Structural Health Monitoring of Power Plant Components Based on a Local Temperature Measurement Concept

J. RUDOLPH, S. BERGHOLZ, R. HILPERT, B. JOUAN
and A. GÖTZ

ABSTRACT

The fatigue assessment of power plant components based on fatigue monitoring approaches is an essential part of the integrity concept and modern lifetime management. It is comparable to structural health monitoring approaches in other engineering fields. The methods of fatigue evaluation of nuclear power plant components based on realistic thermal load data measured on the plant are addressed. In this context the Fast Fatigue Evaluation (FFE) and Detailed Fatigue Calculation (DFC) of nuclear power plant components are parts of the three staged approach to lifetime assessment and lifetime management of the AREVA Fatigue Concept (AFC). The three stages Simplified Fatigue Estimation (SFE), Fast Fatigue Evaluation (FFE) and Detailed Fatigue Calculation (DFC) are characterized by increasing calculation effort and decreasing degree of conservatism. Their application is case dependent. The quality of the fatigue lifetime assessment essentially depends on one hand on the fatigue model assumptions and on the other hand on the load data as the basic input. In the case of nuclear power plant components thermal transient loading is most fatigue relevant.

Usual global fatigue monitoring approaches rely on measured data from plant instrumentation. As an extension, the application of a local fatigue monitoring strategy (to be described in detail within the scope of this paper) paves the way of delivering continuously (nowadays at a frequency of 1 Hz) realistic load data at the fatigue relevant locations. Methods of qualified processing of these data are discussed in detail. Particularly, the processing of arbitrary operational load sequences and the derivation of representative model transients is discussed. This approach related to realistic load-time histories is principally applicable for all fatigue relevant components and ensures a realistic fatigue evaluation.

Keywords: Local fatigue monitoring approach, operational load sequences, model transients, Fast Fatigue Evaluation (FFE), Detailed Fatigue Calculation (DFC)

Dr. Jürgen Rudolph et. al., e-mail: rudolph.juergen@areva.com
AREVA NP GmbH, Henri-Dunant-Str. 50, 91058 Erlangen

INTRODUCTION

The safety check against cyclic operational loads, i.e. the fatigue check, takes a central position within the aging management of nuclear power plants (NPPs). The storage of the acquired data should start right at the beginning, i.e. the commissioning phase. For this purpose, AREVA provides the fatigue monitoring system FAMOS with its standard power plant type EPR®. FAMOS itself is embedded in the AREVA Fatigue Concept (AFC) as the data provider that acquires the operational load data. Three harmonized evaluation processes SFE (Simplified fatigue estimation), FFE (Fast Fatigue Evaluation) and DFC (Detailed Fatigue Calculation) are available within the graded AFC approach. AREVA recommends a local acquisition of load data for the follow-up of fatigue trends. This way it is ensured, that the local loads at the locations of interest with regard to fatigue (e.g. thick walled nozzles) are captured. The operational measurement instrumentation - generally measurements based on thermal (immersion) wells – is usually neither positioned appropriately for local fatigue follow-up nor disposes of the required measurement dynamics in order to deliver the loading data.

LOCAL FATIGUE MONITORING STRATEGY

During the early operation of NPPs in the 1970s and 1980s local loads occurred at different locations causing fatigue cracks. These were either due to new loading conditions which were not considered in the design phase (e.g. temperature stratification) or insufficient manufacturing quality (e.g. welded joints). These problems constituted the starting signal for the development of fatigue monitoring systems. Simultaneously, the compliance with authority demands was assured. In Germany, FAMOS was for instance developed by then Siemens KWU (now AREVA NP GmbH) at the end of the 1980s and installed in German NPPs.

