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# Excessive creep strain design check with simulations based on material properties from material standards

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## ABSTRACT

The possibility of doing the Excessive Creep Strain Design Check (ECS-DC) according to EN 13445-3 Annex B based on simulations was investigated. As a constitutive law for creep, Norton's law and, as an alternative, a hyperbolic sine law were considered. Creep strain limits given in material standards are the basis for the parameters of these creep laws. A check for reversal creep ensures that repeated primary creep does not occur. The application of this method on a nozzle in a spherical shell shows the calculation of the parameters of the constitutive law and possibilities of damage determination. The geometry is analysed both at constant temperature and with uniform materials as well as with non-uniform material and temperature variations.

The focus of the paper is the conservative creep damage determination for design calculations. Therefore, the use of safety factors is included, and appropriate values are discussed.

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## KEYWORDS

Creep design; EN13445; design by analysis; direct method; pressure vessel; nozzle; reference stress; excessive creep strain design check

## Introduction

Design calculations require conservative creep damage determinations in accordance with regulations. Therefore, EN 13445-3 Annex B [1], Design by Analysis Direct Method specifies an Excessive Creep Strain Design Check (ECS-DC), but does not allow the use of the given principal, which specifies the maximum allowable creep strain, directly. The standard justifies this by the missing agreement on the design creep constitutive laws, based essentially on data in material standards. The requirement that the data from the material specification should be used originates from the European Pressure Equipment Directive (PED) [2]. Instead of the given principle, the user has to use application rules, which use reference stresses based on limit load calculations.

The methods in the application rules are practicable for cases with constant load and temperature. In cases with considerable load and temperature variations, however simulation-based approaches are necessary. Such methods need simple constitutive laws based on standardised material values. The goal is to get conservative results.

Here, Norton's creep law, a power law, provides a solution. The creep strain limits given in the material standards and the associated mean creep rates are the basis for the parameter calculation of this power law.

One problem with Norton's law is that small Norton exponents are appropriate for small stress and large ones for large stresses. Norton's law fits creep data only in the appropriate stress range. Therefore,

appropriate results are expected for stress levels within the relatively small range of the given creep strain limits. For stress values outside of this range, the determined Norton's law may be non-conservative. As an alternative, a creep law based on hyperbolic sine is taken.

A second problem arises with the secondary creep laws being used here: These creep laws are based on mean creep rates, and primary creep is not separated from secondary creep. For design purposes, this approach is sufficient as long as primary creep takes place only once at the beginning of service. In the case of creep reversal within operating cycles, repeated primary creep may take place. In such cases, the constitutive laws, which are used here, considerably underestimates the creep strain. Therefore, a check for creep reversal is included here.

This paper is focused on the determination of creep damage usage factor, and, for this purpose, three methods are considered. If stress variations occur, the fatigue damage usage factor has to be determined separately and creep fatigue interaction must be considered.

The design calculations considered in this paper, are of special interest in solar energy and energy storage applications. In comparison with the classical boilers, temperature and pressure variations occur more frequently. Due to limited financial resources, excessive material data are not available, and simple conservative methods have to be used.

Based on one of the examples within Seifert's diploma thesis [3], the possibility of doing the Excessive Creep Strain Design Check (ECS-DC) based on simulations was investigated. A very similar example was used in [4,5], where the basic approach of the creep design checks is described. Design by analysis calculation of a similar example, although not in the creep range, can be found in [6].

### Nozzle with single material and constant temperature

In a first step, the example is analysed with locally as well as temporally constant material parameters, resulting in one constant set of material parameters for the whole body.

#### Geometry, material, operation conditions

Figure 1 shows the geometry of the calculation model. In this model, the wall thicknesses are already reduced by the negative tolerances and the corrosion allowance. The material is 10CrMo9-10 and the parameters are those given in the material standard for steel plates EN 10028-2 [7]. For the operation conditions, a pressure of 11.5 MPa (stationary operation) and a temperature of 475°C are chosen.

Within this part of the paper, partial Safety factors for material parameters arise in the formulae, but in the calculations, all safety factors (including the ones for pressure action  $\gamma_p$ ) are set to one for simplification. In the generalisation for multiple material and temperature variation (Figure 14, Figure 15) (like in usual design checks), partial safety factors are used.

#### Global reference stress

Within this paper, the same type of global reference stress (Eq. 1) as in [4] is used. This reference stress is similar to the one used in [8-10], but in the calculation of the limit load the strain criterion of EN 13445-3 Annex B [1] is included.

$$\sigma_{rG}^{(k)} = \frac{A^{(k)}}{A_u} \cdot RM \quad (1)$$

With the linear-elastic ideal-plastic material law, a yield stress  $RM = R_{p1\%,475^\circ,10000h} = 190\text{MPa}$ , the modulus of elasticity according to EN 13445-3 Annex O [1], and a strain limit of 5%, a limit pressure ( $A_u$ ) of 15.56 MPa is calculated. For the stationary operation condition with a pressure of 11.5 MPa, the global reference stress is calculated as follows:

$$\sigma_{rG}^{(1)} = \frac{11.5\text{MPa}}{15.56\text{MPa}} \cdot 190\text{MPa} = 140.42\text{MPa} \quad (2)$$

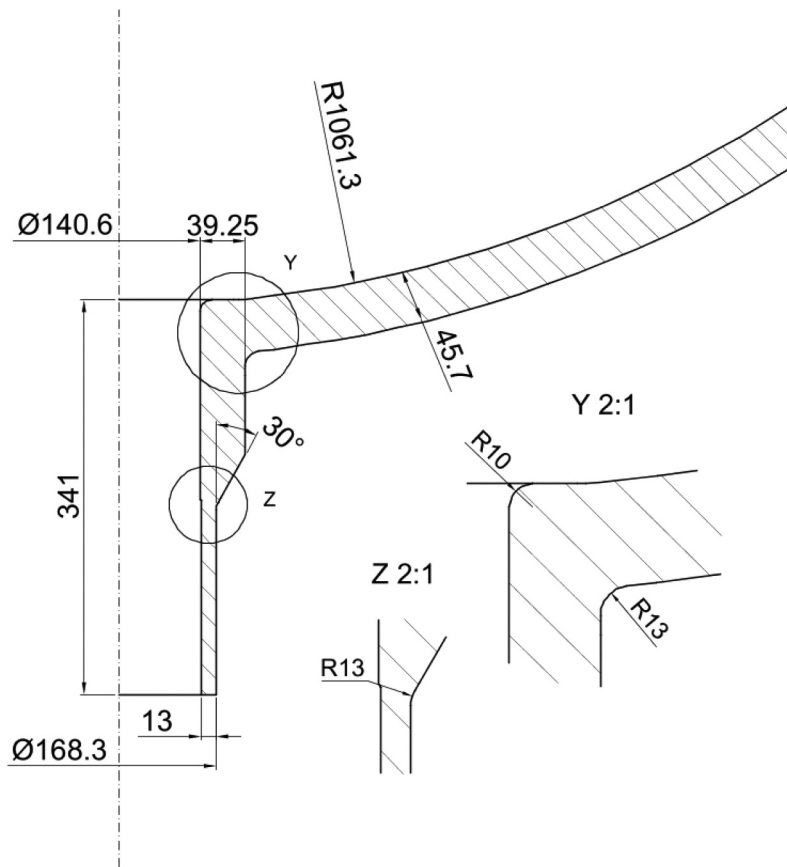


Figure 1. Geometry of model.

Because in this case the yield stress does not vary within the structure, for constant operation conditions, a single global reference stress is calculated.

The global reference stress is used

- as stress, which characterises the global load of the structure,
- for characterising the most important region of the creep law,
- as reference value for strain concentration factors.

If the limit load was calculated by classical limit analysis, the reference stress would be independent from yield stress (RM) and the modulus of elasticity (E). Here, the limit load is determined according to EN 13445-3 Annexe B [1], and, therefore, the resulting reference stress weakly depends on RM and E.

### Constitutive law for creep simulation

If we look at material standards (in this example [7]) for parameters, which characterise the creep strain rate, only the creep strain limits are suitable. The creep strain limits are stress levels at which at a given temperature and time a specified strain value (usually 1%) is reached. For the given creep strain limits, mean creep strain rates are determined and associated with the given stress values, resulting in points of a secondary creep law (Table 1).

Based on the limited material data, only simple creep laws, with few parameters are practical.

