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EXPLORING THE POTENTIAL FOR PROGRESSIVE FAILURE OF GRAPHITE IN AN ADVANCED GAS COOLED REACTOR CORE

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ABSTRACT

Advanced Gas Cooled Nuclear Reactor (AGR) cores comprise of many graphite components whose geometry and mechanical properties change under prolonged exposure to neutron irradiation. The changes in the mechanical properties of the graphite have the potential to result in cracking of the graphite bricks later in the operational life of the core. This could result in disruption to the core geometry with possible negative implications on fuel cooling and/or control rod insertion. This component ageing issue needs addressing in both the computational and the physical models employed in the seismic resilience assessments. This paper looks at the particular issue of the potential for progressive failure of multiple graphite bricks during a seismic event as dynamic loads get redistributed around the core. To this end a model AGR core brick has been designed that will crack when a predefined force is applied to it. For practical reasons it was not appropriate to create such a brick using modelled materials, and it was also desirable that the brick could be repeatedly reset and allowed to crack again in subsequent tests. These "Crack on Demand" CoD bricks are therefore manufactured from Acetal in two halves. At the start of a seismic test the brick halves are held together using electromagnets powered by an adjustable current supply. During the tests the contact between the two brick halves is monitored by the electronics within the brick. When the hold force of the magnets is overcome, and any movement between the two half bricks is detected, the electromagnets are automatically switched off and the two halves of the brick are allowed to move freely. This paper describes the design and calibration of the CoD bricks and outlines the results from initial testing of an AGR model including these bricks. An initial assessment of the potential for progressive failure of graphite bricks in an AGR Core during seismic excitation is also discussed.

Keywords: nuclear power stations; progressive failure; shaking table test

1. INTRODUCTION

The Advanced Gas Cooled Nuclear Reactor (AGR) cores in nuclear power stations in the UK consist of thousands of graphite moderator bricks, interconnected through a graphite keying system which acts to resist relative motion between bricks. The graphite components are stacked together in vertical columns and provide the channels for fuel assemblies, control rods and coolant flow. The vertical faces between

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neighbouring bricks are separated slightly to allow for thermal expansion during reactor operation and the radial keying system allows free radial movement of the bricks during thermal expansion and contraction of the surrounding steel structures, and provides reaction forces to lateral movement once the clearances between the keys and the keyways have been taken up. As the AGR cores age the geometry and mechanical properties of the graphite components change under prolonged exposure to neutron irradiation. These changes in the mechanical properties of the graphite have the potential to result in cracking of the graphite bricks later in the operational life of the core. This could result in disruption of core geometry possibly impacting fuel cooling and/or control rod insertion. This component ageing issue needs addressing in both the computational and the physical models employed in the seismic resilience assessments and a particular issue is the potential for progressive failure of graphite bricks during a seismic event as dynamic loads get redistributed around the core. (Cowell and Steer 2017). The existing dynamic FE models of the AGR reactors, GCORE (Kralj et al 2005), are nonlinear multi-body stick/spring/mass simulations that can include pre-cracked bricks in the simulations. However, these models do not currently allow modelling of new component damage during the seismic motion, so an interactive approach to analysis of progressive failure is currently adopted. In this approach a seismic analysis is made, then the stresses in the components during that shaking are calculated, and an assessment is made as to the likelihood of any of the components cracking. If components are shown to have been subjected to high enough stress to crack, then these components in the FE model are modified to include the cracks and the analysis is re-run. This is believed to be conservative for predicting displacements that might compromise the channel straightness required for the unimpeded entry of the Primary Shut-Down (PSD) system control rods.

However, this approach does not model the potential for dynamic changes to the core behaviour due to progressive damage during seismic loading. More complex models are currently being developed, e.g. SOLFEC (Bicanic & Koziara 2008), that will allow calculation of brick stresses and subsequent changes to the model during a seismic analysis but it is recognized that seismic testing is needed to validate experimentally these new computer models and to enhance the understanding of core dynamics, especially where components may behave in ways not adequately modelled by computational analyses. To this end a ¼ scale physical model of an AGR was developed by the University of Bristol (Dihoru et al 2015) to allow testing of a variety of degradation scenarios along with measurement of the behaviour of the components in the core during seismic excitation (Dihoru et al 2017). In order to extend this work to investigate the potential impact of progressive damage on the AGR cores some bricks, that can Crack-On-Demand (CoD), have been developed and these have been tested in a ¼ scale single layer model of an AGR core (Figure 1). In this particular experimental arrangement, where different damage patterns can be quickly setup, the bricks are supported on a thin layer of fine glass spheres to reduce sliding friction and the single layer allows the use of camera tracking systems to capture the motion of every brick in the array.

