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Division II

Automated Fatigue Crack Growth tool developed on the basis of ASME Code Case N-809 for the application on real time plant data measured using FAMOSi

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ABSTRACT

Framatome uses an automated measurement and data evaluation software FAMOSi (FAtigue MOnitoring System integrated) for fatigue evaluation of components in power plants. This software uses its own proprietary system for the measurement of thermal loads at points of interest, and subsequently calculates the thermal stresses for further evaluation. In addition to performing fatigue evaluations with FAMOSi, power plant operators have shown increasing interest in performing fracture mechanics assessments within the FAMOSi framework. Historically, fracture mechanics assessments using FAMOSi measured load histories have only been performed on a case to case basis. An automated tool has now been developed to perform fatigue crack growth calculations using the ASME Code Case N-809 for austenitic steels operating under pressurized water reactor (PWR) environmental conditions. This tool widens the capabilities of FAMOSi, making it possible to calculate fatigue crack growth of postulated cracks for selected thermo-mechanical load histories. One of major benefits of this developed tool is that, it can be used as a screening criteria for a detailed fracture mechanics assessment.

As per ASME Code Case N-809, fatigue crack growth rate, da/dN, is dependent on the applied stress intensity factor range, ΔK, temperature, R ratio (K_{min}/K_{max}), and the rise time of the cycles. This cyclic data from the input load history can be extracted using an appropriate cycle counting method, and in this tool, the Rainflow cycle counting method described in ASTM E1049-85 has been used to perform cycle counting. The stress intensity factors are calculated using a simple plate based solution developed by Newman and Raju (1986). This paper describes the methodology used in the application of the aforementioned methods within the tool to perform a fatigue crack growth analysis on real time plant data. Additionally, an example will be presented for an austenitic steel pipe operating under PWR environmental conditions.

INTRODUCTION

The safety checks against cyclic operational loads, i.e. fatigue check, takes a central position within the ageing management of power plants. 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. Framatome provides its own fatigue monitoring solution FAMOSi (“i” = integrated) as part of the Advanced Fatigue Solution (AFS) (see Figure 1). It serves as a load data provider and uses them as input for three different evaluation processes in a graded concept: SFE (simplified fatigue estimation), FFE (fast fatigue evaluation) and DFC (detailed fatigue calculation). FAMOSi is capable of performing Fast Fatigue Evaluation, a methodology developed by Framatome, to directly process the temperature measurements recorded by the fatigue monitoring system, and calculate the stress tensor history and cumulated usage factor on component locations. All aspects of AFS are comprehensively described in Rudolph et al. (2012).

In addition to fatigue evaluations, power plant operators are increasingly interested in performing structural integrity assessments in combination with their periodic in-service inspection programs. ASME Code Section XI, Nonmandatory Appendix C, for instance, provides analytical procedures and criteria for determining acceptability for continued service of flawed pipes for specified evaluation periods. The Nonmandatory Appendix C also provides procedures for flaw growth analysis based on fatigue and stress corrosion cracking. Flaw growth analysis based on fatigue requires information on cyclic temperature and load transients obtained from either design documentation or plant operation data. FAMOSi is unique in this context, since the operational data collected for fatigue evaluation can also be used for performing fatigue crack growth analysis. Therefore, a pilot project was launched to develop a standalone tool for performing fatigue crack growth analysis of flaws in austenitic pipes using the operational data collected by FAMOSi. The developed standalone tool is capable of performing fatigue crack growth analysis using a simplified methodology and is intended to be used for screening for a detailed structural integrity assessment. The next planned phase of the project is to introduce the tool directly into the FAMOSi framework.

