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Component tests to verify fatigue strength under media conditions

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ABSTRACT

The start of this project was postponed from late 2023 to early 2024 and is, at the time of submission deadline, in the funding approval phase with the project responsible body. Overarching objective of this planned project is to create an experimentally confirmed database for the verification and further development of advanced methods for fatigue assessment. Therefore, thermal fatigue tests with components harvested from the nuclear power plant Ringhals in Sweden will be performed under well replicable operational load and boundary conditions. In combination with a material characterization, this enables an improved statement on the fatigue behavior of components used in nuclear power plants under the influence of the reactor coolant of light water reactors (LWR) and creates a basis for comparative benchmark analyses. The focus of the investigations lies on components made of austenitic steels.

Within this project, three different geometries such as elbows, T-junctions or straight pipe pieces will be investigated. These components will be used to perform tests with measurement of the relevant loadings like pressure, fluid temperature or displacement due to thermal expansion and stratification. Therefore, components from ongoing harvesting efforts with Ringhals 2 will be used to determine the remaining life of the harvested components. For the according numerical investigations coupled fluid-structure simulations will be carried out. Based on these calculations fatigue analyses and validations with available calculation models as well as comparison of the results will be performed. The final test data of the project will be prepared for international benchmark analyses.

INTRODUCTION

Material fatigue, particularly under the influence of the reactor coolant (corrosion fatigue), is one of the main influencing mechanisms that limits the service life of nuclear components and thus the service life of nuclear facilities. For the service life extensions of up to 80 years, the basis of the design, which has been confirmed and proven by experiments, is clearly exceeded. Since the first studies in the mid-90s, with laboratory specimen under the influence of the reactor coolant on the fatigue strength of the materials used in nuclear power plants, numerous national and international research projects have dealt with the various influencing variables on the material behaviour, Keisler et al (1995), Chopra et al (2014). However, these developments are mainly based on investigations of laboratory samples, which can only partially reflect the conditions in real plant operation. There is still a lack of experimental investigations on representative components under realistic operating conditions, Steininger et al (2017), Wright (2017), which could be used to determine the suitability of the verification methods for a reliable extended fatigue assessment of power plant components under operation conditions.

In order to investigate component behaviour under environmentally assisted fatigue, component tests at the fluid-structure-interaction (FSI) test loop at MPA University of Stuttgart shall be carried out which aim for the verification and comparison of different, international calculation methods. Within this contribution an overview of the test facility, the planned testing procedure and the time schedule with its work packages (WP) in the range of the project with the acronym COVER, is presented.

GOALS

The overall objective of the project is to create an experimentally validated database for the verification and further development of advanced methods for fatigue assessment by carrying out thermal fatigue tests on components, representative for nuclear power plants under reproducible and near-operational load and boundary conditions. This, in turn, enables an improved statement on the fatigue behaviour of components used in nuclear power plants under the influence of the reactor coolant of light water reactors (LWR) and creates a basis for international, comparative benchmark analyses. The focus of the investigations is on components made of austenitic steels as well as on the performance of thermal fatigue tests on pipe components under the influence of fluid and the characterization of these materials.

As part of the project, the experimental basis for the verification and validation of engineering calculation concepts, which can be used to improve the reliability of safety-related analyses and assessments, will be developed, considering the relevant parameters that influence fatigue behaviour. A direct comparison of the methods used to date for the quantitative determination of fatigue damage with actual fatigue damage to materials used in nuclear power plants (NPP) will be carried out. With the help of the experimental data obtained in the project, the development potential of advanced fatigue analyses can be identified. In addition, the knowledge gained can be used in engineering calculation concepts which, for example, also enables condition assessment of components. The investigation results obtained in the project will be used to expand the basis for understanding the combined corrosion and fatigue process that takes place under the influence of a medium. The general understanding of the damage processes occurring under fatigue loading will be deepened and the database for the optimization and further development of the design and assessment concepts of components will be expanded. For this purpose, three typical pipe components from the Ringhals 2 plant made of austenitic steel (F304, WP316/316) will be tested under thermally transient loads by feeding cold water into a hot main line. Crack initiation is the desired end of these component tests. The material characterization will be carried out on laboratory samples, manufactured from the harvested components.

