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INTERROGATION OF 'BIG DATA' FROM SHAKER TABLE TESTING USING VIRTUAL REALITY

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ABSTRACT

This paper describes how VRML (Virtual Reality Modelling Language) techniques can be used to quickly visualise and interpret large multidimensional experimental data sets. The data sets were created by a series of experimental tests investigating the seismic response of the UK's Advanced Gas Cooled Reactors (AGRs). At the University of Bristol a quarter scale physical model of an AGR core was developed to support, via experimental testing the existing numerical models that assess the seismic resilience of the AGRs. Outputs from the rig consist of highly detailed acceleration and displacement datasets that contain all the challenges of 'big data' processing. A particular challenge has been the interpretation of the response data from even a single shake, which comprises 6DOF time dependent displacement responses of many components. Traditionally this data would be viewed as a series of time histories, but the combination of hundreds of linked 6DOF motions, which all vary with time, makes interpretation of such plots practically impossible. To combat these problems a 3D VRML model including all the instrumented components has been developed. The test data is mapped into this VRML model to produce a 3D animation with the ability to pan, tilt, rotate and zoom in. This allows the user, in real time, to discover any behaviour that looks significant. The VRML model can also be used to look at responses from different tests and allow visual comparison of multiple data sets. This visualisation technique also has applicability for interpretation of other large experimental data sets.

Keywords: VRML; advanced gas cooled reactor; seismic resilience; physical model

1. INTRODUCTION

1.1 Advanced Gas Cooled Reactor

The Advanced Gas-Cooled Reactors (AGR) are the second generation of British gas-cooled nuclear reactors and use carbon dioxide coolant and graphite as the neutron moderator. EDF Energy Generation operates seven AGR power stations within the United Kingdom, and each has two identical reactors. To ensure safe operation there is a requirement that the reactors should be safely shut down, held down and cooled down in the event of an earthquake with a probability of exceedance of 10^{-4} per annum. This seismic capability needs to be proven throughout the stations' lifetime and consider the consequences

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of radiolytic oxidation and fast neutron irradiation for graphite component behaviour. These degradation processes have been covered extensively in previous papers (e.g. Neighbour 2013, Flewitt and Wickham 2015), and include effects such as geometrical changes, strength degradation, and the possibility of differential shrinkage induced cracking. All these effects need to be taken account of within any numerical models of the reactor core and, where practicable, in any physical models of the cores.

Currently, the AGR core seismic responses are calculated using the GCORE simplified "stick and spring" finite element (FE) model (Kralj et al. 2005) and the SOLFEC solid-body code (Bicanic and Koziara 2008). Both numerical tools can determine the displacements, forces, stresses and velocities that occur when individual bricks and keys collide or when they come into contact under the influence of various loadings. These numerical models require experimental validation, especially for higher percentages of degraded components associated with AGR cores late in their life cycle. There is also a need to enhance the understanding of core dynamics in aspects that are not currently explicitly modelled, such as post key disengagement behaviour. There was therefore a need for a suitably representative physical model.

