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Shaking Table Testing of an Advanced Gas Cooled Reactor Core Model with Degraded Components

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Abstract
The graphite components of an Advanced Gas Cooled Reactor (AGR) are subject to ageing processes that lead to changes of geometry and mechanical properties. Such changes need addressing in the safety case strategy of the operator, hence the necessity for both the numerical and the physical reactor models to be conservative and to represent high levels of graphite component degradation. This paper presents a quarter scale physical model of a multi-layer array representative of those in AGR cores. The rig was developed by the University of Bristol to support the seismic capabilities of the existing computer core models. The physical model can embed high percentages of doubly cracked bricks in various pattern distributions. Intact and cracked array configurations were subjected to seismic testing on an earthquake simulator. Relevant results of component displacement in the array are presented together with separation data between doubly cracked brick halves that provide evidence of key-keyway disengagement. The outlined experimental output demonstrates that the model rig is capable of providing an enhanced understanding of the mechanical interactions that take place inside the array with relevance for both the nuclear plant operator and the computer modellers.

Keywords
Reactor core, physical modelling, seismic resilience

INTRODUCTION

While it is not possible to measure directly the response of an actual Advanced Gas Cooled Reactor (AGR) core to a seismic loading of significant magnitude, full-scale physical model testing could be a potential way of assessing their seismic resilience. However, besides the excessively high cost of such an attempt, the overall dimensions of a full scale AGR core model (diameter ~11m, height ~10m, weight >1000tonnes) could not be accommodated by any 6-DOF ('Degrees Of Freedom') earthquake simulator in Europe. Scale model testing on a shaking table is a potential way to seismically qualify the real core but only if a high confidence can be established that a direct relationship between the response of the model and that of the prototype exists. Such an approach would be valid for structures that behave elastically, provided sufficient confidence exists in all the relevant scaling laws for the fundamental properties of the model, e.g. component geometry, material density and material stiffness. However, an AGR core is a highly non-linear array of bricks and keys, in which the relevant forces are the impact forces generated during collisions between the components and the inertia driving and restoring forces due to the seismic and gravity accelerations respectively. Therefore, the solution is to employ computer modelling of the actual AGR cores to determine the expected response. Assurance is then required that the computer model is adequate and conservative in predicting reality. The role of scale model testing is to provide such assurance by experimental validation of the numerical tools.

Currently, the seismic responses of the AGR cores are calculated using the GCORE finite element (FE) model (Kralj et al, 2005). GCORE uses the explicit dynamic solver, LS-DYNA. The GCORE approach is based on modelling the graphite bricks as rigid bodies connected with non-linear springs and dampers to represent the contacts and clearances. Given the ages of the AGR cores, there is a need to validate the use of GCORE for cores with a large number of components with significant levels of postulated degradation (e.g. 30-50% doubly cracked bricks and beyond). There is also a requirement to enhance the understanding of core dynamics, especially where components may behave in ways not explicitly modelled by the computational analysis (e.g. behaviour post key disengagement). A suitably representative physical model was required for this purpose. Since 2008, the University of Bristol (UOB) has conducted an extensive body of technical work that lead to the design and build of a quarter scale physical model of an AGR core, known as the Multi-Layer Array rig (the 'MLA rig') (Dihoru et al, 2011). The complexity and the unprecedented experimental design of the rig make it one of the most advanced tools for non-linear dynamics research in the world: its number of model components (> 44,000) and the number of measurement sensors (> 3,000) are pushing the boundaries of design in instrumentation, data acquisition and data processing.

This paper describes the testing of an MLA configuration containing 30% model double axially cracked bricks (DCB), with relevant outputs of component displacement and cracked brick separation being presented.

MLA RIG DESCRIPTION

The MLA rig contains an 8-layer assembly of quarter scale model bricks and model keys made of a rigid engineering plastic (Acetal)**.** In plan, the MLA is octagonal in shape and has 20 bricks across its cardinal directions (Figure 1).