### Basic Norton creep law ( $n_{int}$ )

Figure 2 illustrates the determination of the Norton's law (Eq. 3), which is performed by Eq.4 and 5

$$\dot{\epsilon}_c = K_{(int)} \left( \frac{\sigma_{eq}}{\sigma_0} \right)^{n_{(int)}} \quad (3)$$

$$n_{(int)} = \frac{\log\left(\frac{\dot{\epsilon}_{c,A}}{\dot{\epsilon}_{c,B}}\right)}{\log\left(\frac{\sigma_A}{\sigma_B}\right)} \quad (4)$$

$$K_{(int)} = \dot{\epsilon}_{c,B} \left( \frac{\sigma_0}{\sigma_B} \right)^{n_{(int)}} \quad (5)$$

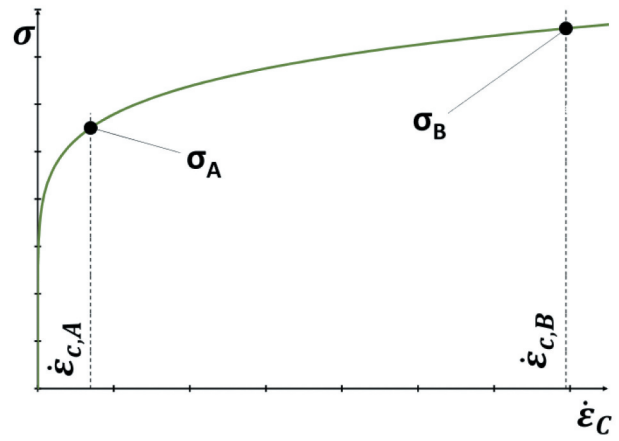


Figure 2. Determination of Norton's law  $n_{int}$ .

With the values from Table 1 and  $\sigma_0 = 1MPa$ , the parameters of Norton's law are  $n_{(int)} = 7.12$  and  $K_{(int)} = 1.6563E-26 \text{ s}^{-1}$ , which were input in the Finite Element software.

### Variation of Norton exponent

The parameters of Norton's law are varied in such a way that the intersection of all considered Norton's laws is at the global reference stress  $\sigma_{rG}^{(k)}$  (Figure 3). Because  $\sigma_{rG}^{(k)}$  depends on the load, a relevant load case (k) has to be chosen in the case of multiple load cases.

Two values of the Norton exponent are chosen. In this example, these values are 3 and 9 and they are called  $n_{(var)}$ , resulting in a constant of the Norton Law  $K_{(var)}$  (Eq. 7 and 8, Table 2) for the Norton law (Eq. 6). The creep rate at the global reference stress  $\dot{\epsilon}_{rG}$  (Eq. 7) is determined by logarithmic interpolation between the given data points, which is the same as inserting  $\sigma_{rG}$  in Eq. 3.

$$\dot{\epsilon}_c = K_{(var)} \left( \frac{\sigma_{eq}}{\sigma_0} \right)^{n_{(var)}} \quad (6)$$

$$\dot{\epsilon}_{rG}^{(int)} = K_{(int)} \left( \frac{\sigma_{rG}^{(k)}}{\sigma_0} \right)^{n_{(var)}} \quad (7)$$

$$K_{(var)} = \dot{\epsilon}_{rG}^{(int)} \left( \frac{\sigma_0}{\sigma_{rG}} \right)^{n_{(var)}} \quad (8)$$

### Constitutive laws for creep based on hyperbolic sine

One of the problems with Norton's law is that the Norton exponent varies with the stress level, which may lead to non-conservative results. The Norton exponent will be too large for stresses smaller than the considered creep strain limits and too small for stresses larger than the considered creep strain limits. The hyperbolic sine function is approximately linear at small arguments and exponential at large arguments. Therefore, the parameters of the sinh-function can be

Table 1. Material specification (partial safety factor  $\gamma_R = 1$ ).

Point	Creep strain limit	Mean creep Strain rate $\dot{\epsilon}_{c,...}$
A	$\sigma_A = R_{p1\%/475^\circ\text{C}/10000\text{h}}/\gamma_R = 190 \text{ MPa}$	
B	$\sigma_B = R_{p1\%/475^\circ\text{C}/10000\text{h}}/\gamma_R = 137,5 \text{ MPa}$	$\dot{\epsilon}_{c,B} = 10^{-7} \text{ h}^{-1}$

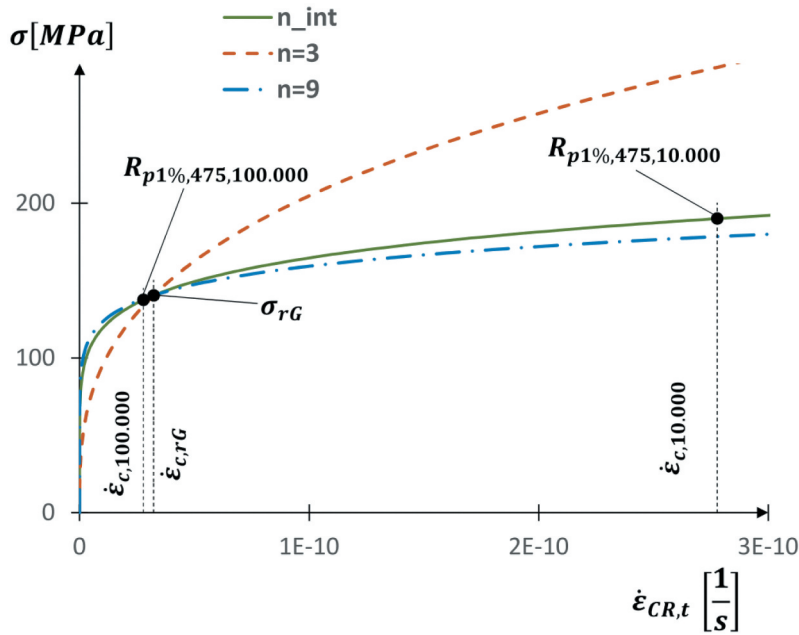


Figure 3. Variation of Norton's law.

Table 2. Parameter variation for Norton's law (partial safety factor  $\gamma_R = 1$ ).

$n_{(var)}$	3	9
$K_{(var)}$	$1.1652E-17 \text{ s}^{-1}$	$1.5199E-30 \text{ s}^{-1}$

chosen in a way, that it is near to Norton's law in the region of the considered strain limits and conservative outside of this region.

Constitutive laws based on hyperbolic sine were proposed by McVetty (1943) and Garofalo (1965) [11]. To have the minimum of two parameters ( $C_1$  and  $C_2$ ), the simplest form of these constitutive laws is chosen (Eq. 9).

$$\dot{\epsilon}_c = C_{1()}\sinh\left(C_{2()}\cdot\frac{\sigma_{eq}}{\sigma_0}\right) \quad (9)$$

If, for the considered temperature, the material standard provides two creep strain limits (as in this example), the parameters of the sinh-function can be chosen so that the points of Table 1 are on the curve (curve called 'sinh\_int' in Figure 4).

For the calculation of the parameters of the constitutive law 'sinh\_int', one gets two equations by inserting  $\sigma_A$  and  $\dot{\epsilon}_{c,A}$  for  $\sigma_{eq}$  and  $\dot{\epsilon}_c$  for the first equation and  $\sigma_B$  and  $\dot{\epsilon}_{c,B}$  for the second equation (Eq. 10). With a partial safety factor  $\gamma_R = 1$ , the system is solved for  $C_{1(int)} = 1.3356 \cdot 10^{-13}$  and  $C_{2(int)} = 0.04386$ .

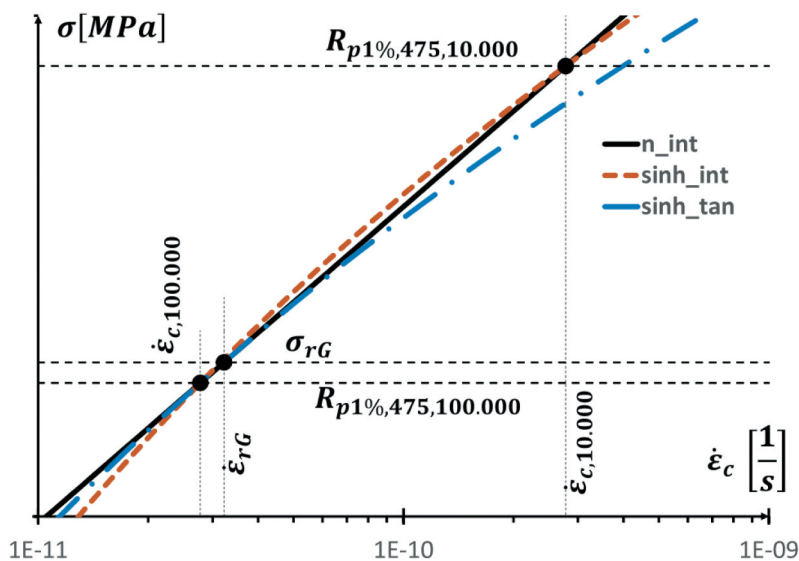


Figure 4. Norton's creep law interpolated (n\_int), sinh interpolated (sinh\_int), and sinh tangential to Norton's law (sinh\_tan) – logarithmic axis.

$$\begin{cases} \dot{\epsilon}_{cA} = C_{1(int)} \sinh\left(C_{2(int)} \cdot \frac{\sigma_A}{\sigma_0}\right) \\ \dot{\epsilon}_{cB} = C_{1(int)} \sinh\left(C_{2(int)} \cdot \frac{\sigma_B}{\sigma_0}\right) \end{cases} \quad (10)$$

Between the used creep strain limits, the constitutive law 'sinh\_int' lies on the non-conservative side of the Norton law. To make it conservative in comparison to Norton's law, a sinh-curve can be fitted to be tangential to Norton's law. This could be done at any point of Norton's law – here the reference stress  $\sigma_{rG}^{(k)}$  was chosen (curve called 'sinh\_tan' in Figure 4).