PLANNED INVESTIGATIONS

This paragraph gives an overview of the general approach of the planned investigations. This also includes an overview of the fluid-structure interaction (FSI) test loop at MPA University of Stuttgart and the available components as well as the project time schedule.

General Approach

At MPA University of Stuttgart a test facility for environmental fatigue testing on component level has been set up in different projects over the last 10 years (FSI test rig) see Kammerer et al (2017). This test rig allows the execution of component tests with different scenarios like hot and cold water mixing or the investigation of stratification phenomena. Within the herein described project piping modules from harvesting activities at the Ringhals 2 site will be exposed to water environments with alternating temperature conditions. The specific testing conditions are to be defined during the first phase of the project. Generally speaking, room temperature water is injected into the hot main loop at specific locations which results in thermal induced loading situations. Consequently, thermal stratification and thermal shocks cause localized stresses and strains in the tested pipe pieces.

The tests will be carried out on three piping sections including a bend, a T-piece and a sockolet or straight pipe. These sections will be equipped with weld neck flanges and included to the FSI test loop. The FSI test loop is then used to execute component tests with thermal-transient and alternating loads. As many as possible of the flow variables will be recorded as well as the component temperatures and the piping displacement due to stratification in the on the FSI loop to gather all relevant load defining influence factors.

The test parameters will be defined based on numerical simulations of the flow conditions and the resulting component stresses. Sections of the delivered pipe components will be used to carry out material characterizations. Tensile as well as fatigue tests are specified accordingly in the project proposal. Based on the numerical investigations and the measurements different calculation methods for fatigue analysis will be carried out and compared. The focus lies on the preparation of data sets that can be used for international benchmark analysis including load history, material characterization, acceptance certificates and the test results from the FSI test loop.

FSI Test Loop

The FSI test loop is designed as an open piping system and can be operated in the pressure range from around 5 bar to a maximum of 80 bar internal pressure and in the temperature range from 15 °C to 280 °C water temperature, see Figure 1. The system parameters are controlled from a shielded control room and are largely automated. In addition to the recording of all measured values, the status of all main components and valves is saved during operation. The heated part of the FSI test loop is made of seamless pipes consisting of austenitic steel 1.4404 and 1.4550 and has a nominal diameter of 80 mm in the hot part of the loop and a nominal diameter of 40 mm in the cold leg. A four-stage piston diaphragm pump feeds water with a maximum mass flow rate of 200 g/s from the storage tank into the FSI test loop through the cold part of the loop. The pressure in the loop is set via a controlled needle valve, through which a corresponding amount of water can be discharged through a heat exchanger. The heat exchanger cools the water down to 16 °C before being routing it back into the storage tank. The heat sink of the heat exchanger is a cooling unit with a nominal output of 138 kW. The mass flows are recorded at up to three positions in the test loop using Coriolis flow meters. The fluid is circulated in the circuit with a single-stage canned motor pump at a maximum flow rate of 1 kg/s and can be regulated via a valve. Over a total length of around 22 m, the piping in the hot section of the loop is heated from the outside using heating mats. This part of the system forms the heating section, which is powered by three annealing units providing 48 kW each and one annealing unit with an output of 84 kW. The FSI test loop is constructed of modular pipe which allow for a relatively flexible installation of various components, see Figure 2. Thus, a wide variety of configurations can be realized with little effort regarding the test setup. The water quality is controlled by a water treatment system that is connected to the storage tank. It consists of a mixed-bed water desalinator, an activated carbon filter and a UV irradiation device and continuously circulates the water in the storage tank during operation.

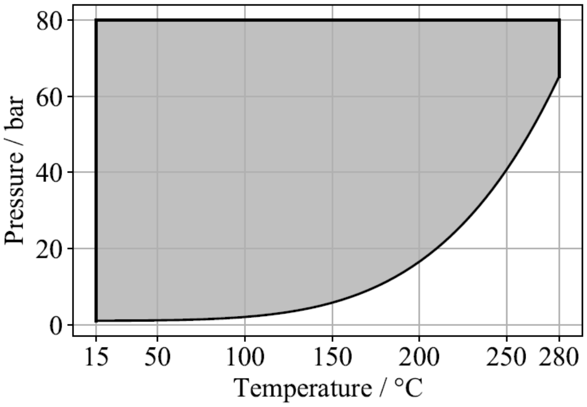

Figure 1. Parameter range of the FSI test loop with liquid phase in the grey area

