Preliminary Seismic Analysis of Graphite Core for Gas-Cooled Microreactor

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Abstract

To evaluate the structural safety of the graphite core in gas-cooled microreactors and obtain the stress state of core graphite components under seismic excitation, this study compared acceleration and velocity curves from small-scale graphite block collision experiments with simulation results. The results show that the simulation can reflect the collision behavior of graphite blocks, and that collision stiffness and damping parameters can be identified from the acceleration and velocity curves. Based on the key stiffness and damping parameters obtained from experiments, simulations of core graphite components were carried out and applied to the seismic analysis of the reactor core. Finally, computational simulations of the full-core model were performed to obtain the interaction forces between graphite components, and the structure was evaluated using a failure probability method. The results indicate that the graphite core meets the ASME design code requirements under seismic loading.

Full Text

Preamble

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Preliminary Study on Seismic Analysis of Graphite Cores for Gas-Cooled Microreactors

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Abstract

[Background]: Graphite is a critical structural material in high-temperature gas-cooled reactors. Ensuring its integrity under seismic loading is essential for core safety. **[Purpose]:** This study aims to evaluate the seismic response of a gas-cooled microreactor core and verify its compliance with the ASME design code. **[Methods]:** Collision tests and simulations of small-sized graphite blocks were conducted to identify stiffness and damping parameters. A simplified core model with equivalent spring-damper elements was established and analyzed through time-history simulations. **[Results]:** The Kelvin collision model effectively captured graphite block interactions, with stiffness ranging from 1.70×10^{9} to 2.20×10^{9} N/m for collision angles of 0.02°-0.05°. The maximum collision force between graphite components reached 1.21×10^{5} N. Stress evaluation based on the Weibull distribution indicated a failure probability below 0.5% under design-level seismic loads. **Conclusions:** The proposed stiffness-equivalent method provides an efficient approach for simulating nonlinear core behavior, confirming the structural safety of the graphite core under seismic conditions.

Keywords: Graphite core; Seismic analysis; Stiffness; Damping; Failure probability

Introduction

Since its first application in the CP-1 (Chicago Pile-1) reactor in 1942, the structural integrity of nuclear graphite has remained a central issue in reactor safety research [1]. The development of fourth-generation Very High Temperature Reactors (VHTR) has further highlighted the importance of seismic performance in graphite cores [2]. In high-temperature gas-cooled reactors, graphite serves as the primary material for core structures such as reflectors and moderators [3]. Ensuring graphite integrity is crucial for overall core safety. Due to the nonlinear pin-key matching contact connections between graphite blocks, the entire structure can be regarded as a multi-body system that exhibits complex nonlinear dynamic characteristics under seismic loading, forming a coupled system of multi-body nonlinear forces and deformations [4]. Reliable experimental data are required to validate and support numerical simulations during structural seismic design. However, due to limitations in model size, mass, cost, and experimental facilities, tests often employ scaled or partial models for comparison with numerical models. Ikushima et al. [5-6] and Iyoku et al. [7] conducted seismic test evaluations on hexagonal graphite blocks used in high-temperature gas-cooled reactors, covering various model types including 1:2 scale single-column models, partial planar models, and vertical/horizontal section models. Theymann et al. [8] performed experimental studies to assess the seismic stability of pebble bed cores, including 1:2 scale side reflector models, 1:3 scale side reflector models, and 1:6 scale cylindrical core models. To verify structural safety under seismic conditions, China' s High Temperature Test Reactor (HTTR) conducted a series of tests. Sun Libin et al. [9] performed seismic studies on 1:2 scale double-layer structural models to examine deformation patterns and analyze primary factors affecting the dynamic characteristics of graphite structures. Tian Qing et al. [10] tested single-column graphite models to obtain fundamental frequencies and damping characteristics. Lai Shigang et al. [11] validated and optimized computational programs based on full-scale double-layer four-brick graphite assembly tests. Wang Dexin et al. [12] designed a 1:4 scale overall model of the graphite core support structure, analyzed dynamic characteristic data from seismic tests, and verified that the support structure met safety requirements. For large and heavy core structures, existing methods study local dynamic characteristics first, then extrapolate to obtain the global model response under seismic excitation.

