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CREEP-FATIGUE CRACK PROPAGATION IN CURRENT INTERNATIONAL CODES FOR COMPONENTS AT ELEVATED TEMPERATURES IN NUCLEAR ENGINEERING: COMPARISON, PROGRAMMING AND CASE STUDY

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ABSTRACT

Evaluation of creep-fatigue crack propagation behavior is an important part of structural integrity of cracked components in nuclear engineering. Existing international high temperature design codes (such as RCC-MRx, R5, etc.) provide assessment procedures for creep-fatigue crack propagation analysis, but they usually involve various analysis strategies and huge calculation efforts. In this work, the analysis procedures of the two international standards (i.e. RCC-MRx and R5) are reviewed and compared with each other. Then, to realize the automation and programming of crack propagation evaluation of components, the program of creep-fatigue crack propagation analysis is developed using the Fortran language based on the procedures in RCC-MRx. Meanwhile, a typical case study on the nuclear component subjected to creep-fatigue loading conditions is conducted following the above program. This program enhances the efficiency of the creep-fatigue crack propagation analysis of the cracked components significantly.

INTRODUCTION

In nuclear engineering, there are many critical components bearing the interaction of high temperature and cyclic load in service. It can be expected that the creep-fatigue interaction is a main failure mode for these components (Floreen and Kane, 1979; Winstone et al., 1985). Engineering practices indicate that defects such as holes and inclusions are unavoidable during the manufacturing, processing, and service stages. These initial defects evolve into cracks and grow continuously in creep-fatigue conditions, and failure occurs when the critical crack size is reached. Therefore, it is of great significance to evaluate the crack propagation behavior in creep-fatigue conditions to ensure the structural integrity of nuclear power components.

So far, various countries have carried out the structural integrity evaluation technology of the components containing defects, and some codes and standards have been formulated. Typical codes including defect evaluation are as follows: ASME XI (USA), BS7910 and R5 (UK), Appendix A16 of RCC-MRx (France), JNC (Japan). Among the above codes and standards, R5 and A16 are widely accepted and used for crack evaluation of components working at elevated temperatures in nuclear engineering. It should be stated that the procedures of defect evaluation in the current international mainstream codes are very complex, needing huge computational efforts. To reduce the workload of the defect evaluation, it is essential and necessary to develop a program, which can provide an efficient tool to evaluate the defect behavior of key components in nuclear power plants.

The main structure of this work is arranged as follows. Comparisons of the defect evaluation codes between RCC-MRx A16 and R5 in creep-fatigue conditions are provided in Section 2. The framework of the program about the defect evaluation of RCC-MRx A16 is given in Section 3. A typical case study on defect evaluation in creep-fatigue conditions is reported in Section 4, with the comparisons of the calculated results based on RCC-MRx A16 and R5 included. Concluding remarks gained in this work are summarized in Section 5.

COMPARISON BETWEEN THE EVALUATION METHOD OF A16 AND R5

Evaluation Method Of A16 (ACFEN, 2015)

At the preparatory stage, following works shall be done: crack representation, material data collection, and the service condition determination (both history and future). At the calculation stage, the main purpose is to calculate the crack growth rate and to check the stability and initiation of current crack. At the re-estimate stage, crack size after propagation is used for assessment again, and remedial measures may be taken.

A16 uses the linear superposition method to calculate the propagation in creep-fatigue conditions. For each cycle, this method adds the fatigue propagation, δa_{fa}, and creep propagation, δa_{fl}, to initial crack length of this cycle, a_0. Fatigue propagation, δa_{fa}, is calculated as follows:

(1) Firstly, calculate the effective stress intensity factor range, ΔK_{eff}, considering crack closure effect and plasticity effect.

$$\Delta K_{\mathrm{eff}} = q \cdot \sqrt{E^* \cdot \Delta J_{\mathrm{s}}} \tag{1}$$

