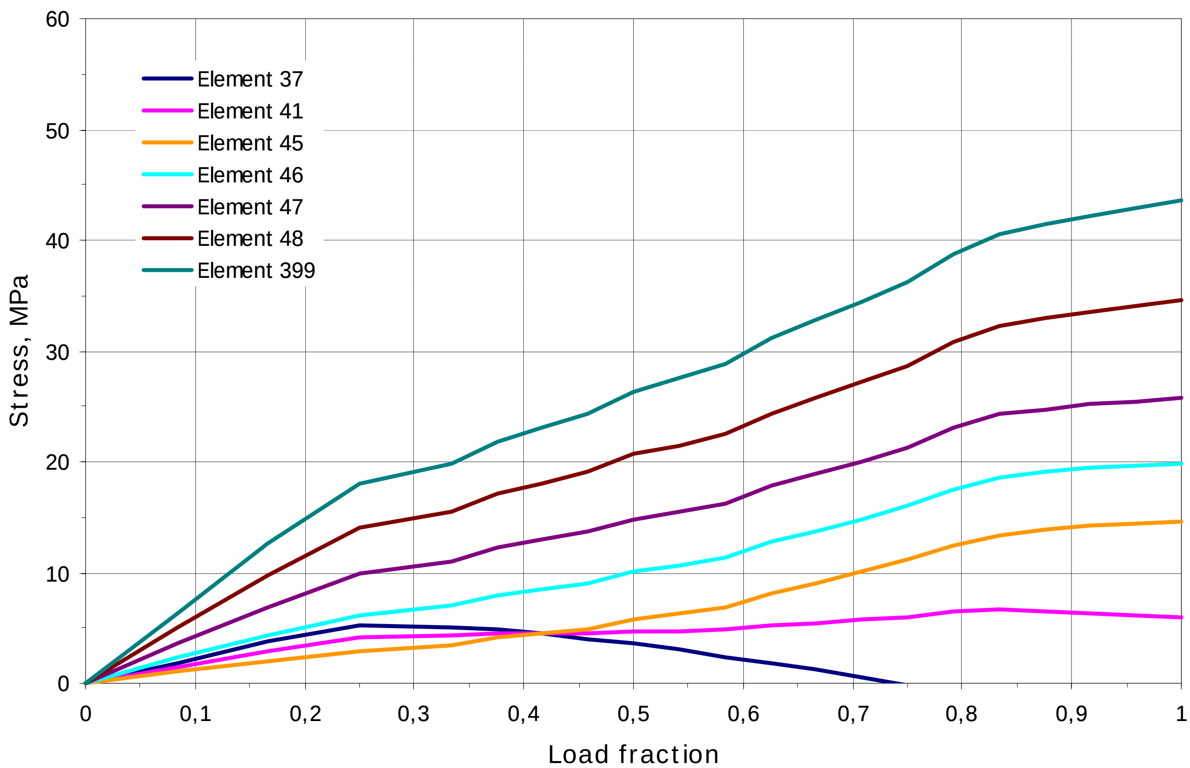


Figure 77 Maximum principal stresses in weld region during loading. Load case 1.

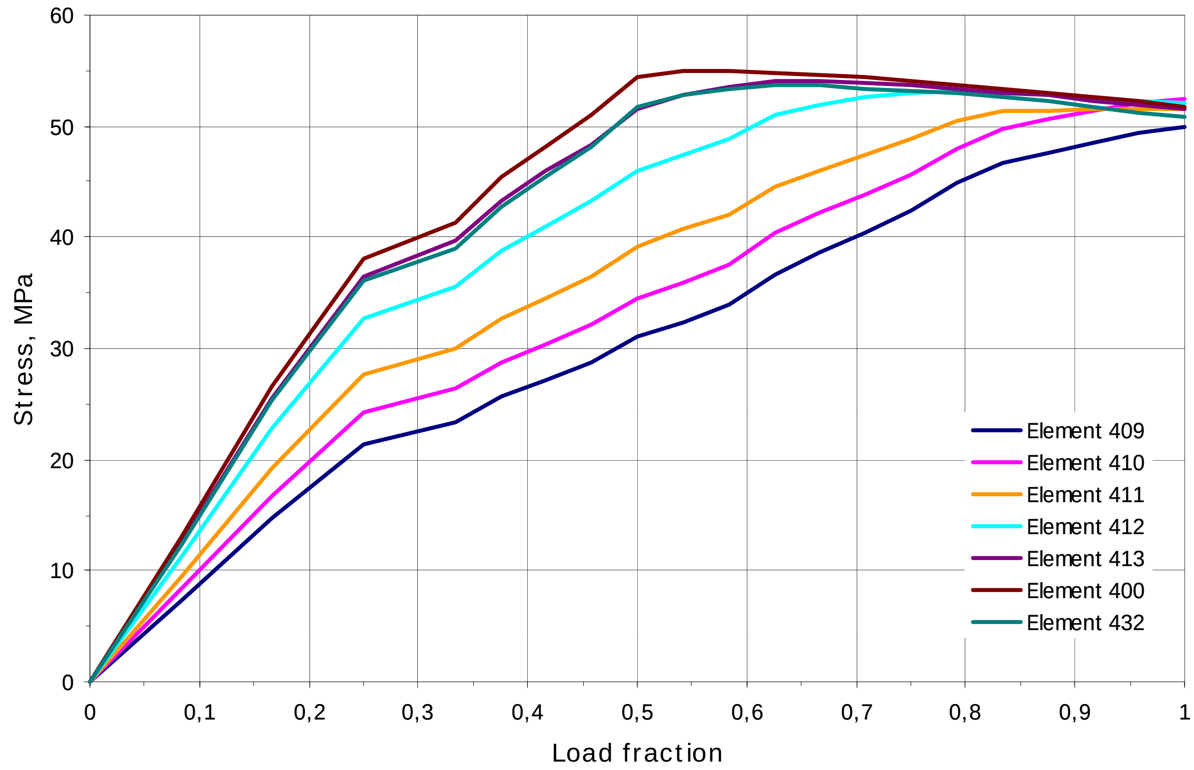


Figure 78 Maximum principal stresses on cylinder outside during loading. Load case 1.

Load case 2, μ =0.15 between lid and cylinder

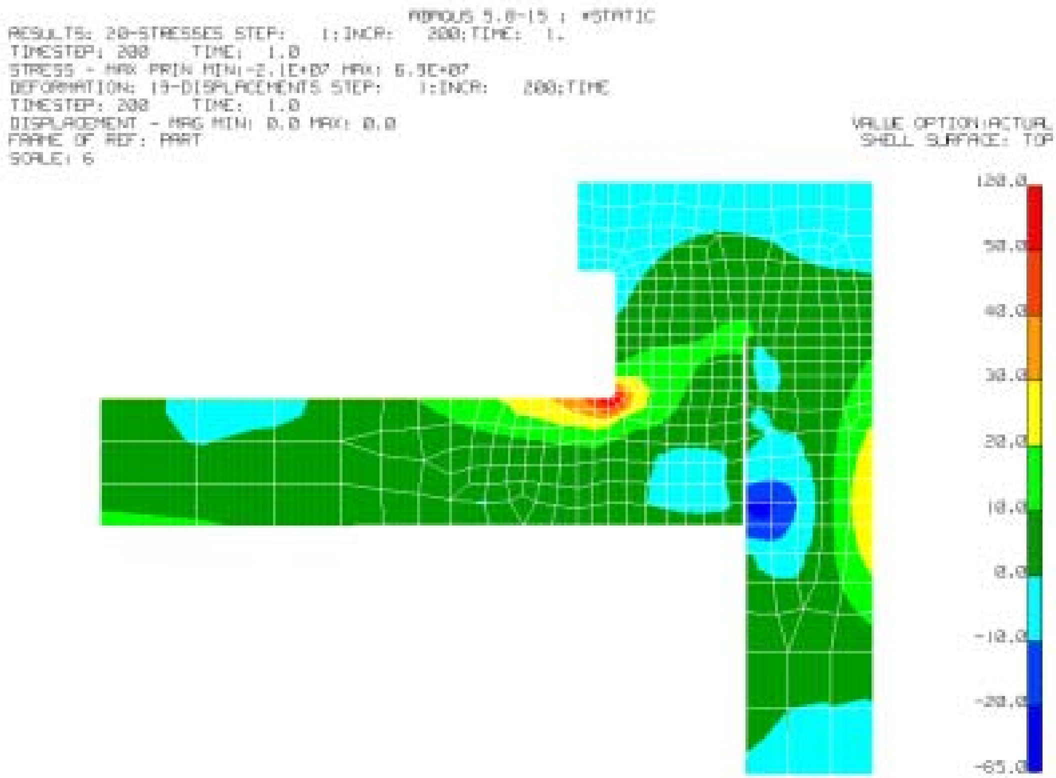


Figure 79 Maximum principal stress (MPa). Load case 2 at a load fraction 0.2.

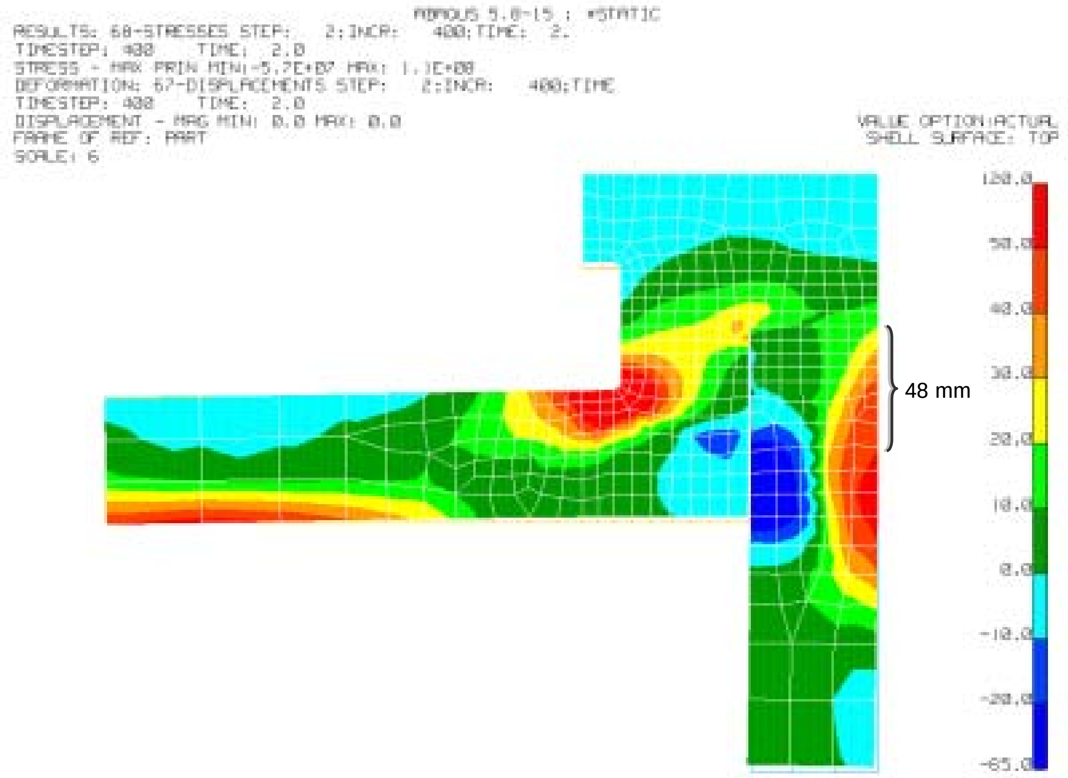


Figure 80 Maximum principal stress (MPa). Load case 2 at a load fraction 0.6.

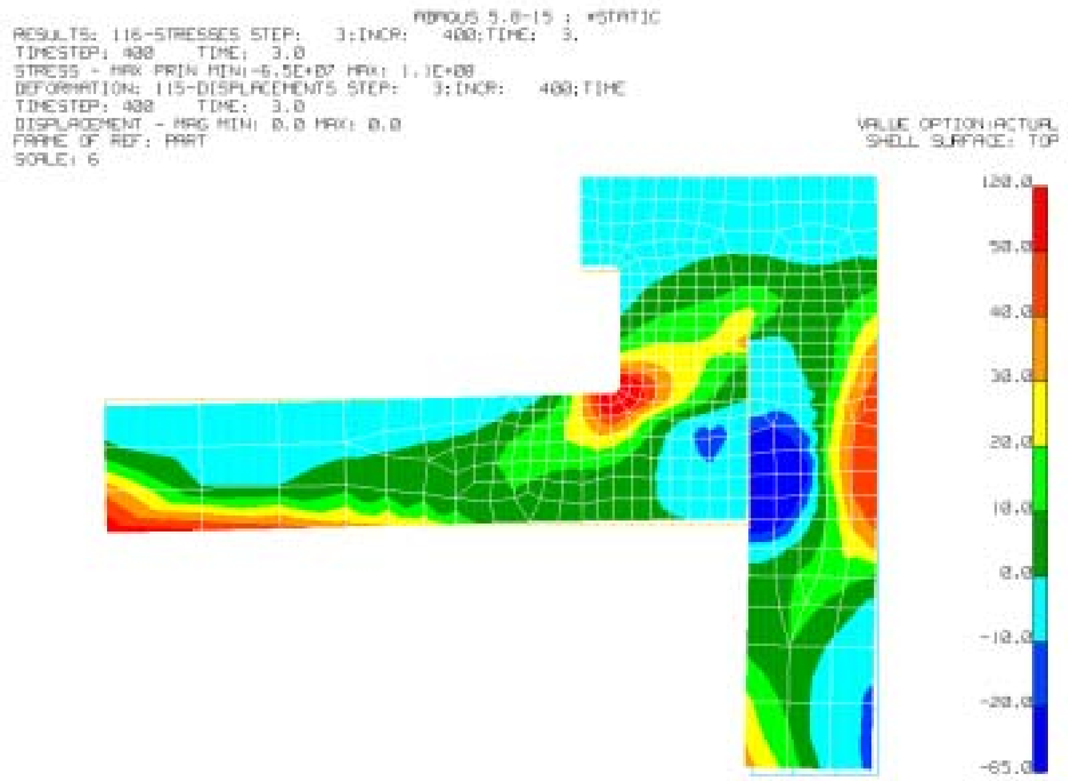


Figure 81 Maximum principal stress (MPa). Load case 2.

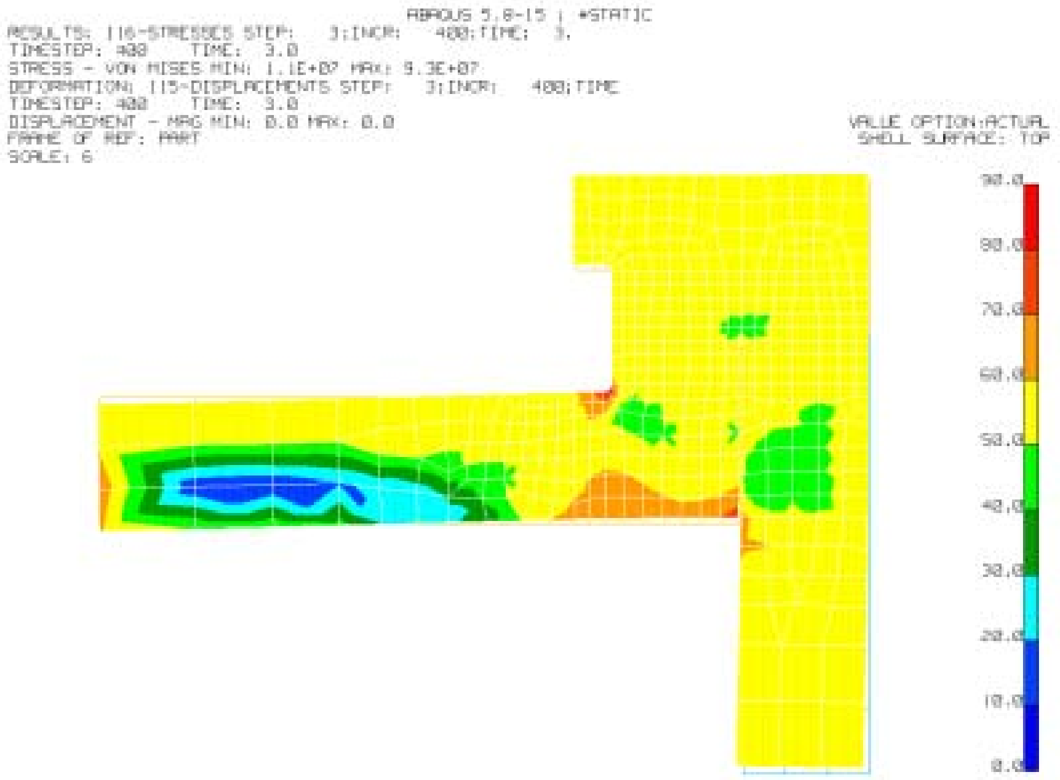


Figure 82 von Mises stress (MPa). Load case 2.

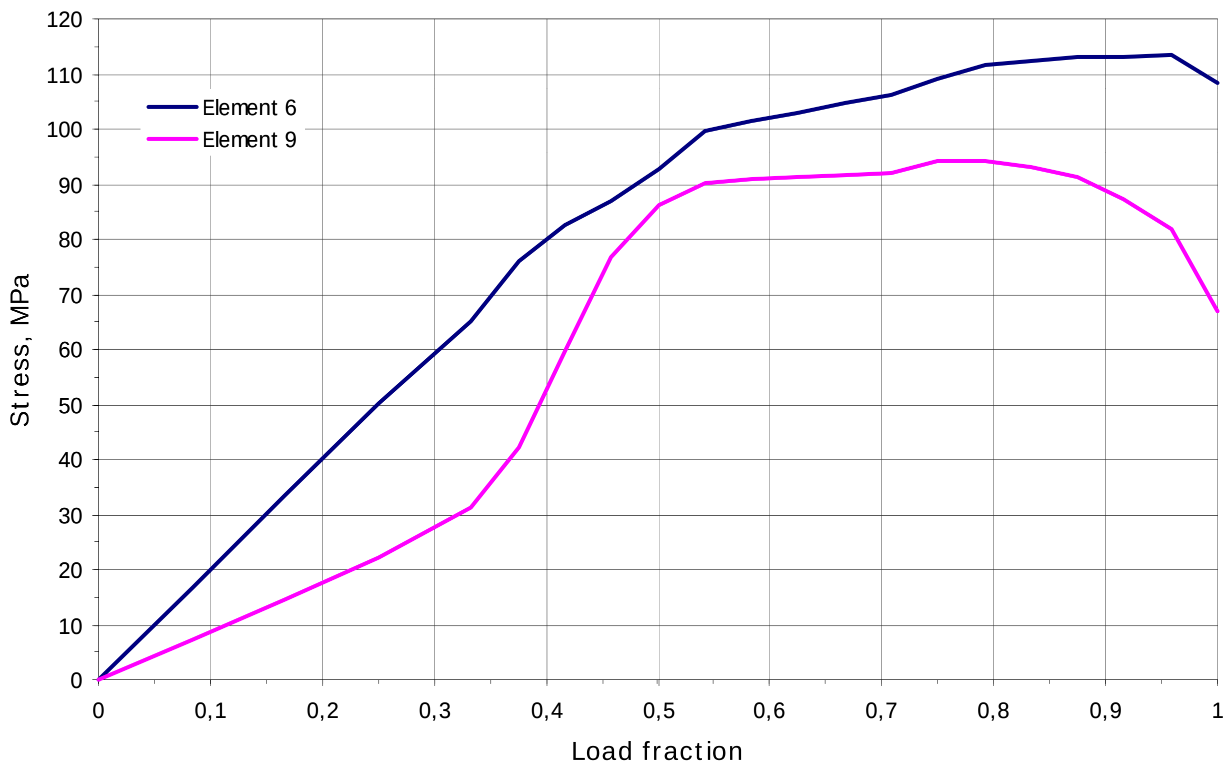


Figure 83 Maximum principal stresses in lid fillet during loading. Load case 2.

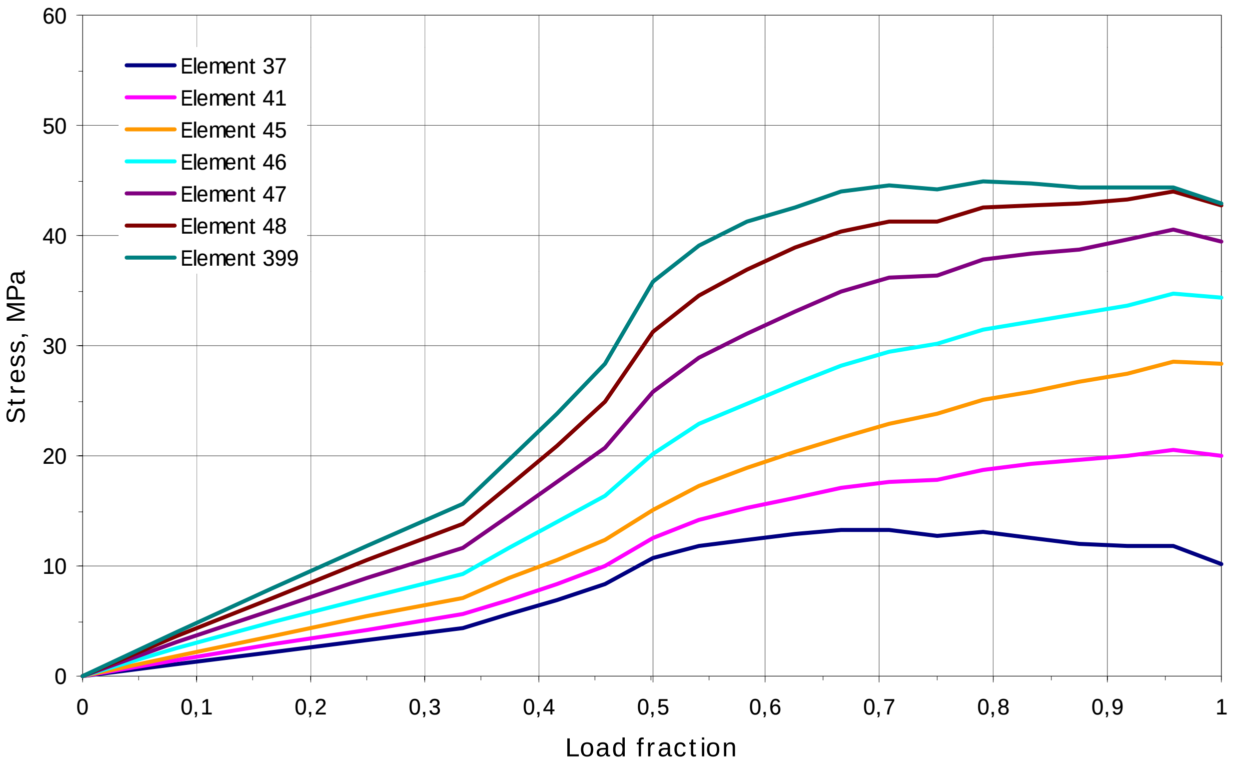


Figure 84 Maximum principal stresses in weld region during loading. Load case 2.

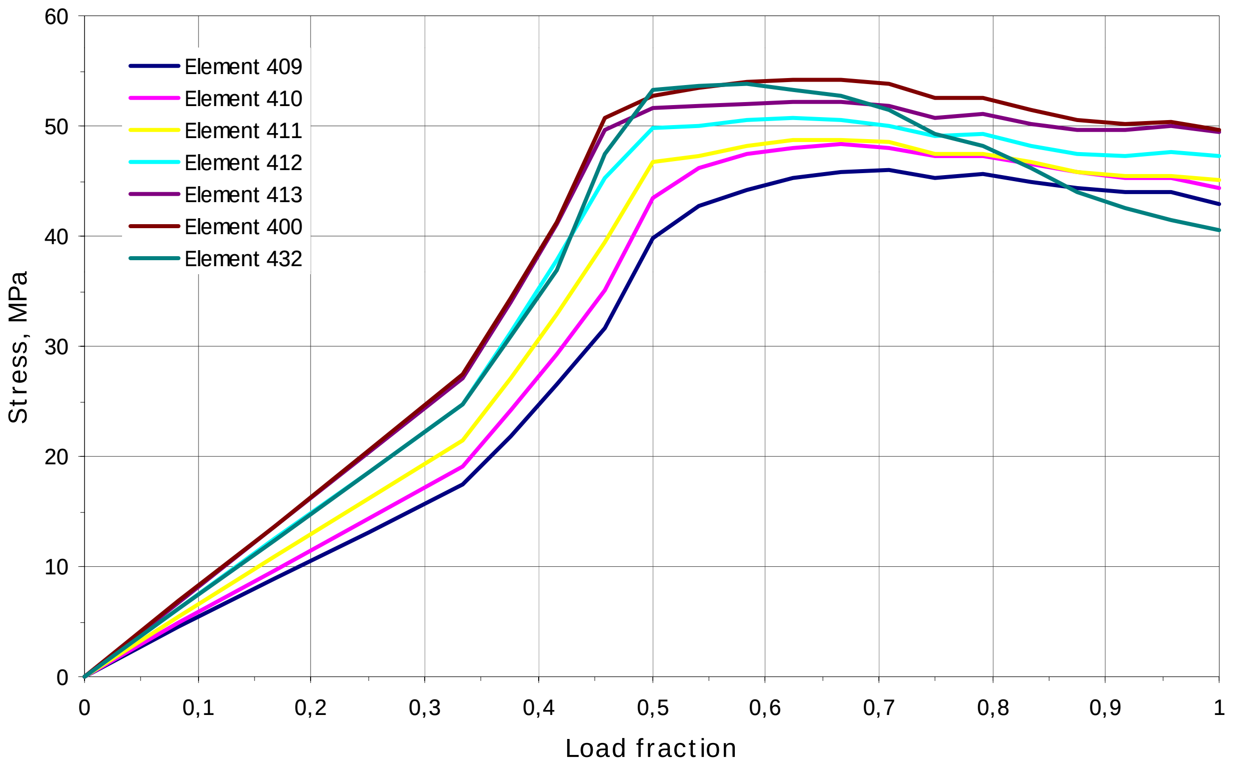


Figure 85 Maximum principal stresses on cylinder outside during loading. Load case 2.

Load case 1, varying friction coefficient between lid and cylinder

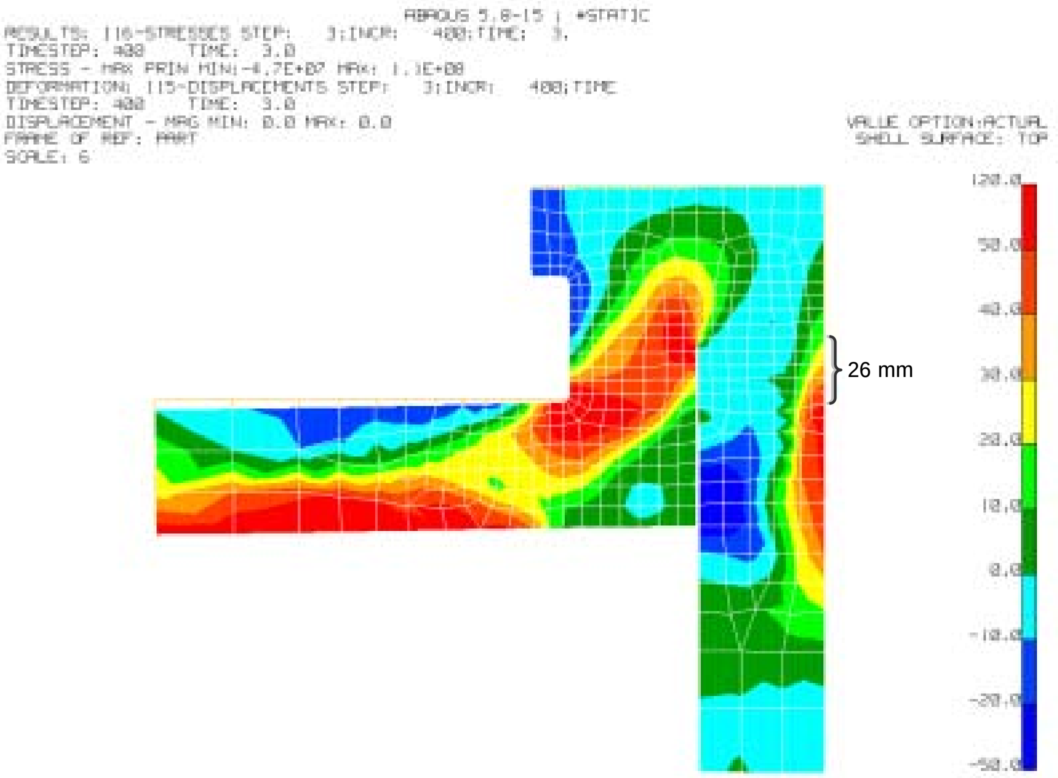


Figure 86 Maximum principal stress (MPa). Load case 1. Friction coefficient μ=0 between copper lid and cylinder.

