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ANALYSIS METHODS FOR INTEGRITY ASSESSMENT OF STEAM GENERATOR TUBES UNDER HIGH TEMPERATURE AND PRESSURE LOADS

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ABSTRACT

The integrity of steam generator tubes in pressurized water reactors (PWR) is of particular concern in accident conditions as well as in normal operation. These tubes may show degradation due to corrosive effects especially during increased service time. In consideration of a postulated high-pressure core melt scenario based on thermal-hydraulic calculations, different analysis methods have been compared concerning their predictive capabilities to assess creep induced failure of pressurized components. In a first step, material data for the steam generator material Alloy 800 (mod.) has been composed. A failure time surface has been generated by structural finite element analyses of steam generator tubes. Larson-Miller Parameters (LMP) were fitted to approximate the failure time surface using a weighting algorithm. Different methods available under the GRS-developed platform ASTOR (Approximated Structural Time Of Rupture) were tested on their applicability in this context. ASTOR includes methods based on linear damage accumulation of failure times, a method based on the reduction of highly symmetrical components to a single infinitesimal element and an automatic coupling to the Open-Source FEM-program Code_Aster with pre-generated models. For a selected application case the different failure assessment methods are compared and the application limits as well as the accuracy of the methods are discussed.

INTRODUCTION

In face of severe accident scenarios with melted core material the integrity assessment of primary circuit components requires a special concern. Steam generator tubes as part of the pressure boundary of the primary circuit form a barrier for the retention of radioactive materials [1]. An early failure during a high-pressure core-melt scenario can cause a release into the secondary circuit. A reduced outer diameter due to wastage corrosion of steam generator pipes can further support an early failure [2].

GENERATION OF ALLOY 800 (MOD.) MATERIAL REPRESENTATION

Compilation of material data curves

The nickel based material Alloy 800 (mod.) is used as material for steam generator tubes of the German pressurized water reactors. Due to a lack of available material data, similar material Alloy 800 and Alloy 800H are employed here for the generation of a material representation. In table 1 the linear elastic material properties of Alloy 800 (mod.) are displayed [3].

Table 1. Linear-elastic material data of Alloy 800 (mod.) [3]

T (°C)	E (MPa)	Poisson's Ratio
20	196500	0.339
500	165000	0.367
600	157700	0.373
700	150100	0.381
800	141300	0.394
900	132500	0.394
1000	123700	0.394

Figure 1 shows the synthetic temperature dependent true stress strain relation of Alloy 800 (mod.). The data were derived from different literature sources [3][4][5][6].

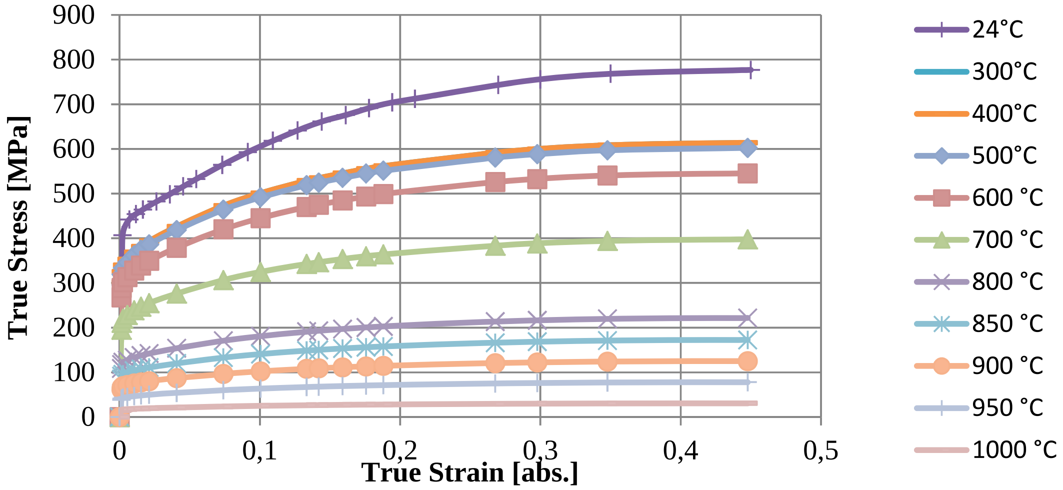

Figure 1. True stress-strain curves of Alloy 800 (mod.) [3][4][5][6]

