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3D MODELLING OF AN AGR REACTOR CORE FOR PLANT LIFETIME EXTENSION

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ABSTRACT

The Graphite Core Plant Lifetime Extension programme is intended to increase the understanding of the future behaviour of the AGR graphite cores beyond keyway root cracking, and hence contribute to underwriting the safety cases for operation of the cores to their ultimate lifetimes.

As the AGR graphite core ages, the components of the core change shape, lose weight and the fuel bricks are postulated to crack. As a consequence, the geometry of the core will alter from the original design and hence there is a need to know the distorted geometry in order to demonstrate the safety functions of the core.

For the life extension of the AGR power plants, it is therefore desirable that decisions should be based on results and conclusions with the least number of simplifying assumptions and conservatisms. An example is the development of a whole-core modelling and analysis methodology based on the use of 3D solid finite elements to model the graphite components.

The aim is to demonstrate the viability of the solid modelling methodology in a phased approach; initially starting with small size arrays of core components and gradually increasing the array size to that of a full core with cracked fuel bricks.

To support the computational work, experimental testing on quarter-scale components is run in parallel to the computational analysis. These experiments can then be used as a source of validation of the corresponding computational models. This paper presents the current computational work to date.

INTRODUCTION

For EDF Energy to meet its site licensing conditions, it is necessary to perform safety reviews for each of its Advanced Gas-cooled Reactors (AGRs) which includes demonstrating the continuing safety of the graphite moderator cores over a future period against the existing safety case requirements.

The safety and functionality of the AGR cores are based on the requirements for unimpeded movement of both fuel and control rods and the provision of adequate cooling of the fuel and moderator, which are principally related to the geometry of the fuel and control rod channels.

The current whole-core modelling is based on the AGRIGID modelling and analysis methodology. AGRIGID is a FORTRAN code that takes a description of the geometry keying arrangement and the restraint of an AGR graphite core as an input, including ageing effects due to irradiation and generates an Abaqus model file suitable for static non-linear analysis. The model that AGRIGID generates is a simplified representation of the core components and the keying system using rigid beams and non-linear springs.

Notwithstanding the confidence in the AGRIGID results, it is recognised that a number of simplified, yet conservative, assumptions are inherent in the AGRIGID solution and results. For life extension of the AGR power plants, it is desirable that relevant decisions should be based on results and conclusions with the least number of simplifying assumptions and conservatisms.

The EDF Energy graphite core Plant Life Extension programme (PLEX) is intended to deliver the work required to increase the understanding of the behaviour of the AGR graphite cores beyond keyway root cracking to their ultimate lifetimes. The PLEX programme involves computational and experimental work which includes the development of an alternative independent whole-core modelling and analysis methodology to that of AGRIGID. The new modelling and analysis methodology, titled Solid Analysis of Loaded Core (SALCOR), will account for features and core behaviour not covered by AGRIGID, e.g. channel distortions due to opening/deforming cracked bricks, offset by irradiation creep, and channel distortions due to disengagement or failure of keys.

To demonstrate the viability of the new solid modelling and analysis methodology, a phased approach; initially starting with small size arrays of core components and gradually increasing the array size to that of a full core, will be investigated. To that end, 3D solid finite element bricks representative of Hinkley Point B (HPB) and Hunterston B (HNB) bricks have been created, as well as hybrid AGR quarter-scale bricks, as shown in figure 1. To support the computational work, experimental tests using quarter-scale AGR components on specially commissioned test rigs known as Quarter-scale Rig (QSR) and Junior Quarter-scale Rig (JQSR). These experiments can then be used as a source of validation of corresponding computational models.

This paper presents the FE analysis for one such quarter-scale test using hybrid AGR bricks and the comparison against rig test results from the JQSR.

3D ARRAY MODEL

A FE model 5x5x2 (5 rows of bricks, 5 columns of bricks, 2 layers of bricks) array was built in Abaqus CAE as shown in figure 2. The model comprises of 48 fuel bricks, 32 interstitial bricks, 79 loose bearing keys and a doublet of Singly Cracked Bricks (SCBs) located in the centre of the array. The array model was meshed with the element type C3D8R.