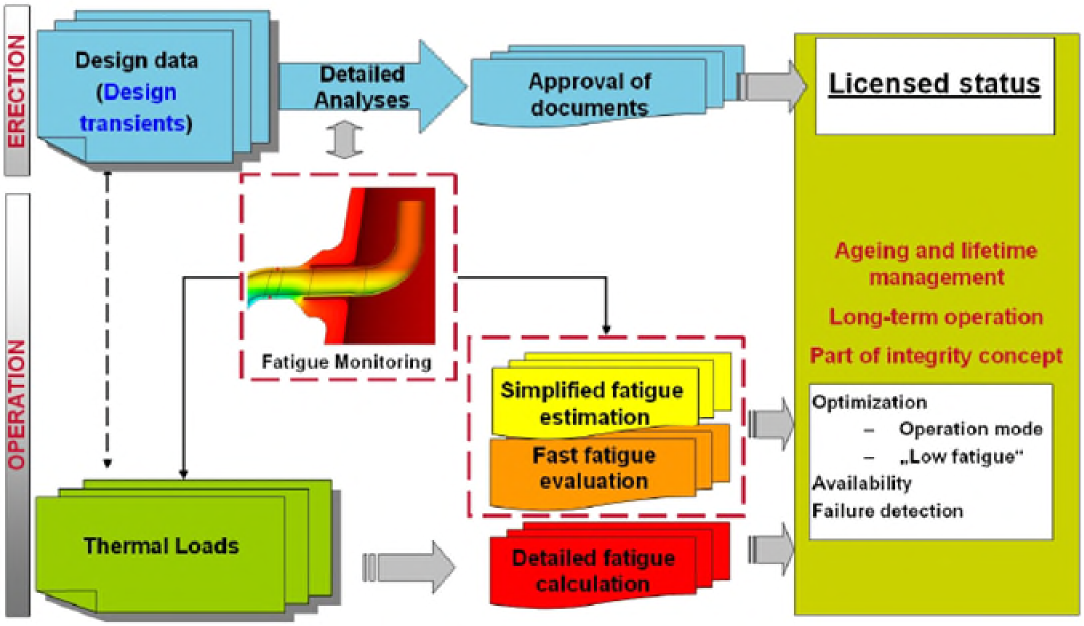


Figure 1: Advanced Fatigue Solution (AFS)

FLAW GROWTH ANALYSIS

The cyclic fatigue crack growth rate, da/dN, of a material is generally characterized by the range of the stress intensity factor, ΔK, a scaling parameter C_0, and the slope, n, of the $\log(da/dN)$ versus $\log(\Delta K)$ curve as shown in Equation 1 (Paris law).

$$\frac{da}{dN} = C_0 \Delta K^n \tag{1}$$

For fatigue crack growth analysis in austenitic steels operating under PWR environmental conditions, the code case N-809 has been developed by the ASME Section XI Working group on Flaw Evaluation Reference Curves (WGFERC). According to code case N-809, the parameter C_0 is calculated as shown in Equation 2 below.

$$C_0 = C S_T S_R S_{Env} \tag{2}$$

where:

$C = 0 \; for \; \Delta K < \Delta K_{th}$
$C = 9.1 \times 10^{-6}$ for $\Delta K > \Delta K_{th}$

$S_T = 3.39 \times 10^5 \, e^{\left[\frac{-2516}{T_K} - 0.301 T_K\right]}$ for 20°C ≤ T < 150°C
$S_T = e^{\left[\frac{-2516}{T_K} - 0.301 T_K\right]}$ for 150°C ≤ T ≤ 343°C

$S_{Env} = {T_r}^{0.3}$

$S_R = 1 + e^{8.02(R - 0.748)}$ for 304 and 316 stainless steel
$S_R = 1$ for $R \leq 0.7$ for 304L and 316L stainless steel
$S_R = 1 + 1.5\,(R - 0.7)$ for $R < 1$ for 304L and 316L stainless steel

The crack growth rate, da/dN, is in mm/cycle, T is the metal temperature (°C), T_K is the temperature in Kelvin, T_r is the load rise time (sec), R is the R-ratio computed as K_{min}/K_{max}, K_{min} is the minimum stress intensity factor for a cycle (MPa√m), K_{max} is the maximum stress intensity factor for a cycle (MPa√m), ΔK is the stress intensity factor range (MPa√m) computed as $K_{max} - K_{min}$, and ΔK_{th} is the threshold stress intensity factor which is equal to 1.10 MPa√m.

