Structural Health Monitoring Solutions for Power Plants

Benoît Jouan, Jürgen Rudolph, Steffen Bergholz

7th European Workshop on Structural Health Monitoring
July 8-11, 2014. La Cité, Nantes, France

STRUCTURAL HEALTH MONITORING SOLUTIONS FOR POWER PLANTS

Benoit Jouan, Jürgen Rudolph, Steffen Bergholz

AREVA GmbH, Erlangen, Germany

benoit.jouan@areva.com

ABSTRACT

Structural health monitoring solutions gain in importance not only as part of the ageing management of nuclear power plant components but also in the context of conventional power plants and renewables such as wind power plants. Consequently, lots of operators have to deal with demanding security requirements to ensure the safe operation of power plants and to cope with plant lifetime extension (PLEX) related issues. AREVA disposes of a long tradition in the development of structural health monitoring (SHM) solutions. Nuclear and conventional power plant applications require the qualified assessment of measured thermo-mechanical loads. The methodology is transferable to mechanical loading conditions such as those of wind energy plants. The core challenge is the identification and qualified processing of realistic load-time histories. In terms of the nuclear industry, the ageing management of power plant components is nowadays a main issue for all actors: states, regulatory agencies, operators, designers or suppliants. As regards fatigue assessment of nuclear components stringent safety standards imply the consideration of new parameters in the framework of the fatigue analysis process: new design fatigue curves, consideration of environmental fatigue (EAF) parameters and stratification effects. In this general context AREVA developed the integral approach AREVA Fatigue Concept (AFC) with new tools and methods in order to live up to operators expectations: Simplified Fatigue Estimation (SFE), Fast Fatigue Evaluation (FFE) and Detailed Fatigue Check (DFC). Based on real measured thermal loads and superposed mechanical loads the Fast Fatigue Evaluation (FFE) process allows a highly automated and reliable data processing to evaluate cumulative usage factors of mechanical components. Calculation and management of results are performed within the software frontend FAMOSi, thus impact of operating cycles on components in terms of stress and fatigue usage can be taken into account in order to plan optimized decisions relating to the plant operation or maintenance activities. This paper mainly describes the SHM methodologies developed within the AREVA Fatigue Concept (AFC).

KEYWORDS : *Structural Health Monitoring, Fatigue Monitoring, Ageing Management, Power Plants, AREVA Fatigue Concept (AFC), Fast Fatigue Evaluation (FFE), FAMOSi*

INTRODUCTION

The safety check against cyclic operational loads, i.e. the fatigue check, takes a central position within the ageing management of nuclear power plants and constitutes the prevailing failure mechanism to be controlled in other technical areas. It is to be shown that the fatigue ageing mechanism (in power plants normally due to cold and hot feed operations) does not result in an increased incipient crack probability. In the context of extended operational times (nowadays 60 years) of new power plants the monitoring of operational loads as well as the storage of the acquired data should start right at the beginning, i.e. the commissioning phase. This is a substantial and basic recommendation for the implementation of a fatigue monitoring approach.

AREVA provides its own fatigue monitoring solution as part of the AREVA Fatigue Concept (AFC). It serves as a load data provider and uses them as input for three different evaluation processes: SFE (simplified fatigue estimation), FFE (fast fatigue evaluation) and DFC (detailed fatigue calculation). The SFE and FFE parts are fully implemented and highly automated in the fatigue assessment software FAMOSi. In the case of increased usage factors the DFC module provides a detailed load case counting and the possible application of realistic material models within the finite element analysis.

Basically, a local acquisition of load data for the follow-up of fatigue trends is recommended. 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.