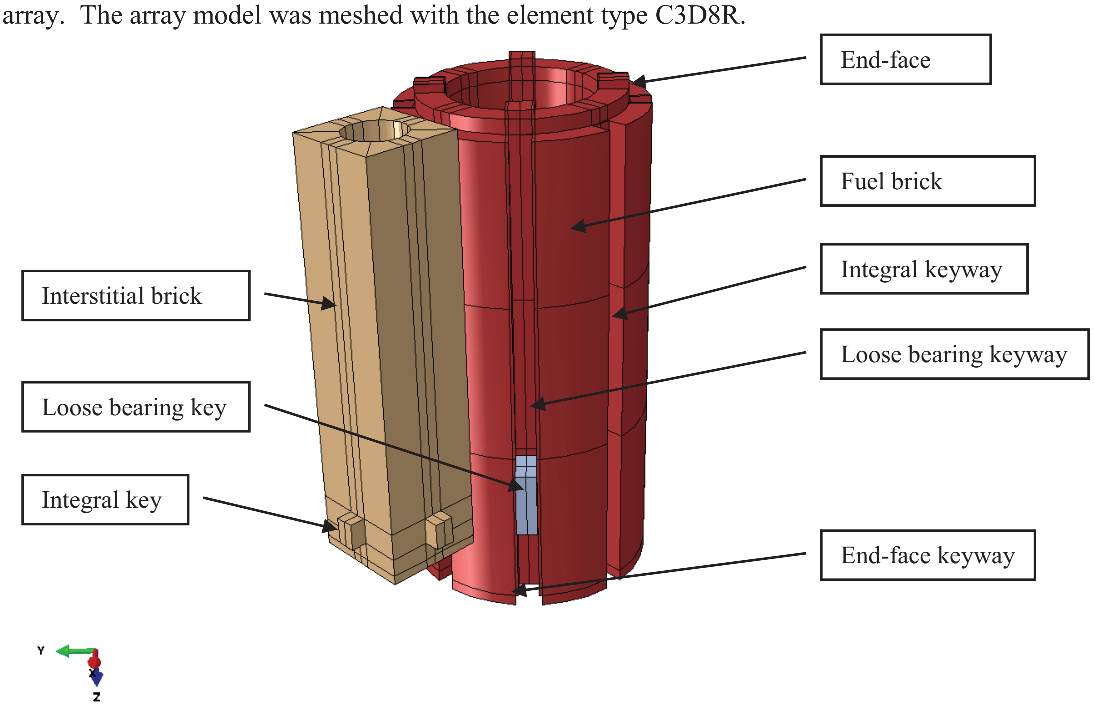


Figure 1. Schematic of the key features of the quarter-scale components. Inverted elevation view.