The parameters for the sinh-function sinh\_tan, which touches the Norton's law n\_int, are calculated by solving Eq. 11 for C2S and, afterwards, using Eq. 12 and 13.

$$C2S \cdot \frac{\cosh C2S}{\sinh C2S} = n_{(int)} \quad (11)$$

$$C_{2(tan)} = C2S \frac{\sigma_0}{\sigma_{rG}^{(k)}} \quad (12)$$

$$C_{1(tan)} = \frac{\dot{\epsilon}_{rG}^{(int)}}{\sinh(C2S)} \quad (13)$$

For this example (partial safety factor  $\gamma_R = 1$ ) this results in  $C_{1(tan)} = 5.2187 \cdot 10^{-14}$  and  $C_{2(int)} = 0.050704$

### Constant pressure 100000h creep

As the simplest load case, creep with constant load (pressure) was investigated. The simulation starts from the initial stress-free condition at 475°C, and the pressure of 11.5 MPa is applied at time zero (step loading) and is held at a constant value for 100,000 h.

At the beginning of the simulation, the linear-elastic stress distribution arises (Figure 5), and the maximum equivalent stress appears at the crotch corner (point A at the inside of the nozzle). During creep, stress redistribution takes place, and at 100,000h, the stress distribution (Figure 6) is nearly stationary. Due to the stress redistribution the maximum equivalent stress moves from point A at the inside to the onset of the fillet at the outside of the nozzle (point B at Figure 6).

Within all considered constitutive laws, the maximum creep rate arises at point A. At the beginning of the simulation, and at point B at the end of the simulation (100000h). Due to the stress redistribution, it depends on the used constitutive law, if the maximum equivalent creep strain arises at point A or B. Here, further evaluations (Fig. 7 and 8) are done for point B.

When the results for Norton's law with different Norton exponents are compared (Figure 7), the maximum creep strain arises for the large Norton exponent ( $n = 9$ ).

The comparison of Norton's law (n\_int) with the sinh-based constitutive laws (sinh\_int and sinh\_tan in Figure 8), shows that the sinh\_int lies

### Beginning (linear-elastic)

Type: Equivalent (von-Mises) Stress  
Unit: MPa

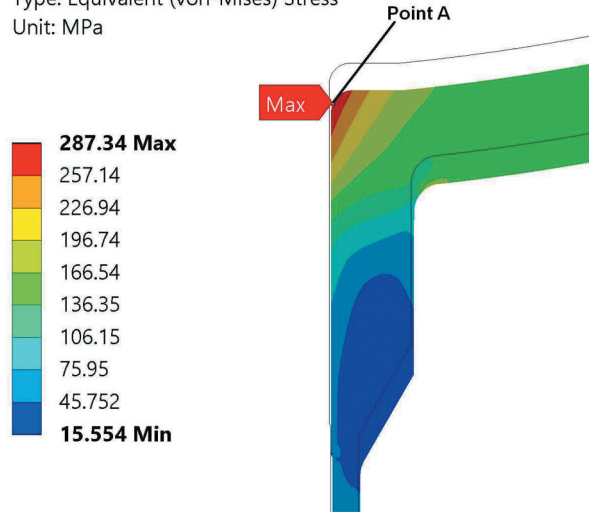


Figure 5. Equivalent stress distribution after application of pressure.

### Creep n\_int 100000h

Type: Equivalent (von-Mises) Stress  
Unit: MPa

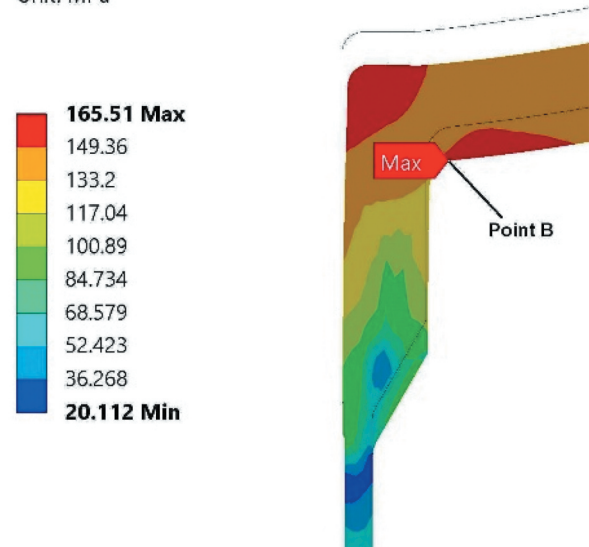


Figure 6. Equivalent stress distribution after 100,000 h creep (n\_int) at constant pressure.

slightly on the non-conservative side of the Norton law n\_int and sinh\_tan slightly on the conservative side. This is consistent with the location of the creep laws in region of the reference stress (Figure 4).

The following subsections describe three different possibilities for the determination of the creep damage. The determined creep damage usage factor should be the base for the damage accumulation necessary for determination of creep fatigue interaction.

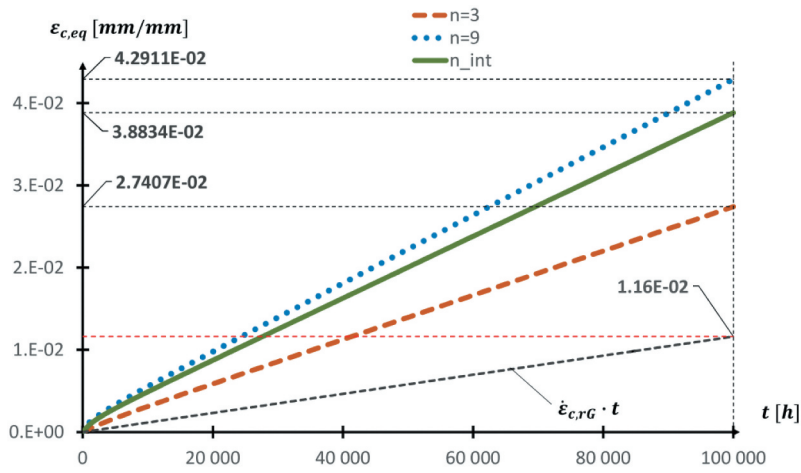


Figure 7. Equivalent creep strain in point B for variation of Norton exponent.

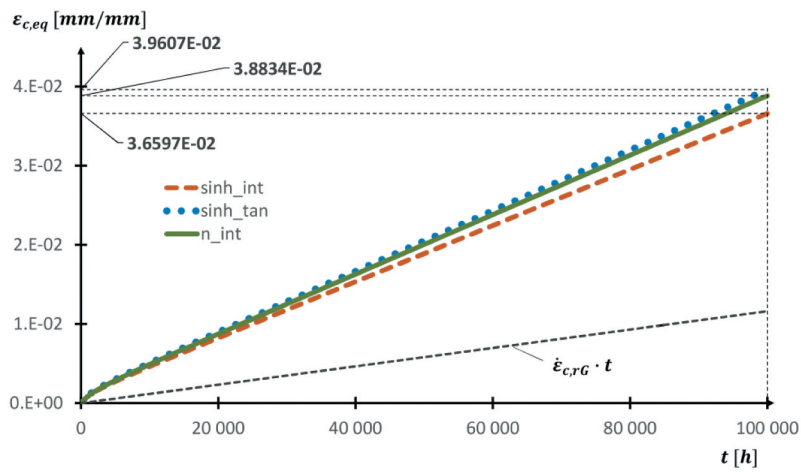


Figure 8. Equivalent creep strain in point B for sinh-based creep laws and Norton interpolated.

### Usage of stress maximum and Linear Damage Fraction Rule (LDFR-SMAX)

The application rule for Excessive Creep Strain Check (ECS\_AR) of Annexe B of [1] uses Linear Damage Fraction Rule in combination with the reference stress  $\sigma_{ref}$  for the determination of the creep damage usage factor. The reference stress  $\sigma_{ref}$  there is an estimate for the maximum stress in the component during stationary creep. Using formula (Gl. B.9–2) of the standard in the form of [4] (Eq. 14, 15) results in a value for this reference stress of 159.5 MPa.