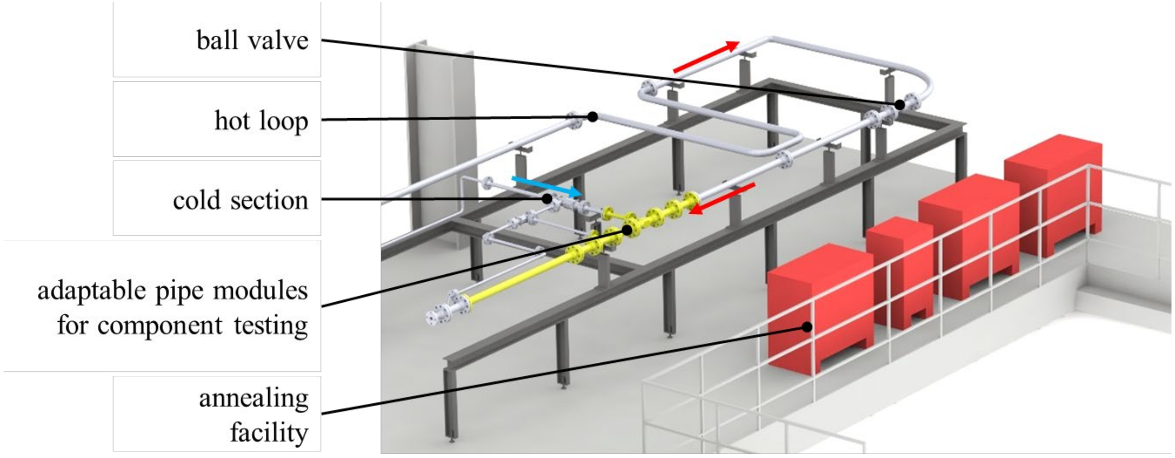

Figure 2. FSI test loop with main components, configuration for component testing

Components To Be Tested

All components need to be free of radioactive contamination and released prior to shipping to MPA Stuttgart. The pressurizer (PRZ) spray line components selected for harvesting and testing are depicted in Figure 4 and numbered by priority, see also Table 1. The nominal diameter of the components is 4 " while the size of the cut-outs is planned to be 900 mm for straight pipe pieces. T-pieces are planned with 400 mm length for the run pipe and 150 mm length for the branch pipe, see Figure 3.