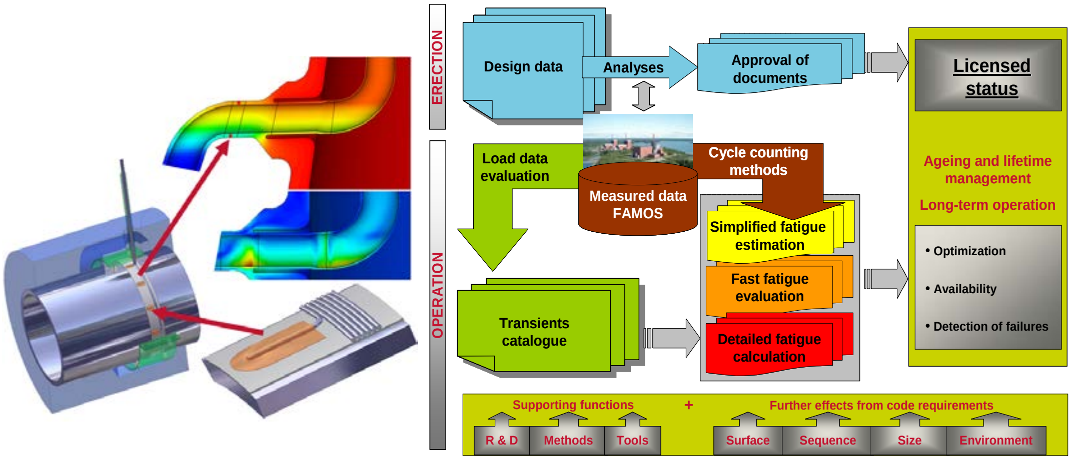

Figure 1. Exemplary local measurement section and modules of the AFC.

The installation is carried out as a clamped measurement strap on the outer wall surface of the pipe nearby the fatigue relevant location as it is shown in figure 1. Nowadays, the measurement system is based on a modern data management approach (data bus structured; SQL database; live network data stream) and is very flexible in installation and application. The modern system design ensures an easy system installation and relatively low costs.

These experiences gave rise to a better understanding of the ongoing loading phenomena. The fatigue assessment induced the necessity of retrofitting of components or the modification of the operating mode. For instance, the feedwater sparger of the steam generator was subsequently designed in a way that the stresses of cyclically occurring stratification transients were minimized. Nevertheless, the technology of the data logging system at that time still had certain limits with respect of the frequency of data logging and the recording and storage. A data logging frequency of 10s (0.1Hz) constituted the upper limit (nowadays, 1s respectively 1Hz is usual). Furthermore, the capacitive effect of the applied measurement sections was underestimated in their transient behavior. Nowadays, this effect is appropriately considered.

As mentioned before, fatigue monitoring strategies are firstly to be classified into global and local approaches [1]. The global monitoring is based on existing operational measurement. The corresponding operational signals could be fluid pressure, fluid temperature, the position of valves etc. measured at different parts of the systems. Local fatigue monitoring is located at fatigue relevant locations at the outer surface of pipes in the proximity of fatigue relevant components and is based on additional temperature measurement by means of thermocouples (see figure 1). Local effects such as the swapping flow after feeding interruption can only be recorded in the load data set this way. It is to be pointed out that the safety check against cyclic loads of the components has to be a permanent operation accompanying procedure. The German KTA rules regulate this issue as part of the rule for operational monitoring (KTA 3201.4) [2].

THE THREE STAGED AFC MODEL

AREVA develops its own integrated fatigue concept AFC [3]. This concept provides for a multiple step and multidisciplinary process (process engineering, fatigue monitoring, fatigue analyses etc.) against fatigue before and during the entire operation of NPPs. The structure and the modules of the AREVA Fatigue Concept (AFC) are shown in figure 1. The central position of the fatigue monitoring module is underlined. AREVA now offers FAMOSi ("i" = integrated) as a modern central data logging system (for further description and explanation see [3] and [4]).

The subsequent fatigue evaluation methods can principally be split up in three steps:

Step 1: Simplified Fatigue Estimation (SFE)

Simple estimations of fatigue relevance of real loads for components are based on thermal mechanical considerations using the equation of ideal thermally constrained strains. A basic decision about fatigue relevance (yes/no) for the monitored position is made. In case of fatigue relevance a further evaluation is proposed according to step 2.

Step 2: Fast Fatigue Evaluation (FFE)

A code conforming (cumulative) usage factor (U, CUF) is calculated in a highly automated way based on the simplified elasto-plastic fatigue analysis route of relevant design codes such as [5] or [6]. If $U \leq U_{admissible}$ the fatigue check is successfully finished. If $U > U_{admissible}$ further analyses should be based on step 3.

