

# INFLUENCE OF AXIAL LOADING ON THE STRESS REDISTRIBUTION IN A WELD UNDER CREEP CONDITIONS

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## 1. Introduction

The safety and reliability assessment of structures exposed to high temperature, for example steam pipelines, turbines or other power plant components, represents difficult problem. Usually, the systems operating under the creep conditions are large and consist of many critical points, which can affect lifetime of structure. For example a typical steam pipeline contains tens or hundreds of elbows, T-pieces, Y-pieces and huge number of welds.

This paper concerns on an analysis of one critical point of piping, namely a circumferential weld. Generally, welds represent a stress concentrator. Due to geometrical changes, i.e. shape of the weld, an increase of stress components appears in its vicinity. This effect can be described by the stress concentration factor.

From the metallographic point of view, a weldment is not a homogenous metal. It can be split into a number of regions. These are the parent metal, weld metal and heat affected zone (HAZ). Every of these parts has different structure and it is reasonable to expect that their creep behaviour and resistance will differ. The difference in the creep strain rate could influence strongly the stress state in vicinity of the weld. Thus the process of the stress redistribution, which is characteristic for creeping structure, will be differ for such “composed” weldment than for a homogenous structure.

Presented study concerns on stress redistribution calculation in vicinity of a weld between a header and a pipe. Generally, this task is not possible to solve analytically. There are some analytical solutions (for example [1]), but for simplified shape of the weldment only. With respecting complex geometry of the weld and connected parts, such investigation is possible only with help of the numerical methods. In this case, the finite element method was used and following issues were modelled:

- Different creep behaviour of the parent and weld metal.
- Different axial loading.
- Thickness reduction on the border header-weld.

## 2. Constitutive law

For the solution of the problem, the complex creep model was used according [2]. This model describes all phases of creep – primary, secondary and tertiary phase. In uniaxial case, the creep strain  $\varepsilon_c$  is expressed by:

$$\varepsilon_c(t | \sigma, T) = \varepsilon_0 \left( \frac{\varepsilon_m}{\varepsilon_0} \right)^{g[\pi(t)]} \quad (1)$$

where  $t$  is time,  $\sigma$  is stress and  $T$  is temperature. Quantities  $\varepsilon_0$  and  $\varepsilon_m$  represent initial and limit strains, respectively. The limit strain  $\varepsilon_m$  is expressed by equation:

$$\varepsilon_m = \exp \left[ M_1 + M_2 \tanh \left[ \frac{\ln(t_r) - M_3 - M_4 T}{M_5} \right] \right] + \frac{\sigma}{E(T)} 10^2 \quad (3)$$

where Young's modulus  $E(T)$  as a function of temperature  $T$  is given by:

$$E(T) = E_1 + E_2 \exp \left( \frac{E_3}{T} \right) \quad (4)$$

Function  $g[\pi(t)]$  is so-called damage function expressed by:

$$g[\pi(t)] = [\pi(t)]^N \left[ \frac{1 + \exp\{-2[\pi(t)]^K\}}{1 + \exp(-2)} \right]^M \quad (5)$$

Damage  $\pi(t)$  is defined by ratio  $t/t_r$  where the time to the rupture  $t_r$  can be determined from equation:

$$\log(t_r) = A_1 + A_2 \log \left| \frac{1}{T} - \frac{1}{A_5} \right| + A_3 \log \left| \frac{1}{T} - \frac{1}{A_5} \right| \log[\sinh(A_6 \sigma T)] + A_4 [\sinh(A_6 \sigma T)] \quad (6)$$

According the above described model, each material needs 17 constants ( $A_1 - A_6$ ,  $M_1 - M_5$ ,  $E_1 - E_3$ ,  $N$ ,  $M$ ,  $K$ ). As mentioned above, different creep behaviour of the parent and weld material was modelled. There was assumed that the creep resistance of the weld metal is higher than the resistance of parent metal of the header and pipe. In addition, a difference between the material of header and material of pipe was taken into account. The modelled case presented situation with low creep resistant header material, so its creep resistance was the lowest one. Creep curves for the materials, which were used in the analyses, are shown in Fig. 1.