The stress (σ) and temperature (T) dependent creep strain rate ($\dot{\varepsilon}$) is described by the Norton equation using Parameters c_1 and c_2:

$$\dot{\varepsilon}_{creep} = c_1 \cdot \sigma^{c_2} \tag{1}$$

In figure 2 the temperature dependent creep strain rates are displayed. The parameters are taken from literature sources [3][7].

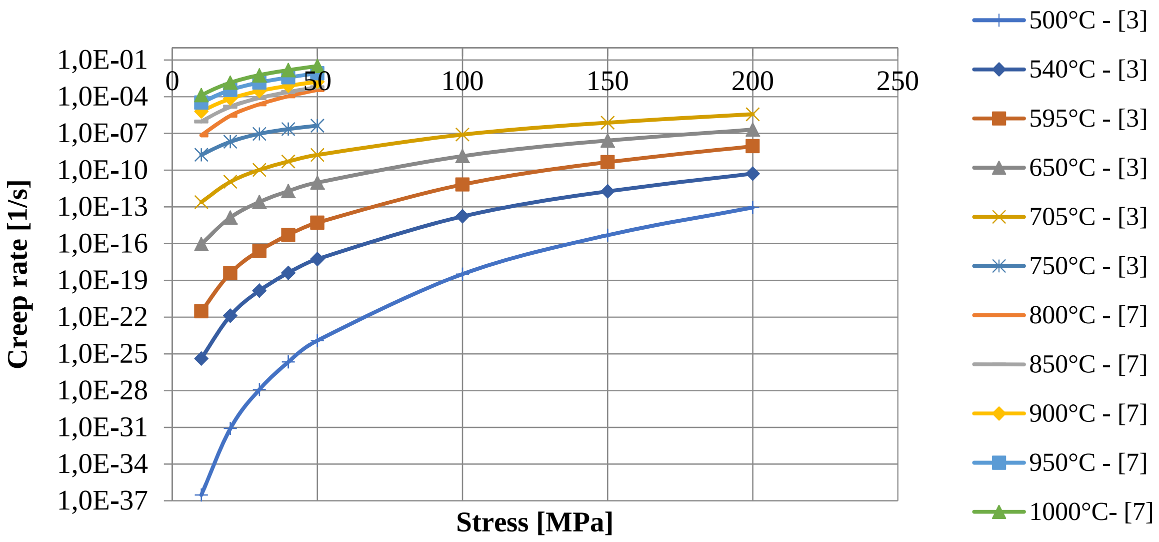

Figure 2. Creep rates of Alloy 800 (mod.) [3][7]

Due to the need for creep rates related to high stresses which may occur in the short time domain, artificial creep rate curves are required. Therefore, trend analyses for all creep rate curved were performed by employing the Norton equation (formula 1).

As an example in figure 3 the trend analysis of a creep rate at 900°C is shown. The Norton parameters are determined by $c_1 = 2.0E\text{-}09$ and $c_2 = 3.48$.