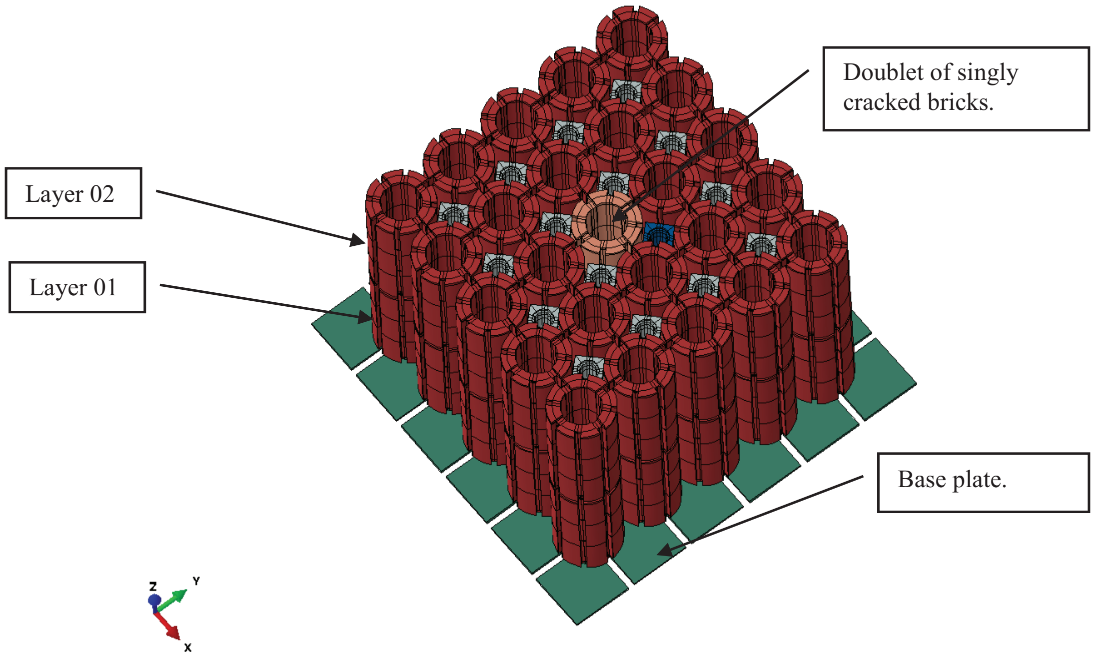


Figure 2. Quarter-scale SALCOR FE model of 5x5x2 array with doublet of SCBs.

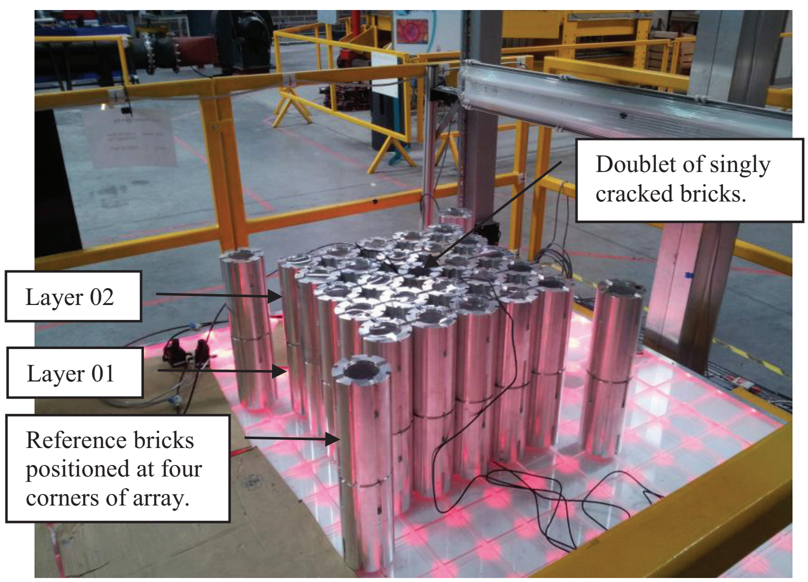


Figure 3. Junior Quarter-scale Rig (JQSR) set up with 5x5x2 array with a doublet SCBs.

Boundary Conditions

The end-face keys (EFKs) of the bottom layer of fuel bricks (layer 01) and the bottom singly cracked brick are located on a base plate representative of the quarter-scale rig, figure 3. The bottom surface of the base plate was constrained in the x-direction, y-direction and z-direction, figure 4. The interstitial bricks sit on the top surface of the base plate with the bore of the brick located by a boss, figure 4. The bottom surface of the boss was constrained in the x-direction, y-direction and z-direction.

