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A SINGLE LAYER RIG FOR EXPLORING THE DYNAMICS OF AN ADVANCED GAS COOLED REACTOR GRAPHITE CORE: COMMISSIONING AND PROPOSED VALIDATION STUDIES

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Abstract: The consequences of the ageing of Advanced Gas Cooled Reactor (AGR) need to be assessed for their continued safe and reliable operation. This includes consideration of their behaviour under external hazards of which the most significant is seismic. The numerical tools that support the seismic assessments for the AGR cores must be conservative and able to cope with a wide variety of damage types and damage levels for the graphite components. A new computational model is under development using the novel simulation code SOLFEC based on this Non-smooth Contact Dynamics method. This code would enable solid-body dynamic simulations to be carried out using explicit representation of individual bodies, providing greater detail than the existing models. The development of SOLFEC will be supported by shaking table tests carried out at the University of Bristol on a quarter scale single layer rig. This paper presents the commissioning activities carried out to demonstrate that the rig is fit for purpose in all its geometrical, mechanical and dynamic aspects. A planned schedule of work intended to provide validation data to SOLFEC is described.

Introduction

The Advanced Gas Cooled Reactor (AGR) is a type of nuclear reactor that employs graphite as a moderator and carbon dioxide as a cooling agent. In the UK, there are currently seven nuclear power stations with two identical AGR reactors each, all of them operated by EDF Energy. Attenuation of fast neutrons by graphite causes differential dimensional changes that may lead to component cracking. The long-term behaviour of the core is also affected by radiolytic oxidation that leads to exponential decay in graphite elastic modulus and strength [Steer 2005]. These ageing degradation issues need to be addressed to ensure continued safe operation of the reactors, hence the requirement for the reactor core models to be conservative and able to represent high levels of graphite component degradation. Current international standards require that a nuclear plant should be qualified against at least 0.1 g peak ground acceleration, while the operators require that their nuclear power stations (AGRs) can be safely shut down and held down in the case of a more severe seismic event with a probability of exceedance of 10^{-4} per annum. It is recognized that seismic testing is needed to validate experimentally the reactor core computer models and to enhance the understanding of core dynamics, especially where components may behave in ways that cannot be represented using the current computational methods [Kralj et. al. 2005].

This paper presents a collaborative framework set up by EDF Energy, Atkins and the University of Bristol (UOB) in order to address the seismic tolerance of the AGR cores in both experimental and numerical modelling. The experimental programme conducted at UOB for

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the design, build and testing of a single layer array (SLA) physical model of a core is presented together with a plan of validation studies for SOLFEC, a novel simulation code, under development at Durham University [Koziara and Bićanić 2011]. SOLFEC offers the prospect of carrying out detailed solid-body simulations to supplement the existing simplified dynamic models. This paper gives a general presentation of SOLFEC's usability as an engineering tool for AGR seismic assessments.

Physical Modelling Considerations

In general, the complexity of a physical model is determined by its number of components and level of precision in reproducing the geometry and scaled dimensions. The more complex the scale model, the higher its level of representation for the dynamic behaviour of a 'generic' prototype. The simpler the physical model, the more sophisticated the mapping software that extrapolates the experimental results should be for a realistic prediction of the prototype response.

A summary of scaling factors for earthquake response of structures can be found in Crewe 1998. In general, a true replica model implies simultaneous duplication of inertial, gravitational and restoring forces and full compliance with the similitude laws. Such a model would require scaling of density and stiffness at the same time. One way would be to find a material whose properties satisfy scaling requirements simultaneously. As this is in practice impossible, an adequate approximation has to be sought. A method frequently employed in physical modelling is the artificial mass simulation method. It requires adding extra material of a non-structural nature to simulate the required density of the model. Such mass can be lumped or distributed. This method is difficult to apply to the scaled AGR core model because of the large number of components that have a role in the system's dynamics. Distributing an artificial mass within such a complex array of rigid blocks would be technologically impractical. A third type of modelling can be used where gravity forces can be neglected. In the particular case of a graphite core under seismic loading, the gravitational forces cannot be neglected, so this type of scaling law cannot be used.

It is therefore proposed that the graphite core model should be an 'adequate model' which maintains 'first-order' similarity. This implies that the physical parameters that have the significant influence on the seismic response are accurately scaled, while 'second-order' parameters of less significance are only approximately scaled. In this way a modified version of a true replica model will be created. For the modelling work at UOB, it was proposed that the geometrical properties of the core would be scaled, as the channel shapes and the general distortion of the core are governed by the brick-to-brick and the key-keyway clearances. It was decided that the brick and key design would be a quarter scale design based on cores that have been subjected to the highest dose of radiation.