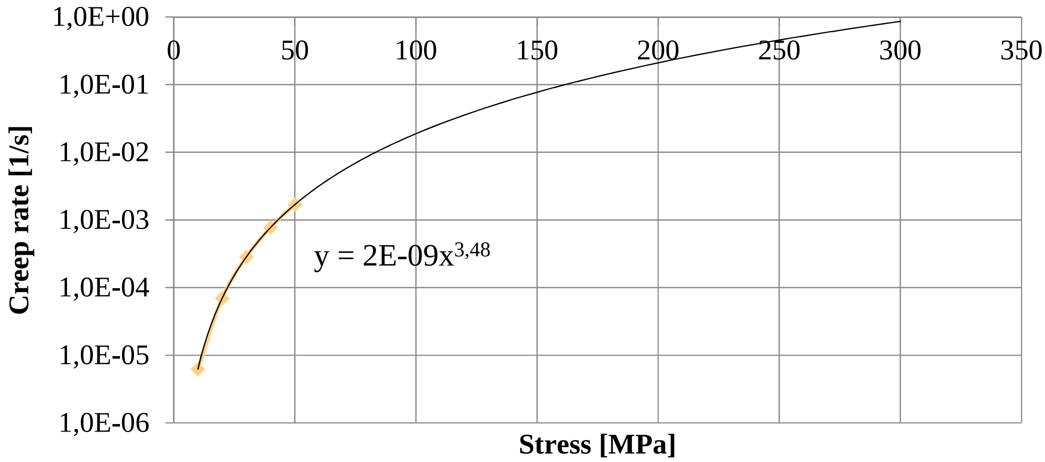

Figure 3. Extrapolation of a creep rate curve

In figure 4 the artificial creep rates based on Norton parameter sets are displayed [3][7].

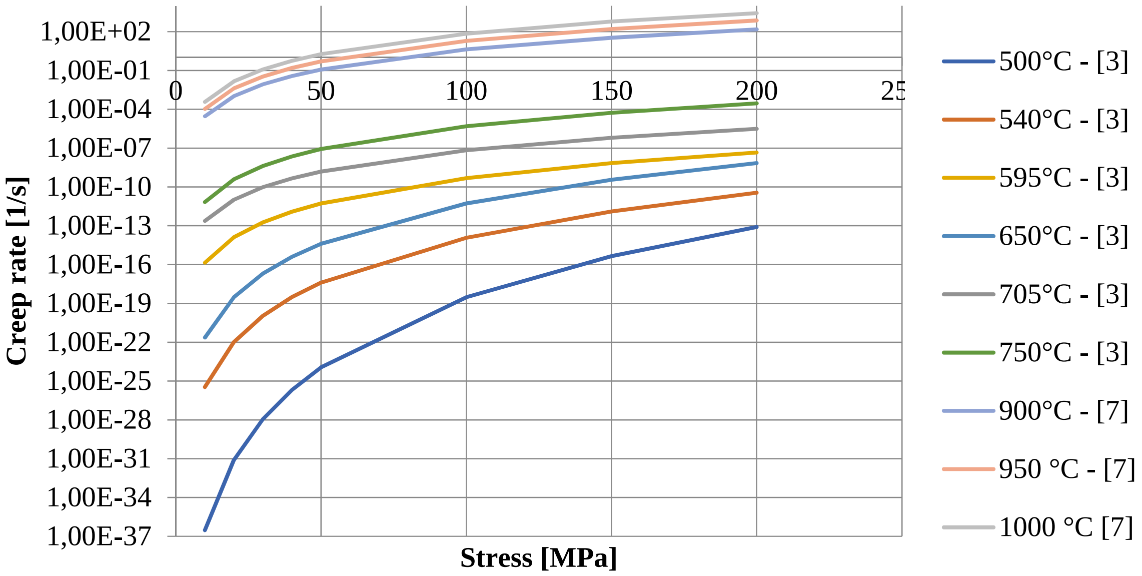

Figure 4. Artificial creep rates of Alloy 800 (mod.) [3][7]

Derivation of Failure-Time Surfaces

Failure times of the pipe structure under combinations of pressure steps and temperature steps are determined by finite element analysis with the FE code ADINA [8]. Performing several numerical analyses of this kind to cover the ranges of temperatures and pressures to be expected in an accident yields a series of structural failure times which can be regarded as discrete pivots of a continuous failure time surface in the failure time-temperature-pressure space.

