Analysis and Numerical Study of Stress Response of Graphite Reflector in High-Temperature Reactors under High Temperature and Irradiation: Postprint

Authors: Lan Tianbao

Date: 2025-11-01T21:42:03+00:00

Abstract

The core components of high-temperature gas-cooled reactors are primarily composed of graphite materials. Under high temperature and irradiation, the mechanical properties of graphite materials undergo changes, ultimately affecting the load-bearing capacity of the core components. Therefore, evaluating the stress response of graphite structures under high temperature and irradiation is essential for ensuring safe operation. Based on publicly available material performance data for IG-110 graphite structures under irradiation, an analysis of the mechanical response of IG-110 graphite structures in high-temperature gas-cooled reactors under high temperature and irradiation was conducted. First, a simplified theoretical analysis model for the reflector was established; then, a numerical program with user-defined material capabilities was developed to calculate the stress field of IG-110 graphite structures and analyze the mechanical response of the structure under high temperature and irradiation. The calculation results demonstrate good agreement between the numerical solution and the derived analytical solution, thereby verifying the accuracy of the numerical program. The research conclusions are as follows: High temperature directly affects the irradiation threshold for material transformation, leading to changes in the structural stress state; structural strain primarily depends on irradiation-induced strain; with increasing time and irradiation dose, the circumferential and axial stresses of IG-110 graphite structures first reach a peak and then gradually decrease, while the radial stress is significantly smaller than the circumferential and axial stresses; it is recommended that structural gaps generated by temperature, irradiation, and creep factors be simultaneously considered in the seismic design phase of high-temperature gas-cooled reactor graphite cores. This work provides numerical methods and theoretical validation for subsequent high-temperature reactor types employing graphite materials as

core components.

Full Text

Analysis and Numerical Study of Stress Response in Graphite Reflector of High-Temperature Reactor Under High Temperature and Irradiation

Lan Tianbao, Zhang Shichao, Shen Teng, Sheng Feng
(China Nuclear Power Engineering Co., Ltd., 100840 Beijing, China)

Abstract

The core components of high-temperature gas-cooled reactors are primarily constructed from graphite materials, whose mechanical properties undergo significant changes under high temperature and irradiation, ultimately affecting the load-bearing capacity of core components. Consequently, evaluating the stress response of graphite structures under these conditions is essential for ensuring safe operation. Based on published material performance data for IG-110 graphite structures under irradiation, this study analyzes the mechanical response of IG-110 graphite components in high-temperature gas-cooled reactors under combined high temperature and irradiation. A simplified theoretical analysis model for the reflector was first established, followed by the development of a user-defined material numerical program to calculate the stress field in IG-110 graphite structures and analyze their mechanical response under high temperature and irradiation. The calculation results demonstrate good agreement between the numerical solutions and derived analytical solutions, thereby verifying the accuracy of the numerical program.

The research conclusions are as follows: High temperature directly affects the irradiation threshold for material transformation, leading to changes in the structural stress state, while structural strain primarily depends on irradiation strain. Over time and with increasing irradiation dose, the circumferential and axial stresses in IG-110 graphite structures first reach peak values and then gradually decrease, with radial stress being significantly smaller than both circumferential and axial stresses. It is recommended that the seismic design of graphite cores in high-temperature gas-cooled reactors simultaneously consider structural clearances generated by temperature, irradiation, and creep effects. This study provides a numerical methodology and theoretical validation for subsequent high-temperature reactor designs utilizing graphite materials as core components.

Keywords: graphite; high temperature; irradiation; UMAT; reflector

1. Material Performance Changes of IG-110 Graphite Under High Temperature and Irradiation

In complex environments involving high temperature and neutron irradiation, the crystal structure of IG-110 graphite undergoes transformation. The macroscopic dimensions of IG-110 graphite exhibit a characteristic pattern of initial shrinkage followed by expansion with increasing neutron dose. Compared with room temperature conditions, high-temperature environments reduce the irradiation threshold for this dimensional transition. Research by the Japan Atomic Energy Agency [16] employed curve fitting methods to express irradiation strain as a quadratic function of neutron dose:

$$\varepsilon_d = a_1 N^2 + a_2 N$$

where ε_d represents irradiation strain, N denotes neutron flux ($10^{26}\,\mathrm{n \cdot m^{-2}}$, $E > 0.1\,\mathrm{MeV}$), and a_1 and a_2 are temperature-dependent constants with values listed in Table 1 .

