Probabilistic Fracture Mechanics Analysis Code CANIS-P

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ABSTRACT

This paper describes a function of a computer code CANIS-P and its applications to parametric sensitivity analysis of pipings in pressurized water reactors and in fast breeder reactors. CANIS-P can calculate the failure probability of the pipings in nuclear plants and in other engineering plants, especially in FBRs operated at creep temperature range under several assumptions.
key word: probabilistic fracture mechanics, crack, structural integrity, creep

1 INTRODUCTION

In design of the large fast breeder reactors, FBRs, higher grade analyses will be requested from the view point of safety. Structural integrity analysis is one item of them, therefore, Power Reactor and Nuclear Fuel Development Corporation,PNC, started to prepare the method in this engineering field from about five years ago. PNC's program of structural integrity study based on fracture mechanics includes following three items. The first item, "METHOD IN CREEP TEMPERATURE", covers crack behavior estimation method of structures containing assumed defects at creep temperature[1]. The second items, "STRUCTURAL RELIABILITY", which includes the content of present paper, has the objective to develop the measures for assessment of the structural reliability using statistical database and/or probabilistic method. The third item, "LEAK BEFORE BREAK OF STEAM GENERATOR TUBES", intends to show the failure mode related to leak before break, and is one of the feasibility study of the steam generator with double-wall tubes.

Reliability analysis is divided into two categories; namely one based on statistical method and the other probabilistic method[2]. In statistical method, failure rate of structure is estimated from relevant failure rate database. Well categorized large database and the improvement factor, which represents progress in material fabrication method, design method, fabrication skill, nondestructive examination method and so on, enables estimation of the failure rate. The estimated failure rate for unexperienced structures,therefore, had little confidence in itself. On the other hand, probabilistic method usually used in structural reliability engineering is able to calculate failure probability of newly proposed structures with probabilistic density functions of random variables. It was the weak point of the method for which many probability density functions relevant to each event should be prepared. In spite of that, a study of probabilistic method was chosen because of its applicability to various structures and clearness of failure processes.

2 ANALYSIS CODE

Probabilistic structural integrity assessment method should be considered from three view points; those are material data, reliability of deterministic analysis method, and component data as shown in Fig.1. Material data includes probability density function of material behavior and strength with environment effect, and that of an initial defect, especially for weldment. The second item is reliability of deterministic analysis method usually used in design and its evaluation by codes or standards. Reliability of all of those analysis methods should be included in this

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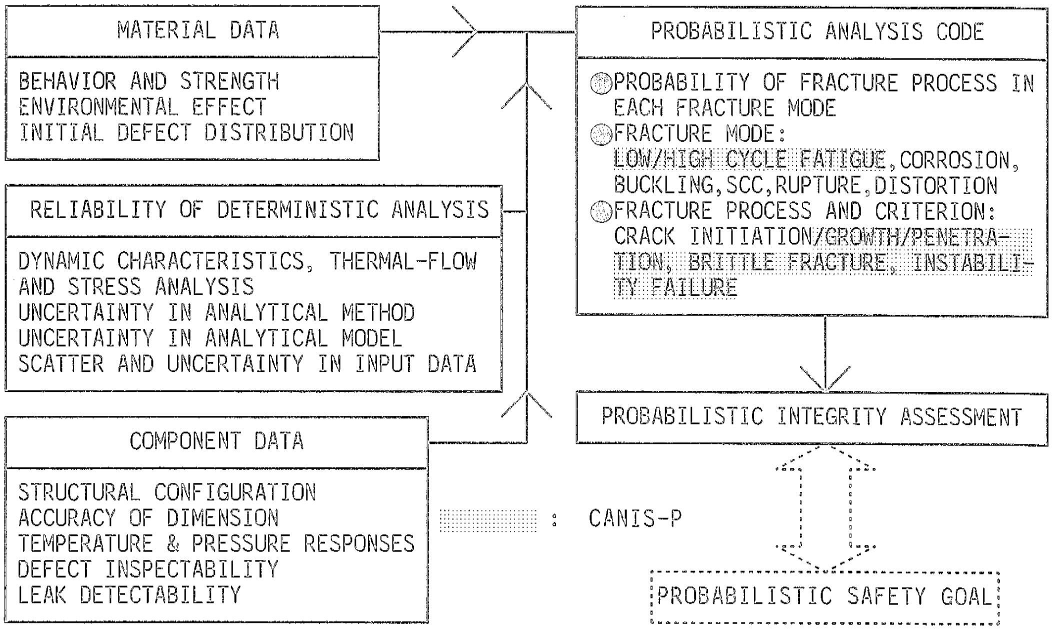