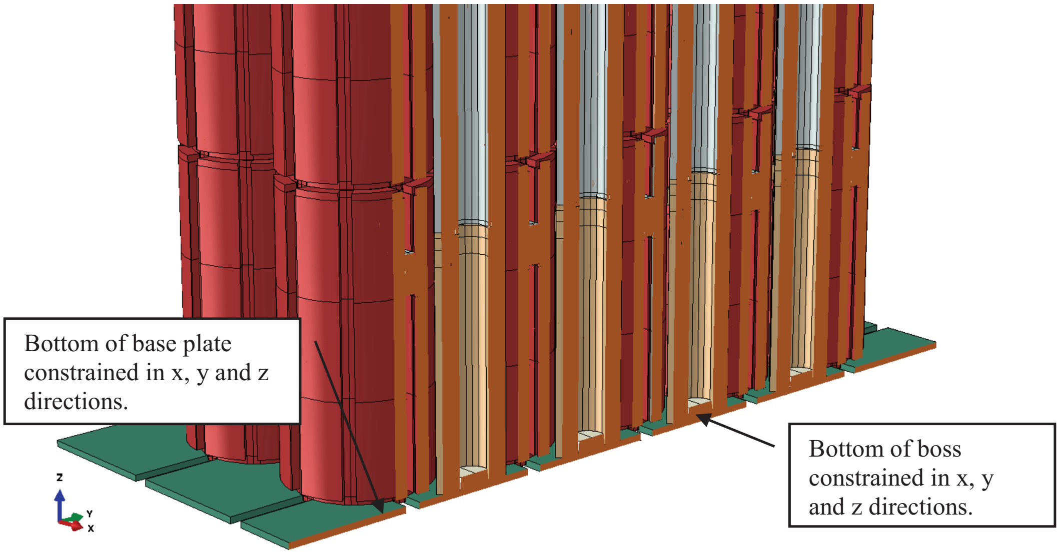


Figure 4. Cross-section through 5x5x2 array, showing boundary conditions used.

Crack Modelling Methodology

An axial crack can be inserted into the FE model of a fuel brick through element definition and the use of coincident nodes. Two crack scenarios were modelled, where the crack extends radially through the middle of either the loose bearing keyway or the integral keyway, with the crack extending the full height of the fuel brick in both scenarios.

Several methods of opening the SCB in the FE model were investigated to simulate the quarter-scale test rig, Figure 5, including applying displacement to nodes on the top of the brick, applying a pressure to the cracked surfaces and applying a temperature to the bore of the singly cracked brick. The temperature method was chosen as it allowed unconstrained movement of the brick, required minimal local stabilisation by springs and dashpots, did not result in un-natural brick shapes (i.e. barrelling) or movement of the brick (i.e. excessive vertical movement) and is independent of the model size.

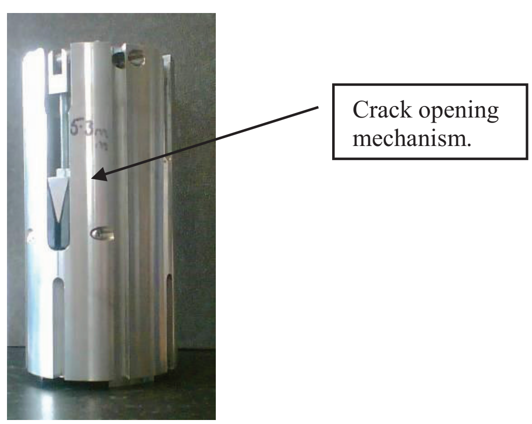


Figure 5.Quarter-scale test rig SCB.

Analysis Configuration

For this analysis configuration (FE model and test rig), the crack was aligned with the loose bearing keyway (90 degrees clock-wise from North) for the layer 01 SCB. For the top SCB (layer 02), the crack was aligned with the integral keyway (45 degrees clock-wise from North), Figure 6.

Several test iterations were run on the quarter-scale rig to achieve a crack opening of 5mm at the outside edge of the SCB, requiring the removal of EFKs from the SCB on layer 01. Three of the four EFKs were removed, with only the EFK opposite the crack remaining. In addition, the loose bearing key adjacent to the crack was removed, as this would interfere with the opening mechanism of the SCB. On layer 02, the four EFKs were intact, with the integral key adjacent to the crack removed to avoid interfering with the opening mechanism of the SCB.

The removal of EFKs, loose bearing keys and integrals keys was replicated in the FE model, figure 6. In the FE model, the SCBs are pre-cracked at the beginning of the analysis with an increased temperature applied to the bore of the SCBs to achieve a crack opening of 5mm.