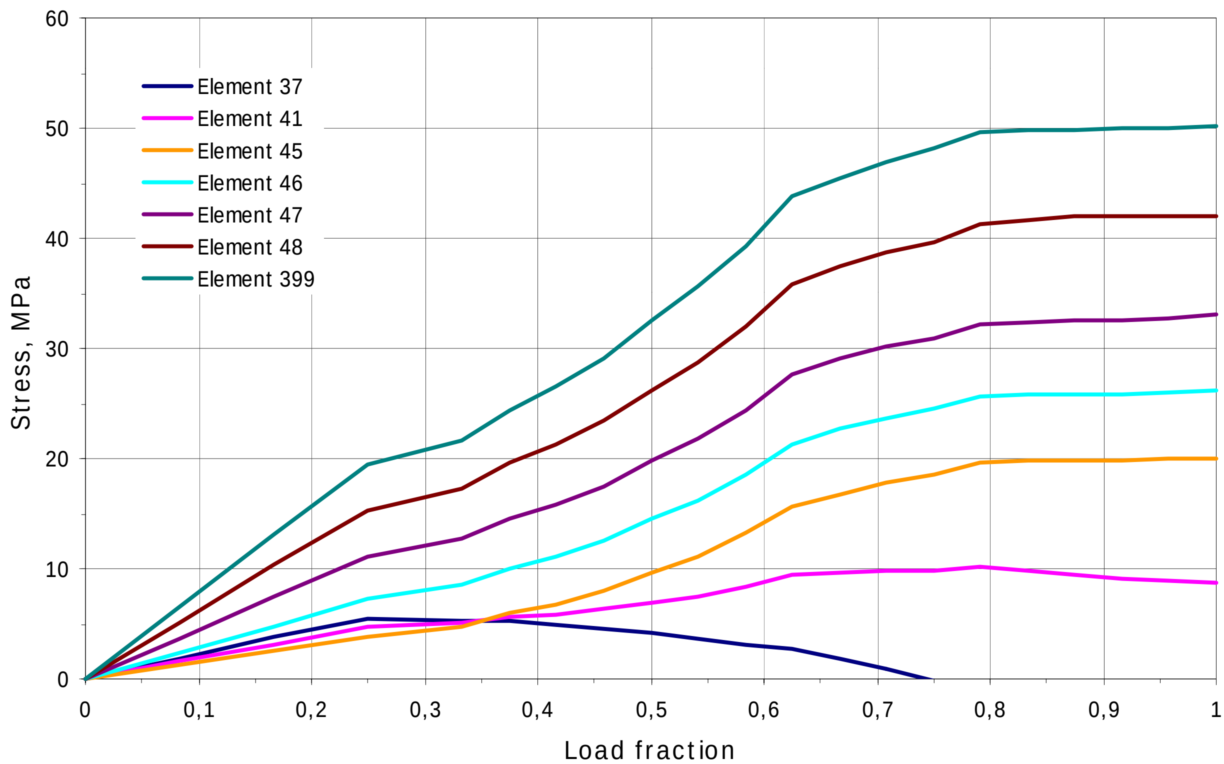


Figure 87 Maximum principal stresses in weld region during loading. Load case 1. Friction coefficient μ=0 between copper lid and cylinder.

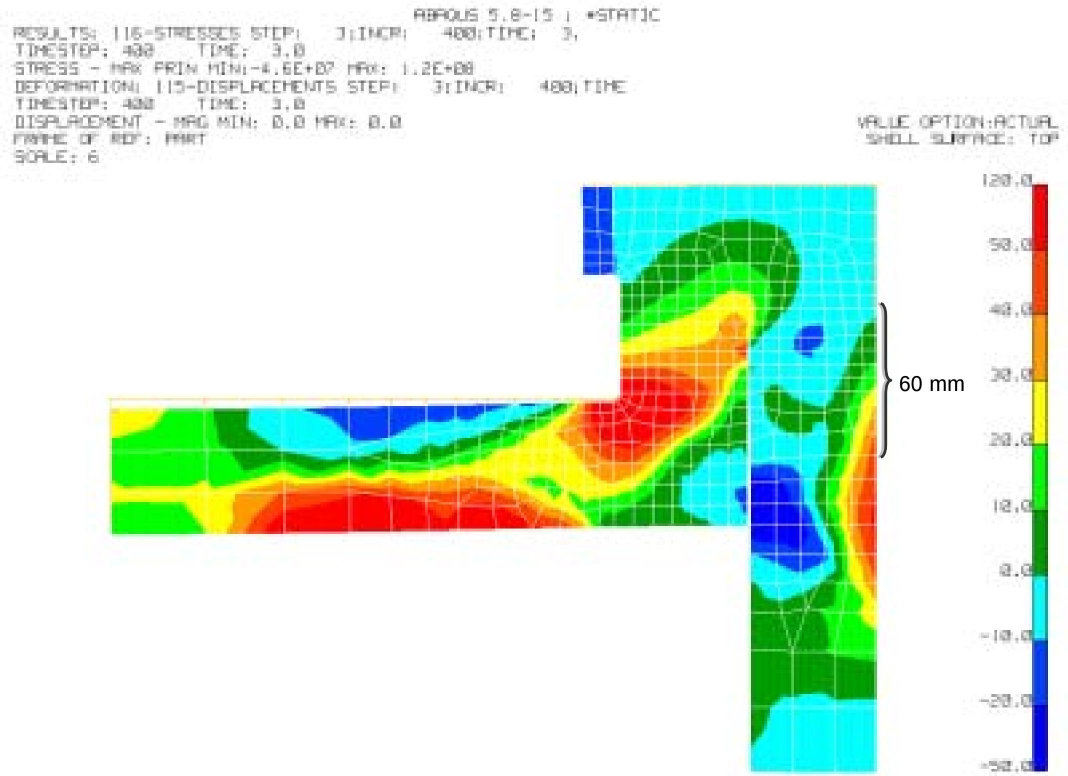


Figure 88 Maximum principal stress (MPa). Load case 1. Friction coefficient μ=0.3 between copper lid and cylinder.

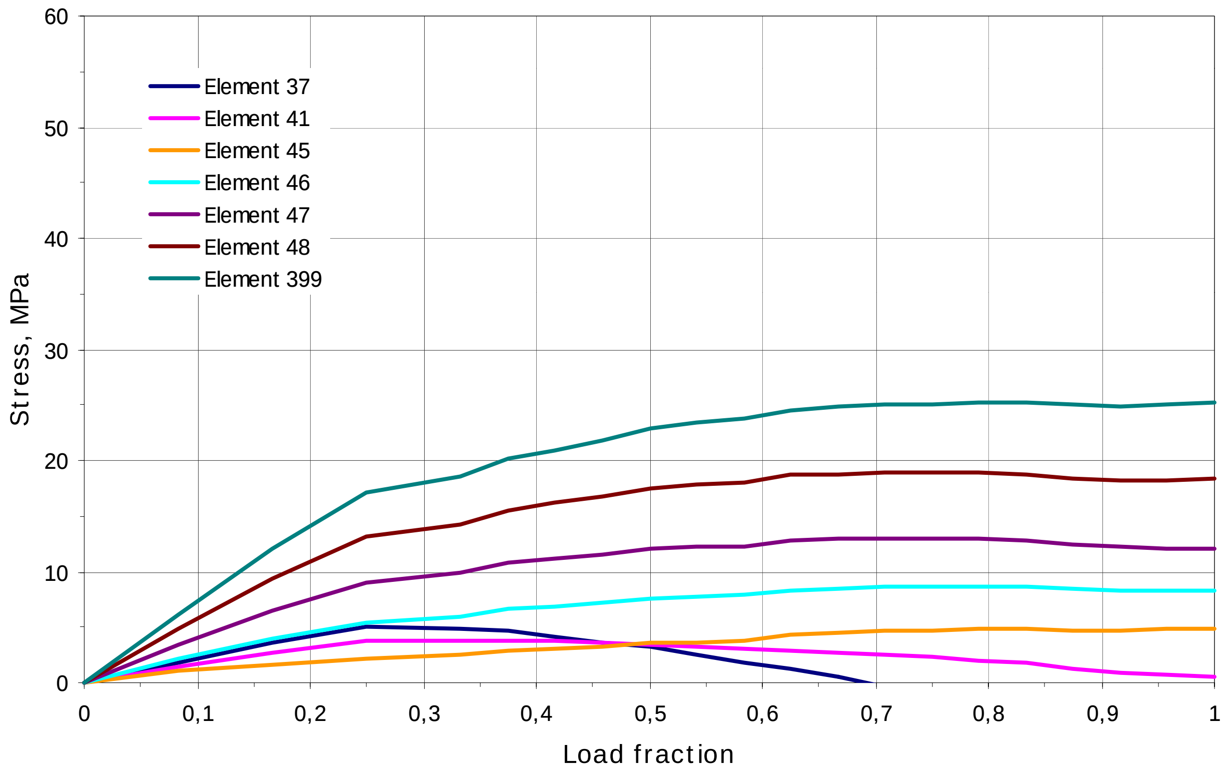


Figure 89 Maximum principal stresses in weld region during loading. Load case 1. Friction coefficient μ=0.3.

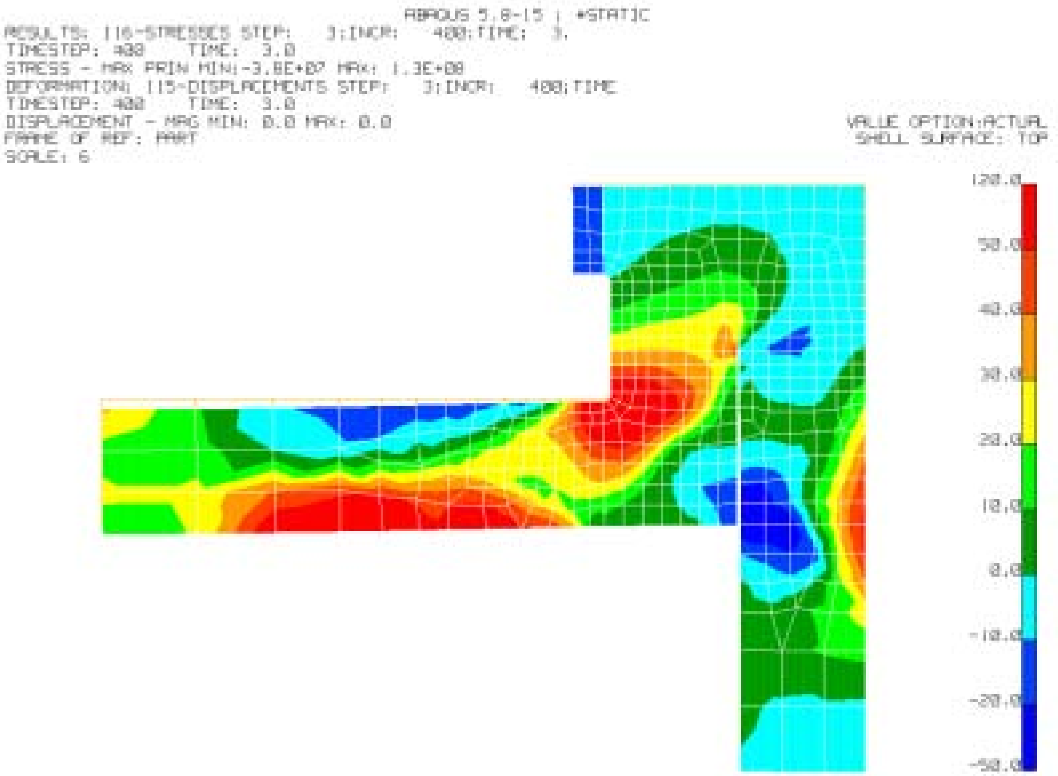


Figure 90 Maximum principal stress (MPa). Load case 1. Friction coefficient μ=0.5 between copper lid and cylinder.

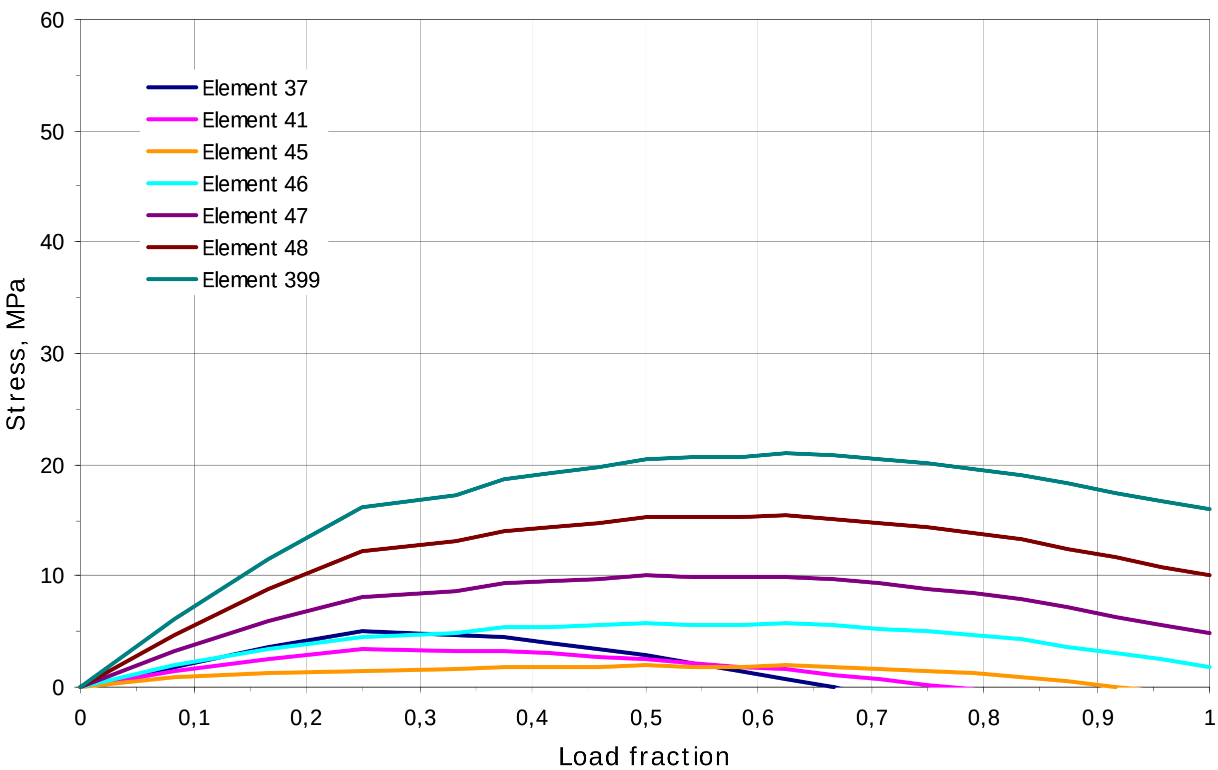


Figure 91 Maximum principal stresses in weld region during loading. Load case 1. Friction coefficient μ=0.5.

H.1.3 Strain

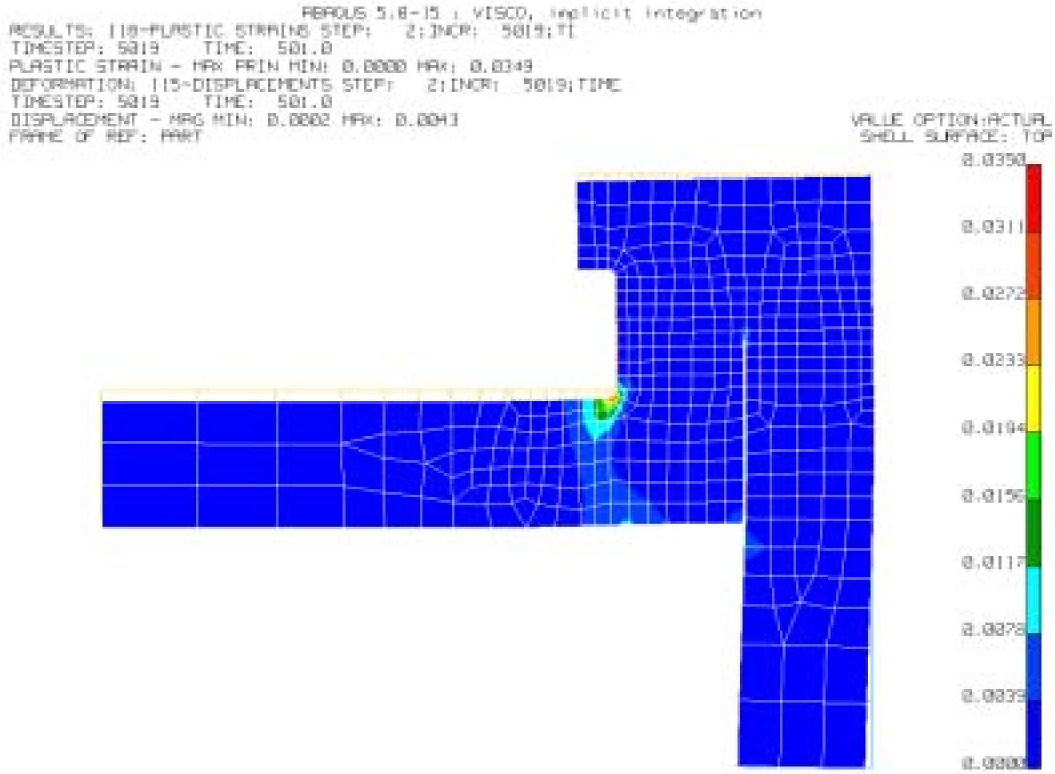


Figure 92 Maximum principal plastic strain. Load case 1. Friction coefficient μ=0.15 between copper lid and cylinder.

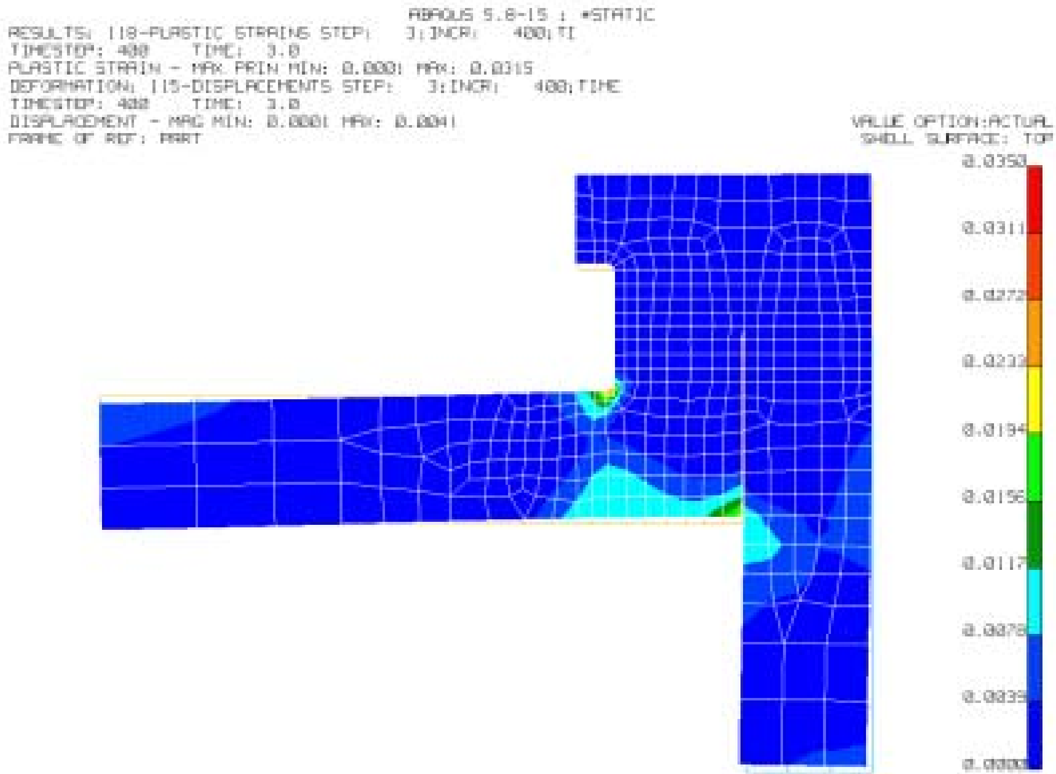


Figure 93 Maximum principal plastic strain. Load case 2. Friction coefficient μ=0.15 between copper lid and cylinder.

H.2 Creep — Load case 1

H.2.1 Contact

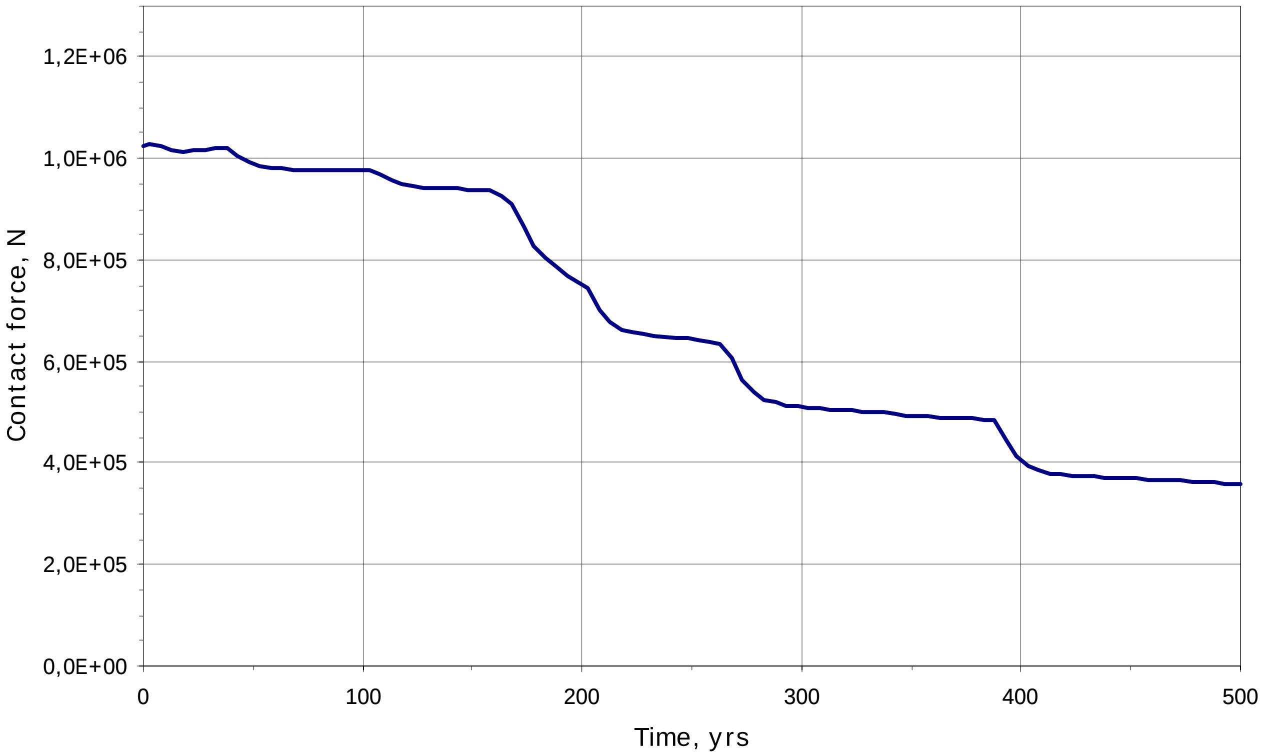


Figure 94 Contact force (N) between lid lower edge and copper cylinder during creep for 500 years. Load case 1.

H.2.2 Stress

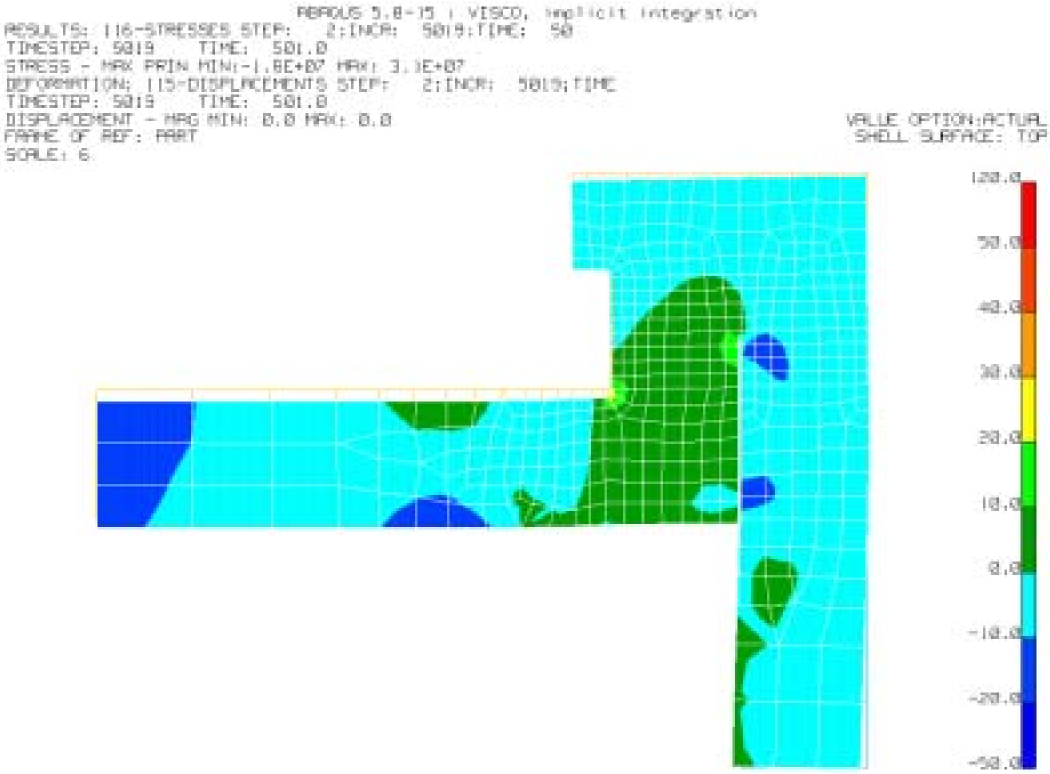


Figure 95 Maximum principal stress (MPa). Load case 1, creep 500 years.

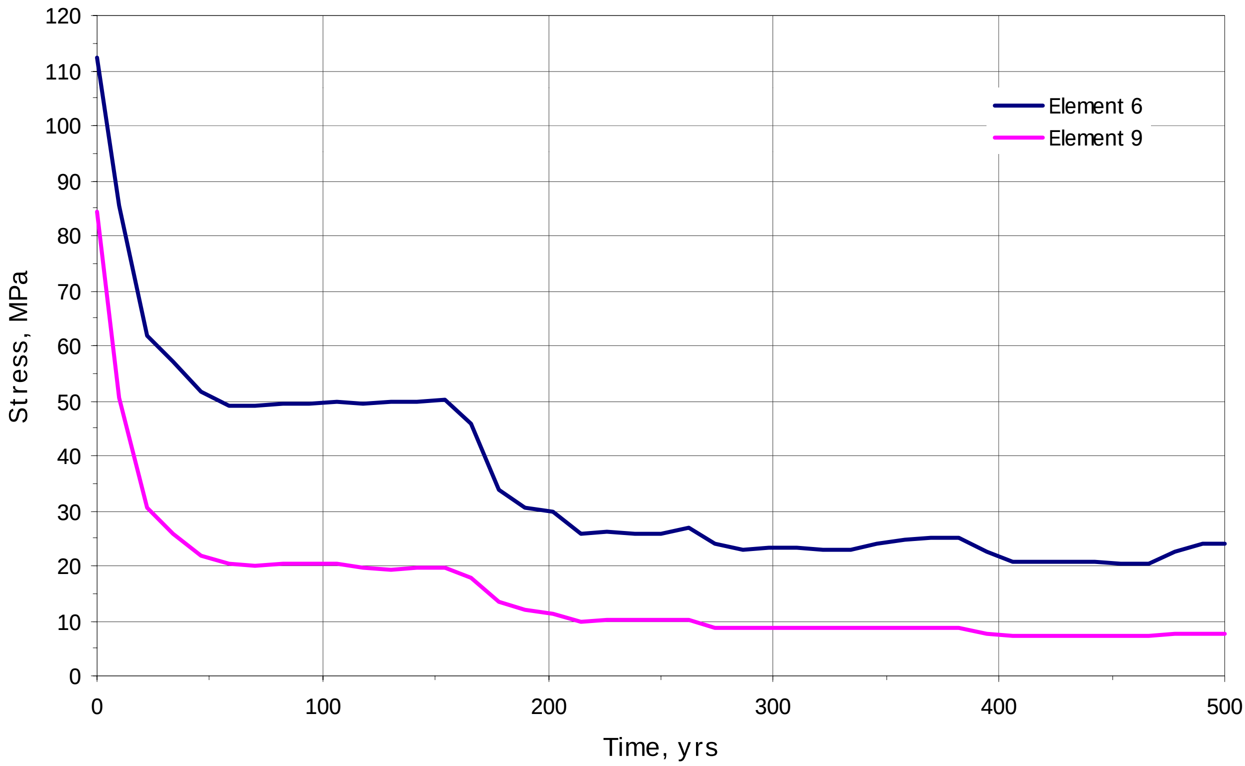


Figure 96 Maximum principal stresses in lid fillet during creep for 500 years. Load case 1.