1. Overview of the AREVA fatigue Concept

AREVA developed within the integral approach AREVA Fatigue Concept (AFC) tools and methods against fatigue for a multiple step and multidisciplinary process (process engineering, fatigue monitoring, fatigue analyses etc.). The structure and the modules of the AFC are shown in Figure 1

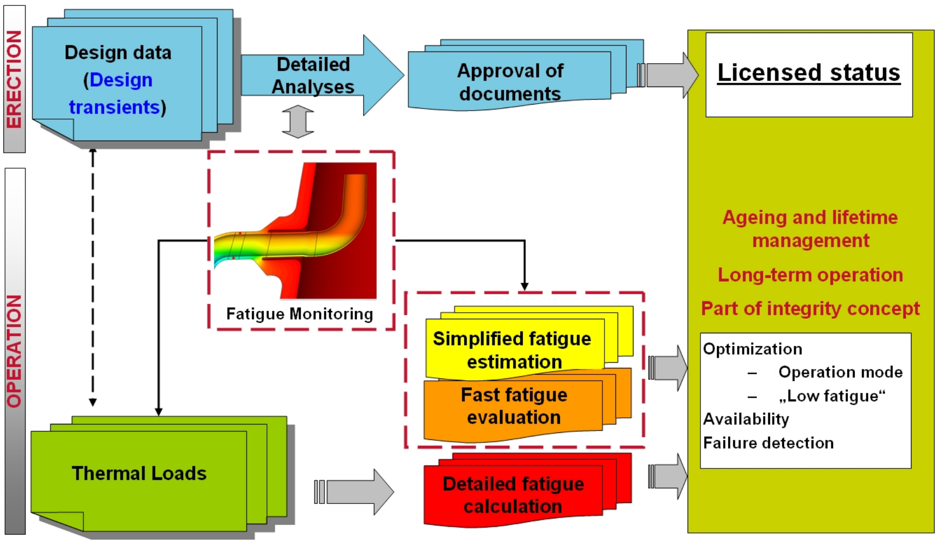

Figure 1 : AREVA Fatigue Concept

AREVA offers FAMOSi as a modern central data logging system (FAMOSi Local Measurements in Figure 1). This is the central data provider for the entire fatigue assessment process. Subsequently, a qualified load evaluation by system engineering takes place and allows for the compilation of a model transients catalogue and an update of design transients (see left branch in the scheme of Figure 1). This part is not described in further detail in the framework of this paper.

The available fatigue evaluation methods (see right branch in the scheme of Figure 1) 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 design code conforming (cumulative) usage factor U is calculated in a highly automated way based on the simplified elasto-plastic fatigue analysis route of relevant design codes. The measurement sections are implemented at the proximity of a fatigue relevant component at the outer surface of the adjacent pipe or directly on elbows. Usually, the points of interest are at the inner surface of the component. Therefore, the calculated temperature at the inner surface of the pipe will be transferred to the inner surface of the component. The thermal load cycles are well known after that step and the stress time history is calculated with the Greens function approach. This approach deals with one unit (elementary) transients of +100 K/s, which is used to scan the original temperature time history at each time step. By means of elementary transients, stresses are calculated at all fatigue relevant locations which are monitored. Pressure cycles as well as section forces and moments will also be evaluated based on the Greens function approach.

- **Step 3: Detailed fatigue calculation (DFC)**

In this case, fatigue analysis is based on a set of model transients from a catalogue (see Figure 1). The fatigue analysis for primary circuit components is based on design codes such as the ASME code. Fatigue calculations are usually carried out as simplified elasto plastic or elasto plastic analyses based on appropriate material models. Note that environmentally assisted fatigue (EAF) is considered both in step 2 and step 3 approaches according to the latest international guidelines [1,2].

For more details on this section, see [3].

2. FAMOSi THE AREVA FATIGUE MONITORING SYTSEM INTEGRATED

A typical FAMOSi measurement section is composed of thermoelements installed on a thin measurement tape which can be clipped on the outer surface of pipe and protected by a protection plate at proximity of the fatigue relevant components. Thermocouple cables are gathered in a junction box with a cold compensation module. A trunk cable leads the analog signals to one or several information module (IM). The IM acts as a bus coupler, collects the data from the thermocouple measurement modules and from the PT100, digitizes the data and sends the information to the processing unit (PU).