Because the maximum stress during stationary creep is calculated within the simulation, the value can be used, and the estimate is not necessary. From the model based on Norton's law with  $n_{int}$ , the maximum stress after 100000h creep  $\sigma_{eq,max,n_{int},100000h}$  is 165.5MPa. This value is a higher value than the one estimated by the standard.

$$\sigma_{ref} = [1 + 0.13 \cdot (\chi - 1)]\sigma_{rG} =$$

$$[1 + 0.13 \cdot (2.046 - 1)]140.42 = 159.5\text{MPa} \quad (14)$$

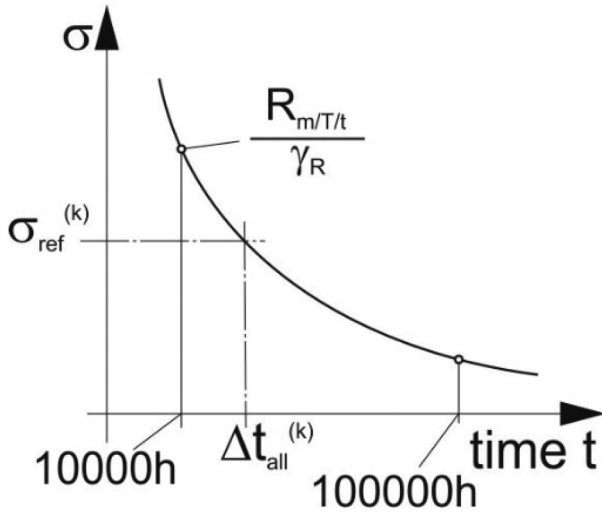
$$\chi = \frac{\sigma_{el,max}}{\sigma_{rG}} = \frac{287.3}{140.42} = 2.046 \quad (15)$$

Because in the application rule of [1], the calculation of  $\sigma_{ref}$  is based on the elastic limit load  $A_e$  for the whole structure, the maximum stress concentration within the structure has to be used. When the maximum elastic stress in point B, where within the simulation the maximal creep strain occurs, would be used, the estimate would be even worse.

The creep damage usage factor is calculated using the reference stress  $\sigma_{ref}$ , the creep rupture strength values from the material standard (Table 3), and the duration of the creep load case (Eq.16). Therefore, the allowable lifetime  $\Delta t_{all}^{(k)}$  for the load case  $k$  is determined by logarithmic inter- or extrapolation (Figure 9).

Table 3. Creep rupture strengths according to material standard [7] (partial safety factor  $\gamma_R = 1$ ).

Point	Creep rupture strength	Time to failure $t_r$
A	$\sigma_{Am} = R_{m/475^\circ\text{C}/100000h}/\gamma_R = 179 \text{ MPa}$	$t_{Am} = 100000h$
B	$\sigma_{Bm} = R_{m/475^\circ\text{C}/200000h}/\gamma_R = 160.5 \text{ MPa}$	$t_{Bm} = 200000h$



**Figure 9.** Determination of allowable lifetime for reference stress.

$$D_c = \sum_k \frac{\Delta t^{(k)}}{\Delta t_{all}^{(k)}} \quad (16)$$

The results of the damage determination are summarised in Table 4. In this case, logarithmic extrapolation is used if the resulting time is larger than the largest time for which creep rupture strengths are given in the standard. This is not in accordance with chapter 19 of [1] where the time  $\Delta t_{all}^{(1)}$  is limited to the largest time for which creep rupture strengths are given.

Using the stress maximum from the simulation is a direct extension to the ECS\_AR of the standard. This approach (LDFR-SMAX) results in the following shortcomings:

- Due to the nonlinear creep law, small failures in the calculation of stress result in large failures in the calculation of damage
- The stress concentration, and, therefore, the maximum stress shows large dependence on the creep constitutive law, especially on the exponent  $n$  of the power law.
- Creep strains due to stress redistribution are not included.

Therefore, alternative approaches based on strain results are used within the next chapters.

**Table 4.** Creep damage usage factor determined for ECS\_AR and LDFR-SMAX (partial safety factor  $\gamma_R = 1$ ).

	ECS_AR	LDFR-SMAX (simulation)
Used stress	$\sigma_{ref}$ (Eq. 14)	
Stress value [MPa]	159.5	165.5
$\Delta t^{(1)}$ [h]	100,000	100,000
$\Delta t_{all}^{(1)}$ [h]	208,000	164,580
$D_c^{(1)}$	0.481	0.608

### Linear Damage Fraction Rule combined with strain concentrations (LDFR-EPC)

With this method, which is similar to the one proposed in [3], a strain concentration factor (EF, Eq. 17), which is based on the creep strain rate at the global reference stress ( $\dot{\epsilon}_{c,rG}^{(k)}$ ), is calculated. The strain rate  $\dot{\epsilon}_{c,rG}^{(k)}$  is calculated by inserting the global reference stress  $\sigma_{rG}^{(k)}$  (Eq. 1) into the creep constitutive law of the model (Eq. 3, 6 or 9).

At first, the creep damage usage factor at the global reference stress (Eq. 18) is determined. Afterwards, this damage is linear scaled (multiplied) by the determined strain concentration (Eq. 19). The allowable time for creep at the reference stress,  $\Delta t_{rG,all}^{(k)}$ , is calculated based on the creep rupture strengths (Table 3) by logarithmic interpolation according to (Figure 9).

In comparison to the application rules given in EN13445-3 Annexe B [1], the stress concentration, which is estimated based on the linear elastic one in the application rule, is replaced by the strain concentration from the simulation. Linear scaling of the damage with the strain concentration factor is based on the assumption that creep damage is proportional to the creep strain.

$$EF = \frac{\epsilon_{c,eq,sim}}{\sum_k \dot{\epsilon}_{c,rG}^{(k)} \cdot t^{(k)}} \quad (17)$$

$$D_{c,rG} = \sum_k \frac{\Delta t^{(k)}}{\Delta t_{rG,all}^{(k)}} \quad (18)$$

$$D_{c,LDFR-EPC} = D_{c,rG} \cdot EF \quad (19)$$

For the example above and Norton's creep law  $n_{int}$ , the calculation of the creep damage usage factor in point B ( $D_{c,LDFR-EPC,B}$ ) is shown in the following equations (partial safety factor  $\gamma_R = 1$ ):

$$EF_B = \frac{0.038834}{3.226E - 11 \cdot 3.6E8} = 3.344 \quad (20)$$

$$\dot{\epsilon}_{c,rG}^{(1)} = 3.226E - 11 \frac{1}{s} \quad (21)$$

$$D_{c,rG,B} = \frac{100000h}{4.676E5 h} = 0.214 \quad (22)$$

$$D_{c,LDFR-EPC,B} = 0.214 \cdot 3.344 = \underline{0.715} \quad (23)$$

For the determination of the allowable time for creep at the reference stress,  $\Delta t_{rG,all,B} = 4.676E5h$ , the creep rupture strengths from the material standard [7] are used. In this first example, the partial safety factors for the resistance are set to one.



Advantages of this method:

- This method uses creep rupture data for the damage determination. This is in accordance with other methods given in the standard. In some material standards only creep rupture data is given.
- Instead of stress concentrations, strain concentrations are used. Strain concentrations are less sensitive to variations of the creep law.
- Creep stain due to stress redistribution can be included within the strain concentration factors.

Disadvantages of the method:

- Determination of the global reference stress is necessary for every load case. This is relatively simple for load cases with constant temperature and one set of material parameters. However, in the case of load variations and multiple material sets, it may become very complicated.
- Due to the determination of the allowable creep time with the global reference stress, which does not include stress concentrations, the logarithmic interpolation of the material values (Figure 9) is performed with smaller stress values. Therefore, the determined allowable creep time  $\Delta t_{rG,all}^{(k)}$  is often larger than the greatest duration for which creep rupture data is provided, and extrapolation is necessary (in the example above  $\Delta t_{rG,all}^{(k)} = 467600h$  and the creep rupture data is provided up to 200000h).

#### Damage determination based on direct usage of calculated strain – Ductility Exhaustion Rule (DEM)

With the Ductility Exhaustion method (DEM), the calculated strain values can be used directly. The method is already used in [12] and in [13] Eq. 24 for the creep damage usage factor is given.

$$D_{c,DEM} = \frac{t \varepsilon_{c,eq}^d}{\varepsilon_f(\varepsilon_c)} \quad (24)$$

If the critical ductility  $\varepsilon_f(\varepsilon_c)$ , which is a function of the creep strain rate, is larger than a specified allowable creep strain  $\varepsilon_{c,all}$  within the relevant range of  $\varepsilon_c$ , it is conservative to use the accumulated creep strain, and replace  $\varepsilon_f(\varepsilon_c)$  by this constant value of  $\varepsilon_{c,all}$  resulting in Eq. 25.

$$D_{c,DEM} = \frac{\varepsilon_{c,acc,sim}}{\varepsilon_{c,all}} \quad (25)$$

The accumulated creep strain, which was calculated by the model with the power law and  $n_{int}$  for 100000h creep, is 0.038834. Using the allowable creep strain  $\varepsilon_{c,all}$ , which is specified in EN 13445–3 [1] with 5%, results in a creep damage usage factor of 0.7767

(Eq. 26). Within this method, the partial safety factor for the resistance (here  $\gamma_R = 1$ ) had to be included in the constitutive law (Table 1).

$$D_{c,DEM,B} = \frac{0.038834}{0.05} = 0.7767 \quad (26)$$

Advantages of the method:

- Determination of reference stresses is not necessary.
- Strains due to stress redistribution are included.
- Load variation can be considered, as long as the model with the creep constitutive law results in acceptable strain values.

Disadvantages of the method:

- In contrast to the other methods used within EN 13445–3, creep rupture data is not used for the damage determination. Less common material parameters, creep strain limits and allowable creep strain, are used.

#### Unloading cycle – creep reversal

A simple cycle with unloading at constant temperature (Figure 10) is simulated to demonstrate a simple check for creep reversal. The unloading in this example is different to the common shutdown of pressure equipment because the temperature is kept constant. Due to the decrease of temperature, the danger of creep reversal within a shutdown is less than in this example.