The coefficient of thermal expansion represents a crucial physical indicator for evaluating the thermomechanical performance of IG-110 graphite. The Japan Atomic Energy Agency compiled measurement data for the thermal expansion coefficient of IG-110 graphite after irradiation, establishing the following relationships:

$$\frac{\alpha}{\alpha_0} = b_1 N^3 + b_2 N^2 + b_3 N + 1, \quad N \le N_{ca}$$

$$\frac{\alpha}{\alpha_0} = b_4 N + b_5, \quad N > N_{ca}$$

where α is the thermal expansion coefficient of irradiated IG-110 graphite ($10^{-6}/^\circ\mathrm{C}$), α_0 is the pre-irradiation thermal expansion coefficient ($10^{-6}/^\circ\mathrm{C}$), and b_1, b_2, b_3, b_4, b_5 are temperature-dependent constants with values provided in Table 2 .

Under neutron irradiation, the elastic modulus of IG-110 graphite increases rapidly during the initial stage before reaching a maximum value. With continued irradiation dose accumulation, the elastic modulus gradually decreases. Higher irradiation temperatures result in lower peak transformation values for the elastic modulus and correspondingly lower transformation doses. This behavior is described by:

$$\frac{E}{E_0} = c_1 N + c_2 + 1, \quad N \le N_c$$

$$\frac{E}{E_0} = c_3 (N + c_4)^2 + c_5 + 1, \quad N > N_c$$

where E represents the elastic modulus after irradiation (Pa), E_0 is the pre-irradiation elastic modulus (Pa), and c_1, c_2, c_3, c_4, c_5 are temperature-dependent constants listed in Table 3 .

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2. Constitutive Relationship of IG-110 Graphite Material

Based on the preceding discussion, stress analysis of IG-110 graphite involves small deformation and material nonlinearity. The constitutive relationship can be established from the strain components, where the total strain matrix for IG-110 graphite components under high temperature and irradiation is:

$$\varepsilon = \varepsilon_e + \varepsilon_d + \varepsilon_t + \varepsilon_c$$

where ε is the total strain matrix, ε_e is the elastic strain component matrix, ε_d is the irradiation strain component matrix, ε_t is the thermal strain component matrix, and ε_c is the creep strain component matrix.

The relationship between elastic strain and stress can be expressed as:

$$\varepsilon_e = \frac{1}{E}\begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix}\sigma$$

where ν is Poisson's ratio. For simplification and unification, the symmetric components are represented in compact form.

The irradiation strain component matrix is:

$$\varepsilon_d = [\varepsilon_d \ \varepsilon_d \ \varepsilon_d \ 0 \ 0 \ 0]^T$$

The thermal strain component matrix is:

$$\varepsilon_t = [\varepsilon_t \ \varepsilon_t \ \varepsilon_t \ 0 \ 0 \ 0]^T$$

The secondary creep strain component matrix is:

$$\varepsilon_{sc} = [\varepsilon_{sc} \ \varepsilon_{sc} \ \varepsilon_{sc} \ 0 \ 0 \ 0]^T$$

Creep strain is divided into primary and secondary components:

$$\varepsilon_c = \varepsilon_{pc} + \varepsilon_{sc}$$

The primary creep strain component matrix is:

$$\varepsilon_{pc} = C_0 p(1 - e^{-qN}) \cdot \sigma$$

where C_0 is the primary creep coefficient, $p = 1.0 \times 10^{-10}$, and $q = 450 \times 10^{26}\ \mathrm{n \cdot m^{-2}}$.

The secondary creep coefficient K $(10^{-29}\,(\mathrm{MPa} \cdot \mathrm{n/m^2})^{-1})$ is temperature-dependent:

$$K = 0.7163e^{0.0012T}$$

where T is in °C. The creep Poisson's ratio ν_c is related to graphite material properties [14].