FFE includes the following process steps: transfer of temperatures from the outer wall to the inner wall pipe position and the inner surface of the pipe to the inner surface of the component. The thermal load cycles are well known after that step and the stress time history is calculated based on the elementary transients (Green's function) approach.

Step 3: Detailed Fatigue Calculation (DFC)

Fatigue analysis is based on a detailed catalogue of transients. This catalogue of transients results from the evaluation of the real loads for the monitored component.

Usage factors are calculated for the current state of the plant and until the end of life (e.g. 40 or 60 years). Fatigue calculations are usually carried out as simplified elasto-plastic or elasto-plastic analyses according to the design code rules (e.g. [5]).

The determination of cumulative usage factors requires the application of appropriate cycle counting procedures. The peaks and valleys approach of the ASME code [5] NB-3222.4 is often applied for the determination of the required stress ranges. As soon as the load history is directly considered the peaks and valleys method can be combined with or replaced by a rain flow algorithm.

APPLICATION EXAMPLES

Example 1: Pressurizer spray line

Figure 3 gives an example of operational and local measurement configuration in the primary circuit of a pressurized water reactor (PWR). The pressurizer spray lines are known to be fatigue relevant sections and one pipeline of interest is pointed out in red color in figure 3. One exemplary fatigue relevant location is the component (nozzle). The next operational measurement location is marked as a light blue rectangle and pointed out by a circle. The temperature T_{sl} (index "sl" for "spray line") is measured at this location. As it can be seen in the scheme this operational measurement is located behind the valve. The next operational measurement delivers the pressurizer temperature T_{pr}. Any global monitoring approach has to rely on the operational measurements T_{sl} (spray line), T_{pr} (pressurizer) and T_{mcl} (main coolant line).

In terms of specifications from the design phase (see figure 1) temperature transients T_{des} are given for the spray line between the valve and the pressurizer.

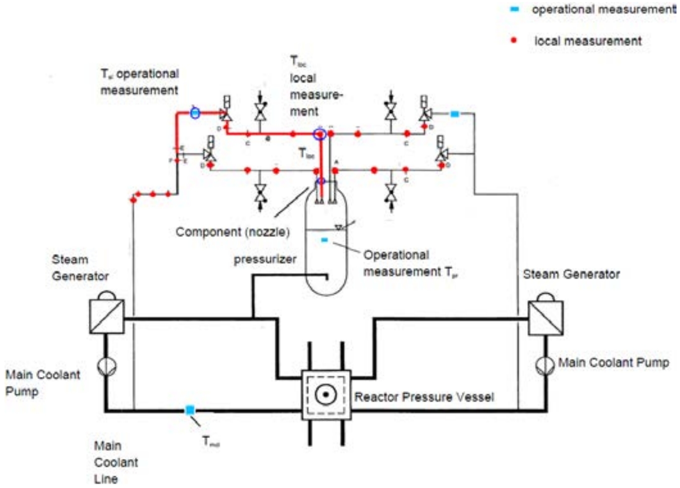

Figure 3. Operational and local measurement within the primary circuit of a PWR.

The additional local measurement section is located at a U-bend close to the component (nozzle) and yields the local temperature transients $T_{loc,i}$ and $T_{loc,e}$ at the intrados (index “i”) and extrados (index “e”) positions.

The measured temperature transients for an exemplary shut-down process are shown in figure 4. The range of temperatures is limited by the (operational) measurement results of the pressurizer T_{pr} and the spray line T_{sl}. The measured spray line temperature T_{sl} does not differ very much from the measured main coolant line temperature T_{mcl}. Detailed information about the temperature transient at the location of the component (nozzle) is based on the local temperature measurement $T_{loc,e}$ and $T_{loc,i}$. Differences between $T_{loc,e}$ and $T_{loc,i}$ at a certain time are indicators of stratification flows. These are visible near the 06:00 a.m. measurements.

