Probability Finite Element Assessment Method for Nuclear Graphite Components

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ABSTRACT

In this paper the probability finite element assessment method is developed to evaluate the security of graphite components in reactors. The MSC.MARC non-linear finite element program is used, and using its user-defined subroutines (UDS) the irradiation thermal analysis subroutine, irradiation static analysis subroutine and probability assessment subroutine are embedded into it. The recompiled MARC program can consider irradiation induced-changes in graphite components such as the coefficient of thermal conductivity, the coefficient of thermal expansion, the creep coefficient, the elastic modulus, and the strength. An axis-symmetrical thick-wall cylinder was used as an example to verify the accuracy and reliability of the program. The failure probability of the graphite components in HTR-10 (10MW High Temperature Gas-cooled Reactor-Test Module) is evaluated. It is shown that the probability finite element assessment method is an effective tool to assess the probability of structure failure.

KEY WORDS: Graphite, Failure Probability, Probability Finite Element Assessment, Irradiation, Creep, MARC.

INTRODUCTION

With the advance of computer technology, the finite element method will provide increasingly accurate analysis for complex structures. But for failure assessment, because most materials present dispersivity property characteristics, such as the tensile strength of graphite[1-3], the deterministic analysis method might meet some difficulty. However the probabilistic approach is very suitable for analyzing failure assessment problems, and so the probability finite element theory has come into being as a product of structure reliability theory and finite element theory.

The initial idea of probability finite element method is to directly combine the Monte-Carlo simulating method with the finite element results. This kind of method is not applicable to complex structures, because of the tremendous workload. Therefore, a stochastic differential equation has been considered, from which the stochastic finite element model was built. [4-7]

The probability assessment method has also been studied for many years in relation to reactor structure, and some relative rules and criterions have been developed. The 'KTA 3232' criterion and JAGURA program of Germany, the VIENUS-STEP program of Japan, and the ADGRA program of China, all adopt the probability assessment theory. With many nuclear power plants gradually approaching their design deadlines, the probability assessment method is being applied more widely. [8]

The HTGR core graphite reflector directly influences the safety and stability of the reactor plant. Especially for the pebble bed reactor, the reflector structure cannot be replaced throughout the whole operating period. Therefore, the mechanics analysis and safety assessment of the graphite reflector structure is very important for reactor safety. So this paper develops the probability finite element assessment program for graphite reflector bricks on the basis of the MARC code, according to its UDS character. This assessment program uses the strength distribution function and the stress field of graphite components to obtain the failure probability through finite element analysis. If the failure

probability value is within the acceptable range limits, the component should be safe; otherwise it is disabled. This will provide an academic basis for safety monitoring, operating maintenance, safety evaluation and optimization design for HTGRs.

The tensile strength distribution of graphite is considered following the Weibull equation[1,2], whose parameters can be obtained through experimentation. For graphite IG11, the two parameters are: $m_t = 15.5$, and $\eta_t = 24.7MPa$[3].

PROBABILITY FINITE ELEMENT ANALYSIS PROGRAM[9]

The probability finite element analysis program of graphite components is based on the MARC non-linear finite element code, which contains many kinds of analysis modules and can do non-linear static analysis, modal analysis, dynamical response analysis, contact analysis, buckling analysis, and failure analysis.

The user can define his own subroutine through the User-Defined Subroutine (UDS) of MARC. The UDS can help the user to complete several functions: 1) define special load conditions, boundary conditions and new state variables (such as neutron field, electromagnetism field); 2) define special material properties and constitutive models (such as anisotropic property, visco-elastic model, visco-plastic model, and plastic model); 3) change the geometry and mesh characteritics of the finite element model; and 4) define new output variables for postprocessing.

The user should add his own code into corresponding subroutines offered by MARC. And the new modified subroutines will be used to form a new executable file for MARC, which can meet the user's special requirements.

The probability finite element analysis program for graphite components mainly includes three parts: a temperature analysis program (Graphite_Heat), a stress analysis program (Graphite_Stress), and a probability assessment program (Graphite_Probability). Graphite_Heat includes two subroutines, ANKOND and FLUX; Graphite_Stress includes three subroutines, ANEXP, ANELAS, and CRPLAW; and Graphite_Probability includes two subroutines, PLOTV and ELEVAR. The functions of these subroutines are shown in Table 1.

