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A Study on the Thermo-Mechanical Fatigue Loading for Attaining Minimum Cycles in Fabricating an Artificial Cracked Specimen

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Abstract

In the nuclear facilities, fatigue cracks are often observed in pipes during the operation of the Reactor Coolant System (RCS), which originate from the cyclic loading caused by thermal stratification. Though the NDT methods are employed to detect the crack, sufficient number of repeated exercise should be preceded using artificial cracked specimen of a same kind for the reliable on-site detection. The crack of this kind, which has less than 150 μm width, can not be made by the conventional machining methods such as EDM, but should be made under thermal cyclic load that is close to that of the RCS. The time for obtaining the wanted crack, however, is prohibitively long, which makes it difficult to be supplied in sufficient number for NDT evaluation. In this work, single edge crack of a rectangular plate is considered as a preliminary study, in which constant tensile as well as repeated thermal loads are applied to let the crack grow. Optimum loading condition is sought that minimizes the time for fabricating the wanted crack size. The crack growth phenomenon is evaluated through the coupling of crack growth simulation software Zencrack with the general purpose analysis code ANSYS.

Keywords: *Thermo-Mechanical Fatigue, Crack Growth, Stress Intensity Factor, Artificial Crack*

1 Introduction

Many components in nuclear power plants are subjected to repeated thermo-mechanical loading. Due to this nature, thermal fatigue cracking is often observed in pipes of the surge line or the main feed water lines of the Reactor Coolant System. Since this may bring about serious damages in the RCS, many efforts have been taken recently to detect and measure these cracks under in-service conditions using the Non-Destructive Testing (NDT) methods based on Ultrasonic or Radiographic Techniques. The fatigue cracks due to the thermo-mechanical loading, however, can not be detected easily by the conventional manner due to the size as small as 10 μm width, which requires more elaborate training and exercise to achieve higher accuracy and reliability. A crack detection procedure has been established in this regard by the authorities as a means of NDT validation by preparing a number of simulation specimens that resemble the crack in service as closely as possible. The cracked specimen, however, can not be created by the conventional machining methods such as EDM, because the EDM yields crack with at least 150 μm width. Recently, one of the authors has successfully developed fabricating cracked specimen with required width and depth by applying proper combination of thermal and mechanical load cycles to the STS 304 plates and pipes using the MTS and induction heater, which consist of applying steady tensile force and cycle of heating up for a minute, cooling down for another minute [1]. In the range of 10,000 ~ 20,000 cycles, which amount to 20 ~ 40 days, cracks growing up to specific depth could be obtained. The time for obtaining the wanted crack, however, is prohibitively long, which makes it difficult to be supplied in sufficient number for NDT evaluation. In this study, a new loading condition is sought such that the cycle time is reduced while creating the wanted crack size. The crack growth phenomenon is evaluated through the coupling of crack growth simulation software Zencrack [1] with the general purpose analysis code ANSYS [3]. A simple model - single edge cracked rectangular plate, of which the analytical solution for crack growth behavior can be found in textbook, is considered in this study for verification purpose. The design parameters to be determined are the method and speed of heating and cooling process as well as the steady tensile force.

Only a few works have been found for the numerical study of the crack growth simulation under the thermal cyclic loading. In ref. [4], a numerical approach for the analysis of crack propagation under thermal transient load has been presented in an effort for more efficient calculation of the stress intensity factor (SIF) ranges. The crack propagation analysis results have been compared with those of the actual observation for the piping structure subjected to thermal striping load in a liquid metal fast breeder rector. In ref. [5], thermal fatigue behavior of Pressurized Water Reactors (PWRs) was studied focused on the AISI 304L stainless steel cracking network. The simulation results were compared with observations, as far as the evolution of the mean and deepest cracks during cycling are concerned. In ref. [6], a computational procedure was developed for 2D modeling of multiple crack propagation within the finite element software Code Aster® to evaluate the crack growth rate and shielding effects in a multi-cracked structure in thermo-mechanical fatigue. A set of parametric studies was analyzed for a cracked pipe to evaluate the influence of geometrical and loading parameters on the residual lifetime of the crack network. Most of the studies, however, were focused on the efficient simulation of the crack growth behavior, or accuracy validation by comparing with those by experiments. The aim of those papers was to predict efficiently and accurately the residual life time of the cracked components, and seek further ways to slow down the crack growth, to increase residual life time. The current study, on the contrary, is focused on the way to reduce time for faster crack growth due to the reason mentioned earlier.