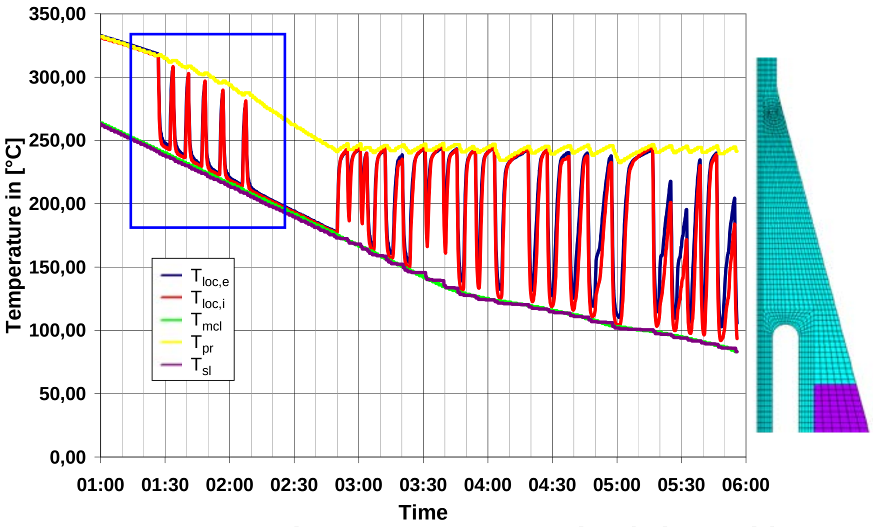

Figure 4. Measured temperature transients and meshed FE model.

In the following stress analysis example the spraying processes indicated by the local measurement results between 01:20 a.m. and 02:10 a.m. (pointed out by the blue box in figure 4) are considered in more detail. As there is no indication of significant stratification flows ($T_{loc,e}$ and $T_{loc,i}$ are nearly identical) the exemplary analyses are exclusively based on the measured intrados temperatures $T_{loc,i}$ at the local measurement section T_{loc}. Additionally, figure 4 shows the meshed 2D axially symmetric component model (nozzle) for the structural finite element analyses. Temperature dependent material data for the austenitic nozzle and cladding (stabilized austenitic stainless steel X6CrNiNb18-10, e.g. 1.4550 respectively ANSI 347) and the ferritic body material (20 MnMoNi 5 5, e.g. 1.6310 respectively ASTM A 533) are taken from KTA rule 3201.1 [7]. Finite element analyses are carried out for the design and model temperature transients as well as the locally measured temperature transients.

Exemplary linearly elastic stress responses (σ_z) and the corresponding local temperature transients $T_{loc,i}$ are plotted in figure 5. The stress responses reveal that both the design and the model temperature transients cover conservatively the stress response to the locally measured temperature transients.

Note that the stress response to the real operational load sequence (Sz_FFE_loc,i) covers the whole time history from 0s to 3000s while the stress responses to the design and model transients (Sz_DesignTr and Sz_ModelTr) refer to half cycles.

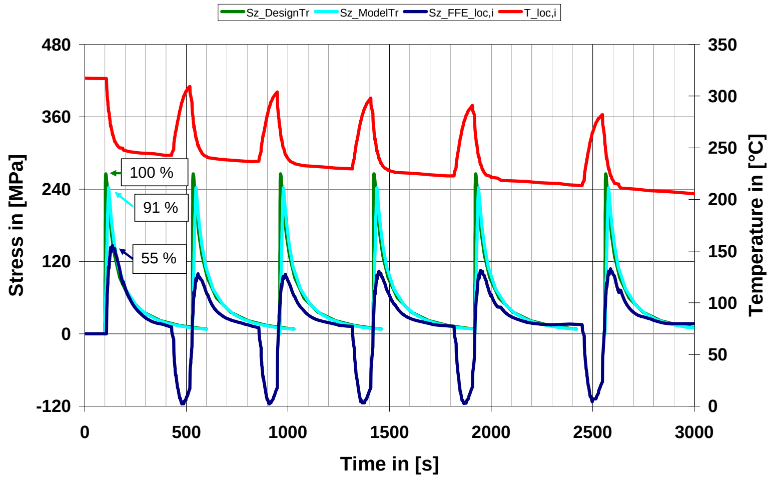

Figure 5. Exemplary stress results.

Thus, the comparison of the stress peaks or amplitudes is most significant. Figure 5 shows that the linearly elastic stress peak response to the design transient is about 45% higher (more conservative) than the response to the real operational load sequence. More details can be taken from [8].