METHODOLOGY

A simplified flowchart of the methodology used in the development of the tool is shown in figure 2. The input transients for performing fatigue crack growth (FCG) analysis are obtained directly from FAMOSi measurements. For the acquisition of this data, FAMOSi uses data from existing operational measurement and data delivered by the local FAMOSi temperature measurement (see Miksch et al. (1988)). The local temperature measurement by FAMOSi Hardware (HW) – i.e. measurement sections - is focused on fatigue relevant locations and delivers the outer surface temperature of pipes. The measured thermal loads are transferred to the inner surface of the pipe and then used to calculate the time dependent thermal stresses. These thermal stresses are calculated using either simple analytical equations or complex finite element methods. In addition to thermal stresses, stresses from other loads such as pressure are also calculated.

Once the input transients in the form of thermal loads, through-wall thermal transient stresses and mechanical loads are loaded into the tool, input data for performing the FCG calculations are entered by the user. The stresses could be just thermal stresses or stresses resulting from the superposition of thermal stresses and stresses from mechanical loads. In cases where only the time dependent pressure loads are given as input, the tool calculates the stress components internally using simple analytical equations and performs the superposition of the through-wall stresses. When the measured mechanical loads come from the system engineering level, the measurement frequencies of thermal loads (local fatigue monitoring frequency is usually 1 Hz) and mechanical loads usually don't coincide. This mismatch is easily treated within the tool to ensure the resulting superposed through-wall stresses have the same frequency.

The maximum through-wall stress at every time increment is determined and stored in an array, which serves as input for performing cycle counting. The Rainflow cycle counting method described in ASTM E1049-85 has been used to perform cycle counting within this tool. All the counted cycles along with the residuals, and the time increments at which the stresses defining each cycle are determined, are stored in a matrix. The time related information is used to sort the counted cycles with increasing time, and also to calculate the rise time of each cycle. The raw data generated from Rainflow counting are also written out for visualization purposes.

The crack growth calculations are performed only on ascending cycles for two flaw configurations. The first configuration is a crack with an aspect ratio (a/c ratio or crack depth to half-length ratio) equal to 1. The second configuration is a crack with an aspect ratio equal to 0. The stress intensity factor K for each cycle is calculated using a simple plate based solution by Newman and Raju (1986). Instead of calculating K_{min} and K_{max} to obtain ΔK and R, ΔK and R are calculated directly from $\Delta\sigma$, σ_{max} and σ_{min} values of each cycle. This way of calculating ΔK and R is only valid since the stresses making up each cycle are treated as either pure membrane or pure bending stresses. This translates to calculating ΔK and da/dN four times for each cycle, i.e. for the $a/c = 0$ crack with $\Delta\sigma$ applied as pure membrane stress, for the $a/c = 0$ crack with $\Delta\sigma$ applied as pure bending stress, for the $a/c = 1$ crack with $\Delta\sigma$ applied as pure membrane stress and for the $a/c = 1$ crack with $\Delta\sigma$ applied as pure bending stress. Such an approach ensures that only the maximum crack growth rates are used to update the crack depth and length after each cycle.