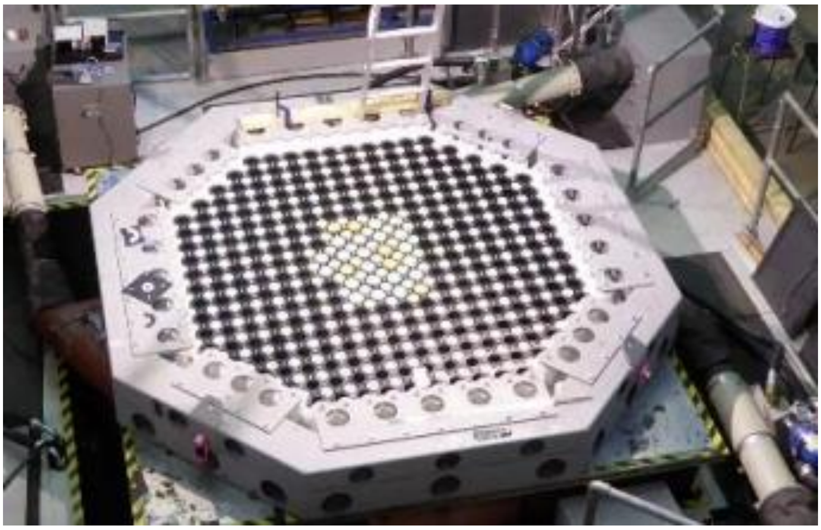


Figure 1: The SLA mounted on the shaking table at BLADE

2. CRACK ON DEMAND BRICKS

The Single Layer Array (SLA) (Figure 1) was designed to investigate, using quarter-sized model Acetal components with simplified geometry, the seismic response behaviour of AGR graphite cores containing cracked fuel bricks. In this physical model, bricks with double axial cracks can be simulated by pairs of half fuel bricks that are cracked throughout the seismic excitations. Comparisons between numerical predictions and measured responses of the physical model can then be used to validate the analytical modelling methods that are used for the seismic assessments of the AGR cores. These simulated cracked fuel bricks are reasonably representative of the worst condition in terms of dynamic response of an AGR core, late in life, with keyway root initiated cracking caused by irradiation induced dimensional changes in the graphite. However, developing a brick that simulate some of the possible damage scenarios occurring during seismic excitation allows further extension of the validation of the seismic assessments.

2.1 The Crack on Demand Brick concept

Initial work looked at various concepts for holding pairs of simulated double cracked brick halves together to recreate intact bricks. Various methods for controlled the separation of the brick halves, either on demand via an external signal or spontaneously as the result of the load on the brick exceeding a set force, were explored. This initial work suggested that the use of electromagnets was viable and would allow the manufacture of bricks where the separation of the brick halves could occur at set times simultaneously in all the bricks or in a pre-determined sequence; and bricks which would separate when the load on the bound brick parts exceeded an adjustable binding load. The current design concept for the CoD bricks is therefore based on the use of two electromagnets holding the brick halves together. At the start of a seismic test the brick halves are held together using electromagnets powered by an adjustable current supply. During the tests the contact between the two brick halves is monitored by the electronics within the brick. When the hold force of the magnets is overcome, and movement between the two half bricks is detected (using non-contact magnetic field Hall sensors), the electromagnets are automatically switched off and the two halves of the brick are allowed to move freely. The use of electromagnets means that once the power is cut the magnets cannot reengage and the brick remains broken.

2.2 Design of the Crack on Demand Brick

All of the bricks used in the ¼ scale SLA are made of Acetal, a low friction thermoplastic with high strength and stiffness, that can be easily machined. To provide contrast for easier video tracking of the bricks, black and white materials were used for the two halves of the CoD bricks which were connected by pair of electromagnets (Figure 2a). The electromagnets were embedded in the surface of the brick directly facing a steel disc in the opposing face, to which the energized magnets were attracted.

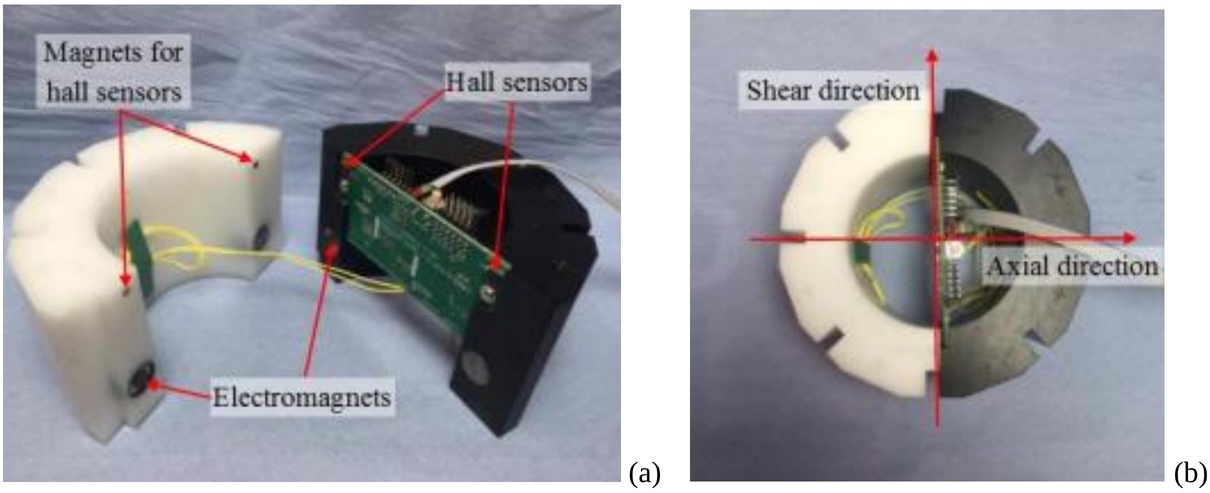


Figure 2: (a) A CoD brick with main components labelled (b) showing axial and shear failure directions

A simple circuit board was created to control the current supplied to each electromagnet and to switch off the current when required. Magnetic retentivity was observed in the electromagnets used so, rather than simply switching off the current to separate the brick halves, a brief pulse of reverse polarity current was applied to the electromagnets before the current was completely switched off. This eliminated any residual hold by the electromagnets. The circuit board was installed in one half of the CoD brick and includes the hardware to control the current supplied to the electromagnets and the firmware that interprets the data from the Hall sensors and then controls the supply to the electromagnets. The Hall sensors were installed on the circuit board itself with small magnets installed opposite the sensors to provide a magnetic field, the strength of which could be detected by Hall sensors.

The firmware in the control board accepts an external trigger to separate the brick into two halves manually, or uses an internal trigger generated once the forces on the brick cause a predefined axial or shear displacement of the brick joint to be exceeded (Figure 2b). Six pairs of jumper pins were included on the board to allow different operational modes to be selected. Code was written to allow for 'crack once hold force is exceeded', 'manual triggering', and 'calibration settings' to be chosen from via the jumper pins. The hold force of the electromagnets (i.e. the current sent to the electromagnets) can be changed in the firmware by connecting the CoD brick to a computer. The firmware can also be updated using the same USB connection.