In the following a failure surface of a steam generator tube with the geometry inner diameter 19.54 mm and wall thickness 1.23 mm is considered. In figure 5 the calculated times of failure due to different constant temperature/difference pressure loads are summarized. A total of 95 FE-computations were performed. There are 5 pressure steps from 9 MPa up to 18 MPa. The temperature progression covers temperatures from 660 °C up to 840 °C (19 temperature steps). The correlation between increase of failure time and decrease of pressure and temperature is obvious. Failure times above a time limit of 40000 s are not considered. The load steps of 9,11,13,15 and 18 MPa are displayed.

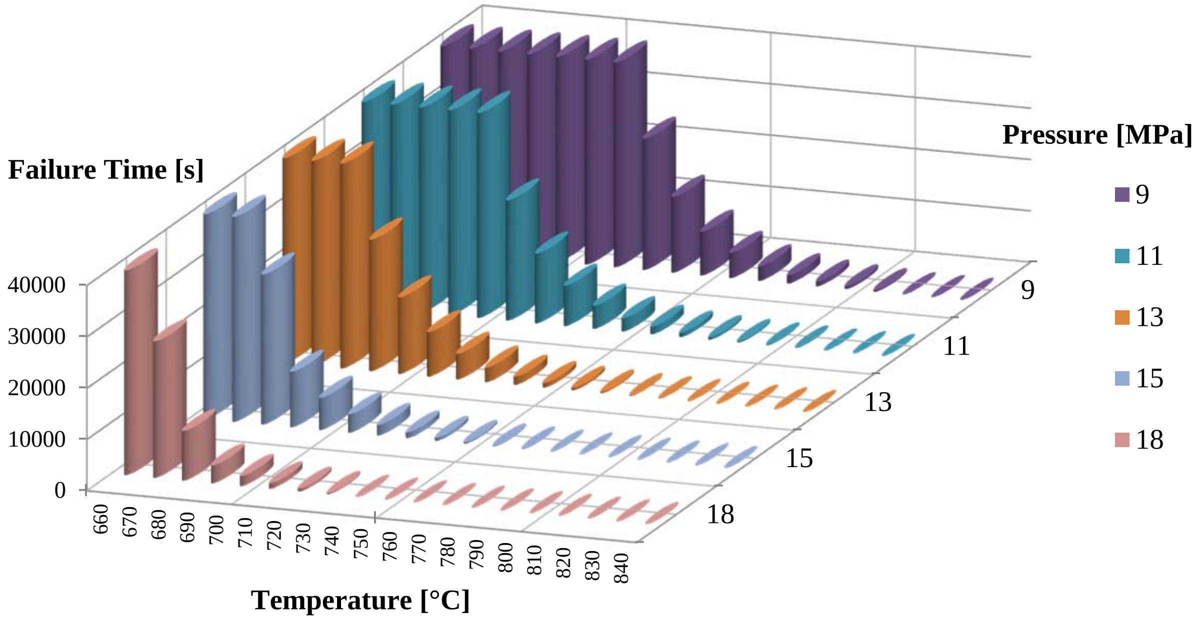

Figure 5. Failure time surface for steam generator tube

Derivation of Larson-Miller Parameters

There are several empirical formulas in use which, on different levels of sophistication, describe the dependence of the rupture time on stress and on temperature [9]. The Larson-Miller Parameter approach is a simple way of predicting the time of failure [10][11] (equation 2):

$$P_{LM}(\sigma) = T \cdot [log(t_F) + C] \quad (2)$$

with: P_{LM}: Larson-Miller Parameter, σ: Stress [MPa], T: Temperature [K], t_F: stress failure time [h], C: material constant.

The Larson-Miller Parameter can be described by stress dependent formulations (equations 3 and 4):

$$P_{LM}(\sigma) = a_1 + a_2 \cdot log(\sigma) \; [straight\ formulation] \quad (3)$$

$$P_{LM}\,(\sigma) = a_1 + \sqrt{a_2 + a_3 \cdot log(\sigma)} \; [parabola\ formulation] \quad (4)$$

The parameters a_1, a_2, a_3 and C are calculated for the linear formulation and the parabola formulation by the numerical method of least squares. As input data the results of the FE-analyses (failure time surfaces) are employed. In the table 2 the parameter sets are displayed.