At the embedded computer of the PU, runs the FAMOSi core software and performs the following functions:

- Low pass filter for the incoming data with wire break detection (for instance damage on a thermocouple).
- Analyzing of data in real time: ”Gradient High” (if the rate of temperature change at the measured location exceeds a defined limit value), ”Stratification High” (if temperature difference between 12 o’clock and 6 o’clock thermocouples exceeds a defined limit value).
- Storage of data with the data reduction method

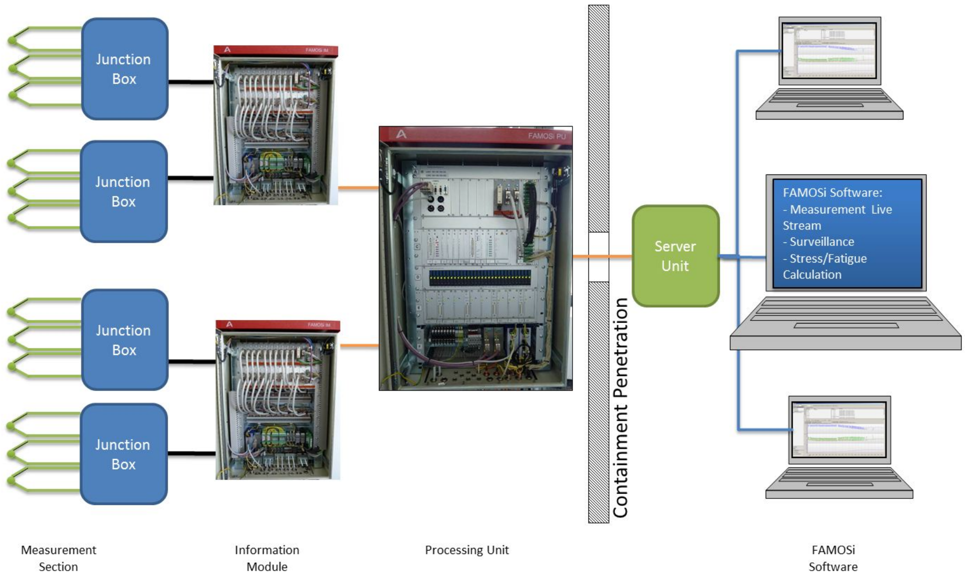

Figure 2 : FAMOSi: i=Integrated Hardware and Software

A server unit is typically installed for the streaming of data to the operating terminals with installed FAMOSi software. Moreover supporting surveillance functions are implemented for the detection and the diagnostic of failures by an operator.

As integrated solution the FAMOSi software can be used for the configuration of the hardware (thresholds, signals definition, material or geometrical properties) but also for analysis purpose as described in section 3..

For more details on this section, see [4]

3. Data Processing: Fast Fatigue Evaluation

One of the major issues of a monitoring system is the automation of the data evaluation. Without a powerful data processing methodology a fatigue monitoring system should be in fact limited to a temperature monitoring system. Before an automated processing of data some requirements should be assessed:

- **The temperature monitoring system is qualified**. Behavior of the measurement chain should be known in operating conditions. In this way test campaign can be necessary to test and validate the system design.
- **Process is highly automatized**. A fatigue monitoring system should be installed to support the engineering decision and reduce the engineering or maintenance activities.
- **Results can be verified**. Evaluation process is not a black box and results can be calculated partially by other methodology.

3.1 Application of the FFE approach for nuclear power plant components

The following section shows an example of application of measurement data processing done by the AREVA software FAMOSi. A fatigue calculation of the spray line flange was carried out. An illustration of a similar system with a flange is given in Figure 3.