Where ΔK_{eff} is the effective stress intensity factor range. q is a coefficient that takes into account the effect of crack closure ($R < 0$) and average stress ($R > 0$), given in A16 as a function of load ratio, R. E^* depends on how the compendiums for K are established as a function of the hypotheses adopted: "plane strain conditions" ($E^* = E/(1-\nu)^2$) or "plane stress conditions" ($E^* = E$). E is Young's modulus. ΔJ_{S} is the range of j integration and it can be calculated using the following formula:

$$\Delta J_{\mathrm{s}} = \Delta J_{\mathrm{el}} \cdot \frac{E \cdot \varepsilon_{ref}}{\sigma_{ref}} \tag{2}$$

Where ΔJ_{el} is the range of j integration assuming linear elasticity of material. $\varepsilon_{\mathrm{ref}}$ is reference strain; σ_{ref} is reference stress.

(2) Calculate fatigue propagation, δa_{fa}, using Paris law:

$$\delta a_{\mathrm{fa}} = \sum_{i=1}^{N} C \cdot (\Delta K_{\mathrm{eff}})^n \tag{3}$$

Where N is cycle numbers. C and n are the coefficient and exponent of Paris law, which are material and temperature dependent constants.

In A16, it is not necessary to calculate the creep propagation at medium temperature and it should be considered only at high temperature. The creep propagation is calculated as follows:

(1) Calculate the creep propagation parameter C_S^* during the holding time:

$$C_s^* = J_{el} \cdot \frac{E \cdot \dot{\varepsilon}_{ref}}{\sigma_{ref}} \tag{4}$$

Where, J_{el} is j integration assuming linear elasticity of material.

(2) Calculate the creep propagation δa_{fl} during the holding time：

$$\delta a_{fl} = \int_t^{t+t_h} A \cdot (C_s^*)^q \, dt \tag{5}$$

Where, A and q are the coefficient and exponent of creep law, which are material and temperature dependent constants. t_h is holding time.

Evaluation Method Of R5 (British Energy Generation Ltd, 2003)

The steps of defect evaluation in creep-fatigue conditions are as follows:

Step 1: Establish the causes of cracking and characterize the initial defects. The determination of the cracking causes can provide certain information for the subsequent steps.

Step 2: Define the service conditions. Similar to the A16, it is necessary to determine not only loads, temperatures, etc. in service, but also possible service conditions in the future.

Step 3: Collect materials data. Collection of materials data aims to basic mechanical properties, cyclic and creep properties if needed, and so on.

Step 4: Perform basic stress analysis. The purpose of this step is to calculate the parameters in the crack propagation law and to consider the influence on the overall structural response caused by defects.

Step 5: Perform significance analysis of creep and fatigue. In order to simplify the evaluation process and calculation, a simple calculation is made to indicate whether creep or fatigue effects are taken into account.

Step 6: Evaluate the defects. This step can be divided into the following steps:

(1) Ensure that the initial cracks are stable under all possible short-term operation or failure loads.

(2) Calculate the rupture life, that is to say, calculate the failure time of the component caused by creep damage due to the existence of defects, and compare it with the remaining assessment time.

(3) Calculate crack tip parameters, including the fatigue propagation parameter ΔK_{eff} and creep propagation parameter C^*.

(4) Calculate incubation time, t_i.

(5) Calculate the stress redistribution time, t_{red}. This step is required only if cyclic loads are not significant.

(6) Calculate the time when the cycle is stable, t_{cyc}. This step is required only if creep loads are not significant.

(7) Calculate crack size after growth. The calculation method is as follows:

When the crack is completely located in the cyclic plastic zone on the surface of component, the total crack growth rate is obtained by combining the creep damage occurred during the dwell period with the fatigue propagation under high strain.

