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FAILURE SIMULATION OF A VHTR CORE REFLECTOR BRICK

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ABSTRACT

The core of a Very High Temperature Reactor (VHTR) is made up of nuclear graphite components. When exposed to neutron irradiation, the physical properties and dimensions of graphite change, leading to the development of stresses inside the reactor core components which may cause them to fail by cracking. The present work focuses on modeling such failure in a prismatic reactor core reflector brick. An ABAQUS-based user material (UMAT) subroutine was developed for modeling the mechanical behavior of graphite under irradiation and predicting the stress distribution within the component. In parallel with the stress analysis, failure of the brick was simulated using the Extended Finite Element Method (XFEM) in ABAQUS. The results shed light on the possible lifetime, failure location and crack propagation in nuclear graphite components.

INTRODUCTION

Due to its excellent mechanical and thermal properties, nuclear graphite is used in the VHTR core where it serves as a neutron moderator, reflector as well as structural material. When exposed to fast neutron irradiation, graphite undergoes dimensional and physical property changes which may restrict the movement of control rods through the core and produce stresses that undermine the latter's structural integrity. Thus, it is imperative to assess the level of irradiation-induced stresses and the likelihood of failure in VHTR graphite components.

Efforts have been made to assess the structural integrity of graphite bricks. For example, Yu et al. (2004) used the finite element method (FEM) to compute stresses in a HTR-10 (a test reactor of the pebble bed design) reflector brick and evaluated the failure probability using the Weibull model (Weibull 1939, 1951). Li et al. (2008) conducted an analytical study on the axial and hoop stresses in a hypothetical cylindrical moderator brick undergoing dimensional changes induced by irradiation. Tsang and Marsden (2006) presented a constitutive model which described the complex behavior of graphite under irradiation. Mohanty et al. (2012) developed a finite element code for performing coupled thermal-structural analysis of graphite core components under high temperature and irradiation conditions. The present authors are using the user-subroutine feature of ABAQUS to evaluate the integrity of VHTR nuclear graphite core components.

METHOD

The work presented in this paper focuses on the numerical prediction of the stress distribution in a prismatic reactor core reflector brick (Fig. 1) and its subsequent failure on a common computational platform. The work involved the development of a UMAT, which is a user material subroutine in the commercial finite element software ABAQUS for the prediction of irradiation-induced stresses. The stress prediction process was combined with the Extended Finite Element Method (XFEM) in the same software to simulate failure of the component. The simulation covered an operation period of 30 years.

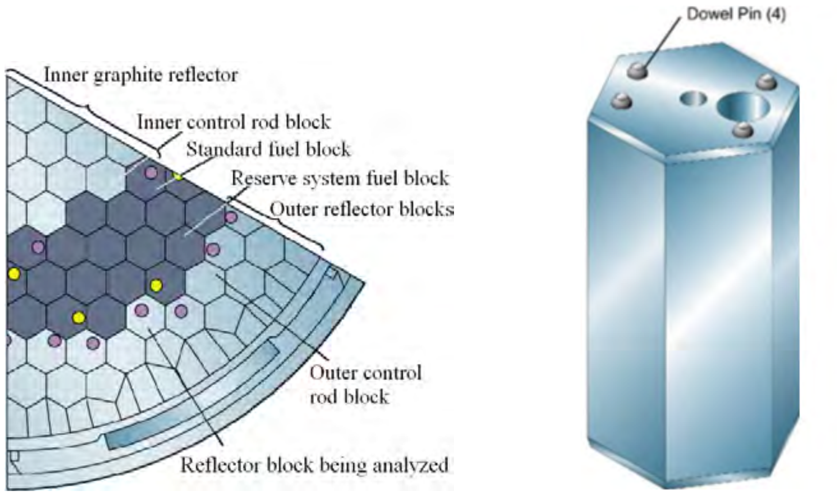

Figure 1: The prismatic reflector brick (right) considered in the failure analysis and its location within the core (left) (source: Bratton (2009)).