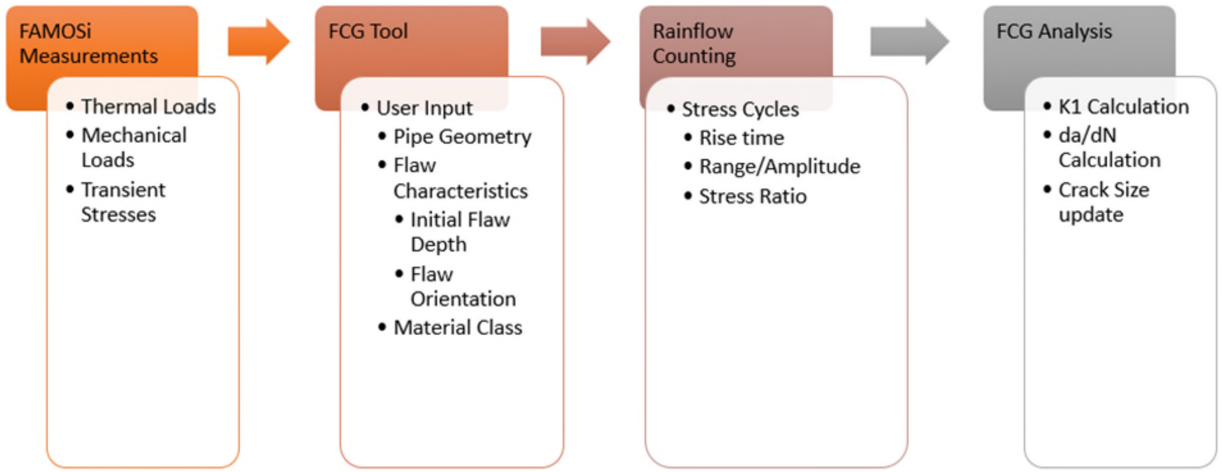


Figure 2. Methodology used to develop FCG tool.

EXAMPLE

The FAMOSi data collected for an austenitic steel pipe of 80 mm inner diameter and a wall thickness of 10 mm operating under PWR (wet) conditions is used to perform FCG analysis on an initial postulated crack of 1 mm depth. The input transient loads (temperature, thermal stresses and pressure) for a period of 10 days are given as input data to the tool. The input transients for temperature and pressure loads are shown in figure 3. The through-wall thermal transient stresses calculated using the thermal loads are shown in figure 4. The raw data generated from Rainflow counting are stored in an excel file in the format shown in figure 6. The final results of the FCG analysis are shown in figure 6.

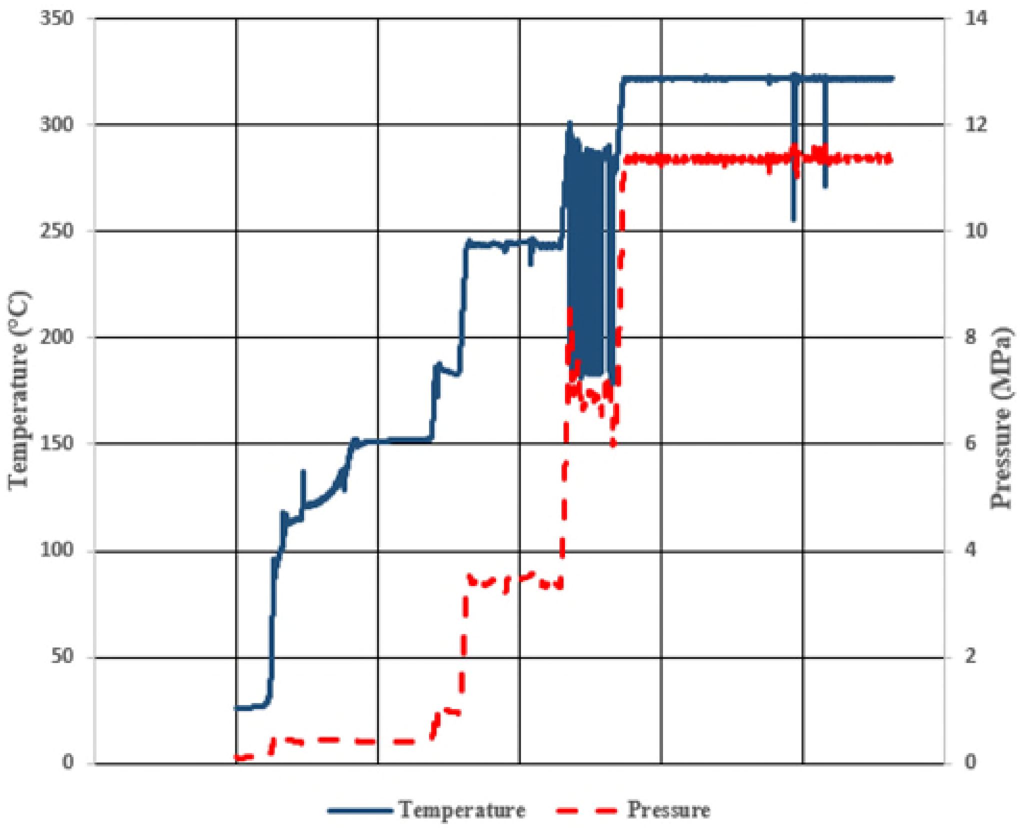


Figure 3. Temperature and pressure transients obtained from FAMOSi.