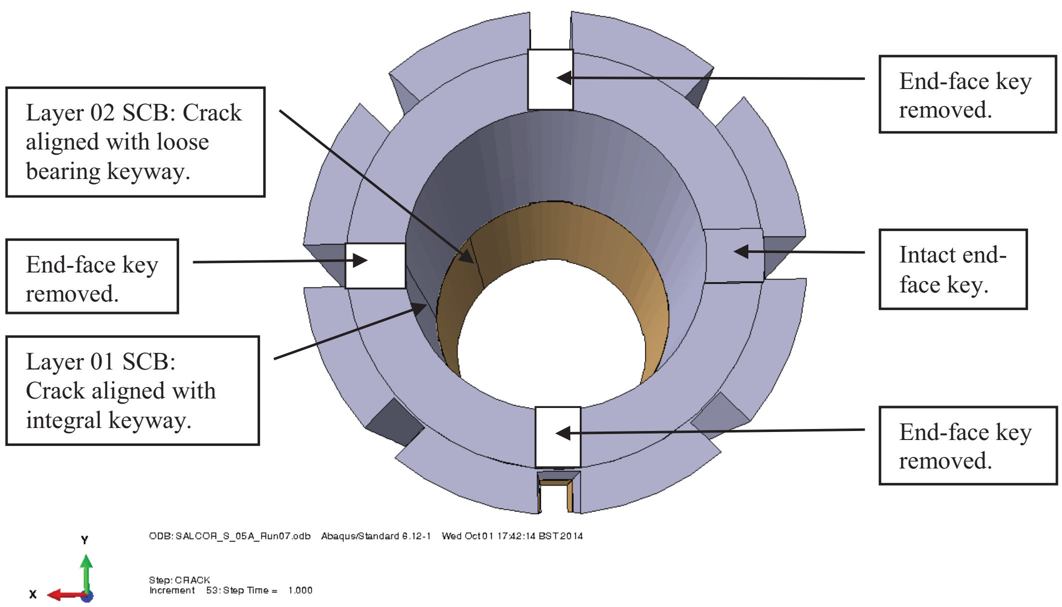


Figure 6. Doublet of SCBs. Inverted elevation view.

Contact Interaction

The contact interactions due to the thermal opening of the SCB was described by the general contact option in the finite element software Abaqus, which allows contact between all regions of a model with one another.

To prevent unconstrained rigid body motion of the array and aid in convergence of the solution during the general contact analysis, two types of stabilisations were employed. A global contact stabilisation and a local stabilisation of each component. The basic principle is to apply damping forces to local regions that develop instabilities and smooth the discontinuity in response, so that a converged solution can be obtained.

The global stabilisation allowed contact; whilst not over damping the model, which has the effect of allowing components in space to move which are not yet in physical contact. The stabilisation was kept on during the analysis, to manage the constantly changing contact. The default in Abaqus is for the global stabilisation to ramp to zero at the end of the analysis step, which has the effect of turning off the stabilisation. In this case, turning the stabilisation off would cause convergence issues.

The local stabilisation consisted of DASHPOT1 elements (dashpot coefficient 6.9999 N s/mm) and SPRING1 elements (spring stiffness 7.9999 N /mm). These values are sufficient to hold the components in place without over constraining them. For each component, at least four springs and dashpots were needed to hold the components in the x-direction, y-direction and z-direction.

In addition, gravity was applied, which ensures positive contact between the contacting surfaces and helps with contact chattering which can cause convergence problems or result in small time steps, thereby increasing the solution time.

Material Properties

The components used generic aluminium material properties; aluminium being selected for the quarter-scale bricks for the test rig due to its dimensional and thermal stability and availability.

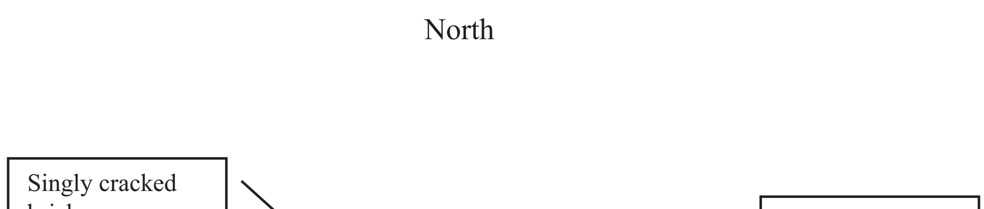
RESULTS AND ANALYSIS

FE Results

The temperature applied to the SCB causes the brick to open in a circular manner with the maximum brick movement occurring in the vicinity of the crack and reducing around the circumference of the brick, with only a small amount of movement of the SCB opposite the crack, figures 7 and 8. The movement of the SCB is propagated through the array to the rest of the fuel bricks by the loose bearing keys and the integral keys.

The resultant displacement plots of the fuel bricks for layer 01 and layer 02 are shown in figure 7 and figure 8. The movement of the SCBs is propagated to the fuel bricks positioned adjacent to the crack by either the integral keys (layer 01) or the loose bearing keys (layer 02) positioned either side of the crack. There is some movement of the fuel bricks positioned either side of the SCBs with negligible movement of the fuel bricks positioned behind the SCBs. There is little movement of the fuel brick directly in front of the SCBs.