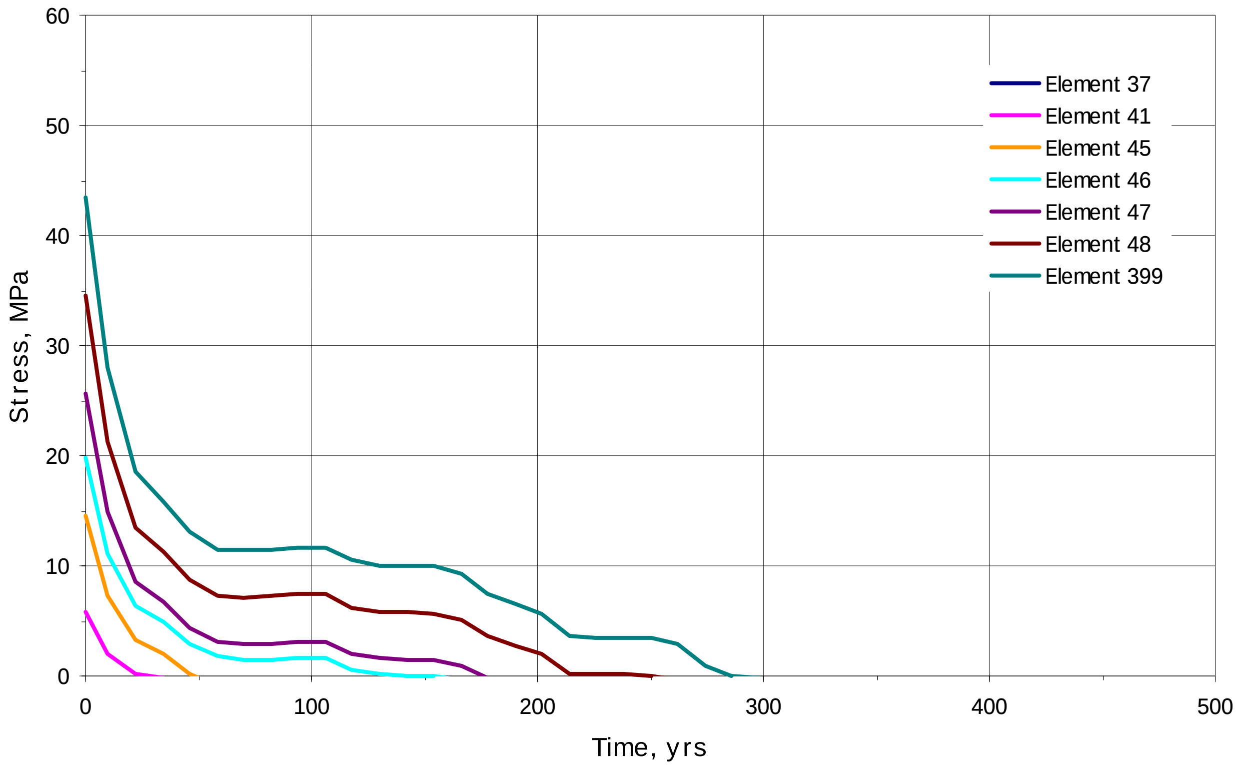


Figure 97 Maximum principal stresses in weld region during creep for 500 years. Load case 1.

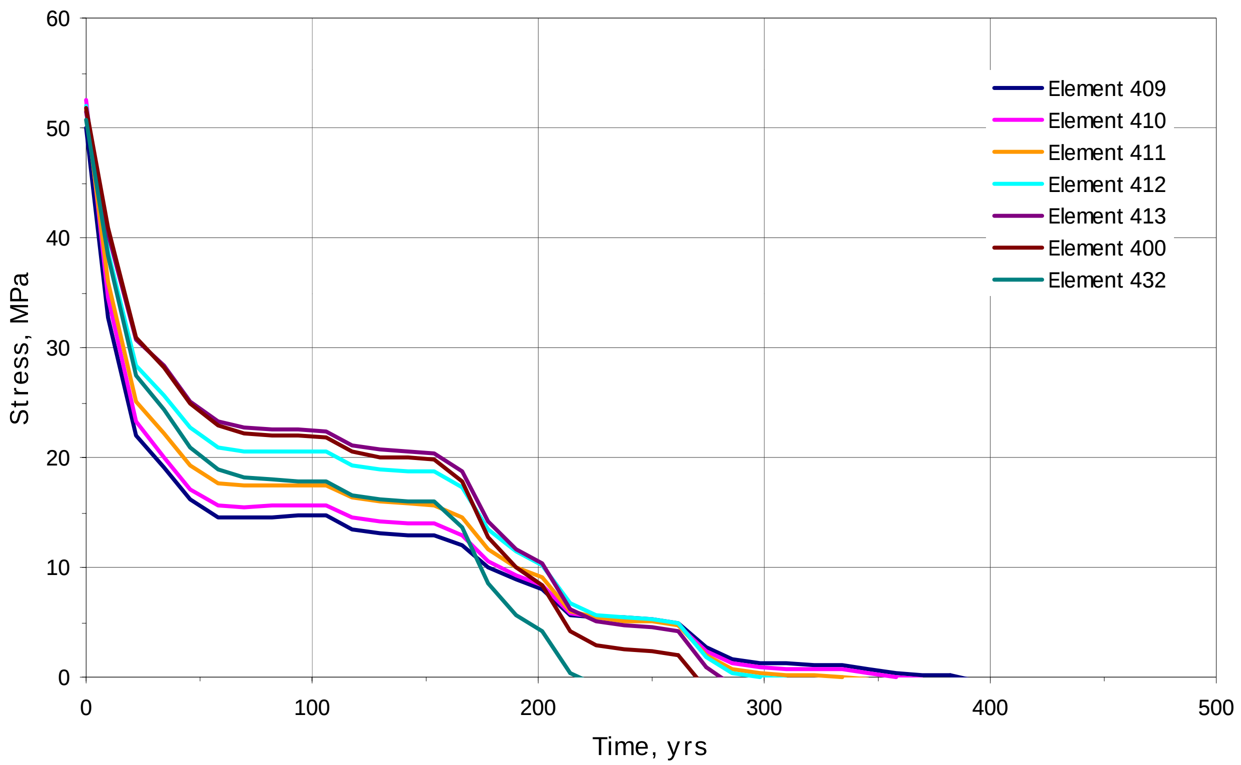


Figure 98 Maximum principal stresses on cylinder outside during creep for 500 years. Load case 1.

H.2.3 Strain

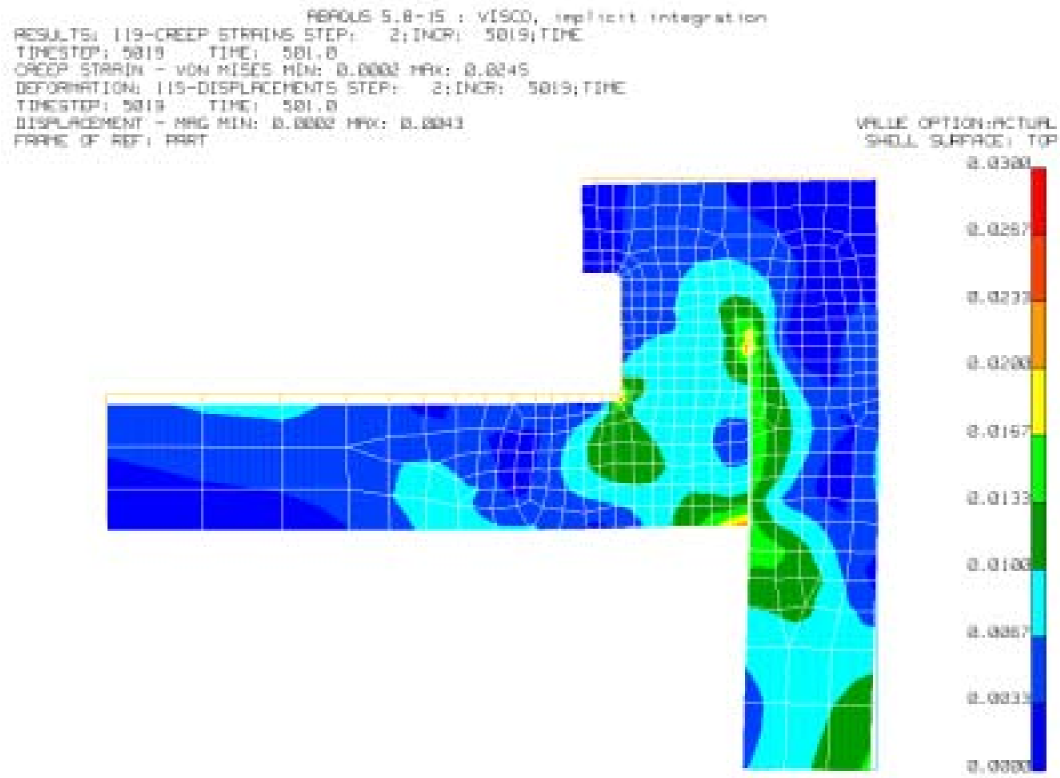


Figure 99 Maximum principal creep strain. Load case 1, creep 500 years.

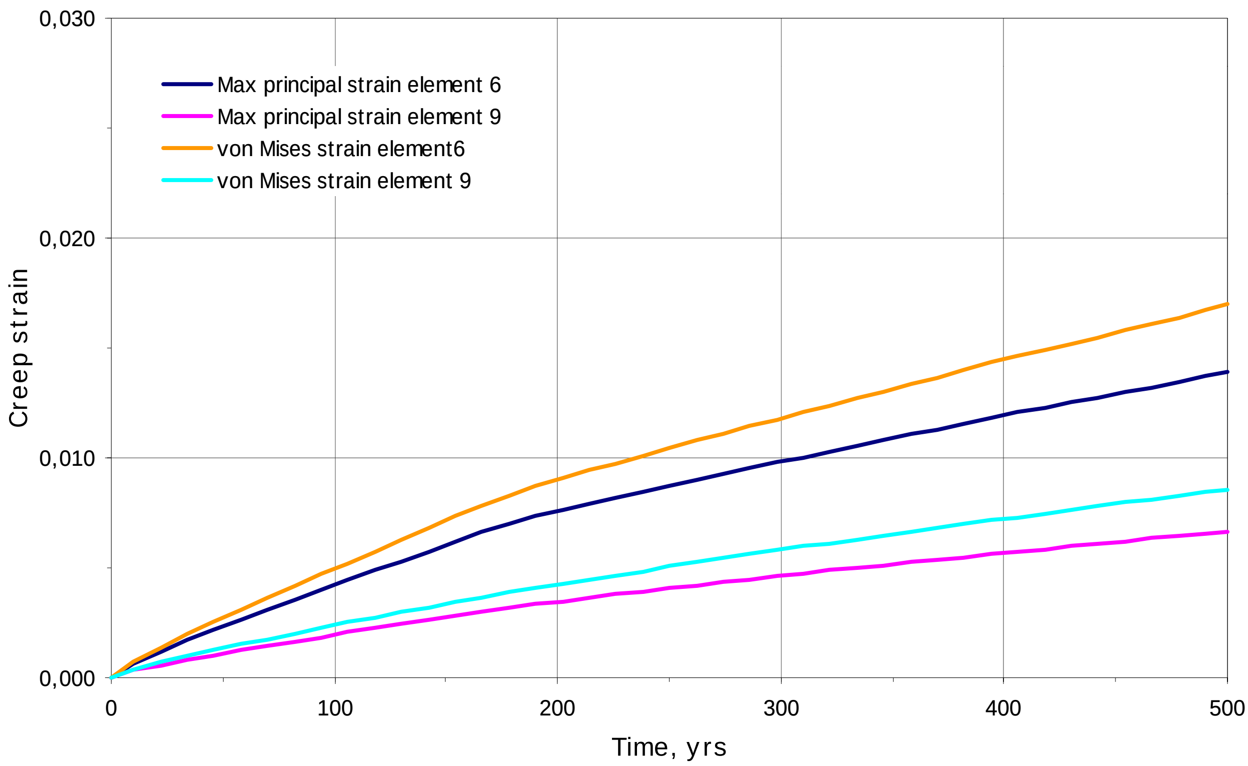


Figure 100 Maximum principal creep strain in lid fillet during creep for 500 years.

I Results from originally performed analyses

Figure 101 Elements in the lid fillet region for axisymmetric analyses.

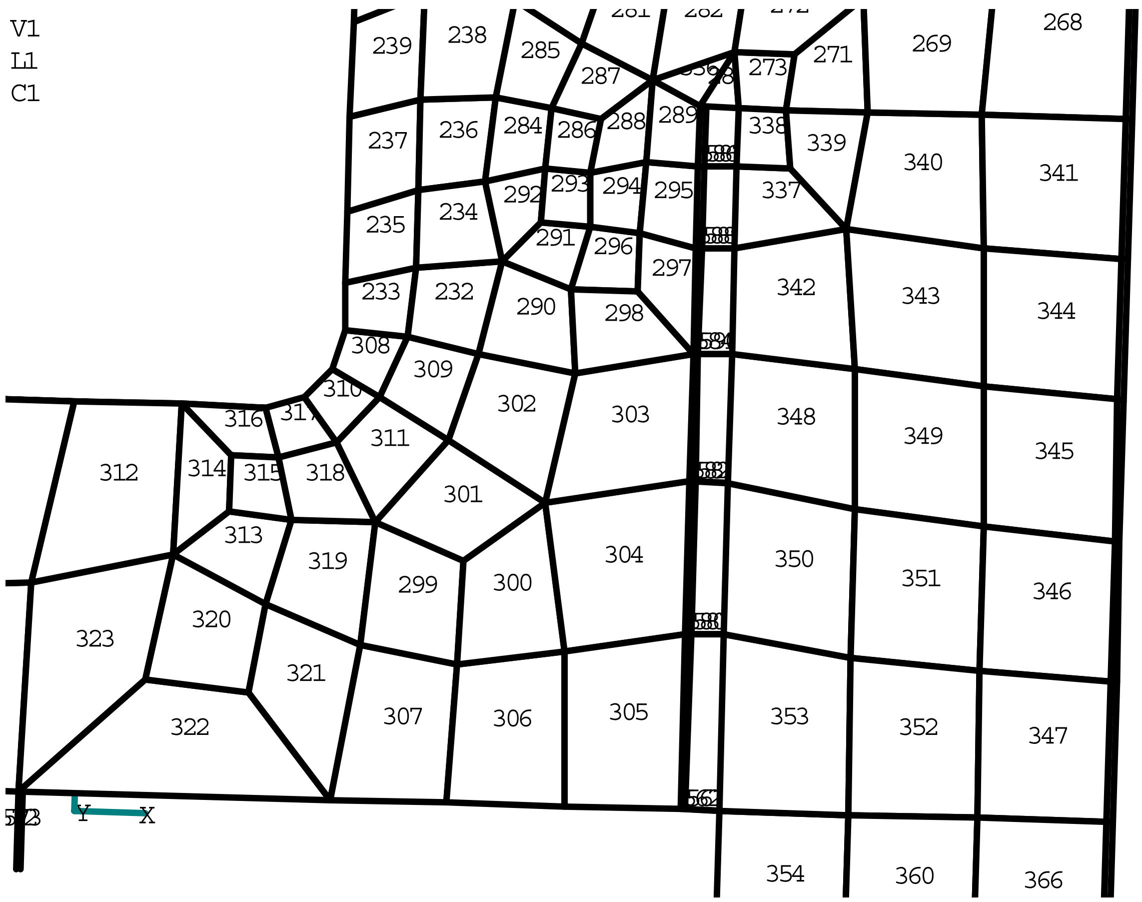


Figure 102 Elements in the contact region of lid and cylinder for axisymmetric analyses.

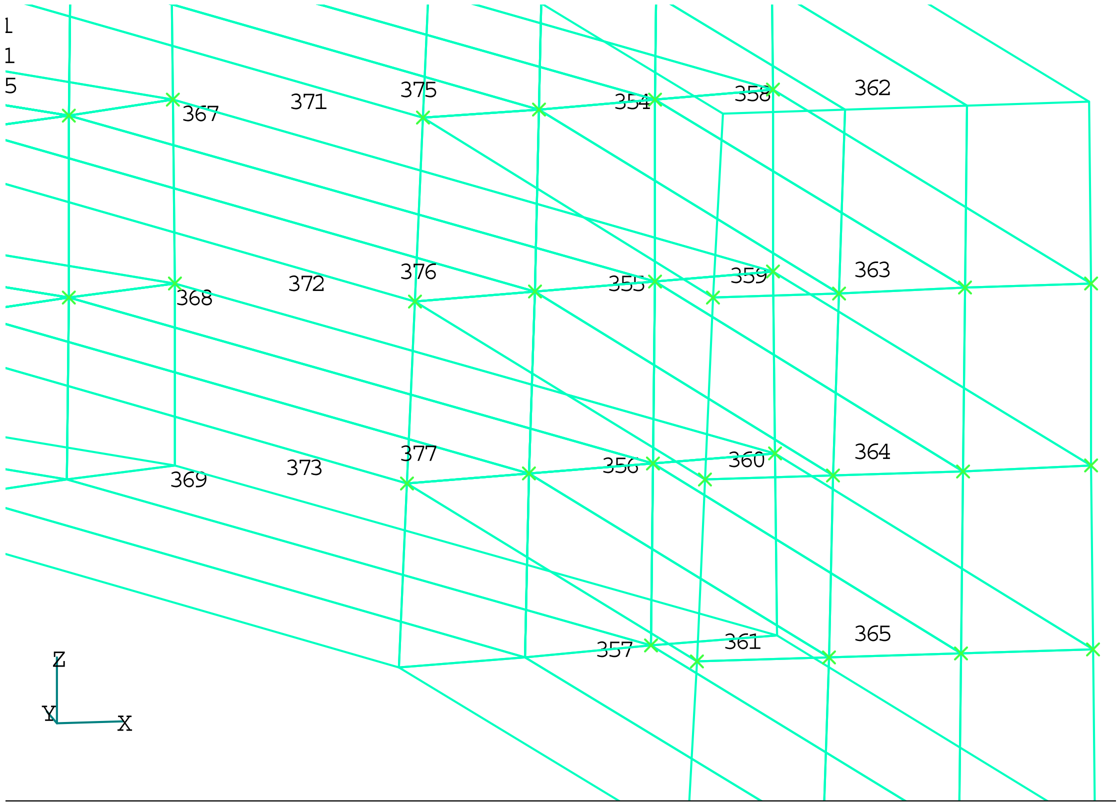


Figure 103 Elements in the weld and the cylinder between weld and the lid lower edge for the 3D model.

I.1 Load case 1

General
No contact between the lid lower edge and casing to relieve the lid fillet.

Fillet
Maximum principal stress is 98 MPa and remains relatively constant for increasing pressure.

Outer side of cylinder casing
Stresses and strains are negligible.

Weld
Mainly compressive stresses. Tensile stresses appearing at the surface are low.

Strain
Maximum plastic strain 2.3 % appears in the lid fillet.

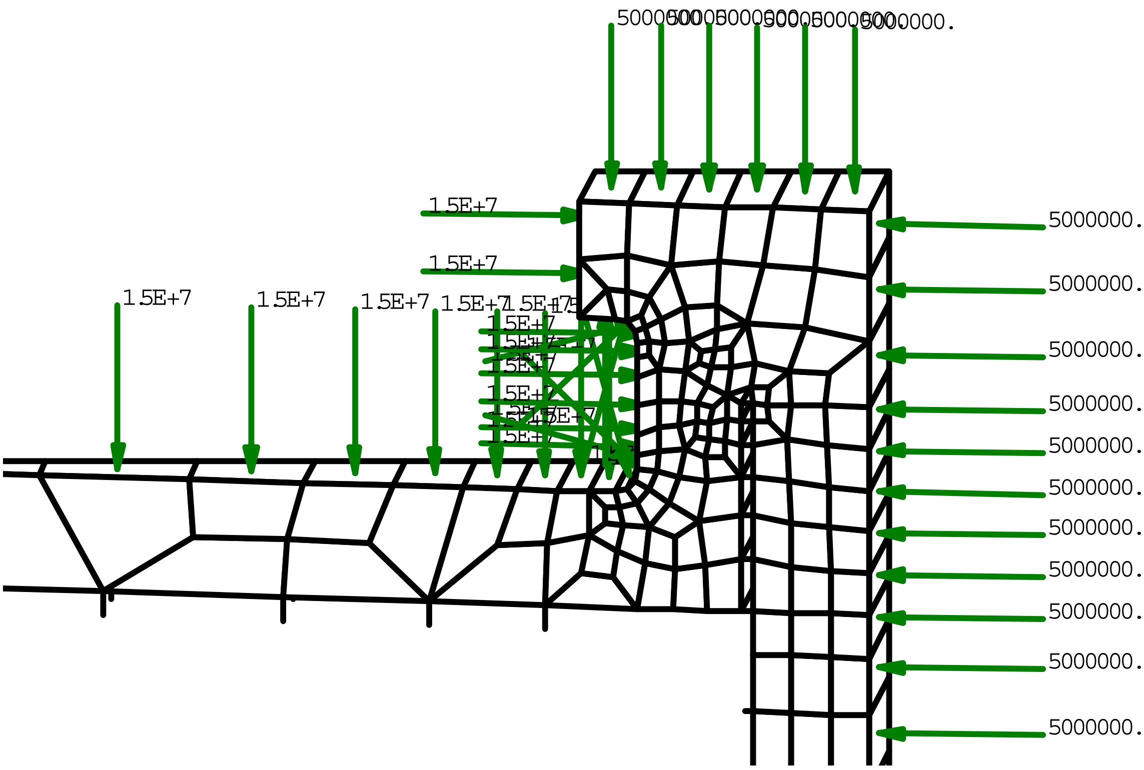


Figure 104 Axisymmetric loading. Load case 1: pressure 15 MPa on lid inside and 5 MPa on lid top. Outer pressure 5 MPa on cylinder.

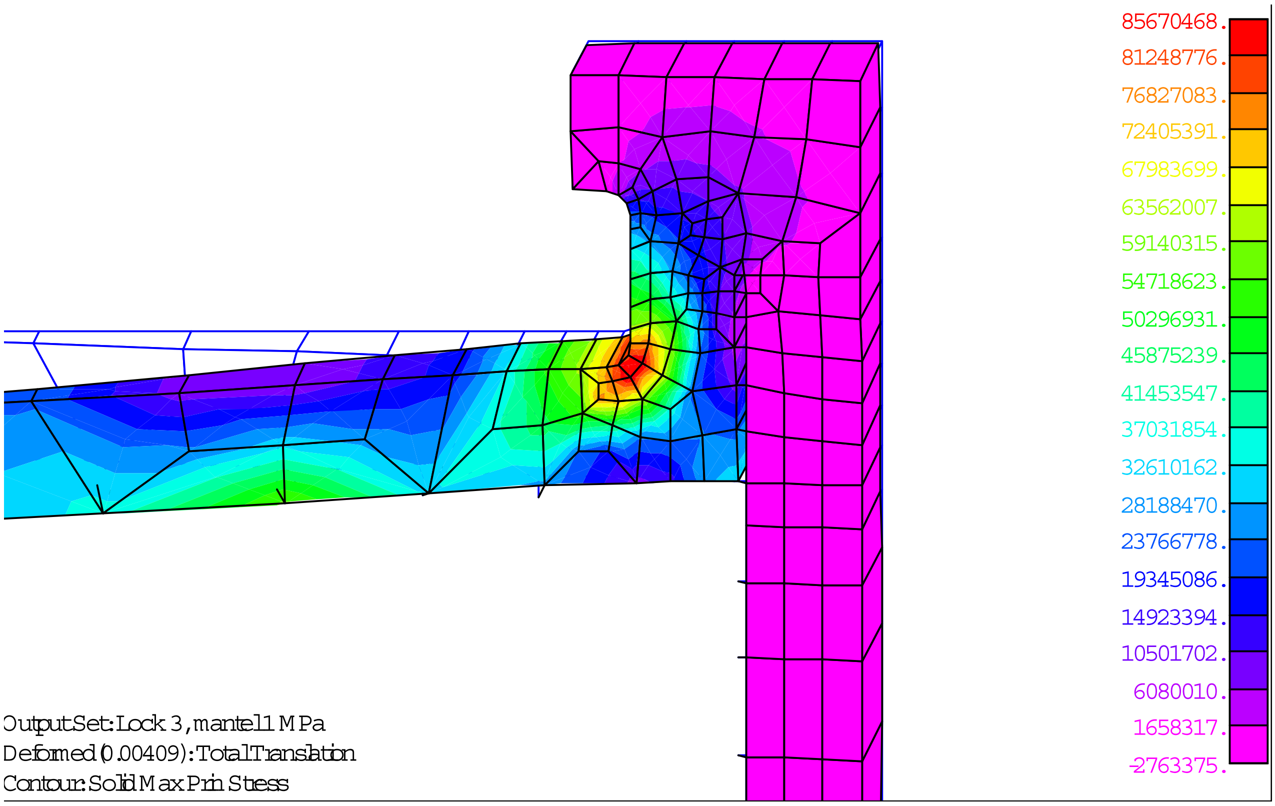


Figure 105 Maximum principal stress (Pa). Load case 1 at 20% (lid 3MPa/cylinder 1 MPa) of final load. Maximum stress 86 MPa appears in the fillet.

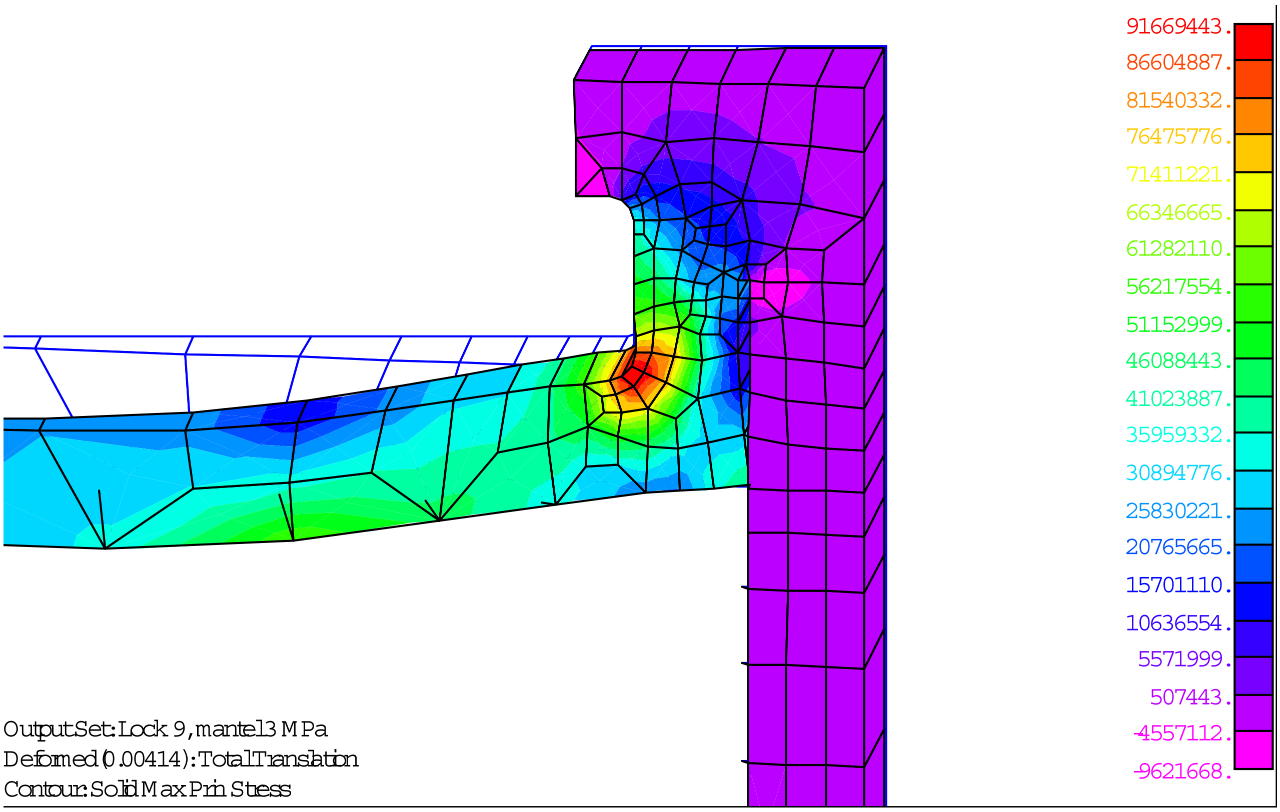


Figure 106 Maximum principal stress (Pa). Load case 1 at 60% percent (lid 9 MPa/ casing 3 MPa) of final load. Maximum stress 92 MPa appears in the fillet.

