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New approach for fracture assessment of graphite

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ABSTRACT : A new method for the fracture assessment of graphite was developed. This method treats two fracture modes, surface and internal fracture modes, on the basis of the competing risk theory in which the Weibull distribution is adopted as a strength distribution. The parameters used in this model were evaluated from the tensile strength data since the data could comprise above two fracture modes. The applicability of this method was demonstrated from the bending test and the component test in which 1/4 model specimens of the HTTR graphite structures were used.

1. INTRODUCTION

The graphite structures of core internals in the high temperature gas–cooled reactor is subject to thermal and mechanical stresses due to the thermal distribution and the earthquake load as well as a residual stress by irradiation–induced creep and/or dimensional shrinkage under neutron irradiation condition. As a result, complex stress which consists of membrane, bending and peak stress components is imposed on the graphite structures. It is, therefore, necessary to estimate the fracture load of the graphite component under complex stress conditions.

It is well–known that the fracture of graphite is influenced by the stress gradient condition and the Weibull strength theory has been applied to roughly predict the fracture in various stress conditions (Brocklehurst 1975). However the Weibull strength theory sometimes shows a large disagreement between the prediction and the test result (Price and Cobb 1970).

In stead of the Weibull strength theory the more realistic fracture model based on two types of fracture models, the surface fracture initiated by the surface flaw and the internal fracture by the internal flaws, should be developed for the purpose of the strength estimation.

We have tried, therefore, to develop a new method for the fracture assessment considering two fracture modes. In the new method, competing risk theory is adopted and the Weibull strength theory is modified such that the surface and the internal fracture modes can be treated. In the present study, the new assessment method was proposed and the availability of this approach was discussed.

2. FRACTURE MODEL

In the new fracture model for fracture estimation of the graphite, the following are considered:

1) two fracture modes, surface fracture and internal fracture, are adopted applying the competing risk theory,
2) the Weibull distribution is adopted as a strength distribution,
3) surface fracture mode is applied to the surface thin layer which depth is assumed to be a maximum grain size,
4) The parameters used in this model are derived from the tensile test result.

The risk of ruptures to the surface fracture, R_S, and internal fracture R_I for Weibull's uniaxial distribution function can be written as (Weibull 1939)

$$R_S=\int_{V_1}\left(\frac{\sigma-\sigma_{u1}}{\sigma_{01}}\right)^{m_1}dV_1 \quad , \quad R_I=\int_{V_2}\left(\frac{\sigma-\sigma_{u2}}{\sigma_{02}}\right)^{m_2}dV_2 \qquad (1)$$

where m is a parameter known as the Weibull modulus, σ applied stress, σ_u minimum fracture stress below which the fracture probability is zero, σ_0 a normalizing parameter, V the volume of tensile stress region and the suffix 1 and 2 means the surface and internal fracture modes.

Unfracture probability of the body, 1–F(σ), is generally given as (Matsuo 1984)

$$\begin{aligned} 1-F(\sigma) &= (1-F_1(\sigma))\,(1-F_2(\sigma)) \\ &= \exp(-(R_s+R_I)) \\ \therefore\ F(\sigma) &= 1-\exp(-(R_s+R_I)) \end{aligned} \qquad (2)$$

The risk of rupture for two fracture modes are written as

$$R=R_S+R_I \qquad (3)$$

3 DETERMINATION OF MODEL PARAMETERS

In order to determine the model parameters, m_1 ,m_2 ,σ_{01} and σ_{02}, in eq. 1 and 2 tensile test data which are obtained under uniform stress was used since the two fracture modes, surface and internal ones, could be observed. The tensile test was performed using PGX graphite, which is a coarse grained nuclear grade graphite. The shape of the specimen is shown in Fig.1. Obtained test data are plotted in the Weibull probability form as the normalized value in Fig. 2. From this figure we can categorize the data into two major data groups, group 1 and group 2.

From the fracture mechanics, fracture toughness for the surface crack and the internal crack can be written for uniform stress σ in Fig. 3.

$$K_I=\sigma\sqrt{\pi a}\cdot F \qquad (4)$$

where a and 2a are lengths for surface and internal cracks, W width of the specimen, and F a factor depending on the specimen geometry and so on. From the calculation the factor F for the surface crack is greater than that of the internal one. Hence, we can suppose easily that the surface fracture would be observed at low applied stress level if the stress intensity factor K_I reaches the critical value K_{IC} and the crack is the same size for both location. We could presume, therefore, that the lower strength group 1 would be mostly governed by the surface fracture mode because it is unlikely that only internal flaws are extremely large, on the other hand, the higher strength group 2 by the internal mode because surface flaws happen to be small. From this assumption we obtain the model parameters of each fracture mode as listed in Table 1.