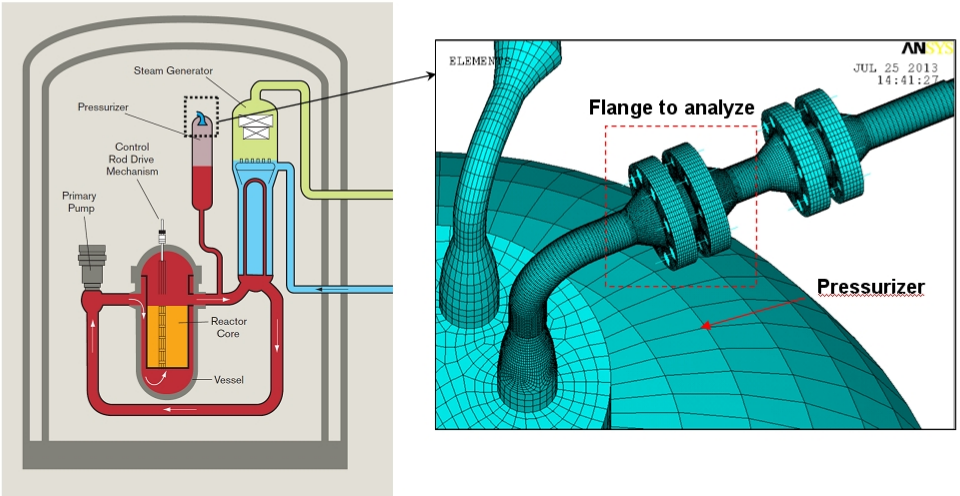

Figure 3 : Location of Measurement Section and Observed Component

3.2 Thermal load: determination of the inner temperature

Thermal changes in the structure are resulting from temperature changes in the fluid. The heat transfer between fluid and structure can be modeled by Newtons law. For unsteady state transients, all the difficulty to solve this equation results from the knowledge of the heat transfer coefficient depending from several parameters like flow, pressure, temperature, geometry. Because of the high number of approximation to be performed on the heat coefficient determination, the inverse approach was developed in the FFE process. To do it, the decomposition of the measured temperature into Unit Transients (UT) is applied. Between two consecutive time steps the measured temperature variation is compared to the temperature variation resulting from a reference unit transient applied at the inner surface of the pipe.

Within some linearity hypothesis, for instance, material properties constant with temperature, linear comportment of the temperature response at the outer surface pipe can be used to determine the load at the inner surface. Indeed it can be observed that the proportion between two impulses input with different gradient and the proportion between the two calculated responses at the outer surface is respected. In this way the comparison at the outer surface of a thermal response with a response of a reference impulse can be sufficient to determine the inner temperature.

The first step consists of calculating the thermal response of the considered component to a reference impulse. An analytical solution can be used for that purpose, but a finite- element model with consideration of different material properties delivers more accurate results. At the inner surface of the pipe, an impulse with characteristic gradient and amplitude will be applied as conductivity boundary conditions. The thermal response at a node corresponding to the thermocouple sensor will be observed and saved. This last one will be used as reference in the determination of the inner temperature.

Once the preprocessing work is performed, the measured data (FAMOSi measurement section at proximity of the flange) can be imported in the software FAMOSi for a first plausibility check. This process is partially automatized, measured data are scanned, higher temperature ranges or gradients are found and can be corrected with linear interpolation or manual corrections. The data are now ready for processing. Data are read step by step and temperature differences between two load steps are compared to the response to a reference elementary transient. A scaling factor between measured and reference temperature gives the temperature at the inner surface of the pipe. The process is really fast and stable (no oscillations or parameters to be optimized), on the other hand this method is limited by the thickness of the pipe where the measurement tape is installed.

3.3 Thermal load: verification of the inner temperature

A verification of the results can be performed on a few load steps of previously calculated temperature. Calculated temperature with FFE (inner temperature) is used in the finite element software ANSYS. The conduction problem is solved, then the temperature calculated at the outer surface of the pipe/model and the measured temperature can be compared. For the majority of pipes where installation is performed, an accuracy of the method higher than 95% is expected.

3.4 Boundary conditions for stress determination

The elementary transient method is also applied to calculate thermal stress for components with complex geometry where no analytical solution is possible. The component should have locally a linear character: no material differences, or contact connections close to observed location. A finite element model of the component is built for the initialization of the fast fatigue method.

Instead of applying thermal transients (design transients or catalogue transients) as boundary condition, a unit transient (impulse with reference amplitude and gradient) is applied. The resulting thermal stress is calculated. Fatigue relevant locations are determined at high thermal stress locations or welds. At these locations time-dependent stress results are saved in the FAMOSi data base.
The saved stress references will be scaled according to the previously calculated inner temperature load with a frequency up to 1Hz, single contributions are summed-up time dependently in order to build the thermal stress history at the observed locations.