Table 2. Stress dependence of calculated Larson-Miller Parameter

Material	Stress dependence	a_1	a_2	a_3	C
Alloy800 (mod.)	Linear Formulation	*4.4 10^4*	-7.1 10^3		28
Alloy800 (mod.)	Parabola Formulation	*5.9 10^3*	*1.5 10^9*	*-3.9 10^8*	*30*

GRS CODE ASTOR

The code ASTOR (Approximated Structural Time of Rupture) was developed by GRS in the early 90s containing a single method for fast assessment of component integrity under severe accident loads [12]. This method is based on a time-step-wise linear damage accumulation. Damage increments are calculated for each time-step from the relation between current time-step-length dt and failure-time t_F for a situation, where current loads would be applied constantly (see equation 1). Failure can be assumed when the damage parameter D(t) reaches a value of 1 or smaller if safety factors are included (see equation 5).

$$D(t) = \sum \frac{dt}{t_F\,(T(t), p(t), \ldots)} \tag{5}$$

The failure time t_F is obtained by interpolating in a pre-calculated matrix, where results of numerical analyses or experimental results are stored, covering a range of loads to be expected in a specific accident. Typically, this matrix is a two-dimensional failure time surface and refers to dimensions inner pressure and global temperature, but arbitrary loads and higher dimensions are possible, e. g. for the assessment of RPV integrity with inhomogeneous loads [13] or steam generator tubes with different degrees of damage. A downside of the method is a certain inflexibility due to the pre-calculated matrix being inevitably linked to a specific component geometry, material and load range. Furthermore, the simplifications of this method induce some inescapable errors. To overcome this problems ASTOR was extended by additional methods with compensating advantages and disadvantages. It was further ported into a JAVA environment and provided with a self-explaining graphical user interface to increase usability, especially for users without specific knowledge of structural mechanics. A library of geometry and material data was integrated and can be used beside user-defined data. The program now forms a single interface for methods for failure assessment under severe accident loads and can be used either stand-alone or as post-processing-tool in conjunction with codes for severe accident analysis, such as ATHLET/ATHLET-CD [14], ASTEC [15] or MELCOR [16].

As a first additional method, failure assessment using Larson-Miller Parameters (LMP) was integrated into the ASTOR code. The method also employs a linear damage accumulation, but failure time is calculated from the Larson-Miller relation (see equation 2). The Larson-Miller Parameter depends on component geometry, load and material, but can be represented as a function of normal stress for a specific material so that a component dependency is dispensable. Although this method is known to be only medium precise, it has the advantage of getting along with only little material data. It is currently used as standard method in a series of international codes for severe accident assessment [17].

The second additional method FAST (Fast Assessment of Symmetric Component Rupture Time) was newly developed by GRS. In this approach, the component is reduced to a single 0-dimensional element, which represents the stress and strain state all over the component. This restricts the calculation to symmetric geometries and loads, such as pipes, spheres, plates or rods under homogeneous mechanical and thermal loads. However, there are tricks implemented to calculate components under simple asymmetrical loads (e. g. thermal gradient, bending momentum). For each time-step stress, strain increment and geometry are iteratively recalculated (see figure 6). FAST allows the correct consideration of effect of large deformations on the load situation. By furthermore taking into account the separation of ductile and viscoplastic strain as well as the non-linearity of the material properties by taking comprehensive material data relationships into account, the accuracy is further improved. The need for material data can be met by import of material models used in finite element codes. The method is very fast and fills the gap between simple damage accumulation methods and complex finite element models.