The gas-cooled microreactor core employs graphite materials for both fuel assembly and reflector structures. Nuclear graphite features high purity, thermal conductivity, irradiation stability, and thermal oxidation resistance, along with low thermal expansion coefficient and low elastic modulus to avoid significant thermal stress. With high neutron scattering cross-section, low neutron absorption cross-section, excellent high-temperature mechanical properties, and good neutron irradiation resistance, graphite is an appropriate moderator material. Its material properties, influenced by manufacturing processes, exhibit brittle or quasi-brittle behavior [13-14]. During manufacturing, raw material grain characteristics, high-temperature carbonization and graphitization environments, and cooling processes leave approximately 20% porosity in the final product [15], causing strength dispersion in graphite materials. Probabilistic methods are therefore more suitable than deterministic approaches for failure evaluation. Under irradiation, graphite volume first contracts then expands, affecting component clearances which in turn influence structural collisions. Consequently, seismic analysis must address two key characteristics: graphite volume changes in irradiation environments and material strength dispersion. This study incorporates irradiation-induced volume contraction into component clearances and employs the Weibull distribution model from ASME codes to account for material dispersion effects in structural integrity assessment.

The graphite core structure is a critical component in nuclear reactors, and its seismic performance is vital for safe operation. During seismic events, graphite components may collide with each other or with the reflector, potentially causing cracks or loss of support function. Therefore, safety assessment of the gas-cooled microreactor core structure is necessary. Previous research has primarily focused on vertical core structures, with limited studies on horizontal configurations. The gas-cooled microreactor features a horizontal stacked structure with pin-key connections between graphite components and existing gaps. Seismic loading induces numerous contact collisions throughout the core. Such problems are often simplified in numerical simulations due to excessive computational demands, typically reduced to multi-rigid-body dynamics problems with springs and dampers. This paper presents seismic analysis calculations for a horizontal core structure, establishing a stiffness-equivalent model through combined parameter identification experiments and simulations, performing seismic time-history analysis, and conducting preliminary investigations into core structural response.

1. Core Structure Description

The gas-cooled microreactor core adopts a horizontal arrangement, primarily consisting of three layers of hexagonal graphite blocks with 31 components per layer, as shown in [Figure 1: see original paper]. Layers are positioned through pin-key connections, with radial constraints provided by the reflector and axial constraints by front and rear reflectors. The reflector is preloaded with springs, though this preload condition is conservatively ignored in seismic calculations. The core structure connects to a metal container through binding straps, though the metal container and reflector are not considered in this study.

2. Theoretical Methods

Graphite cores experience collisions under seismic excitation. For discrete masonry systems, establishing a complete elastoplastic collision numerical model for the entire core is typically impractical due to high computational costs associated with contact identification between graphite blocks and the resulting model degrees of freedom. Engineering applications require simplified equivalent models that capture overall structural response through contact collision relationships between graphite blocks and pin-key connections. Common continuous contact force models include linear elastic, Kelvin, Hertz, and Hertz-damp models [16].

According to classical collision theory, the relationship between contact force F and collision gap can be described as:

$$ddd \tag{2.1}$$

where k and c represent the equivalent stiffness and damping between colliding bodies, e is the coefficient of restitution, $0d¢$ is the initial relative velocity, d is the relative displacement during collision, and $d¢$ is the relative velocity of colliding objects. Different values of n and m represent different collision models. When $n = 1$ and $m = 0$, the equation represents the Kelvin-Voight model. Adjusting k can align the identified contact time with experimental results, yielding appropriate equivalent stiffness k and damping c.

(2.2)

The primary experimental objective is to obtain acceleration and velocity variations during graphite block collisions, determine collision duration and pre-/post-collision relative velocities, and identify contact model parameters. Acceleration data are acquired from accelerometers mounted on graphite blocks, while velocity data come from acceleration integration. The test apparatus is shown in [Figure 2: see original paper], with the excitation mechanism on the left and the collision block on the right. A pendulum connected to a parallelogram structure is released from a certain height to impact the active block specimen, imparting initial velocity for collision with the passive block. Both blocks are placed on sliding rails to minimize friction effects. Buffer pads behind the blocks ensure safety after collision.