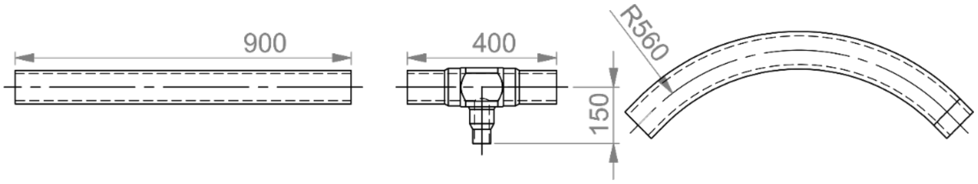

Figure 3. Approximate size of the harvested components from Ringhals 2

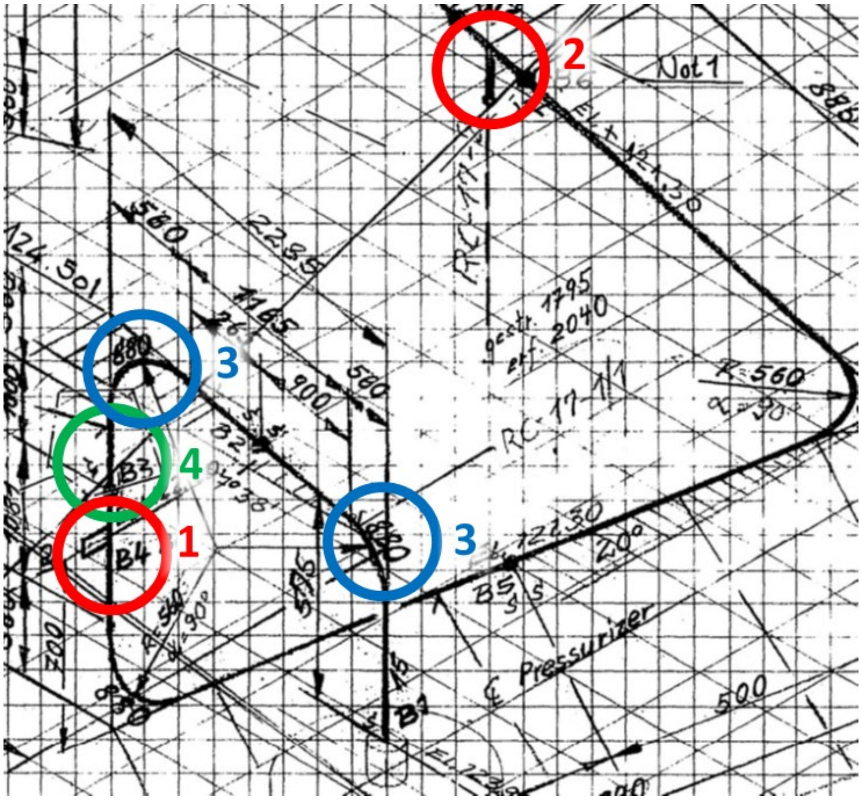

Figure 4. Piping layout with planned components for harvesting at Ringhals 2 with priorities. With kind permission from Ringhals.

Table 1: Planned components for harvesting at Ringhals 2.

Priority	Component	Diameter	Description/ Material
1	Sockolet	4”-2”	A182 F304
2	T-piece	4”-4”	A182 WP 316
3	Elbow	4”	Sch 120 A376 TP316
4	Straight pipe	4”	sch 120 A376 TP316

Time Schedule And Work Packages

The time schedule for the project is given in Table 2 with an overall project duration of three years. The project is divided into six main work packages which are described in the following subsections.

For the pipeline components (straight pipe, elbow, T-piece) taken from the Ringhals 2 plant, the optimum test conditions with regard to the project objectives are to be determined within work package 1 (**WP1**). This concerns the determination of the installation configuration, i.e. vertical or horizontal arrangement of the components in the test loop, taking into account the results of numerical calculations from WP4 and the original position of the component in the piping layout. The test loop allows for lowfrequency cycles with high temperature change (high stress) by valve switching or high-frequency cycles with low temperature change (low stress) by turbulent flow. As part of the design work for the piping modules, the metrological planning for the piping modules is determined from the point of view of structural mechanics and fluid mechanics. Essentially, this concerns temperature sensors, and possibly also pressure measurement technology, on the modules, which should be designed in a similar way to previous work on the FSI test loop with T-piece or thermocouple module. If necessary, special micro-thermocouples will be used to measure flow temperatures close to the pipe wall. Displacements and strains are recorded using optical methods (DIC). As the global displacements caused by thermal expansion due to stratification phenomena significantly determine the stress on the component, the displacements occurring in the pipeline are measured and recorded inductively using differential transformers (LVDT). Thermocouples for solid and fluid are applied to record the wall temperatures and flow temperatures in the boundary layer close to the wall. A proposal for the planned component tests and the measured variables to be recorded will be presented to a specialist committee and discussed in the range of a milestone meeting in the third quarter of the first year.

Table 2: Schedule for the project

		Year 1				Year 2				Year 3			
Work Package 1-6 (WPx)		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WP1	Selection of component and measurement method	▨	▨	▨	▨								
WP2	weld components / material characterization		▨	▨	▨	▨	▨	▨					
WP3	Experimental investigations				▨	▨	▨	▨	▨	▨	▨	▨	
WP4	Numerical investigations of fluid dynamics (CFD)	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
WP5	Numerical investigations of stresses (FEA)				▨	▨	▨	▨	▨	▨	▨		
WP6	Fatigue analysis						▨	▨	▨	▨	▨	▨	▨

The pipeline components are taken from the Ringhals 2 plant in the range of harvesting activities and shipped to MPA. The Material Transfer Agreement has already been prepared. The components will be installed in the FSI test loop using standard welding neck flanges. Modifications and extensions to the FSI test loop are carried out by the MPA workshop in the range of **WP2**. The material characterization is carried out depending on the amount of material that is provided by Ringhals. In addition to the base material, weld metal can also be characterized if available to a sufficient extent. However, the characterization primarily includes the base material of the components. Table 3 lists the test matrix for the basic characterization of the materials. The purpose of these tests is to determine the initial state and material properties at room temperature (RT) and operating temperature. Under medium conditions, tests can be carried out at 70 bar pressure up to a temperature of 240 °C. In addition to the characterization, data from the quality assurance documents (chemical analysis, material certificate, welding procedure specification, etc.) are requested from the operator.