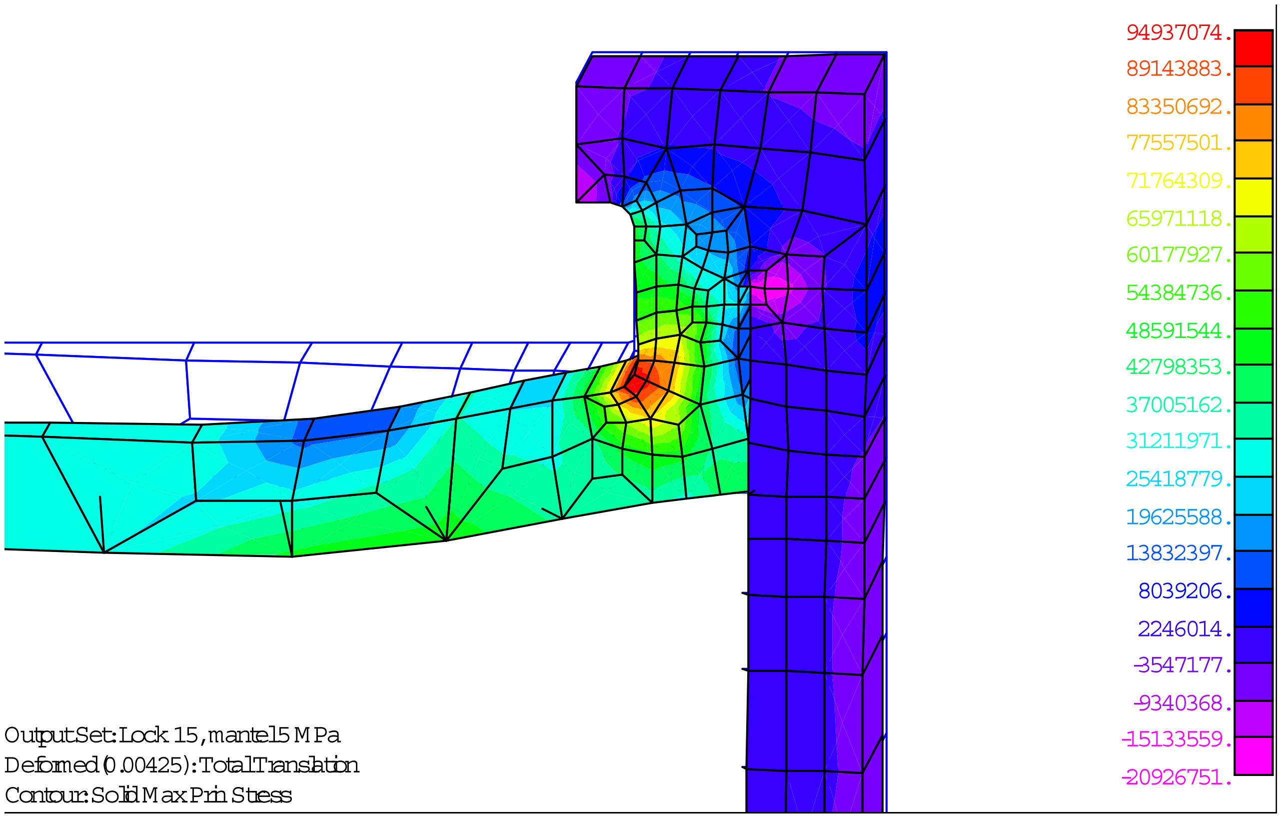


Figure 107 Maximum principal stress (Pa). Load case 1 at final load (lid 15 MPa/casing 5 MPa). Maximum stress 95 MPa appears in the fillet.

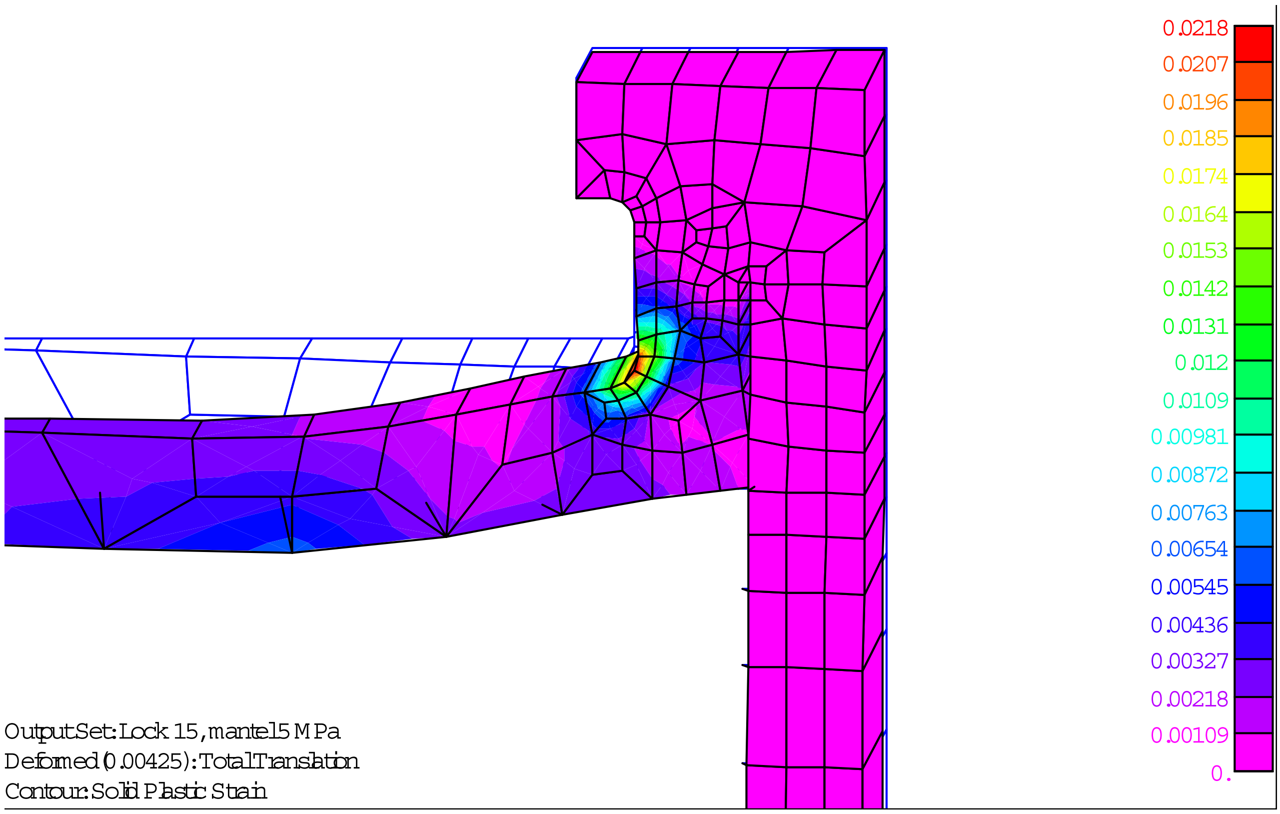


Figure 108 Plastic strain. Load case 1 at final load. Maximum plastic strain 2.2% appears in the fillet.

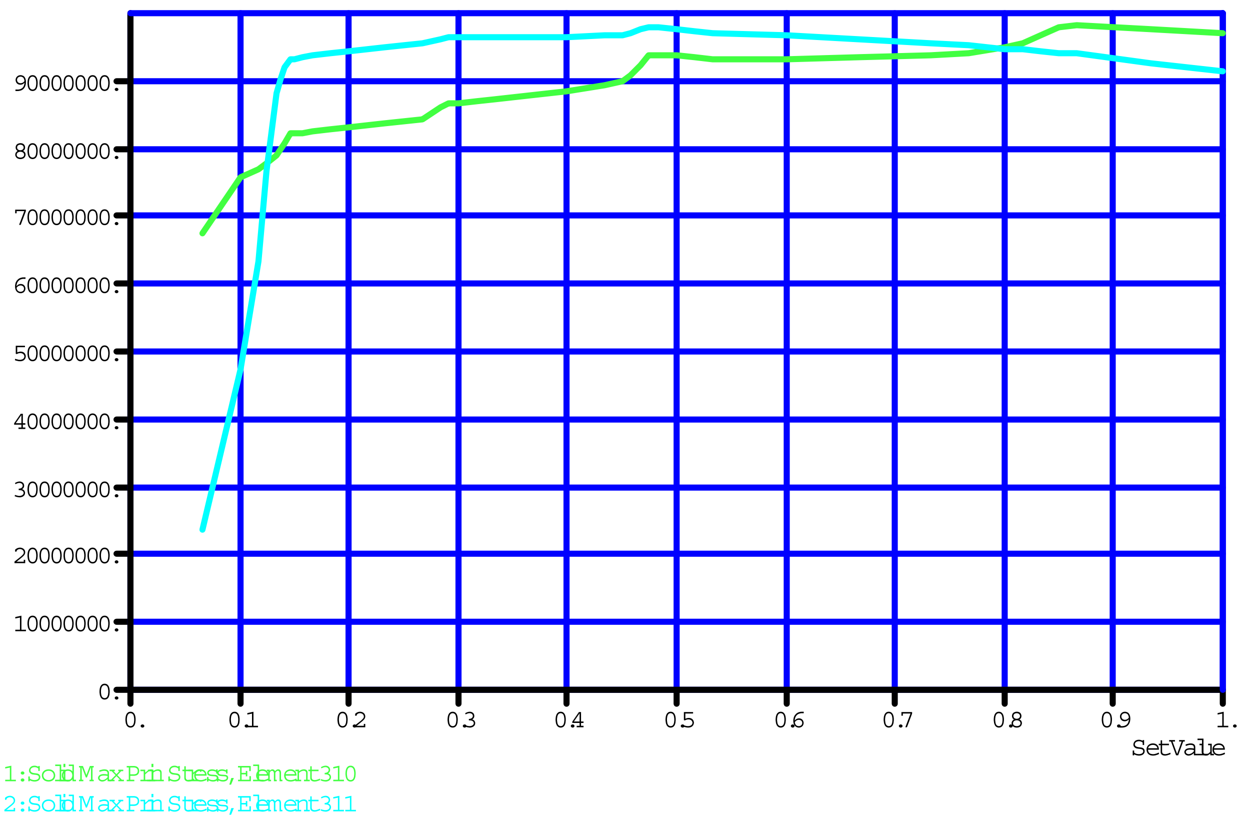


Figure 109 Max principal stresses (Pa) in lid fillet. Load case 1.

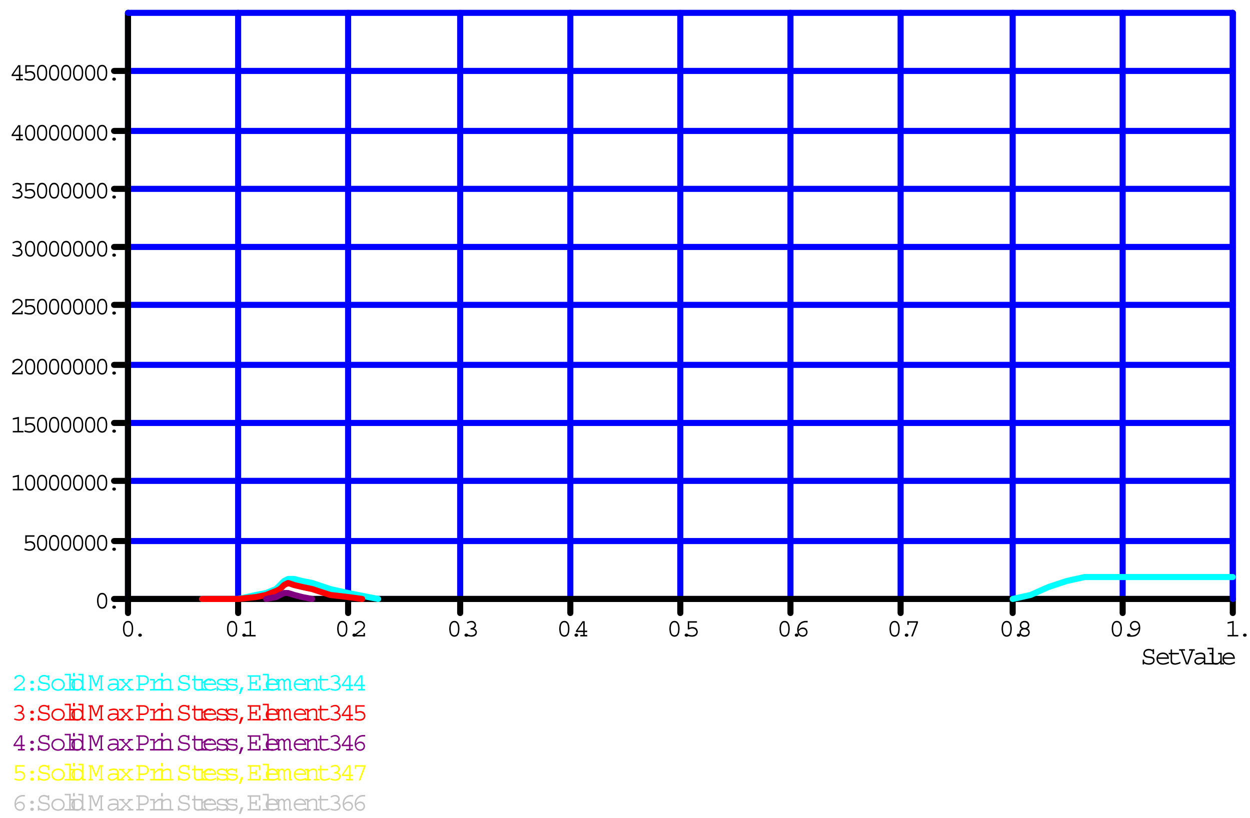


Figure 110 Max principal stresses (Pa) in cylinder casing. Load case 1.

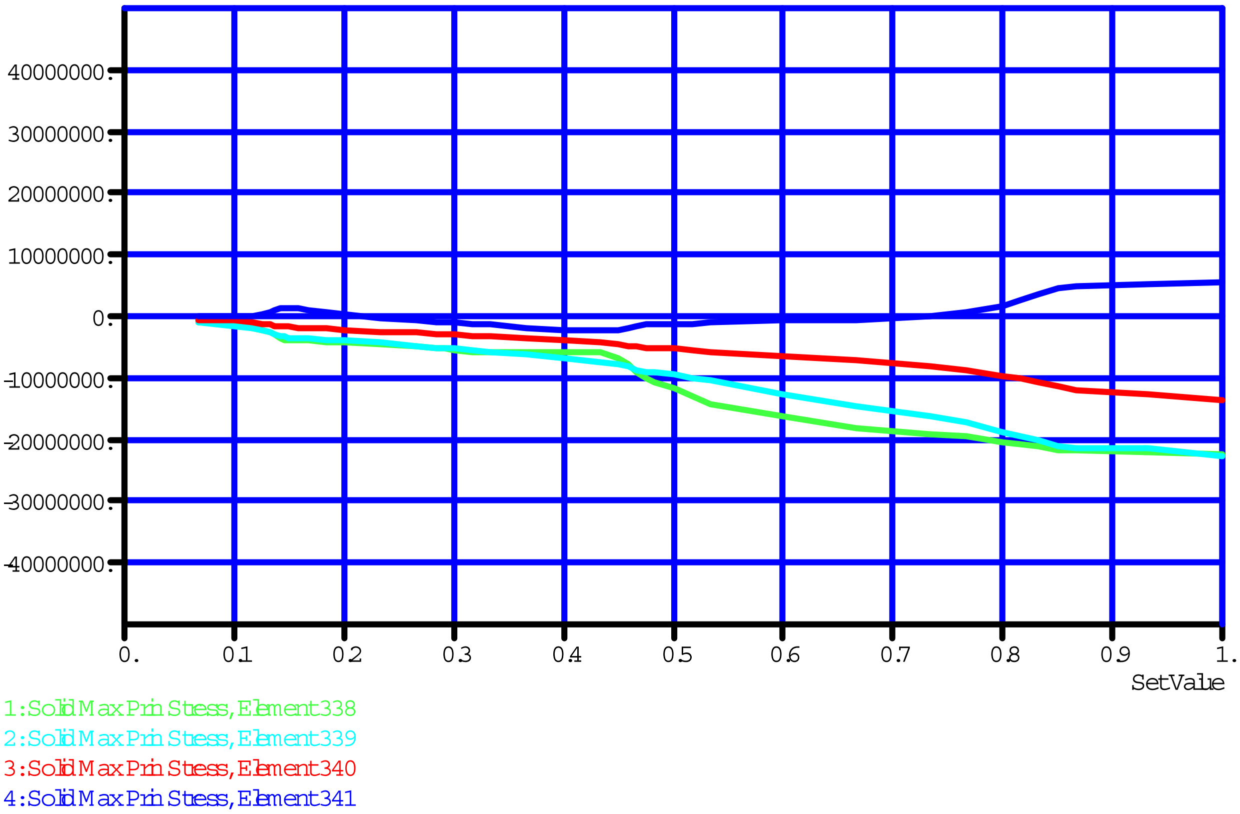


Figure 111 Max principal stresses (Pa) in weld. Load case 1.

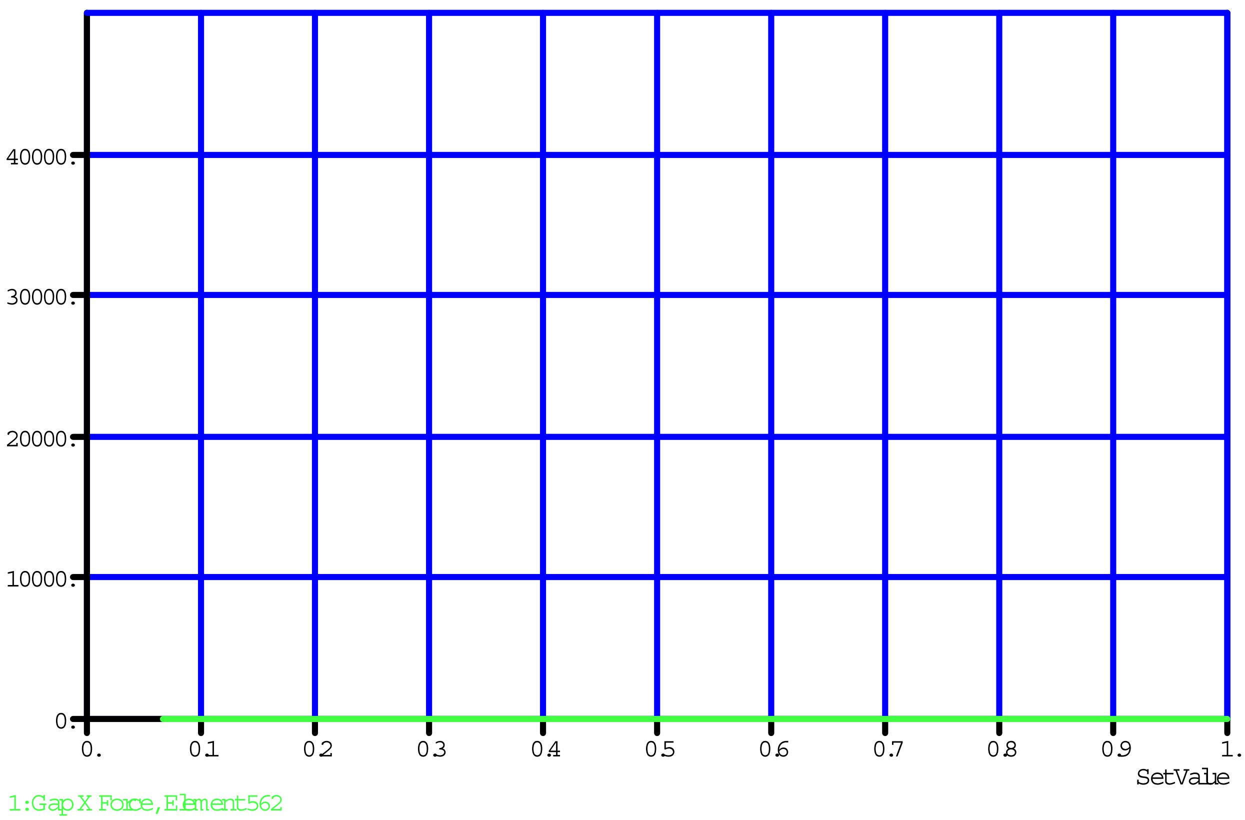


Figure 112 Contact force (N) in element 562. Load case 1.

I.2 Load case 2

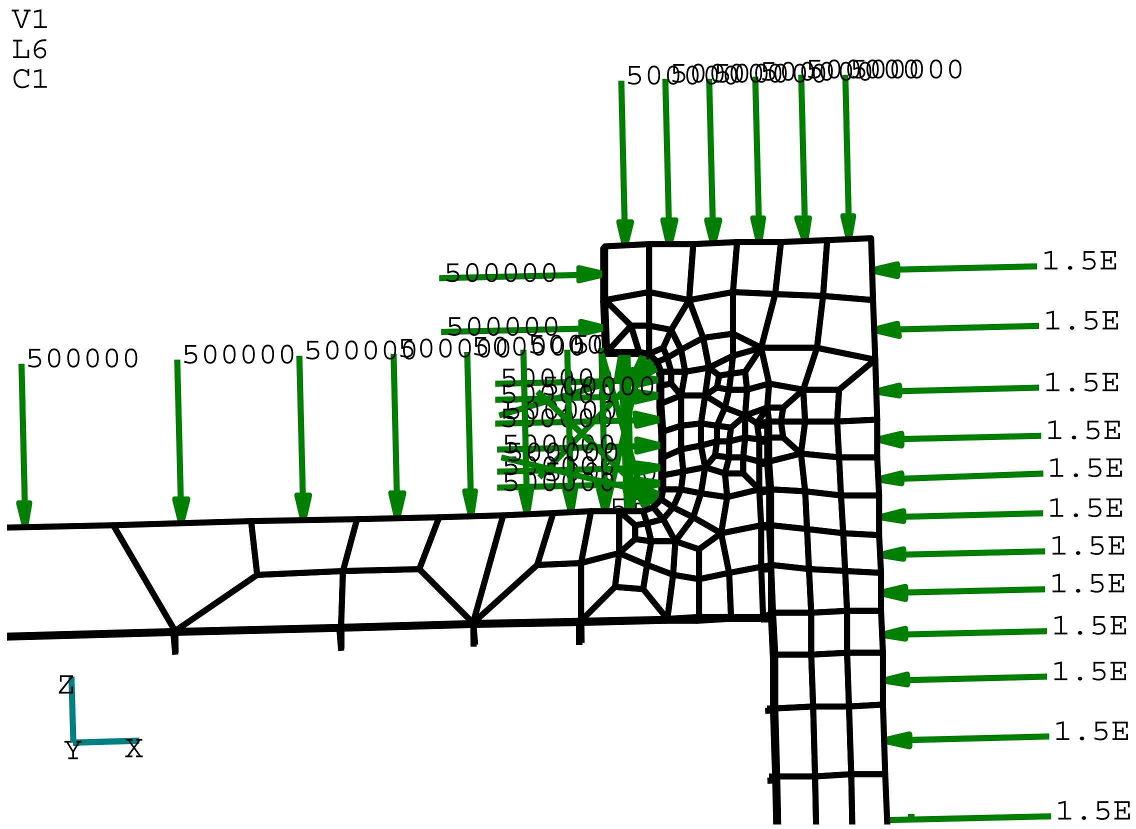


Figure 113 Load case 2.

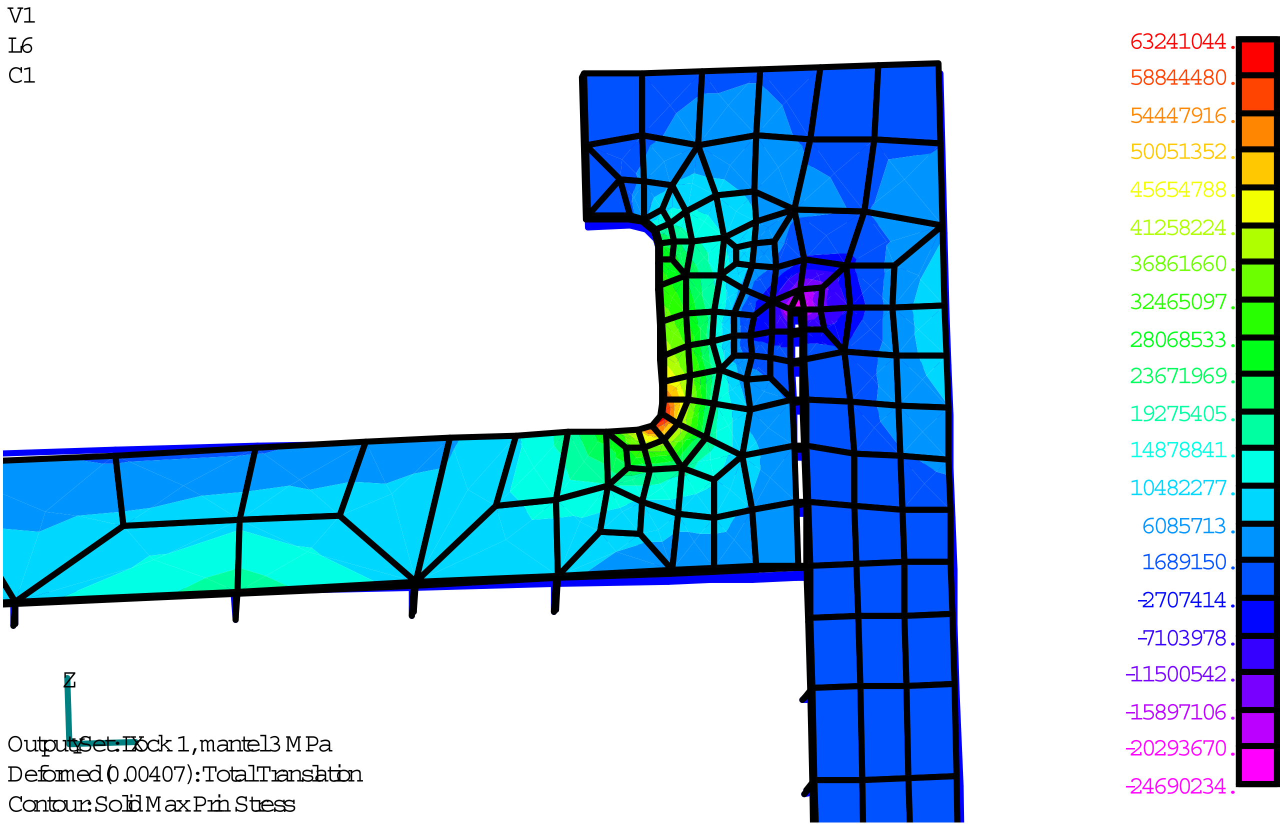


Figure 114 Maximum principal stresses (Pa). Load case 2 at 20% (lid 1 MPa/casing 3 MPa) of final load. Maximum stress 86 MPa appears in the fillet.