The scaling of material properties also had to consider the dynamic problem at the centre of this investigation. During a seismic event, the core will behave as an array of rigid bodies 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. As impact forces depend on the local contact properties (i.e. contact stiffness and coefficient of restitution), then the correct assessment of these properties becomes relevant in scaling. Brick-to-brick testing ('feature testing') of model components are being made to determine the contact characteristics of the for various component combinations.

All the above physical modelling considerations were part of an extensive study carried out at UOB that investigated several candidate rigs from the point of view of their feasibility and from the point of view of their experimental capabilities [Dihoru et. al. 2011]. Rig feasibility involves aspects such as manufacturing cost, manufacturing time, challenges of design and manufacturing, complexity and convenience of the measurement systems, number of personnel required for handling and testing. The reasoning behind the feasibility study lead to the conclusion that a phased modelling approach would be the most suitable way forward. Therefore, out of the possible component layouts that could be used in physical modelling, two simpler models, i.e. the ‘mini-core’ (a 4x4x8 array) and the single layer array, have been selected as ‘learning tools’ before a more complex model (i.e. the multi-layer array rig) could be designed. This paper addresses the design, development and testing of the single layer array (SLA), which was selected as a simple but potent tool for studying the fundamentals of core dynamics, mainly because of its simple boundary conditions and fast test turnaround.

The Single Layer Array (SLA) Physical Model

The SLA rig is a near-full core single layer rig with 20 model lattice bricks, which perform the same mechanical function as fuel bricks in the AGR cores, across the maximum dimension and a rigid octagonal restraint frame. The model array consists of lattice bricks, interstitial bricks with integral keys and bearing keys joining neighbouring lattice bricks. All are made of a rigid engineering plastic (Acetal). The geometry of the model components is based on the as-manufactured geometry of the prototype components of the graphite cores with the highest irradiations. A general view of the SLA rig is given in Figure 1 left and a more detailed view of the model components is shown in Figure 1 right.

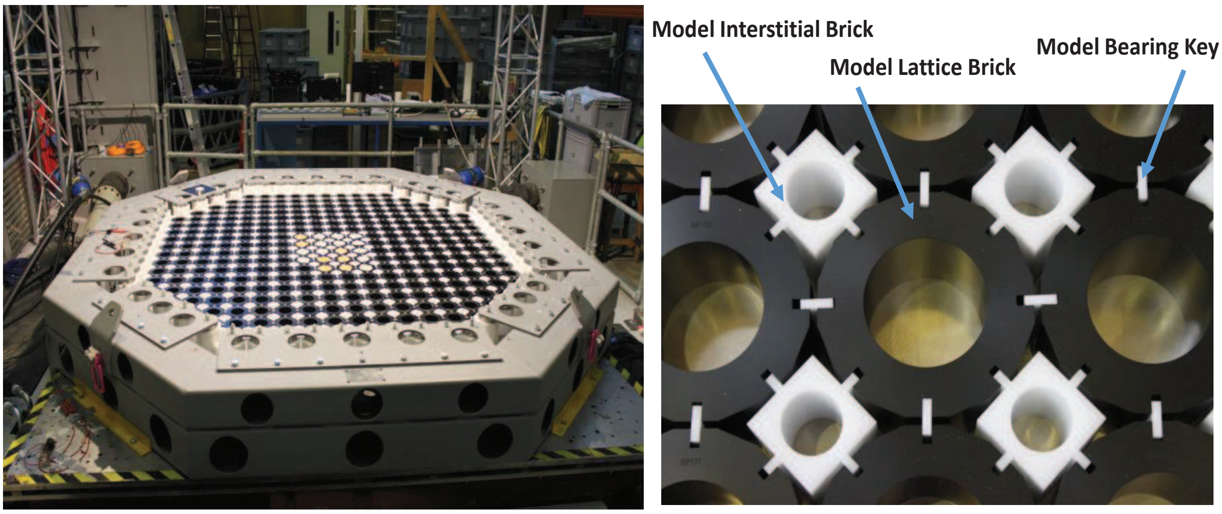

Figure 1. Left: The SLA rig assembled on the shaking table platform. Right: The SLA rig model components.