2.3 Calibration of the Crack on Demand Bricks

Calibration of two aspects of the CoD bricks was necessary:

a) The hall sensors needed to be calibrated to determine an output that equated to axial and shear movements of approx. 0.1mm - a value assumed to be indicative of a slip in the joint between the bricks indicating that the electromagnetic hold force had been overcome.
b) The electromagnet hold forces needed to be calibrated to standardise the bricks to allow compensation for any manufacturing differences between the bricks, ideally ensuring each brick separated at the same predefined force.

2.3.1 Calibration of displacement sensors

To assess the ability of the Hall transducers to measure small movements between the brick halves, the output from the hall transducers was recorded for a range of potential axial and shear displacements. Biaxial Hall transducers were fitted in the bricks to assess the potential for differentiating between axial and shear displacements. Figure 3 shows a typical calibration curve for one of the hall sensors. The sensor output is clearly nonlinear and depends on both the axial and shear displacement of the two halves of the brick.

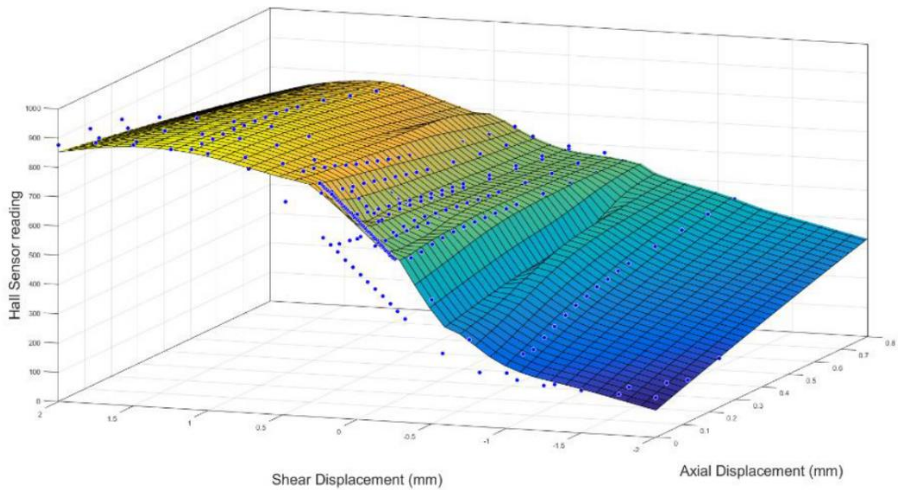
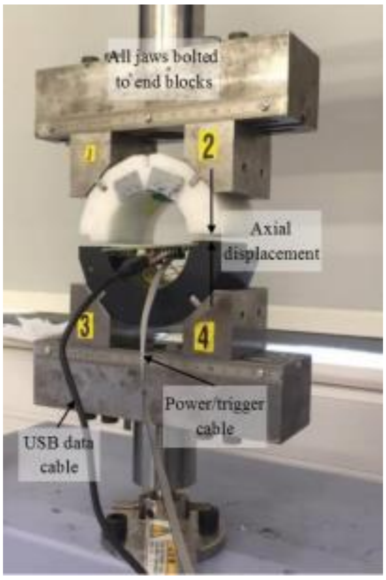


Figure 3: Relationship between hall sensor output and axial and shear displacements

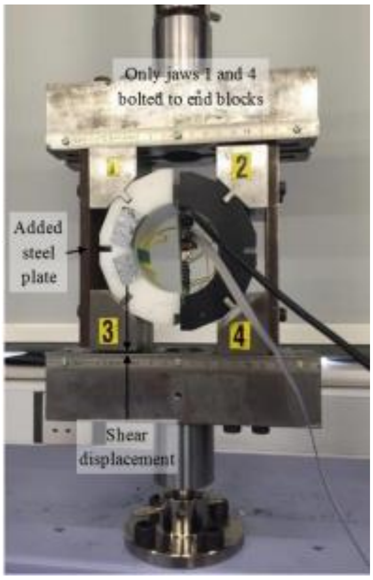
Rather than trying to incorporate calibration surfaces like this into the CoD bricks a simpler approach was adopted where a change in sensor output equivalent to approx. 0.1mm was used as an indication that the forces applied to the brick have overcome the hold force of the electromagnets. This 0.1mm movement of the joint is then used as a trigger to switch off the electromagnets and allow the brick to fully separate into its two halves.

2.3.2 Calibration of electromagnetic hold forces

To measure the hold forces produced by the electromagnets powered at different current levels, the CoD bricks were tested in a 1kN axial test machine. Each half of a COD brick was held in a steel rig (Figure 4) that replicated the keying arrangement in the AGR. This ensured that the brick halves could be displaced, either axially or in shear while measuring the hold force of the electromagnets.



(a)



(b)

Figure 4: Arrangement for calibration of hold forces, (a) For axial displacement, (b) for shear displacement

Force-displacement data was recorded for each test which began with the brick in very slight compression, allowing a clear peak to form when the maximum hold force occurred. Data from a typical axial test is shown in Figure 5. Tests were repeated and the axial hold force for a particular current supply was found to be consistent within around 0.1N.