Fig.1 Probabilistic structural integrity assessment and CANIS-P code

article, but for the probabilistic structural integrity assessment, any structural design codes and standards with safety margin should be excluded because the objective of the method is to assess pure reliability which is identical to 1.0 - failure probability. In other word, the individual safety margin to be needed in structural design should be determined from the probabilistic structural integrity assessment. The third item is a component data. The data included structural configurations and local dimensions at weldment, temperature, pressure and flow rate encountered in real operation, defect inspectability, and leak detectability. All of these data had better to express in randam variables or frequency histograms. On the basis of these items, a probability analysis computer code is necessary to calculate probability of structural fracture processes for each fracture mode. Some part of the code have been developed at elsewhere.

The PRAISE code[3] is well known in probabilistic fracture mechanics for application to PWRs' piping. The PRAISE code was extended to the PRAISE-B for application to boiling water reactor and to the PRAISE-CC analyzing stress corrosion cracking. Other computer codes such as the COVASTOL[4], the OCA-P[5], the VISA-II[6], and the PARIS[7] were recently developed for probabilistic defect assessment in light water reactors.

Construction of the probabilistic structural integrity analysis code was started in a field of the precedents. Considering to structural integrity assessment for FBR, the new code was constructed based on the PRAISE code improving following ability: ① in addition to stress intensity factor, ΔK, to use J-integral range, ΔJ, in fatigue crack-growth model, ② to calculate creep crack-growth based on creep J-integral range, ΔJ_c, which was formulated recently in a simple formula[8], ③ to calculate net section stress and tearing modulus for unstable crack penetration judgement in addition to the original PRAISE's judgement in which non-dimensional crack depth, $\alpha = a/t$ where a was crack depth and t was wall thickness, was used, ④ for break judgement, K_{IC} criterion and tearing modulus criterion were added to original criterion; break occurred when net section stress, σ_{net}, is greater than flow stress, σ_f, ⑤ crack opening area calculation scheme and Bernoulli's equation for FBR's coolant condition of low pressure were added to original simplified equation for PWR's condition, ⑥ material elastic-plastic characteristics should be considered for calculation of ΔJ, crack opening area and so on, because rather high-ductility material will be used than high-strength material in FBRs.

The new code CANIS-P (Crack Analysis by Numerical Integral Scheme - application to Probabilistic structural integrity assessment) code has the functions as follows. ① Exponential and log-normal distributions were prepared for probabilistic density function of an assumed initial crack depth,a, and aspect ratio,a/b. ② Stress perpendicular to cross section without cracks was classified into primary and secondary membrane stresses and secondary bending stress; primary membrane stress corresponded to load controlled stress due to dead weight, σ_{DW}, internal pressure,σ_P, and earthquake, σ_{EQ}. On the other hand, secondary stress included thermal expansion and thermal transient stresses. Stress redistributions due to plasticity and creep can be considered by the parameters of q_{EP} and q_c representing stress concentration at the crack front in the cracked cross section. ③ Stress intensity factor for three sorts of crack configuration was prepared; namely half elliptical surface crack by Newmann and Raju[9] ,penetrated cracks subjected to membrane stress of a plate and of a cylinder[10,11] , and one side infinite length crack in a plate and in a cylinder in both axial and circumferential directions. ④ Fatigue crack growth is based on either stress intensity factor, ΔK, or elastic-plastic J-integral,ΔJ_{EP}. Elastic-plastic J-integral is calculated based on the simplified equation in CEGB R6 option 2 with modification in reference stress,σ_R, such that $\sigma_R = F_{SM}(\sigma_T + 0.8\sigma_B)$, where F_{SM} is an correction factor due to cracked-section, σ_T nominal membrane stress, σ_B nominal bending stress, and 0.8 represents a correction factor of nominal bending stress[8] . ⑤ Creep crack growth was calculated by a simplified method using reference creep strain[8] .⑥ Failure and rupture judgement include four criteria; crack depth criterion or crack length criterion,K_{Ic} criterion, flow stress criterion, and tearing instability criterion. ⑦ Crack opening area and leak rate are calculated, then leak detection probability is calculated. The opening area was calculated by the simplified equation derived from the consideration of energy balance[12] . Two methods were prepared for leak rate calculation; one for PWR's condition and the other for FBR's condition. ⑧ The effect of pre-service inspection,PSI, and in-service inspection,ISI, were evaluated from the probabilistic density function shown by LLNL[13] , PNL[14], and UKAEA[15] .