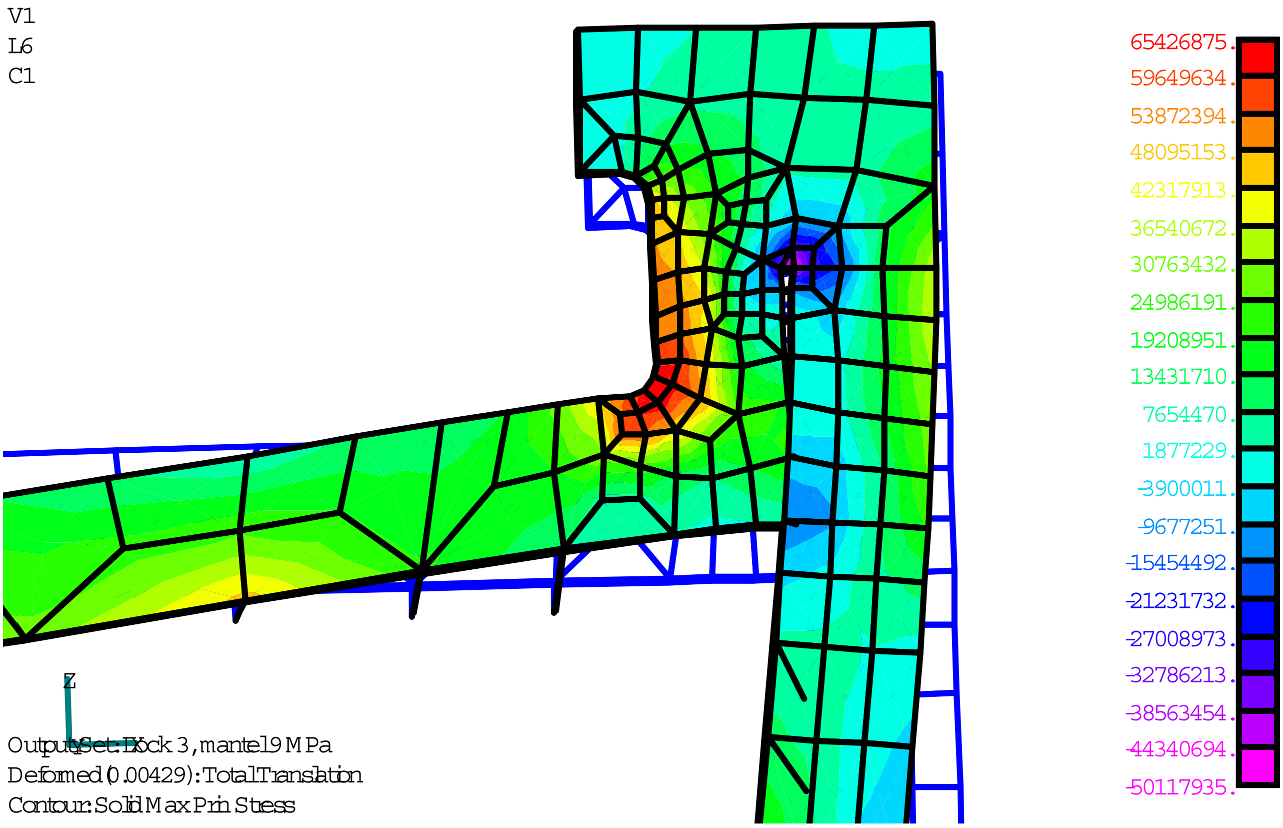


Figure 115 Maximum principal stresses (Pa) . Load case 2 at 60% (lid 3 MPa/casing 9 MPa) of final load.

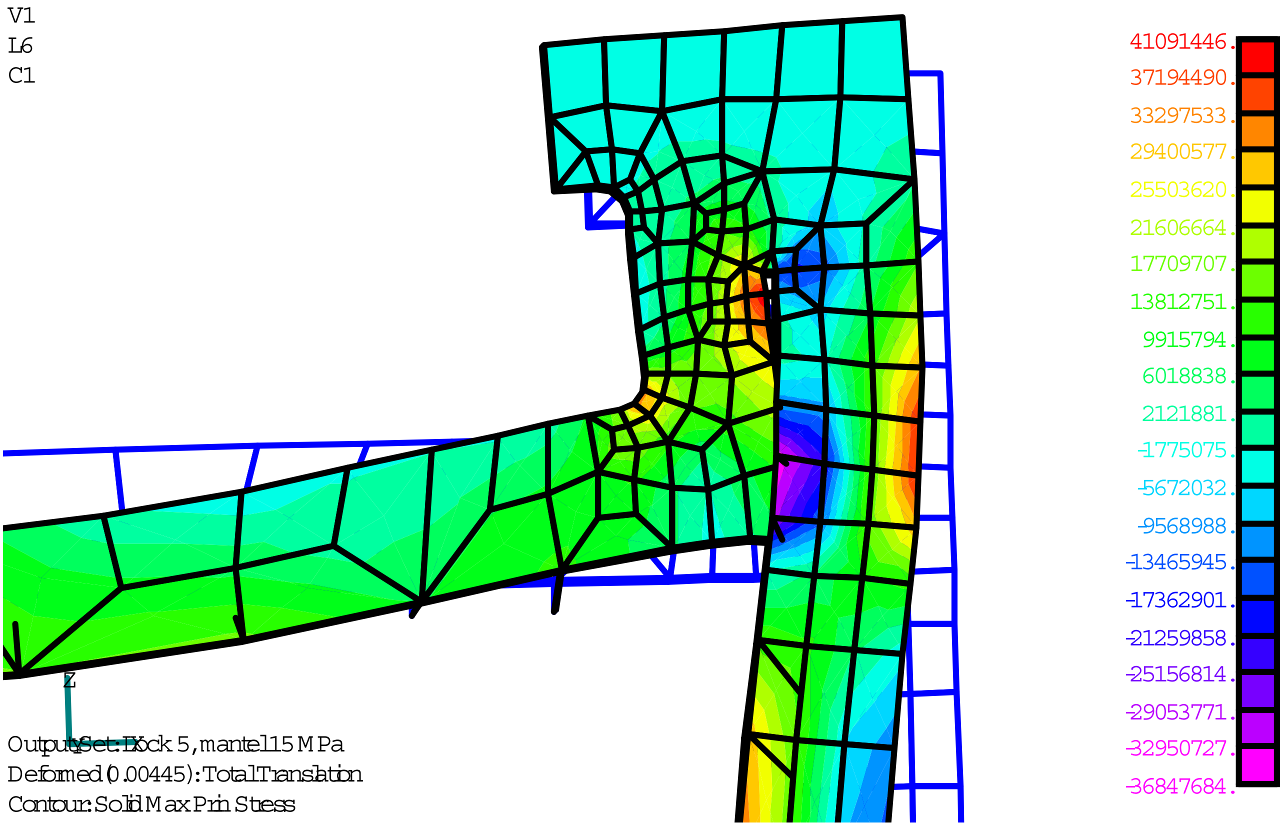


Figure 116   Maximum principal stresses (Pa). Load case 2.

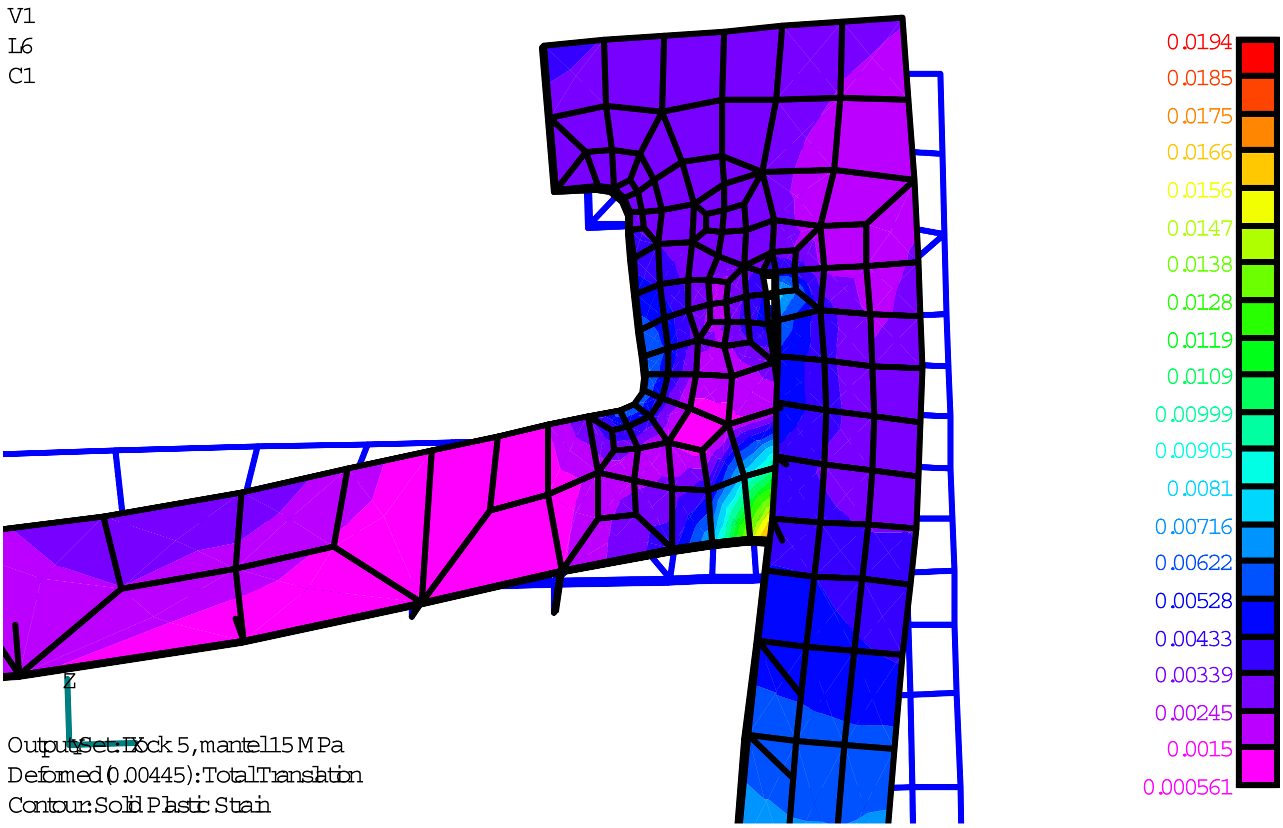


Figure 117   Plastic strain. Load case 2.

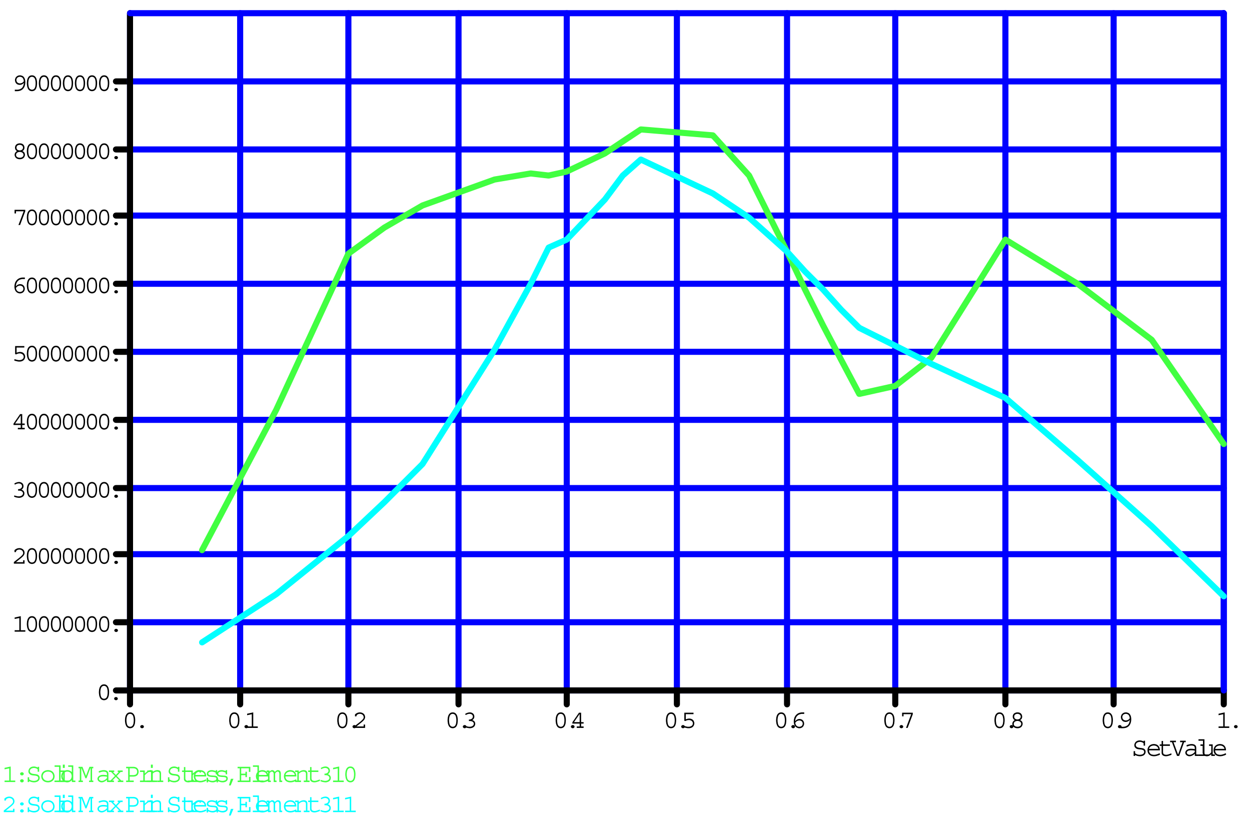


Figure 118   Max principal stresses (Pa) in lid fillet during loading. Load case 2.

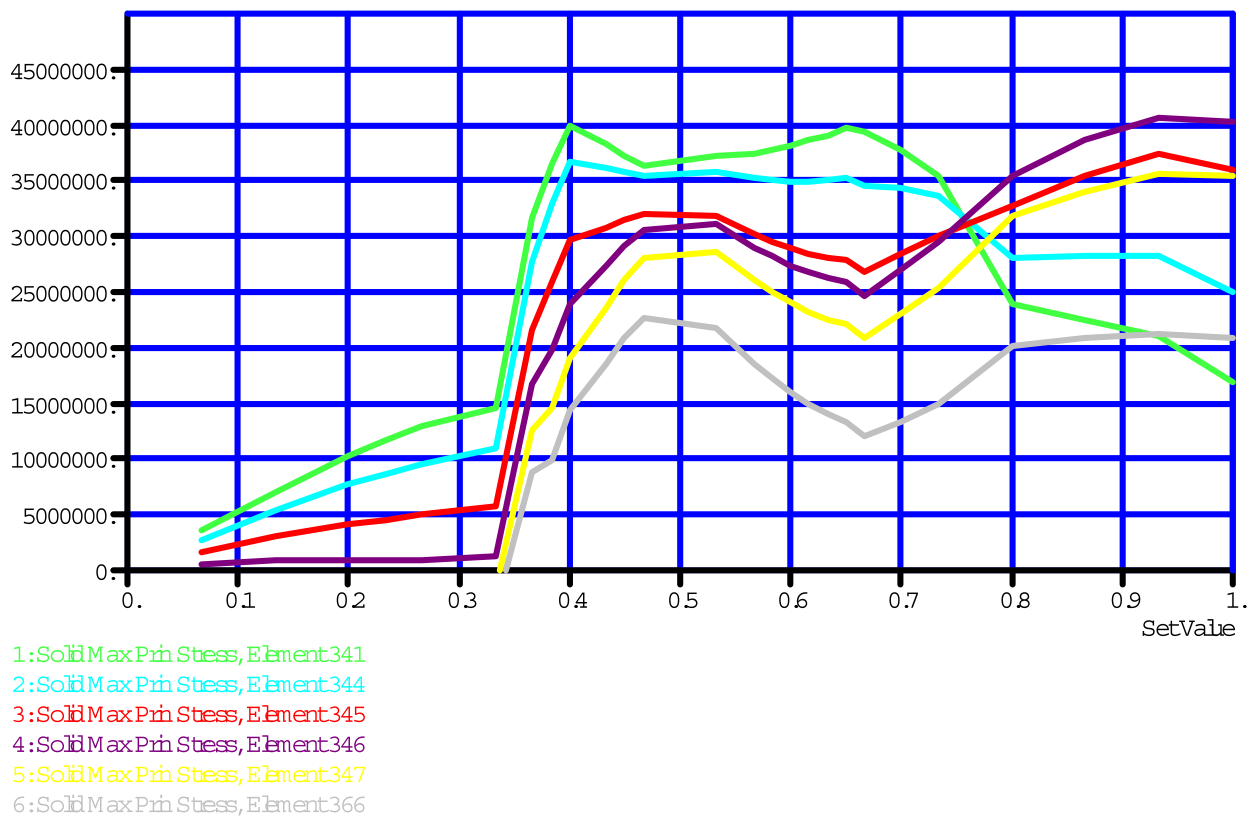


Figure 119   Max principal stresses (Pa) in cylinder during loading. Load case 2.

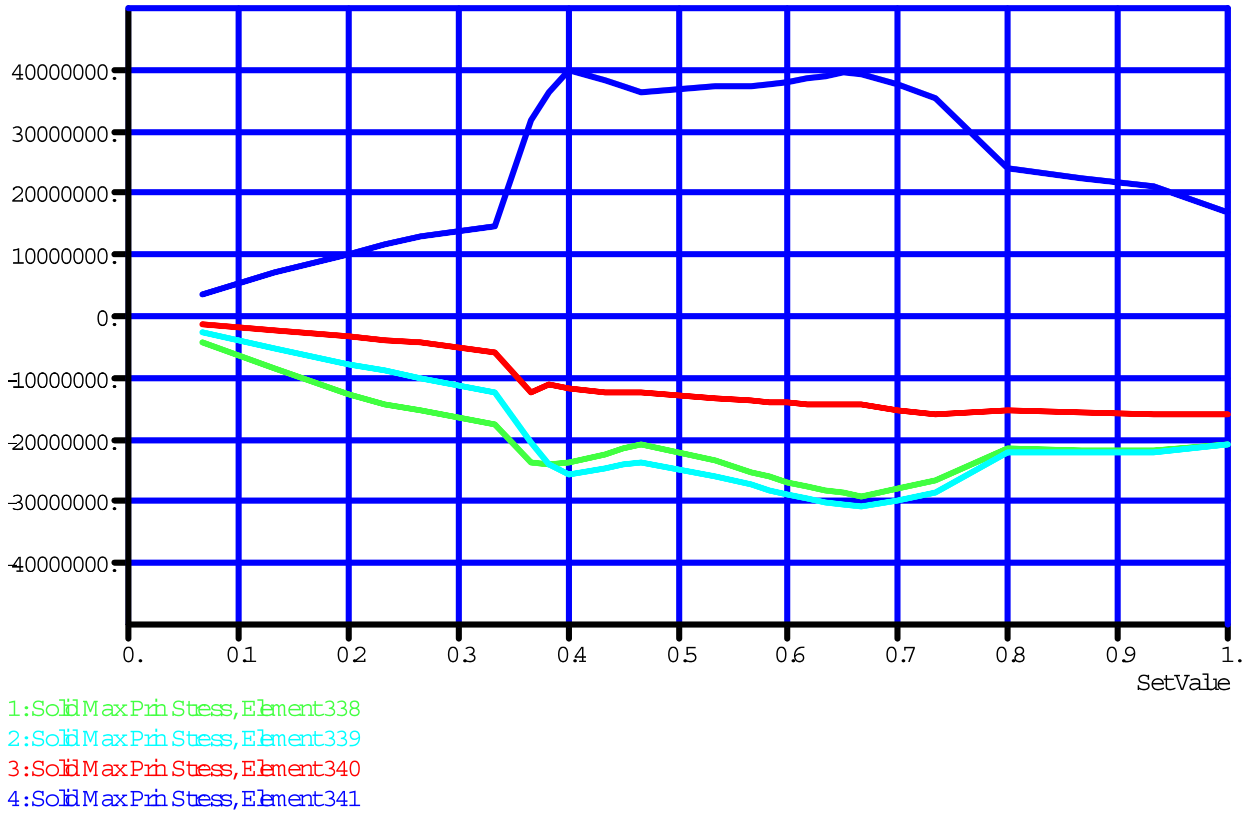


Figure 120 Max principal stresses (Pa) in weld during loading. Load case 2.

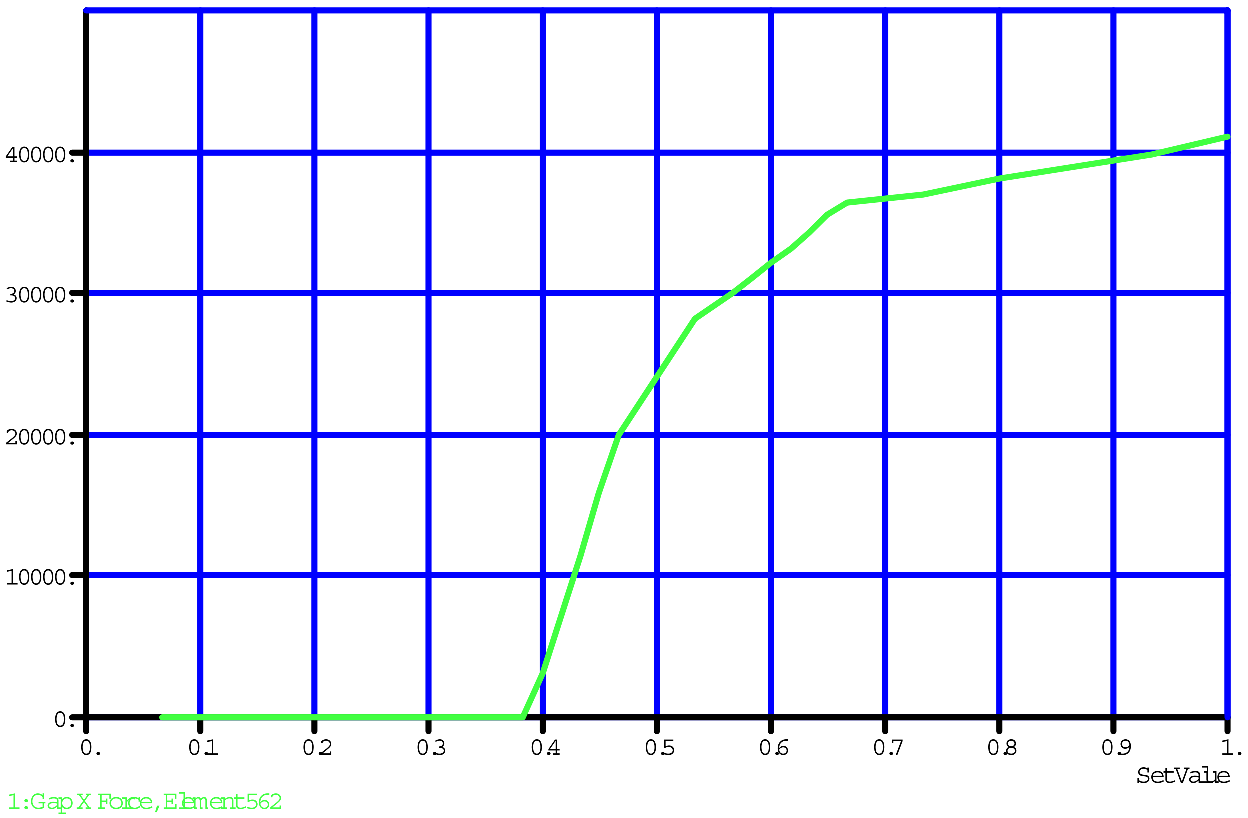


Figure 121 Contact force (N) in element 562 during loading. Load case 2.

I.3 Load case 3

General
Load up to 20 MPa.

Set value 0.1 = 2 MPa, 0.2 = 4 MPa, etc

The lid lower edge comes into contact with the cylinder at the pressure 6 MPa.

Lid fillet
Element 310 (surface), 311 (10 mm from the surface)

Maximum tensile stress 95 MPa in the weld surface at approximately 6 MPa. Decreases with increasing load.

Outer side of casing
Element 341, 344 – 347, 366

Maximum stress in element is approximately 30 MPa.

Large stress gradient towards the surface.

Maximum principal stress is 56 MPa at a node on the surface.

Weld
Compressive stresses except at the weld surface (element 344).

Strain
Plastic strain less than 2% at 15 MPa.

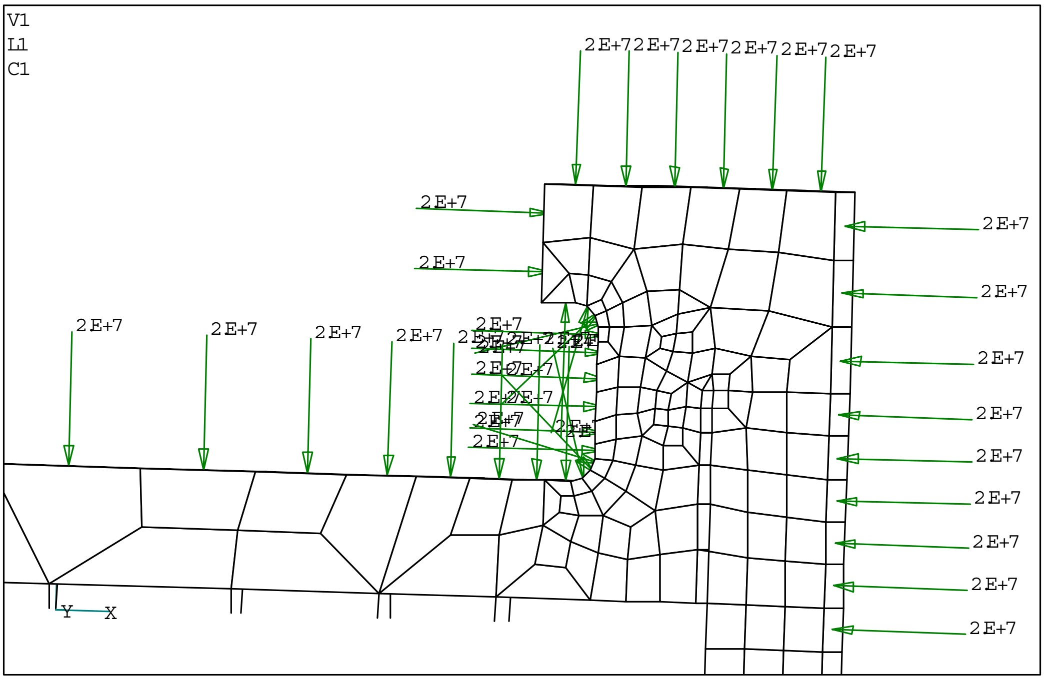


Figure 122 Load case 3.

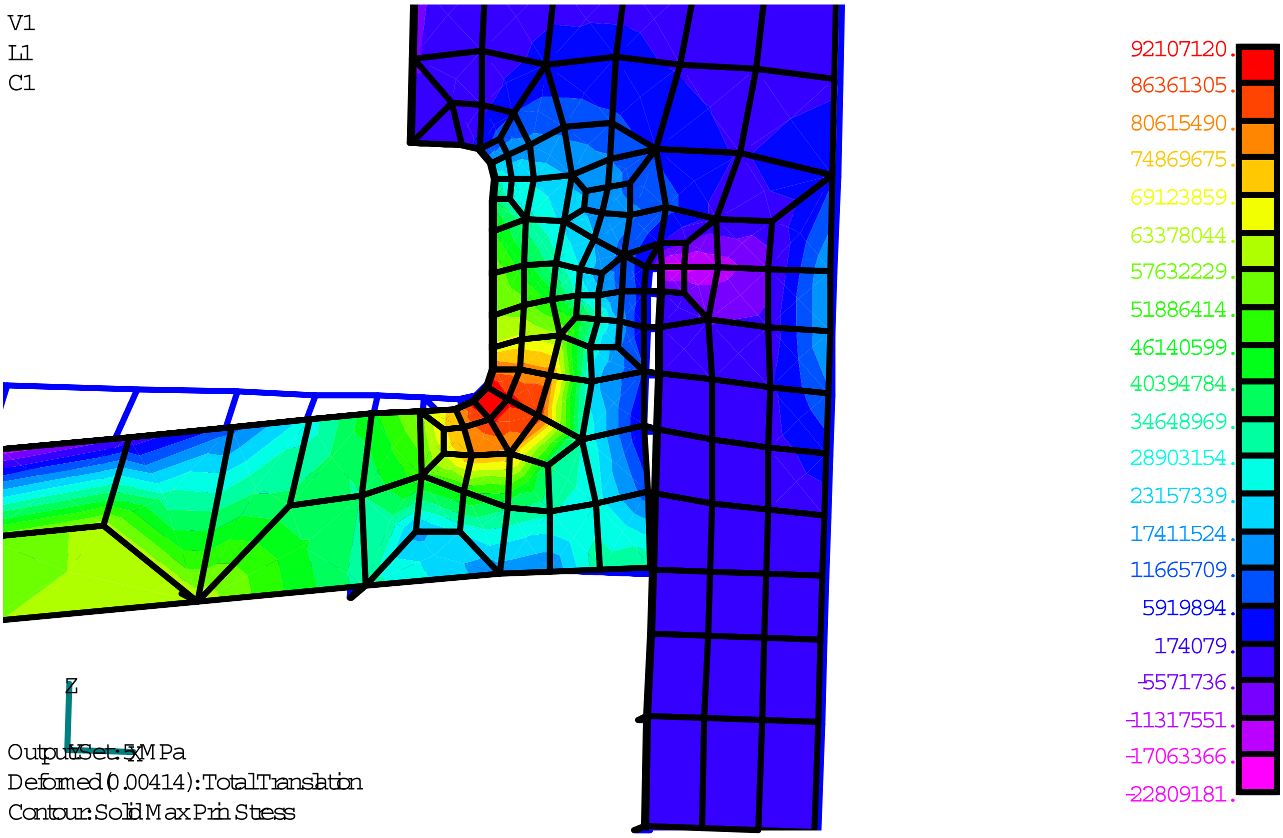


Figure 123 Max principal stresses (Pa). Load case 3: uniform pressure 5 MPa.