The fatigue crack growth rate under high strain can be calculated as follows:

$$(da/dN)_{\mathrm{f}} = B' \cdot a^{Q} \tag{6}$$

At this point, the crack growth rate in creep-fatigue conditions is

$$da/dN = (da/dN)_{\mathrm{f}} \cdot \left(1 - D_{\mathrm{c}}^{\mathrm{surf}}\right)^{-2} \tag{7}$$

Where $D_{\mathrm{c}}^{\mathrm{surf}}$ is the total surface creep damage accumulated up to the current time from every cycle:

$$D_{\mathrm{c}}^{\mathrm{surf}} = \sum_{\mathrm{j}=1}^{\mathrm{N}} \int_{0}^{t_{\mathrm{h,j}}} \frac{\dot{\bar{\varepsilon}}_{\mathrm{c}}}{\bar{\varepsilon}_{\mathrm{f}}(\dot{\bar{\varepsilon}}_{\mathrm{c}})} dt \tag{8}$$

Where $0 \leq t \leq t_{\mathrm{h,j}}$ is the creep dwell period of the j'th cycle. $\dot{\bar{\varepsilon}}_{\mathrm{c}}$ is the instantaneous equivalent creep strain rate during the dwell, and $\bar{\varepsilon}_{\mathrm{f}}(\dot{\bar{\varepsilon}}_{\mathrm{c}})$ is the creep ductility at that creep strain rate.

When the crack tip is in the elastic zone, the total propagation is obtained by linear superposition of fatigue propagation and creep propagation.

The creep propagation can be calculated as follows:

① When the cyclic load is negligible and the total time for the assessment is greater than the stress redistribution time, t_{red}, the creep propagation per cycle is:

$$(da/dN)_{\mathrm{c}} = \int_{0}^{t_{\mathrm{h}}} A_{\mathrm{c}} \cdot (C^{*})^{q}\, dt \tag{9}$$

Where, A_{c} and q are material constants. t_{h} is dwell period. C^{*} is approximately estimated from the reference stress.

② When the cyclic load can be ignored and the total time for the assessment does not exceed the stress redistribution time, t_{red}, the creep propagation parameter can be represented by $C(t)$:

$$(da/dN)_{\mathrm{c}} = \int_{0}^{t_{\mathrm{h}}} A_{\mathrm{c}} \cdot [C(t)]^{q} dt \tag{10}$$

Where, $C(t)$ is the characteristic parameter of the transient creep at the crack tip, and the approximate relationship between $C(t)$ and C^{*} is:

$$\frac{C(t)}{C^{*}} = \frac{(1+\varepsilon_{\mathrm{c}}/\varepsilon_{\mathrm{e}})^{1/(1-q)}}{(1+\varepsilon_{\mathrm{c}}/\varepsilon_{\mathrm{e}})^{1/(1-q)}-1} \tag{11}$$

Where, ε_{c} is cumulative creep strain at time t. ε_{e} is an elastic strain to reference stress.

③ When the cyclic load can not be ignored and the assessment time of early cycle creep is less than the cycle time, t_{cyc}, R5 adopts a new characteristic parameter $\overline{C^*}$:

$$\overline{C^*} = \left(\sigma_{\mathrm{ref}}^{\mathrm{cyc}=1} + \sigma_{\mathrm{ref}}\right) \cdot \dot{\varepsilon} \cdot R'/2 \tag{12}$$

Where $\dot{\varepsilon}$ is evaluated as $\dot{\varepsilon}\left[\left(\sigma_{\mathrm{ref}}^{\mathrm{cyc}=1} + \sigma_{\mathrm{ref}}\right)/2\right]$. The propagation in the t_{cyc} is mainly based on the accumulation of the creep strain, so the propagation at the beginning of the cycle can be calculated as follows:

$$(da/dN)_{\mathrm{c}} = \int_0^{t_{\mathrm{h}}} A_{\mathrm{c}} \cdot [\overline{C^*}]^q dt \tag{13}$$

The fatigue propagation is:

$$(da/dN)_{\mathrm{f}} = C \cdot \Delta K_{\mathrm{eff}}^{\lambda} \tag{14}$$

Where C and λ are the coefficient and exponent of Paris law respectively, and both are material and temperature dependent constants. ΔK_{eff} is effective stress intensity factor range.

Step 7: Assess the significance of the results. At the end of the evaluation process, one of the following situations inevitably occur:

①The evaluation of the final defect size shows an acceptable end-of-life reserve factor. In this situation, a sensitivity analysis should be performed to ensure that the safety margin is not sensitive to input parameters.