Example 2: Feedwater nozzle

The second example addresses an exemplary fatigue calculation for a steam generator feedwater nozzle of a nuclear power plant (see figure 6). Fatigue assessment for the period of one operating cycle (see figure 6) is based on the FFE technology.

An adequate FE-model has to be created containing all the relevant geometry and material properties. One 3D model of the nozzle is needed to calculate the stresses occurring in the nozzle, one 3D model of the pipe is needed to calculate the piping loads applied to the nozzle and one 2D model of the measurement section on the LAB pipe near the nozzle is needed to calculate the inner wall temperature.

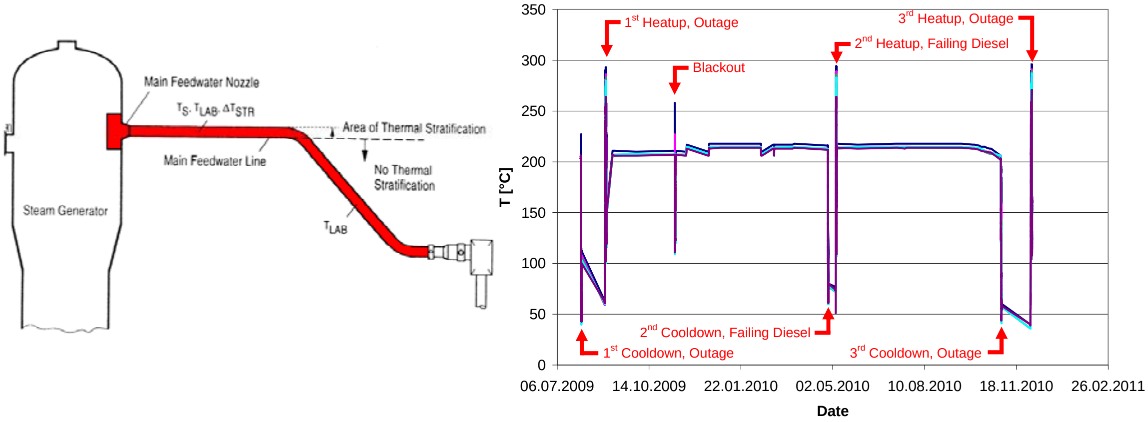

Figure 6. Relevant geometry and measured temperature as a function of time.

After these necessary preparations the evaluation is done in the following steps:

- Reviewing the measured data
- Calculation of the inner wall temperature
- Calculation of the stress caused by thermal transients within the nozzle
- Calculation of the stress caused by internal pressure

- Calculation of the stress caused by piping loads due to stratification and thermal expansion of the pipe
- Superposition of the stresses
- Fatigue evaluation

The evaluation is done for several locations at the 12 o'clock position and at the 6 o'clock position of the nozzle due to possible stratification effects to be considered.

Concerning materials the feedwater nozzle and the cylindrical shell of the steam generator are made of the ferritic steel 20 MnMoNi 5 5 (material no. 1.6310). The piping of the feedwater system and the transition piece are made of 15 NiCuMoNb 5 (material no. 1.6368).

All relevant transient data required for the application of the FFE method are available based on local measurements. Seven relevant operational events (see figure 6) were identified. The following analysis steps are taken:

1) Calculation of inner wall temperatures at the location of the measurement;
2) Transfer of inner wall temperatures to the location of the component;
3) Calculation of stresses induced in the feedwater nozzle by application of the elementary transient method (see figure 7). Note that the thermal properties of the steam in the gap between sleeve and nozzle were considered in the (thermal) calculation. The associated "steam" elements (see figure 7, left part) were eliminated in the subsequent structural mechanical analyses (see figure 7, right part). A linear scaling function is used to determine the "real" stresses.

The locations of interest with an exemplary stress response (contour plot) at a discrete time step is shown in figure 7.