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3. Theoretical and Analytical Derivation

3.1 Basic Assumptions

IG-110 graphite material is assumed to be continuous, homogeneous, and isotropic, remaining in the elastic stage with small deformation during reactor operation [6]. Based on operational data from high-temperature gas-cooled reactors worldwide, this assumption is reasonable.

3.2 Structural Model

The reflector, constructed from IG-110 graphite, approximates a thick-walled cylindrical cavity as shown in Figure 2

. The cylinder has inner and outer radii of 1.55 m and 2.3 m, respectively, with a length of 13.6 m. The structure is constrained in the longitudinal direction, satisfying plane strain conditions. Structural parameters are derived from literature [17].

The environmental irradiation dose N in the IG-110 graphite structure varies linearly with radius and time, decreasing from the center to the periphery, with the highest dose at the center, as illustrated in Figure 3

. The neutron irradiation field in cylindrical coordinates is expressed as:

$$N = 75(r - 1.55)t$$

where r is the radius (m) and t is the operating time (years).

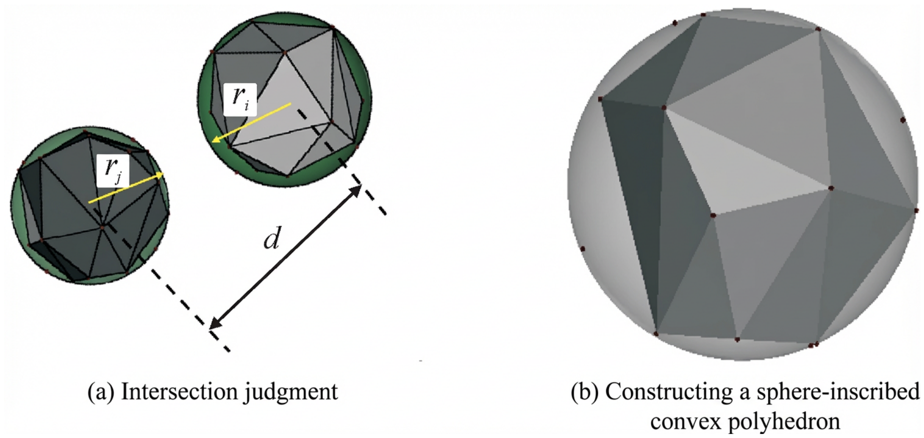

Figure 1: Figure 2

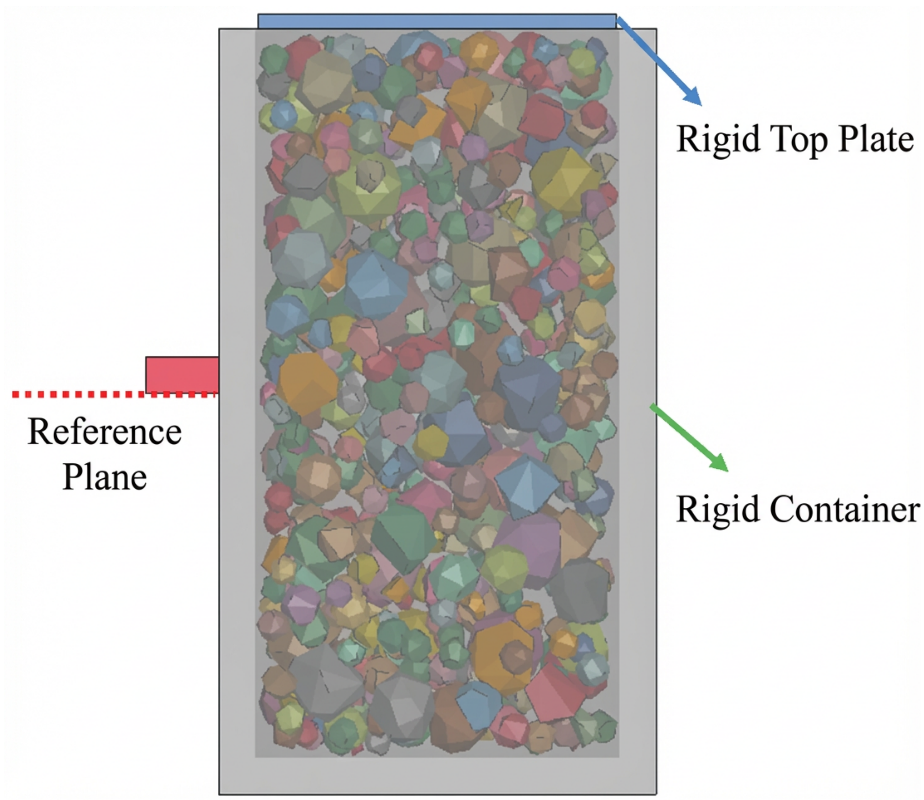

Figure 2: Figure 3

3.3 Derivation of Analytical Solution

Based on the material performance changes and constitutive relationships of graphite under high temperature and irradiation, a simplified structural theoretical model was derived. According to the total strain equation, the strain at any point in the reactor IG-110 graphite component comprises the sum of elastic strain ε_e, secondary creep strain ε_{sc}, irradiation strain ε_d, and thermal strain ε_t. Primary creep strain ε_{pc} is relatively small compared to secondary creep and can be neglected in the derivation. The creep Poisson's ratio is assumed equal to the elastic Poisson's ratio ($\nu = \nu_c$) [18].