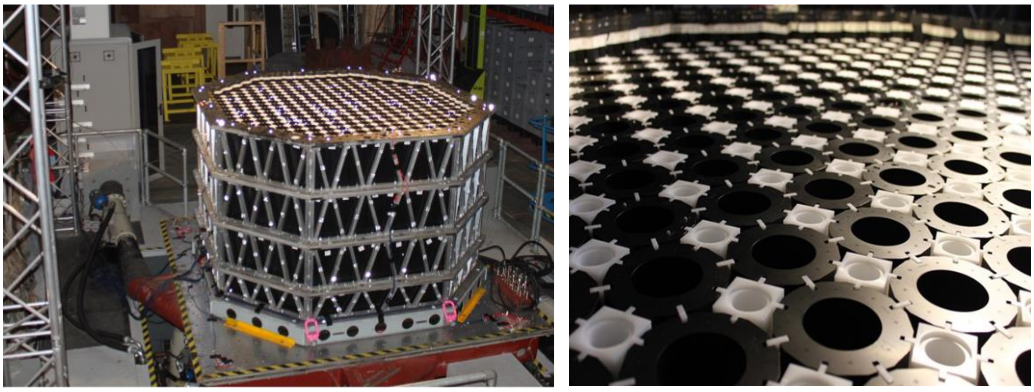

FIGURE 1: The MLA rig (left: general view, right: view of the top layer).

All the AGR graphite component types are modelled in the rig, i.e. fuel (lattice) bricks, interstitial bricks, filler bricks, filler, spacer and loose bearing keys. Model DCBs can be included in the array in various layouts and percentages (Figure 2). The present paper will focus on a cracked array configuration with 30% DCBs in layers 4-7. The cracking pattern follows a computer generated random distribution. The top layer of the array is intact. The array is enclosed by a rigid support frame and confined at the bottom by a rigid arrangement of plastic plates in which the bottom component of each vertical column is rigidly mounted.

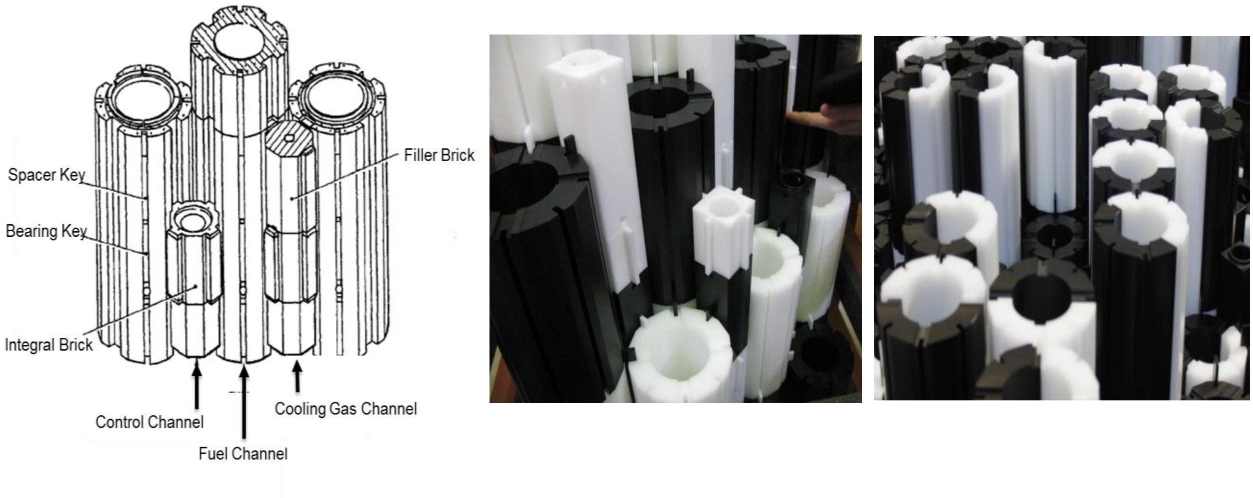

FIGURE 2: Arrangement of columns of bricks and keys in an AGR core (left). Layout of columns in the MLA rig (middle). Doubly cracked bricks in the MLA cracked configuration (right).

To be conservative, the MLA rig is designed to generate brick displacements of sufficient amplitude to exceed the current seismic assessment limits when simulating the effects of component degradation (i.e. doubly cracked bricks) and the increased brick-to-brick clearances arising from irradiation shrinkage in the AGR cores. The 16mm brick-to-brick gaps in the AGR prototype are scaled to 4mm in the MLA model. More details on rig development and operation can be found in Dihoru et al 2014 and Dihoru et al 2015.

MEASUREMENTS AND INSTRUMENTATION

A summary of the physical parameters that were measured in the rig and the instrumentation employed for this purpose is given in Table 1.