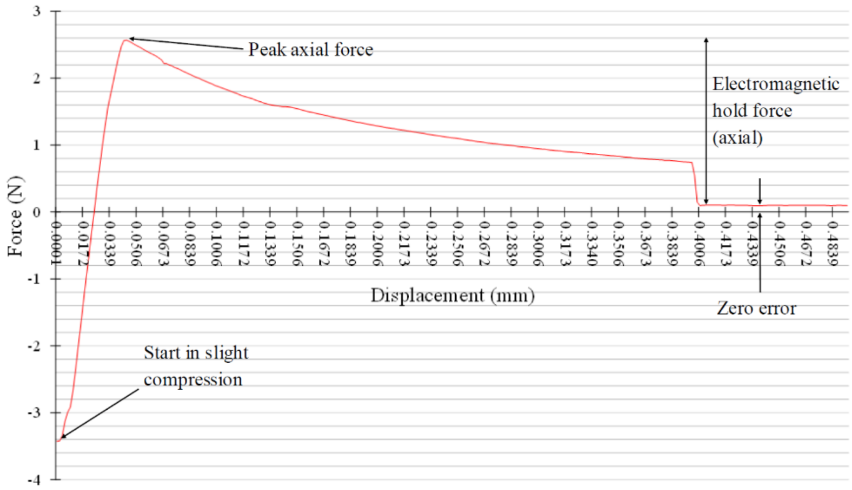


Figure 5: Typical axial force displacement curve for a CoD brick

For the shear tests it was necessary to isolate the effects of friction between the brick halves resulting from the testing arrangement. Therefore, for the shear tests, the magnets were released in the middle of each shear test, and the drop in force was taken to be representative of the hold force (Figure 6). Again clear, repeatable changes were always evident when magnets were released. A further observation from Figure 6 is how the force drops then slightly increases again after magnets are released. This is because a reverse current is applied to electromagnets when a release is triggered in order to combat any semi-permanent residual magnetism (Knapek, 2012).

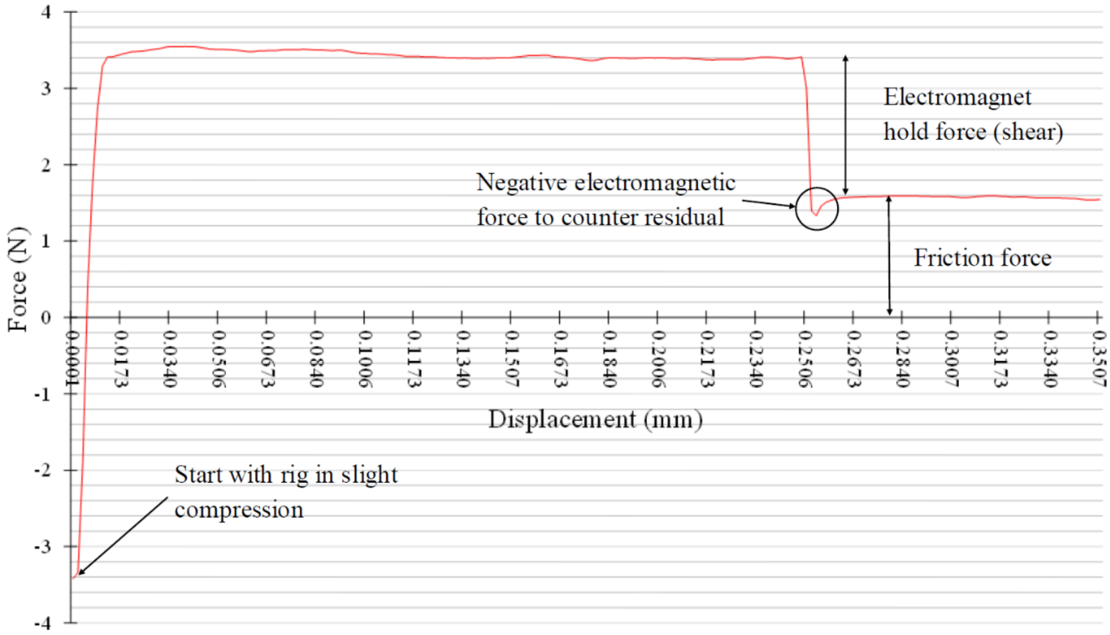


Figure 6: Typical shear force displacement curve for a CoD brick

Table 1 summarises the test results from two CoD bricks. It clear that the biggest challenge with the calibration of the electromagnets is the fact that, for the same supply current, the shear hold force is generally lower than the axial hold force. Therefore, while it is possible to apply calibration adjustments to each brick to adjust the current such that the shear or axial hold forces in two bricks are the same it is not possible to make the axial and shear hold forces in a brick identical.

Table 1. Hold forces for various currents in two of the CoD bricks

Brick number	**Test type**	**Current across each electromagnet (mA)**	**Maximum magnet hold force (N)**
316	shear	100	2.3
316	shear	200	2.7
316	shear	255	2.3
316	axial	200	2.3
168	shear	100	1.6
168	shear	150	1.8
168	shear	200	1.8
168	shear	250	1.8
168	axial	200	2.6

3. DYNAMIC TESTING OF CoD BRICKS

Three CoD bricks were placed in the SLA (Figure 7) which was mounted on a shaking table. A variety of different tests were conducted with the CoD bricks placed in three locations in the array (at A, B, C). The majority of tests were conducted with brick 316 in position A, brick 168 in position B, and brick 164 in position C. Each test started with the CoD bricks all held intact, already broken or various combinations of intact and already broken. A 1 Hz ramping sinewave was chosen as the input excitation building to a maximum amplitude of 16mm over 20 secs, followed by 5 secs at full amplitude and then a 5 sec ramp down (Figure 8b, black line). Data was collected from accelerometers at 5kHz and from video cameras at 50 frames per second. The video was processed to calculate the absolute displacement profile of each white interstitial brick during each shake. MATLAB was used to analyse the video and identify shapes with a high contrast, i.e. the white interstitial bricks (Figure 8a). By calculating the differences between the image frames the brick displacements were calculated.