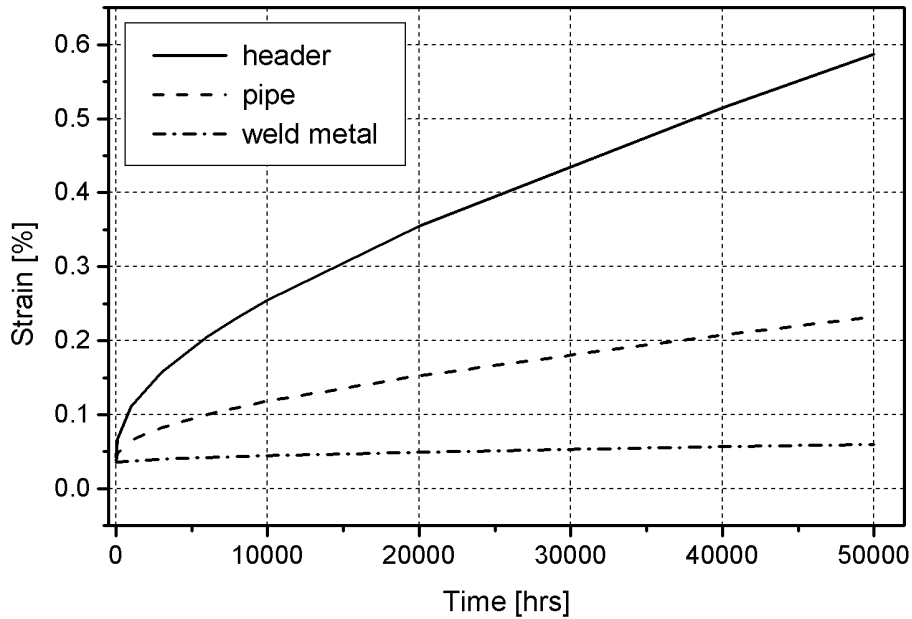


Fig. 1 Creep curves of header material, pipe material and weld metal; temperature 540 °C, stress 100 MPa.

### 3. Calculation model

Geometry of the studied weldment is shown in Fig. 2. The dimensions are:  $R_{HO} = R_{PO} = 109.5$  mm,  $R_{PI} = 89.5$  mm,  $R_{HI} = 81.5$  mm and  $\alpha = 20^\circ$ . A thickness reduction was taken into account. The wall thickness on the border header-weld was  $t_m = 18.4$  mm and it represents the local thickness reduction about 1.6 mm.

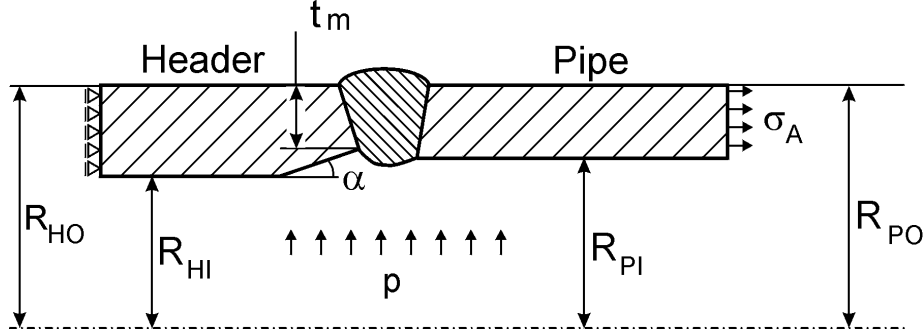


Fig. 2 Weld connecting header and pipe

As mentioned above, the finite element method was used for the calculations. The shape of the weldment allowed to simplify the solution and to use an axisymmetrical model. The mesh of elements was created using isoparametric elements with 6 and 8 nodes respectively. A typical mesh with refinement in the vicinity of HAZ consisted of approximately 3400 elements and 10 000 nodes. This reasonable size of the model allowed repeating calculations without extended computer time consumption.

The model was subjected to the internal pressure  $p = 9.6$  MPa and an axial loading. Several levels of the axial loading were assumed. The basic case was given by the axial stress  $\sigma_{A0}$  applied on the cross-section of the pipe (see fig. 2). This stress represents the axial load effect of the internal pressure only and its value can be determined by relation:

$$\sigma_{A0} = p \frac{R_{PI}^2}{R_{PO}^2 - R_{PI}^2} \quad (7)$$

Using the input data,  $\sigma_{A0} = 19.32$  MPa. Other two levels of axial loadings were taken into account, namely an increase about 10% and 25%, respectively. It means that the total applied axial stress in such cases was  $1.1\sigma_{A0}$  or  $1.25\sigma_{A0}$ .