1.2 Quarter Scale Rig

The AGR cores consist of thousands of graphite bricks interconnected through a graphite keying system which acts to oppose motion between bricks. The keying system is slack at room temperature to allow thermal expansion to occur without damaging the bricks. These bricks are then arranged in vertical columns to provide channels for fuel pins, coolant and control rods. The deformed shape of these channels during a seismic event is a key issue for the seismic assessments of the AGRs. The weight of the graphite bricks in a full scale core is approximately 2000 tonnes, whereas the shaker table at the University of Bristol has a nominal payload limit of 15 tonnes; there was therefore a requirement to scale the full scale model down. After close scrutiny of scaling factors to reduce to a quarter scale model, the material Acetal^{TM} was selected for the bricks and keys (Oddbjornsson et al. 2017). The initial built rig was of an uncracked array and is herein referred to as MLA1. The rig contains all the AGR graphite component types, i.e. lattice bricks, interstitial bricks, filler bricks and keys (spacer, filler and loose bearing) (Dihoru et al. 2016). The lattice bricks are stacked on top of one another to form 8 layer columns. A view of the quarter scale rig can be seen in Figure 1. Figure 2 shows a close up of the upper layer, and the keying system between bricks.
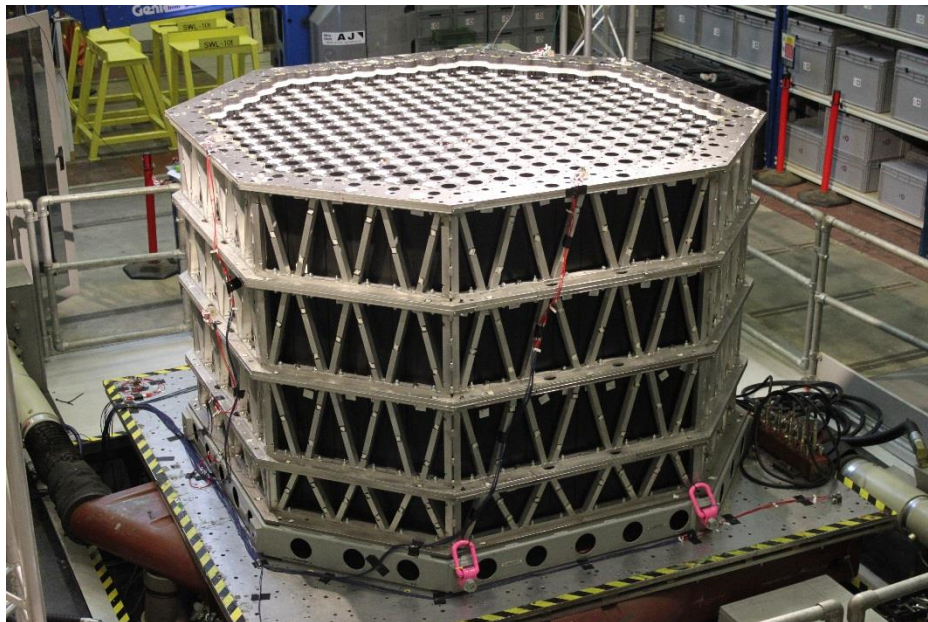

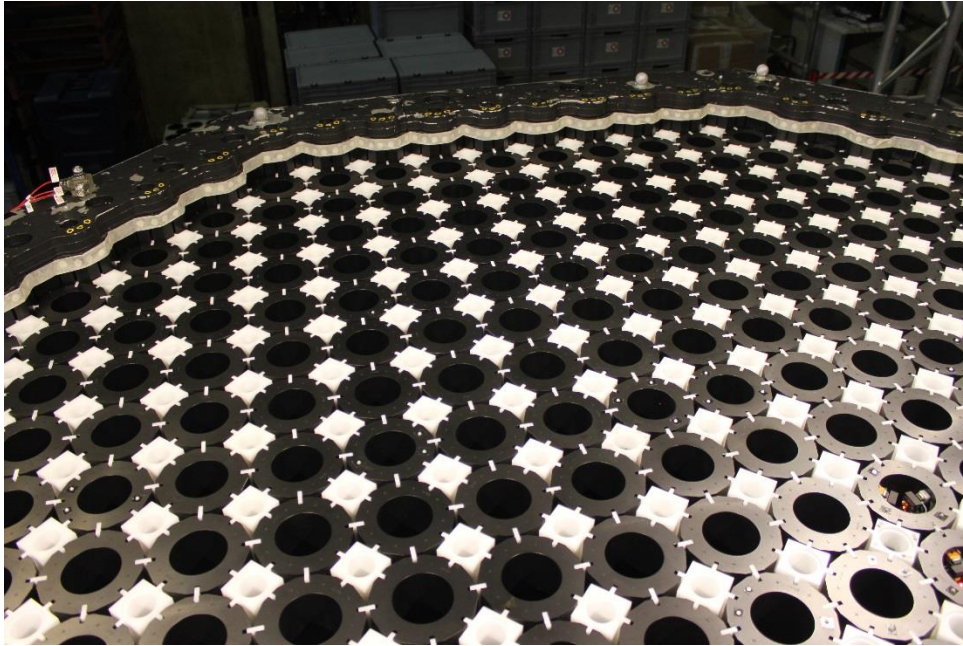Figure 1. General view of the quarter scale rig developed at the University of Bristol