The calculated creep strain history (Figure 11) can be used for further analyses. Within this paragraph, only the check for creep reversal is described.

#### Check for creep reversal

From the resulting creep strain history (Figure 11), it is difficult to identify creep reversal. For assessing the maximum strain, it is possible to use the accumulated equivalent strains ( $\varepsilon_{c,acc}$ ) or the ones calculated from the current strain tensor ( $\varepsilon_{c,eq}$ ). The accumulated

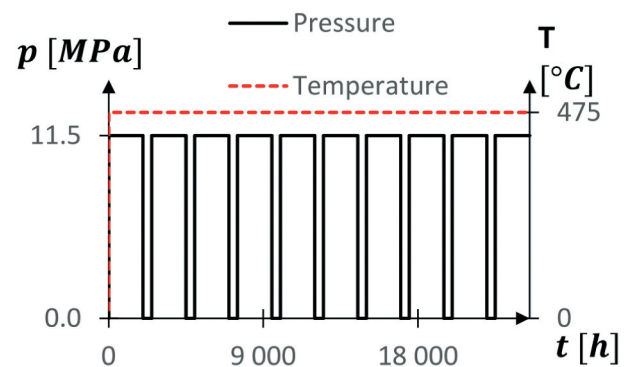
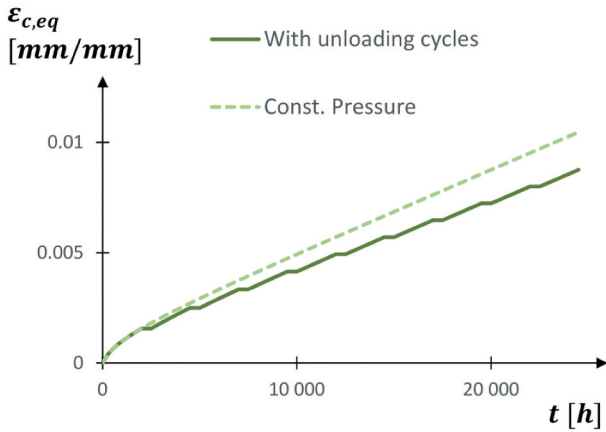


Figure 10. Pressure and temperature history for simulation with unloading cycle.



**Figure 11.** Equivalent creep strain in point B for Norton creep ( $n_{int}$ ).

values cannot decrease, and, therefore, these values are not appropriate for recognising reversal. The ones calculated from the current strain tensor are positive definite, and creep reversal is possible, if these values do not decrease.

Therefore, a check based on the following is used. Only, if the tensor of the creep strain rate does not change 'direction' (varies proportional), the equivalent creep strain calculated from the current strain tensor ( $\varepsilon_{c,eq}$ ) is equivalent to the accumulated creep strain ( $\varepsilon_{c,acc}$ ), otherwise it is less. Therefore, the difference between these two equivalent strain values (Eq. 27), which can be calculated with Finite Element software (e.g. ANSYS®), can be used to check, if the flow was unidirectional during the whole history.

$$\varepsilon_{c,Diff} = \varepsilon_{c,acc} - \varepsilon_{c,eq} \quad (27)$$

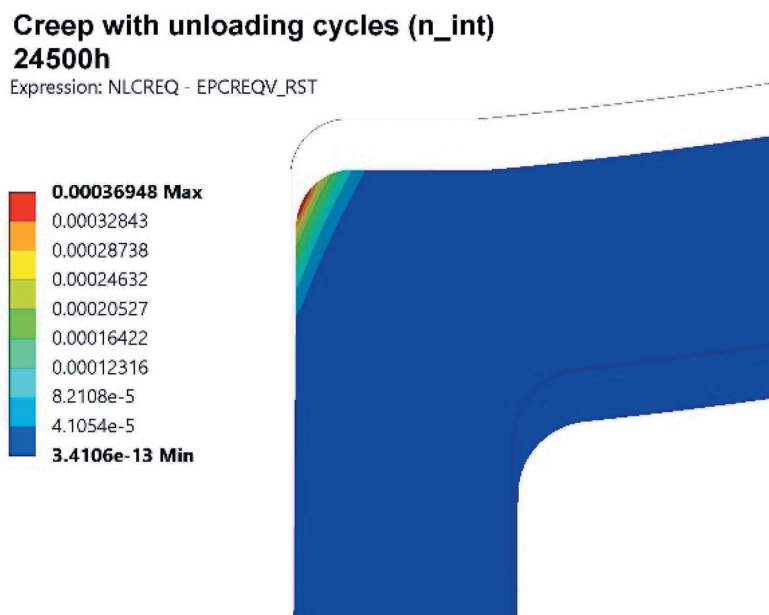
The plot of the strain difference,  $\varepsilon_{c,Diff}$ , for the specified load history (Figure 12) shows small but considerable change of flow direction at the crotch corner. Therefore, the stress and strain components for this location were further investigated and reversal flow in the circumferential direction were detected (Figure 13).

The example shows that plotting the difference between accumulated and equivalent strain is an appropriate method to check for reversal flow. One problem of this check is, that the difference is never zero, because redistribution of stress at the beginning and numerical failures will always result in small differences. Therefore, limits have to be determined.

Another problem arises, if small zones of reversal flow, like in the example above, are detected. If the zone affected by reversal flow is small in comparison to the cross section of the part, the global behaviour of the structure will not change significantly. If the reversal flow results from constraints due to geometric discontinuities, it is expected that the calculated strain history will not be too far off the real one. Of course, the stress history calculated for such zones needs corrections.

In the case of large zones with creep reversal, constitutive laws based on mean strain rates are not appropriate, which means in the usual cases that the structure is not admissible for the considered load history. Because of the absence of experience, no limits can be given here.

Within Seifert's master theses [3] a similar load history with unloading to a pressure of 9 MPa was investigated. In this case, no creep reversal was detected.



**Figure 12.** Difference between accumulated and equivalent creep strain for  $n_{int}$ , after loading history of Figure 10.

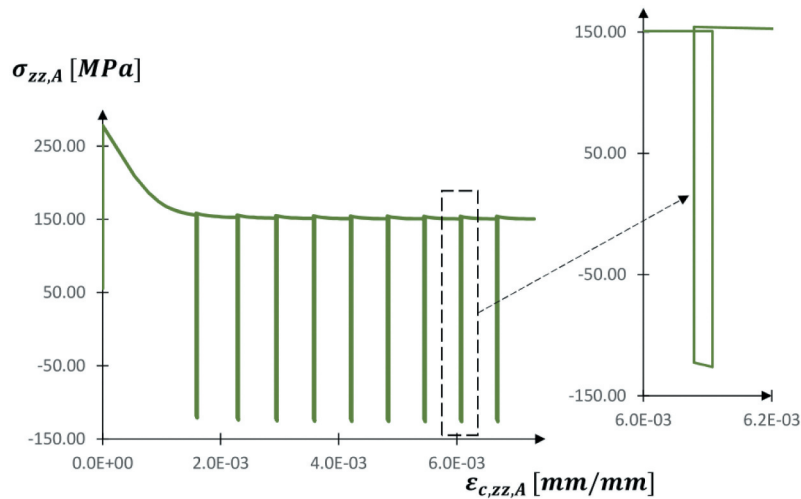


Figure 13. Plot of circumferential stress vs. circumferential strain for crotch corner (max. in Figure 12).

### Multiple material and temperature variation – cold media injection

In the next step, the example was changed to be close to industrial design. Instead of the uniform material, different materials were used for the shell, the reinforcement, and the nozzle (Figure 14). Also a partial safety factor for the material,  $\gamma_R$  of 1.25, was used. All partial safety factors for actions (pressure and temperature) were set to one.

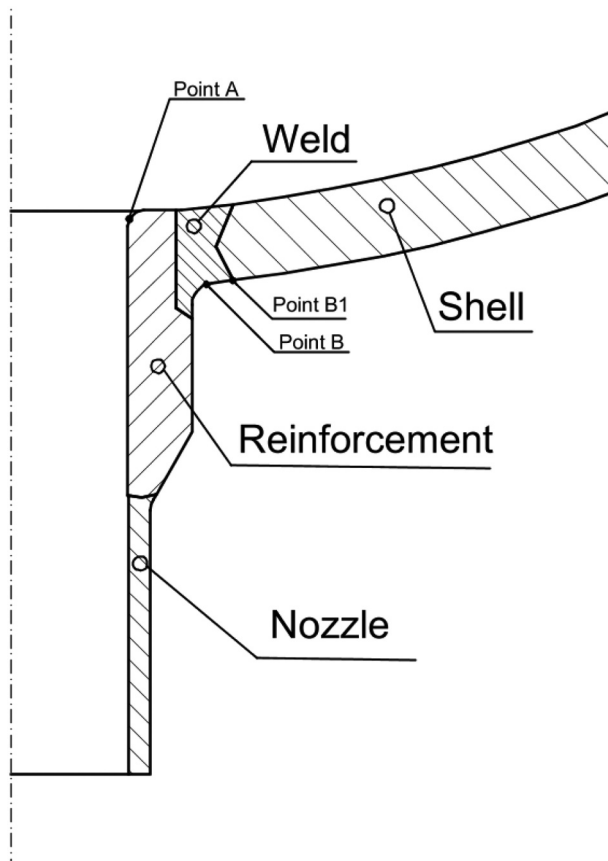


Figure 14. Geometry of nozzle example with multiple material.