By substituting the elastic, creep, and irradiation strain components into the constitutive relationship and converting the matrix equations into strain equations in the three directions r, θ, and z, three equations are obtained:

$$\varepsilon_r \approx \varepsilon_r^e + \varepsilon_r^{sc} + \varepsilon_d + \varepsilon_t = \frac{1}{E}(\sigma_r - \nu\sigma_\theta - \nu\sigma_z) + KN(\sigma_r - \nu\sigma_\theta - \nu\sigma_z) + \varepsilon_d + \varepsilon_t$$

$$\varepsilon_\theta \approx \varepsilon_\theta^e + \varepsilon_\theta^{sc} + \varepsilon_d + \varepsilon_t = \frac{1}{E}(\sigma_\theta - \nu\sigma_r - \nu\sigma_z) + KN(\sigma_\theta - \nu\sigma_r - \nu\sigma_z) + \varepsilon_d + \varepsilon_t$$

$$\varepsilon_z \approx \varepsilon_z^e + \varepsilon_z^{sc} + \varepsilon_d + \varepsilon_t = \frac{1}{E}(\sigma_z - \nu\sigma_r - \nu\sigma_\theta) + KN(\sigma_z - \nu\sigma_r - \nu\sigma_\theta) + \varepsilon_d + \varepsilon_t$$

Defining $B = \varepsilon_d + \varepsilon_t$, the analytical solution for stresses in a cylindrical structure under irradiation and temperature, considering secondary creep, is derived as:

$$\sigma_r = \frac{E}{1+KNE}\left[\frac{1}{r^2}\int_a^r \frac{Br}{1-\nu}dr - \frac{r^2-a^2}{b^2-a^2}\cdot\frac{1}{r^2}\int_a^b \frac{Br}{1-\nu}dr\right]$$

$$\sigma_\theta = \frac{E}{1+KNE}\left[\frac{B}{1-\nu} - \frac{1}{r^2}\int_a^r \frac{Br}{1-\nu}dr - \frac{r^2+a^2}{b^2-a^2}\cdot\frac{1}{r^2}\int_a^b \frac{Br}{1-\nu}dr\right]$$

$$\sigma_z = \frac{E}{1+KNE}\left[\frac{\nu B}{1-\nu} - \frac{2\nu}{b^2-a^2}\int_a^b \frac{Br}{1-\nu}dr\right]$$

4. Development of Numerical Calculation Program

4.1 Implementation of IG-110 Graphite Structure Stress Analysis Program

This study developed an IG-110 graphite stress analysis program for high-temperature irradiation environments based on the ABAQUS user material subroutine (UMAT). By introducing neutron dose as a variable simplified as a function of coordinates and time, stress distributions within the IG-110 graphite structure were obtained.