2 Crack growth simulation

The studied model is given in Fig.1, which includes a single edge crack and is subjected to constant tensile load as well as repeated thermal load. The height, width and thickness are 90, 30, and 5mm, respectively. The material is STS304. Initial crack size is assumed as 0.5mm. The aim is to evaluate crack growth behavior, which is to get the crack length information in terms of the number of cycles due to this fatigue loading.

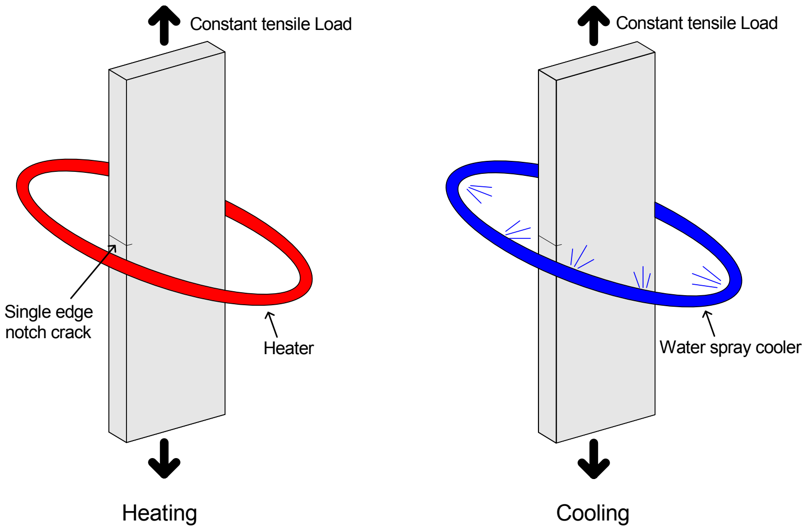

Figure 1.Studied model and loading condition

The magnitude of constant tensile load is 50,000 N. The heating and cooling is simulated by applying convective boundary condition at the surface area with height 5mm above and below the crack line, which is

$$q = h_{coef}\left(T - T_a\right) \qquad (1)$$

where h_{coef} is assumed as 1000 $W/m^{2\circ}C$, and T_a is 450 $^\circ C$ when heating during the first 60 seconds, and 30 $^\circ C$ when cooling during the next 60 seconds. Therefore the cycle time t_{cyc} of this fatigue loading is 120 seconds. Since this is repeatedly applied, the temperature history reaches cyclically steady-state after a number of cycles. In this study, one gets this state after 4 cycles as given in Fig.2, which is the temperature history at the crack front. Fig.3 shows the plot of maximum temperature in a cycle in terms of the number of cycles, which shows that the temperature changes are reduced less than 1 $^\circ C$ after the 3rd cycle. Also the temperature contours at the end of heating and cooling are given in Fig.4.

