Lifetime management - Assessment of Damage in Piping Systems operated in the Creep Range

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Abstract

The accurate determination of lifetime exhaustion for heavy duty components is indispensable for a safe and at the same time cost-effective operation of power plants. The most important parameters evaluated hereby are material and geometry parameters, as well as measurement data seized from the ongoing operation of the plant.

Concerning the measured parameters, uncertainties within the data may arise and must be taken into account. Due to these uncertainties, appropriate safety margins and factors must be provided within the design phase. On the other side, considering safety aspects by the calculation of the lifetime consumption may lead to a high overestimation of the real value. By avoiding this overestimation, operational reserves could emerge which were really economically relevant.

In the following, the assessment of the remaining lifetime of components is presented, while especially focusing on the accurate determination of calculation parameters and some progressive assessment methods.

1 Motivation and concepts

In order to ensure a long-term and safe operation of power plants, operational changes within the plant must be assessed with very high accuracy. Regarding the lifetime aspects, all loads acting on the corresponding components of a plant must be considered accordingly.

The lifetime of pressurized components operated in the high temperature range is, besides of the manufacturing and installation based defects, limited by some operational, material damaging processes. The most important of these processes result from two types of loading: the creep range temperature and the cyclic loading.

Figure 1 shows schematically the frequency of component failures depicted in dependence of operation time ("Bath Tube Curve"). Shortly after the initial start-up, an increase must be expected due to deficits in the manufacturing and installation quality. Subsequently, there is a longer phase of low failure frequency, followed by a phase where the frequency of component failures is increasing again.

![Figure 1: Schematic illustration of the failure frequency of power plant components](image-url)
The reason for the increase can be

a) the normal material degradation of material properties due to operational influences, or
b) some additional operational load, not covered by the design rules, or a changed mode of operation causing a related additional damage contribution.

The damage resulting from case a) is in concordance with the damage value calculated according to the design rules.

The scatter band of the increase in figure 1 has the following reasons:

1. Quality of manufacturing
2. Input values for the damage assessment
   o Operational data
   o Loads not considered within the design process
   o Deviations from the designed geometry
3. Stress evaluation using common methods
   o Applied evaluation methods and stress failure hypotheses
   o Safety factors
4. Lifetime assessment
   o Material parameters (reference values)
   o Damage accumulation rules

Interferences between primary and secondary loadings, but also between different damaging mechanisms

1.1 Creep related damage

For the assessment of the creep related damage of components, the lower bound of the scatter band of the creep rupture strength is taken into consideration. Under normal circumstances, the real value of the creep rupture strength of the corresponding steel cast is in fact higher than this lower bound. This automatically leads to an overestimation of the calculated damage, whereby deviations of many 100 % may arise [2], especially if the real creep rupture strength is located within the higher area of the scatter band.

The relation between the real damage occurring within the material, e.g. over the process of pore formation during creep range loading, and the assessed damage is influenced by the factors mentioned above, figure 2. In contrast to the assessed damage, the relation between the material degradation, e.g. creep pores formation, and the operation time must not be linear. In fact, the relation is rather of another kind, i.e. the damage is showing a progressive development.

If the loads occurring during the operation time are consistent with the design specifications and the quality of manufacturing is satisfactory, then the material degradation will be not significant when the end-of-life point specified by design is reached. This generally means that, in the case of pure creep loading, there will be no damage (like e.g. pores) observable by means of usual light-optical methods. This is a consequence of the safety factors defined by design, e.g. the lower bound of the scatter band, see [3].
The interesting question here is for how long the operation time can be extended under the present conditions, or even under changed conditions, i.e. for modified load parameters. Operational incidents or other loads not covered by the design rules, e.g. continuous, but unobserved process changes, can lead to a high increase of the damage. In these cases, components will have defects that can be detected. The question here is, how long the remaining lifetime is and which conditions must be required for a continuing safe operation.

These statements suggest that the so-called remaining lifetime, i.e. the residual operation time during which the failure of a component can be safely excluded, must be determined based on the real degree of material degradation. Therefore, non-destructive testing methods like replica or other specific methods see e.g. the ultrasonic laminography approach [1], can be used in order to obtain a better understanding of the current damage state in components.

### 1.2 Cyclic load related damage

Cyclic load related damage is caused by load changes due to changes in the pressure or temperature differences along the wall of a component yielding (secondary) thermal stresses. Figure 3 shows a typical course of values measured on a specific component of a power plant.

From an economical viewpoint, fast start-up’s and rundown’s are desirable which unfortunately lead to very high thermal stresses, therefore considerably reducing the lifetime of the corresponding components.

Considering the steady development of regenerative energy sources where the energy production is subjected to climatic fluctuations, there is an increasing need of operating the existent power plants more frequently in a mid-load and peak load range. As a consequence hereof, the assessment of damage related to cyclic loading grows more and more important.
Figure 3: Temperature and pressure values as provided by a specific point of measurement

Figure 4 shows the configuration of temperature sensors provided for measuring the temperature difference within the wall of a component. This kind of sensor configuration is the default setup in older power plants, but it is relatively expensive due to the need of two sensors and the inherent installation complexity. Unfortunately, the expensiveness of this configuration is not always correlated with its accuracy because the probability of missing the ideal sensor positions is in practice quite high. However, an adaption of the measured values is usually possible (even for a misplaced configuration) and can be performed by using the so-called $f_k$ factors, [6], [7].