Figure 2. Top layer view showing the keying system between bricks

Due to the small model brick sizes, instrumentation and data acquisition becomes challenging, and so an innovative method for acquiring displacements at brick interfaces was created and utilized (Dihoru et al. 2017). Within instrumented lattice bricks, four traditional potentiometric, linear displacement transducers were installed to capture roll, pitch and vertical movements of the bricks at each interface; these are shown in Figure 3. These lattice bricks also contain Micro-Electro-Mechanical-System (MEMS) based accelerometers (Dihoru et al. 2015) both at the top and bottom which are capable of 6 Degrees Of Freedom (DOF) acceleration measurements.
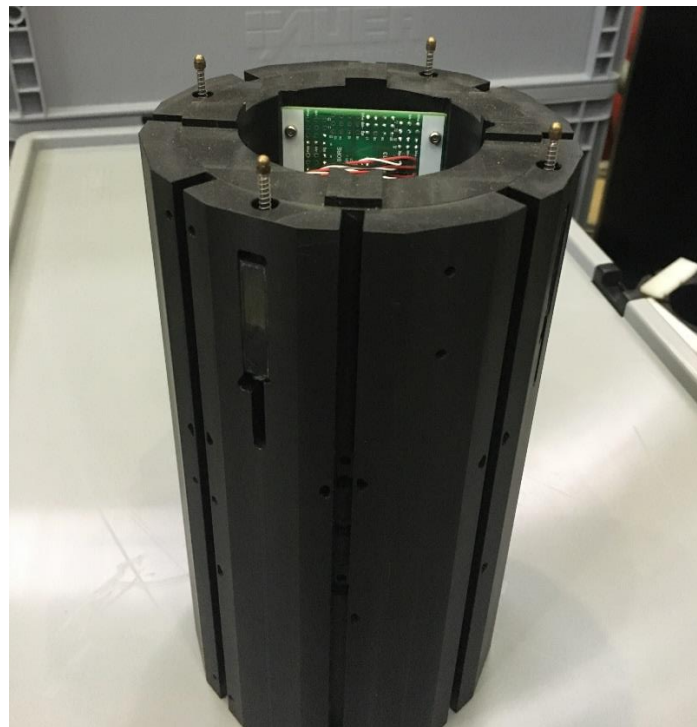

Figure 3. Lattice brick with four potentiometric transducers. Inside the brick is the data acquisition system for the transducers

Instrumented interstitial and filler bricks utilize miniature PCB boards, each carrying 4 hall effect magnetic sensors, in three of the filler brick's corners, combined with magnets, allow the interface movements to be measured in 6DOF through changes in the magnetic field. A filler brick containing the three hall effect sensor boards and a MicroDAQ data acquisition system alongside an interstitial brick containing three magnets are shown in Figure 4. Each instrumented filler and interstitial brick also contains a MEMs accelerometer at centre height capable of 3DOF acceleration measurements.
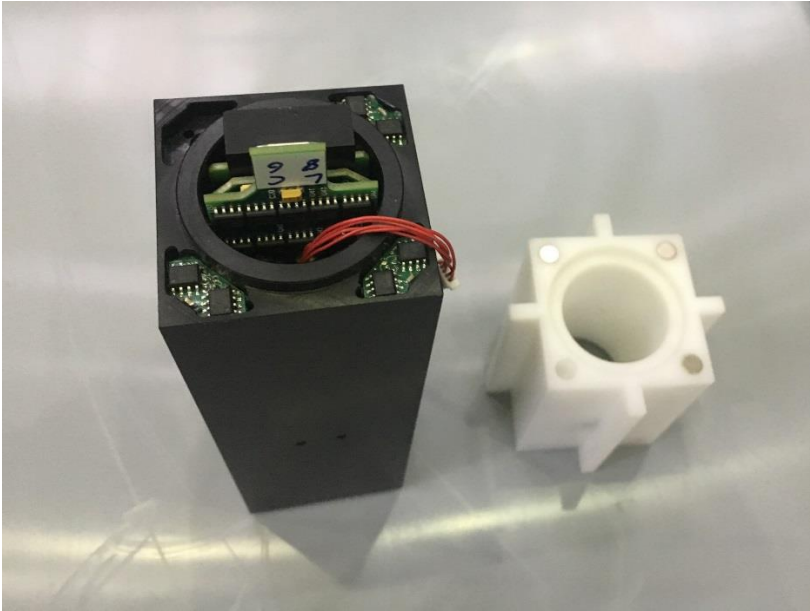