The SLA model embeds the increased potential for brick displacements due to component degradation and the increased brick-to-brick clearances arising from advanced shrinkage. The general dimensions of the model components are quarter scaled from the prototype dimensions late in life, with the model lattice bricks reduced in height (i.e. a third of their quarter scaled height). This has a number of practical advantages; including the removal of the need to devise a means of maintaining the bearing keys at their correct height, and the minimization of rocking associated with full-height bricks that affects the accuracy of the infra-red vision system. These simplifications are possible because the multi-body array kinematic behaviour is dominated by movements and loads in the horizontal plane. The brick-to-brick clearances between the lattice bricks are 4mm, quarter-scaled from the approximately 16mm brick-to-brick clearances predicted for the prototype. The key-keyway clearances are also quarter-scaled for the correct reproduction of rotational and translational movements of the key in the keyway (prototype clearance: 1.04 - 1.52 mm), although slightly looser because of limitations with the machining the Acetal components to true quarter-scale tolerances.

The bricks are free to slide on a flat horizontal stainless steel base, within the confinement of the octagonal rigid frame. The lateral restraint systems of AGR graphite cores vary across the designs and are complex arrangements of beams and rods. Although these have an effect on the dynamics of the brick arrays and are included in the dynamic models used to assess the reactor cores, the purpose of the experiment is to investigate the special nature of the multi-body kinematics between the individual bricks and keys. Consequently, it was decided that the restraint system of the physical rig would be simplified to be dynamically rigid in the range of frequencies and displacements employed in seismic testing so that its behaviour would not have a significant influence of the response of the array.

In addition to the intact array components, the SLA rig can also include simulated doubly cracked model lattice bricks (DCBs) that can be used in various percentages and orientations inside the array. Figure 2 shows an example layout of DCBs employed in a sinusoidal test (T40: sinusoidal input at 45deg, a_{max} = 0.321g) in which crack opening and key disengagement were monitored.

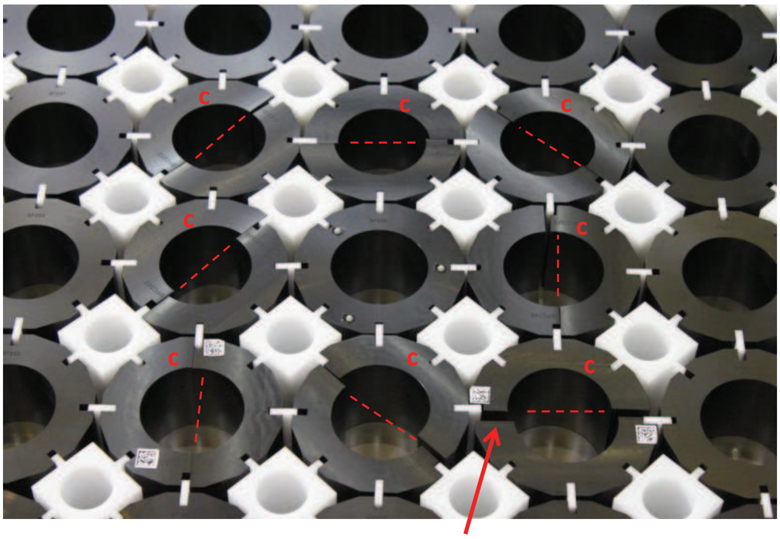

Figure 2. SLA array containing eight doubly cracked bricks with random cracked orientation after test T40 (sinusoidal input on XY direction, a_{max} = 0.321g). Crack opening and half brick shearing. No key-keyway disengagement.

SLA Objectives

The SLA dynamic testing programme will be designed to suit the validation needs of SOLFEC. Overall, the very simple boundary conditions in the SLA rig make the rig data easier to understand and compare with the outputs of the numerical model. The following measurements will be carried out in the SLA tests:

- Measurement of relative and absolute displacements for selected array components
- Measurement of local and global core distortion
- Measurement of separation between selected cracked brick halves
- Measurement of position of selected keys in the keyways.
- Measurement of acceleration of selected model bricks

The earthquake simulator at UOB is capable of generating a wide range of inputs, such as: sinusoidal waveforms, sinusoidal sweeps, real earthquakes and artificial earthquakes. For this particular application, the following types of inputs will be considered:

- Sinusoidal dwell inputs to explore the frequency response of the model and its ability to replicate the basic mechanics. The sinusoidal dwell probes will reveal onsets of changes response characteristics more clearly than more random seismic loads would.

- Sinusoidal sweep inputs to explore the frequency response of the model and to investigate its response over a wider range of frequencies. Degradation of stiffness (arising from key disengagement for example) can be observed via repeated sine sweeping.
- Seismic input runs at different amplitudes so as to detect onset of changes in behaviour. Running sets where the dominant input frequency is below, at, and above the 'natural frequency' of the core may also be considered with the purpose of checking the frequency response of the numerical models. The input records will be based on power spectra and not on response spectra, as the former will contain the same input energy, allowing the same base for comparison.