Figure 4: Measuring the temperature difference in the wall of a component

The uncertainties regarding the assessment of damage are also related to the problem of exactly evaluating the secondary stresses and their impact on the corresponding integrity
assessment concept. Moreover, the damage assessment is negatively influenced by the fact that operational data can only be recorded at previously selected places. Thus, the most critical components exhibiting the highest wall thicknesses are usually preferred hereby and the measured values are typically, in the sense of a conservative approach, used for the evaluation of other components. However, this “typical” approach is questionable since it is based on the assumption that the damaging effects of temperature changes are less pronounced in thin-walled components when compared to the thick-walled ones.

As generally known, the thermal stresses emerging in the wall of a component are not only depending on the temperature changing velocities, but also on the duration of the up and down events [6]. Moreover, the highest thermal stresses are arising during the quasi-stationary state. For the sake of damage assessment this quasi-stationary state is postulated, which is perfectly acceptable for thin-walled components, but is not always applicable to thick-walled ones, possibly leading to an over-conservative estimation of the damage. The reason for this is that the quasi-stationary state is not reached for short-term temperature changes, and hence the real thermal stresses are not as high as the (postulated) quasi-stationary stresses.

2 Damage Assessment Details

Nowadays, the calculation of the remaining lifetime of components, and hence their degree of damage, is regulated by corresponding normative instances. In Germany, the old technical rules for steam boilers, TRD 508 ([3], [4]), are still used for assessing the degree of damage of components within the area of steam boilers, especially if the plant, and hence the associated monitoring system, was designed according to it. The new regulatory work DIN EN 12952 ([5]), issued as a European Standard (EN), will replace the old fashioned TRD 508, but the majority of concepts, at least those concerning the calculation of damage, are still very similar.

The calculation of damage in components by TRD 508 highly depends on an online monitoring system, which steadily records the state of the component by measuring some parameters. The main parameters needed within TRD 508 are temperature and internal pressure, which are then used to determine the stress distribution within the component. In the present work, the transformation of the measured values into stress distributions throughout the component's wall is of main interest, and, in this case, especially the influence of the temperature measurements.

The main problem concerning the temperature induced stresses is the uncertainty related to transforming the temperature into a well-founded stress distribution. The first difficulties arise already while considering the location of the temperature sensors: some are positioned in the component itself while other are only measuring the temperature of the medium. In the former case, the common procedure is to record the temperature in the middle of the components wall and at the inside (the side touched by the medium) and then building a temperature difference throughout the whole (!) wall based on these two values. The latter case, where only the temperature of the medium is provided, is seemingly a more complex one, since the induced stress distribution is deduced from potentially only one measured entity. Nevertheless, this case is dealt with by using temperature changing velocities (plus possibly other medium parameters) and the procedure is yielding, according to their users/developers (see e.g. [8], [9], [10] and [11]), quite good results. Another possibility, which looks like something in between the temperature difference approach and the medium temperature approach, consists in having only one temperature sensor at the outside of the components wall, [13]. In this case, the resulting temperature difference is built up from one temperature only, like in the medium temperature approach, but the temperature is recorded within the wall, similar to the temperature difference approach.
All methods presented so far have in common that they are calculating the stress distribution within the wall of a component based on measured temperature values, but also the measured internal pressure. This stress contribution is used within TRD 508 for determining the cyclic fatigue portion of the damage by a cycle counting procedure which assesses the stress ranges of the corresponding cycles encountered. In this case, the so-called reference temperatures of the cycles are recorded together with the stress ranges into 2D-classes, i.e. the respective class is incremented for each 2D-tuple of a cycle belonging to it. Finally, when all cycles are counted, the mean reference temperature of each 2D-class is taken to determine the appropriate cycle fatigue curve, and then the corresponding mean stress range is used to calculate the damage value as the number of cycles counted divided by the maximum number of cycles allowed by the reference curve.

Another crucial part considered within the calculation of damage acc. to TRD 508 is the creep induced damage. In this case, the time span during which the component is subjected to a specific temperature and internal pressure is used for assessing the damage. Analogous to the prior case of fatigue damage, the time spans are recorded into 2D-classes which are now based on the temperature and internal pressure encountered. After the time span recording phase, i.e. after processing the measured values, the mean temperature of each 2D-class is taken again to determine the appropriate creep fatigue curve, and then the corresponding mean stress, calculated from the mean internal pressure of the same class, is used to obtain the damage value from the current reference curve.

3 Summary and conclusion

In order to achieve a high energy conversion efficiency power plants must operate at high temperatures and pressures, which unfortunately leads to high component damaging due to creep effects. Therefore it is necessary to permanently assess the state of a component by performing pressure and temperature measurements. However, as the need for calibration suggests, these measurements are not always accurate, so this is an issue which must be addressed accordingly.

Regarding the assessment of cyclic load related damage this process is more complex and depends on several other aspects. The most important aspects here are the temperature changing velocity and the time span of temperature changing events. In order to calculate the thermal stresses needed for the assessment of cyclic load related damage, a large number of points of measurement are usually installed, yielding the needed temperature differences. Depending on the chosen setup, these points of measurement may eventually provide inaccurate values [11], [12].

Besides the operational parameters detected by measurements, there are also geometry values needed for performing damage assessment, i.e. for calculating the stresses within the wall of a component. These geometry values should correspond to the real component geometry, but for the case that this geometry cannot be determined, minimal values specified by design can be used too. However, it must be taken into account that these values are also a source of uncertainty, especially if they are far away from the real component values.

By performing damage assessment, e.g. acc. to [3] or [5], one must be aware that the evaluation may sometimes be overly conservative. In such cases, the reason for this behavior must be detected in order to be able to quantify the real reserves available for operation, i.e. the real remaining lifetime of the system.
References


[4] TRD 301 Annex 1:1996-08: Calculation for cyclic loading due to pulsating internal pressure or combined changes of internal pressure and temperature