For the solution, the PMD code [3] was used. This code enables to analyse creep problems using the constitutive model described in section 2. Components of the creep strain rate tensor are determined by:

$$\varepsilon_{ij}^c = \frac{3}{2} \frac{\varepsilon_c}{\sigma_e} S_{ij} \quad (8)$$

where  $\varepsilon_c$  is strain rate for uniaxial case derived from the equation (1),  $\sigma_e$  is the equivalent von Mises stress and  $S_{ij}$  are the deviatoric stress components. The solver which is built in the PMD program integrates the equation (7) using the Euler's forward scheme with automatic subincrementation. The time step length is set on the basis a posteriori estimate of the solution error (for details see [4]). All analyses covered the time period 100 000 hrs of service.

#### 4. Results

Performed analyses provided huge amount of data, but special attention was paid to redistribution of the axial stress and the parameter triaxiality  $h$  (for details see below). Selected results are presented in forms of graphs, where calculated values are drawn along radial and axial paths (r1,r2 and a1,a2), which are shown in Fig. 3.

This section concerns mainly on the most interesting area of the studied weldment, i.e. on the boundary between the weld metal and header. On the one hand there is an important difference in creep behaviour between the weld metal and the material of the header and on the other hand a stress concentration is situated on the internal surface of the header.

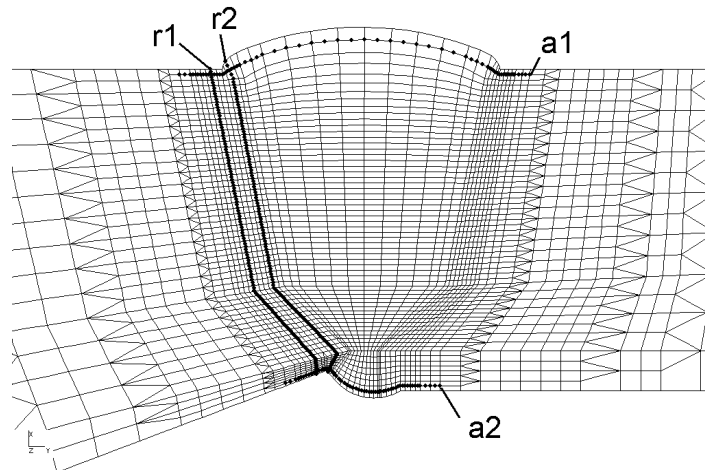


Fig. 3 FEM mesh in vicinity of the weld

Dependence of the axial stress on time in radial direction along paths r1 and r2 is shown in Fig. 4. The graphs concern the case, when the axial loading reaches  $1.25\sigma_{A0}$ . The radial coordinate with value about 90 mm corresponds to internal surface of the piping.

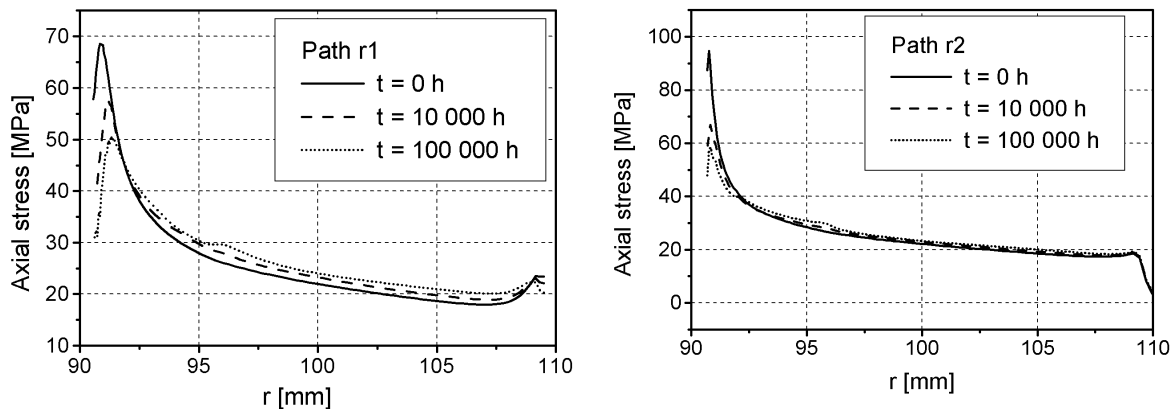


Fig. 4 Axial stress in radial direction in dependence on time; axial loading  $1.25\sigma_{A0}$

The stress concentration is remarkable on the internal surface. It is because of the notch in this location (see fig. 3). Due to the relaxation, the axial stress redistributes and comparing the results for time 100 000 hours, the maximum reaches about 50 MPa in the header material and about 60 Mpa in the weld material.

