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# CONSIDERATION OF IMPORTANT EFFECTS IN ENVIRONMENTALLY ASSISTED FATIGUE (EAF) OF AUSTENITIC AND FERRITIC STEEL COMPONENTS INCLUDING WELDS AND DEVELOPMENT OF A PRACTICAL FATIGUE ASSESSMENT CONCEPT

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## ABSTRACT

The fatigue assessment of pressure boundary components is of importance for the aging management, regarding safety and reliability in power plants. Current state of the art methods account for lifetime influencing effects, by the application of reduction factors for fatigue lives curves, which, are derived from laboratory test data. Some effects, such as environmental effects or hold times, are often considered with high levels of conservatism or are not taken into account at all. On the one hand, this may lead to non-conservative predictions of the materials fatigue behavior, as seen in laboratory specimen testing, while on the other hand, operating experience reveals much higher fatigue lifetimes as the predictions from the design curves. Therefore, Framatome GmbH, Erlangen, and the Material Testing Institute MPA University of Stuttgart are conducting a cooperative research program, aiming to improve the understanding of environmental and loading effects on fatigue lifetime on relevant steels and welds.

Emanating from various previous and ongoing research projects, the results and findings from experimental and numerical approaches contribute to the proposal of an engineering fatigue assessment concept, allowing more specific differentiation in the influencing factors for component fatigue life prediction. Furthermore, hold time effects are simulated based on further developed material models.

## INTRODUCTION

Fatigue assessment is an important aspect within the ageing management of safety relevant components in nuclear power plants (NPPs). For pressure retaining components of NPPs thermal transients are the major cause of cyclic loading. Thermal transients usually result from changes in operational conditions, such as start-up and shut-down procedures related to periodic maintenance. Short term variations in loading resulting from fluctuating power output also lead to increased numbers of fatigue cycles. Locations where stress or strain localization can occur need special attention.

The aim of the cooperative R&D projects was to investigate low cycle fatigue (LCF) and high cycle fatigue (HCF) behavior of ferritic steels and austenitic steels and welds under simulated light water reactor (LWR) environment. The goal of the experimental part of the project FATIGUE-II was to generate further data that can be used to enhance the knowledge regarding the fatigue behavior of pressure boundary components in LWR. It constitutes a continuation of the research results obtained in the predecessor project

FATIGUE-I (see Roth, 2014 and Rudolph, 2016). In these investigations the main focus was put on the material behavior under complex loading situations and the following items are particularly addressed

- Behavior as a function of the loading rate
- Behavior under operational loading conditions
- Behavior of austenitic welded specimens
- Behavior of specimens under multi-axial loading
- Behavior of welded components
- Influence of long hold times on the fatigue lifetime and the underlying mechanisms.

The experimental investigations were split up into two major parts:

1) Investigations concerning the influence of the loading parameters and the EAF effects on the fatigue strength of austenitic and ferritic steels on specimens and components.

2) Fatigue tests including long hold times and investigations concerning the behavior of weld seams under cyclic loading conditions.

The first part included the following principle aspects:

- Increase of the existing data base for the evaluation of the influence of the strain rate in connection with the medium effect for the ferritic material 20MnMoNi5-5.
- Investigation of the influences of simple load collectives and operational load collectives on the fatigue behavior in air and in medium environment.
- Investigation of the fatigue behavior of welds by testing specimens of filler material.
- Investigation of the fatigue behavior of welds by testing components (welded pipes DN 80) in a fluid structure interaction test loop under real operational conditions (fluctuating temperatures between room temperature and 280 degrees centigrade at pressures up to 80 bar).

The second part included the following principle aspects:

- Investigations concerning the influence of different parameters during hold times (variation of the load during the hold times; influence of the duration of the hold times on the fatigue lifetime of austenitic stainless steels in high temperature water).
- Investigation of component like weld seam specimens from austenitic stainless steel welds in air and in high temperature water environment (machined and as welded weld seams; different load levels by way of dynamic four point bending tests in high temperature water environment).

Furthermore, it was the goal of the overall project to develop a concept which respects the above mentioned influencing factors and to account for the results obtained during the performed tests, i.e. the development of a practicable engineering fatigue assessment concept.