To model the prismatic reflector brick with FEM, the plane-stress condition was assumed. The model was meshed with 3625 CPS4 (continuum, plane–stress, bilinear, 4-node) elements and 3756 nodes. Figure 2 shows the finite element (FE) mesh and boundary conditions applied.

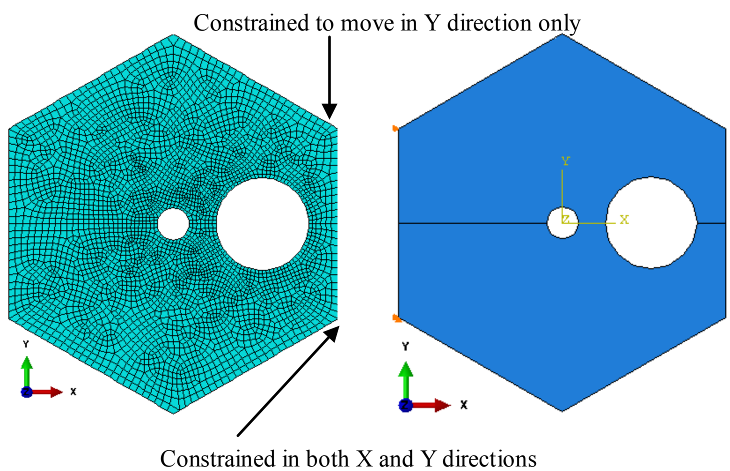

Figure 2: FE mesh (left) and boundary conditions (right) for the reflector brick model.

The irradiation dose distribution was based on the operating conditions for a reflector brick in the Ft. St. Vrain reactor as presented in Bratton (2009). Figure 3 (right) shows the irradiation dose distribution ($x10^{20}$ n/cm^2) at the end of 6 years of operation. The temperature distribution is also shown in Figure 3 (left), which was assumed to remain constant.

The reflector brick was assumed to be made of ATR-2E graphite, the material properties of which were taken from Haad (2005). These properties included the variations of dimensional change strain, coefficient of thermal expansion and Young's Modulus with dose (γ) and temperature. The U.K. creep law was used for incorporating the irradiation-induced creep, i.e.

$$d\varepsilon_c = (0.23/E_c)\int \sigma d\gamma \tag{1}$$

where ε_c is the creep strain, σ the stress and E_c the creep modulus, which was assumed to be a constant.

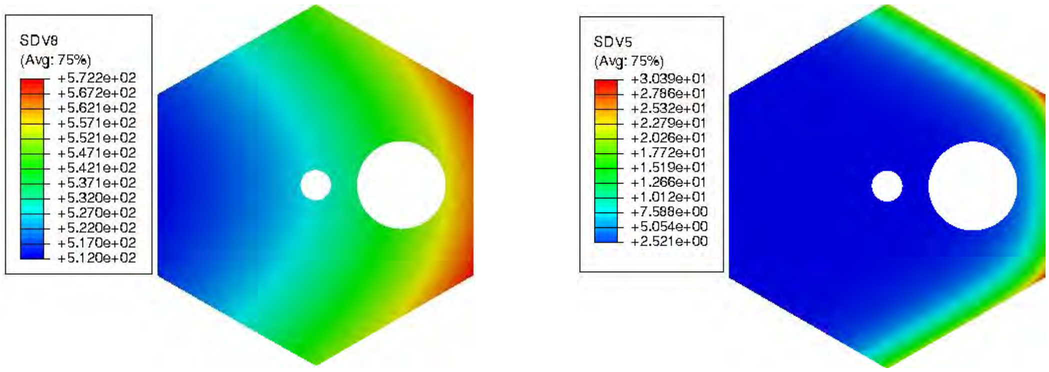

Figure 3: Temperature (°C) distribution (left) and irradiation dose distribution (x10^{20} n/cm^2) (right) in the prismatic reactor core brick at the end of 6 years of operation.