The axial stress in the axial direction along the paths a1 and a2 is shown in fig 5. On the external surface (path a1), the stress does not change significantly and stress concentrations in the vicinity of the borders header-weld as well as pipe-weld are remarkable. The maximum of the axial stress on the external surface is not affected by relaxation.

Different situation occurs on the internal surface. There is a significant stress concentration on the border header-weld metal. Due to the relaxation of the stress, the maximum decreases and reaches about 80 MPa in time 100 000 hrs.

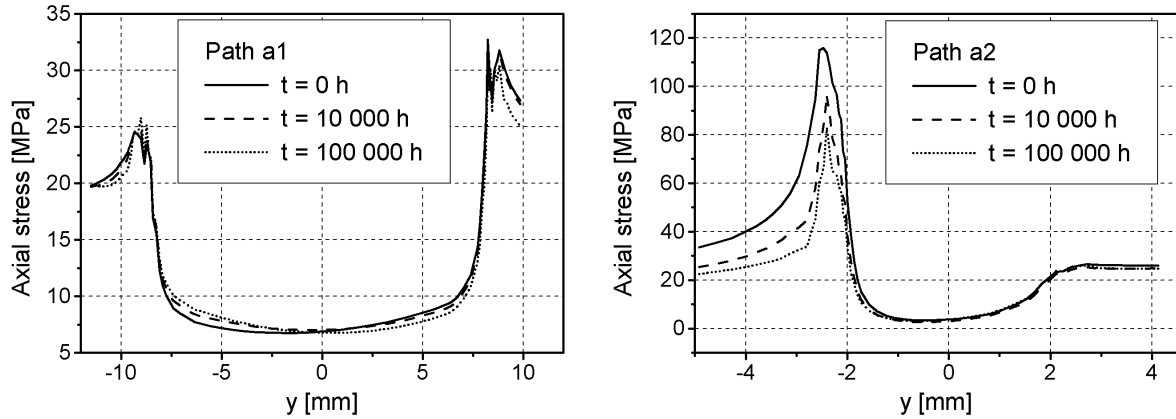


Fig. 5 Axial stress in radial direction along paths a1 (left) and a2 (right); axial loading  $1.25\sigma_{A0}$

Influence of different values of the axial loading applied on the pipe is shown in Fig. 5. The plots represent situation in time 100 000 hrs. Trends are similar on the both sides of the border header-weld metal. The maximum is located on the internal surface because of stress concentration of the notch and the axial stress is proportional to the axial loading, i.e. higher axial loading causes higher axial stress.

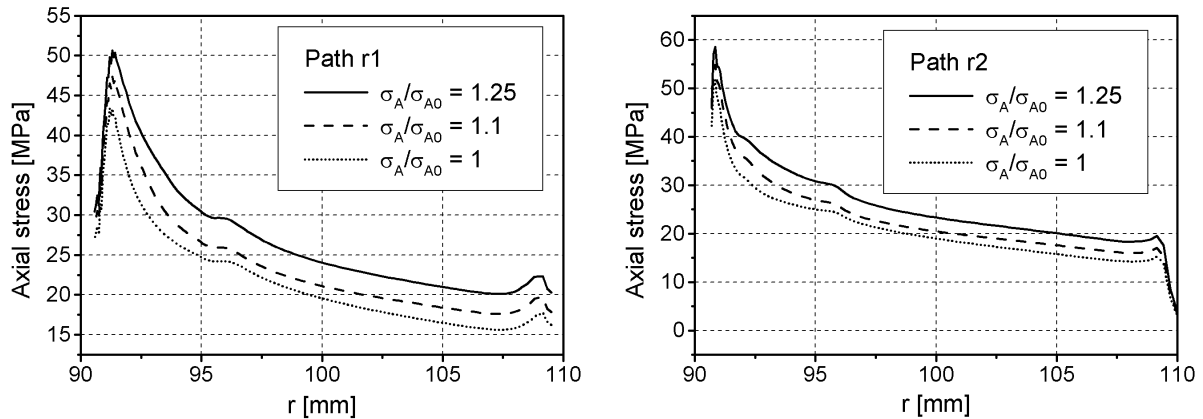


Fig. 6 Influence of different levels of the axial loading on the axial stress in the vicinity of the border header-weld metal; time  $t = 100\,000$  hrs.