## FATIGUE TESTS OF SMOOTH SPECIEMENS UNDER HIGH TEMPERATURE WATER CONDITIONS AT CONSTANT AMPLITUDE LOADING

The Strain controlled fatigue tests under fully reversed conditions (R = -1) were performed with constant strain amplitude and constant strain rate. Failure is defined by a load drop criterion. The cylindrical specimens of diameter 10 mm (see Figure 1) are made from the ferritic steel 20MnMoNi5-5. The tests were conducted in air 240 °C and in high temperature water (HTW) conditions at 240 °C, respectively, to assure transferability of the results and to determine the environmental effects on the fatigue behavior. The strain amplitude (0.25 %) and strain rate (0.1 %/s) were chosen to extend the existing data base for the environmental effected fatigue behavior of 20MnMoNi5-5.

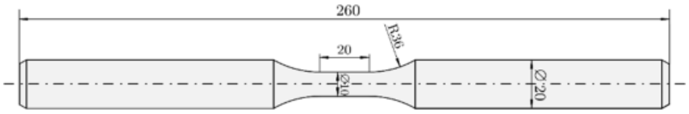


Figure 1: Geometry of fatigue test specimens

Based on the results from the constant amplitude tests, variable amplitude tests are used to simulate more realistic operational conditions. The influence of a small number of significantly higher strain amplitudes within a regime of small strain amplitudes is investigated, see Figure 2. The ratio of high and low strain amplitudes ($n_1/n_2$) is derived from operational data.

Previous research results (see Rudolph, 2016) indicated an effect on the EAF behavior of the ferritic steel. There, the tests conducted in air showed a significant reduction of the observed fatigue lifetime, according to the predictions from the experiments for constant strain amplitudes. This was not the case for tests under HTW conditions.

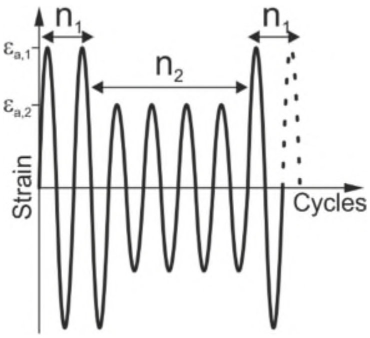


Figure 2: Strain range of variable amplitude

## FATIGUE TESTS OF FILLER MATERIAL UNDER HIGH TEMPERATURE WATER CONDITIONS

The Cylindrical V-notched specimens were used to investigate the EAF behavior of the dissimilar metal weld between austenitic stainless steel and ferritic steel using Ni-base alloy weld filler and buffer material under multi-axial stress conditions, see Figure 3. Strain controlled fatigue tests were performed with constant strain amplitude and constant strain rate at 240 °C. The specimens were taken from a welded pipe with dissimilar welds.

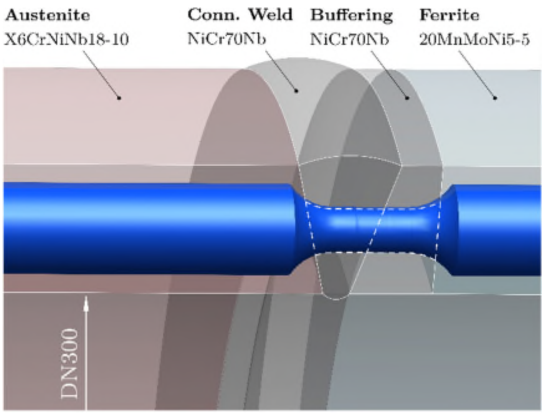


Figure 3: Dissimilar metal weld of 20MnMoNi5-5 and X6CrNiNb18-10 (see Kammerer, 2017)

## COMPONENT FATIGUE TESTS USING WELDED PIPE MODULES OF DN 80

The MPA fluid-structure-interaction (FSI) test loop (see Figure 4) was used to investigate the fatigue behavior of welded pipe modules under realistic operational loading conditions. The test conditions with HTW alternated between room temperature and 280 °C at pressures up to 80 bar. The thermal loading was used to investigate the fatigue behavior of the welds of different qualities due to thermal shocks in conjunction with the HTW environment. The tests were also used to compare the different numerical approaches and to qualify the engineering assessment method**.**

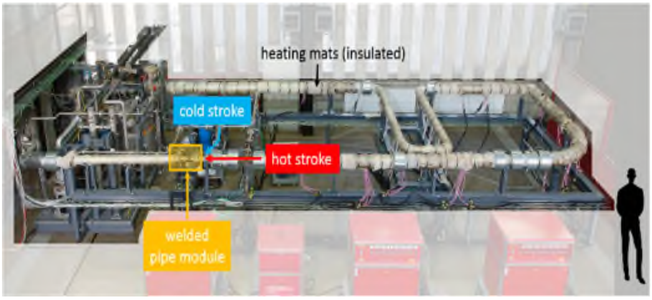


Figure 4: FSI-Loop located at MPA Stuttgart. Welded pipe module under thermal loading conditions (see Kammerer, 2017)