The program requires three input parameters: pre-irradiation elastic modulus E_0, Poisson's ratio ν, and thermal expansion coefficient α_0. Multiple state variables are established to store and update parameters such as elastic modulus and irradiation dose at the end of each increment. Through continuous updating of the Jacobian matrix and stress components, the stress history of the graphite structure throughout the entire calculation period is obtained. The computational flowchart is shown in Figure 4 [FIGURE:4].

4.2 Case Study

This study established a three-dimensional finite element model of the IG-110 graphite structure, representing a cylindrical geometry consistent with Section 3.2. The numerical program was then used to evaluate the structural performance over a 30-year operational cycle. The pre-irradiation material parameters used in this case study were: elastic modulus of 9.8 GPa, Poisson's ratio of 0.3, and thermal expansion coefficient of $4.5 \times 10^{-6}\,^{\circ}\mathrm{C}^{-1}$.

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5. Results and Discussion

5.1 Program Verification

The program results were validated using the analytical solution. According to the derived equations, radial stress values are negligible compared to circumferential and axial stresses. The analytical solution for circumferential stress in IG-110 graphite structures under high temperature and irradiation shows excellent agreement with the finite element numerical solution (Figure 5 [FIGURE:5]), with errors not exceeding 10%, thereby validating both the analytical formulation and computational program.

Using the verified program, stress distribution results were obtained for graphite structures after 5 years of service at different temperatures. As shown in Figure 6 [FIGURE:6], radial stress levels decrease with increasing temperature. This occurs because after 5 years of service, the irradiation-induced shrinkage effect on graphite at high temperatures can partially offset thermal strain, resulting in slightly lower stress levels at higher temperatures compared to lower temperatures. Radial stress initially increases near the inner wall, then decreases with increasing radius, reaching its peak at the mid-radius position.

Circumferential and axial stress values are significantly larger than radial stress values, decreasing with increasing radius as illustrated in Figures 7

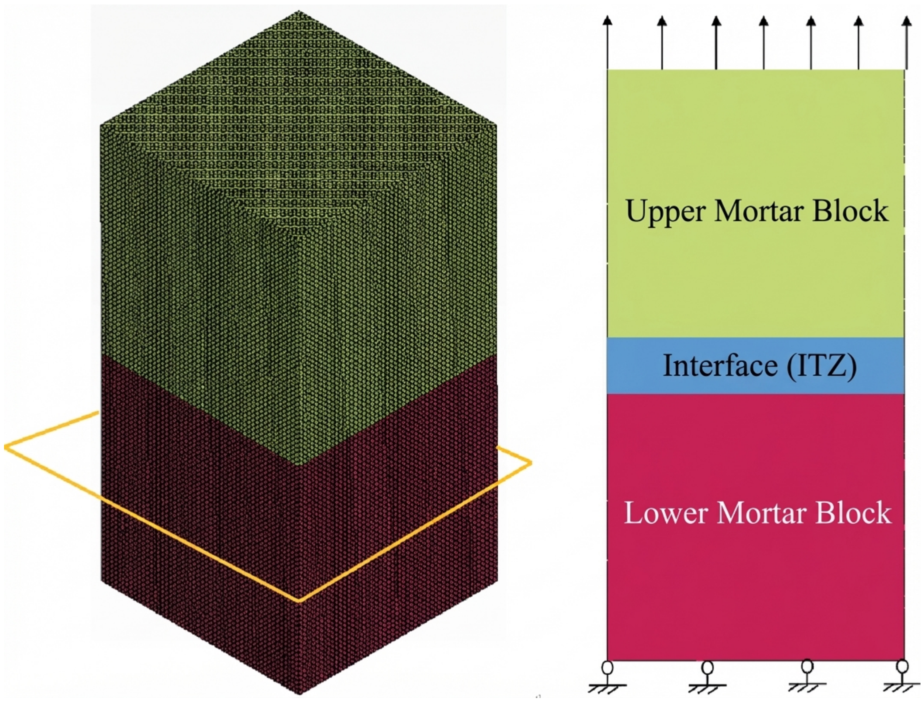


Figure 3: Figure 7

and 8 [FIGURE:8]. Maximum tensile and compressive stresses occur at the inner and outer walls, respectively, indicating a tensile state at the inner wall and compressive state at the outer wall. Higher temperatures result in smaller stress values due to more pronounced creep effects.