The previous results could be expected from nature of the problem. But analyses provided very interesting data about the distribution of the triaxiality parameter  $h$ . This parameter is defined by relation:

$$h = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3\sigma_e} \quad (9)$$

where  $\sigma_{xx}$ ,  $\sigma_{yy}$  and  $\sigma_{zz}$  are the normal components of the stress tensor and  $\sigma_e$  is the equivalent von Mises stress. The parameter  $h$  is able to describe the influence of the hydrostatic stress state. This stress state plays important rule during initiation and growth of cavities in the creep process. Generally, higher value of  $h$  means higher influence of the hydrostatic stress state.

Fig. 6 shows the radial distribution of the parameter triaxiality  $h$  for the case with the highest assumed axial loading. In the initial state, the maximum of the parameter  $h$  is located near the internal and external surface where the notch effect is significant.

This distribution changes in dependence on time. While in the weld metal (path r2) the triaxiality parameter  $h$  decreases, the parameter  $h$  increases dramatically in the material of the header. The increase is significant especially in the middle of the header wall. This result is very important together with the fact that the increase of triaxiality occurs in the area near to low temperature affected zone, often so-called type IV region. This part of weldment is often the weak point. Detection of cracks in this area represents serious problems and defects located in this region can grow rapidly. That is why the increase of the triaxiality in this location could influence adversely lifetime of the weldment.

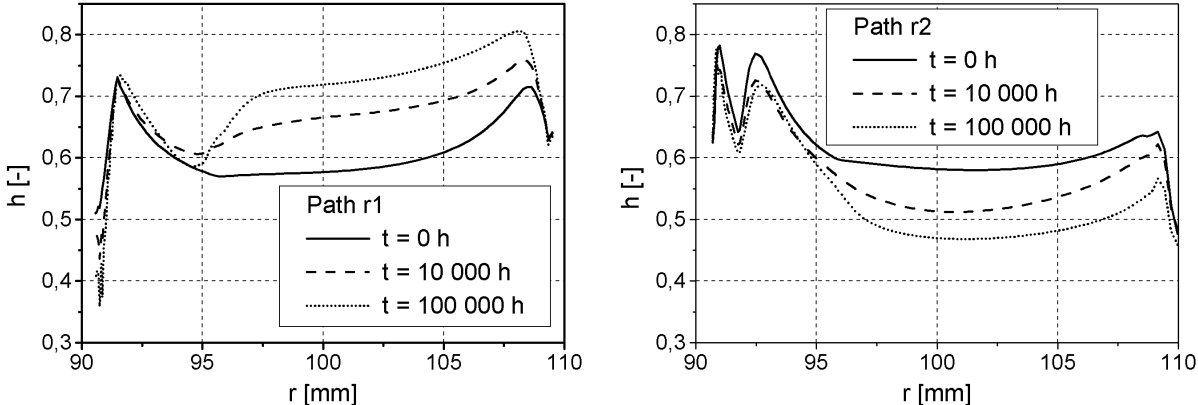


Fig. 6 Parameter triaxiality  $h$  in radial direction in dependence on time axial loading  $1.25\sigma_{A0}$

Influence of axial loading on the triaxiality parameter  $h$  is evident from Fig. 7. Although the distributions along thickness are very similar, the higher axial loading causes higher triaxiality near the type IV region.

