Supprting Information

Verification of the UMAT subroutine

To ensure the correctness of the developed UMAT subroutine, this paper validated the simulation program using both two-dimensional and three-dimensional elements. The following section describes the validation process using a three-dimensional element as an example. As shown in Figure S1, a uniformly distributed load $\sigma_{xx}=1\ \mathrm{N/mm^2}$ was applied to the plane at x = 1 mm using a single three-dimensional solid element. The element temperature was set to 500°C, with an irradiation dose rate of 20×10²⁰ n/cm²/fpy EDND (fpy, full power year). The Poisson's ratio of graphite material is 0.2, with an unirradiated dynamic Young's modulus of $E_{\mathrm{d}}^{0}=10\ \mathrm{GPa}$ and an irradiated static Young's modulus of $E_{\mathrm{s}}=19.7531\ \mathrm{GPa}$. The total simulation duration is set to 1 fpy, with a time step of 1 fpy, meaning only one step is simulated. After simulation completion, the results for each parameter represent its change over one time step.

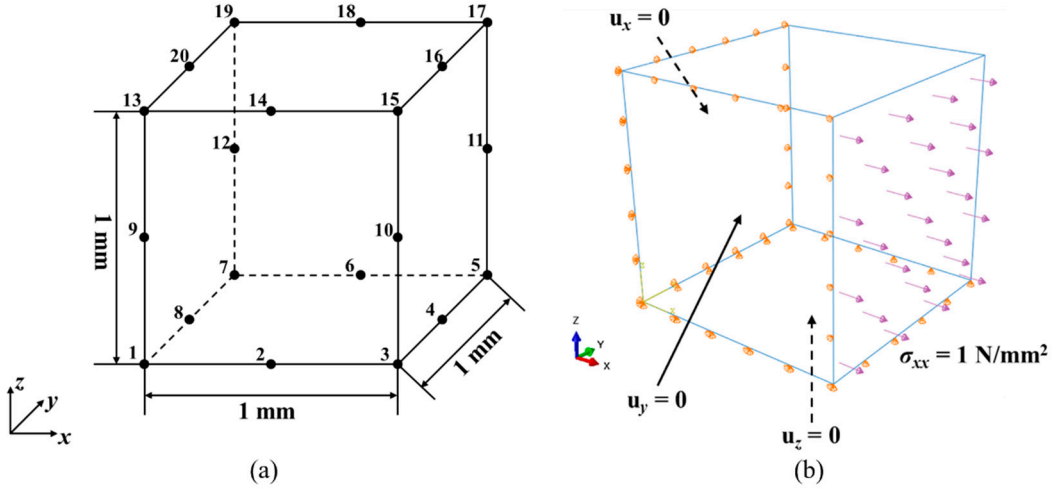


Figure S1. Single three-dimensional solid element. (a) Element geometry and node numbering; (b) Element boundary conditions and load settings.

（1）For the solid element in Figure A1, the relationship between strain and stress is:

$$\begin{aligned}\varepsilon_{xx}&=\frac{\sigma_{xx}-\nu\left(\sigma_{yy}+\sigma_{zz}\right)}{E_{\mathrm{s}}}\\ \varepsilon_{yy}&=\frac{\sigma_{yy}-\nu\left(\sigma_{xx}+\sigma_{zz}\right)}{E_{\mathrm{s}}}\\ \varepsilon_{zz}&=\frac{\sigma_{zz}-\nu\left(\sigma_{yy}+\sigma_{xx}\right)}{E_{\mathrm{s}}},\end{aligned}\tag{S1}$$

There are no loads in the y and z directions, i.e., $\sigma_{yy}=0$ and $\sigma_{zz}=0$. Thus, the total strain can be calculated as:

$$\varepsilon_{xx}=\frac{\sigma_{xx}}{E_{\mathrm{s}}}=5.0625\times10^{-5},\ \varepsilon_{yy}=\varepsilon_{zz}=\frac{-\nu\sigma_{xx}}{E_{\mathrm{s}}}=-1.0125\times10^{-5},\tag{S2}$$

The displacement of nodes at different positions can then be calculated.

（2）$t_0=0$,temperature $T=500\ ^{\circ}\mathrm{C}$, irradiation dose $\gamma=0$. Interpolation of irradiation experimental data yields the corresponding dynamic Young's modulus, CTE, and thermal strain:

$$\begin{aligned}E_{\mathrm{d0}}&=E_{\mathrm{d}}^{0}\times1.6125\times1=16.125\ \mathrm{GPa},\\ \varepsilon_{0}^{\mathrm{th}}&=\alpha_{(T_{\mathrm{ref}}-T)}\times\left(T-T_{\mathrm{ref}}\right)=4.0000\times10^{-6}\times480=1.9200\times10^{-3},\end{aligned}\tag{S3}$$

（3）$t_1=1$ fpy，$\Delta t=1$；$\gamma_1=\Delta\gamma=20\times10^{20}\ \mathrm{n/cm^2}$；$T=500\ ^{\circ}\mathrm{C}$，$\Delta T=0$。