②The evaluation of the final defect size shows that failure or excessive crack growth will appear during the assessment time. In this situation, the evaluation may be revisited with reduced assumed pessimisms. If the safety margins after propagation is still unacceptable, remedial action should be taken.

Comparison Of Defect Evaluation Method between R5 and A16

R5 and A16 both calculate fatigue propagation by Paris law, but there are serveral differences listed below.

1. R5 clearly stipulates that its defect evaluation method is only applicable to austenitic and ferritic steel, while RCC-MR A16 only provides the evaluation methods for $N1_{RX}$ and $N2_{RX}$ austenitic stainless steel components.

2. The Paris law is adopted for fatigue propagation in RCC-MR A16, and C^* parameter is adopted as creep propagation parameter, as shown in Eq. (3) and (5). The total crack propagation is the sum of the fatigue and creep propagations.

In R5, Eq. (5) is adopted when the current defect size is larger than the size of the cyclic plastic zone on the surface of the component. When the defect is within the cyclic plastic zone, Eq. (6) is adopted.

3. For different stages of creep, R5 gives different parameters to calculate the propagation. When creep is in the steady stage, the parameter of the creep propagation is C^*, and the propagation of creep crack over the dwell period is expressed in Eq. (9). When the creep is in the first stage, $C(t)$ parameter is used to calculate the creep propagation (only applicable when the cyclic load is not significant). When the total assessment time exceeds the redistribution time t_{red}, the $C(t)$ parameter is also used to calculate the creep propagation, and the calculation formula is as follows:

$$\dot{a}=2A_c \cdot [C^*]^q \quad when\ t_i \leq t \leq t_{red} \tag{15}$$

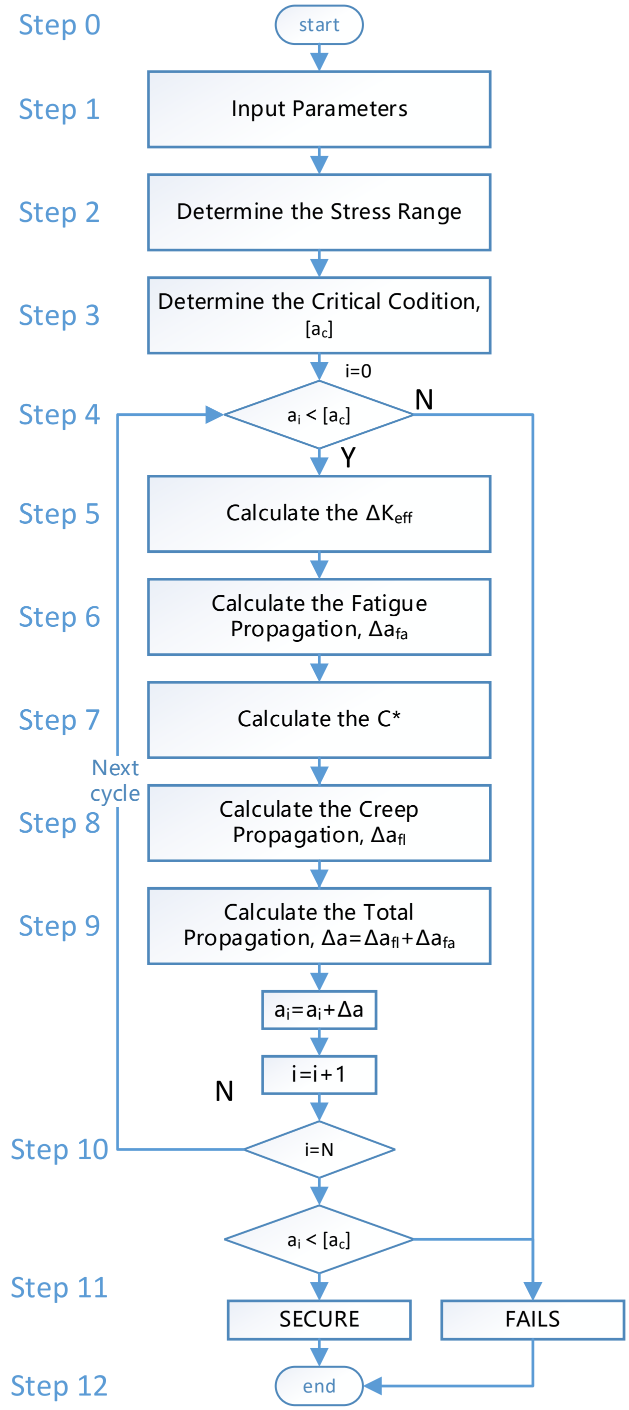
$$\dot{a} = A_c \cdot [C^*]^q \quad when\ t \geq t_{red} \tag{16}$$