The program was further used to analyze stress distributions after 30 years of service at different temperatures. The results indicate that temperature plays a crucial role in structural stress evolution, particularly during later stages of reactor operation. As shown in Figure 9

, at $T = 800\,^{\circ}\mathrm{C}$, the radial stress state at various points in the graphite structure reverses compared to the initial stage. Figures 10

and 11

demonstrate that circumferential and axial stress evolution follows similar trends: when temperature increases from $400\,^{\circ}\mathrm{C}$ to $800\,^{\circ}\mathrm{C}$, the maximum tensile stress (at the inner wall) and maximum compressive stress (at the outer wall) values decrease by nearly 30%.

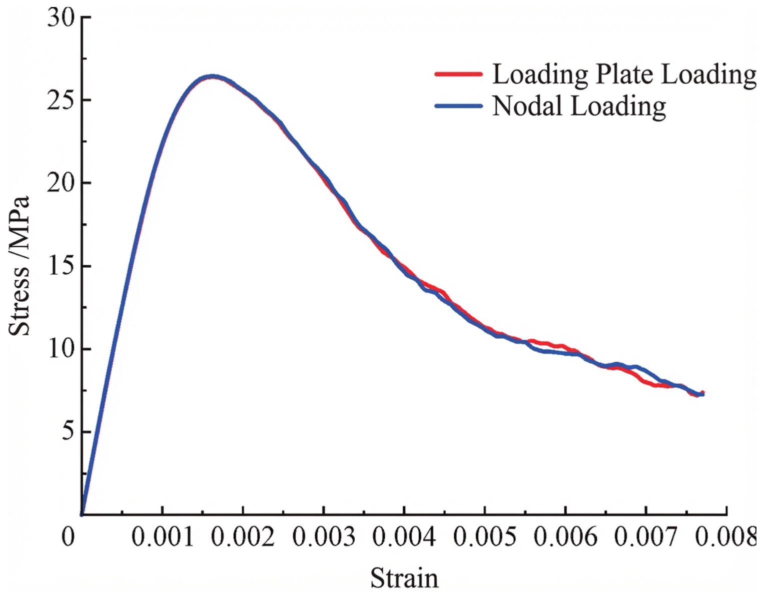
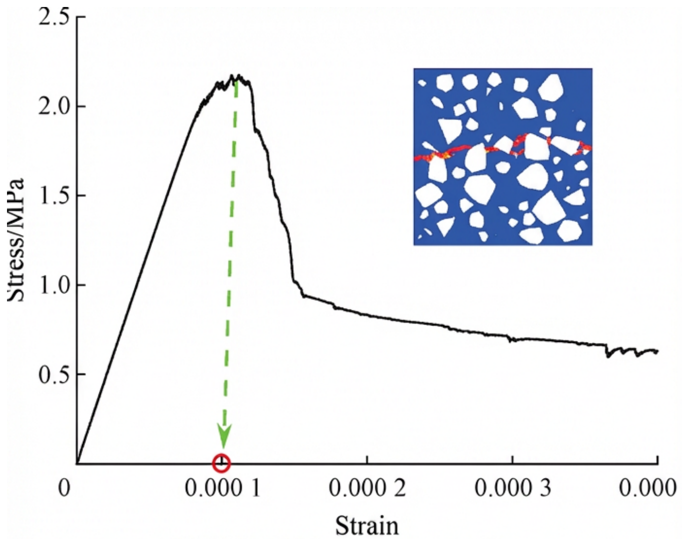


