Application of finite element simulation in the feasibility study of in-core residual stress measurement within graphite moderator bricks using deep-hole drilling technique

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Abstract This paper summarises results from a preliminary study using the finite element analysis (FEA) to model the deep-hole drilling (DHD) measurement process carried out across Hunterston B/Hinkley Point B (HNB/HPB) graphite moderator bricks. The motivation of the FEA study conducted prior to the scheduled programme of DHD measurements was to investigate on the feasibility for performing DHD measurements within virgin and irradiated advanced gas-cooled reactor (AGR) graphite moderator bricks.

The DHD measurement tool was planned to be positioned in the graphite brick using three pneumatic rams equally spaced with a positional accuracy of ±6°. The measurement was proposed to use a reference hole of diameter 10mm with an unconventional core-to-reference hole diameter ratio in order to (1) increase the resolution and accuracy of the strain measurement, (2) increase the measurement range of the air gauge, (3) utilise a more robust drill, air gauge and trepanning cutting tool preventing breakages of the cutting tools within the graphite in-core, (4) reduce the effect of methane holes on the reference hole drilling process and (5) measure a blind reference hole, i.e. not drilled completely through the brick wall thickness.

The FEA simulation was used to (1) study the influence of ram holding the lab tool in position and interpret DHD measured results due to ±6° positional accuracy, (2) study the influence of core-to-reference hole diameter ratio on the 'measured' residual stress, (3) study the influence of methane holes on the DHD measured results and (4) study the influence of blind hole measurement.

Model description

According to [1] the DHD simulation was positioned at 142.5mm from the brick top, Fig. 1. Due to XZ and YZ symmetry planes a quarter model was constructed. The methane holes running along the vertical axis of the brick were also modelled. Two simplifications were made. The partial length keyways in the mid-length of the brick and the end face keyways were not modelled as the position of the DHD was far away (142.5mm) from the top surface to have any influence on the DHD measurement simulation. The DHD model comprised a full 835mm length with the end face keyways thicknesses. Fig. 1 illustrates the location and direction of the DHD measurement simulation. The centreline of the DHD measurement simulation was at 22½°. A user-specified

Fig. 1 Quarter 3D model of moderator brick

Cartesian coordinate system, X'Y'Z' rotated anticlockwise by 22½° was also created for the DHD measurement simulation. The DHD measurement was thus simulated along X' and the reconstructed in-plane residual stresses included $\sigma_{Y'Y'}$, $\sigma_{Z'Z'}$ and $\sigma_{Y'Z'}$.

The drill region comprised 13 drill parts, D_1, D_2,…, D_{13}, with drill depths ranging from 3.0 to 11.2mm. These drill parts were sequentially removed in different steps to represent drilling process using the keyword "model change, remove" in ABAQUS to deactivate these parts. Following drilling simulation, the trepanning process was simulated by sequentially removing trepanning parts T_1 to T_{13} in different steps with the trepan depths same as the drill depths. Fig. 2 shows the reference hole, core and trepan dimensions. The reference hole (drill part) diameter is 10mm and the core diameter (trepan inner diameter) is 19mm. The trepan thickness (i.e., the electrode thickness) is 1mm. The core thickness is 4.5mm. The core-to-reference hole diameter ratio is 19:10; the conventional ratio is 10:3. Fig. 3 illustrates the possible DHD measurement paths due to the ±6° positional accuracy of the DHD lab tool in

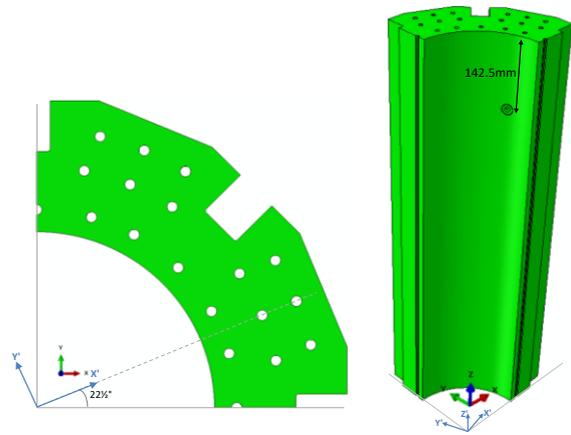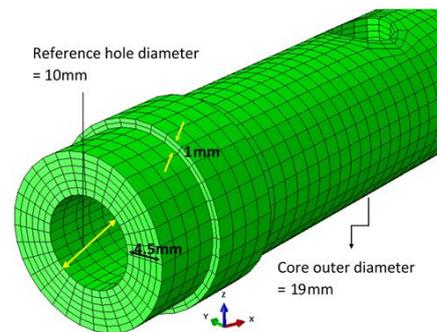**Fig. 2** Reference hole, core and trepan dimension