Real time acceleration and displacement of selected components inside the array will be measured. Time histories and frequency responses as well as phase information (ideally displacement vs. velocity) will be the target test outputs. Since the characterisation of the starting conditions for the physical core model will be difficult, making direct validation comparisons will be difficult. The comparisons with the numerical model will have to be more generic, perhaps looking at envelopes of response. It is recognised that the existing numerical model (SOLFEC) will have to be enhanced in order to interpret or extrapolate and map the observed physical model behaviour. The SLA will provide information on the upper levels of displacements that might be expected for the components under dynamic excitation and will provide data for validation of 2-D computer model layouts. The single layer rig will also provide proof of concept and possibly highlight experimental aspects that need considering in the second phase of work, when a multi-layered rig will be tested.

Measurement Systems and Commissioning Activities

The SLA commissioning work consisted of a complex set of assessments carried out in order to demonstrate that the rig is fit for purpose in all its dimensional, geometrical and dynamic aspects. The following activities were carried out:

- Assessment of support frame and base plate conformity
  - Assessment of levelness of the support frame
  - Assessment of flatness and friction properties of base plate
  - Assessment of natural frequencies of support frame
- Assessment of stiffness / frequency of restraint bricks installed in frame
- Assessments of Brick Array
  - Building procedure
  - Assessment of array anisotropy
  - Assessment of potential for key-keyway disengagement
  - Assessment of component mapping system
  - Assessment of instrument coding system

The rigidity of the restraint frame is an important aspect of the rig, as no frame deflection should contaminate the array response for the range of amplitudes and frequencies employed in testing (i.e. typical accelerations up to 1g, typical frequencies up to 30Hz). The restraint frame commissioning tests revealed that no significant resonances occur below 30Hz. The lowest significant resonance of the frame is in the vertical direction at ~49Hz having ~3% damping. Towards the support frame’s boundary, both on the restraint system’s top plate and on the frame boundary section, some minor resonances were observed in the horizontal plane. The lowest of these resonances is a highly damped slight resonance at ~22Hz with a second one at ~40Hz. These resonances observed in the horizontal plane are very small with low level of amplification and high level of damping and therefore would not have significant influence on the dynamics of the support frame. Figure 3 shows the transfer functions between the accelerometer response on the frame and the shaking table input on X and Y directions, for two modal tests carried out with random white noise over a frequency range of 0-100Hz.

Similarly, the restraint bricks embedded in the restraint frame were proved to be rigidly connected to the frame, exhibiting no significant resonances for the typical dynamic test parameters.

In general, it is important to keep the response characteristics of the experimental rig as simple as possible and ensure no unwanted experimental artefacts exist. One of the unwanted effects which could significantly add to the complexity of the problem would be rocking of rig components. To ensure rocking is not an issue, an investigation into the single layer rig components potential for rocking was carried out. Even for individual interstitial bricks (not in an array), having unfavourable width to height aspect ratio of close to 1, the rocking was so small that it could not be explicitly measured. The small level vertical accelerations measured, independent of the horizontal excitation amplitude, are most likely related to the surface roughness/flatness of the brick to friction base contact. The only single layer rig component that couldn't be thoroughly tested is the loose bearing key, which could potentially slowly make its way up and out of the keyways. For the type of tests expected to be carried out on the single layer rig, normally lasting no more than 30 seconds, keys making their way up and out of keyways is considered unlikely and will be dealt with subsequently should the problem arise.