3.5 Stress determination

The temperature calculated at the inner surface is applied as thermal load in FAMOSi for stress determination. In local temperature measurement approach, thermocouple sensors (FAMOSi measurement sections) are placed close to the fatigue relevant locations (for instance spray lines, feedwater nozzles, surge line, flange connections, regenerative heat exchangers). If instrumentation is not directly installed close to the analyzed component, some correction factors can be applied. The calculated temperature is scanned with a frequency up to 1Hz and decomposed into unit transients. The stress contribution of every unit transient is superposed to calculate total stresses and linearized stresses. Results are saved in the FAMOSi data-base and can be easily plotted or used for further data processing. The data base was structured to manipulate high amounts of data (several power plants with full monitoring locations and operating cycles). Except the storage quantity on hard drive or server units, the visualization of channels is not impacted by the amount of recorded data.

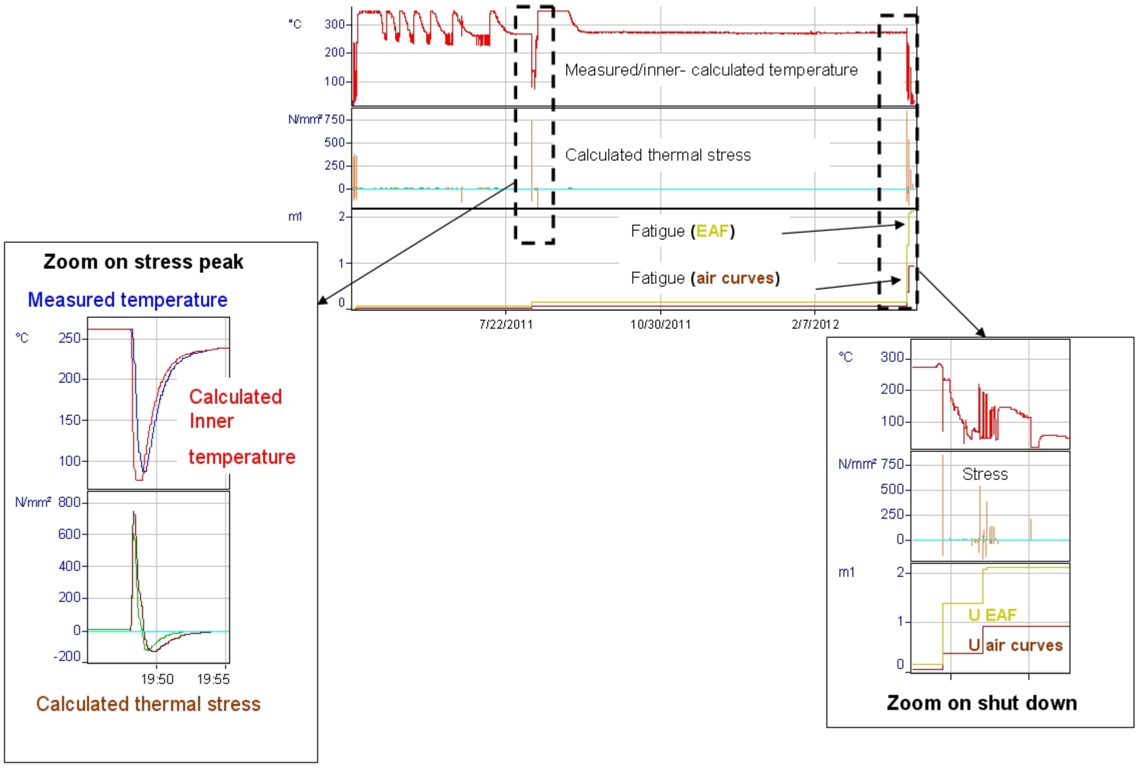

Figure 4 : Inner Temperature, Thermal Stresses and Fatigue for one Year Measurement at a Flange Location

For instance stress determination (6 stress components, 6 linearized components and a temperature channel) for a whole fuel operating cycle at a weld seam location is performed within few minutes on standard computers. Thermal stress results calculated at inner side of a flange weld for a whole operating cycle is plotted in Figure 4. If pressure or piping loads variation has influence on the stress at the observed location, mechanical stress can be added to thermal stress in the software. This operation is particularly relevant at welds.