## FATIGUE TESTS CONCERNING THE INFLUENCE OF LONG HOLD TIMES AND ADDITIONAL LOADING DURING HOLD TIMES

The effect of long hold times on the fatigue time of low-alloy steels and austenitic stainless steels was investigated in air and under high-temperature water conditions (see Roth, 2014 and Rudolph, 2016). The results of such tests showed a life-extending ("positive") effect of holds on the actual fatigue lifetime of the tested materials particularly in air. In order to further study the effects that have been observed during such investigations, further fatigue tests with multiple holds under high-temperature water conditions were performed using round bar fatigue specimen manufactured from a 304L type austenitic stainless steel. These tests focused on the effect of the actual strain/stress during holds, as well as the number and duration of holds during fatigue tests in high-temperature water. As a conclusion, the life-extending effect was found to be less pronounced under high-temperature water conditions.

## DEVELOPMENT OF THE ENGINEERING CALCULATION CONCEPT

### *General outline of the calculation concept*

The fatigue assessment procedure follows the flow diagram shown in Figure 5 and was first initiated within the first project phase FATIGUE-I (see Roth, 2014 and Rudolph, 2016). Depending on the material to be evaluated a specific mean data curve is derived that covers also the influence of temperature (Schuler, 2013). In the following the mean data curve is modified according to the loading situation. Factors on load shift the mean data curve in vertical direction. These effects are dominant in the low cycle fatigue regime. Factors on life shift the mean data curve in the horizontal direction. These effects are dominant in the high cycle fatigue regime. Some effects do influence the fatigue life both in low and high cycle fatigue regime and must therefore be considered depending on the number of loading cycles. Existing approaches e.g. for the consideration of the dynamic notch effect (Taylor, 2000) and load spectra (Haibach, 1975) are scrutinized with respect of their applicability in the present engineering concept.