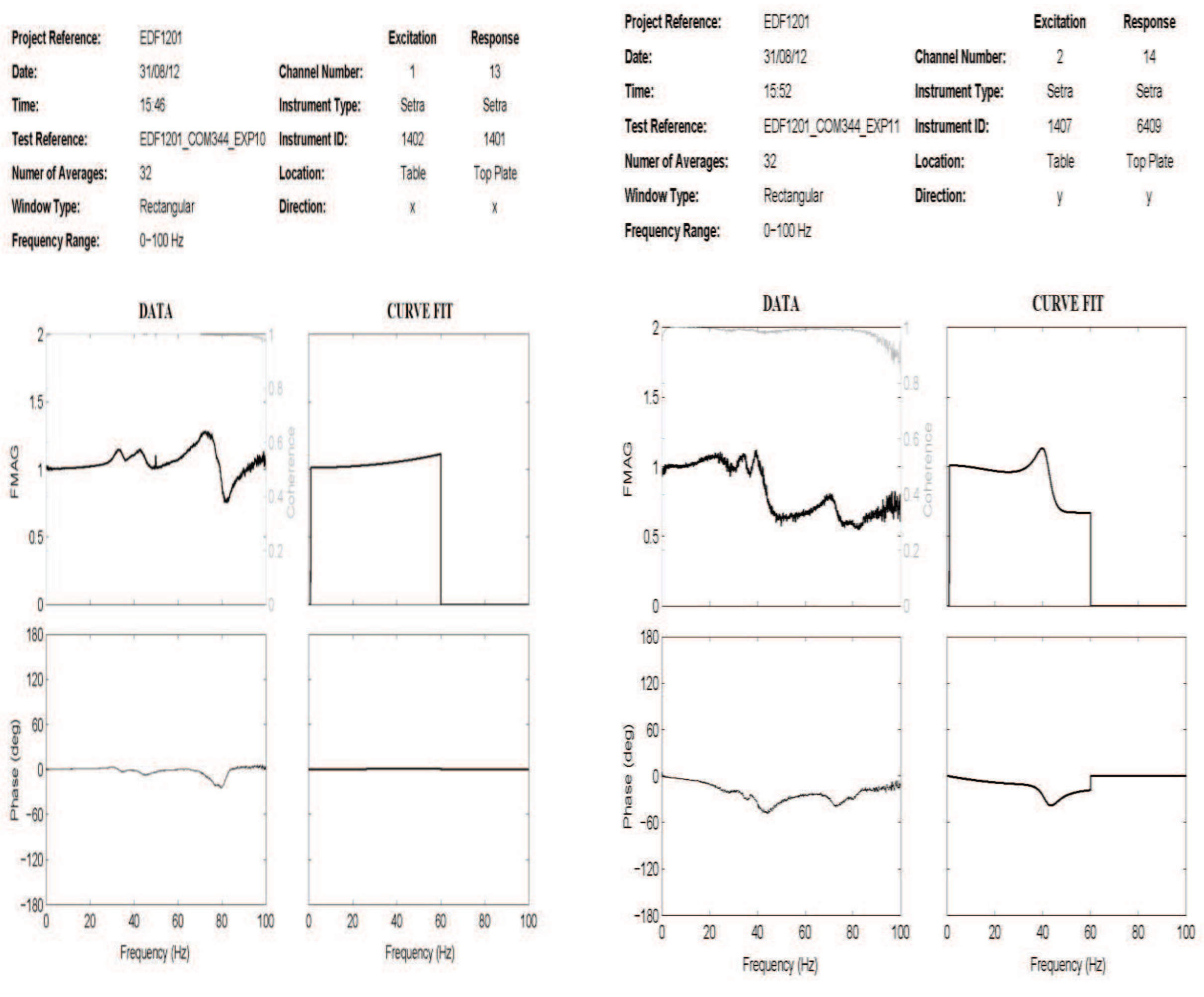

Figure 3. Transfer functions between acceleration response signal on the SLA frame and the shaking table input for white noise tests, frequency range: 0-100Hz (left: X direction, right: Y direction).

Another unwanted phenomenon in the SLA rig is the friction between the base plate and the rig components. The mechanics of the friction with its three stages, stick-stick (sticks over the whole forcing cycle), stick-slip (slides over a part of the forcing cycles, sticks over the rest) and slip-slip (slides over the whole forcing cycle), need to be understood. A dynamic friction test was carried out at selected amplitudes for an individual interstitial brick sliding on the restraint base. The input acceleration and the response acceleration were plotted together on diagrams showing the ramp up (transient) state and the steady state response of the block relative to the input motion, (see Figure 4), for a range of input motion amplitudes. At small input motions, 0.20g PGA and smaller, a stick-stick state exists and the block moves with the motion of the shaking table. At large input motions, above 0.5g PGA, the block responds with slip-slip behaviour, isolating itself from the large motions of the shaking table. At intermediate levels, the block responds with stick-slip behaviour, where the block slides over a part of the forcing cycles and stick over the rest. The stick-slip behaviour can be clearly observed in Figure 4 for 0.25g and 0.30g PGA. The sliding (the level of the plateau in the time histories) acceleration observed is between 0.20g and 0.25g giving a coefficient of friction μ in the range 0.20-0.25. In order to minimize the friction between the array and the restraint base, an uniform layer of glass beads (average diameter ~0.5mm) will be placed at the interface. Empirical tests on arrays on glass beads show that the coefficient of friction at the base interface drops well below 0.1. Minimizing the friction in the rig reduces the need for more complex modelling of friction in SOLFEC. The need for a ‘frictionless’ base stems from the fact that in the real AGR the bricks do not slide on the base – hence friction in the SLA (and the resulting large reduction in motion) is not really appropriate.