TABLE 1: Instruments and measurands in MLA rig testing

Instrument/ Measurement System	Measurands
Infrared Vision System (IRVS)	Displacement of array components, ML restraint frame, shaking table
High Speed Video System (HSVS)	Displacement of array components in top layer
Accelerometers (SETRA type)	Acceleration of shaking table and ML restraint frame
Accelerometers (MEMS* type)	Acceleration of interstitial/filler/lattice bricks
Hall Effect Sensors	Interstitial channel profile, loose bearing key position in the keyway, doubly cracked brick monitoring
Linear Potentiometric Transducers	Lattice channel profile

Note: MEMS* stands for Micro-Electro-Mechanical-System

The lattice channel measurements are obtained with potentiometric transducers installed on the bottom face of each model lattice brick in the instrumented column (Figure 3.1). Each filler and integrally keyed brick in the instrumented interstitial columns are equipped with a 3-axis accelerometer, while each lattice brick in the instrumented lattice columns contains 2 off 3-axis accelerometers (at the top and bottom). The interstitial channel profiles are measured using

Hall effect sensors mounted on both the top and bottom faces of each filler brick (Figure 3.2) in the instrumented column. Sets of three magnets are embedded in the vertically adjacent integrally keyed bricks (Figure 3.3) to interact with the Hall effect sensors in the filler bricks. These produce sensor voltages that can be converted into 6 DOF (degrees of freedom) of the filler-to-interstitial brick interface. The channel sensor outputs are acquired by a novel distributed micro data acquisition system (microDAQ) system consisting of a multitude of 16/32-channel DAQ systems hosted by the instrumented filler and the instrumented lattice bricks. The brick interface measurements are integrated up the columns to generate channel profiles. The MLA array also contains a pattern of infrared markers rigidly attached to selected components in the top layer that can be tracked by an infrared camera system. Figure 3.4 shows an example of 3 infrared markers (A, B and C) attached to a lattice brick in the top layer.

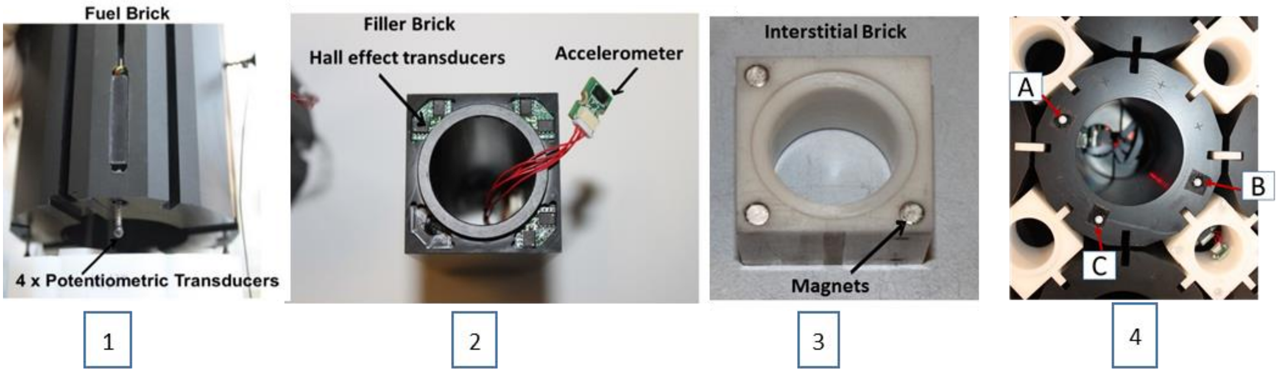

FIGURE 3: Instruments in the MLA - 1: instrumented lattice brick, 2: instrumented filler brick, 3: instrumented interstitial brick, 4: lattice brick with infrared markers (A, B and C).

A selection of model DCBs are equipped with magnets and Hall effect transducers to measure the 6DOF displacement of one half relative to the other half (Figure 4).

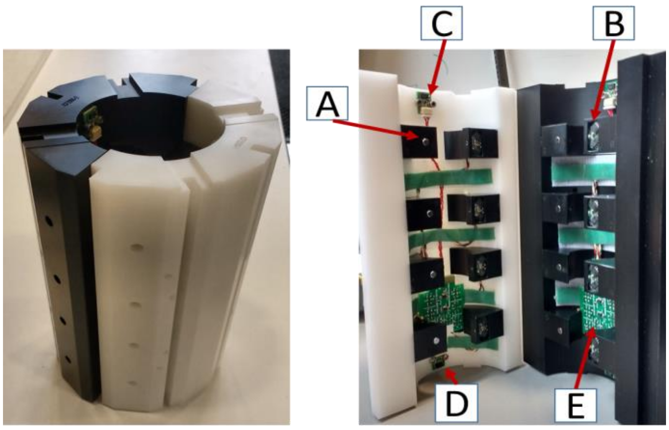

FIGURE 4: Instrumented doubly cracked brick: A: magnets, B: Hall effect sensors, C and D: triaxial accelerometers, E: terminal board for the microDAQ system.