When the cycle is not stable yet, $\overline{C^*}$ parameters are used to calculate the creep propagation, and Eq. (4) is used to calculate the propagation during the dwell period.

4. After the evaluation and analysis of propagation is completed, RCC-MR A16 stipulates that the defect instability analysis shall be carried out again, and the reduction in section resistance due to the presence of a defect shall be considered. After the defect growth evaluation analysis, R5 requires sensitivity analysis on service load conditions, material data extrapolated to service conditions, size and shape of defects, and uncertainty of input data.

PROGRAMING THE DEFECT EVALUATION PROCESS OF A16

The method of defect evaluation in the existing international codes is complex and much computation efforts are needed for defect analysis. Therefore, it is necessary to develop a program for creep-fatigue crack growth evaluation. In this work, the defect evaluation method in A16 is chosen for programing, and the method in R5 is the future work.



Step 1: Input parameters such as the initial crack size, fracture toughness, cycle number, holding time, etc.

Step 2: Extract the stress distribution. Determine the maximum and minimum stress, and the stress range.

Step 3: Calculate the critical crack size as the judgement condition.

Step 4: Determine whether the crack size is less than the critical crack size. If so, proceed to the next step; If not, the output "FAIL".

Step 5: Calculate the effective stress intensity factor range.

Step 6: Calculate the fatigue propagation in a single cycle.

Step 7: Calculate the C^* parameter.

Step 8: Calculate the creep propagation during the holding time.

Step 9: Calculate the propagation in a creep-fatigue cycle.

Step 10: Determine if the count is equal to the number of cycles. If so, go back to step 4. If not, proceed to the next step.

Step 11: Determine whether the final crack size is less than the critical crack. If so, output "PASS"; If not, output "FAIL".

CASE ANALYSIS

In this paper, the finite element method is applied to analyze the structure in A8.6 of R5, and the solution calculated by program is compared with the solution given by R5.

The structure for creep-fatigue crack growth evaluation is shown in Figure 1. It is a pressure pipe made by homogeneous Type 316 Stainless Steel, with the internal radius of $R_i = 300$ mm and the wall thickness of $w = 100$ mm. A defect is assumed to be fully circumferential on the inside of the pipe with the initial depth, a_0, taken as 3mm.

The operating condition of the pipe is a repeated cyclic loading from a shutdown condition at 0 MPa, 20°C to an operation condition at 16 MPa(internal), 600°C, and a through wall axial and hoop thermal bending stresses of 200 MPa. In this example, 500 equal cycles with 3000-hour holding time at operating conditions are assumed to occur during the desired future service life of 1.5×10^6 hours.

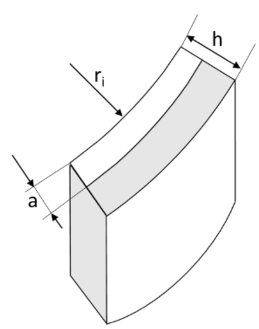


Figure 1. Pressure pipe geometry for creep-fatigue crack evaluation

Main steps and material parameters in A16

For the cylindrical pipe with an internal, part-penetrating, fully circumferential defect under cyclic loading, the K_I expression is shown as follows:

$$K_{\mathrm{I}} = \left[\sigma_0 \cdot i_0 + \sigma_1 \cdot i_1 \cdot \left(\frac{a}{h}\right) + F_{\mathrm{gb}} \cdot \sigma_{\mathrm{gb}}\right] \cdot \sqrt{\pi \cdot a} \tag{17}$$

Where, i_0, i_1 and F_{gb} are influence factors, which can be obtained in the table of A16 by linear interpolation method according to the geometric size and the crack size. a is the crack size. σ_0, σ_1, σ_{gb} can be obtained by the elastic finite element analysis of defectless structures, and the expressions of some typical structures are given in A16. Stress values during shutdown and operation are shown in Table 1.