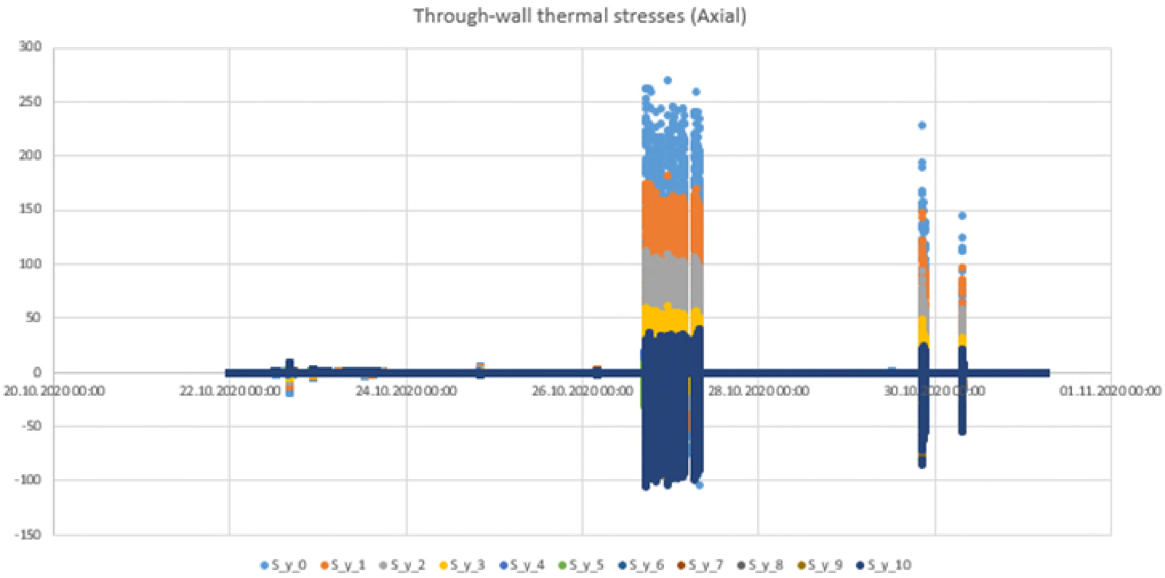
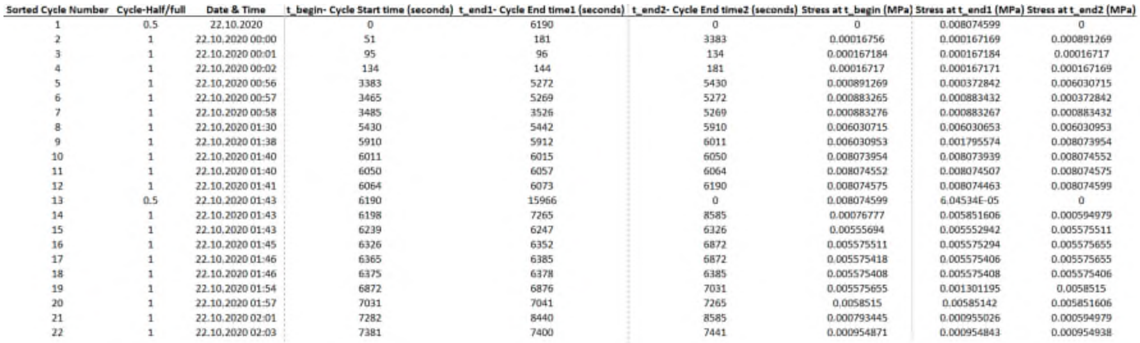


Figure 4. Through-wall thermal transient stress.