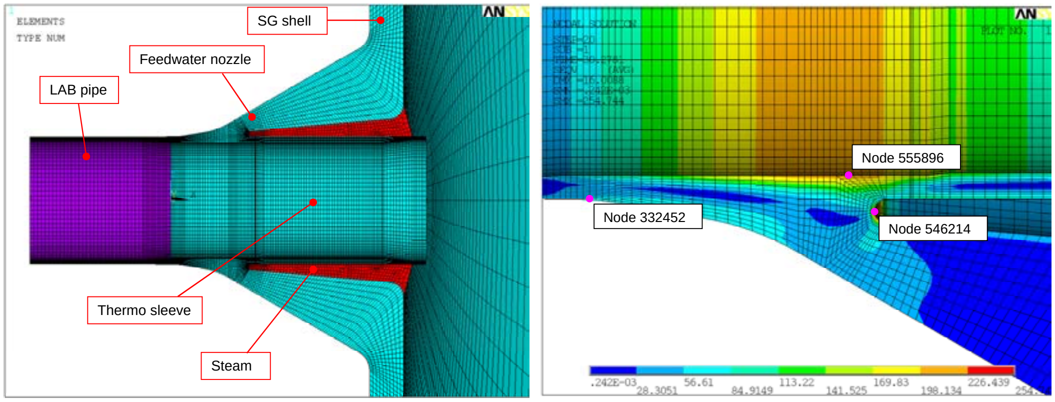

Figure 7. FE model of the feedwater nozzle and locations of interest.

Additionally, stresses caused by static internal pressure and by piping loads are analysed. The latter requires two steps. In a first step the forces and moments have to be calculated which are caused by the thermal expansion of the pipeline including the phenomenon of stratification. In a second step the stresses have to be calculated at the locations of interest caused by the piping loads.

The superposition of all load portions was done for three locations at the bottom of the nozzle and the top of the nozzle.

Finally, the fatigue evaluation for the period of the operating was based on KTA3201.2 [6], chapter 7.8. The appropriate fatigue curve of [6] was used to determine the partial fatigue usage factors based on Miner's linear damage accumulation rule. The thermal sleeve connection results to be the most fatigue relevant location.

SUMMARY AND CONCLUSIONS

Aspects of structural health monitoring in power plants have been discussed with an emphasis on the fundamental differences between global and local approaches. The most accurate load input is ensured by direct processing of the locally measured temperature data.

This described approach is equally applicable in other engineering disciplines such as conventional power plants, chemical plants, wind energy plants etc..

REFERENCES

1. Miksch, M. ; Schön, G. ; Thomas, B.: “FAMOS – a tool for transient recording and fatigue monitoring” PVP-Vol. 138/NDE-Vol. 4 “Life extension and assessment: nuclear and fossil power plant components”, presented at the 1988 ASME Pressure Vessels and Piping Conference, Pittsburgh, Pennsylvania, June 19-23, 1988.
2. KTA rules (Safety Standards of the Nuclear Safety Standards Commission). KTA 3201.4 (06/96): Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 4: In-service Inspections and Operational Monitoring. (Komponenten des Primärkreises von Leichtwasserreaktoren; Teil 4: Wiederkehrende Prüfungen und Betriebsüberwachung).
3. Rudolph, J.; Bergholz, S.; Heinz, B.; Jouan, B.: “AREVA Fatigue Concept – A Three Stage Approach to the Fatigue Assessment of Power Plant Components," in “Nuclear Power Plants”, ISBN 979-953-307-170-0, Book edited by: Dr. Soon Heung Chang, KAIST Department of Nuclear & Quantum Engineering, Korea, South.
4. Abib, E.; Bergholz, S.; Rudolph, J.: “German experiences in local fatigue monitoring.” Proceedings of ICAPP ’12, Chicago, USA, June 24-28, 2012, Paper 12150.
5. 2010 ASME Boiler & Pressure Vessel Code. Section III Division 1 - Subsection NB: Class 1 Components. Rules for Construction of Nuclear Power Plant Components.
6. KTA 3201.2 (06/96). 1996. Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 2: Design and Analysis.
7. KTA 3201.1 (06/98) Components of the Reactor Coolant Pressure Boundary of Light Water Reactors Part 1: Materials and Product Forms.
8. Rudolph, J.; Bergholz, S.; Hilpert, R.: “Detailed fatigue checks based on a local monitoring concept” Proceedings of the ASME 2012 Pressure Vessels & Piping Division Conference, July 15-19, 2012, Toronto, Ontario, Canada, PVP2012-78042.