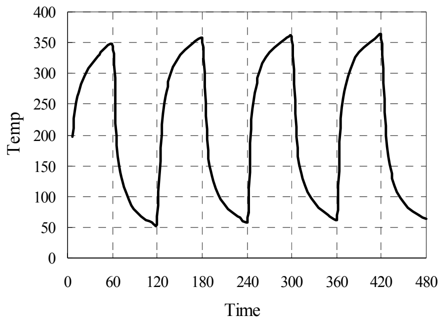

Figure 2. Temperature history of the crack front

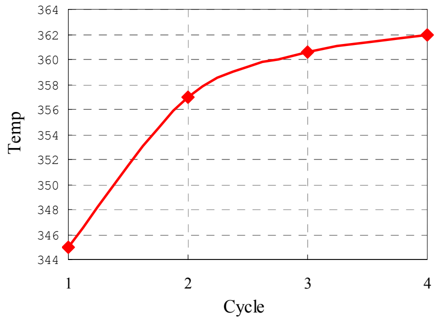

Figure 3. Temperatue with respect to the number of cycle

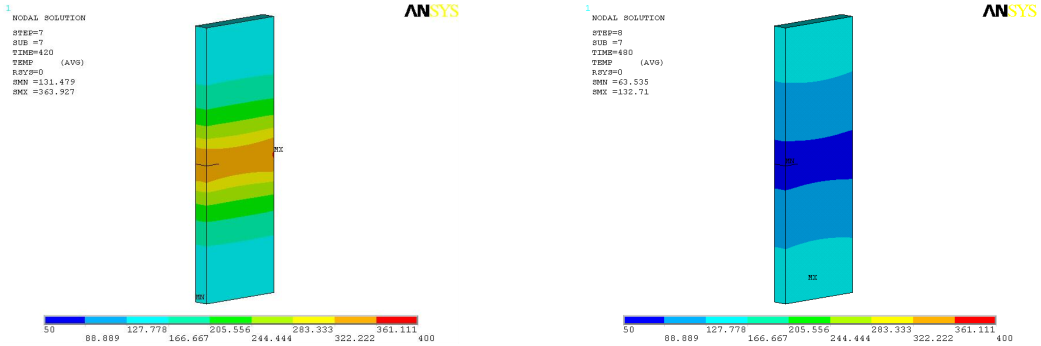

Figure 4. Temperature contours at the end of heating and cooling

Based on the thermal result, one can perform structural analysis under the cyclic temperature loading as well as the constant tensile load. This doesn’t have to be conducted for the entire cycles. The analysis is just carried out at the last cycle, i.e., 4th cycle of the Fig.2, which represents cyclic steady-state. In the structural analysis, crack geometry should be taken into account. To this end, Zencrack is used which is a finite element (FE) software tool that uses concept of 'crack-blocks' for fracture mechanics applications. The concept is that Zencrack takes an uncracked 3D mesh supplied by any FEA codes such as ANSYS, which is the case of this study and inserts cracks into the mesh. The cracked mesh is then submitted to the code for the FE analysis under a given cyclic loading. Results of the FEA are extracted and processed to calculate stress intensity factor range during the cycle. Using a proper crack growth law, magnitude and direction of crack front in the mesh are predicted to obtain updated crack geometry in the FE model. This is repeated until the analysis reaches a termination point, which can be, for example, $K_{\max}$ reaches the value of K_{IC}. A schematic diagram of these steps is given in Fig.5.

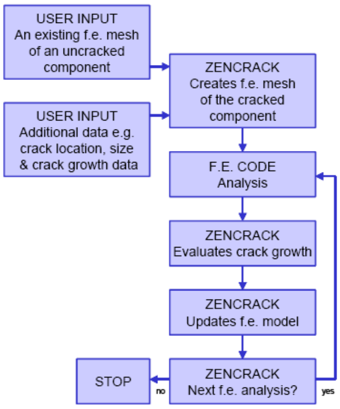

Figure 5. Overall procedure of crack growth simulation by Zencrack

Crack growth rate is assumed to be described by the simplest Paris' law, which is

$$\frac{da}{dN} = C(\Delta K)^n \tag{2}$$

where a is crack size, N is number of cycles, C, n are numerical constants, which are 5.61E-12 $(mm/cycle)/(MPa\sqrt{m})^n$ and 3.25 respectively, and ΔK is the stress intensity factor range, i.e., $K_{\max} - K_{\min}$ during the cycle. The crack growth direction is also assumed to occur based on the maximum tangential stress criterion

$$\theta = \cos^{-1}\left(\frac{3K_{II}^2 + \sqrt{K_I^4 + 8K_I^2 K_{II}^2}}{K_I^2 + 9K_{II}^2} \right) \tag{3}$$

where K_I, K_{II} and K_{III} are mode I, II, and III stress intensity factors, respectively. Based on these two equations, one can predict the magnitude and direction of crack front for a small given increase dN.

Before solving the thermo-mechanical fatigue problem, crack growth simulation is conducted with a problem of which the analytical solution is available as a verification purpose. The same model is considered but under constant amplitude of mechanical load only. In Fig.6, stress intensity factor K as a function of crack length a, obtained from Zencrack is given as blue color curve, which shows good agreement with that of analytical solution. The difference however increases as the crack length increases where the analytical solution does not hold any longer.