Plotting the contact pressure of the layer 01 SCB, figure 9, shows the points of contact between the SCB and the surrounding bricks with end-face key/keyway contact occurring between the layer 01 and layer 02 SCBs. The points of contact indicates anti-clockwise movement of the top SCB, relative to the bottom SCB.



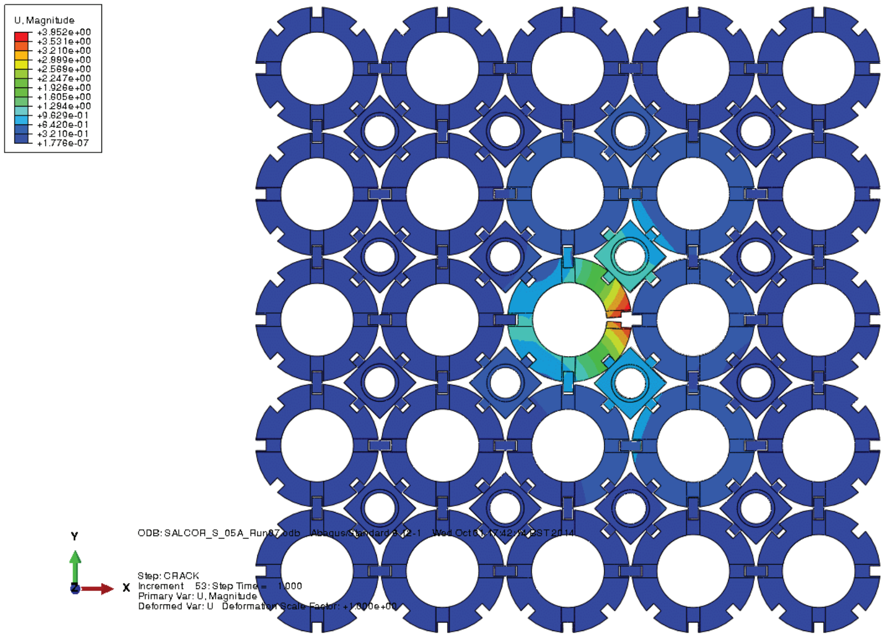


Figure 7. Resultant displacement of fuel bricks and SCB, layer 01.