the graphite brick. Three main paths are considered. 1. DHD-a at 22½°, the reference hole intersects through the outer two methane holes. 2. DHD-b at 28½°, the reference hole intersects most part of the innermost methane hole, and the trepanning electrode partially intersects the outermost methane hole. 3. DHD-c at 19½°, the reference hole completely misses out the methane holes and the trepan electrode partially pierces through all the methane holes.
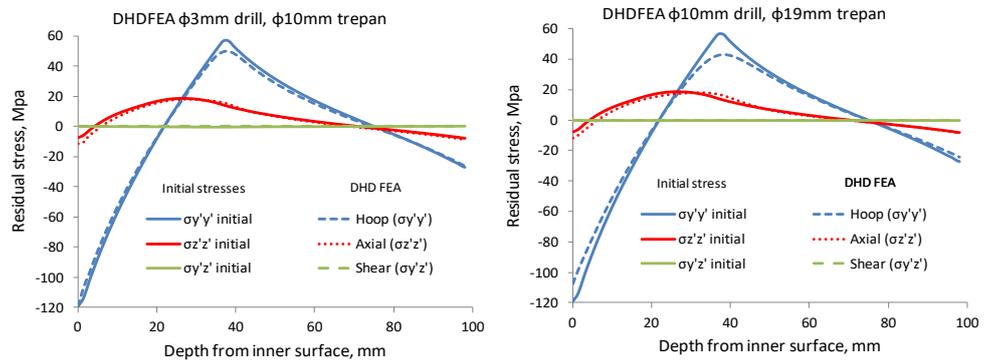
DHD measurement simulation results

In order to investigate effects of different parameters on the DHD simulated results an autofrettage initial stress was simulated in the graphite model.
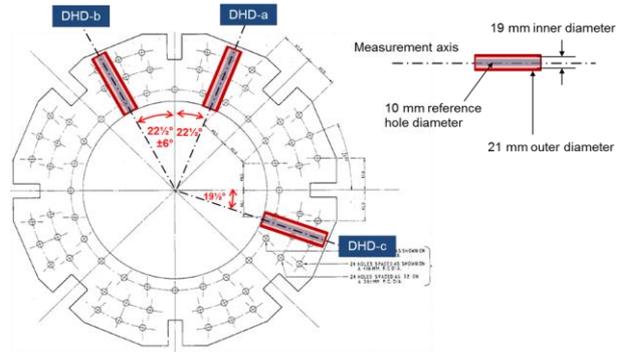
Fig. 3 Cross-section of HNB/HPB graphite brick with possible DHD positions

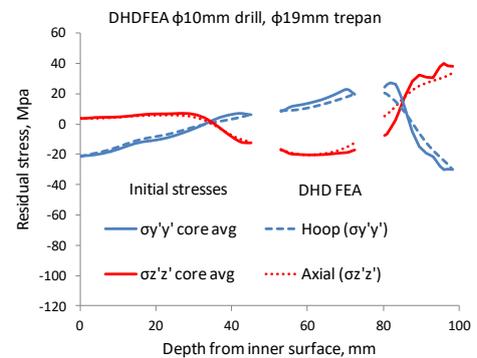### Influence of core-to-reference hole diameter ratio

A separate model without methane holes was constructed. The DHD parts included both 10:3 and 19:10 core:reference hole diameter ratios. Fig. 4 compares DHD simulated result with initial residual stress. Excellent correlations exist illustrating negligible influence of core-to-reference hole diameter ratio on DHD measured simulation.
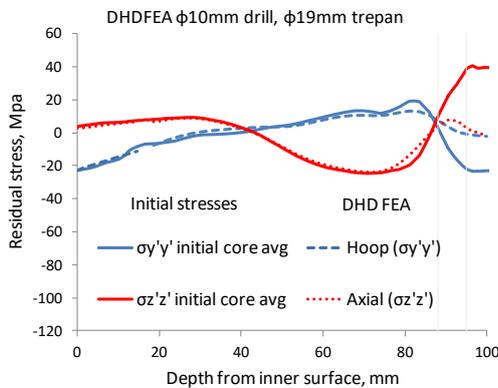
Fig. 4 Influence of core-to-reference hole diameter ratio on the DHD measured simulation

Influence of methane holes The FEA simulations of the DHD measurement process using model DHD-a (see Fig. 3) was used to study the effect of methane holes. The FEA reconstructed DHD results are compared with the initial stresses in Fig. 5. An excellent correlation exists with a very limited redistribution ahead of the outermost methane hole, at 80mm depth from the inner surface.

Influence of blind holes The simulation using the model DHD-b (Fig. 3) was repeated with the drill and trepan parts D_{12}, D_{13}, T_{12}, T_{13} towards the end discarded in order to simulate a blind hole DHD operation. The simulated measurement compares well with the initial residual stress in Fig. 6 up to depth of 88mm. The blind DHD is thus valid up to a depth of 88mm from the inner surface.

Fig. 5 Influence of methane holes on DHD measured simulation

Fig. 6 Influence of blind holes on DHD simulated measurement

Conclusion

The study showed that the influence of core:reference hole diameter ratio was negligible. Note that the FEA simulation of the DHD measurement process was carried out fully elastically. This is because the stresses expected in the graphite brick are sufficiently low and the material removal results elastically.

The influence of ram on the residual stresses shown elsewhere [2] was essentially negligible.

The presence of methane holes contributed to a limited degree of stress redistributions ahead of the outermost methane hole at 80mm depth from the inner surface.

Blind DHD simulations carried out up to a depth of 88mm showed no influence on the DHD simulated measurement.

References

[1] Risktec "Assessment of the effects of Hybrid Trepanning Equipment Operations on AGR Performace and Integrity", Document No: BEL-92-R-07, Issue: 1.0, 22 February 2011.

[2] S. Hossain, DHD measurement finite element simulation in graphite brick, Report, 2012.