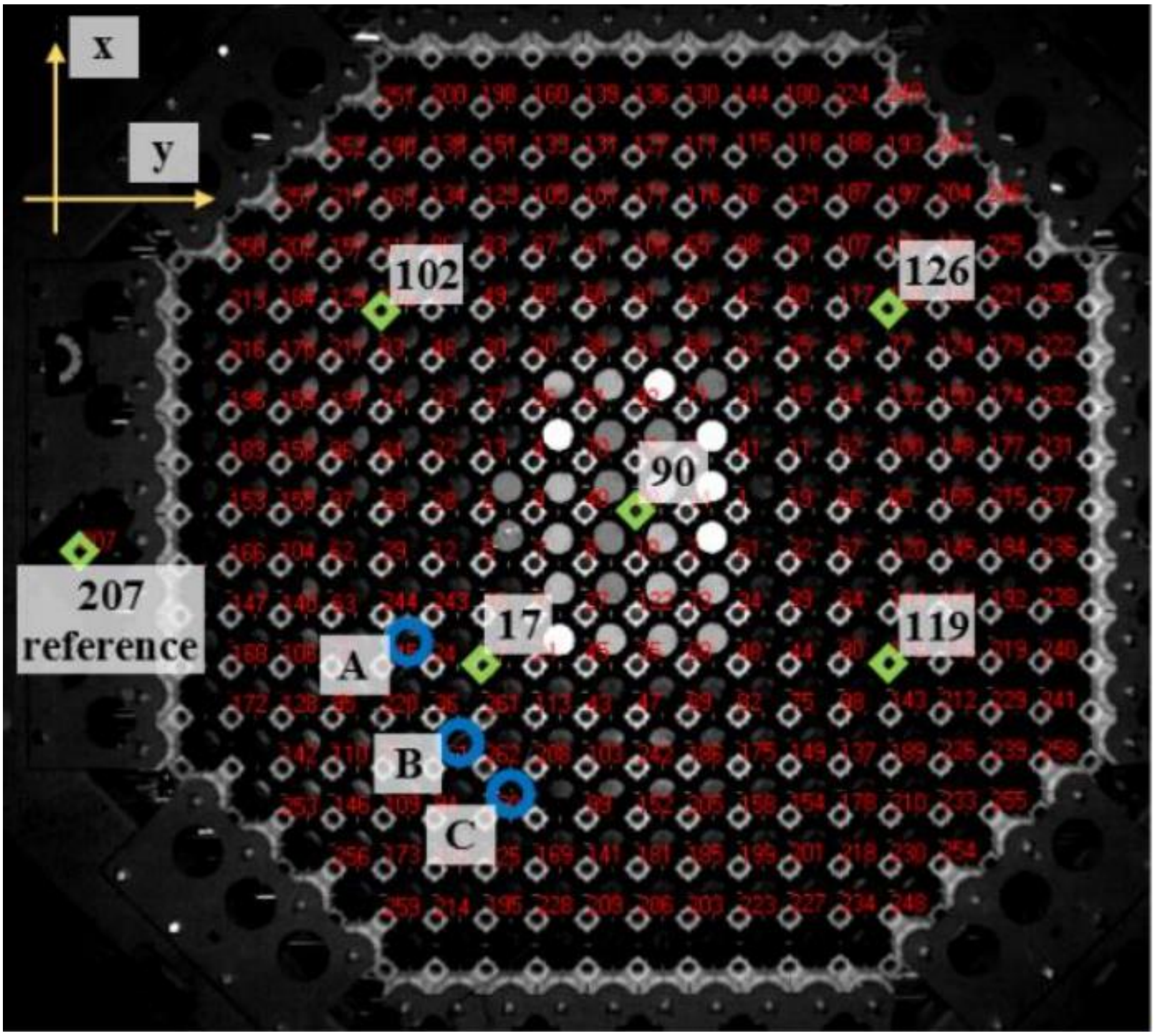


Figure 7: Location of the reference point (207), CoD bricks (A, B, C), monitored interstitial bricks (17, 102, 119, 126) and the table axes

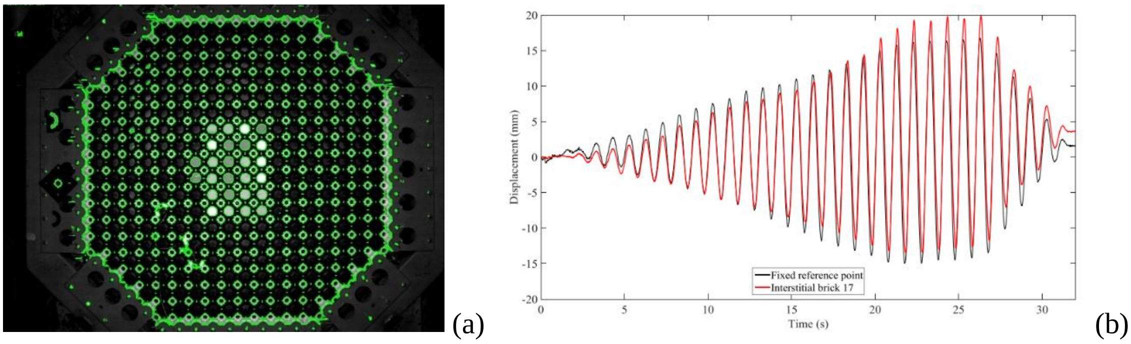


Figure 8: (a) Boundaries of bricks identified by image processing software (b) x-axis displacement for brick 17 during test