EXPERIMENTAL WORK

Test Schedule

The MLA programme of testing is driven by the computer modeller needs, being designed to generate results for comparison against primary GCORE model outputs such as brick-to-brick displacements and channel profiles. The main objectives are to reduce the uncertainties in the numerical tool, to investigate the interactions between keys and keyways before and after disengagement and to investigate how far the current assessment limits are from cliff-edge behaviour. The focus of testing is on scaled input motions that are derived from the hazard inputs and resulting responses predicted by the seismic assessments of the UK's AGR stations. The seismic inputs are applied as directional rosettes with 22.5^{o} or 45^{o} increments, at acceleration magnitudes varying from 0.05g to 1g. A summary of typical inputs employed in testing is presented in Table 2.

TABLE 2: Typical Inputs Employed in MLA Testing

Input Type	Input Characteristics	Input Direction	Comments
White noise	Frequency range: 0-100Hz Acceleration amplitude (RMS*): 0.04g	X, Y, Z	Modal testing for MLA restraint with and w/o array. Explore resonant frequencies. Investigate symmetry of restraint.
Sinusoidal dwell	Frequency: 1Hz, 2Hz, 3Hz, 4Hz, 5Hz Acceleration amplitude (pk-pk*): 0.1g, 0.25g, 0.3g, 0.8g	X, Y	Explore frequency response and ability to replicate basic mechanics.
Seismic	Time history generated from secondary response spectra at AGR power stations, $10e^{-4}$ probability of occurrence. Time scaled (time scaling factor*=2)	rosette	Explore onset of changes of behaviour. Amplification of response for certain frequencies and energy bands. Effect of input scaling on response.
Seismic	Time history generated from secondary response spectra at AGR power stations, $10e^{-4}$ probability of occurrence. Unscaled	rosette	

*RMS: Root Mean Square (quadratic mean of acceleration); *pk-pk: peak to peak; *time scaling factor of 2 derived from length scaling factor of 4.

Typical Experimental Results

Array Response

Under dynamic excitation, the array behaves like a system of rigid bodies in which the relevant forces are the impact, the inertial and the gravity forces. The energy restitution after a brick-to-brick collision depends heavily on the actual layout of components in a region of investigation (i.e. component-to-component gap, presence or absence of bearing key, presence or absence of interstitial key, locking of key, etc). In general, the array behaviour is displacement driven, being governed by the brick-to-brick and the key-keyway clearances. The relative movements of the bricks in the central region of the array move more due to gap accumulation effects than the bricks at the periphery whose movements are restricted by the presence of the frame boundary (Figure 5).

At the end of each test, the columns of the array recover their vertical positions under gravity restoring forces, with the brick-to-brick gap of 4mm being restored by the radial keying systems. Some variations in positions will occur between the end and the beginning of each test, as the loose bearing keys depth in the keyway will vary. These differences as well as those caused by variations in dimensional tolerances and friction may affect the subsequent responses including their symmetry about the XY plane. Repeat tests confirmed that the array responses were not sensitive to these variations in starting conditions.

The top layer displacement response was investigated for the cracked array with 30% DCBs randomly distributed in layers 4-7 (MLA3). Figure 6 shows the displacement relative to the frame for four lattice bricks in the top layer, situated near the centres of the four quadrants (i.e. LB3331- centre of the NW quadrant, LB1531- centre of the NE quadrant, LB3317- centre of the SW quadrant and LB1517- centre of the SE quadrant), during a seismic test (i.e. Test 1129, seismic RRS compatible Eurocode, quarter scale, X direction, shaking table input acceleration ~0.64g).