Material properties are taken from the material standards (Table 5) and Annexe O of [1]. Because no creep data for the weld are available, for the strength values including creep strain limits, 80% of the ones of the weaker adjacent base material are used. Because no creep strain limits are given in EN 10216–2 (pipe material), the values from EN 10222–2 (forging material) were used.

To have a more complex loading cycle, cold media injection through the nozzle was included (Figure 15, Table 6). During long-term operation, the part is operated at constant pressure and temperature, and only three times during an operating period, a colder medium streams in by the nozzle. During these short periods, the temperature within the nozzle changes to  $T_N^{(i)}$ , resulting in non-uniform temperature distribution. To simplify the example, here slow thermal transients are assumed, and, therefore, stationary calculated temperature distributions are used. The temperatures  $T_{sh}$  and  $T_N$  were applied directly at the surface, which approximates conditions with large heat transfer coefficients.

Table 6 shows the specified load values. The temperature at stationary operation is the same as for the simple example with single material and constant temperature, but the pressure had to be reduced because of the use of the partial safety factor for the resistance ( $\gamma_R = 1.25$ ).

### Reference stress

The reference stress  $\sigma_{rG}^{(k)}$  depends on load and temperature, and, therefore, for each load case a set of different reference stress values is calculated. It is a set of reference stress values, because different values are calculated for different material regions.

Because it provides information about the most important stress region, which is important for the constitutive law, the values for the stationary creep period are given in Table 7.

Values for all load cases are necessary for LDFR-EPC (see 3.4.2) and are determined in [3].

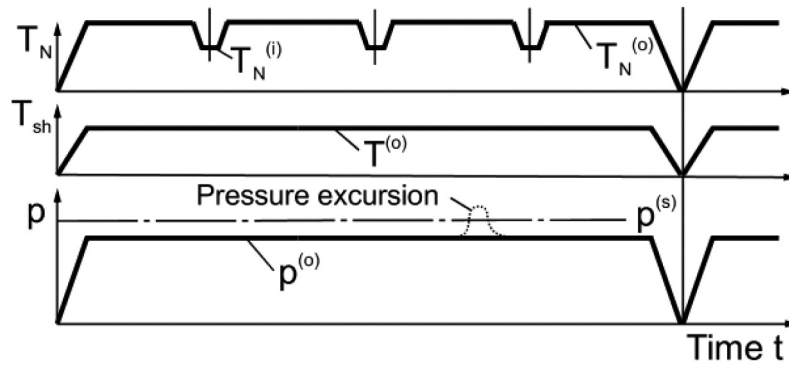


Figure 15. Cold media injection – load history.

Table 5. Materials for example with multiple materials.

	Shell	Reinforcement	Weld	Nozzle
Material	10CrMo9–10	11CrMo9–10+ QT	80% of 10CrMo9–10	16Mo3
Material standard	EN 10028–2	EN 10216–2 (EN 10222–2)		EN 10216–2 (EN 10222–2)

Table 6. Cold media injection – pressure and temperature specification for the operation period of 2000 h.

Load Case	Index	Nominal conditions
Maximum allowable	(s)	$p^{(s)} = 85 \text{ bar}$ , $T^{(s)} = 480^\circ\text{C}$ , 12 h within each operating period simulated
Stationary operation:	(o)	$T_{sh}^{(o)} = T_N^{(o)} = 475^\circ\text{C}$ ; $p^{(o)} = 80 \text{ bar}$ , 1916 h during each operating period
Cold media injection	(i)	$T_{sh}^{(i)} = 475^\circ\text{C}$ ; $T_N^{(i)} = 415^\circ\text{C}$ ; $p^{(i)} = 80 \text{ bar}$ , short duration, 3 injection cycles within each operating period, duration of one injection cycle 24 h
Shutdown (unloading)		$T_{sh}^{(o)} = T_N^{(o)} = 20^\circ\text{C}$ ; $p^{(o)} = 0 \text{ bar}$ , Duration of 1 h within simulation

Table 7. Global reference stress for stationary operation load case.

	Shell	Reinforcement	Weld	Nozzle
Material	10CrMo9–10	11CrMo9–10+ QT	80% of 10CrMo9–10	16Mo3
Reference Stress $\sigma_{IG}^{(k)}$ [MPa]	99	99	79	91

### Constitutive law for temperature variations

In cases with temperature variations, temperature dependence of the creep constitutive law has to be included. For this example, a very simple but conservative approach (Figure 16) was used:

The Norton coefficient ( $n_{(int)} = 7.12$ ) is based on the creep strain limits for the most important temperature (in this case  $475^\circ\text{C}$ ) (Eq. 4). For this temperature can be calculated by Eq. 5, resulting in a creep law which fits

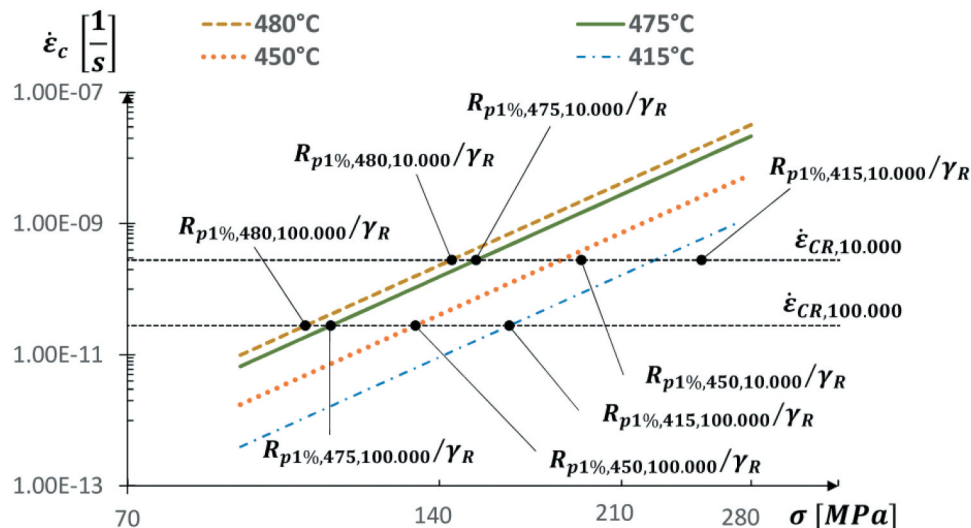


Figure 16. Norton creep law ( $n_{(int)}$ ) for 10CrMo9–10, temperature dependent with partial safety factor  $\gamma_R = 1.25$ .

the two used creep strain limits. Because a partial safety factor for the resistance is used here, the resulting value ( $K_{(int)} = 8.11E - 26s^{-1}$ ) is greater than the one determined for the simple case with single material and constant temperature.

For other temperatures where creep strain limits are given in the material standard, is left constant, and  $K$  is adjusted to be on the conservative side. The temperature dependence of  $K$  is input into Finite Element software (ANSYS®), and the linear interpolation (performed within the software) of  $K$  between temperature values results in a curve for temperature dependence as shown in Figure 17. This approach results in greater creep rates than using the usual exponential dependence of the creep rate on temperature, and, therefore, is conservative.

In the software (ANSYS®) the exponential dependence of the creep rate to the temperature is also implemented [14]. In this case, the parameters could be determined by parameter optimisation. This should be done in such a way that the resulting creep law is on the conservative side.

This type of creep parameters were calculated for the shell, the reinforcement, and the nozzle material. For the weld material, 80% of the creep stain limits of the shell material were used.

### Results of simulation

The temperature distribution was determined by a thermal analysis prior to the structural analysis. Figure 18 shows the temperature distribution during cold media injection. During all other load cases, there are spatial constant temperatures.

At the beginning of the simulation, the stress and strain show the greatest values in point A (Figure 14). After stress redistribution, the greatest values arise in point B. This point B is also the location with the maximal accumulated creep strain (after 10000h). The stress variations are greater at point A, and, because fatigue is expected to be greater there, evaluation of this point is also necessary.

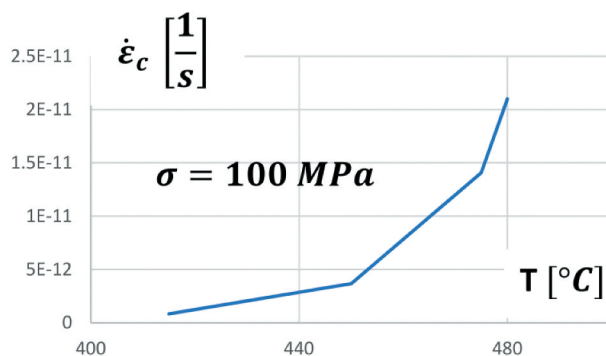


Figure 17. Norton creep law ( $n_{int}$ ) for 10CrMo9-10, modelling of temperature dependence by linear interpolation of  $K$ .

