Determination of Small-Specimen Crack Initiation Behaviour in Nuclear Graphite using Combined Full-Field Strain Measurement and Finite Element Simulation

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Abstract. Operation of graphite moderated nuclear reactors requires predictions of the onset of core cracking. The graphite components have stress-raising features, so quantifying the likelihood that any sharp corners will cause failure is of great significance. Small volumes of the reactor's graphite are extracted for monitoring the changing properties, but no standard technique exists for measuring notch sensitivity in such volumes. A potential geometry is single edge notched beams tested in flexure. A dataset of the failure of over 100 beams with seven notch geometries is created, and analysed by calculating notch sensitivity ratios and testing potential failure criteria. The four-point flexure is monitored in situ with a multi-camera setup and analysed by digital image correlation and finite element simulation implementing both linear and non-linear elastic stiffness models. Notch strengthening factors and notch sensitivity ratios are calculated to compare the analytical and numerical solutions, with favourable comparison to historical results. The adoption of a critical strain energy density failure criterion is also considered.

Introduction

In the UK's advanced gas-cooled nuclear reactors (AGRs) a core of graphite bricks is used for neutron moderation. The bricks are machined with 90° corners with radii of ~1 mm that are believed to be a crack initiation features when tensile stresses are generated during operation [1]. It is vital to accurately predict the crack initiation rate. Currently, structural integrity assessments are conducted using finite element (FE) models to predict peak stresses; fracture is predicted when a fracture criterion such as critical stress is met, assuming the stress concentration behaviour of a "notch sensitive" homogeneous linear elastic solid, as in [2]. The graphite is a medium-grained artificial graphite with a bi-phase and porous microstructure, with a particle size of up to 1 mm [3]. Non-irradiated ('virgin') graphite is approximately isotropic, has a non-linear stiffness, and the failure criterion is poorly understood. Furthermore, specimens with minimum dimensions above 20 mm are relatively notch insensitivity to features sharper than 1 mm radius, which is attributed to microstructural coarseness [4-8]. Modified by fast neutron irradiation and radiolytic oxidation [4], the evolving properties are characterised by post-irradiation examination (PIE), which includes flexural strength testing of plain 6 x 6 x 19 mm beams. There is very limited data on the notch sensitivity of irradiated graphite, partly because there is no standard technique for measuring it in the small specimens (relative to the microstructural scale) available for routine PIE. The structural integrity simulations assume that the notch sensitivity is invariant to irradiation and oxidation, and so measurements of notch sensitivity in irradiated graphite would reduce the uncertainty in this approach. In this work, the stress concentration behaviour of over 100 small specimens will be examined using a multi-camera set up and digital image correlation (DIC) to determine the strains and directly inform finite element simulations. With the FE simulations, stresses will be determined from both linear and non-linear elastic stiffness models and potential fracture criteria tested.

Experiment and Simulation

102 specimens of edge-notched 6 x 6 x 19 mm beams were prepared from virgin UCAR-manufactured IM1-24 gilsocarbon comprised of seven notch geometries. The notch variables were tip geometry and depth: the notch tip geometries were 'blunt' (1.00 mm radius 'U' slots) and 'sharp' (90° 'V' slots with tip radii of 0.03 mm), while the depths were unnotched, 'shallow' (1.0 mm), 'half-depth' (3.0 mm) and 'deep' (4.5 mm). The preparation, fracture testing and pop-in load detection are described in [8]; in brief, the beams were tested in quasi-static four-point bend, with three-camera in situ imaging by a low resolution stereoscopic pair, and a high resolution camera. Full-field surface deformations were calculated by digital image correlation (DIC) from the stereo pair, and strains between the inner rollers determined from the monoscopic DIC. Linear elastic FE simulations of each geometry were matched to the experimental deformations (see also [8]). For each geometry an apparent 'bulk' Young's modulus was determined; these apparent values were found to decrease linearly with loading. The notch tip stress and strain at failure were extracted, and used to determine statistically-valid distributions for each geometry. The simulations were repeated using a non-linear elastic model derived by [9] (the "non-linear UMAT"). Fig. 1 compares the notch sensitivity ratio to notch tip radius, as calculated separately by an analytical 'reduced ligament' approach and the non-linear UMAT, and relative to the linear elastic solutions. Failure described by a predictable notch sensitivity formulation would indicate a suitable failure criterion. An alternative fracture criterion (critical strain energy density, SED) was also tested against these data, using the formulation used by e.g. Lazzarin and Berto in [10] and Gomez et al. in [11].