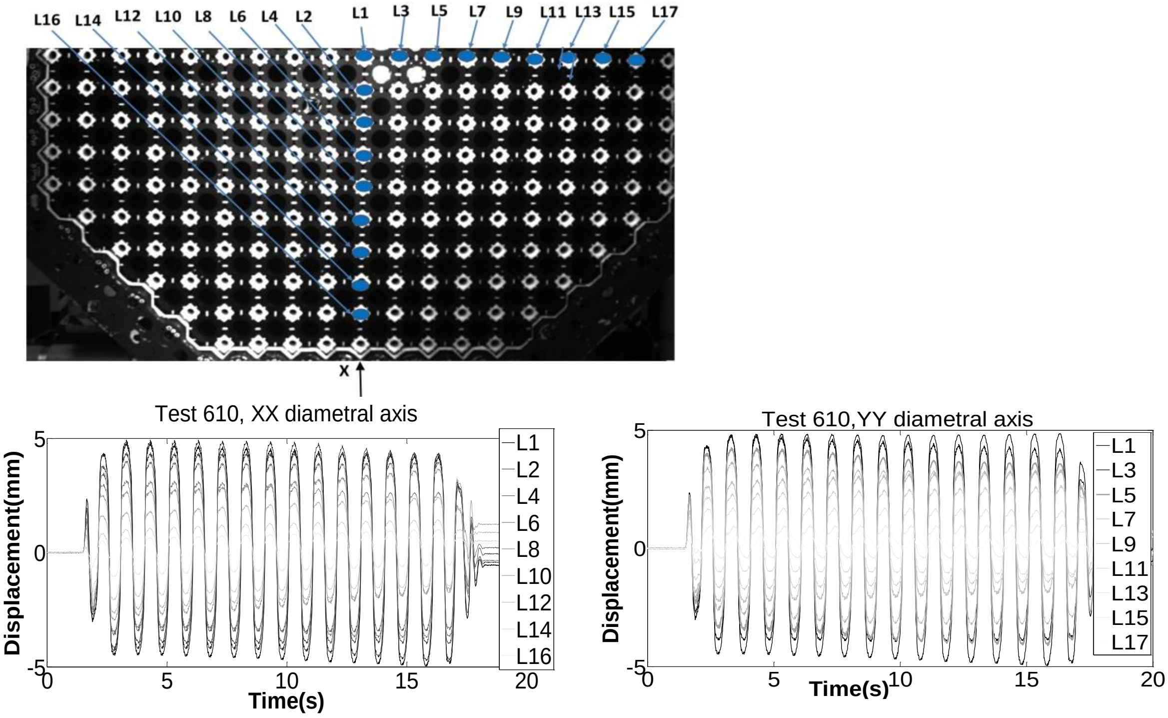

FIGURE 5: Relative displacements of interstitial bricks in an intact array (MLA1) across the XX and the YY array axes via HSV in Test 610 (sinusoidal dwell, f=1Hz, A=36mm, acceleration magnitude ~0.3g peak-to-peak).

The relative displacement of the four bricks ranges between +/- 3mm. The magnitude and phase of the transfer functions computed between the frame displacement input and the brick displacements (Figure 7) show that the centres of the quadrants appear to move together with no significant phase shift in their response. The response of the centres of the quadrants was also analysed in a test conducted on Y direction (Figure 7 right, Test 1131, seismic RRS compatible Eurocode, quarter scale, Y direction, shaking table input acceleration ~0.64g). A similar pattern of response was previously observed in the intact array (MLA1). This shows that the intact top layer has an ‘anchoring’ effect on the array and that the presence of 30% DCBs in layers 4-7 does not affect significantly the symmetry of response in the top layer.

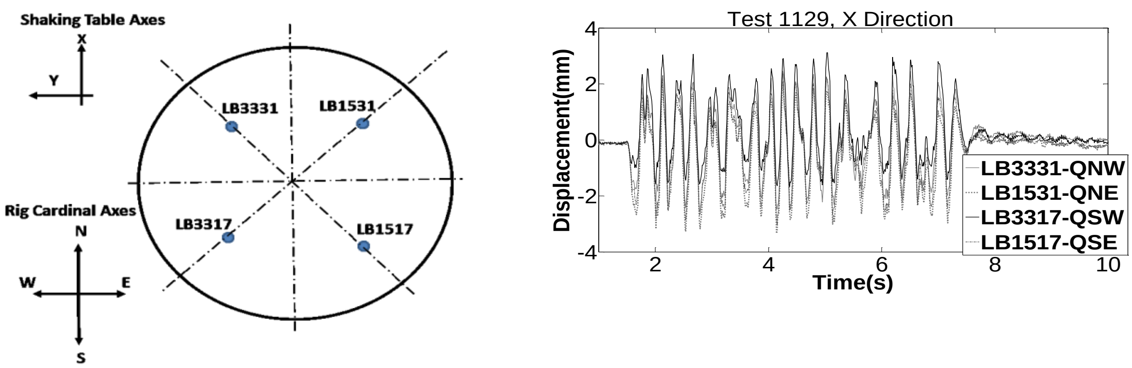

FIGURE 6: Relative displacement of the centres of the quadrants in cracked array MLA3. Test 1129 (Seismic RRS compatible Eurocode, quarter scale, X direction).