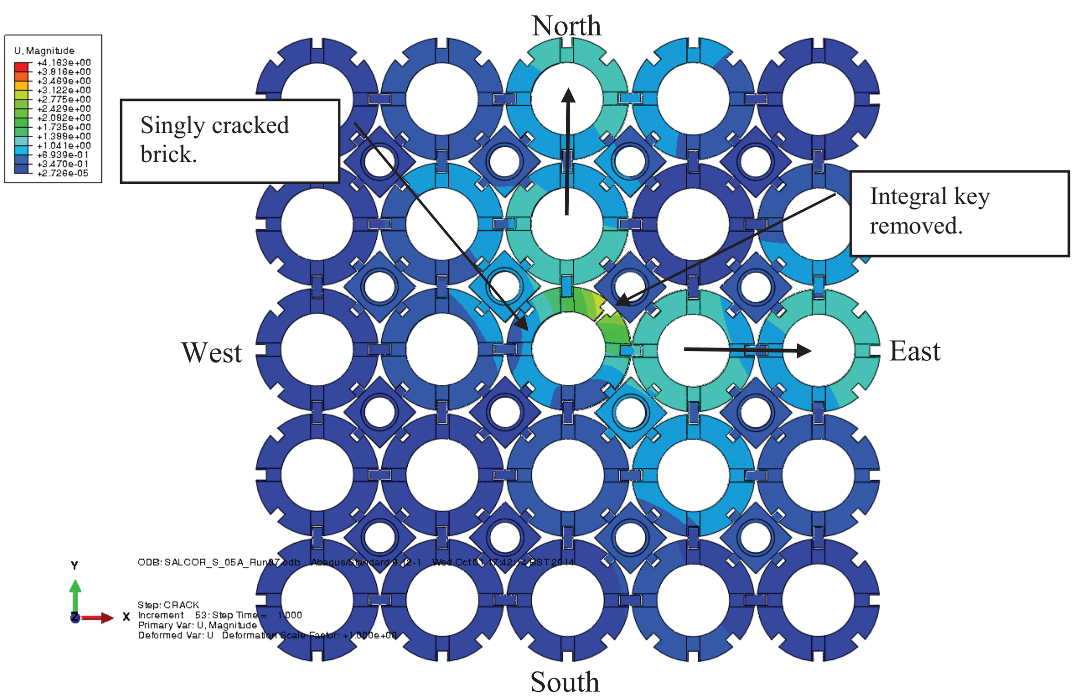


Figure 8. Resultant displacement of fuel bricks and SCB, layer 02.

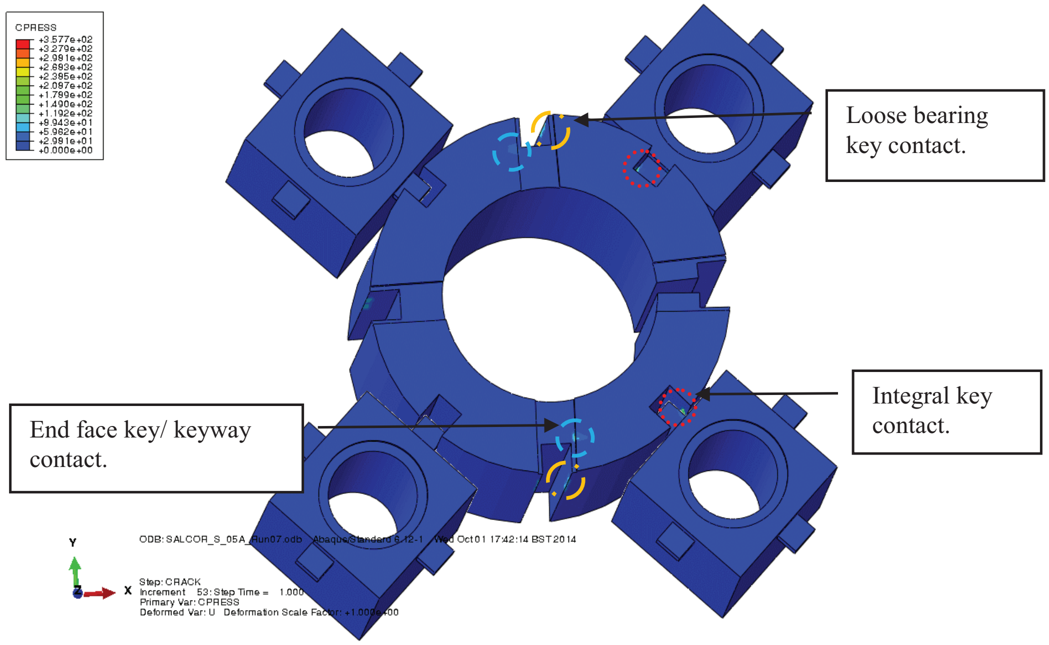


Figure 9. Contact between SCB and surrounding components, layer 01.

Validation of FE results against Quarter-scale Rig Results

The quarter-scale rig is fitted with an automated camera system which views each channel, capturing images of optical targets fitted to each brick. The camera takes an image of each brick before and after the SCBs are opened and using post-processing software, the resultant movement of each brick is calculated. The distortion of the fuel bricks and fuel channel shapes can be determined from this data and compared against the displacement of nodes on top of the FE bricks. For validation of the FE model, the displacement of the bricks at the end of the FE analysis is compared against the quarter-scale rig results; however, the fuel bricks do not necessarily move in a linear fashion; but in a curve.

Vector displacement plots (figure 10 and 11) allow the individual fuel brick movements of the FE model to be compared against the quarter-scale rig test result relative to the rest of the fuel bricks in the array, where the SCB is positioned in the centre (L21). The plots show good agreement in the magnitude and direction between the FE and the test rig results, particularly with the bricks surrounding the SCB, with the majority of the FE results within the scatter of the test rig results.