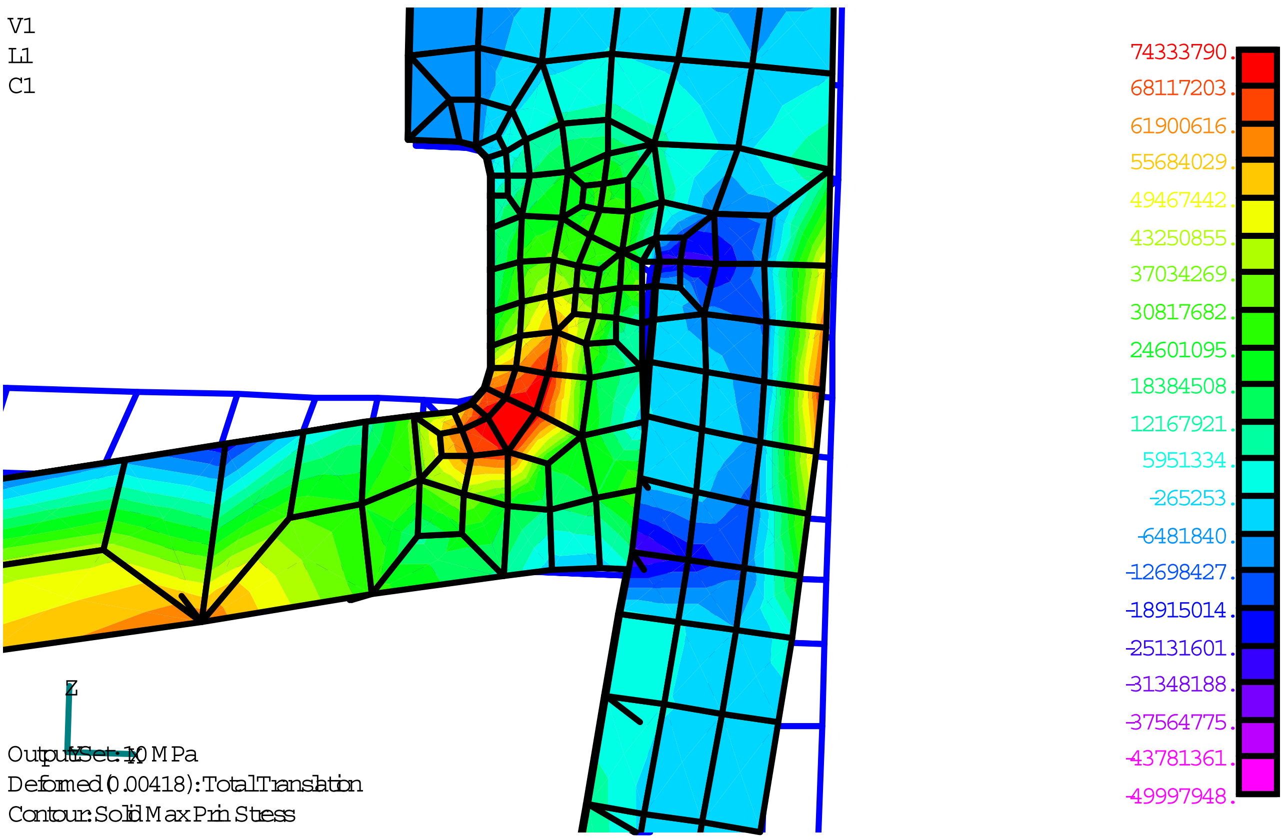


Figure 124 Max principal stresses (Pa). Load case 3: uniform pressure 10 MPa.

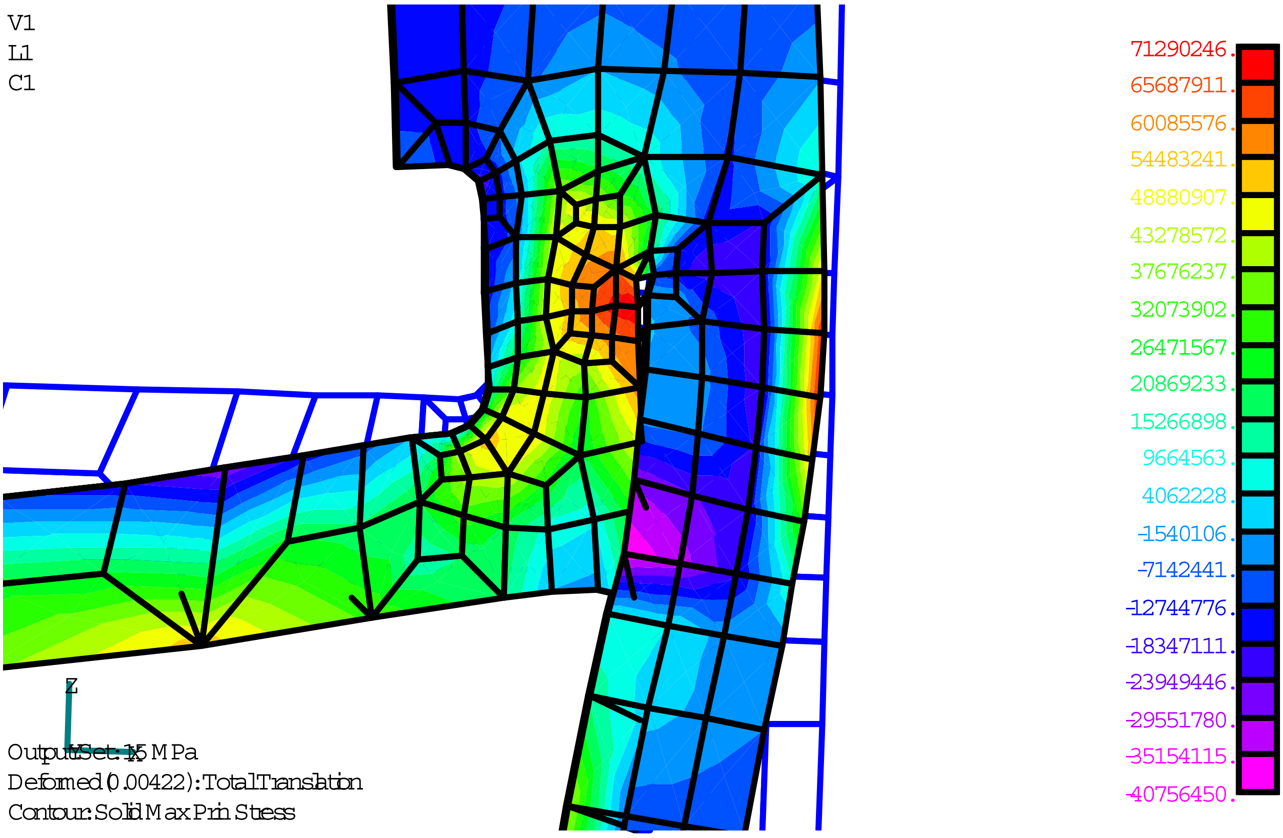


Figure 125 Max principal stresses (Pa). Load case 3: uniform pressure 15 MPa.

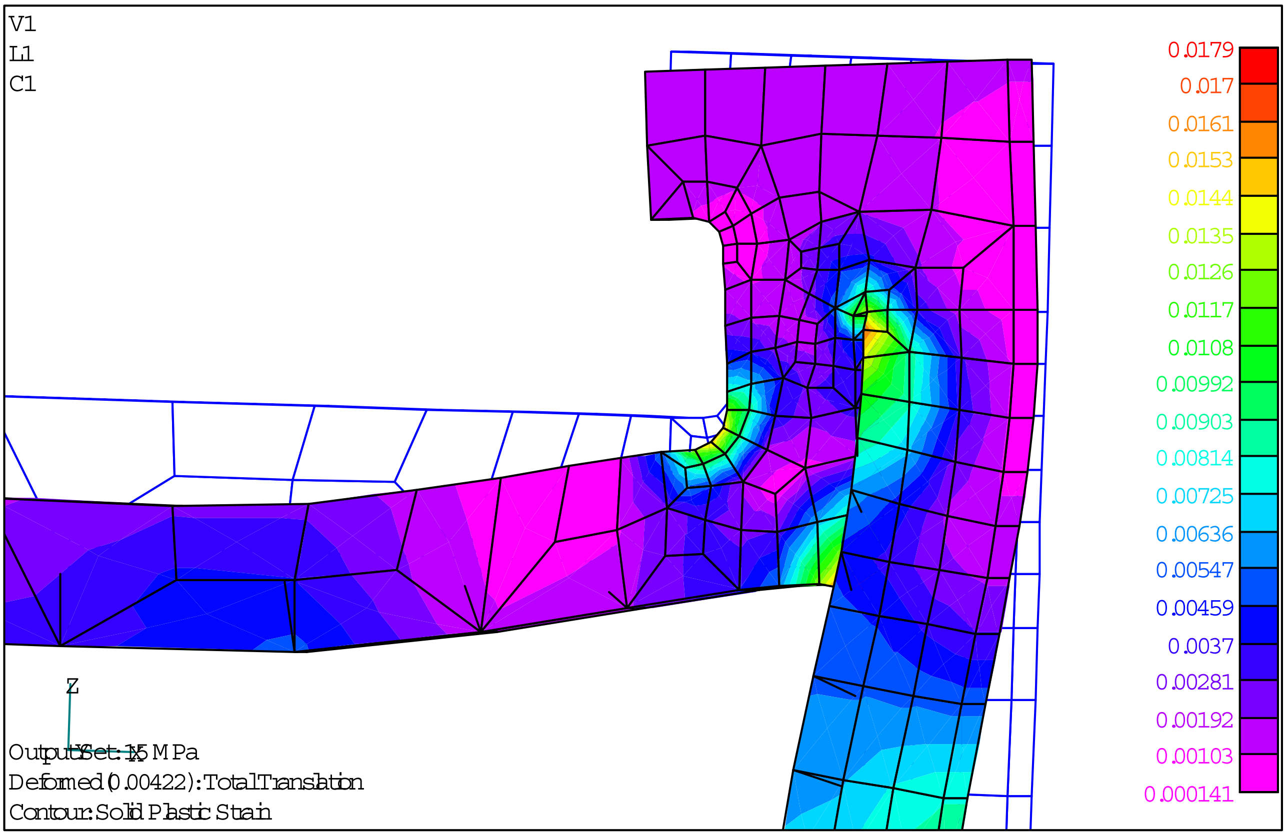


Figure 126 Plastic strain. Load case 3: uniform pressure 15 MPa.

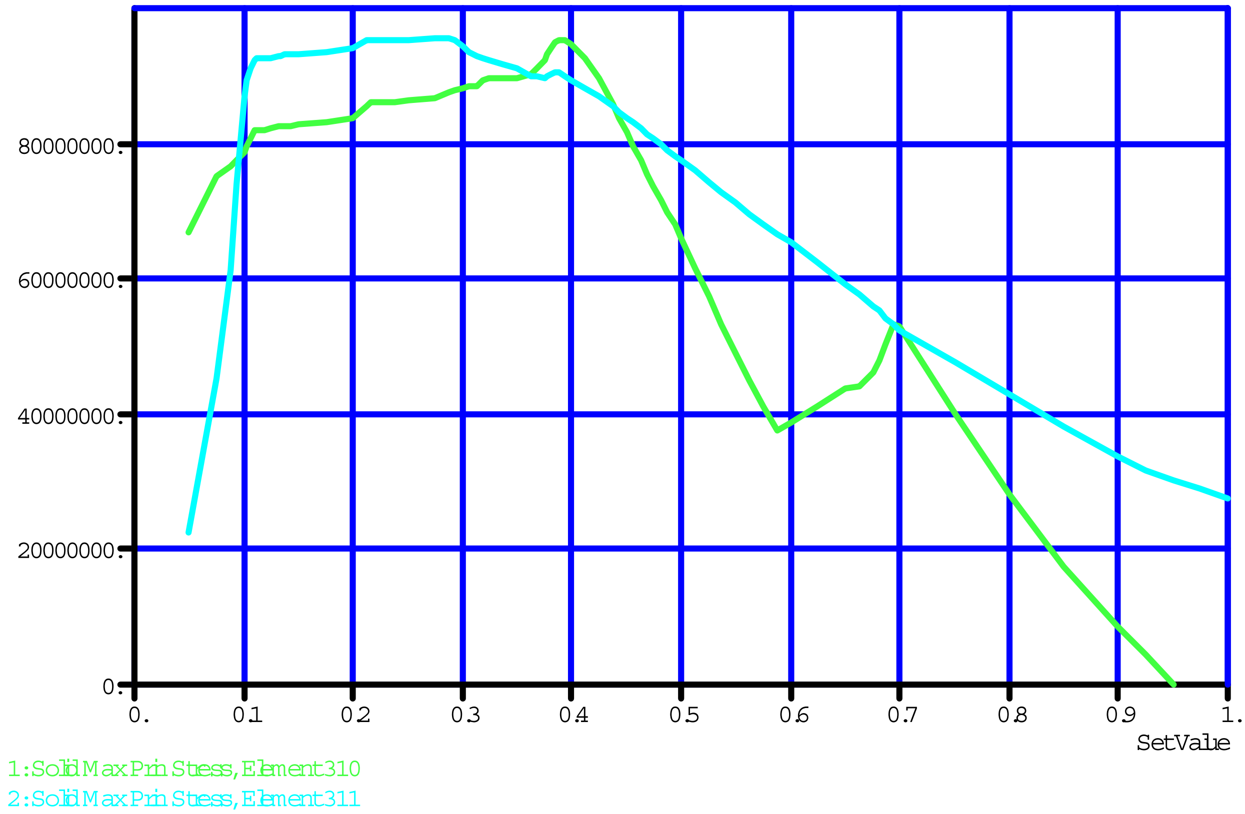


Figure 127 Max principal stresses (Pa) in lid fillet during loading. Load case 3.

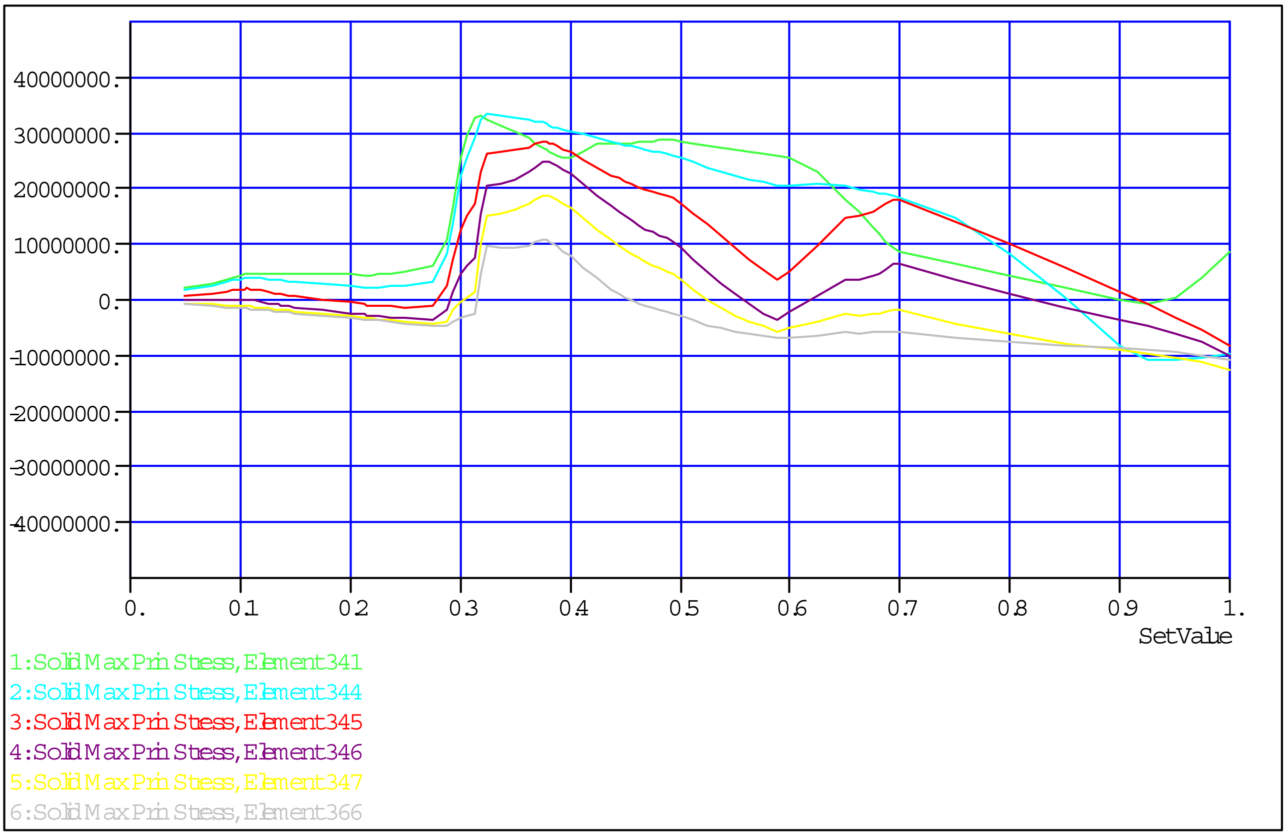


Figure 128 Max principal stresses (Pa) in cylinder during loading. Load case 3.

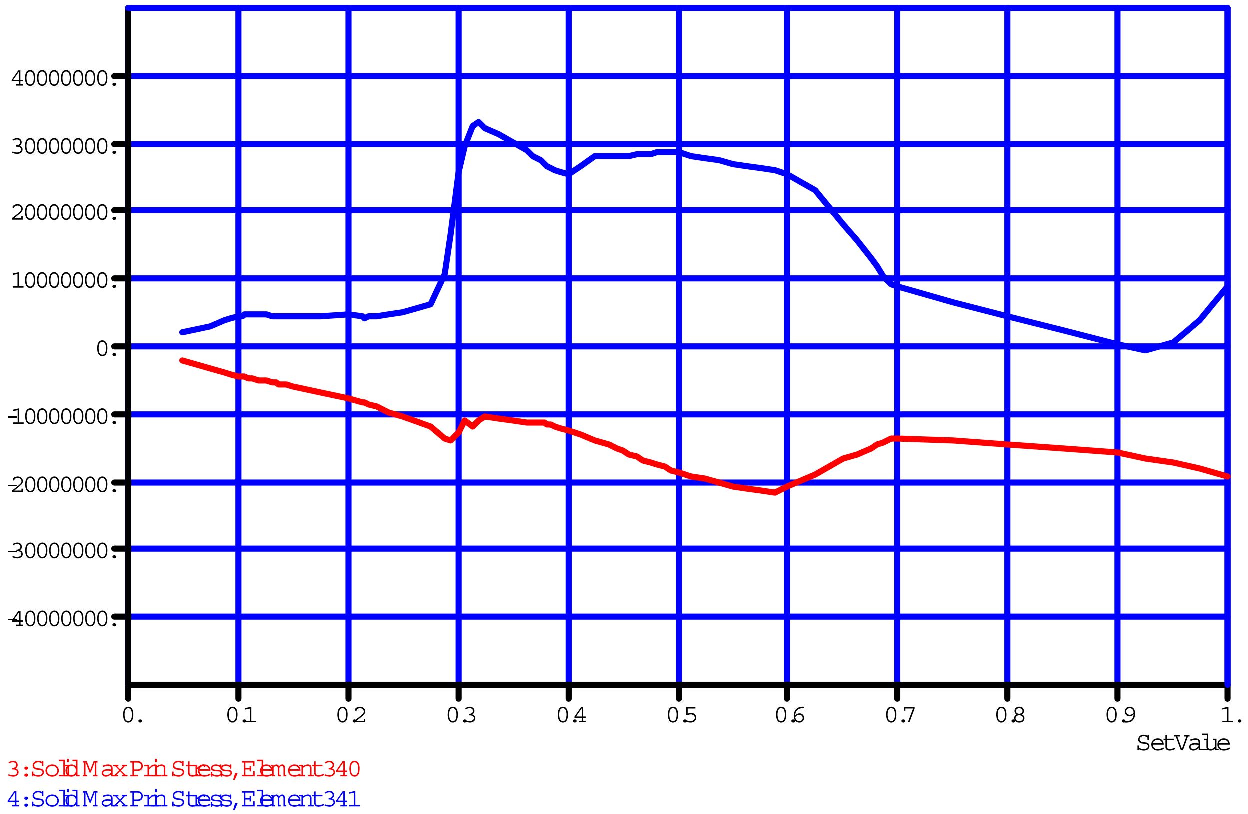


Figure 129   Max principal stresses (Pa) in weld during loading. Load case 3.

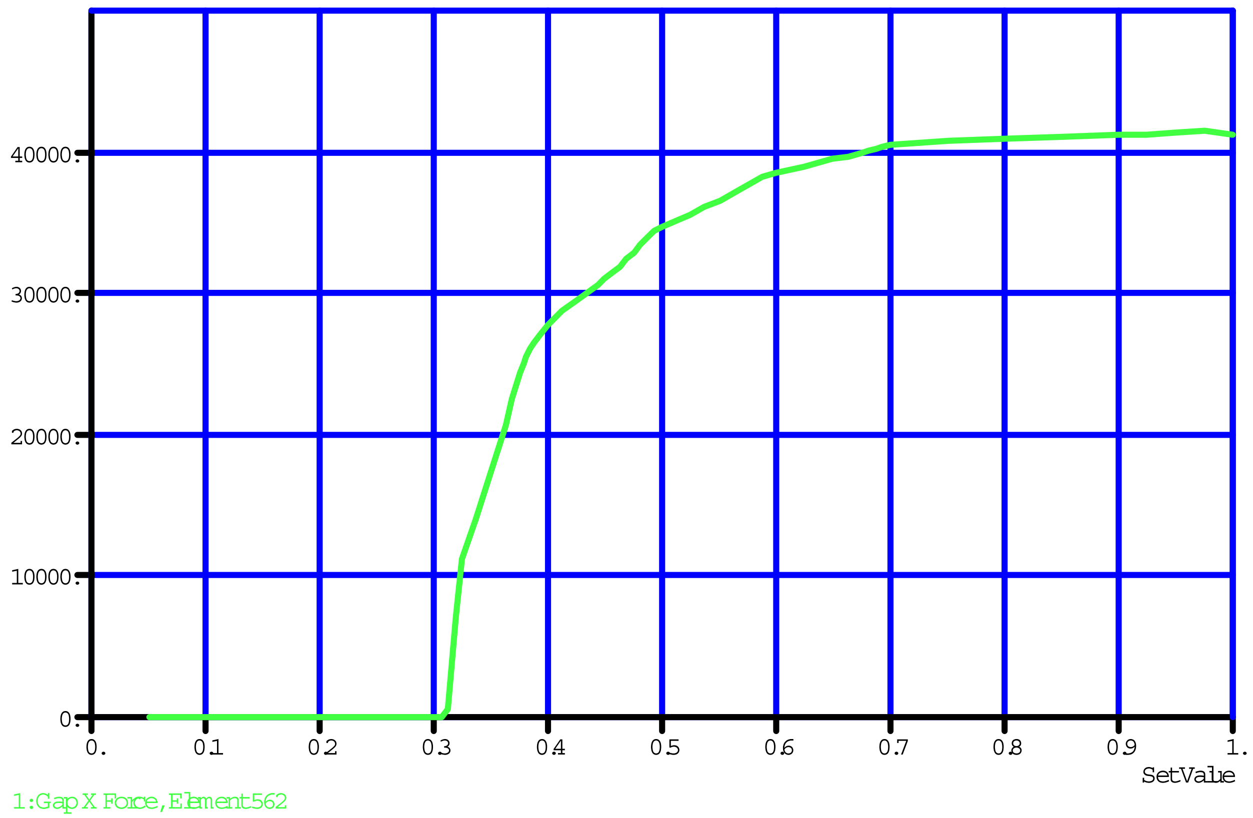


Figure 130   Contact force (N) in element 562 during loading. Load case 3.

I.4 Creep—Axisymmetric load

General
Output set 1 = loading, 2 = 100 years, 3 = 200 years,… 6 = 500 years.

Lid fillet
Element 310 (surface), 311 (10 mm from the surface)

The stress at the surface decreases from initial 120 MPa to 80 MPa after 200 years, and is then kept at a constant level.

Outside of cylinder casing
Element 341, 344 – 347, 366

Maximum tensile stress in element is approximately 5 MPa.

Weld
Compressive stresses except at the surface (element 344).

Strain
Largest creep strain appear in the lid fillet, approximately 4% after 500 years.

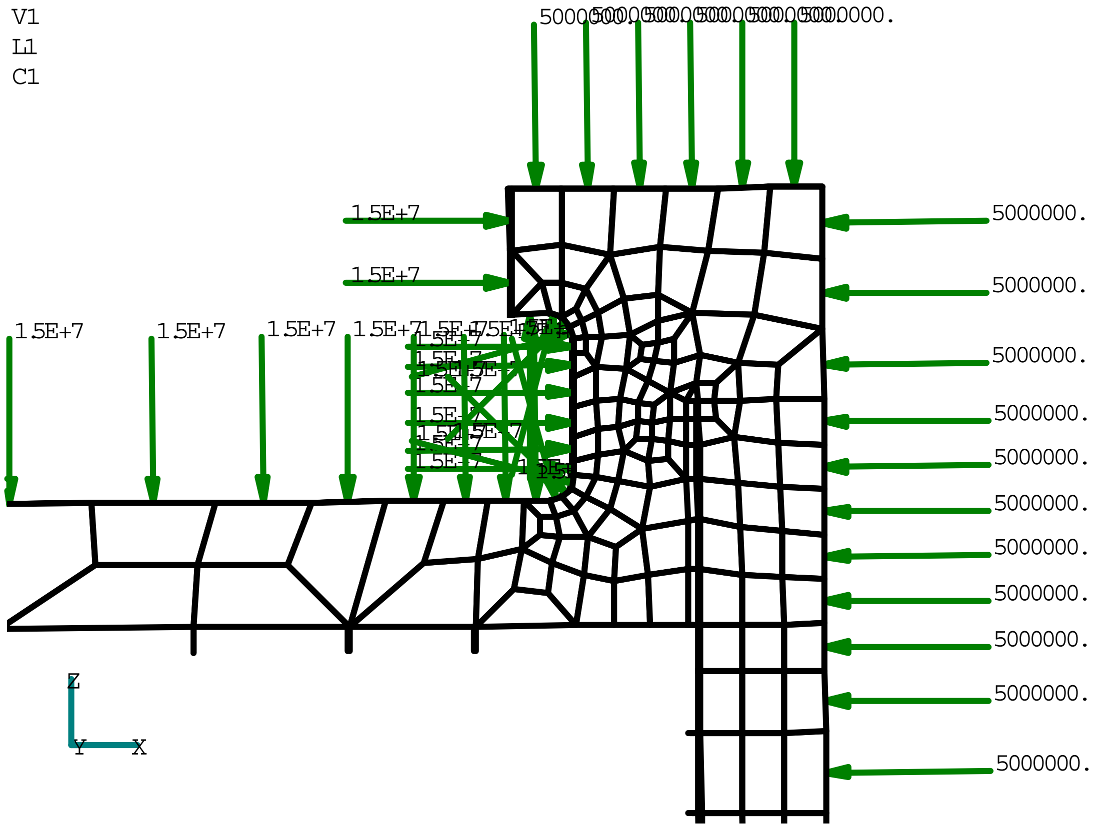


Figure 131 Load case 1.