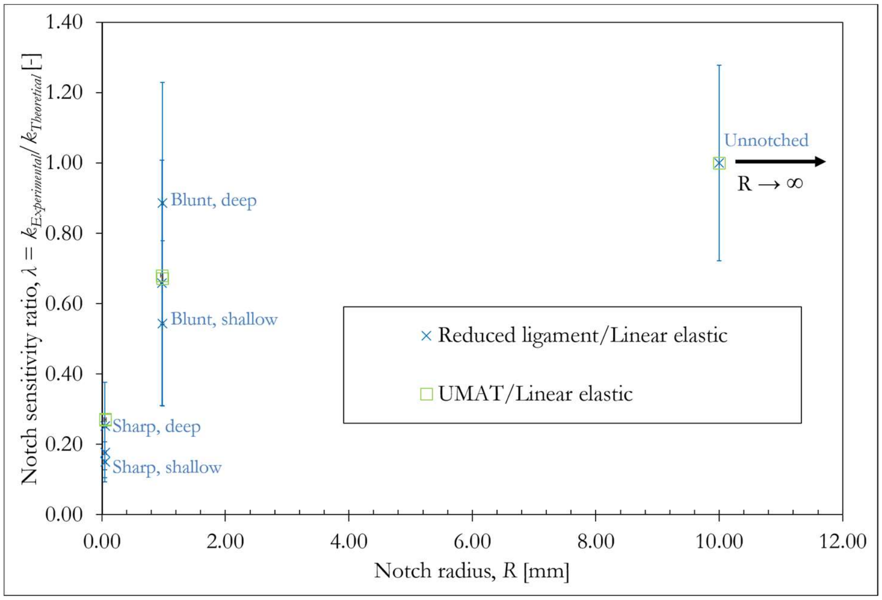

Figure 1: The dependence of notch sensitivity ratio on notch radius for the different geometries.

Discussion and Conclusions

A statistically significant dataset is now available to further analysis of crack initiation in small nuclear graphite samples. Supplementary to the load-crosshead displacement data, the use of DIC-informed FE simulation ensured that specimen deformations were accurately captured for the non-standard fracture testing of squat, notched beams of a heterogeneous material in four-point bend (e.g. see [12]). Matching both the deformation and resultant load enabled prediction of the complete stress-strain state within the specimen, enabling deeper insights into the fracture behaviour and the ability to test various fracture criteria.

Notch sensitivity ratios indicate the degree to which a feature in the material behave like an ideal solid; if behaving ideally, the notch sensitivity ratio is unity for all radii. To predict the likelihood of cracking at a feature, an experimentally-derived curve would be used to convert linear elastic FE-simulated stresses to realistic distributions for comparison against the material strength. The logarithmic-type fitting function in Fig. 1 for both the analytical and non-linear UMAT ratios confirms the relative insensitivity of Gilsocarbon to small radius notch tips ($\lesssim$ 1 mm); since the notch sensitivity ratio is less than unity for sharp notches, this suggests that assuming linear elasticity in the current structural integrity assessments is a conservative position. This insensitivity is in-line with historical testing of larger specimens. For the analytical values, an effect of notch depth is observed, with notch sensitivity ratios closer to unity for deeper notches. In contrast the UMAT predictions were invariant to notch depth. It is clear that neither maximum Mode I stress nor strain are good fracture criteria for graphite. A major benefit of the full-field imaging and FE simulation was the opportunity to test alternative criteria. Critical SED was historically calculated using only analytical forms, and found to be deficient, despite potential benefits in predicting the failure of oxidised material. A generalised numerical form of critical SED was applied to this data with a degree of predictive success. The validation of a small specimen test enables the testing of reactor-extracted material for continual PIE. Combined with simulations of the evolving radiolytic oxidation weight loss in the reactors, this could be a tool for enhancing the structural integrity assessments of keyway root cracking, as part of work towards plant life extension.

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