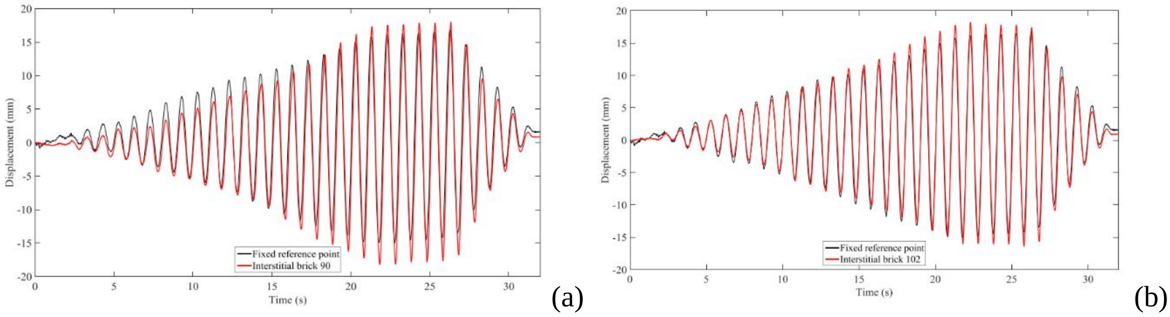


Figure 9: (a) x-axis displacement for brick 90 (b) x-axis displacement for brick 102

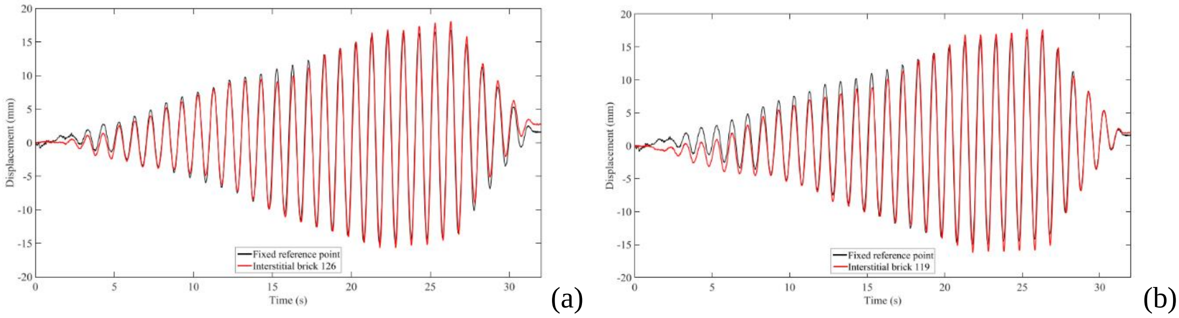


Figure 10: (a) x-axis displacement for brick 126 (b) x-axis displacement for brick 119

Figures 8(b) through 10(b) show displacement data from a typical test. The black line on each figure is for brick 207, a dummy brick fixed to the support frame for the SLA, this essentially records the table input motion. The red lines on the figures are the absolute x-direction displacements of some specific interstitial bricks spaced fairly symmetrically around the array. In this case the test began with the CoD brick at position B already broken, but the bricks at A and C intact. At around 14.5s into the test, the brick at position A cracked, the brick at position C remained intact. The CoD brick positions and the location of the interstitial bricks are shown in Figure 7.

At the start of the shaking the absolute motions of the bricks are fairly similar to that of the table showing that the brick motions are largely driven by the (albeit very low) friction between the bricks and the base of the array. A slight phase shift can also be seen between the excitation and the brick responses. As the amplitude of the excitation increases, the amplitudes of the interstitial bricks motions start to exceed the excitation amplitude as the bricks are moving enough to take up the clearances in the array. Interstitial brick 90 exemplifies this effect (Figure 9a) being in the centre of the array with the highest number of joints between it and the edge restraint frame.

The breaking of the CoD brick at A has a small, but significant effect, on many of the brick responses throughout the array. Interstitial brick 17 (Figure 8b) is situated very close to the CoD brick at A (and the pre-broken brick at B) and brick 17's motion becomes more asymmetric after CoD brick A cracks at around 14.5s. After that point the array becomes distorted and, at the end of the shake, brick 17 shows a significant residual displacement. Brick 126 is at the opposite corner of the array to the CoD bricks, yet it shows the largest change in response when the CoD brick at A cracks. Figure 10a shows a 2mm drop in the peak displacement of brick 126 at 15s. However, by 18s the amplitude has built back up again to what would be expected relative to the reference point. Brick 119 (Figure 10b) shows a similar but less pronounced response. These results suggest that the breakage of the CoD brick redistributes the forces in the keying system between the bricks throughout the whole array. However, brick 102, which is in line with the excitation direction and CoD brick A, seems to show very little change in response due to cracking of brick A (Figure 9b). A possible explanation for this is that the crack in brick A was orientated at 45° clockwise to the x-axis (pointing approximately towards brick 126), and this may have focused the redistribution of forces more towards the centre of the array.

4. INITIAL ASSESSMENT OF IMPACT OF PROGRESSIVE FAILURE IN AN AGR

In order to more fully assess the impact of the CoD bricks separating during seismic excitation, as compared to a case where they are already split into two halves at the start of any seismic excitation, it was necessary to develop ways to rapidly view the displacement response of the whole array for each test. This was done by creating videos that showed the relative displacements of every brick in the array. A snapshot from one such video is shown in Figure 11. This type of analysis allowed identification of areas of the array that were particularly affected by the separations of the CoD bricks during seismic excitation.