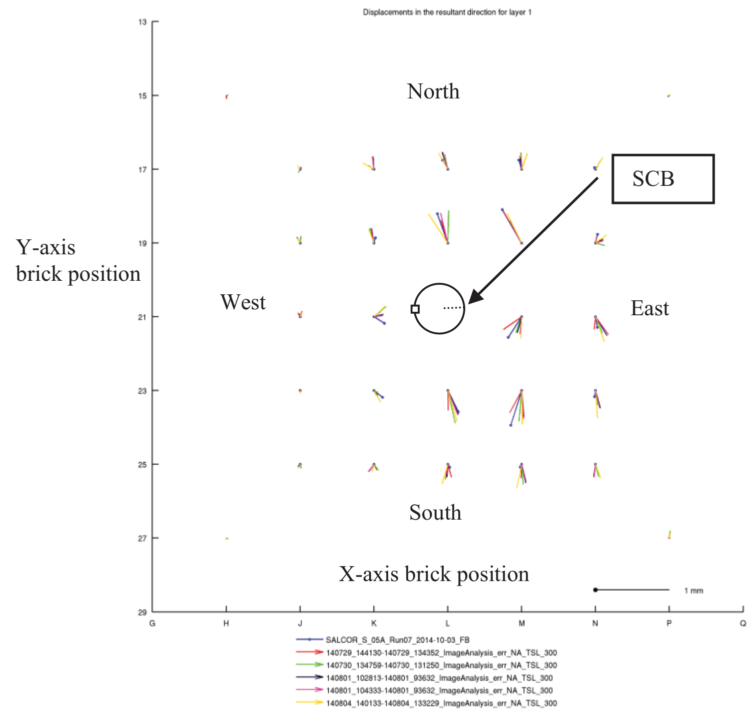


Figure 10.Comparison between FE and JQSR, layer 01.

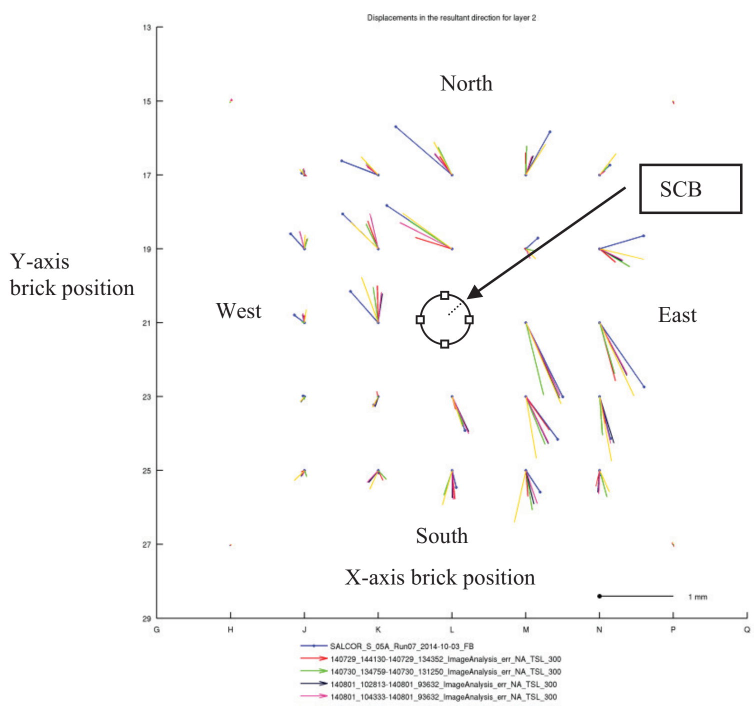


Figure 11.Comparison between FE and JQSR, layer 02.

CONCLUSIONS

A 3D finite element whole-core modelling and analysis methodology (SALCOR) has been developed which can model features (i.e. end-face keys) and core behaviour (i.e. key/keyway disengagement) not covered by the current AGRIGID models.

The results from the SALCOR quarter-scale models analysed to date have been validated against the quarter-scale rig results and shown that the SALCOR modelling and analysis methodology gives satisfactory results against test rig results. The thermal method of opening the SCB in the FE model provides an acceptable crack opening method which is comparable to the test rig results.

SALCOR is now being used for sub-modelling areas of interest identified from AGRIGID and for the investigation of singly cracked brick scenarios for the HPB/HNB lifetime safety case.

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REFERENCES

None.