4. APPLICATION OF THIS MODEL

4.1 4–point Bending Test

From eq. 1 and 3 the risk of rupture for 4-point bending test with rectangular specimen as shown in Fig. 4 is calculated as

$$R_{bend}=1/(\sigma_{01})^{m_1}(\sigma_{bmax})^{m_1}R_{bs}+1/(\sigma_{02})^{m_2}(\sigma_{bmax})^{m2}R_{bI} \qquad (5)$$

here,

$$R_{bs}=\left(\frac{h}{2}-\left(\frac{2}{h}\right)^{m_1}\left(\frac{h}{2}-h_s\right)^{m_1+1}\right)\left(\frac{2ab}{(m_1+1)^2}+\frac{bl}{m_1+1}\right)$$

$$R_{bI}=\frac{2ab}{(m_2+1)^2}\left(\frac{2}{h}\right)^{m_2}\left(\frac{h}{2}-h_s\right)^{m_2+1}+\frac{bl}{m_2+1}\left(\frac{2}{h}\right)^{m_2}\left(\frac{h}{2}-h_s\right)^{m_2+1}$$

where σ_{bmax} is maximum bending stress and h_s depth from the surface layer to be considered as a surface fracture mode.

To evaluate the availability of this new model, the 4-point bending test was performed using PGX graphite with rectangular specimen, h=25.4 mm, b=50.8 mm, l=50.8 mm and 2a=101.6 mm in Fig. 4. The specimen was cut so as to obtain the across grain data. Here, we assume that the h_S is around the maximum grain size, 0.8 mm, in this estimation. The estimated bending strength by this model is compared with the obtained data in Table 2. The developed model gives slightly lower bending strength than the experimental one. The bending strength was also estimated from the Weibull strength theory. The estimated strength by this theory was 9.4 MPa, which was lower than that of the developed model. We can find that the developed new model gives good strength estimation in almost linear stress gradient condition.

4.2 Component Test

We can apply this model to an arbitrary configuration of component. From the stress analytical result, such as the result by an FEM code, we can define the tensile stress region, which is cut n pieces of narrow segments, as schematically shown in Fig. 5. Now we consider i-th narrow segment, which is Δ_{yi} in width and l_i in length, having stress distribution $\sigma_i(x)$, where x is a distance from the inner body surface along the i-th segment in Fig. 5. The risk of rupture for the component is calculated by

$$R_{com}=\frac{1}{(\sigma_{01})^{m_1}}R_{cS}+\frac{1}{(\sigma_{02})^{m_2}}R_{cI} \qquad (6)$$

here,

$$R_{cS}=\sum_{i=1}^{n}h\Delta y_i\int_{0}^{h_S}(\sigma_i(x))^{m_1}dx$$

$$R_{cI}=\sum_{i=1}^{n}h\Delta y_i\int_{h_S}^{l_i}(\sigma_i(x))^{m_2}dx$$

For validating of the evaluation of this developed model the component test was carried out with 1/4 scale specimens of the core support graphite structures in the HTTR as shown in Fig. 6. The stress analysis in an elastic condition was performed with NISA II code (Engineering mechanics research corp. 1992). Maximum principal stress is calculated to estimate the component test result, since the maximum principal stress theory is applicable to the graphite material (Iyoku 1991). Figure 7 shows the maximum principal stress obtained by the two-dimensional stress analysis in which the load is imposed uniformly at a level of 1 MPa. From this stress distribution the risk of rupture is estimated and compared with the obtained experimental data in Table 2. The developed model gives a good estimation in the mean fracture load. We can see that this model can be applicable to the arbitrary configuration body with non uniform stress distribution.

For the application of this developed model to the large graphite structures, the volume effect on the fracture load should be investigated, because this new model is developed on the basis of the Weibull strength theory, which gives over-estimation of the fracture load on the volume effect (Ishihara 1984).

4 SUMMARY AND CONCLUSIONS

The fracture model treating the surface and internal fracture modes on the basis of the competing risk theory was developed. To determine the model parameters the analysis of the tensile strength data was proposed as a most suitable method. For the porous material, such as graphite, the thickness of the surface thin layer in which the surface fracture is dominant is a significant parameter in the developed model. Although in this paper the volume was treated by a maximum grain size layer, the more real measurements of this layer size would be necessary.

The developed new method was found fairly good in strength evaluation under the bending test and the component test. It can be concluded that this model is applicable for the design as well as the evaluation of the structural integrity of graphite structures under complex stress conditions within the negligible small volume effect on the fracture load. In order to apply the developed model for the estimation of the fracture load for the large graphite structures, the volume effect on the fracture load should be investigated.

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Table 1 Obtained data from tensile test for PGX graphite*.

Parameter	estimated value
m_1	15.9
m_2	9.4
σ_{01}	10.5
σ_{02}	12.1

***:Across grain direction**

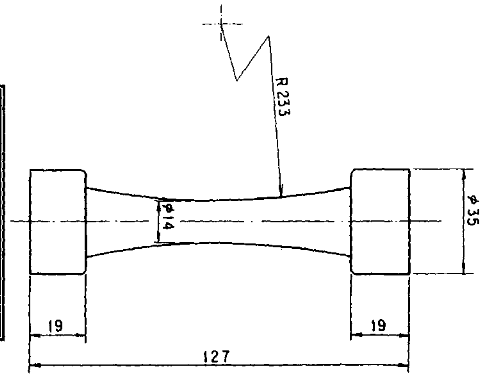


Fig.1 Tensile test specimen.