Type: Temperature  
Unit: °C

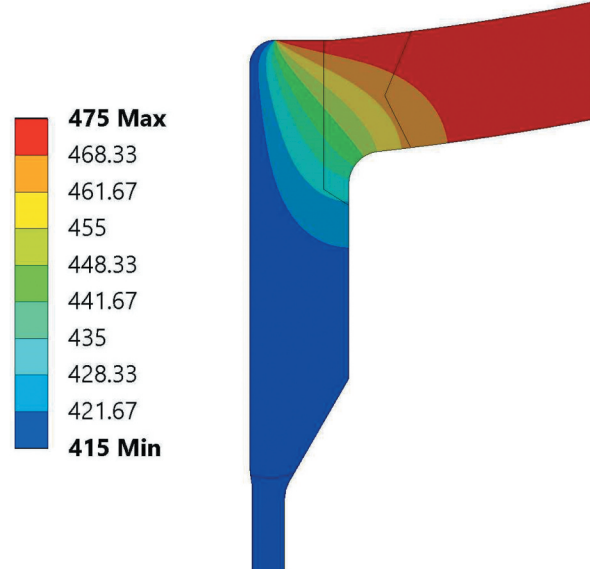


Figure 18. Temperature distribution during cold media injection.

The plot of the equivalent stress (Figure 19) shows the stress redistribution during the first stationary loading period. Due to the injections, peaks in the stress arise. Due to greater strain rates during the injection periods, after the injections stress values are decreased. After each operation period (2000 h and 3 injection cycles), the decrease of stress due to unloading is visible. After the second injection, within each operating period, a short period with the maximum allowable conditions were included. This is the reason why the stress is increased there.

When looking at the equivalent creep strain (Figure 20), the increased creep rate during the injections is visible. After the injections, the creep rate is decreased, which results in a slightly increased equivalent creep strain in comparison to the creep strain during stationary operation.

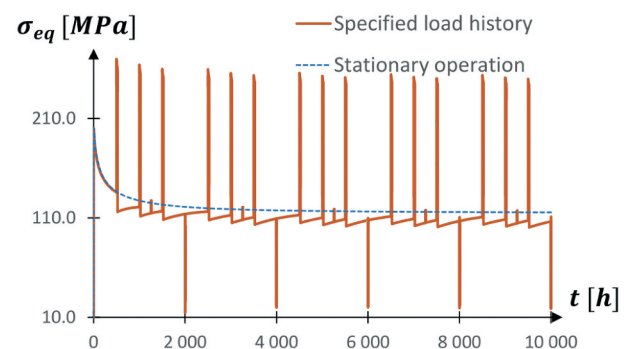


Figure 19. Von Mises equivalent stress in point A (Figure 14) for specified load history (Table 6) and stationary operation.

The plots of equivalent stress do not show information, if tension or compression stresses arise. A plot of the stresses vs. strains, both in circumferential direction, (Figure 21) shows that, due to the stress redistribution, compressive stress occurs after unloading.

In point B, where the greatest creep strain is accumulated, the deviation of the creep strain within the specified load history to the one with constant stationary operation is small (Figure 22).

### Check for creep reversal

The check for reverse creep (see also 3.5.1) is performed by subtracting the equivalent creep strain from the accumulated one at the end of the simulation (Figure 23). Values below 0.0017% are determined

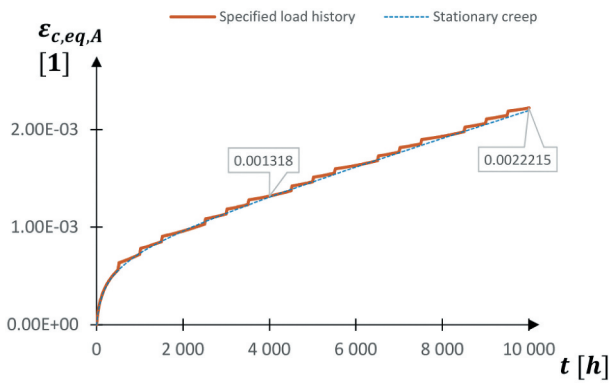


Figure 20. Equivalent creep strain in point A (Figure 14) for specified load history (Table 6) and stationary operation.

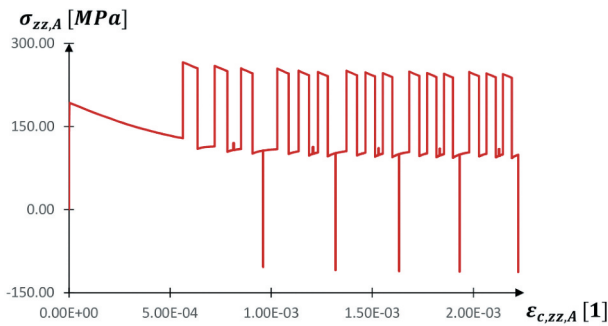


Figure 21. Circumferential stress vs. circumferential creep strain in point A (Figure 14) for specified load history (Table 6).

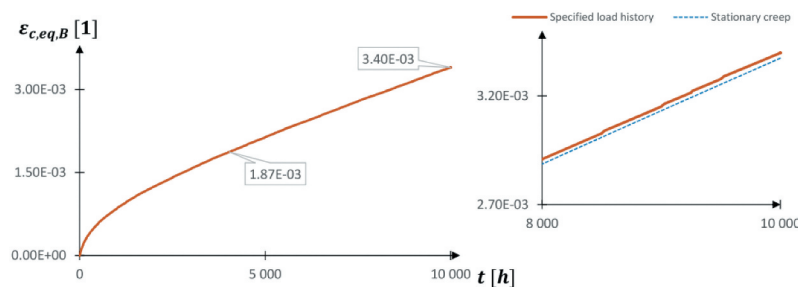


Figure 22. Equivalent creep strain in point B (Figure 14) for specified load history (Table 6) and stationary operation.

with the maximum value at the outside of the shell at the edge of the weld (point B1 in Figure 14). During the investigation of the stress and strain components, in the curve of the circumferential stress v. circumferential strain, very small stress reversal was detected (Figure 24).

Since the area affected by creep reversal is very small, the global behaviour of the structure is not expected to be significantly influenced by repeating primary creep. Only the determined stress values in the small region affected by creep reversal may be incorrect.

### Calculation of damage

#### Linear Fraction Rule combined with strain concentrations (LDFR-EPC)

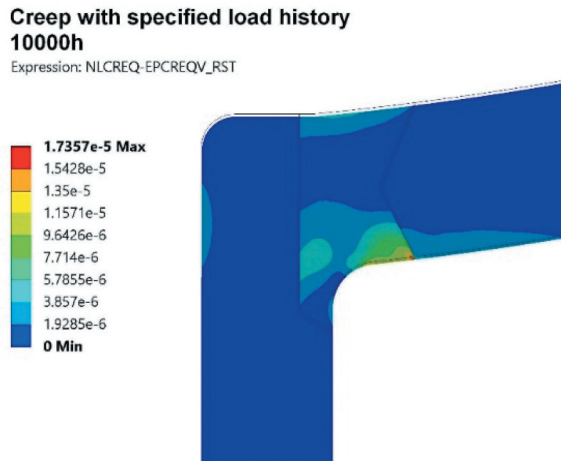
Damage calculation based on the Linear Fraction Rule combined with strain concentrations is relatively complicated and was performed for this example in [3]. The determined creep damage usage factor for 100000h is 0.133 for point A and 0.507 for point B.

#### Ductility Exhaustion rule (DEM)

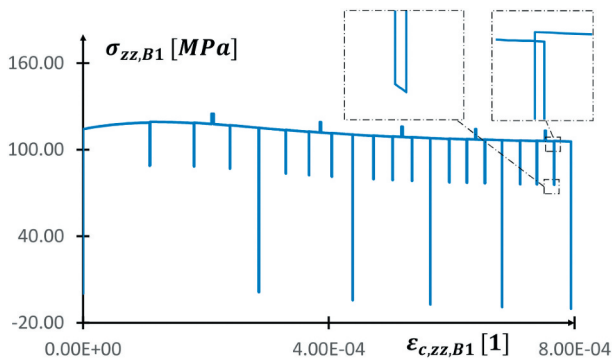
Determination of creep damage according to DEM is relatively simple. As a first step, the creep strain after 100000h is calculated by extrapolation. If continuous decrease of the creep strain, which is accumulated during an operation period, is assumed, such extrapolation is conservative, and the simulation of the first 10000h is sufficient. Afterwards, the creep damage is determined (Eq. 25) with an allowable creep strain of 5% (Table 8).

### Discussion

Reference stresses, especially the global reference stress  $\sigma_{rG}^{(k)}$  are very useful for creep damage calculations. This stress gives information about the stress range, which is important for the global behaviour of the structure. For stationary creep load cases with constant load and temperature, the determination of reference stresses is straightforward. The reference stress is useful in finding the most important region of the creep constitutive law, and for variation of the parameters of the creep law. Additionally, some



**Figure 23.** Difference between accumulated and equivalent creep strain after 10000h of creep with specified load history.



**Figure 24.** Plot of circumferential stress vs. circumferential strain for point B1 (Fig. 14).

**Table 8.** Creep damage usage factor calculated for DEM, load specification according to Table 6, 100000h operation (partial safety factor  $\gamma_R = 1,25$ ).