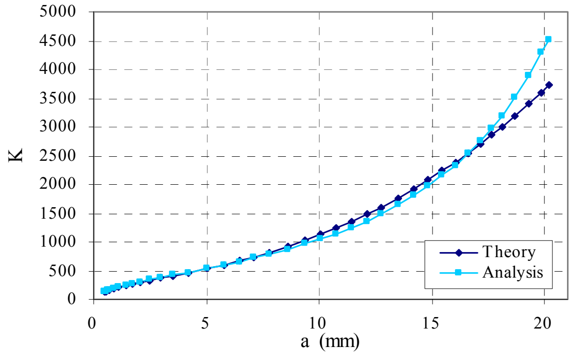

Figure 6. Stress intensity factor in terms of crack length for a verification problem

In Fig.7, close-up view of cracked mesh in which the crack block is replaced by mesh of Zencrack is given. Structural analysis is carried out under the thermal cycle load and constant tensile load. Fig.8 shows history of SIF at a crack front. The value varies between 1000 and 1600. Also the stress contours at the moment of maximum and minimum value are given in Fig.9.

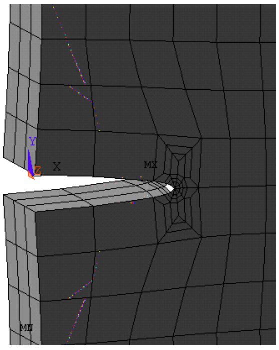

Figure 7. Close-up view of crack mesh generated by Zencrack

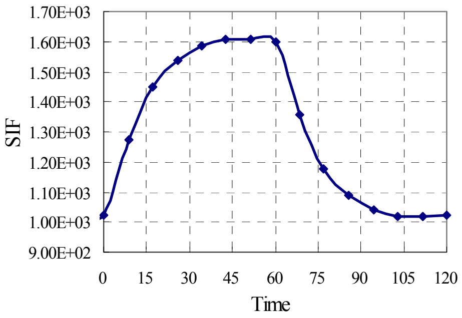

Figure 8. History of SIF during a cycle

After the completion of crack growth simulation by Zencrack coupled with ANSYS, one gets the result for crack length versus the number of cycle, which is Fig.10. The number of cycle required to get the crack length of 10mm is 3605 cycles from this figure.

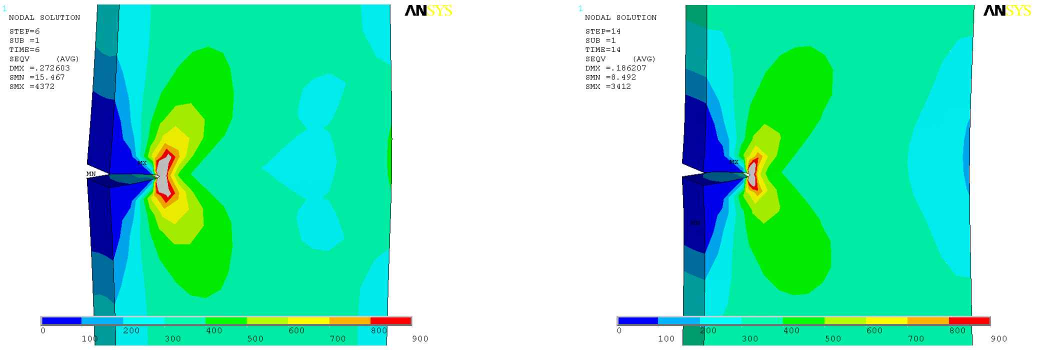

Figure 9. Stress contours at the moment that the stress at the crack front is maximum and minimum-cracked model