To investigate potentially suitable oblique collision angles, finite element simulations were conducted for various cases with oblique angles of 0.01-0.1°, maintaining model dimensions consistent with experiments. Graphite material parameters used in the analysis are listed in .

Table 1 Mechanical parameters of graphite

Parameter	Value
Young' s Modulus (Pa)	9.6$×10^{9}$
Poisson' s ratio	-
Density ($kg \cdot m^{-3}$)	1.8$×10^{3}$

Comparative results for collision acceleration and velocity curves are presented in [Figure 3: see original paper] and [Figure 4: see original paper] (P denotes passive block, A denotes active block). At small oblique angles (below 0.05°), no distinct dual acceleration peaks appear, while 0.08° and 0.1° cases exhibit two peaks. Smaller oblique angles approach ideal head-on collision results, as seen in 0.01° and 0.02° cases. The 0.05° case shows consistent contact time between simulation and experiment, though acceleration peak differences remain significant. During acceleration measurement, peak values differ due to discrepancies between measurement point acceleration and simulated centroid acceleration, whereas contact time demonstrates greater stability and better represents the contact stiffness level of colliding blocks. Therefore, contact time is adopted for stiffness identification. While head-on collisions are idealized, actual collisions primarily involve line contact or local point contact. Consequently, the 0.05° oblique collision case becomes the primary focus for subsequent simulation analysis and parameter identification based on simulation data.

The results in [Figure 3: see original paper] and [Figure 4: see original paper] demonstrate that simulations can capture collision processes, though certain errors persist. The penalty function contact algorithm employed assumes a linear relationship between contact force and penetration. Excessive contact stiffness overestimates force peaks, while insufficient stiffness introduces non-physical penetration. Friction behavior is not considered in simulations, being simplified and incorporated into damping effects. Fixture stiffness and sensor installation factors in experiments are not precisely modeled, leading to idealized simulation boundary conditions. Actual collisions involve certain angles, as perfectly head-on collisions are rare in practice, and collision angle affects both experimental and simulation results. However, parameter optimization can make simulation results approach or remain conservative relative to experimental results, satisfying engineering design requirements.

2.2 Parameter Identification

Based on collision experimental and simulation conclusions, finite element simulations were used to identify collision stiffness and damping parameters. This method was applied to graphite component collisions to provide input for core calculations.

Drawing from graphite cube collision simulation and experimental comparison results, elastic model collision simulations for hexagonal graphite cores were conducted considering small-angle oblique collisions. Ten simulation cases were performed at 0.01° intervals from 0.01° to 0.1°, with collision schematics shown in [Figure 5: see original paper]. Simulation trends align with graphite cube results: as collision angle increases, contact time extends, acceleration peaks decrease, and post-collision relative velocity reduces, as shown in Figure 6: see original paper. Figure 6: see original paper indicates that except for 0.09° and 0.1° cases where post-collision relative velocities fall below head-on oblique collision values, oblique collision results generally lie between head-on and head-on oblique cases.

Detailed data are summarized in . Based on collision test data, head-on collisions rarely occur during actual graphite component movement. Therefore, average values from 0.02–0.05° collision angles are adopted as stiffness and damping parameters. Smaller collision angles yield larger equivalent stiffness, making these values more conservative.

Table 2 Equivalent parameters for hexagonal graphite core collisions

Angle(°)	Max collision force (N)	Max acceleration (m/s^2)	Impact time (ms)	Coefficient of restitution	Equivalent stiffness (N/m)	Equivalent damp (Ns/m)
0	1.684×10^{5}		-	-	2.96×10^{9}	
0.01	1.545×10^{5}		-	-	2.50×10^{9}	
0.02	1.446×10^{5}		-	-	2.20×10^{9}	
0.03	1.376×10^{5}		-	-	2.05×10^{9}	
0.04	1.288×10^{5}		-	-	1.86×10^{9}	
0.05	1.211×10^{5}		-	-	1.70×10^{9}	
0.06	1.157×10^{5}		-	-	1.62×10^{9}	
0.07	1.079×10^{5}		-	-	1.50×10^{9}	
0.08	0.9881×10^{5}		-	-	1.32×10^{9}	
0.09	0.9347×10^{5}		-	-	1.22×10^{9}	
0.10	0.8981×10^{5}		-	-	1.15×10^{9}	
45	0.4485×10^{5}		-	-	0.28×10^{9}	