Point of evaluation	Point A	Point B
Extrapolated strain for 100000h	1.53%	2.54%
Creep damage $D_c$	0.306	0.508

interesting methods of damage calculation are based on reference stresses. In the case of load and temperature variations, finding proper reference stresses is complicated and impractical for design purposes. Therefore, in such cases, all methods, which require consequent determination of reference stresses, are difficult. Such methods are the variation of the Norton exponent based on reference stress (see 3.3.2) and damage determination based on strain concentrations (see 3.4.2).

To do creep simulations, the relation between stress and strain rate has to be described by constitutive laws. If we search in material standards for material parameters, which describe the creep strain rate, the creep strain limit is the only useful parameter. The mean creep rates, which are calculated from these strain limits, are a relative robust basis for the simulation. The calculated

creep strains are in the right order at least for pure forward creep. More complicated approaches, e.g. with minimum creep rates and separated primary creep, may be more accurate, but more complicated with higher risk of errors in the analysis.

The analysis becomes unreliable, if no mean strain rates are available within parts of the considered stress and temperature range. Especially, for the small strain rates which arise at the core of structures, the data basis is relatively poor and conservative approaches (see using sinh-based creep constitutive laws) may be necessary. In some material standards (e.g. EN10216-2) no creep strain limits are given at all. In these cases, creep simulations based on data from the proper material standard is not possible. Using data for similar material (e.g. forging material, EN 10222-2, instead of pipe material, EN10216-2) is technically possible, but not consistent with some regulations (e.g. PED [2]).

Safety factors, which have to be taken into account within the Excessive Creep Strain check, are not properly defined: EN 13445-3 [1] uses partial safety factors within this part of the standard, and is in some parts unclear on the specification of these safety factors [4]. From the technical standpoint, the creep strain limits as well as the creep rupture strengths in European material standards are specified as mean values. Therefore, to be conservative, a partial safety factor for the material (e.g.  $\gamma_R = 1,25$  see also 4.2) had to be used. When we examine at the Design by Formula part of EN 13445-3, safety factors of one are specified for creep strain limits (if used at all). This specification means (as rule of thumb) that the global reference stress  $\sigma_{r,G}^{(k)}$  is limited to the creep strain limit, resulting in a global reference strain of 1% without any safety factors. Therefore, introducing a safety factor for the material of 1.25 may be overly conservative in comparison to the Design by Formulae part of the standard.

The partial safety factors for the actions (pressure,  $\gamma_p$ , and temperature) are set to one in this paper. This is in accordance with the Fatigue Design Check, because creep and fatigue damage have to be added for creep fatigue interaction. Despite that, the considered history of the actions has to be chosen in a way that the resulting damage is conservative.

Hyperbolic sine-based creep laws (Equation 9) were defined as conservative alternative to Norton's creep law. The results with these creep laws are only strictly conservative in comparison to Norton's law, if the creep law is chosen in a way that the curve stress vs. creep rate (Figure 4) is tangential to the one for Norton's law. As long as the relevant stresses (described by the global reference stress) are near to the used creep strain limits, the results are within the same range. In cases where the relevant stresses are

considerably smaller or greater than the given limits, the use of hyperbolic sine-based creep laws may be an alternative. In common cases, this will not be a problem: If the relevant stresses are much smaller than the given strain limits, creep strains will not be relevant. Cases where the relevant stresses are much larger than the creep strain limits are not admissible.

## Conclusions

For the Excessive Creep Strain Check based on material parameter given in material standards, creep strain limits can provide the basis for simple creep constitutive laws. Here Norton's law is the simplest option, and a hyperbolic sine-based creep law may be a conservative alternative in special cases.

These secondary creep laws are based on mean creep rates, which include primary creep once at the beginning. For cases with creep reversal, where primary creep occurs several times, this type of constitutive law will generate non-conservative results. A simple check for creep reversal was used in this paper. If the core of the structure shows pure forward creep (creep reversal only on very small boundary areas), it is expected that the global behaviour is sufficiently covered. If creep reversal in small regions is caused by constraints due to geometric discontinuities, only small errors in the maximum accumulated creep strain values are expected.

Different methods for creep damage determination were considered:

Stress-based methods are straightforward, because creep damage determination in most standards works with stress values, and relevant material data, which is mainly the creep rupture strength, are as well stress values. Within these methods, strains due to stress redistribution are not included. The damage depends highly on the maximum stress, and that depends on the creep law, in case of Norton's law on the Norton exponent.

Methods based on strain concentration can still use the methods given in most standards, but may include strains due to stress redistribution. They are less sensitive to parameters of the creep law (Norton exponent). The most notable disadvantage of these methods is that a reference stress, which forms the basis for the reference strain rate, has to be calculated. Another problem may arise from the fact that an allowable creep life must be determined from the creep rupture strengths for the global reference stress instead of for the larger maximum stress: The smaller stress values may not be covered within the material standard, and, therefore, the design standard may require a very conservative approach.

Ductility Exhaustion Methods (DEM), which use the maximum accumulated creep strain directly, are directly applicable to simulation results and cover

strain due to stress redistribution even in complicated scenarios. It needs no reference stresses, and, therefore, application in situations with load and temperature variation is straightforward. One disadvantage of the method is that the common stress data, which is used in most standard procedures, is not used at all. The resulting damage results from the creep strain limits, which are inputted in the creep law, and the allowable creep strain limit.

In the context of allowable creep strain limits, it must be emphasised that creep design according to EN 13445-3 is limited to creep ductile materials. In this context, an allowable creep strain limit of 5% is specified. Therefore, in the case of CSEF steels (particularly Grade 92), it has to be considered that their creep strain limits may fall below 5% [15,16].

## Nomenclature

### Symbols:

$A^{(k)}$	action (load – here pressure)
$A_e$	action, at which the maximal elastic stress reaches the elastic limit
$A_u$	limit action (load)
$C1, C2$	parameters of sinh creep law
EF	strain concentration factor
$D_c$	creep damage usage factor
$E$	modulus of elasticity
$K$	constant of Norton's creep law
$n$	exponent of Norton's creep law
$p^{(k)}$	pressure at load case $k$
$\Delta t^{(k)}$	time interval for creep damage calculation
$\Delta t_{all}^{(k)}$	allowable lifetime for creep load case ( $k$ )
$\Delta t_{RG,all}^{(k)}$	allowable lifetime for creep at reference stress
$T^{(k)}, T_N^{(k)}, T_{Sh}^{(k)}$	temperature, $T$ at nozzle, $T$ at sphere
$R_{m/T/t}$	creep rupture strength at temperature $T$ and time $t$
$R_{p1\%/T/t}$	creep strain limit for 1% at temperature $T$ and time $t$
RM	yield stress
$\gamma_p$	partial safety factor for pressure action
$\gamma_R$	partial safety factor for resistance
$\epsilon, \epsilon_{ij}$	strain, strain tensor
$\epsilon_c$	creep strain
$\dot{\epsilon}_c$	creep strain rate
$\dot{\epsilon}_{c,G}$	creep strain rate according to global reference stress
$\epsilon_{c,eq}$	equivalent creep strain
$\epsilon_{c,acc}$	accumulated creep strain
$\epsilon_{c,Diff}$	difference between $\epsilon_{c,acc}$ and $\epsilon_{c,eq}$
$\epsilon_{c,all}$	allowable creep strain
$\epsilon_f$	critical ductility for creep
$\sigma, \sigma_{ij}$	stress (one dimensional), stress tensor
$\sigma_{eq}$	Von Mises equivalent stress
$\sigma_{el,max}$	equivalent stress in linear-elastic model; max. value
$\sigma_{ref}$	reference stress for maximum degradation
$\sigma_{rG}^{(k)}$	global reference stress
$\chi$	stress concentration
<b>Superscript:</b> $(k)$	superscript for load cases, s.admissible, o.operating, i. injection

## Abbreviations

PED	European Pressure Equipment Directive
ECS-DC	Excessive Creep Strain Design Check
ECS_AR	application rule for Excessive Creep Strain Design Check
LDFR-SMAX	Linear Damage Fraction Rule with stress maximum

(Continued)



PED	European Pressure Equipment Directive
ECS-DC	Excessive Creep Strain Design Check
ECS_AR	application rule for Excessive Creep Strain Design Check
LDFR-SMAX	Linear Damage Fraction Rule with stress maximum
LDFR-EPC	Linear Damage Fraction Rule with strain concentration
DEM	Ductility Exhaustion Method
n_int	Norton creep interpolated
sinh_int	sinh creep law interpolated
sinh_tan	sinh creep law tangential to Norton's law

## Acknowledgments

The simulation model and most of the simulations shown in this paper are taken from the diploma thesis [3] of A. Seifert. F. Rauscher wrote the actual text. In comparison to the diploma thesis, the damage determination method was updated and extended, and the option of hyperbolic sine-based creep law was included.

For the simulations, the FE-Software ANSYS® Student 2019 R2, and Ansys® Academic Research Mechanical, Release 2020. R2 were used. Images used courtesy of ANSYS, Inc.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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