Interpolation of irradiation test data yields the elastic modulus and creep modulus at this dose and temperature as follows:

$$E_{d1} = E_d^0 \times 1.6125 \times 9.7743 \times 10^{-1} = 15.761 \text{ GPa}, E_c = 9.1106 \text{ GPa}, \quad \text{(S4)}$$

and can calculate dimensional strain, thermal strain, and their increments:

$$\Delta\varepsilon^{dc} = \varepsilon_1^{dc} = -1.5616 \times 10^{-3}, \Delta\varepsilon^{th} = \varepsilon_1^{th} - \varepsilon_0^{th} = 2.7565 \times 10^{-3} - 1.9200 \times 10^{-3} = 8.365 \times 10^{-4}, \quad \text{(S5)}$$

based on experimental data interpolation and $x = x_i + \Delta x/2$, we can calculate $\Delta\boldsymbol{\varepsilon}_1^e$:

$$\Delta\boldsymbol{\varepsilon}^e = \left[\mathbf{I} + \Delta\gamma\left(\frac{1}{1+2\Delta\gamma} + \frac{\zeta}{4}\right)\left(2\mathbf{D}_c^0\mathbf{D}^0 + \mathbf{D}_c^0\Delta\mathbf{D}\right)\right]^{-1} \times\left[\Delta\boldsymbol{\varepsilon}^{total} - \Delta\boldsymbol{\varepsilon}^{th} - \Delta\boldsymbol{\varepsilon}^{dc}\right], \quad \text{(S6)}$$

Subsequently, the values of $\Delta\varepsilon^{pc}$ and $\Delta\varepsilon^{sc}$ were calculated. The comparison between the theoretical calculation results and the ABAQUS simulation results is shown in Tables S1 and S2. It can be observed that the increment values of displacement and strain components at each node, calculated through the aforementioned process, closely match the simulation results. This indicates that the UMAT subroutine developed in this paper is correct and has been properly invoked within the ABAQUS main program simulation. It can be utilized for subsequent finite element simulations of nuclear graphite components.

Table S1. Displacement values at each node

Node number	u_x (10^{-5} mm)		u_y (10^{-5} mm)		u_z (10^{-5} mm)	
	Theoretical value	**Simulated value**	**Theoretical value**	**Simulated value**	**Theoretical value**	**Simulated value**
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	2.5313	2.5314	0.0000	0.0000	0.0000	0.0000
3	5.0625	5.0627	0.0000	0.0000	0.0000	0.0000
4	5.0625	5.0627	-0.5063	-0.5063	0.0000	0.0000
5	5.0625	5.0627	-1.0125	-1.0125	0.0000	0.0000
6	2.5313	2.5314	-1.0125	-1.0125	0.0000	0.0000
7	0.0000	0.0000	-1.0125	-1.0125	0.0000	0.0000
8	0.0000	0.0000	-0.5063	-0.5063	0.0000	0.0000
9	0.0000	0.0000	0.0000	0.0000	-0.5063	-0.5063
10	5.0625	5.0627	0.0000	0.0000	-0.5063	-0.5063
11	5.0625	5.0627	-1.0125	-1.0125	-0.5063	-0.5063
12	0.0000	0.0000	-1.0125	-1.0125	-0.5063	-0.5063
13	0.0000	0.0000	0.0000	0.0000	-1.0125	-1.0125
14	2.5313	2.5314	0.0000	0.0000	-1.0125	-1.0125
15	5.0625	5.0627	0.0000	0.0000	-1.0125	-1.0125
16	5.0625	0.0000	-0.5063	-0.5063	-1.0125	-1.0125
17	5.0625	5.0627	-1.0125	-1.0125	-1.0125	-1.0125
18	2.5313	2.5314	-1.0125	-1.0125	-1.0125	-1.0125
19	0.0000	0.0000	-1.0125	-1.0125	-1.0125	-1.0125
20	0.0000	0.0000	-0.5063	-0.5063	-1.0125	-1.0125

Table S2. Incremental values of each strain component

Strain type	*x*-direction		*y*-direction		*z*-direction	
	Theoretical value	**Simulated value**	**Theoretical value**	**Simulated value**	**Theoretical value**	**Simulated value**
$\Delta\varepsilon^{th}$ (10^{-3})	2.7565	2.7565	2.7565	2.7565	2.7565	2.7565
$\Delta\varepsilon^{dc}$ (10^{-3})	-1.5616	-1.5616	-1.5616	-1.5616	-1.5616	-1.5616
$\Delta\varepsilon^{e}$ (10^{-4})	1.1651	1.1654	1.0738	1.0741	1.0738	1.0741
$\Delta\varepsilon^{pc}$ (10^{-4})	1.9639	1.9634	1.8101	1.8097	1.8101	1.8097
$\Delta\varepsilon^{sc}$ (10^{-4})	4.6300	4.6288	4.2674	4.2663	4.2674	4.2663