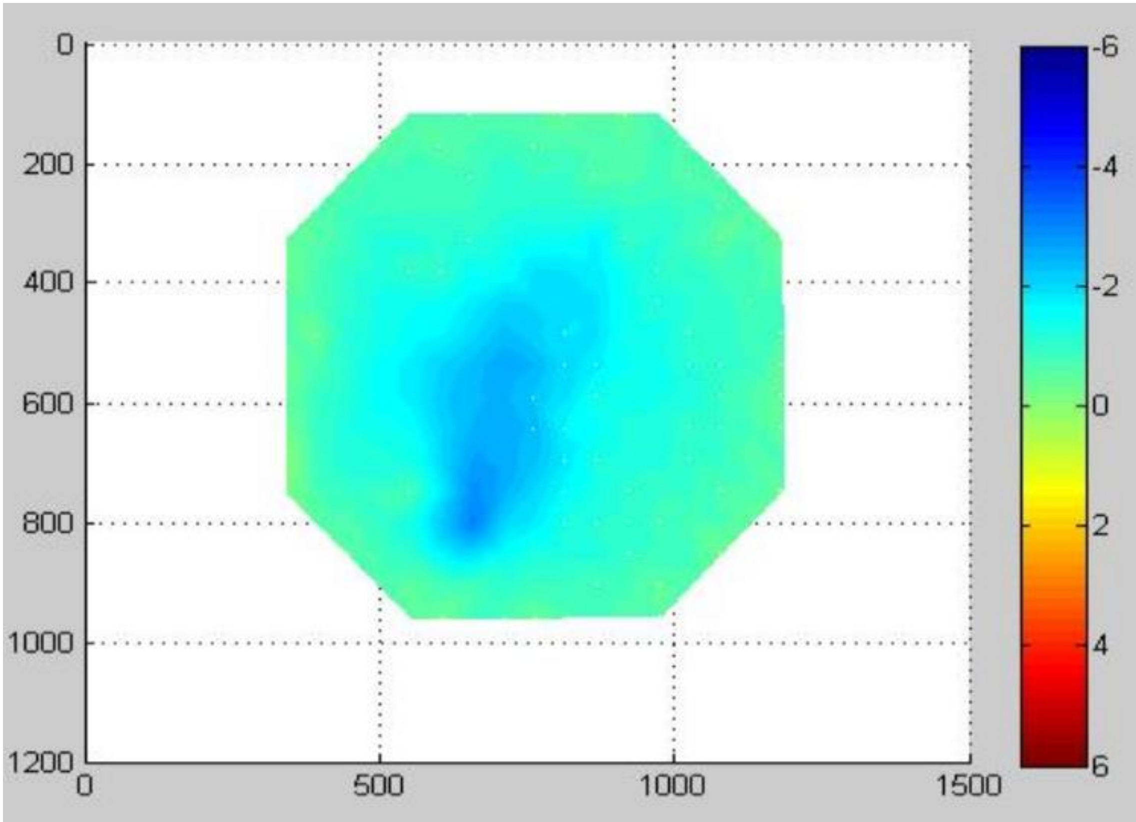


Figure 11: Video snapshot created from processed test data for the relative movement of the bricks in the array.

Two specific initial starting scenarios were compared. Firstly, a case where the CoD bricks were all already separated before the test started and secondly, a case where all the CoD bricks were held together by the electromagnets at the start of the test but then all separated during the test. By analysing these videos some interstitial bricks, such as the one shown in Figure 12, were identified for further analysis.

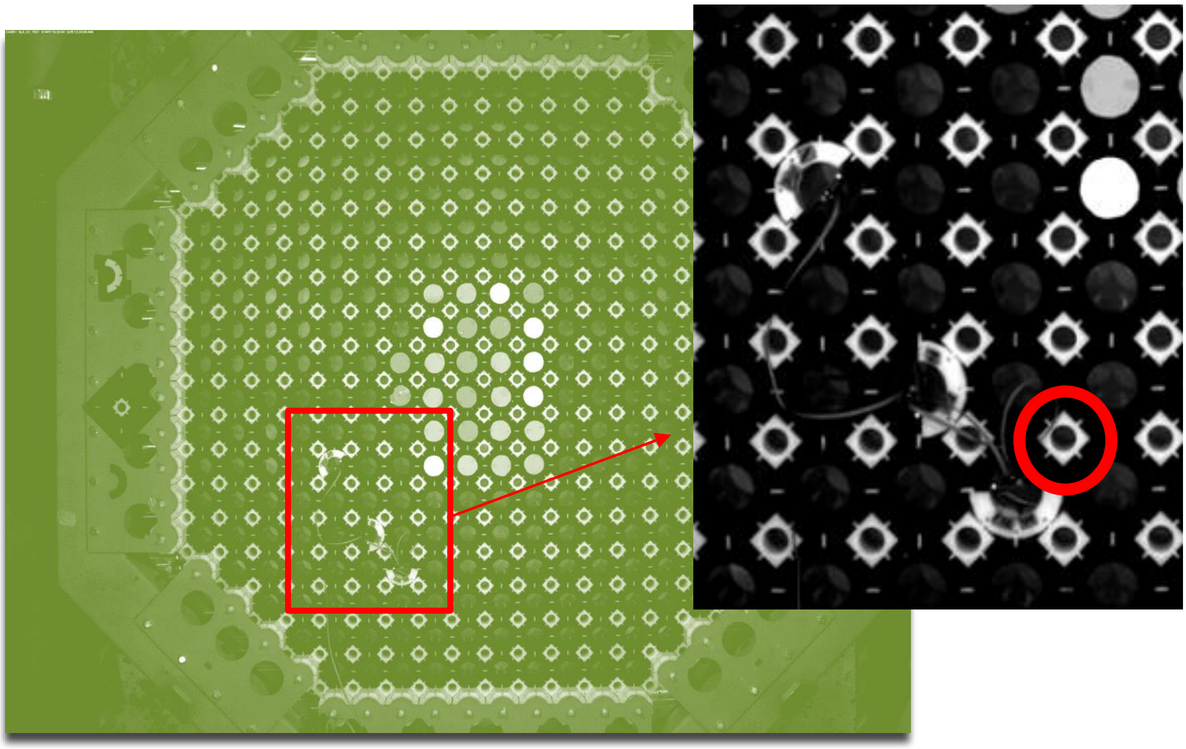


Figure 12: Interstitial brick located close to two CoD bricks that was identified for further analysis