Table 1. The values of σ_0, σ_1, σ_{gb}

stress	operation	shutdown
σ_0[MPa]	20.6	0
σ_1[MPa]	0	0
σ_{gb}[MPa]	15.8	-184.2

For the q in E (1), A16 only gives the certain $q(R)$ expression for two situations: the welded joint of stainless steel, and non-alloy steel. The latter expression is adopted in this paper, as shown below:

$$q = \frac{1-0.5R}{1-R} \; when\; R < 0 \tag{18}$$

$$q = \frac{1}{1-0.5R} when\; R \geq 0 \tag{19}$$

Where $R = K_{\min}/K_{\max}$.

The fatigue propagation is calculated by Eq. (3), where C and n are 2.0E-09 and 3 respectively, and it should be noted that the unit of crack growth rate is m/cycle.

The value of the C^* can be calculated by Eq. (4), where $E = 155000$MPa. J_{el} can be calculated as follows:

$$J_{\mathrm{el}} = \frac{K^2}{E} \tag{20}$$

Main steps and material parameters in R5

Creep propagation only occurs during operation. Therefore, K in Eq. (20) is $K_{\max}$. The value of the reference stress can be obtained by the finite element analysis. In this example, the reference stress is 57.6MPa. The constitutive equation of creep is White formula given in the case of R5, as shown below:

$$\varepsilon = \varepsilon_{\mathrm{P}}[1 - \exp(-r \cdot t^{\mu})] + \dot{\varepsilon}_s \tag{21}$$

Where, ε_p is the maximum strain for the prime creep stage, and it is calculated by

$$\varepsilon_{\mathrm{p}} = A' \cdot \sigma^{m(\theta)} \exp[-P/(\theta + 273)] \tag{22}$$

Where θ is temperature (℃), and $m(\theta) = \alpha - \gamma\theta$. $\dot{\varepsilon}_s$ is the strain rate of the second creep stage.

$$\dot{\varepsilon}_s = B \cdot \exp[-Q/(\theta + 273)]\sigma^n \tag{23}$$

Where, $r, \mu, A', P, \alpha, \gamma, B, Q, n$ are material parameters. Their values are shown in Table 2.

Table 2. Parameters in White formula

r	2.42E-2
μ	0.64
A'	1.632E+35
P	9.292E+4
α	16.32
γ	0.02044
B	1.065E-5
Q	1.97E+4
n	4

The creep fatigue propagation can be calculated by Eq. (5), where A=0.0197 and q=0.89 (it should be noted that the unit of creep crack growth rate is m/h)

Comparisons

The propagation after 1.5E+06h calculated by the programmed A16 defect evaluation method is 4.342mm, while the propagation obtained by the defect evaluation method of R5 is 10mm. Through comparison, the main reason for the difference is the shape influencing factors used for stress intensity factor. The stress intensity factor K_I calculated by R5 is about 10% larger than that calculated by A16, which results in the difference in the creep-fatigue crack propagation.

CONCLUSION

This paper introduces the defect evaluation methods of A16 and R5 and compares their differences. Different from A16, R5 provides two methods for calculating fatigue propagation based on the crack size and cyclic plastic zone, and R5 also provides three parameters for creep propagation based on different creep stages. Although the defect evaluation method in A16 is simpler, it is still very complicated in the practical application process. Therefore, this paper programmed the defect evaluation method of A16, which greatly simplifies the calculation of propagation in practical components. Taking the typical case of R5 as an example, the programmed A16 method is applied to calculate the propagation. The results show that the propagation calculated by the programmed evaluation method of A16 is less than that calculated by R5. This is mainly due to the difference in the calculation of shape factors between the two.

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