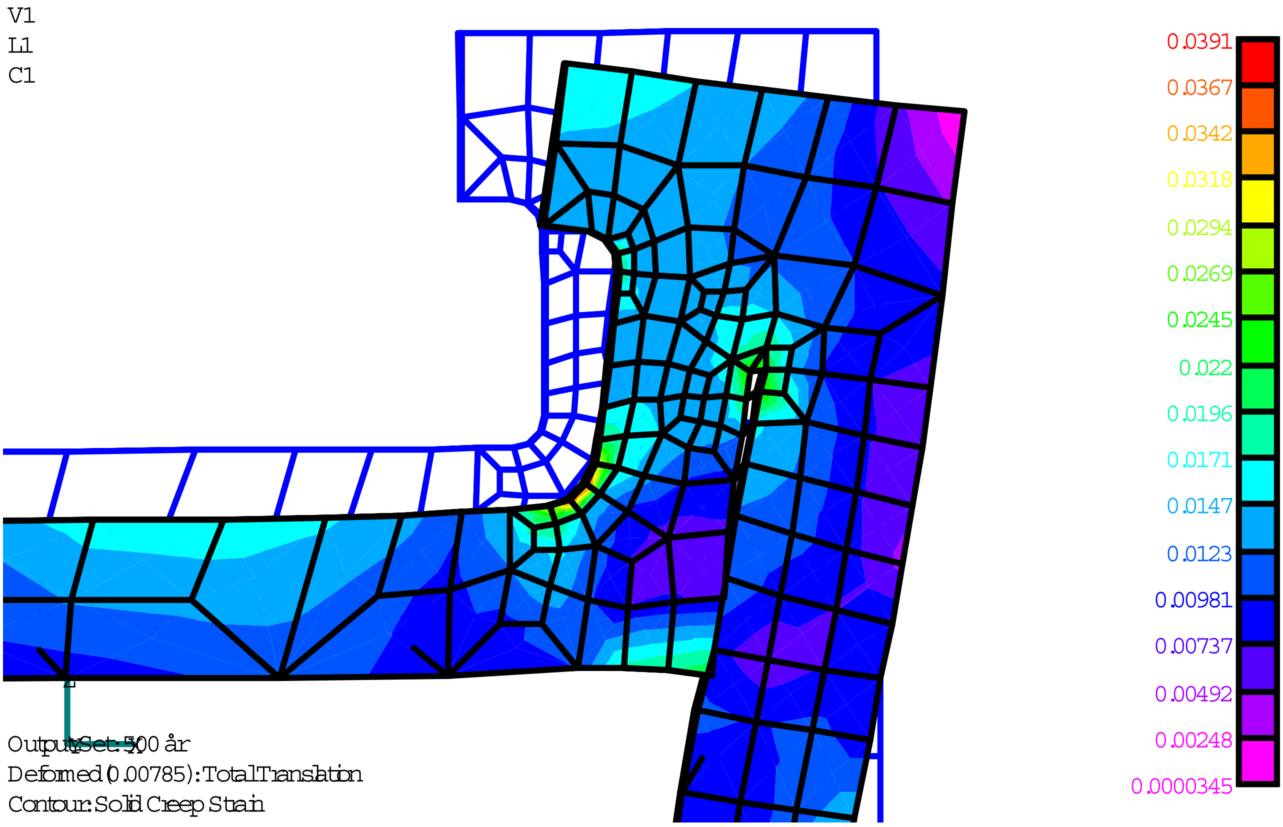


Figure 132 Creep strain. Creep 500 years. Load case 1.

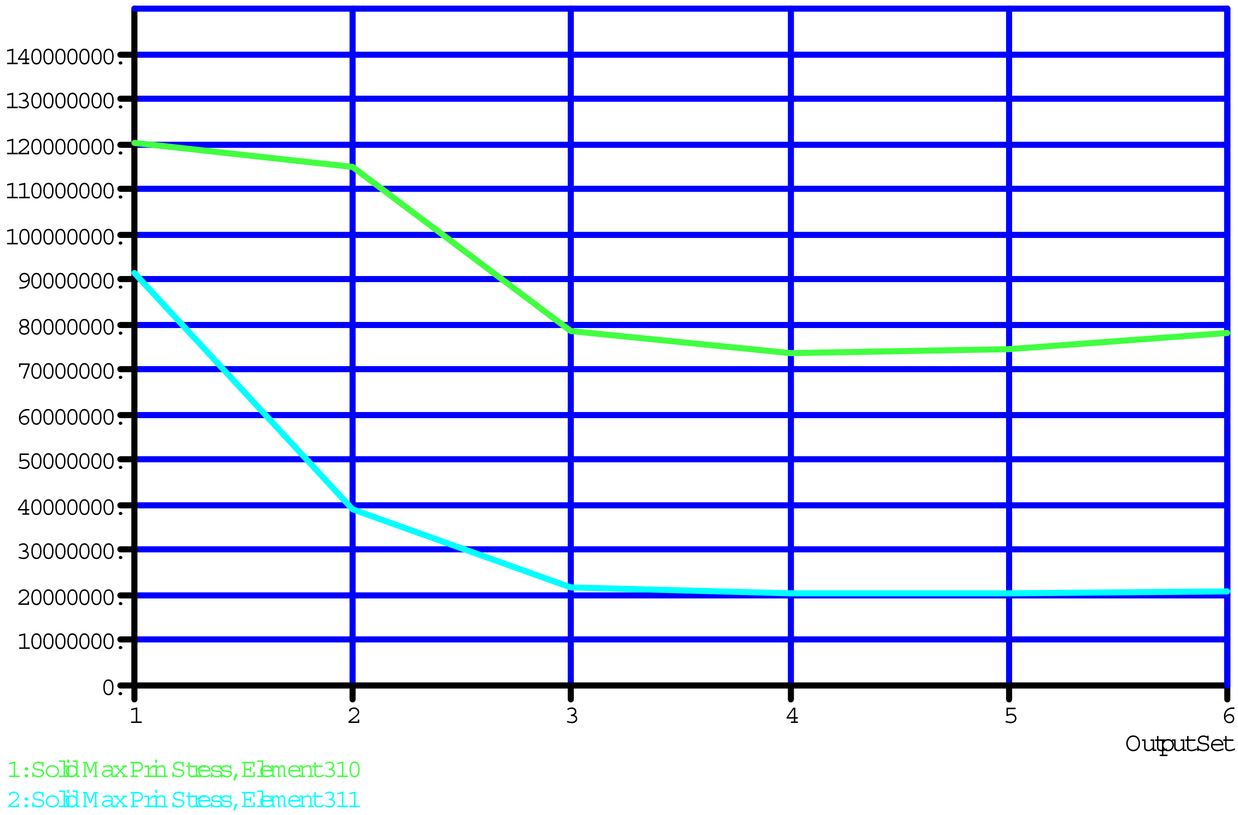


Figure 133 Max principal stresses (Pa) in the lid fillet during creep 500 years. Load case 1.

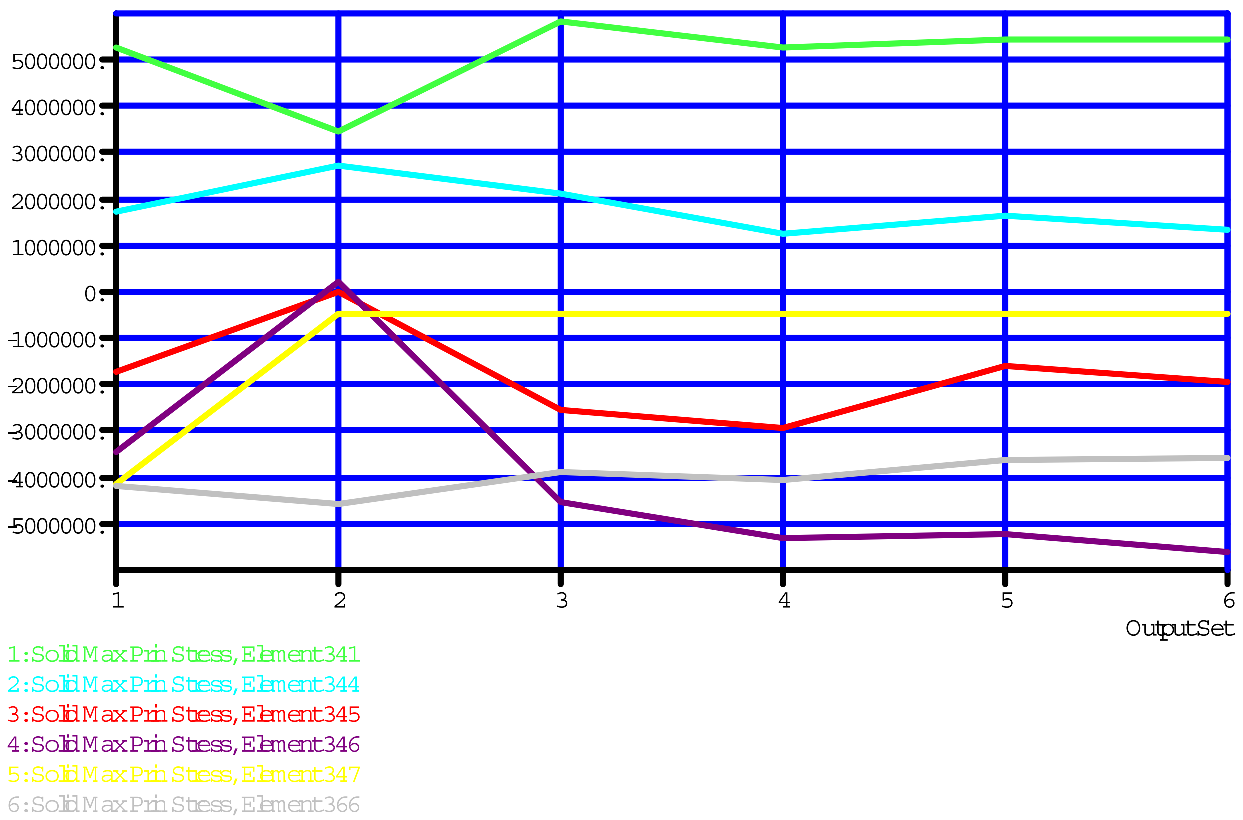


Figure 134 Max principal stresses (Pa) in the cylinder casing during creep 500 years. Load case 1.

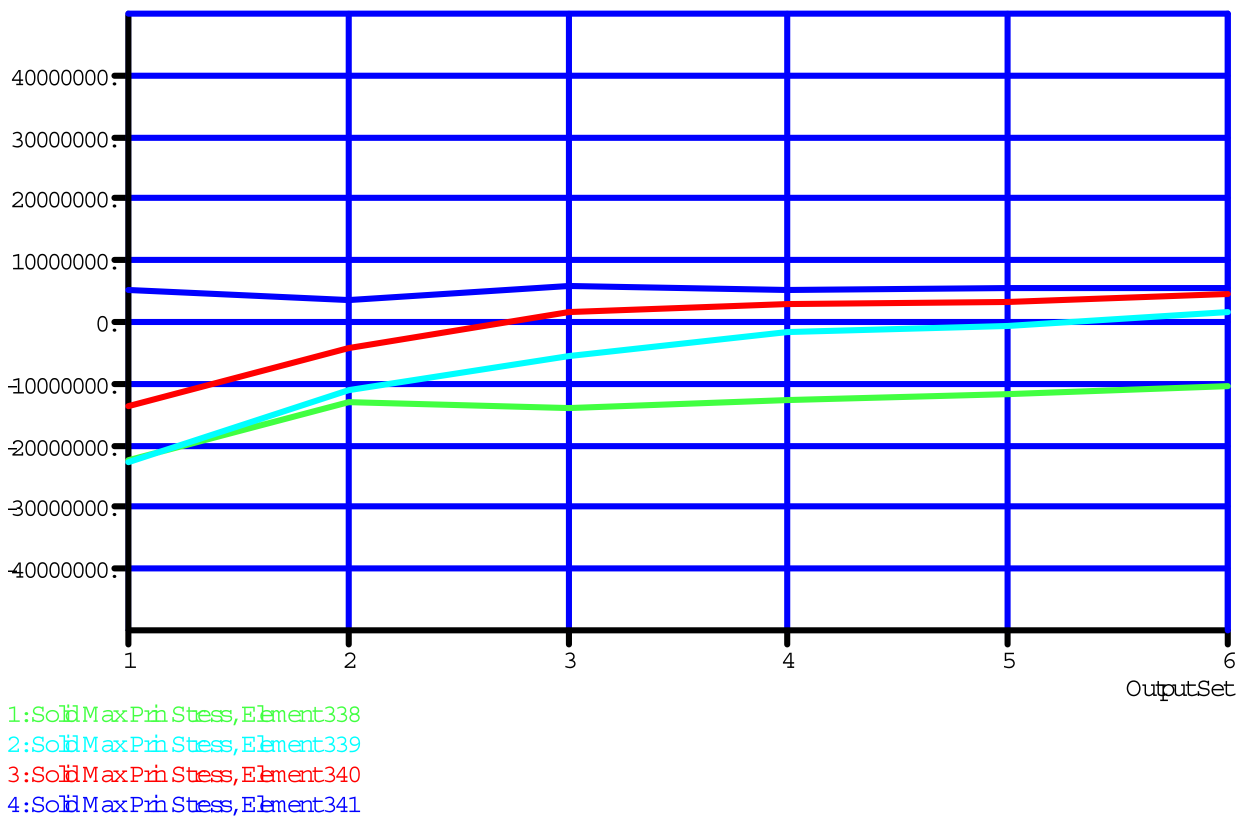


Figure 135 Max principal stresses (Pa) in the weld during creep 500 years. Load case 1.

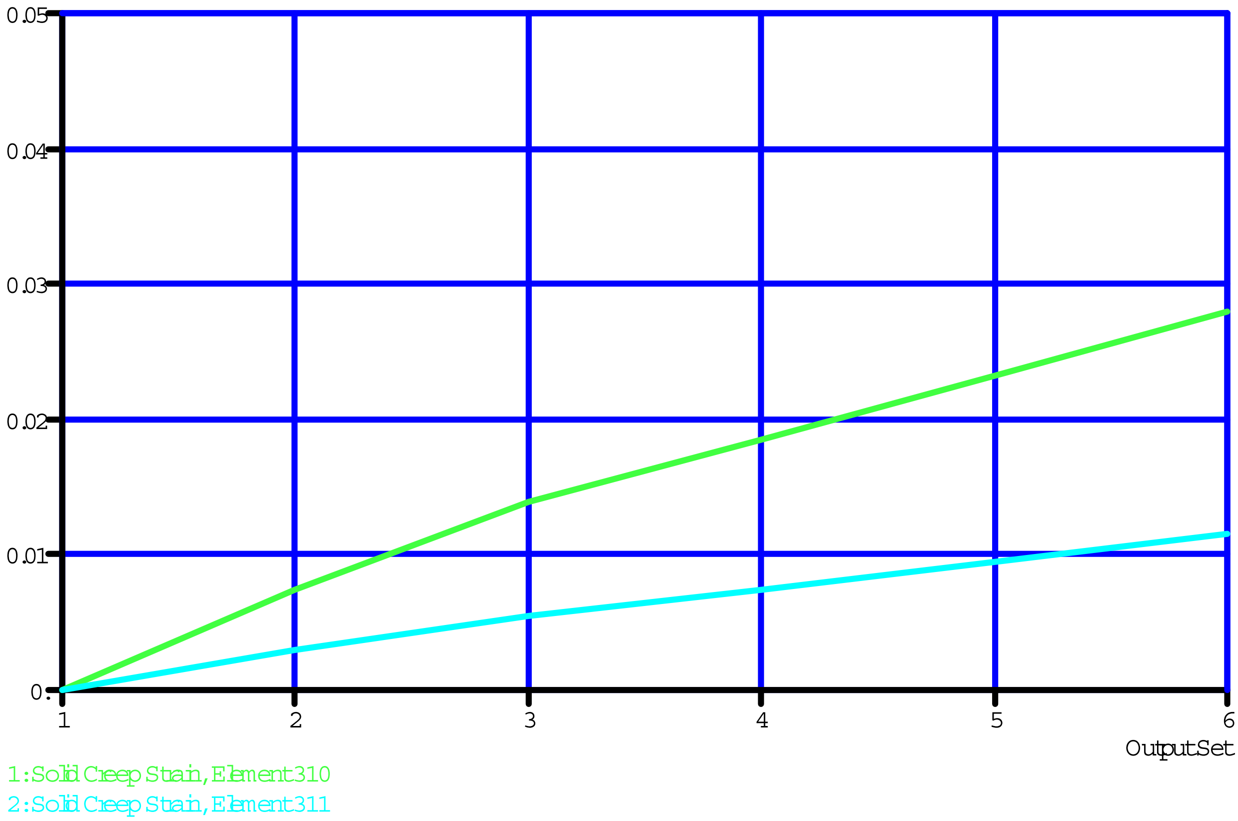


Figure 136 Creep strain in the lid fillet during creep 500 years. Load case 1.

I.5 Load case 4

General
Graphs either have the arguments 0 – 1 or 0 – 20. In both cases, the highest value correspond to the pressure 20 MPa.

Lid fillet
Compressive stresses.

Outer side of casing
Maximum tensile stress is 69 MPa at the level of the lid lower edge.

Weld
Maximum tensile stress is 60 MPa.

Strain
Maximum strain is 2.2 % on the outer side of the cylinder casing at the level of the lid lower edge.

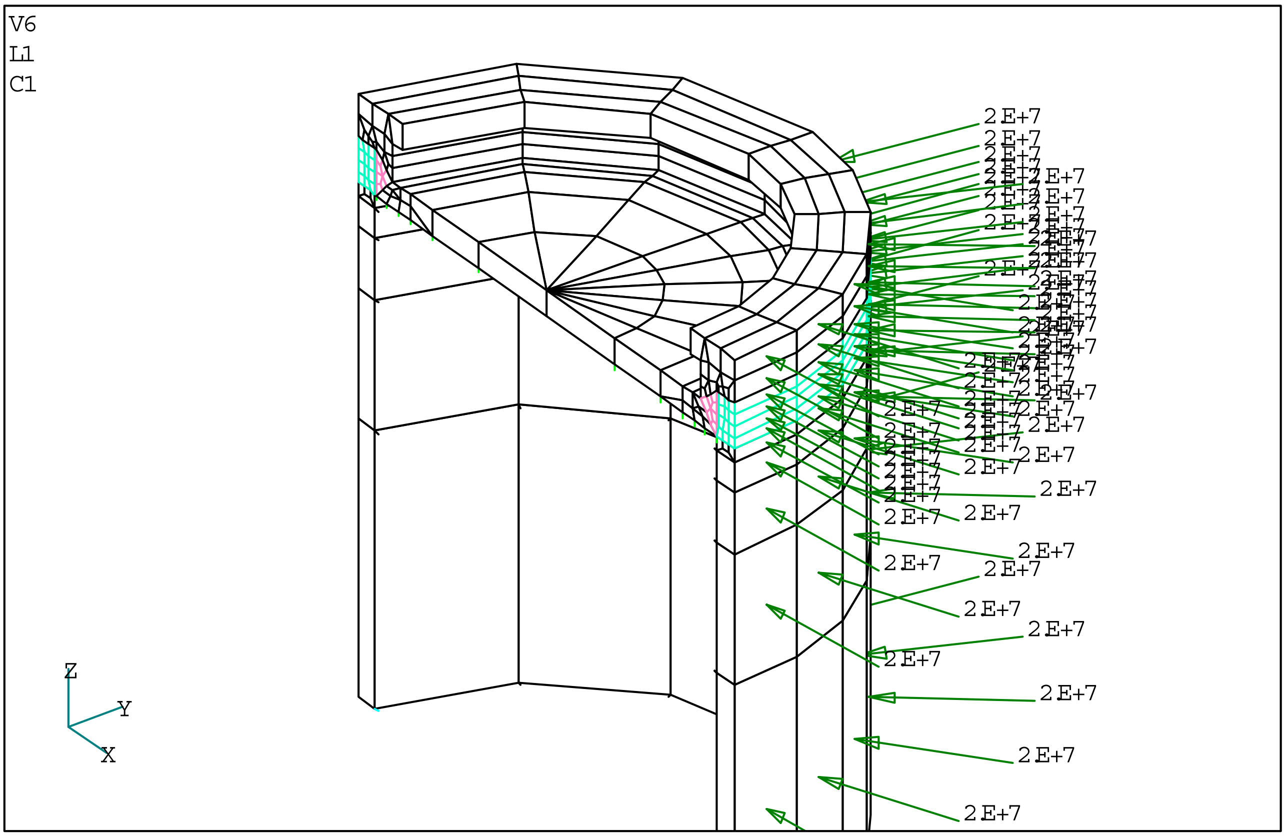


Figure 137 Three-dimensional finite element model. Load case 4: side load 20 MPa.

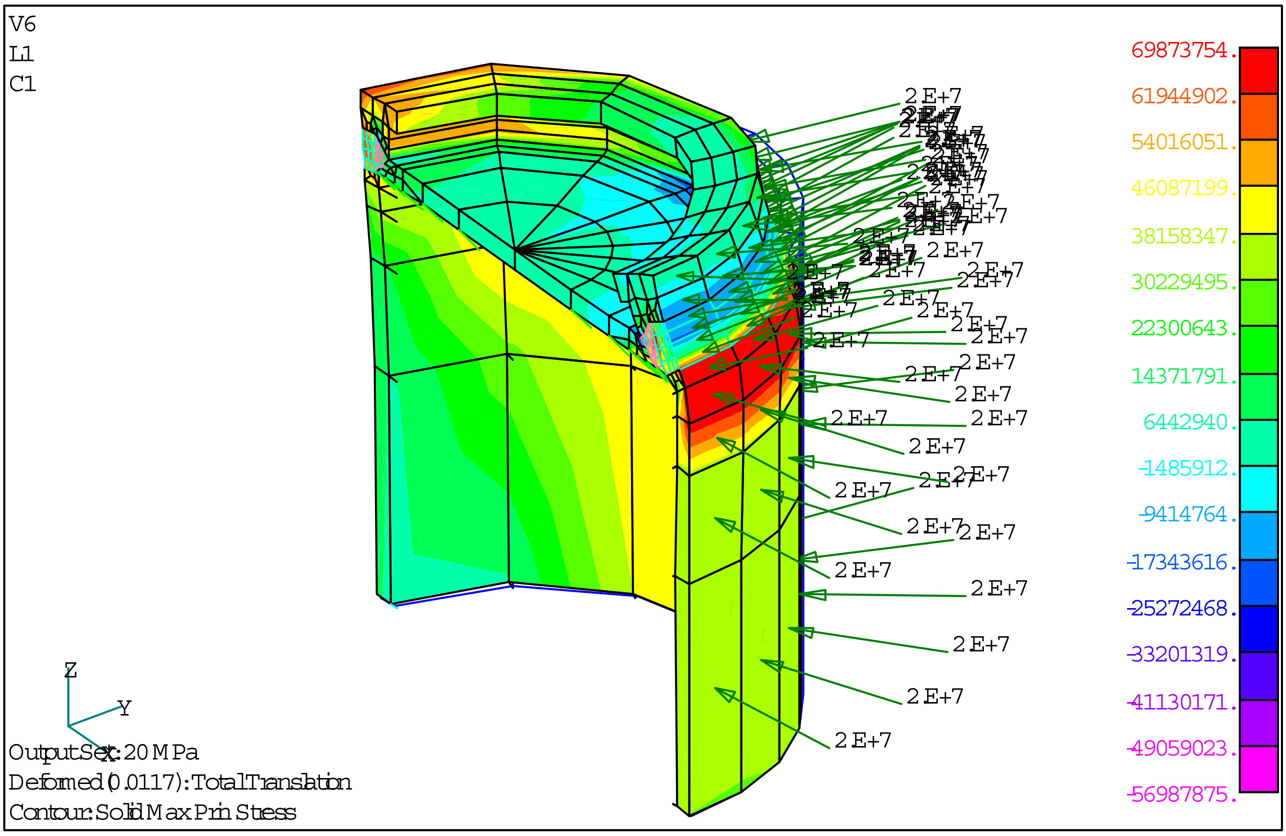


Figure 138 Maximum principal stresses (Pa). Load case 4: side load 20 MPa.

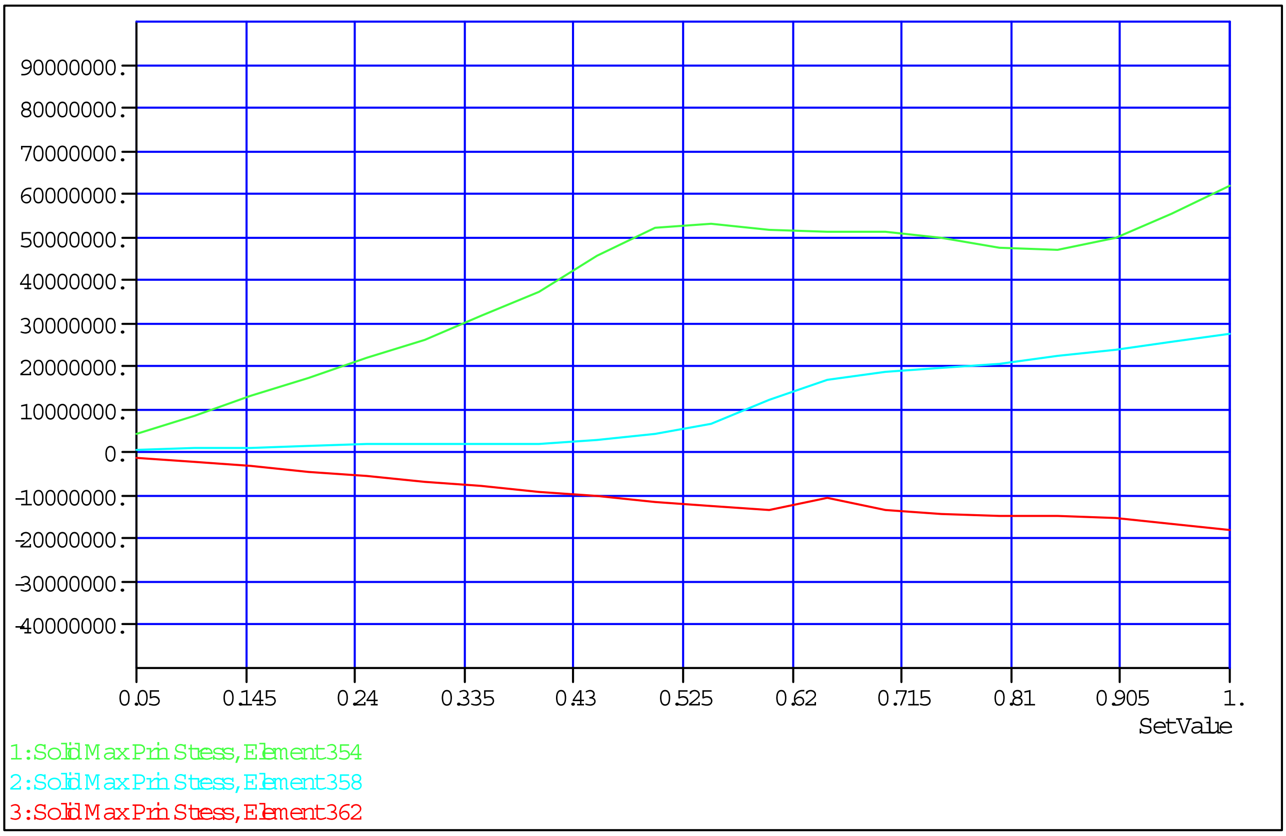


Figure 139Maximum principal stresses (Pa) in weld during loading. Load case 4. (Set value 1 = 20 MPa.)

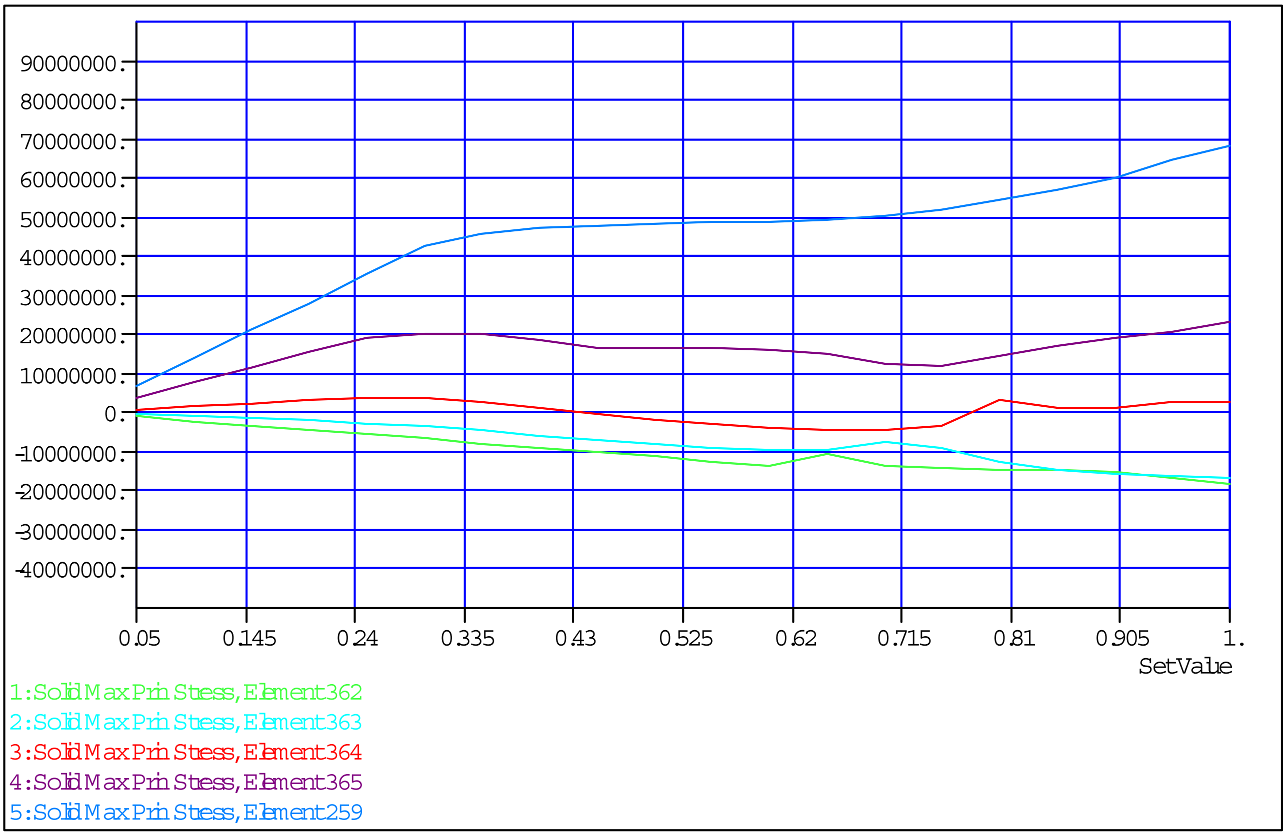


Figure 140 Maximum principal stresses (Pa) along cylinder between weld and lid lower edge during loading. Load case 4. (Set value 1 = 20 MPa.)