An important part of the SLA commissioning activities involved evaluating the displacement measurement system. The SLA displacement measurements are served by an infrared vision system (IVS) and a high-speed video system (HSV). The IVS consists of five high speed cameras (type Oqus400, Qualisys) featuring a 3.0 megapixel sensor capable of 480 Hz full frame resolution at full field of view. Figure 5 shows the SLA rig, the camera and the lighting system (left) and an example of components bearing infrared markers (right).

The cameras include a Near-Infra-Red (NIR) strobe with 30 degree field of view and 16mm lens. The system comes with a bespoke capture software (Qualisys Track Manager) that can track dynamically the position of infrared markers attached to the surface of the SLA rig components, with an accuracy better than 0.1mm. The high-speed video camera (type Oqus310, Qualisys, featuring a 1.3 megapixel sensor) can track the position of all the interstitial bricks in the array, with an accuracy better than 2mm. The HSV camera works in conjunction with a Labview code that tracks position based on a pattern recognition algorithm. A comparison between the two tracking systems was carried out. Figure 6 shows the measured relative displacement time history of model brick LB2121 via IVS and via HSV. The two patterns of displacement are similar. The IVS is evidently a higher resolution system, while the HSV measurement is limited to pixel resolution, which in displacement terms meant approximately 2.1mm resolution. The advantage of the HSV system resides in its wide coverage and fast data turnaround, while the IVS provides high resolution data of selected components.