To simulate cracking of the brick with XFEM, the damage initiation criterion was based on the maximum principal stress since graphite is a quasi-brittle material. The damage evolution law selected was based on the critical fracture energy, and the softening law was assumed to be linear. Table 1 lists the two material parameters (damage initiation strength and critical fracture energy) used in the fracture simulation. They were assumed to be constant, so their variation with irradiation was not considered. The critical fracture energy G_{IC} was calculated from K_{IC} according to the Irwin relationship:

$$G = K^2/E \qquad (2)$$

where E is Young's Modulus.

Table 1: The strength, critical stress intensity factor and fracture energy for virgin ATR-2E graphite

Strength (σ_f)	**Critical stress intensity factor (K_{IC})**	**Fracture Energy (K_{IC})**
12. 5 MPa	1.0 MPa√m	110.1 J/m^2

RESULTS

The finite element model was analyzed using ABAQUS Standard. It was found that a crack appeared in the brick after 8.6 years of operation. Figure 4 shows the maximum principal stress distributions in the graphite brick at the end of 2, 4, 6, 8, 8.6 and 10 years. Figure 5 shows the variation of the maximum principal stress with time at several locations in the reflector brick. Figure 6 shows the crack propagation path through the brick.

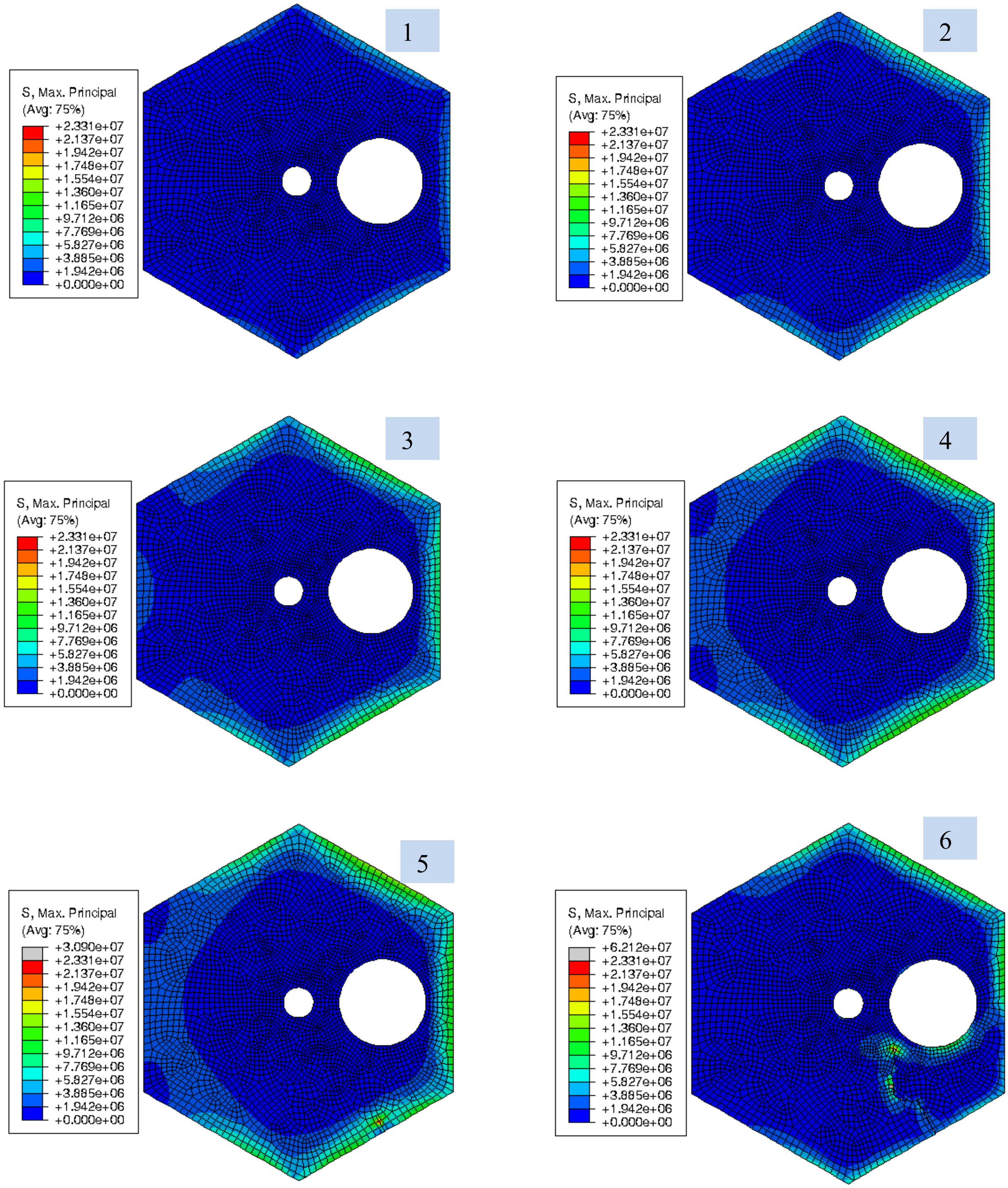

Figure 4: Distribution of the maximum principal stress at the end of 2, 4, 6, 8, 8.6 and 10 years, as shown in pictures numbered 1, 2, 3, 4, 5 and 6, respectively.