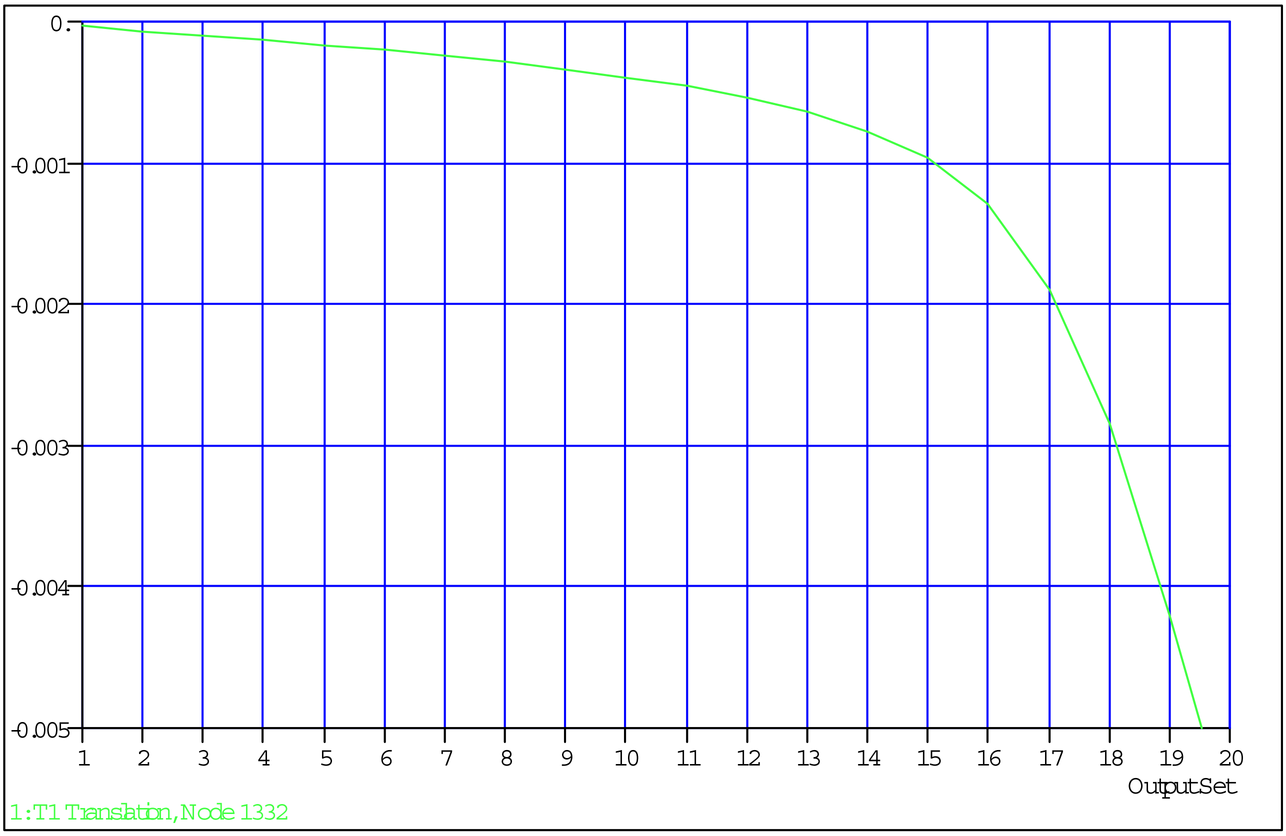


Figure 141 Radial translation (m) of the lid centre point. Load case 4. (Output set = side pressure, MPa.)

I.6 Creep—Side load 10 MPa

General
Set value 1 correspond to *t*=0 years, set value 11 correspond to *t*=1000 years.

Outer side of casing
Maximum principal stress increases to approximately 80 MPa after 100 years and relaxes to 60 MPa after 1000 years.

Weld
Maximum tensile stress increases to 72 MPa in the weld root after 1000 years.

Strain
Maximum creep strain is 7.4% on the outside of the cylinder.

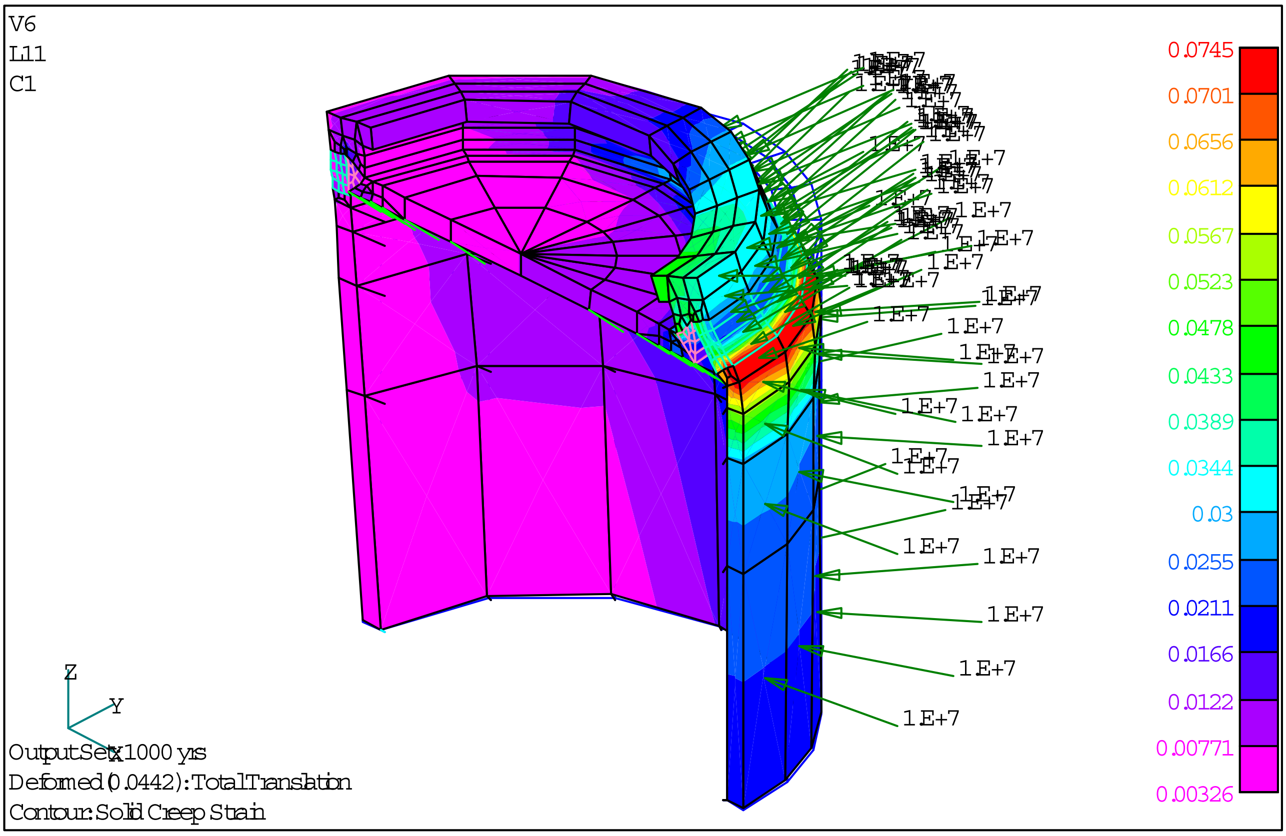


Figure 142   Creep strain after 1000 years. Load case 4: side load 10 MPa.

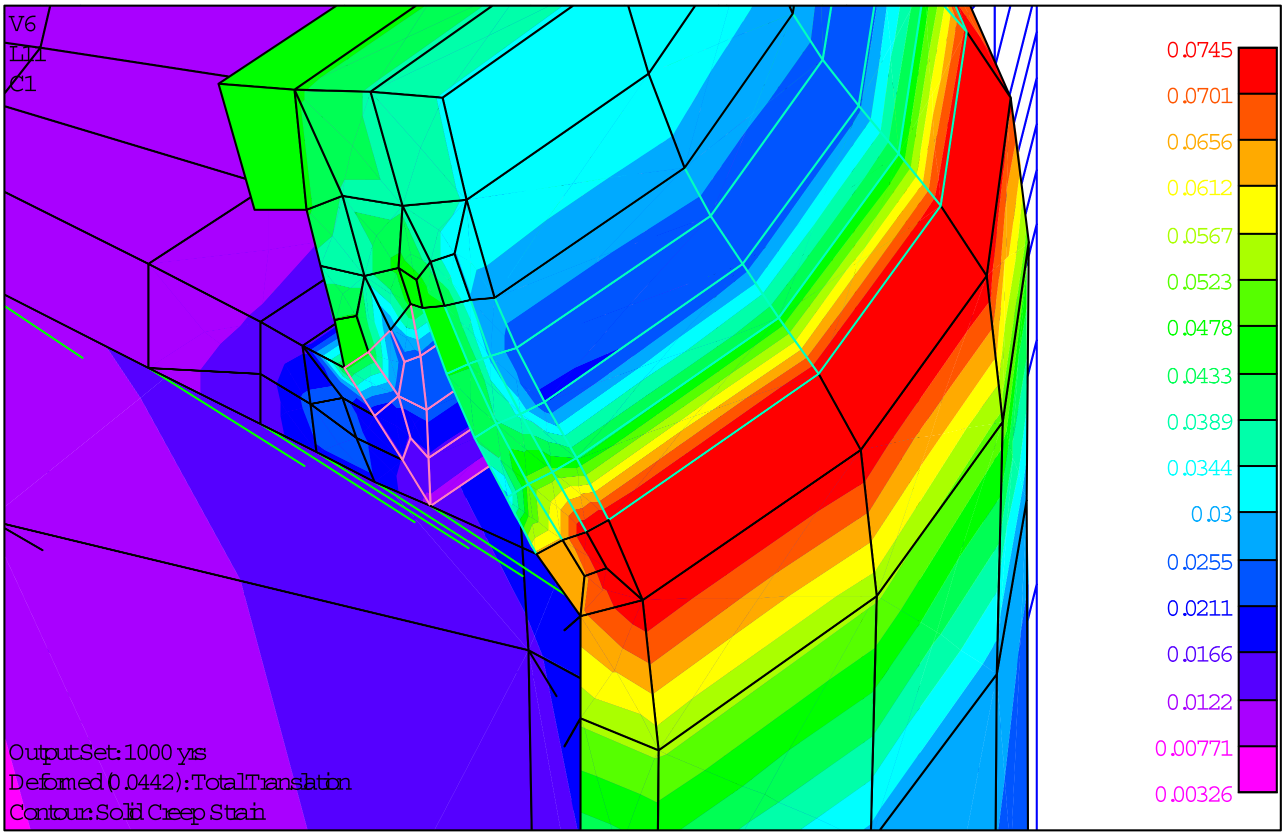
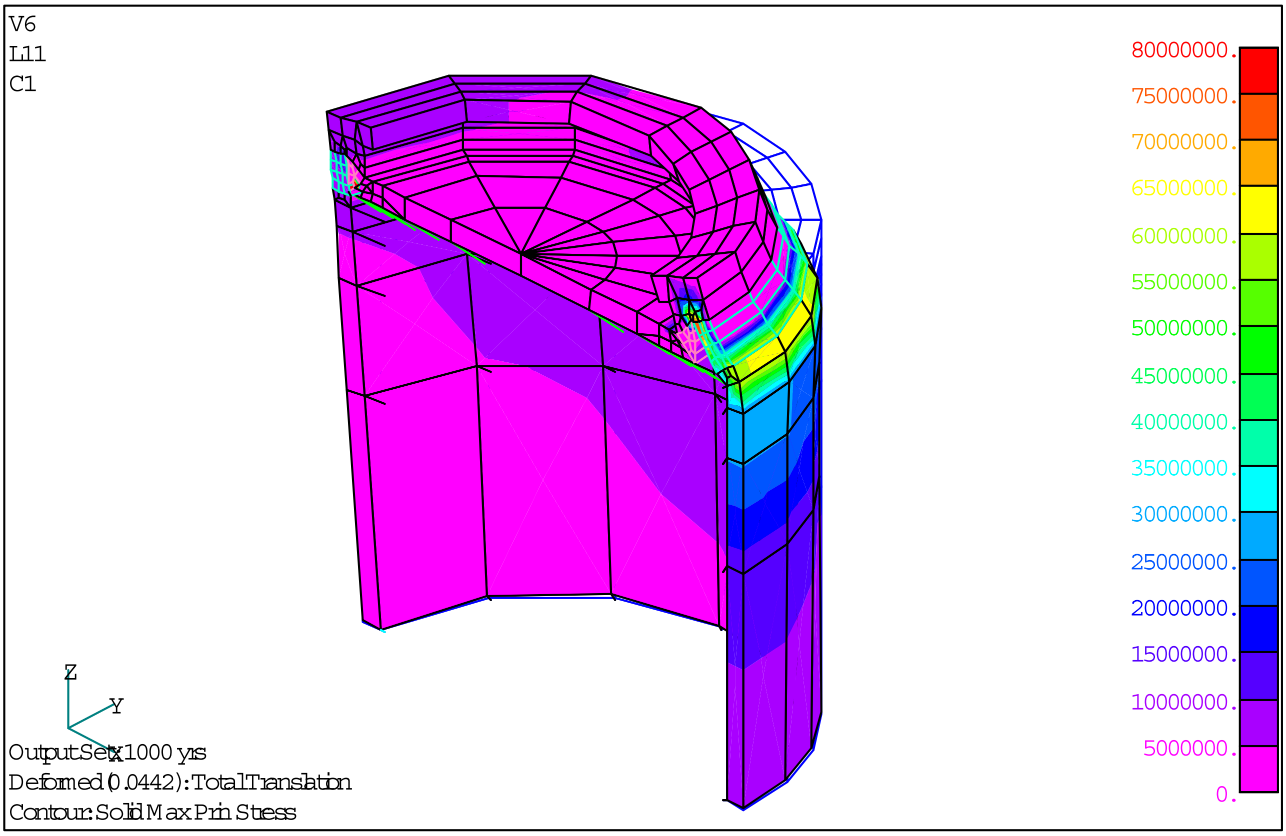


Figure 143   Creep strain after 1000 years. Load case 4: side load 10 MPa.



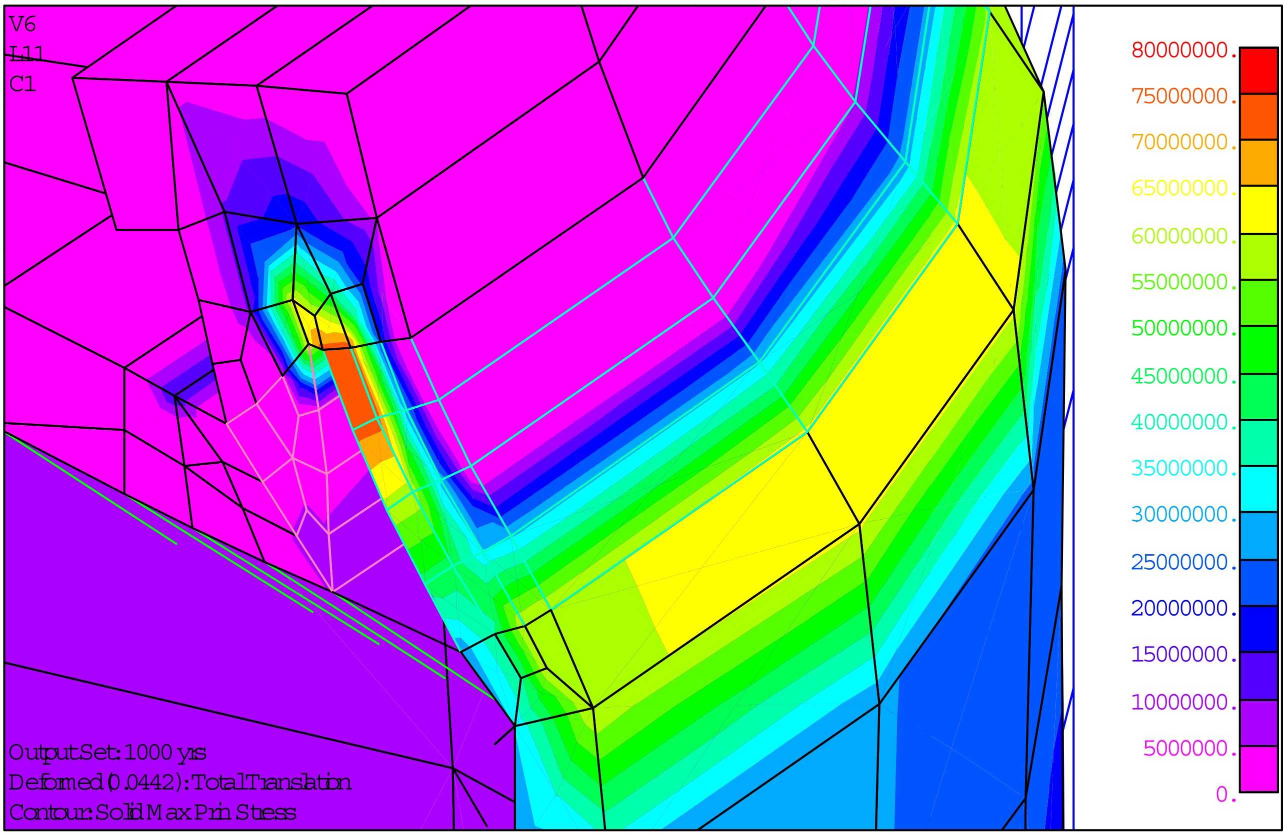


Figure 144 Maximum principal stress (Pa) after 1000 years. Approximately 60 MPa on the outside of the cylinder and maximum 80 MPa on the inside of the cylinder by the weld. Load case 4: side load 10 MPa.

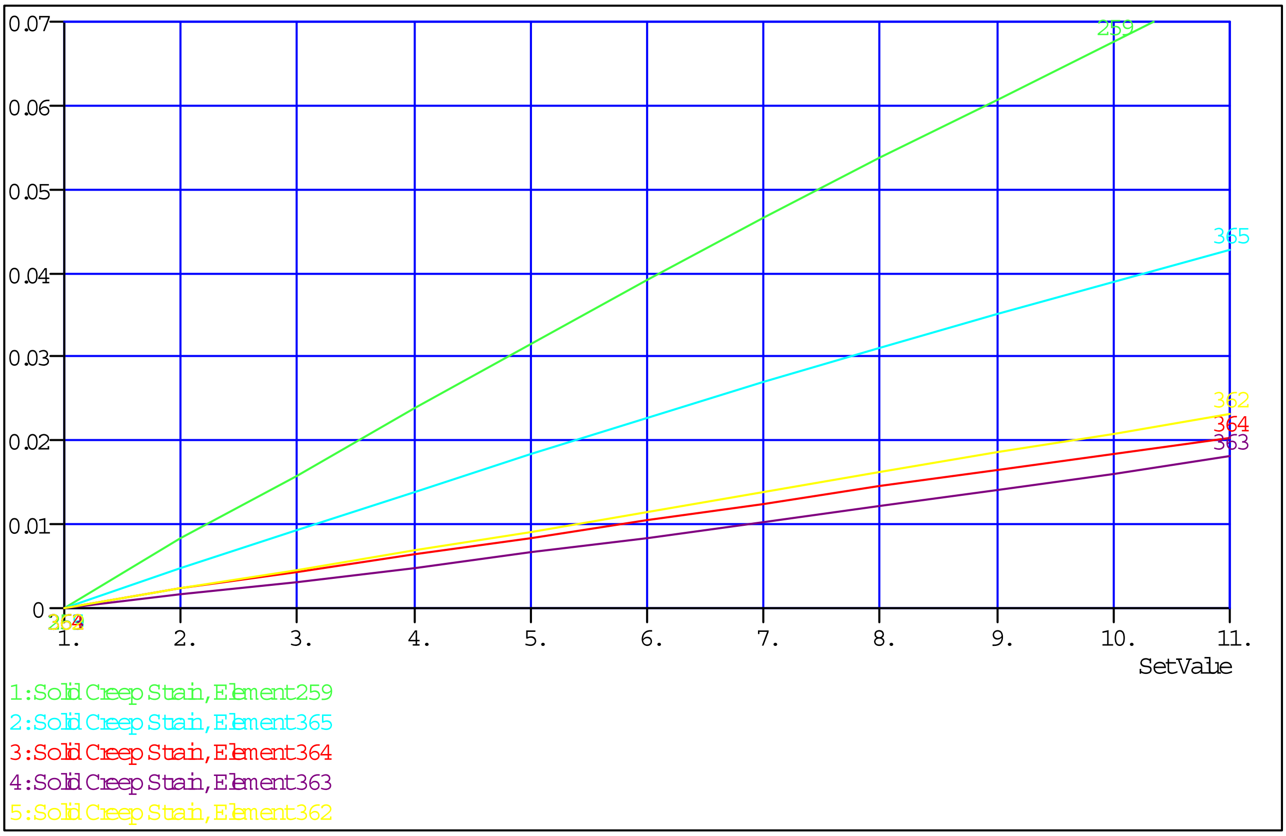


Figure 145 Creep strain on the outer side of the cylinder in a region between the weld and the lower edge of the lid during loading. Load case 4: side load 10 MPa. (Output set 1 = 0 year, 11 = 1000 years.)

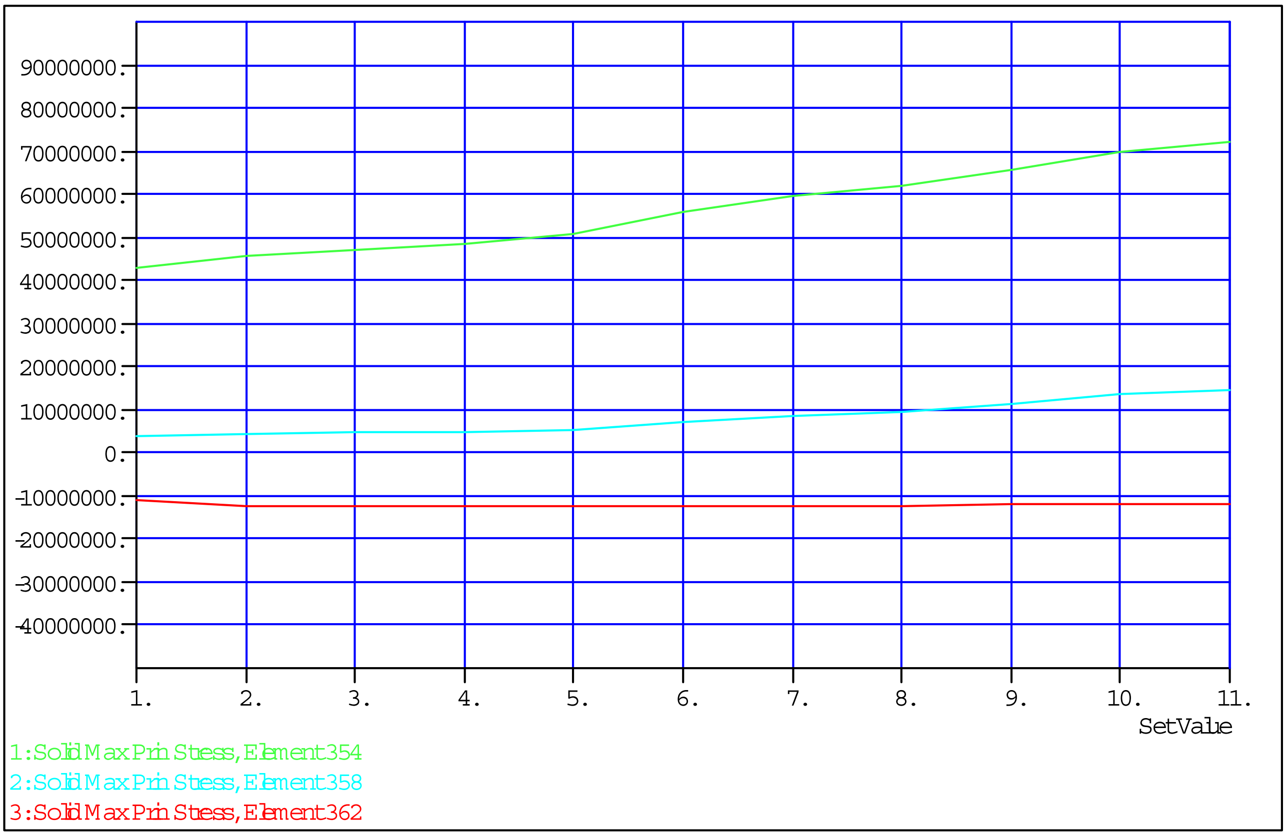


Figure 146 Maximum principal stresses (Pa) in weld during loading. Load case 4: side load 10 MPa. (Output set 1 = 0 year, 11 = 1000 years.)

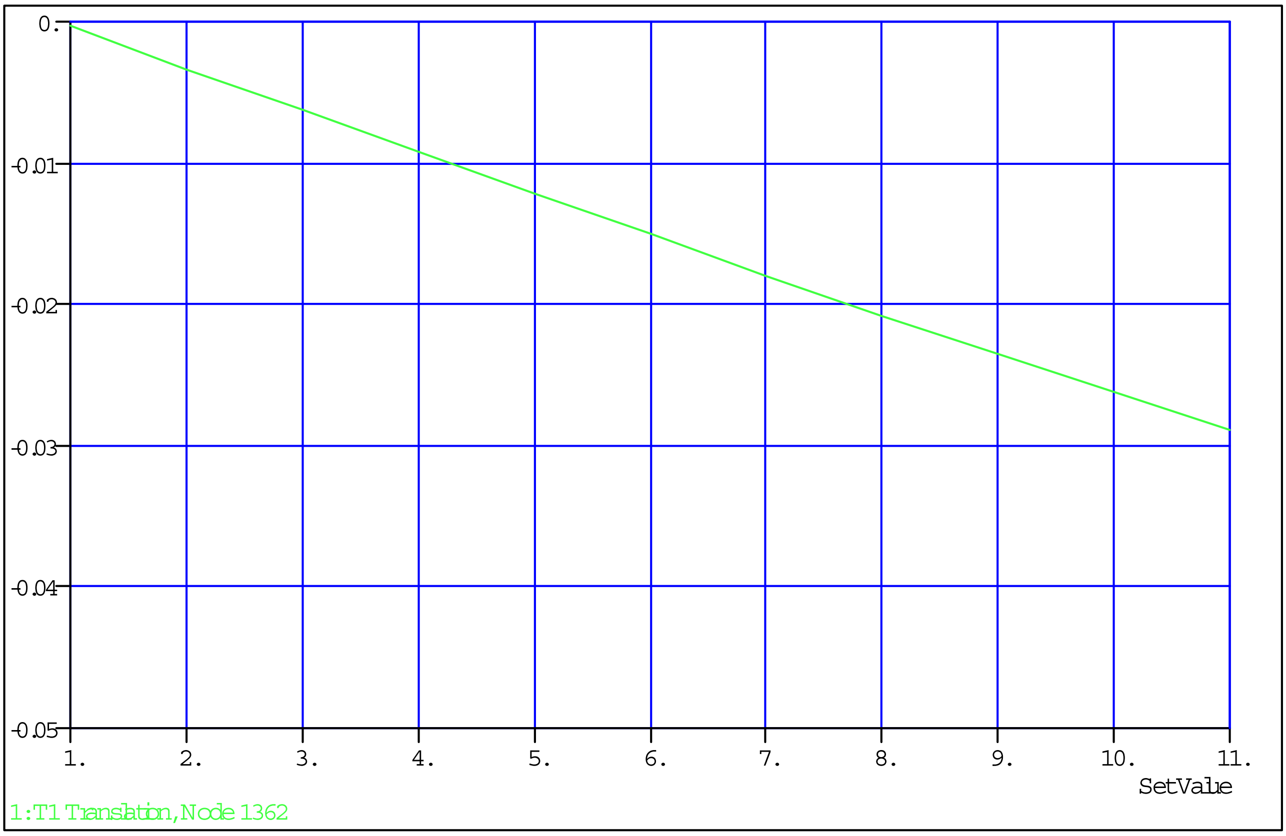


Figure 147 Displacement (m) of the lid centre point. Load case 4: side load 10 MPa. (Output set 1 = 0 year, 11 = 1000 years.)