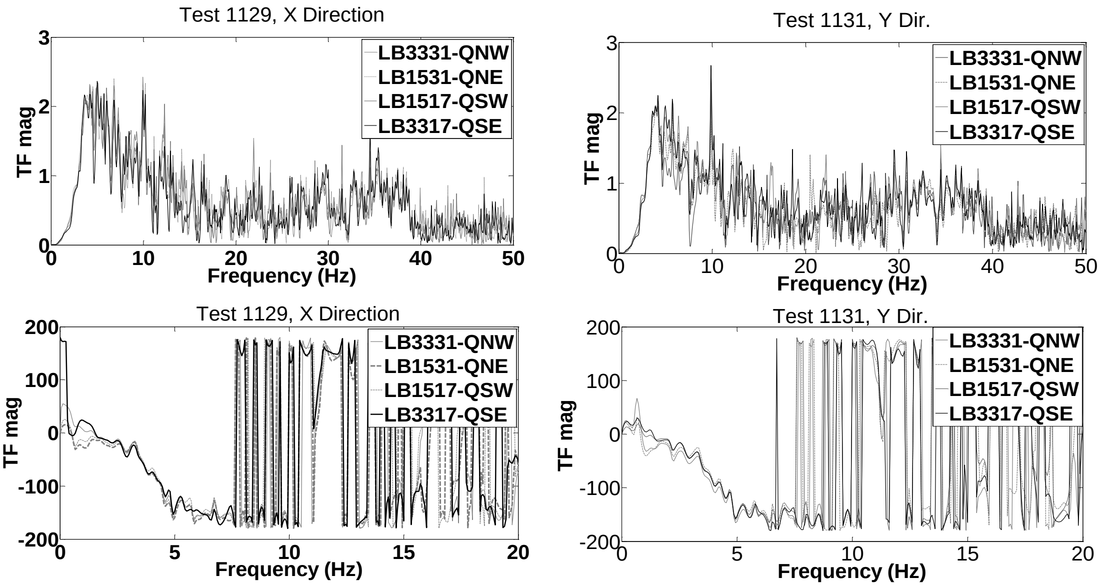

FIGURE 7: Transfer functions between frame input and relative displacement of the centres of the quadrants in cracked array MLA3. Left Top: magnitude of transfer function. Left Bottom: phase of transfer function. Test 1129 (Seismic RRS compatible Eurocode, quarter scale, X direction). Right Top: magnitude of transfer function. Right Bottom: phase of transfer function. Test 1131 (Seismic RRS compatible Eurocode, quarter scale, Y direction).

DCB Monitoring

The cracked array (MLA3) test configuration included 10 instrumented DCBs to monitor the relative movement of the two brick halves. Most of those bricks were placed in vulnerable columns (with aligned cracks spanning two or three layers) having the greatest potential for brick separation and thus key disengagement. No signs of disengagement were observed for the quarter scale seismic motion tests which were conducted up to a maximum level of 1.04g shaking table acceleration. The first signs of disengagement were observed at a shaking table acceleration level of ~1g for the seismic RRS compatible HPB 10^{-4} full scale input motion. Examination of the brick half separation data can give an insight into key disengagements. Figure 8 shows the relative separation between the two brick halves of the layer 6 lattice brick in column 2731 for Test 1244 (Seismic HPB, 10^{-4} p.a., full scale, max input acceleration ~1.2g).