Table 3: Planned tests for material characterization of static and cyclic material behaviour.

		Quantity	Temperature	Material	Strain rate	Environment
Static Material Behaviour	Tensile Test	4	RT & 280 °C	Base Material		Air
	Elastic Modulus	2	RT & 280 °C			Air
	Micro Sections	1	RT			Air
Cyclic Material Behaviour	Fatigue Test	10	RT		1 % s-1	Air
		10	RT		1 % s-1	Air
		10	240 °C		0,4 % s-1	HTW

WP3 includes the experimental investigations carried out on the FSI test loop under close to reality thermal-hydraulic LWR conditions (p_{max} 80 bar, T_{max} 280 °C). The components are tested on alternating thermal loads under the influence of pressure, temperature and flow and, if necessary, external mechanical loads. The scope of testing is adapted depending on the components and pipe sections supplied from the Ringhals plant. Coriolis flow meters, thermocouples and piezo resistive pressure transducers are used in the FSI test loop to measure the fluid conditions. A special thermocouple pipe module, instrumented with micro-thermocouples at several cross-sections at different wall depths as well as other measuring points on the inner pipe surface and in the flow cross-section, can be used to characterize the flow and temperature conditions. The modular pipe design of the FSI test loop makes it possible to install the thermocouple pipe module at different positions in the loop and carry out corresponding temperature measurements.

In **WP4** Three-dimensional numerical simulations of the flow (CFD), coupled with heat conduction in the solid wall material, are carried out on the basis of previous experience like in Kammerer et al (2017). The main focus of the simulations lies on the design of the test parameters to be selected. The methodology described has been successfully applied in previous projects like in Kammerer et al (2018) or Kuschewski et al (2013) or Cenk et al (2021).

Within **WP5**, preliminary calculations are carried out partly based on existing research results. Initially, the focus is on the numerical simulations of the flow. Based on these results and the initial measurement results from the system, the stresses can be calculated. To determine the test parameters, temperature changes are to be estimated from which the stresses on the inner surface result. The thermal transient structural simulation of the thermal-mechanical stresses is carried out using finite element analysis (FEA). Comparable simulations were carried out, for example, in Kammerer et al (2018). These investigations also serve to select the appropriate measurement methods and estimate the expected displacements in the piping system. Numerical calculations are required to determine the test parameters for the experimental investigations planned as part of WP3. Once the tests have been carried out, the calculations are repeated with updated input values using the measured test parameters. These calculations will then be used for further fatigue analysis in WP6.

WP6 includes the fatigue analyses that will be carried out using verified evaluation procedures developed in previous projects, see Herter et al (2019) and Schopf et al (2022). These procedures are evaluated and verified using the experimental data obtained from the projects results. The experimental data obtained in the project will be used to identify the development potential of these procedures. The load collectives set up on the FSI circuit allow a direct comparison of the mathematically determined degrees of fatigue according to various standard procedures with the characteristic damage pattern observed on the component. The works also include the preparation of the data collected during the component tests and material characterizations. The aim is to compile complete data sets which will be used as a basis for carrying out international benchmark analyses. Part of this database will be the temperature measurement data recorded at the FSI test loop, displacements and strains on the component as well as the relevant flow variables such as internal pressure, temperature and flow rate and, for example, the electrical conductivity of the fluid. In addition, measurement data from the complete load history of the components shall be included.

NOMENCLATURE

Table 4: Abbreviations used in the article

CFD	Numerical investigations
FEA	finite elemente analysis
FSI	Fluid-Structure-Interaction
HTW	high-temperature water
LWR	light water reactors
PRZ	Pressurizer
RT	Room Temperature

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