Stratified Monte Carlo method was adopted in CANIS-P code. An analytical procedure guide including the cell division method in stratified sampling have been constructing by many benchmark analyses. The benchmark problem and its result will be shown in Division G of this SMIRT Conference by Dr. Yoshimura et al.

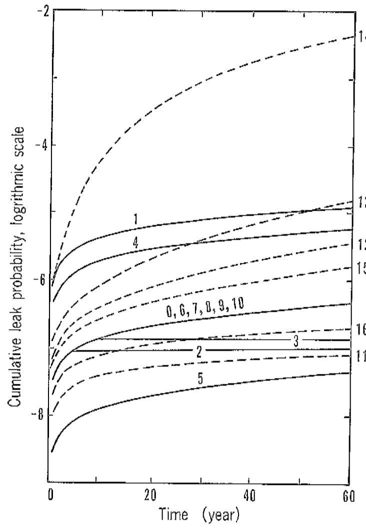
3 SENSITIVITY STUDY AT PWR CONDITION

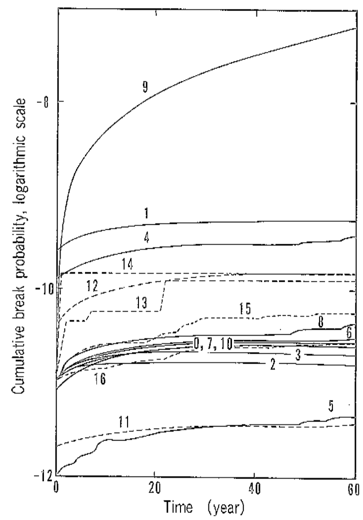
Pipe with 370 mm in inner diameter and 73 mm in wall thickness made of SUS316 stainless steel was analyzed by CANIS-P. The operation condition was so that the maximum temperature 343℃, maximum operation pressure 157 kgf/cm². An analysis condition of referring case, case-0, was as follows. Loading condition was realistic such that stress of 1.212 kgf/mm² arose from dead load, 3.979 kgf/mm² from internal pressure, 6.925 kgf/mm² from thermal expansion, σ_{TE}. Only the event of start up and shut down was considered as five cycles per year. An initial defect was a circumferential half elliptical surface crack with depth of a and length of 2b at the inner surface of a circumferential weldment. Distributions of crack depth and aspect ratio, and stress intensity factor of the cylinder used in present analysis were the same as those used in LLNL's report[13] . Following fatigue crack-growth relation based on domestic material test data was used for the analysis:

$$da/dN(mm/cycle) = 6.5 \times 10^{-12}(\Delta K_{eff})^4,$$

$$where\ \Delta K_{eff} = [K_{max} \cdot \Delta K]^{1/2}, \quad \Delta K_{eff}\ in\ kgf/mm^{3/2}.$$

Failure judgement was such that leak happened when $\alpha \geq 1.0$ and break happened when $\sigma_R \geq \sigma_f$. Normal distribution with mean value of 30.59 kgf/mm² and standard deviation of 1.529 kgf/mm² was used for flow stress. It was assumed that only load controlled stress, σ_{LD}, which was sum of those due to dead weight and internal pressure, was effective in break. Leak rate from a penetrated crack was calculated based on LLNL's equation under PWR condition. Leak detection condition is defined such that more leak





(a) Cumulative leak probability (b) Cumulative break probability

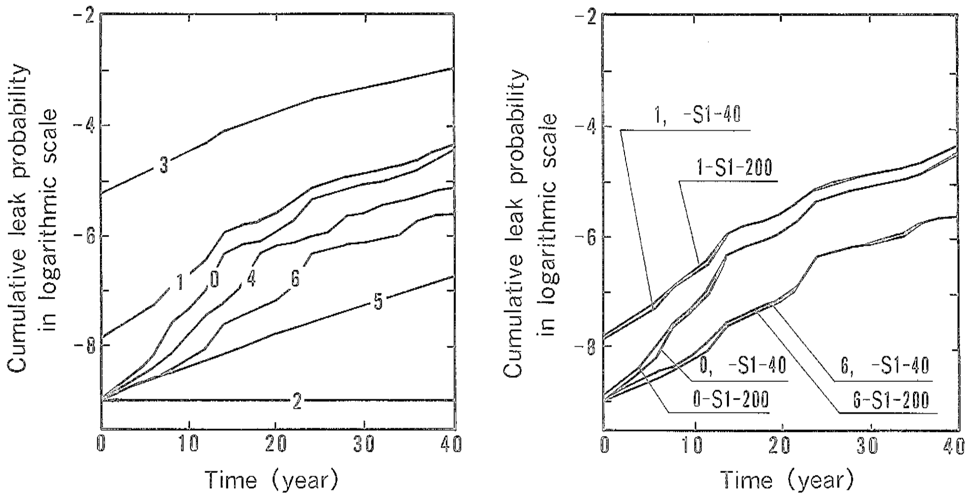
Fig.2 The result of sensitivity study in PWR piping