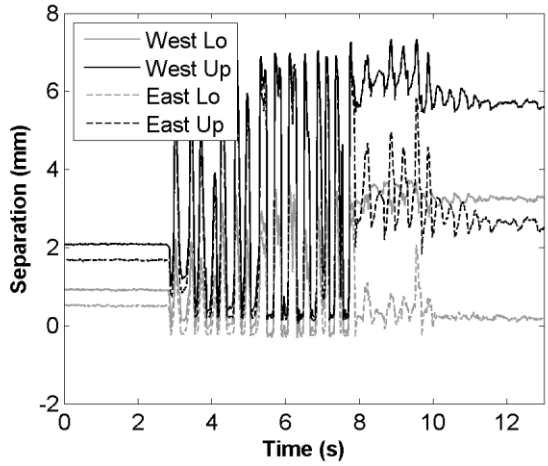

FIGURE 8: Separation between the halves of doubly cracked brick LB2731, Layer 6, Test 1244 (Seismic HPB, $10^{-}4$ p.a., full scale, max input acceleration ~1.2g). Separation is shown for the low and the top end of the brick.

The remanent separation at the top of the DCB shows that a key is most likely trapped between the two halves. The greatest remanent separation is observed at the top west corner of the crack indicating that the key is closest to that position. Furthermore, the fact that the separation is bigger for the two top positions than the two bottom positions indicates that the trapped key is located in the top half of the west crack. Figure 9 left shows a pictorial example of a key trapped between the two halves of a DCB in layer 6 of the array. The top layer (Figure 9 right) shows two empty keyways that suggest a drop in the bearing/spacer key column that may have been caused by a key disengaging and possibly getting trapped in a DCB at a lower layer.

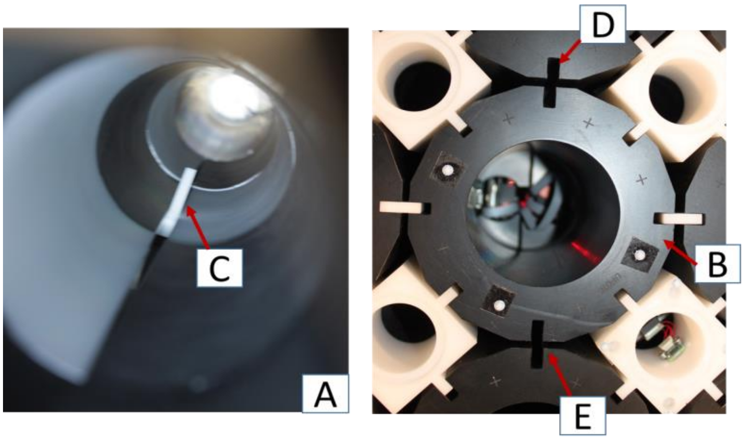

FIGURE 9: A: example of doubly cracked brick inside the array, B: top layer lattice brick in a column containing doubly cracked bricks, C: disengaged key trapped between the brick halves, D and E: empty keyways showing a drop in the bearing key column, caused by disengaged keys in the layers below.

CONCLUSIONS

A highly complex quarter scale physical model of large radially keyed array of bricks, representative of those used in AGR graphite cores, has been presented. Model doubly cracked bricks can be embedded in various layouts and percentages. The model array is fit for purpose from a design and functionality point of view and has the ability to reproduce the basic mechanics of radially keyed arrays with relevant interactions and mechanisms being captured. Examples of measured brick displacements and relative movements of model doubly cracked bricks, which can be employed for validating and tuning of computational models, have been given.

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References

Dihoru, L., Crewe, A.J., Taylor, C.A., Horgan, T. (2011). Shaking Table Experimental Programme, *Proceedings of the Conference on Modelling and Measuring Reactor Core Graphite Properties and Performance*, Aston University, Edited by Gareth B. Neighbour, Cambridge, UK.

Dihoru, L., Oddbjornsson, O., Horseman, T., Dietz, M., Wilson, J., Kloukinas, P., Voyagaki, E., Crewe, A.J., Taylor, C.A. (2014). Multi-Layer Array Rig Work For Seismic Behaviour With Cracked Bricks. *The 4th EDF Energy Nuclear Graphite Symposium. Engineering Challenges Associated with the Life of Graphite Reactor Cores,* Nottingham.

Dihoru, L, Oddbjornsson, O, Crewe, A, Taylor, C & Steer, A. (2015). The Development of a Physical Model of an Advanced Gas Cooled Reactor Core: Outline of the Feasibility Study. *Proceedings of 'Structural Mechanics In Reactor Technology' Conference (SMIRT 23),* Manchester, 10-14 August 2015.

Kralj, B., Humphreys, S.J. and Duncan, B.G.J., (2005*) Proceedings of the Conference on Seismic Modelling of an AGR Nuclear Reactor Core,* pp 193-200, Cardiff.