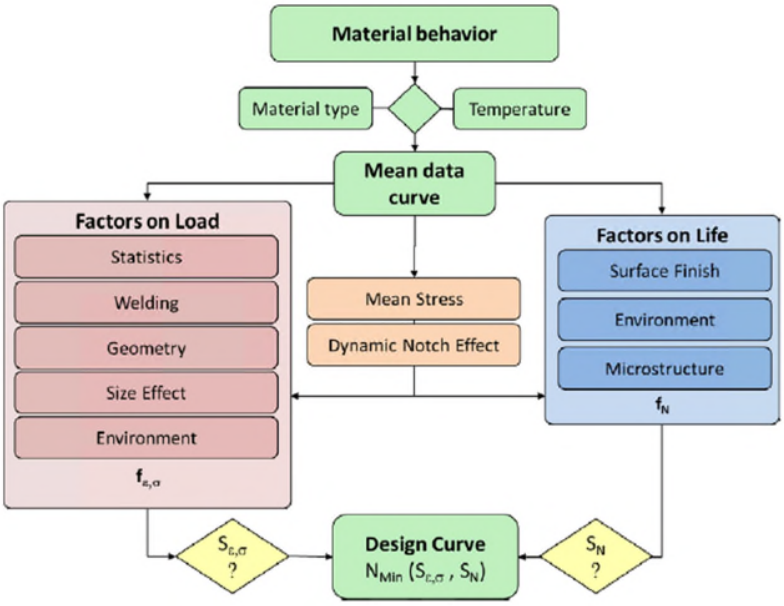


Figure 5: Flow diagram for fatigue analysis

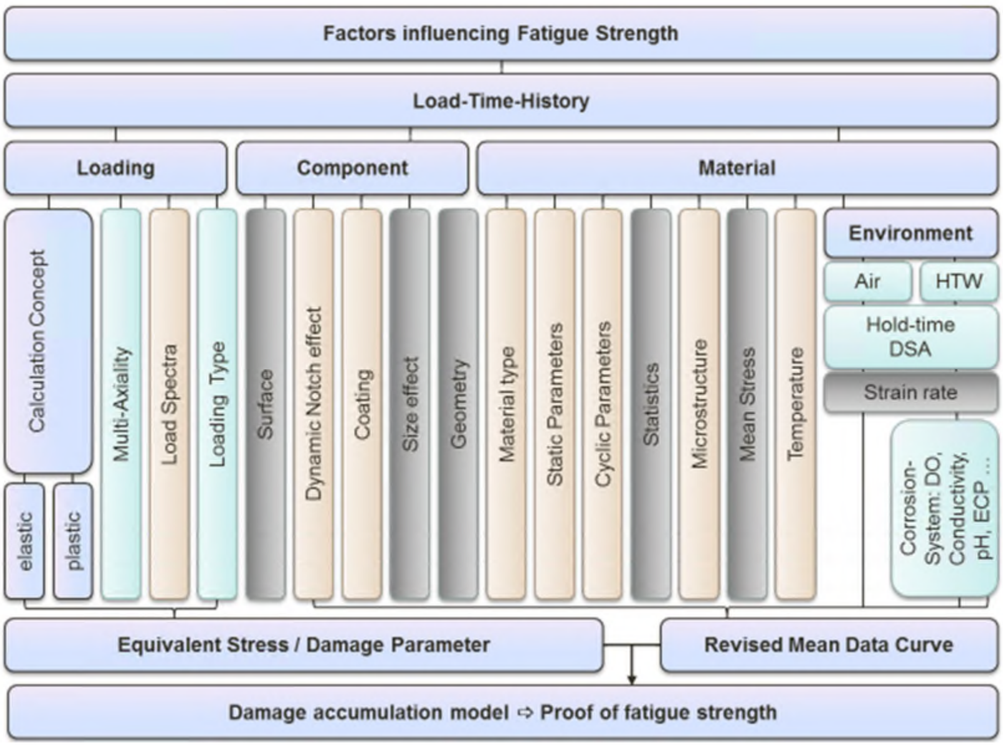


Figure 6: Calculation concept with the main fatigue life influencing factors.

In dependence of the loading state a suitable loading parameter needs to be chosen, see Figure 6. For example in the case of a proportional loading situation the equivalent strain range, as described in ASME-Code Subsection NH, is a good loading parameter. In the case of non-proportional loading advanced fatigue damage parameters may give a better description of the loading state and therefore a better estimation for fatigue life (see e.g. Rudolph, 2021). Finally based on FDP-$N$-curves (Fesich, 2014), which are mean data curves, several effects like data scatter, environment, hold-times etc. are considered to derive a material and loading state specific design curve. This derived fatigue design curve represents a lower degree of conservatism, since the fatigue life influencing factors are directly considered and included in the fatigue assessment.

### *Specific factorial consideration of environmentally assisted fatigue (EAF)*

The environmental influences on the fatigue behavior of steels were investigated in multiple preceding projects (Kammerer, 2017, Kammerer, 2018), where specimens were tested at the environmental conditions of light water reactor (LWR) coolant medium. According to a common methodology, fatigue testing in air (achieved load cycles $N_{Air}$) and at high temperature water (HTW) conditions (achieved load cycles $N_{HTW}$) were conducted to obtain a specific environmental reduction factor $F_{EN}$ for different loading conditions:

$$F_{EN} = \frac{N_{Air}}{N_{HTW}} \qquad (1)$$

Additionally, the formation behavior of oxide layers due to environmental influences as well as the mechanical behavior under fatigue loading were studied. The derived models are described in more detail in (Kammerer, 2020).

Furthermore, specific EAF-models for PWR and BWR were derived based on a wide range of available test data fulfilling defined quality standards (see Wilhelm, 2015 and Wilhelm, 2016).

### *Application of nonlinear kinematic (NLK) material models for the consideration of the cyclic elastic-plastic deformation behavior*

In the numerical assessment of the fatigue lifetime, the materials response to cyclic loading conditions is of high importance. The used material model has to account for the materials behavior for the relevant range of loading, especially in the LCF and HCF regime. Even in the VHCF fatigue assessment, a linear elastic material model does not seem to satisfy the fatigue prediction good enough for a fatigue evaluation (see Schopf, 2021). To account for the real stress-strain correlations, an elastic plastic material behavior has to be considered, as well as cyclic hardening or softening effects that occur during fatigue loading.

Recent research projects showed the applicability of an elastic-plastic material model based on Armstrong-Frederik and Chaboche (AFC) (see Chaboche, 2008 and Frederick, 2007) with three backstresses (see Kammerer, 2020 and Daniel, 2020) where the material parameters were fitted with the stress-strain-hysteresis-data from strain controlled fatigue-testing.