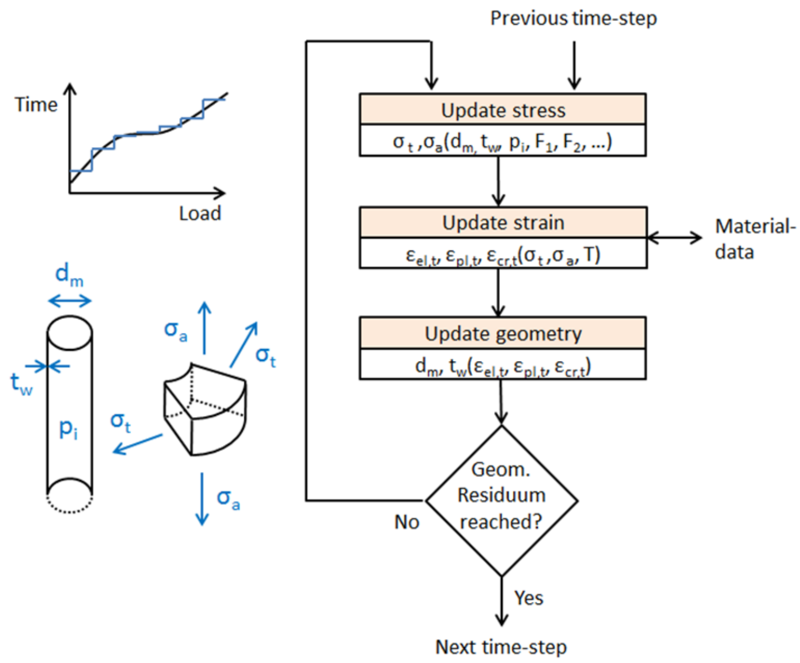

Figure 6. Working scheme of method FAST

Third additional method is the automatic control of the pre-/postprocessor Salome [18] and the finite element program Code_Aster [19]. Both Salome and Code_Aster are distributed under a free license. Prepared input-scripts are supplemented by parameters from user input. Geometry and mesh are generated automatically by Salome. Results are automatically calculated and evaluated by Code_Aster. The aim of this method is to make the diversity, flexibility and accuracy of the finite element method usable in a time-saving and easy-to-handle environment. In this way, also complex components can be assessed. The model library comprises several generic components and is continually being expanded. Simple pipe calculations for example can be performed using an axisymmetric 2D-model.

COMPARISON OF METHODS ON A HYPOTHETICAL SEVERE ACCIDENT SCENARIO

The methods included in ASTOR are compared on a hypothetical severe accident scenario in a PWR of Konvoi type where steam generator tubes made of Alloy 800 (mod.) are significantly heated by steam and hydrogen from the core melt process. A difference pressure between primary and secondary circuit of almost constantly 9 MPa as well as a temperature history of a representative tube (see figure 7) was calculated using the thermal hydraulic code ATHLET. After a constant phase near operational temperature up to about 10000 s temperature rises sharply due to zirconium oxidation in the core. After about 13000 s the temperature gradient slows down and some saturation is achieved. The geometry of the tube in form of outer diameter and wall thickness is taken from original drawings. Along with calculations regarding the original geometry, conditions with 10 % and 40 % abrasive damage, representing wastage, are calculated.