Figure 4: Figure 9

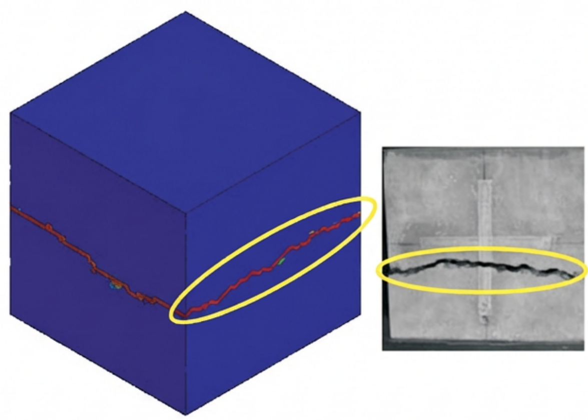
Irradiation-induced dimensional changes in graphite affect internal stress distribution. As neutron flux increases, graphite components exhibit initial shrinkage followed by expansion. Figures 10 and 11 show that the distribution patterns of circumferential and axial stresses along the radius change under different temperatures. At elevated temperatures, the transformation dose at which graphite transitions from shrinkage to expansion decreases. After 30 years of operation at 800 °C, the cylindrical inner wall experiences circumferential and axial compressive stresses. Additionally, with increasing irradiation dose, graphite demonstrates stronger viscoelastic characteristics, and creep stress relaxation significantly influences the stress field.

The evolution of various strain components at the inner and outer surfaces during the 30-year operational period is shown in Figures 14 [FIGURE:14] and 15 [FIGURE:15]. Except for the initial stage, irradiation strain dominates and primarily governs internal stresses. The outer wall continuously shrinks, while the inner wall shrinks to a peak value before rebounding. Thermal strain increases to a peak then continuously decreases, having minimal impact on stress variation. Creep strain becomes influential during later stages, with primary creep being negligible compared to other strain components.

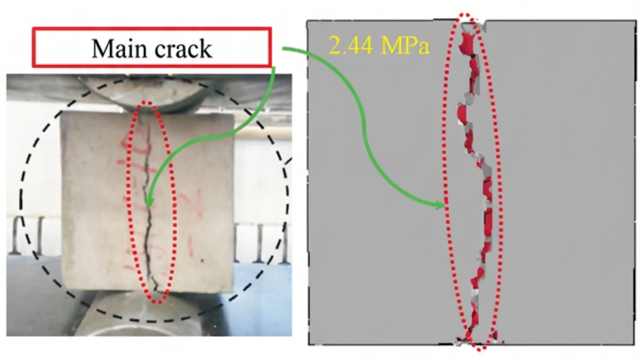
In summary, temperature, irradiation strain, and creep effects significantly influence structural deformation, particularly during later service stages. These deformations affect structural clearances and consequently the seismic performance of graphite cores. Therefore, it is recommended to appropriately increase initial clearances in graphite structures during seismic design.



(a) Uniaxial tensile stress-strain curve



(b) Uniaxial tensile failure comparison[26]



(c) Splitting tensile failure comparison[25]

Figure 5: Figure 10

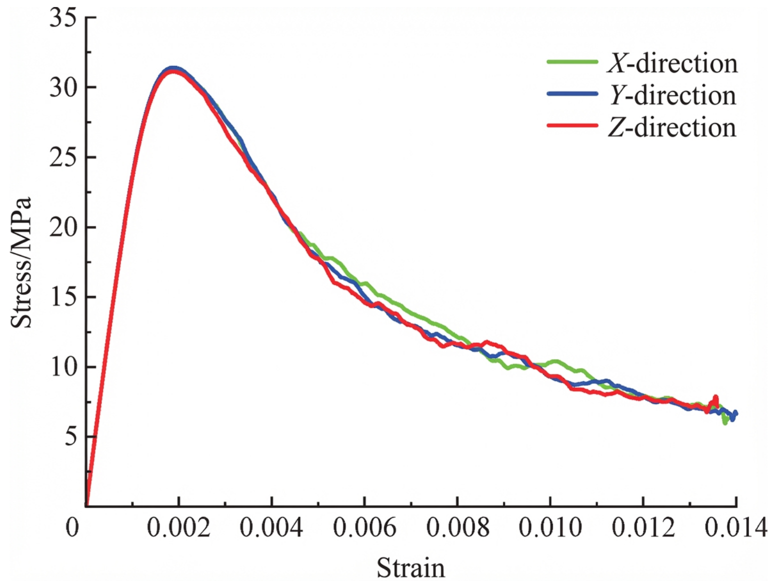


Figure 6: Figure 11

The above conclusions are based on the irradiation field data and IG-110 graphite material performance data provided in this study. These data can be readily replaced during subsequent high-temperature reactor development and design processes.