rate than 5 gallon per minute can be detected. For PSI and ISI, un-detectable probability of LLNL's equation was applied to present analysis.

In case-1, PSI was excluded. ISI was conducted after 5 years operation in case-2, and every 10 years in case-3. In both cases, undetectable probability was expressed by complementary error function. Mean value of initial crack depth was 90 % upper limit,8.382 mm, in case-4 and 90 % lower limit, 5.08 mm, in case-5. A mean value of flow stress was 30.59 kgf/mm² in case-6, 90 % upper limit of 30.59 + 1.282 S in case-7, and 90 % lower limit of 30.59 - 1.282 S in case-8, where standard deviation,S, was 1.529 kgf/mm². Leak detection was not conducted in case-9, and was conducted in case-10 in which perfect detection beyond one gallon per minute was assumed. Stress intensity was one-half in case-11 as small, and 1.5 times in case-12 as large as that of the reference case. The number of load cycles was 10 times in case-13, and one hundred times in case-14 as large as that of the reference case. The constant in crack growth equation was 3 times larger in case-15, and one third smaller in case-16 than that of the reference case.

The cumulative leak probability and the cumulative break probability were shown in Fig.2. The result shows that PSI have large effect on reducing the leak and break probabilities. The probabilities are also reduced by ISI, but the effect is smaller than that of PSI. The effect of ISI is larger in only one ISI after five years than in every ten years. To reduce the mean value of the initial crack depth is powerful in result. The effect of flow stress is smaller if the constant value of 90 % upper or 90 % lower limits is used for the calculation. Reliable leak detection system have much effect in reducing cumulative break probability. Stress intensity reduced leak probability to one-sixth with its reduction of a half, and increased the probability to 8 times with its increase of 1.5 times. The probability can not be influenced so far if uncertainty of stress intensity is about 10 %. The number of cycles of loading have the effect such that ten times increase resulted in 33 times increase of leak probability, and 100 times increase causes 9,000 times in the probability. The effect of uncertainty of the model, in which expected real operation cycle is transfered to ideal one in structural design evaluation, can be small if the number of cycles was limited in 2 times to one-second. The material constant in the crack-growth relation affects cumulative leak probability so that three times large constant increases the probability to about three times, and one-third reduced to one-second.

4 SENSITIVITY STUDY OF FBR PIPING



(a) Cumulative leak probability

(b) Effect of earthquake on the leak probability in the case of -0, -3 and -6

Fig.3 The result of sensitivity study in FBR piping

The subject is an elbow in a hot leg piping of 40 inches outer diameter with 487.4 mm in inner diameter,R, and 20.6 mm in wall thickness,t, made of SUS304 stainless steel,that perspective view was shown previously[12]. The reference condition, case-0, is shown below. The operation condition is such that maximum operation pressure 2.0 kgf/cm^2G, and temperature 500℃ at which material properties was used for the analysis. Normal operation pressure,0.8 kgf/mm^2, is used for leak rate calculation. A design life is 40 years. The stresses are σ_{DW} = 1.0 kgf/mm^2, $\sigma_P = p_{max} \cdot R/(2t)$ = 0.237 kgf/mm^2, and σ_{TE} = 18.0 kgf/mm^2 at a middle of the elbow due to thermal expansion. Two thermal transient events were calculated. Event-1 corresponding to start up and shut down had two cycles per year including creep crack-growth in each cycle, and caused following stresses: membrane stress range, $\Delta\sigma_T = \sigma_P + \sigma_{TE}$, and bending stress range, $\Delta\sigma_B$, was 5.0 kgf/mm^2 with elastic-plastic parameter $q_{EP,TE}$ = 1.5 and creep parameter $q_{c,1}$ = 1.5. Event-2 corresponding to thermal transient has ten cycles per year excluding creep crack-growth in each cycle, and causes following stresses; membrane stress range,$\Delta\sigma_T$= 5.0 kgf/mm^2 and $\Delta\sigma_B$= 15.0 kgf/mm^2 with elastic-plastic parameter $q_{EP,2}$ = 1.0 and creep parameter $q_{c,2}$ = 0.0. The effect of earthquake was considered in two cases,S1-40 and S1-200, by transferring that to static fatigue cycles of 40 and 200 with $\sigma_{EQ} = \pm$ 5 kgf/mm^2 adding to $\sigma_{DW} + \sigma_P$.