Sorted Cycle Number	Cycle-Half/full	Date & Time	t_begin- Cycle Start time (seconds)	t_end1- Cycle End time1 (seconds)	t_end2- Cycle End time2 (seconds)	Stress at t_begin (MPa)	Stress at t_end1 (MPa)	Stress at t_end2 (MPa)
1	0.5	22.10.2020	0	6190	0	0	0.008074599	0
2	1	22.10.2020 00:00	51	181	3383	0.00016756	0.000167169	0.000891269
3	1	22.10.2020 00:01	95	96	134	0.000167184	0.000167184	0.00016717
4	1	22.10.2020 00:02	134	144	181	0.00016717	0.000167171	0.000167169
5	1	22.10.2020 00:56	3383	5272	5430	0.000891269	0.000372842	0.006030715
6	1	22.10.2020 00:57	3465	5269	5272	0.000883265	0.000883432	0.000372842
7	1	22.10.2020 00:58	3485	3526	5269	0.000883276	0.000883267	0.000883432
8	1	22.10.2020 01:30	5430	5442	5910	0.006030715	0.006030653	0.006030953
9	1	22.10.2020 01:38	5910	5912	6011	0.006030953	0.001795574	0.008073954
10	1	22.10.2020 01:40	6011	6015	6050	0.008073954	0.008073939	0.008074552
11	1	22.10.2020 01:40	6050	6057	6064	0.008074552	0.008074507	0.008074575
12	1	22.10.2020 01:41	6064	6073	6190	0.008074575	0.008074463	0.008074599
13	0.5	22.10.2020 01:43	6190	15966	0	0.008074599	6.04534E-05	0
14	1	22.10.2020 01:43	6198	7265	8585	0.00076777	0.005851606	0.000594979
15	1	22.10.2020 01:43	6239	6247	6326	0.00555694	0.005552942	0.005575511
16	1	22.10.2020 01:45	6326	6352	6872	0.005575511	0.005575294	0.005575655
17	1	22.10.2020 01:46	6365	6385	6872	0.005575418	0.005575406	0.005575655
18	1	22.10.2020 01:46	6375	6378	6385	0.005575408	0.005575408	0.005575406
19	1	22.10.2020 01:54	6872	6876	7031	0.005575655	0.001301195	0.0058515
20	1	22.10.2020 01:57	7031	7041	7265	0.0058515	0.00585142	0.005851606
21	1	22.10.2020 02:01	7282	8440	8585	0.000793445	0.000955026	0.000594979
22	1	22.10.2020 02:03	7381	7400	7441	0.000954871	0.000954843	0.000954938

Figure 5. Raw data from Rainflow counting.