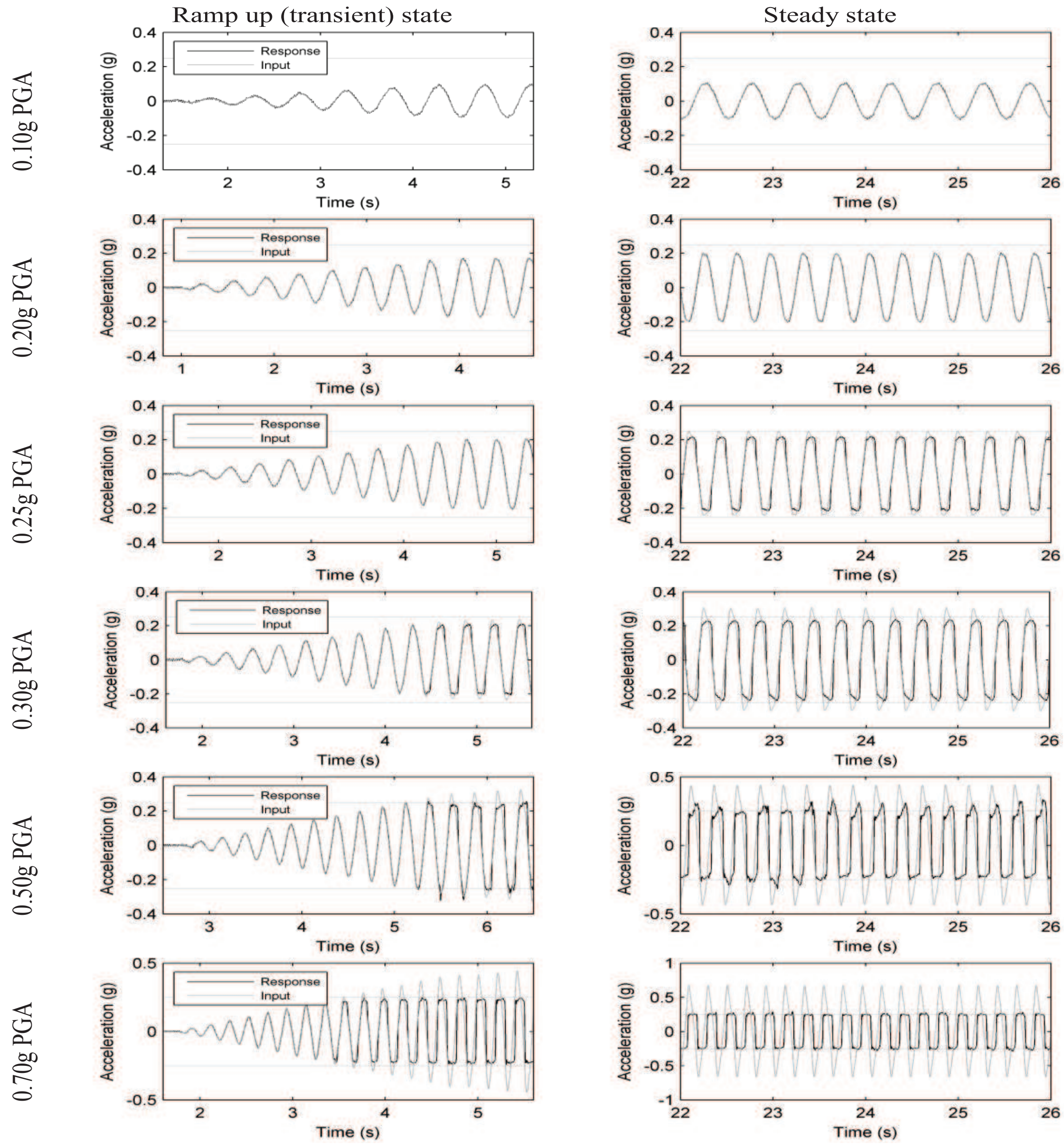

Figure 4. Sliding test results at selected excitation amplitudes, during ramp up (transient) stage (left) and during steady state (right).

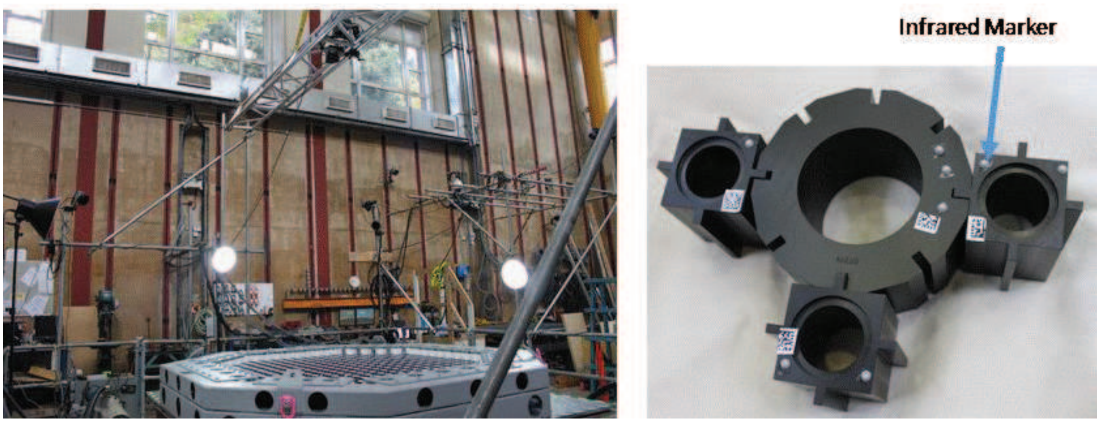

Figure 5. Left: The SLA rig
assembled on the shaking table platform. Right: The SLA rig model components.