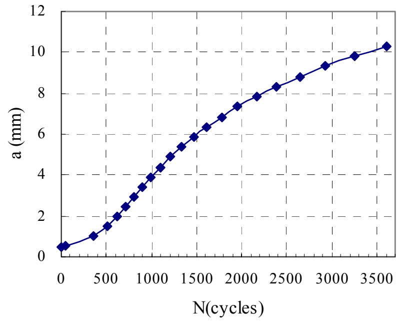

Figure 10. Crack growth prediction of the studied model

3 Optimization study for quickest crack growth

As mentioned above, the goal of this study is to get the crack of the wanted size as quickest as possible. When the cycle time t_{cyc} is 120 seconds, the total time to get the crack with length 10mm is 3,605 cycle * 120 s = 432,600 seconds, which is about 5 days. Let us try longer cycle time than this. Then the max and min temperature will be closer to the ambient temperatures which are 450 and 30 degrees due to the longer heating and cooling time. Accordingly, the range of stress as well as the SIF's will be greater, leading to the smaller number of cycles until the crack length of 10mm is formed. The most important parameter in this study is the total time, which is the cycle time multiplied by the number of cycles. Therefore, an optimization study is carried out to seek the optimum cycle time that will minimize the total time until the crack length of 10mm is made. As this is just one dimensional optimization, any algorithm can be chosen to get the solution. In this study, RSM is used. Three experimental points - 60, 120, 180 seconds are chosen to construct response surface function. Optimum solution is obtained from the function. The result is then verified by running real crack growth simulation at the optimum value. If the values do not agree, the experimental points are modified according to the sequential approximate optimization (SAO) technique [7]. The overall steps are explained as follows. First, select a number of points at the initial design space based on a suitable design of experiment (DOE) algorithm. Second, construct approximate response surface. Third, get the optimum solution from the approximate optimization problem. Finally, compare the approximate and real response value at the optimum point, and check the convergence based on the trust region algorithm. If satisfied, stop. The trust region algorithm is based on the trust region ratio given by

$$\rho^s = \frac{f(x^0) - f(x^s)}{\tilde{f}(x^0) - \tilde{f}(x^s)} \qquad (4)$$

where f and $\tilde{f}$ are the true and approximate values, respectively, and x^0 and x^s are the design at the previous and current approximate optimum solution, respectively, as shown in Eq.(4). If $\rho^s \le 0$, this means the approximation is bad, and the design space should be adjusted. If $\rho^s \approx 1$, this means the approximation is excellent and the convergence is met. If $\rho^s > 0$ or $\rho^s \in (0,1)$, this means the design space should be moved in the right direction. Based on this criterion, optimum value is obtained after three iterations of response surface approximation. The constructed response curve based on these results is given in Fig.11. The optimum cycle time is 50 seconds, and the total time under this cycle time is

265,850 seconds, which has decreased from 432,600 seconds by 38.5 %. The a versus N curve is plotted for the initial and optimum cycle time in Fig.12. As mentioned before, though the number of cycles is increased, the total time is shorter due to the shorter cycle time.

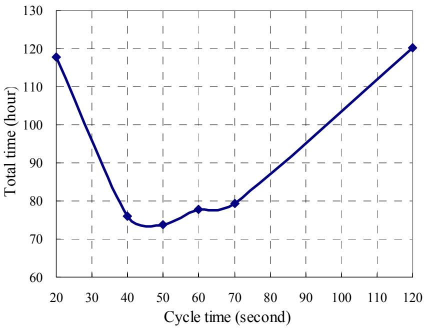

Figure 11. Constructed response curve for total time as a function of unit cycle time.

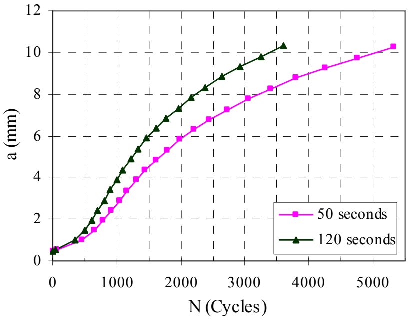

Figure 12. Crack growth prediction with initial and optimum cycle time

4. Concluding remarks

In this study, time for obtaining the wanted crack was minimized by seeking optimum cycle time for the single edge cracked specimen. As a result, the time to get the wanted crack of 10mm was reduced by 38.5 %. Since this is a preliminary study, the study was focused on establishing the right procedure for predicting the crack growth using the available Zencrack and Ansys software. Next work will be on reducing the crack fabrication time made on the inner wall of the pipe, in which more detailed thermal analysis as well as the validation by experiment is included.

Acknowledgments

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