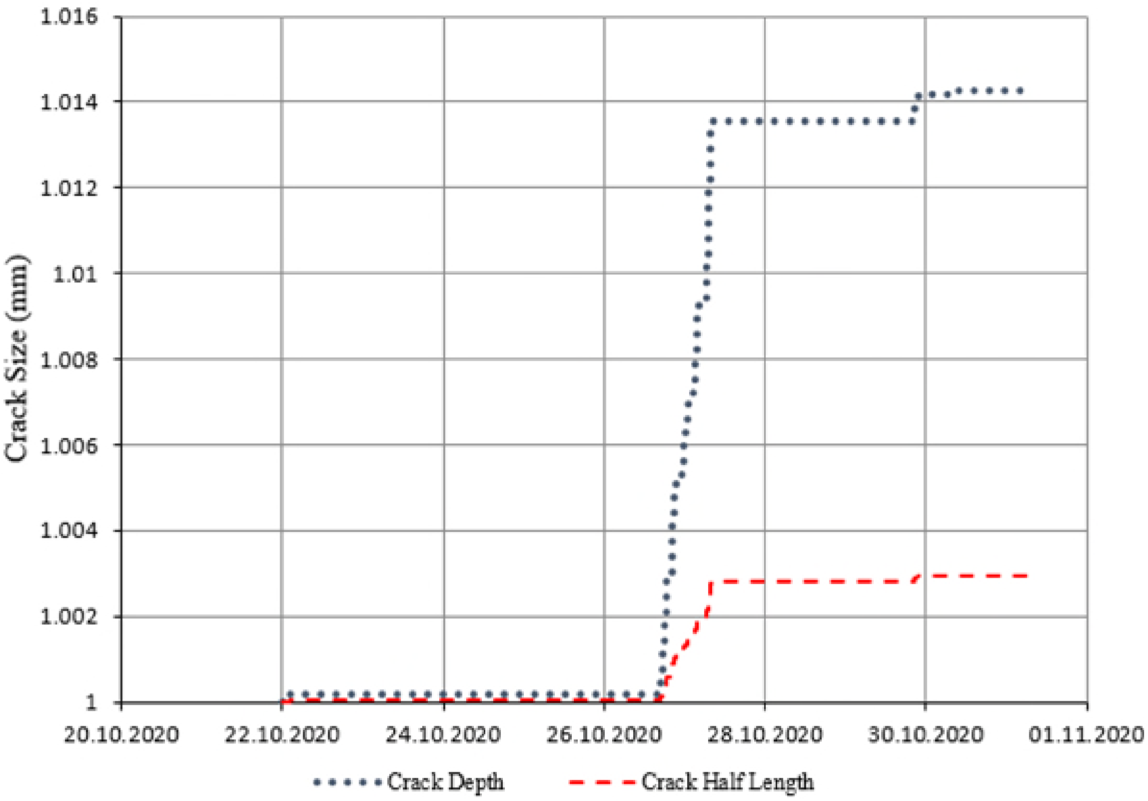


Figure 6. Final results of the FCG analysis.

CONCLUSION

A tool to perform fatigue crack growth analysis based on ASME code case N-809 on data obtained from FAMOSi has been developed as part of a pilot project to introduce fracture mechanics capabilities within FAMOSi. The following conclusions can be drawn regarding the tool:

- It has been developed for austenitic steels operating under PWR environmental conditions.
- Transient stresses from thermal loads and other mechanical loads such as pressure are superimposed internally. The tool is also capable of calculating stresses from pressure loads using simple analytical equations in cases where only pressure loads and not the stresses from pressure are directly available as input data from FAMOSi.
- The Rainflow cycle counting method described in ASTM E1049-85 has been used to perform cycle counting.

- FCG analysis is performed on two crack configurations considering either pure membrane or pure bending stress to obtain only the maximum crack growth rates for each cycle in both thickness and surface directions.
- Raw data generated during the analysis are also written out to excel or text files for post processing and visualization.

The next phase of the project is to introduce the tool directly into FAMOSi. This will bring Framatome closer to fulfilling the increasing demand from power plant operators to introduce fracture mechanics capabilities into FAMOSi. The authors would like to point out here, that while fatigue crack growth analysis forms an important pillar in structural integrity assessments, it's not instrumental when it comes to assessing the actual structural integrity of components. Therefore, the intended tool is only meant for preliminary pre-screenings of transient loads to decide any possible requirement for detailed structural integrity assessments. The methodology employed within the tool is based on conservative assumptions.

ACKNOWLEDGEMENT

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NOMENCLATURE

FAMOSi	FAtigue MOnitoring System integrated
PWR	Pressurized Water Reactor
ΔK	Stress Intensity Factor Range
K_{min}	Minimum Stress Intensity Factor
K_{max}	Maximum Stress Intensity Factor
ASTM	American Society for Testing and Materials
ASME	American Society for Mechanical Engineers
S_T	Parameter defining the effect of Temperature on Crack Growth Rate
S_R	Parameter defining the effect of R-ratio on Crack Growth Rate
S_{Env}	Parameter defining the effect of Environment on Crack Growth Rate
FCG	Fatigue Crack Growth
σ_{max}	Maximum Stress
σ_{min}	Minimum Stress
$\Delta\sigma$	Difference between maximum and minimum Stress (Stress Range)
DTICM	Material-Corrosion-Welding Department at Framatome

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