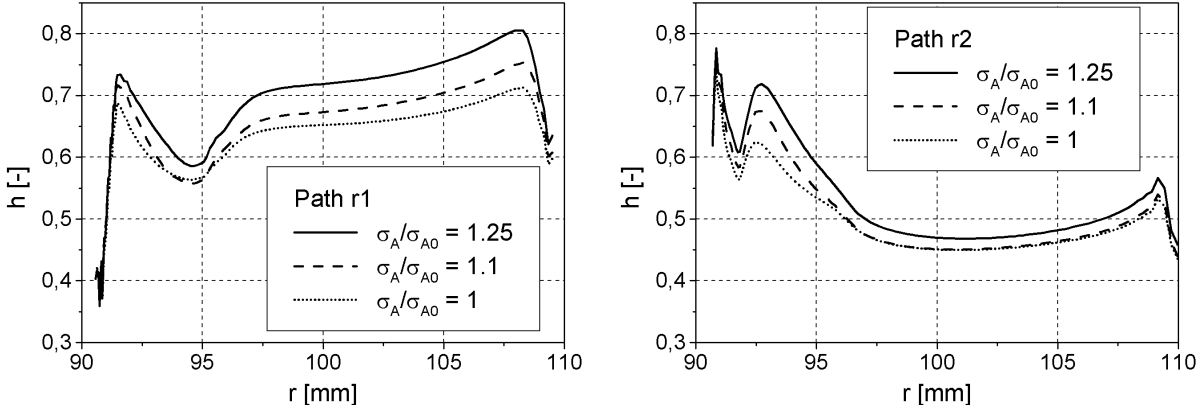


Fig. 7. Influence of different levels of axial loading on the triaxiality parameter  $h$ ; time  $t = 100\ 000$  hrs.

It should be note that a comparative calculation with assuming the HAZ material was performed. But the differences were not important between such solution and simplified solution respecting three different materials only (parent metal of the header, parent metal of the pipe and weld metal), see Fig. 8. There is a problem how to set correct creep parameters for the HAZ metal because of lack of information about the creep behaviour of the HAZ. In addition, the modelling of the HAZ is a difficult task. Its thickness is very small (typically 0.1 mm) and it requires significant refinement of the FEM mesh. This fact could lead to high computer time consumption. Anyway this problem should be solved in the future.

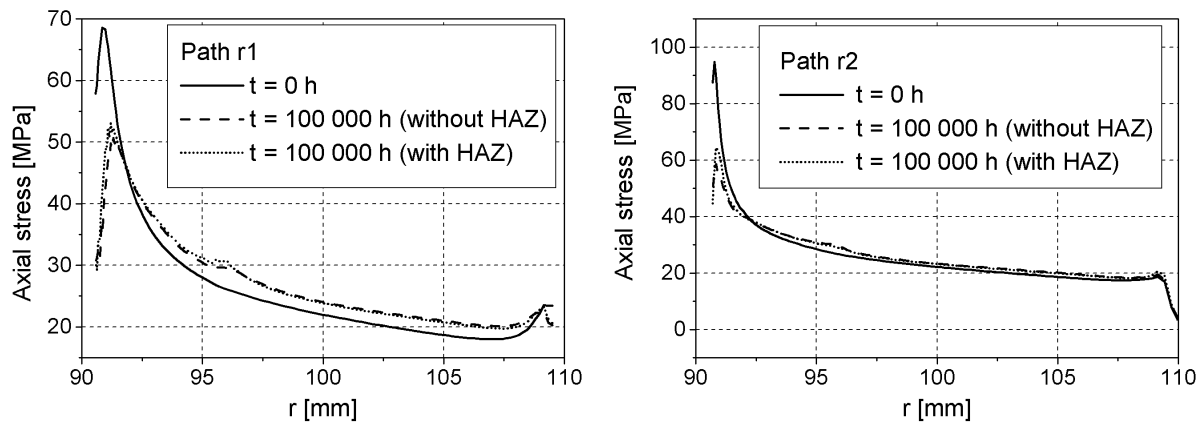


Fig. 8 Influence of the HAZ material on the stress redistribution; axial loading  $1.25\sigma_{A0}$

## 5. Conclusions

Analyses of a weldment were performed and stress redistribution was calculated using finite element method.

The axial stress in vicinity of HAZ decreases in time especially in locations with high stress concentration. In other parts, the decrease of axial stress is not significant.

An increase of the axial loading causes the increase of the axial stress. Because the stress redistribution occurs in the vicinity of stress concentrations only, the level of the axial stress in the weld is strongly affected by any additional axial loading.

Significant changes were detected for the triaxiality parameter  $h$ . This parameter in dependence on time decreases in the weld metal but increases in the header material. These changes are not favourable because the stress triaxiality reaches high values and the increase is most remarkable in the vicinity of the type IV region. Additional axial loading amplifies this adverse process.

Despite the presented study attempted to take into account many factors it represents a simplification the problem. In the future, the influence of residual stresses should be investigated as well as the influence of another type of loading, for example bending. The calculation should also respect different material properties of the HAZ.

## 6. References

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