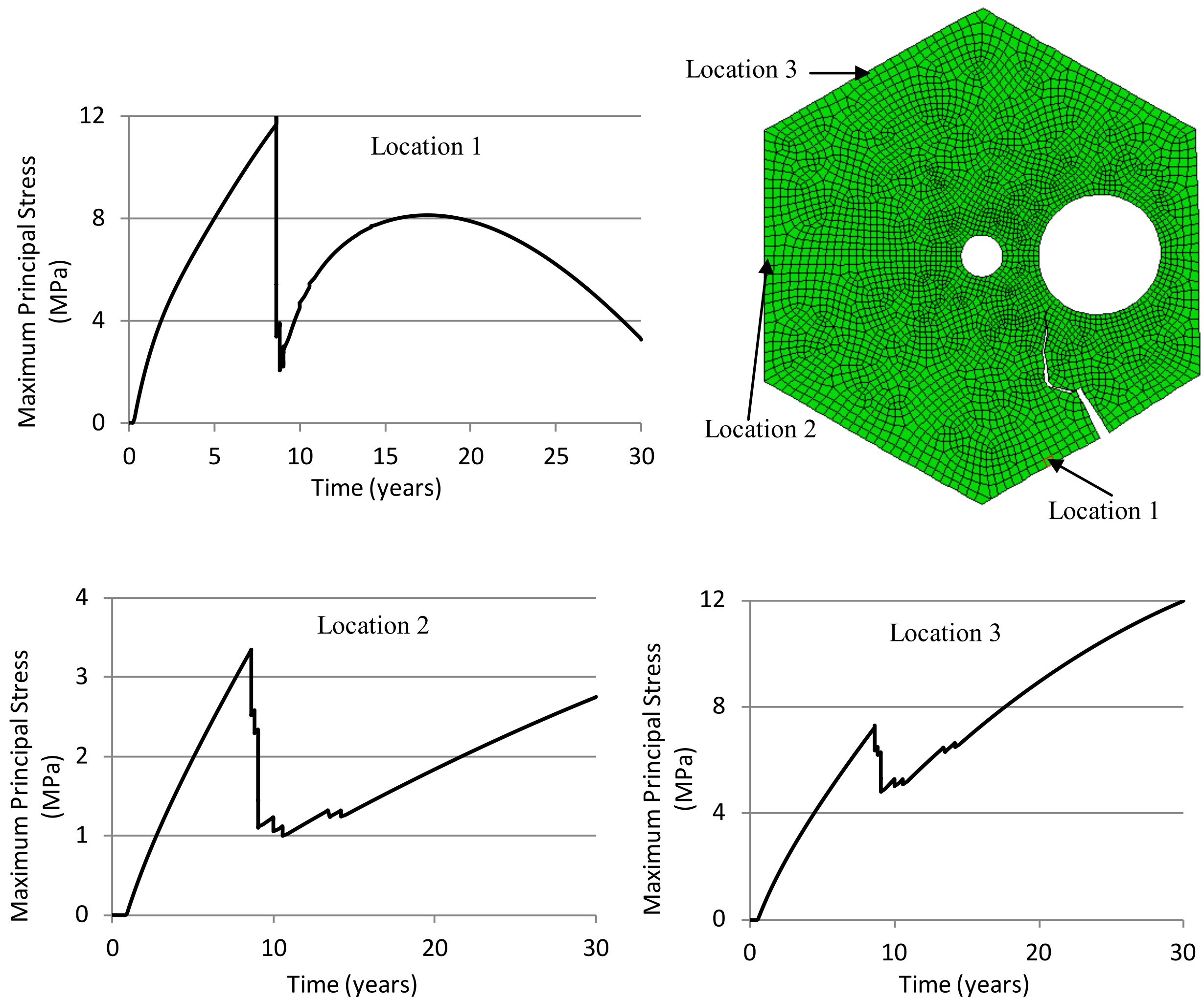

Figure 5: Variation of the maximum principal stress with time at different locations in the brick model.

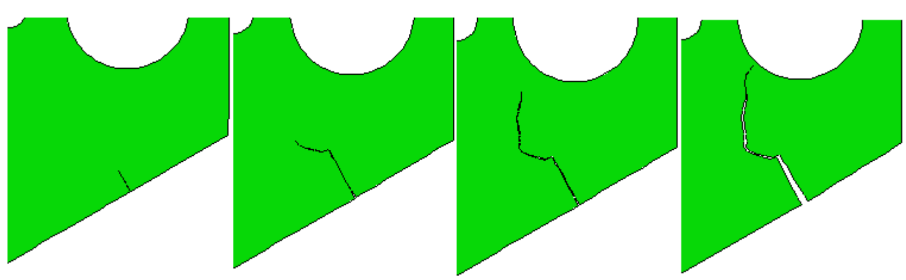

Figure 6: Crack propagation with time in a graphite brick model.

DISCUSSION AND CONCLUSION

Figure 5 shows the variation of the maximum principal stress with time at different locations in the reflector brick. At all these locations the maximum principal stress increased with increasing irradiation. When the crack was initiated, stress was relieved leading to a decrease in the maximum principal stress. The relief in stress was greater for location 1 than locations 2 and 3, which were farther from the crack. After the crack was arrested, the stresses increased again in magnitude. At location 1, a turn-around in the maximum principal stress was observed at around 17 years. This turn-around was not observed at other locations throughout the 30-year operation simulated. This could be attributed to the high irradiation dose at location 1 (see Figure 3) which led to significant changes in the properties and dimensions of graphite and ultimately to such variation of stress in the region. At locations 2 and 3 the irradiation dose was low; therefore, no such turn-around of stress was observed within the simulation period. The life-time of this particular specimen was found to be about 10 years.

It was found that the crack initiated at the right lower edge (shown in Figure 6) of the specimen and propagated towards the control rod channel. Figure 3 shows the presence of a high irradiation-dose gradient near the lower-left boundary of the component which led to the build-up of high stresses in the region and ultimately resulted in cracking. The results indicate that the regions which are near or in contact with the fuel bricks are more susceptible to failure than the other regions. The crack propagation speed was quite high initially and about one-third of the crack path was traversed immediately after the crack initiation. Thereafter, crack propagation was slower and the crack reached the coolant channel in about 1.5 years after its initiation. This indicates that the component may not undergo sudden, rapid failure and the time taken for failure to complete may cover a period of a few years.

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