3. Stiffness-Equivalent Method

3.1 Stiffness Equivalence

To improve computational efficiency, a simplified model of the gas-cooled microreactor structure was established using a rigid-body model to capture responses under seismic excitation, including forces, displacements, and velocities. Graphite bricks have a hexagonal prism structure with holes and keys on their upper and lower surfaces, as shown in [Figure 7: see original paper]. Horizontal displacement of graphite blocks is constrained by adjacent blocks and keys, though keys have limited load-bearing capacity and primarily serve installation and positioning functions. The simplification represents each graphite block as a central mass point connected to rigid beams, ignoring local stress and flexibility. This approach reduces model degrees of freedom while capturing overall displacement, velocity, and acceleration responses, enabling extraction of interaction forces between rigid graphite blocks for subsequent local stress analysis.

In the simplified rigid-body model, springs, dampers, and gaps characterize graphite component collisions. Two primary contact modes exist: block-to-block collisions and pin-hole collisions between keys and holes. [Figure 8: see original paper] illustrates the equivalent element representation for block-to-block collisions, where connections are implemented through contact elements that only resist compression.

3.2 Irradiation Deformation Effects

Graphite components feature contact connections with 预留 gaps to accommodate thermal expansion during high-temperature operation. However, with increasing neutron fluence over the operational lifetime, graphite undergoes physical changes of initial contraction followed by expansion. Structural contraction creates gaps detrimental to seismic performance, necessitating estimation of maximum clearances between components. Based on design neutron fluence, user-defined subroutines were developed to define graphite deformation behavior under neutron irradiation. The neutron fluence distribution expression is:

$$N(x, y, z, t) = (0.136 + 1.605t - 2.36t^2 - 2.36t^3) \times 10^{25} \text{ n/m}^2 \tag{3-1}$$

where x, y, z represent core spatial coordinates, t is operational years (<30 years), and N denotes neutron fluence in dpa. For fast neutrons with $E > 1$ MeV, approximately 1×10^{25} n/m^2 corresponds to 1 dpa of irradiation damage. [Figure 9: see original paper] shows the neutron fluence field in a column of hexagonal graphite prisms.

Assuming irradiated graphite as a linear viscoelastic material, total strain comprises elastic strain, steady-state creep strain (secondary creep), transient creep strain (primary creep), and combined thermal/irradiation strain. For IG110 graphite mechanical properties, the constitutive model expression is derived based on Hooke' s law and material property fitting formulas from literature [17] regarding IG110 performance under neutron irradiation. Calculations require only pre-irradiation elastic modulus E, Poisson' s ratio ν, and thermal expansion coefficient α, with multiple state variables storing and updating elastic modulus and irradiation dose at each increment. The Jacobian matrix and stress components are continuously updated throughout the calculation cycle, yielding stress results for the entire graphite structure. The computational flowchart is shown in [Figure 10: see original paper].

Using the custom subroutine, maximum graphite component deformation was calculated, as shown in [Figure 11: see original paper]. The maximum displacement between Node 1 and Node 2 is 1.895 mm, leading to a conservative top clearance determination of 2 mm.

[Figure 12: see original paper] illustrates the gap configuration for a horizontal graphite core structure, consisting of seven layers with 31 graphite components. The upper core edge gap is 2 mm, the lower core edge gap is 1 mm, and fuel assembly gaps are 1 mm.

The graphite core was modeled using ANSYS 18.0 commercial finite element software, employing rigid beam element MPC184 and contact element CONTA178. Graphite component weights (including fuel) of 30 kg each were concentrated at central mass point elements MASS21. Boundaries connect to fixed constraints through contact elements. Equivalent parameters for relevant components are listed in , reducing the discrete core structure to a mass-spring-damper system.