Table 2 Estimation results by the new model considering surface and internal fracture.

Item	Experiment	Analysis
Bending strength (MPa)	10.75 (7.4)*	9.7 (7.1)
Fracture load of Component test (N)	554, 451, 549, 490 Mean : 511	503

*:Standard deviation

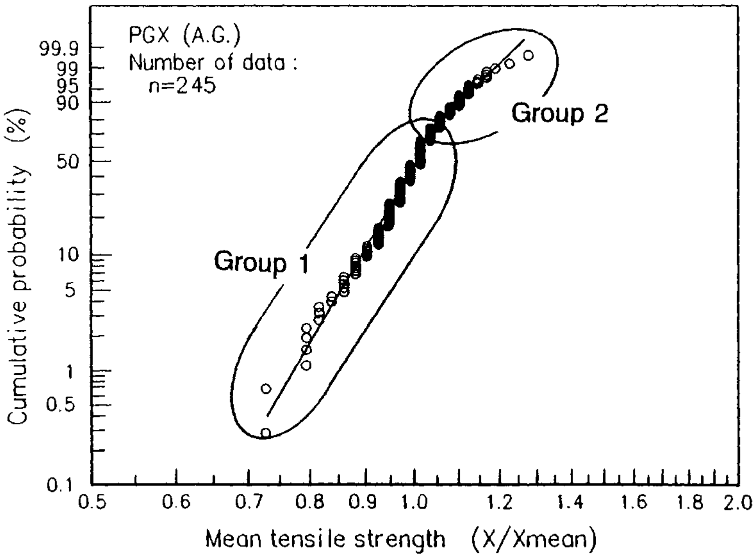
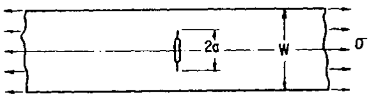


Fig.2 Weibull probability plot of tensile strength for PGX graphite.

(1) Surface crack



(2) Internal crack

Fig.3 Surface and internal cracks under uniform stress condition.

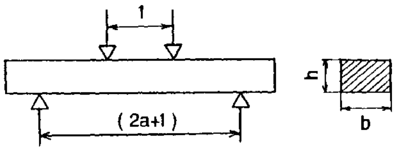


Fig.4 4-point bending test condition.

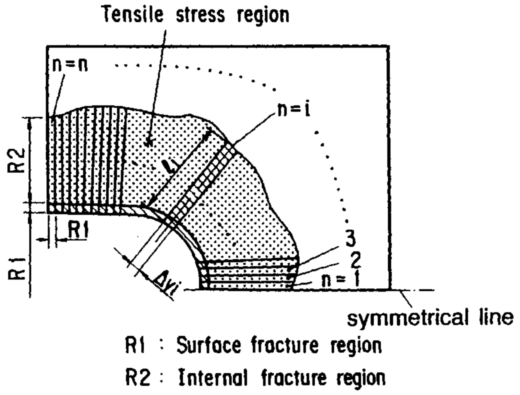


Fig.5 Application of developed model for component test condition.

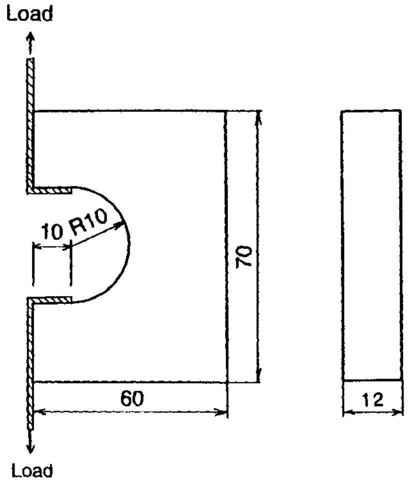


Fig.6 Shape of component test specimen.

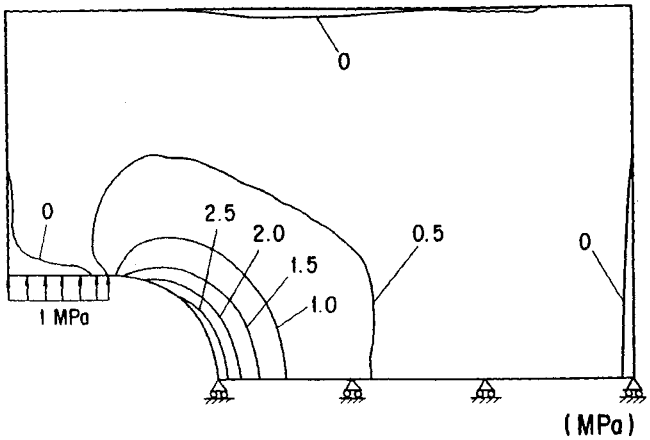


Fig.7 Maximum principal stress distribution analyzed by the NISA II code.