Table 1 Functions of used user-defined subroutines

Name	Description
ANKOND	Define coefficient of thermal conductivity
FLUX	Define heat flux
ANELAS	Define elastic modulus changing with the neutron dose
ANEXP	Define coefficient of thermal expansion
CRPLAW	Define visco-elastic constitutive model
PLOTV	Post-processing subroutine, compute failure probability of the component
ELEVAR	Post-processing subroutine, get element quantities (stress, strain, etc.)
INTCRD	Get coordinates of Gauss Integral Points

In addition, some common blocks are also used to obtain, store and overwrite some necessary operating parameters. The common blocks used here are shown in Table 2.

Table 2 Common blocks used

Name	Description
concom	Obtain the number of each increment step 'inc'
creeps	Obtain the time parameter 'cptim' and time increment 'timinc'
dimen,ablative, space,heat,array4	Get coordinates of Gauss Integral Points 'ccint(I)'

Figure 1 shows the flow chart of the whole program.

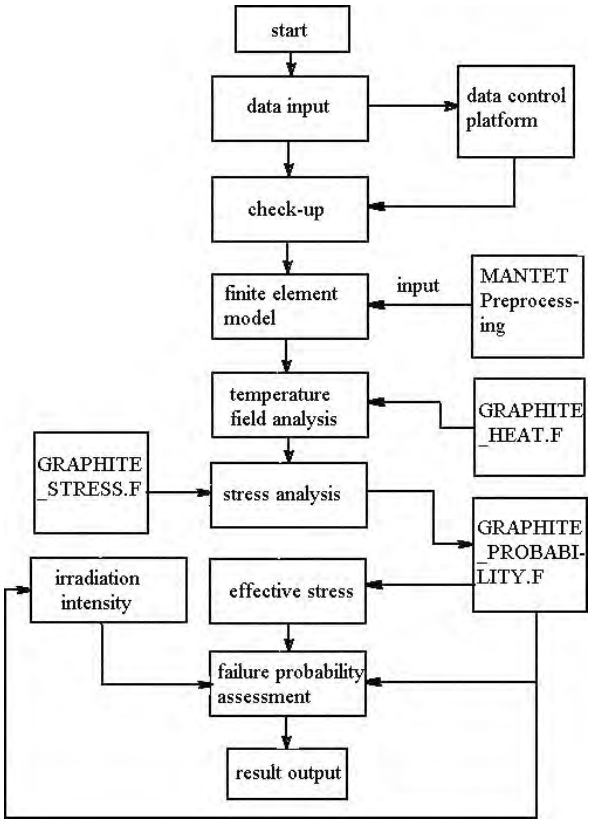


Figure 1 Program flow chart

VERIFICATION OF THE PROGRAM

To verify the accuracy and reliability of the program, an axis-symmetrical thick-wall cylinder was used as an example[10]. The inner diameter was 10mm, the outer diameter was 50mm, the inner surface temperature was 700•, and the outer surface temperature was 650•.

The finite element model used for irradiation effect analysis is shown in Figure 2. The element type was a 4-point plane element. Graphite_Heat.F was first used to make a thermal analysis. The calculated temperature distribution of the cylinder along the radial direction is shown in Figure 3, along with the theoretical value. Then Graphite_Stress.F was used to make a stress analysis, comprehensively considering the temperature field, irradiation deformation, and irradiation creep. The calculated stress and the theoretical value are shown in Figure 4. The results show that the subroutines of Graphite_Heat.F and Graphite_Stress.F are reliable.