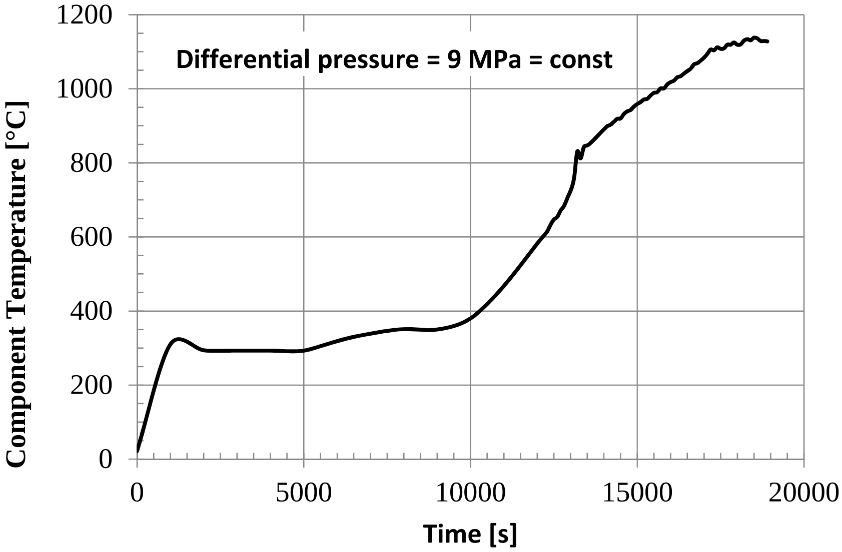

Figure 7. Temperature of the hottest part of a steam generator tube

While the method originally included in ASTOR (here called Classic) and the method based on LMP deliver damage increments as a result, methods FAST and the automatically controlled finite element calculation with Salome and Code_Aster (FEM) deliver strains, so that a pairwise comparison is done (see figure 8 and figure 9).