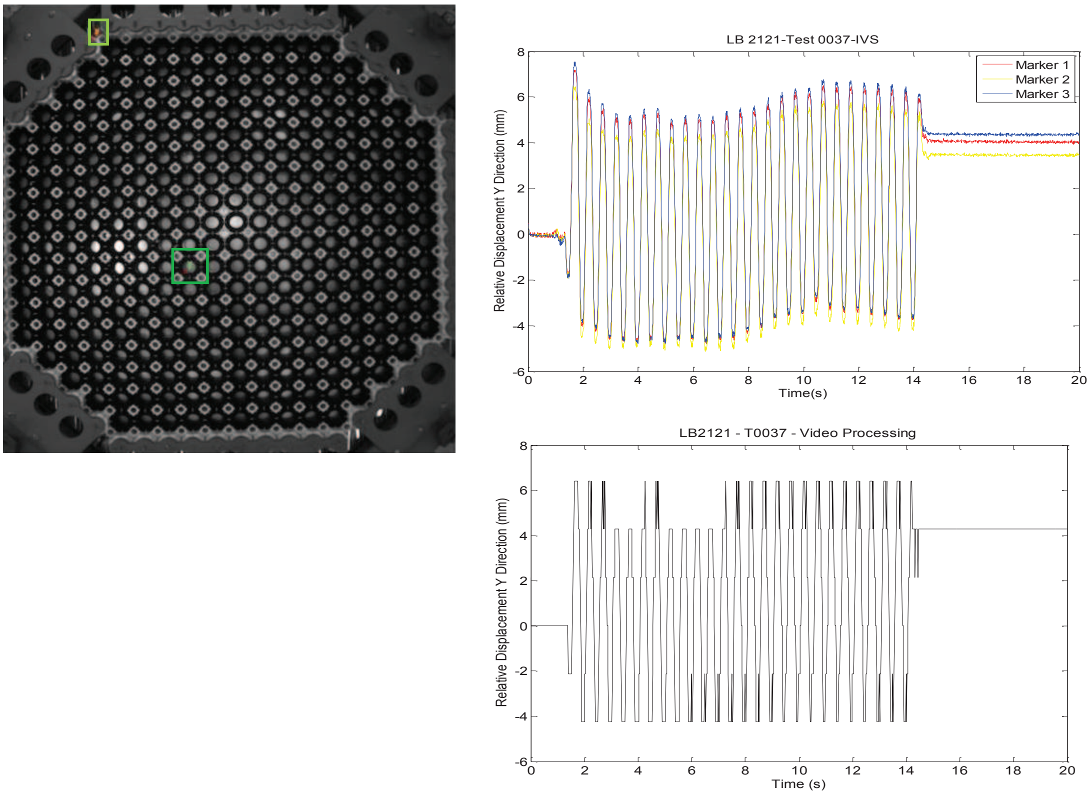

Figure 6 The centre of the brick (LB2121) and a point on the frame (Left: squares shown on image) Right: Displacement of LB2121 measured by the infrared vision system (top) and the high-speed video system (bottom). Input motion: sinusoidal, A= 20mm, f=2Hz, Y-axis, a_{max}=0.32g).

SOLFEC Numerical Model and Proposed Validation Studies

The SLA rig production testing will be tailored to suit the validation needs of SOLFEC. The software code SOLFEC [Koziara and Bićanić 2011] is a code for dynamic simulation of multi-body contacts, i.e. it can determine the displacements, velocities, stresses and forces which occur when individual objects collide or otherwise come into contact with each other under the influence of various loadings. It is a *solid-body* code and therefore includes a 3D representation of the geometry of the bodies being studied. Such a code is clearly of relevance for AGR seismic simulations, where there are multiple bricks and keys separated by variable clearances. However a key challenge in its use is that it provides a large number of modelling options and input parameters as shown in Table 1, many of which are non-physical or otherwise not defined by material properties. There are a number of physical factors which affect the body collisions inside the array. These can be broken down into three main areas:

- Geometry
- Material properties (mass, stiffness, damping)
- Type of contact (normal, tangential, plastic or elastic)

It is proposed that the response from the SLA rig tests will be compared against SOLFEC simulations. The aim of the approach is to determine the likely contact configurations for an array of bricks and match the overall displacement time-history response. The SLA array will be modelled in SOLFEC using a 'co-rotational' Finite Element formulation (suitable for use where deformations are small, and hence the body stiffness does not depend on the deformations). The following aspects of dynamic behaviour will be investigated in both rig and numerical data:

- Displacement amplitudes and phase between brick pairs.
- Impacts between individual bricks/keys
- Kinetic energy in the array and energy loss through impacts
- Force paths and energy distribution in the array

Table 1. Summary of modelling choices available in SOLFEC (see [Koziara T and Bićanić 2011])

Area	Options				
Body deformability:	Rigid	Pseudo-rigid	FEM: Total Lagrangian	FEM: Co-rotational	FEM: Reduced order
Body time-integration:	RIG_POS	RIG_NEG	RIG_IMP	DEF_EXP	DEF_LIM
Material & body properties:	Young's modulus	Poisson's ratio	Density	Damping	Mesh
Contact constraint type & properties:	Signorini-Coulomb: friction coefficient, cohesion coefficient, surface restitution coefficient	Spring-dashpot: spring stiffness, friction coefficient, cohesion coefficient, hpow			
Solver type & parameters:	Gauss-Seidel: timestep, epsilon, maxiter , meritval, failure, diagepsilon, diagmaxiter, diagsolver	Penalty-based: timestep, implicit or explicit solver	quasi-Newton: timestep, meritval, maxiter, locdyn, linver, linmaxiter, max-matvec, (cont. right)	quasi-Newton: (cont) epsilon, delta, theta, omega, gsflag	

Conclusions

A solid-body approach to AGR seismic simulations would significantly extend the behaviour which can be simulated with current methods. Whilst a variety of commercial solid-body dynamic codes exist, they are not considered suitable for the number of bodies and long duration which must be simulated for this type of problem. The Non-smooth Contact Dynamics method implemented in SOLFEC provides a promising alternative. The SLA rig at UOB represents a valuable tool to provide experimental data for a wide variety of input motions and array layouts that will feed into the development and tuning of the numerical code.

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