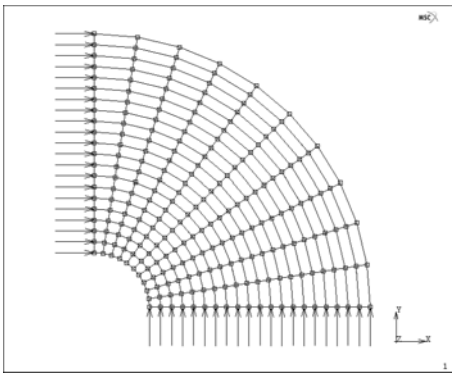


Figure 2 FE model for irradiation analysis

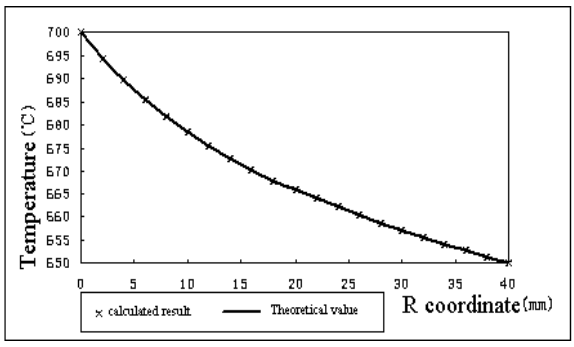
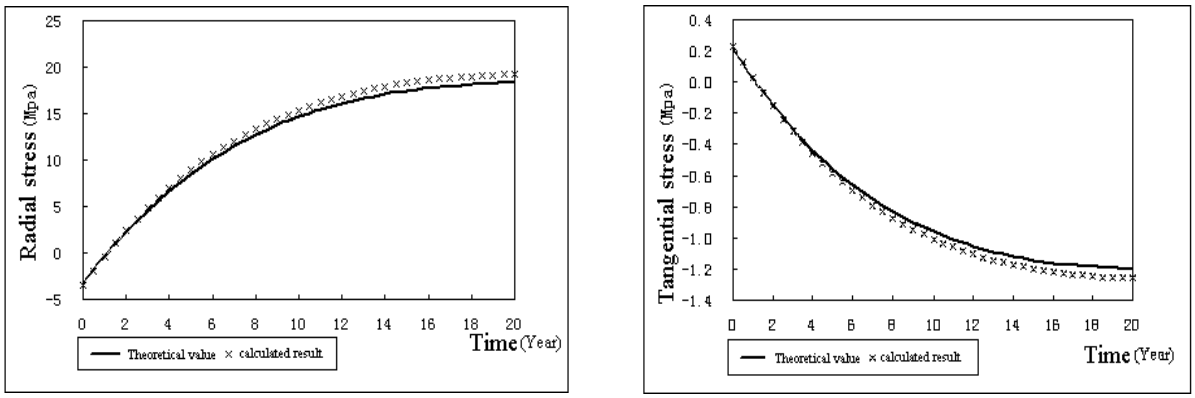


Figure 3 Temperature distribution



(a) Radial stress component (b) Tangential stress component

Figure4 Stress analysis result

The mesh shown in Figure 5 was used to examine the Graphite_Probability.F subroutine. The result is shown in Table 3. Therefore the Graphite_Probability.F program is also accurate and reliable.

Table 3 Failure probability assessment result

Time	Analytical result	Result from the program
0	2.14×10^{-8}	2.137×10^{-8}
1	4.50×10^{-6}	4.501×10^{-6}
2	1.06×10^{-4}	1.055×10^{-4}

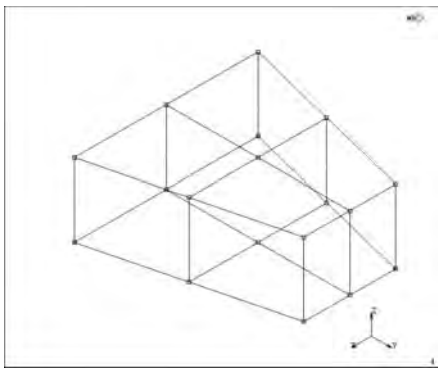


Figure 5 FE mesh for probability verification

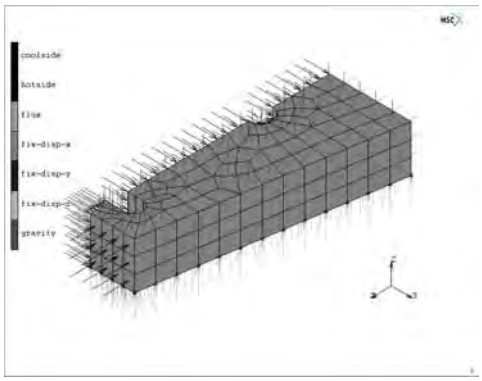


Figure 6 FE model for probability assessment of the HTR-10

PROBABILITY ASSESSMENT OF GRAPHITE REFLECTOR COMPONENTS OF THE HTR-10

Finite Element Model and Boundary Conditions

A single fan-shaped graphite brick was used for probability assessment. According to its symmetrical conditions, only 1/4 of the brick was selected, as shown in Figure 6, including a total of 240 elements and 1493 nodes. The element type was a 20-node 3D element.

All loads and boundary conditions included: 1) self-gravity, -z direction; 2) a heat exchange boundary condition on the helium gas hole (environment temperature: 250•, convection heat exchange coefficient: 0.05W/cm^2.•); 3) a heat exchange boundary condition between the brick and the core (environment temperature: 568.2•, convection heat exchange coefficient: 0.05W/cm^2.•); 4) y-displacement of x-z plane at zero; 5) z-displacement of x-y plane at zero; 6) x-displacement of the origin point at zero; 7) formation heat sources added by user-defined subroutine; and 8) fast

neutron flux added by user-defined subroutine.

Material Characteristics

The physical and mechanical characteristics, such as the thermal conductivity coefficient, the thermal expansion coefficient, the creep coefficient, and the elastic modulus, are all related to temperature and the fast neutron dose. Their relationships can be acquired through material experiments. During computation, the value of each item under a certain temperature and in a certain neutron dose range was acquired by the auto-interpolation method.