This study derived analytical stress expressions for simplified high-temperature gas-cooled reactor reflector graphite structures and developed a UMAT-based numerical program for graphite structural stress calculation. The analytical and numerical solutions show good agreement. The research examined the effects of temperature, irradiation strain, and creep on stress fields and structural deformation in graphite components, providing methodology and insights for evaluating high-temperature reactor graphite structure stress responses. Future research can investigate deformation responses of individual reflector components under combined high temperature, irradiation, and creep. Specific conclusions are as follows:

1. The derived analytical solution for simplified reflector structures is applicable for analyzing parameter effects such as temperature and irradiation dose. The developed finite element program can be applied to complex structural stress calculations, providing accurate and efficient results.

2. During the 30-year operational cycle of high-temperature gas-cooled reactors, high temperature, irradiation, and creep significantly influence IG-110 graphite structural stress levels, particularly during later operational stages. Circumferential and axial stresses in IG-110 graphite struc-

tures exhibit similar variation trends with time, temperature, and neutron dose, reaching peak values before gradually decreasing with increasing irradiation dose. Radial stress is zero at the inner and outer walls, with its absolute value first increasing then decreasing with radius, reaching a maximum at the mid-radius position.

3. Seismic design of graphite cores should consider deformations caused by temperature, irradiation, and creep effects on structural clearances.

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Figures

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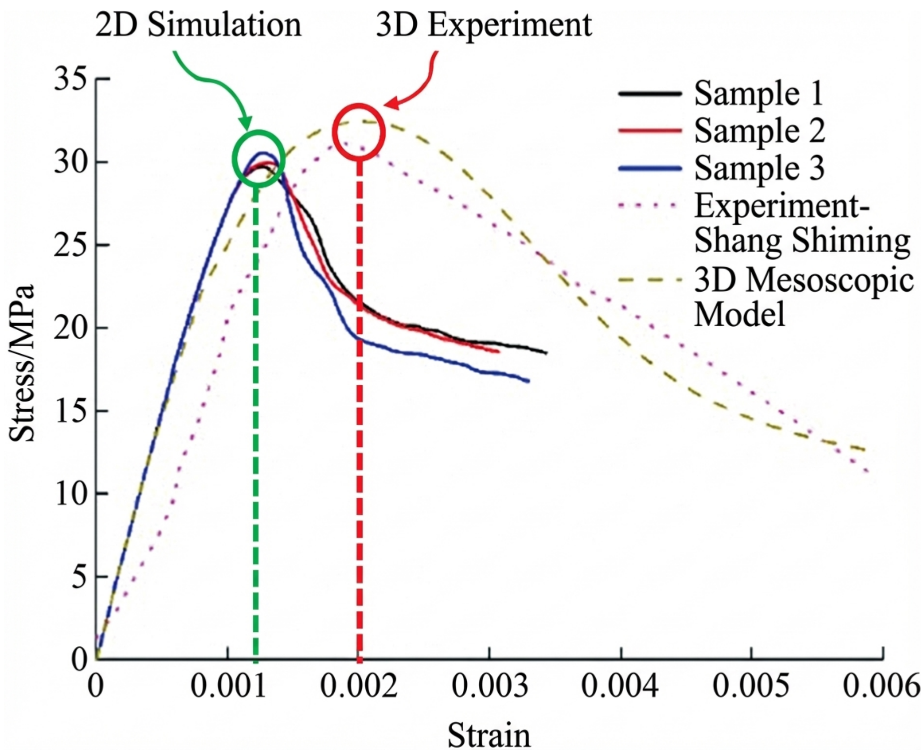

Figure 7: Figure 1