3.6 Verification of the stress calculation

Verification is possible since the calculated load (inner temperature) can be input in a finite element software (ANSYS). Because of high processing time on a three-dimensional FE model, verification is just done for few load steps or conservative transients. The temperature field in the structure is calculated on every node, then the calculated temperature on nodes is read in the structural FE model. Resulting stresses are calculated and can be compared with results of FFE FAMOSi. Comparison of results for several geometries and situations shows that deviation between both methods is typically lower than 3%.

3.7 Consideration of environmental factors F_{en}

In this study, environmentally assisted fatigue (EAF) is considered by means of the factorial approach based on penalty factors F_{en} proposed in [1, 2]. In Figure 4 time-dependent cumulative usage factor calculated in air and under EAF conditions are plotted.

3.8 Cycle counting

The determination of cumulative usage factors CUFs 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. The largest stress ranges are usually determined from outer combinations (e.g. load steps across different transients respectively events). The associated frequency of occurrence results from the actual number of cycles of the participating two events with the smaller number of cycles. This event provides the associated contribution to the partial usage factor CUF. The summing up of all partial usage factors according to Miners rule delivers the cumulated usage factor CUF. As soon as the load history is directly considered a rain flow algorithm, e.g. the hysteresis counting method HCM - according to Clormann and Seeger [6] is recommended.

For more details on section 3., see [7–9].

CONCLUSION

Structural health monitoring is a central item in the context of the ageing management and plant lifetime extension related issues. The fatigue monitoring approaches developed and practiced within the AREVA Fatigue Concept (AFC) are focused on the integration of a qualified hardware and a high-performance data processing software. Based on a time-dependent consideration of the usage factor, better relations between operation modes and structural analysis of components can be performed. Moreover prognostics on lifetime of components can be done and, if needed, correction on operating modes easily applied.

REFERENCES

[1] O Chopra and B Shack. Effect of LWR coolant environments on the fatigue life of reactor materials. Final Report NUREG/CR-6909, ANL-06/08, U.S. Nuclear Regulatory Commission, February 2007.

[2] U.S. Nuclear Regulatory Commission. Office of Regulatory Research. Regulatory guide 1.207, guidelines for evaluating fatigue analysis incorporating the life reduction of metal components due to the effects of the light-water reactor environment for new reactors, March 2007.

[3] J Rudolph, S Bergholz, B Heinz, and B Jouan. *Nuclear Power Plants*, chapter AREVA Fatigue Concept A Three Stage Approach to the Fatigue Assessment of Power Plant Components. InTech, 2012. Available from http://www.intechopen.com/books/nuclear-power-plants/areva-fatigue-concept-a-three-stage-approach-to-the-fatigue-assessment-of-power-plant-components.

[4] B Heinz and D Wu. Areva's modularized fatigue monitoring for lifetime extension and flexible plant operation. Number PVP2014-28726. Proceedings of the ASME 2014 Pressure Vessels & Piping Conference, July 2014.

[5] 2010 ASME Boiler & Pressure Vessel Code. Section III division 1 - subsection NB: Class 1 components. rules for construction of nuclear power plant components, July 2010.

[6] U.H Clormann and T Seeger. Rainflow -HCM, ein Zählverfahren für Betriebsfestigkeitsnachweise auf werkstoffmechanischer Grundlage. In *Stahlbau 55*, number 3, pages 65–71. 1986.

[7] B Jouan, J Rudolph, S Bergholz, G Koenig, and A Manke. Automatic fatigue monitoring based on real loads - calculation example of a flange. Number PVP2013-97660. Proceedings of the ASME 2013 Pressure Vessels & Piping Conference, July 2013.

[8] B Jouan, J Rudolph, and S Bergholz. Automatic fatigue monitoring based on real loads. Number 305. 22nd International Conference Nuclear Energy for New Europe, 2013.

[9] J Rudolph, B Jouan, and S Bergholz. Fatigue monitoring approaches for power plants. Number PVP2014-28100. Proceedings of the ASME 2014 Pressure Vessels & Piping Conference, July 2014.