Table 3 Input parameters

Part	Equivalent stiffness (N/m)	Equivalent damp (Ns/m)
Brick-Brick	1.95$×10^{9}$	-
Pin-Hole	0.11$×10^{9}$	-

3.3 Simplified 3D Model

Following simplification principles, the graphite core structure was reduced to an equivalent model comprising three layers of rigid-body elements, as shown in [Figure 13: see original paper]. Each layer contains 31 graphite components, with axial, lateral, and pin-hole connections represented through simplified stiffness and damping elements.

4. Analysis Results

Time-history analysis was performed on the simplified 3D core model using the acceleration response shown in [Figure 14: see original paper], obtained from the metal container model. Correlation coefficients between the three directional seismic time histories are below 0.3, with peak accelerations below 0.3g.

Interaction forces between graphite blocks were extracted from contact elements. [Figure 15: see original paper] shows the collision forces at 10.22 s when maximum interaction occurs. By extracting these contact forces, static strength analysis of graphite components can be performed.

5. Stress Evaluation

Graphite component failure analysis employs a probabilistic failure model that uses a modified volume-normalized Weibull weakest-link failure criterion. Each group is treated as a single chain to predict failure probability under given stress states. This criterion combines the volume normalization method proposed by Schmidt et al. [18] and the failure probability calculation model by Hindley et al. [19], suitable for coarse-grained nuclear graphite failure prediction.

Parameters for the three-parameter Weibull distribution function were estimated based on unidirectional tensile strength-failure probability curves from experimental data:

$$P_f = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_c}\right)^m\right] \tag{5.1}$$

where P_f is failure probability, σ is equivalent stress, m is shape parameter, σ_c is characteristic strength, and σ_0 is threshold strength. Parameters m, σ_c, and σ_0 are called Weibull three parameters.

Maximum equivalent stress during graphite lifetime must be less than allowable stress corresponding to the required reliability and load levels, which are determined per ASME D5 [20]. Equivalent stress is defined as:

$$\sigma_{eq} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_1\sigma_3 - \sigma_2\sigma_3} \tag{5.2}$$

where σ_i $(i = 1, 2, 3)$ are principal stresses. The coefficient α_i equals 1 for tensile stress and equals the ratio of average compressive strength to average tensile strength for compressive stress.

A UVARM subroutine was developed to output element equivalent stress variables. Applying uniformly distributed pressure on graphite surfaces yields equivalent stress distribution, as shown in [Figure 16: see original paper]. After calculating the stress field using finite element methods, principal stresses σ_i and integration point volumes v are output. Within the effective volume, integration point volumes and stresses are processed per ASME requirements. First, volume grouping is performed where the total volume of Group I should be greater than $(10 \times d_{\max})^3$, with $d_{\max}$ being the maximum grain size of the nuclear graphite. Stress gradients are then limited to less than 7% within each group. The calculated failure probability is 0 under 1 kN collision force. Failure probabilities at different collision forces are shown in [Figure 17: see original paper], revealing that failure probability exceeds 0.5% when collision force surpasses 35 kN.

Conclusions

This study employed a stiffness-equivalent method to simplify the model, conducted graphite block collision tests to obtain stiffness and damping parameters, and simulated multi-body motion responses of graphite. The approach successfully captured graphite displacement, velocity, and interaction forces while significantly reducing computational time. Final stress evaluation confirmed that graphite strength meets ASME code requirements. Key conclusions are:

1) Perfect head-on collisions rarely occur in practice; actual collisions involve small angles. Graphite collision tests demonstrated that the Kelvin model can simulate collision processes and provide stiffness-damping parameters.

2) Stiffness and damping parameters can be identified through acceleration and velocity curves from block collisions. Data from hexagonal graphite brick elastic model simulations were extrapolated to obtain stiffness and damping parameters.

3) A global core model was established to extract interaction forces between graphite components under seismic loading. Local static analysis of graphite blocks confirmed that graphite strength satisfies ASME code requirements.

Author Contributions

Lan Tianbao: Simulation computation, data analysis, experimental guidance, and manuscript writing. Feng Tianyou: Experiment execution and data processing. Huang Zhong: Research conceptualization and theoretical guidance. Sheng Feng: Modeling guidance, project supervision, and review.

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