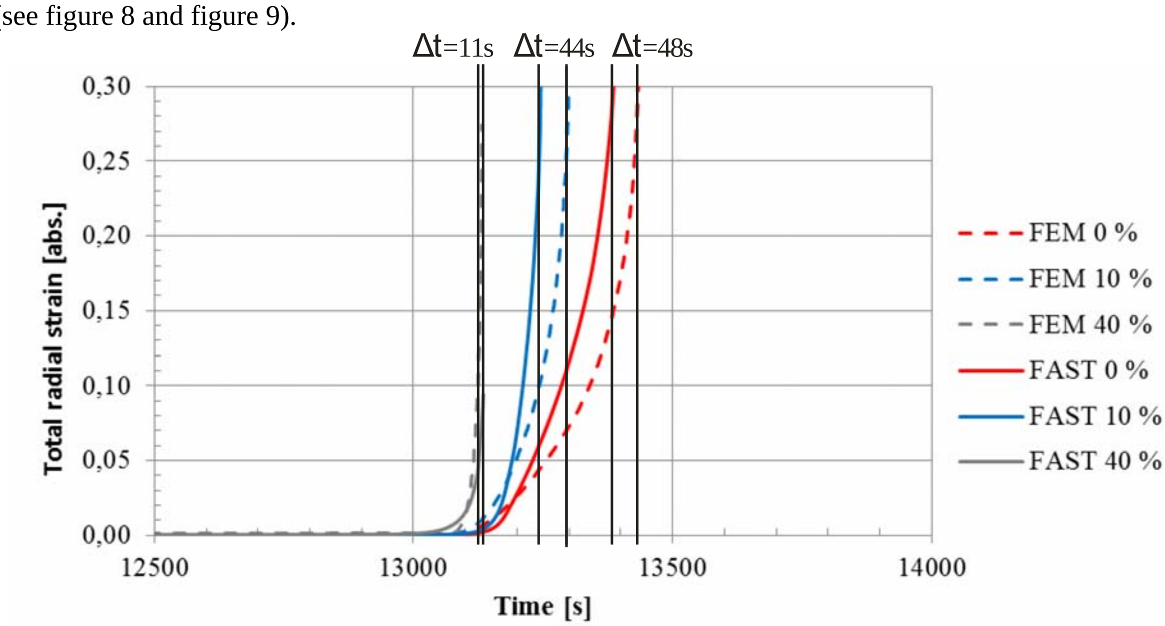

Figure 8. Time history of total strain for methods FAST and FEM

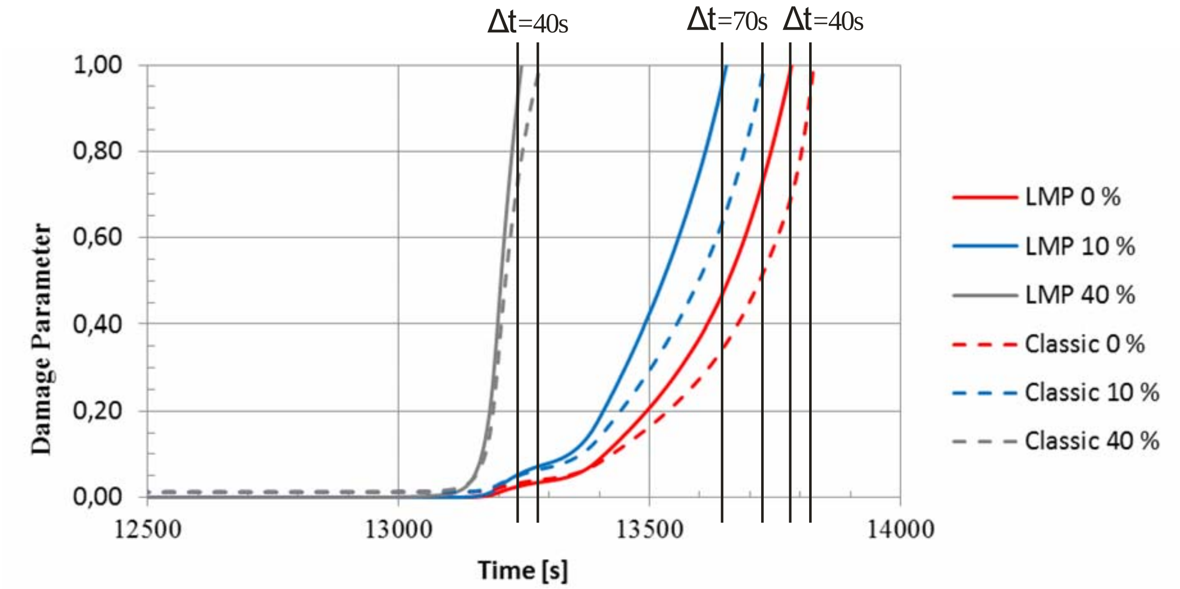

Figure 9. Time history of damage parameter for methods ASTOR classic and Larson-Miller

FAST and FEM are good in line (differences in range from 11 s to 48 s) with each other regarding failure time and strain, especially in the case of 40 % damage. For calculations with 0 % and 10 % damage, viscoplastic strain contributes extensively to the total strain before ductile strains arises (not in picture) and finally leads to failure in form of plastic instability/necking. For 40 % damage, only a small amount of viscoplastic strain is preceding the sudden rise of ductile strains. LMP and ASTOR classic are in good agreement with each other (discrepancies range from 40 s to 70 s) and in acceptable agreement with FAST and FEM, only for the case of 40 % damage, but cannot deliver information about the composition of the strains. The overestimation of the failure time with LMP and ASTOR classic for the damage 0 % and 10 % and the rather gradual increase of damage possibly origin from the error made due to superposition of non-linearities in material behaviour and geometry change, the loss of information during generation of failure time surfaces, and the lack of separation between viscoplastic and ductile deformation. Unlike in the area of life-time-assessment, where only moderate geometry change, mostly constant loads, and little ductile strain is observed, those aspects cannot be neglected for short-time failure. Similar investigations especially with ASTOR classic and FEM have been performed for a large scale test with a sample of a main cooling line as well as a cooling loop of German type Konvoi under postulated severe accident loading [20][21].

CONCLUSION

Material data for the nickel based material Alloy 800 (mod.) has been derived. Failure time surfaces for a steam generator tube made of Alloy 800 (mod.) were generated and Larson-Miller-Parameter were derived. The required data are taken from literature sources and partly include material data of a similar alloy which may cause some uncertainty. Because the material data are only available for a limited range of stresses and temperatures extrapolated data by trend analysis has to be used.

Methods included in the GRS code ASTOR have been presented and compared on a hypothetical severe accident scenario. The advantages and disadvantages of the methods have been discussed. Methods based on linear damage accumulation tend to overestimate failure time in this example.

The further development of ASTOR will lie in the improvement of existing methods, e. g. in form of additional component models, the extension of available hard-coded data and further validation, as well as in the integration of new methods, e. g. methods for bulging and buckling, cracked components and simple methods for the prediction of the leak area in case of local failure. Additionally, the usability of the code will be improved by adding additional possibilities for data input and result visualization.

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