Analysis and Results

In each time step, the thermal analysis was completed first, followed by the stress analysis. Here only the influence of temperature to stress was considered, while the influence of stress to temperature was ignored.

According to the stress analysis results, the effective stress value of each Gauss integral point could be calculated, as well as the irradiation intensity. Then the safety degree of each integral point could be acquired. The failure probability of the graphite brick was finally calculated using the probability finite element model.

Using this probability assessment program, it was possible to discover the graphite brick's failure probability curve along operating time. Figure 7 shows the failure probability curve under normal operating conditions.

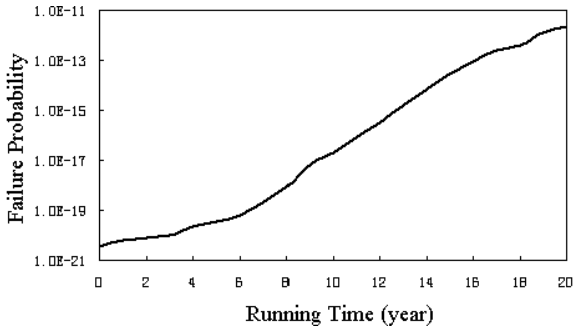


Figure 7 Failure probability curve

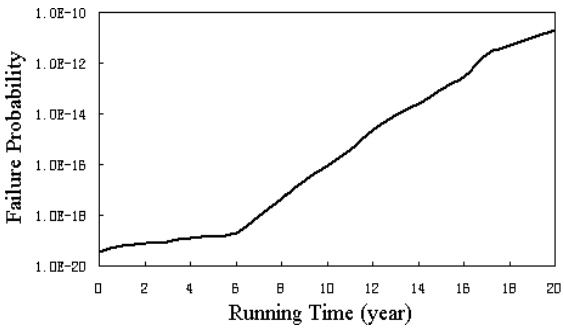


Figure 8 Failure probability curve with irradiation deformation increasing 20%

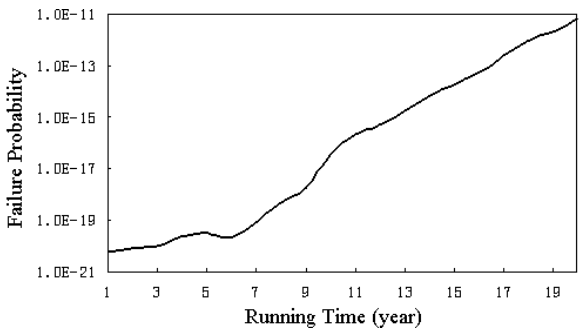


Figure 9 Failure probability curve with creep coefficient decreasing 20%

In addition, to see the influence of irradiation deformation and creep effect on failure probability, further analysis was done with the irradiation deformation increasing 20% and the creep coefficient decreasing 20%. The results are shown in Figures 8 and 9.

Figure 7 shows that the failure probability of the graphite brick after normally operating 20 years is 2.268×10^{-12}. According to the German criterion 'KTA 3232', the HTR-10's graphite brick has 'QSKI' quality grade, its operating condition is 'BST A', and its failure probability limit is 10^{-4}. So the HTR-10's graphite brick can fully satisfy the safety requirements.

Figures 8 and 9 show that the irradiation deformation and the creep characteristic greatly influence the failure probability of the graphite brick. When the irradiation deformation increases 20%, the failure probability after operating

20 years will be 2.041×10^{-11}, which is 8.99 times higher than the original value. When the creep coefficient decreases 20%, the result will be 6.304×10^{-12}, which is 2.78 times higher than the original value.

CONCLUSION

The developed program can take into account the material characteristic changes with temperature and neutron flux, and conveniently complete heat exchange analysis, stress analysis and failure assessment of graphite components under irradiation. By changing relative items through the user-defined subroutines of Graphite_Heat.F, Graphite_Stress.F and Graphite_Probability.F, it can also be used for other kinds of nonmetal brittle materials.

The reliability and accuracy of the program was verified using a thick-wall graphite cylinder.

A failure probability assessment for a graphite brick of the HTR-10 reactor was completed. The result indicated that the failure probability of the graphite brick after operating 20 years is much less than the limit value of 10^{-4}, according to German criterion 'KTA 3232'.

Irradiation deformation and the creep characteristic will greatly influence the failure probability of the graphite brick. Either the increase of irradiation deformation or the decrease of the creep coefficient will increase the failure probability.

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