A recent extension of implemented NLK material models allows for the consideration of (long) hold time effects by including a phenomenological description of the static strain ageing effect in an adapted Chaboche model. This model has successfully been applied in the simulation of hold time tests carried out in the framework of the cooperative research projects mentioned above. An exemplary comparison of hold time test and simulation is shown in Figure 7.

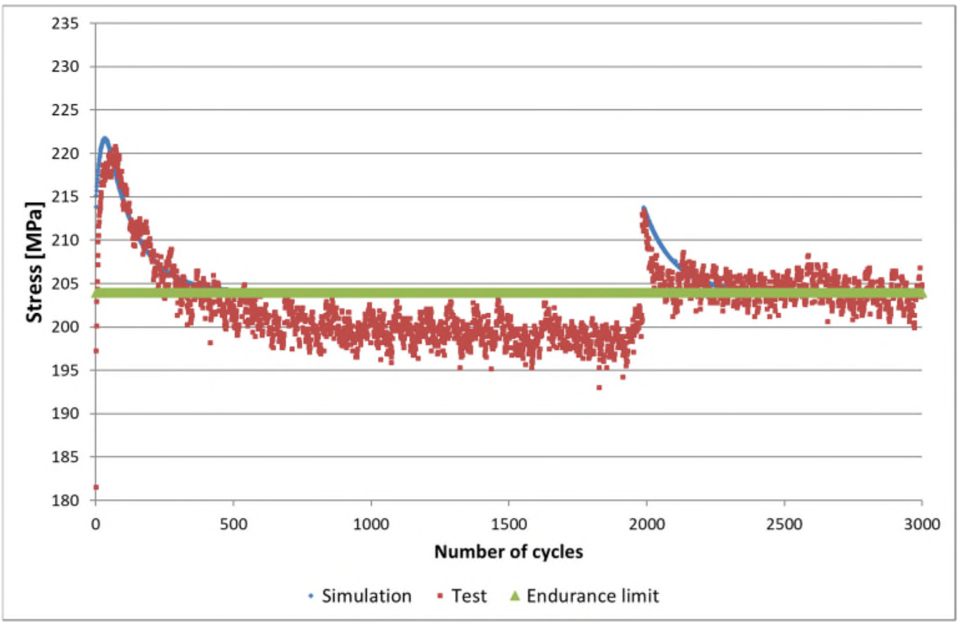


Figure 7: Exemplary comparison of hold time test and simulation

### *Fatigue damage parameter (FDP) concept and damage accumulation*

Advanced fatigue damage parameters include knowledge of short crack fracture mechanics in an effort towards a mechanistic description of the real damage processes with the perspective of including non-linear effects of damage accumulation and the transient endurance limit. At the same time, they mark the borders of description of the real damage process within an engineering calculation concept. Consolidated application for uni-axial loading situations versus dedicated testing is described in (Rudolph, 2021). The multi-axial formulation is on-going.

### *Consideration of welded material and welds*

The consideration of welded material and welds constitutes a relevant part of the calculation concept. So far, while base materials are widely investigated the behavior of weldments is usually accounted for within fatigue analysis by some stress concentration or fatigue strength reduction factors. The influence of microstructure is therefore not explicitly accounted for and the notch effect of the weld is rather roughly covered. Based on dedicated test programs these aspects of the influence of welded material and welds are explicitly addressed and quantified. In terms of the calculation concept welds are included in a multi-axial damage parameter formulation. The further development of this approach is on-going. Furthermore, guidelines for the geometric modeling of the welds in related finite element analysis are elaborated.

## CONCLUSION

The main aspects of cooperative research projects in Germany (MPA Stuttgart / Framatome GmbH) on environmental influences on the fatigue assessment of austenitic and ferritic steel components including welds were outlined. The results of these experimental and theoretical investigations are part of a comprehensive international effort to improve the fatigue assessment particularly under consideration of environmentally assisted fatigue (EAF). The focus of the project was

- Behavior as a function of the loading rate
- Behavior under operational loading conditions
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The dedicated experiments and the findings from the relevant international literature constituted the basis for the further development of a proposal for a practicable engineering concept to a reliable and realistic determination of fatigue lives. In this proposal, the methodology of the international design codes was kept as far as possible. A differentiation of relevant factors of influence and their superposition are a central part of the calculation concept. The proposed calculation concept is in line with the experimental findings of the projects. The methodological bases are in line with those elaborated in (Manjoine, 1983) and (Cooper, 1992).

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