A longitudinal half elliptical surface crack with depth of a and length of 2b at the inner surface was considered at the middle of the elbow. The distribution of crack depth was exponential which was the same as that used in UKAEA report[15] with mean value shifted to 0.05t, 1.03 mm. A log-normal distribution of aspect ratio,b/a, which was identical to LLNL's equation[3], was used in present analysis. The fatigue crack-growth property was given by following equation:

$$da/dN(mm/cycle) = C_f \cdot \Delta J_f^{m_f}, m_f = 1.4435, \quad \Delta J_f \quad in \quad kgf/mm,$$

where the constant C_f was assumed to be log-normal distribution with mean value of 1.2022×10^{-3} and standard deviation 0.9463. A dynamic stress-strain relation of SUS304 stainless steel at 500 ℃ was used for elastic-plastic material property. Elastic J-integral range,ΔJ_e, was calculated from Newmann and Raju's equation[9] assuming plane stress state, then was modified using plasticity modification factor which was similar to CEGB-R6 Option-2[16]. The creep crack-growth during one cycle with hold time,t_h, was calculated by following equation:

$$da/dN(mm/cycle) = C_c \cdot \{\Delta J_c(t_h)\}^{m_c}, m_c = 0.877, \quad \Delta J_c(t_h) \quad in \quad kgf/mm,$$

where the constant C_c was assumed to be log-normal distribution with mean value

0.08795 and standard deviation 0.5777. Creep property at 500 ℃ was used under strain hardening rule. The failure judgement was so that leak happens at a/t = 0.9 and break happens at b/(π R) = 0.5 or $\sigma_R=\sigma_f$ in penetrated crack. Flow stress was assumed as normal distribution with mean value 30.04 kgf/mm² and standard deviation 1.502. This corresponds to $0.55(\sigma_y+\sigma_u)$ at 500℃. For un-detection probability of LLNL's equation[13] was applied to present analysis. Leak rate,Q , was calculated from;

$$Q(mm^3/s)=A_{ep}[2p/(\rho\zeta)]^{1/2},$$

where ρ was sodium density 8.32×10^{-7}kgf/mm³, ζ was pressure loss coefficient of 2.0 and A_{ep} was a crack opening area[8] . Leak rate more than 100 mm³/s was perfectly detected by leak detector, then the crack was removed by repairing.

In case-1, neither PSI nor leak detection were considered. Creep effect was excluded in case-2. The mean value of crack depth was twice of reference case, namely 2.06 mm in case-3. In case-4, about eighty percent stress ranges in thermal expansion stress, membrane and bending stresses due to thermal transients were used in calculation because rather large stress was usually evaluated in structural design. The stresses due to dead weight and internal pressure are identical to those used in reference case because of high certainty of its derivation procedure. 90 % lower limit in the constant C_c, 0.06072, was used in case-5 with creep parameter,q_{c1}, of 0.5 for creep and unloading. In case-6, the initial crack was assumed at a connecting weldment of the elbow and a straight pipe at which σ_{TE} = 10.8 kgf/mm².

The result of cumulative leak probability were shown in Fig.3 with and without earthquake. Comparing case-0, case-5 and case-2, creep had very large effect on the probability. The twice crack depth resulted in the largest probability. No PSI and 80 % stresses had moderate effect on the probability, however, the earthquake had little effect on the probabilities.

The cumulative break probability was also calculated. The result was very small values and had similar effects of those observed in the cumulative leak probability.

5 SUMMARY

As the first step of developing probabilistic structural integrity assessment method, CANIS-P code was developed. CANIS-P code was constructed to assess the failure and break probability of structures by Monte Carlo simulation based on the fracture mechanics. The special feature of the code was to analyze creep crack-growth. The code was applied to sensitivity study of PWR piping and FBR piping. The result showed the effect of each parameter on cumulative leak and break probabilities. An ability of assessment of crack initiation was not included in CANIS-P code yet.

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