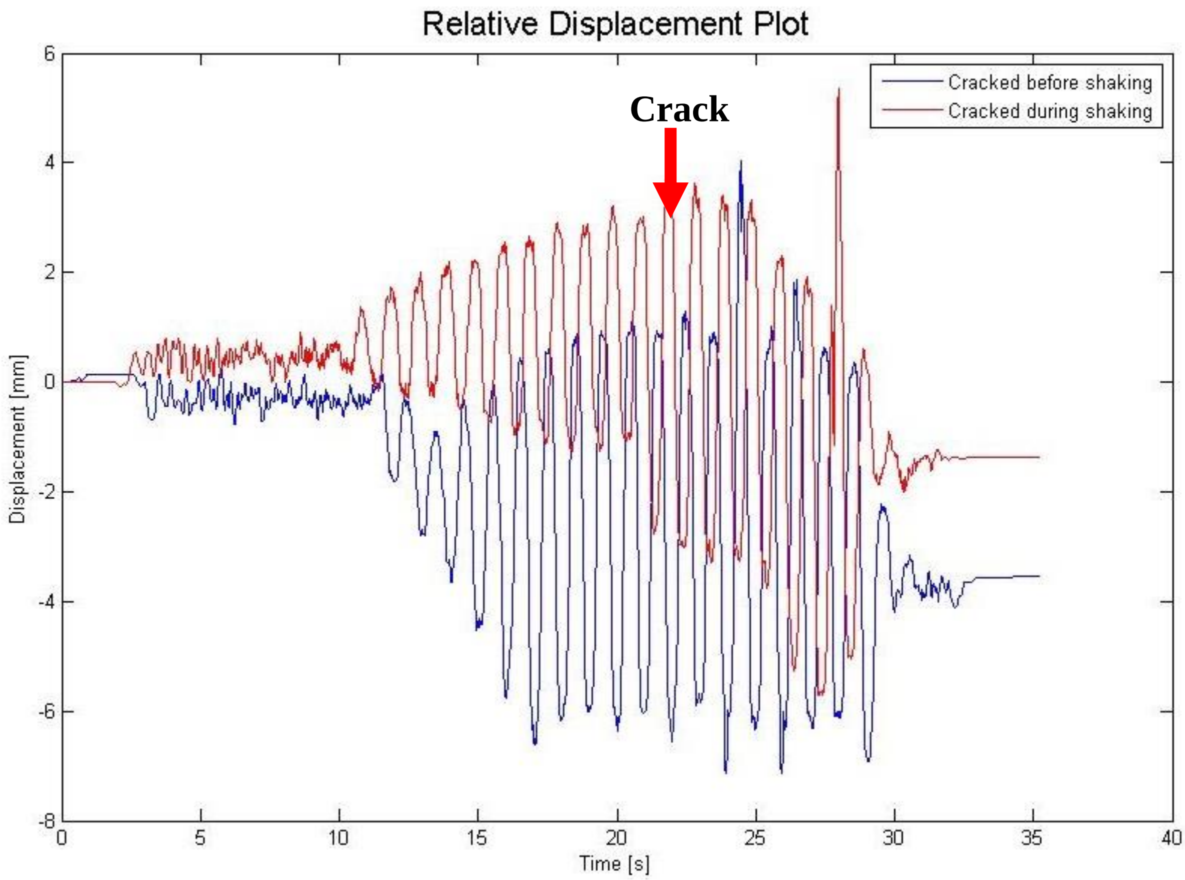


Figure 13: Change in response of interstitial brick when CoD bricks ‘break’ during shaking

Figure 13 shows, for the two different starting scenarios, the relative displacement of this interstitial brick within the array and several differences in the response can be identified. Both responses have approximately the same peak displacement at the end of the test. However, for the case where the CoD bricks were cracked at the start of the test (in blue), this peak displacement is reached rapidly once the excitation starts, and remains relatively constant for most of the excitation. For the case where the CoD bricks cracked during the excitation (in red), the first part of the shake corresponds to the displacement of an intact array i.e. a gradually building displacement. After the first brick 'cracks', the displacement of this interstitial brick suddenly gets larger, and the brick response becomes much more unsymmetrical.

5. CONCLUSIONS

Prototype crack on demand (CoD) bricks have been developed to study the potential for progressive failure of multiple graphite bricks in an Advanced Gas Cooled Nuclear Reactor (AGR) core during a seismic event. The CoD bricks are manufactured from Acetal in two halves held together using electromagnets powered by an adjustable current supply. During testing, in a ¼ scale model of a slice through an AGR core, the contact between the two brick halves is monitored by the electronics within the brick. When the hold force of the magnets is overcome, and any movement between the two half bricks is detected, the electromagnets are automatically switched off and the two halves of the brick are allowed to move freely. The CoD bricks proved challenging to calibrate and it was not possible to independently calibrate the axial and shear strength of the bricks although, through further refinement of the brick design, it is hoped that this can be achieved in the future.

Following an initial assessment of the potential for progressive failure of graphite bricks in an AGR core during seismic excitation the following behaviours have been noted:

- The array behaviour changes, with notable increases in displacement around the crack location, after a brick cracks during seismic excitation.
- Cracking of a brick during seismic excitation causes redistribution of forces around the array. In some of these initial tests, the impact of this was most obvious on the opposite side of the array to the cracked brick. It is possible that reductions in motion noted on the opposite side of the array to the crack are due to more energy being dissipated at the crack location.
- Although the array behaviour changes when cracking takes place it, this effect appears to be temporary and the array response tends to the case where the same bricks were cracked right from the start of the excitation.

Significant further testing is needed to confirm these initial observations about the impact of progressive failure of graphite bricks in an AGR core and to improve the design of the CoD bricks, but this initial research shows that it is possible to study this phenomenon via shaking table testing.

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