Figure 4. (Left, black) Filler brick with twelve hall effect sensors and MicroDAQ system inside the channel. (Right, white) Interstitial brick with three magnets

Approximately 3200 sensors are distributed throughout the ~42000 component system, which upon shaking produce large datasets of detailed acceleration, displacement and 6DOF movement. Although this seems like a very large number of data channels being recorded in actual fact only a relatively small number proportional (~5%) of the total number of components in actually instrumented. Data acquisition was a challenge for the small components, so a novel MicroDAQ chipboard (Figure 5) was developed that could fit within the channel of the filler bricks, allowing data from each brick sensor to be stored locally and downloaded after the earthquake excitation had stopped.
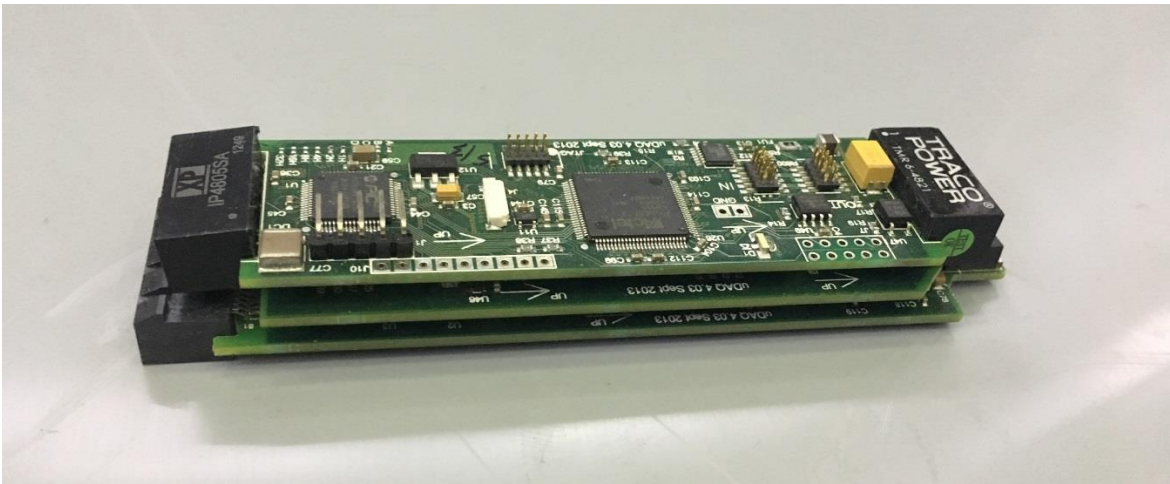

Figure 5. MicroDAQ system small enough to fit inside the channel of the filler bricks

For both the ability to check the accuracy of the channel measurements and as additional redundancy, two vision systems were used for measuring the displacement of the top layer of the array. One system was a high speed video system that measured just the displacement of array components in the top layer. The second system, the infrared vision system, measured markers on the top layer bricks, the restraint frame and the shaking table. The video recording systems were placed above the quarter scale rig (Figure 6).

Figure 6. High speed video system and infrared vision system in each corner of the surrounding frame

1.3 Data Volume and Format

Each quarter scale test configuration produces many hundreds of gigabytes of data, this is mostly from the high speed video and infrared datasets, but a non-trivial portion of the data volume is the brick interface data taken from the instrumented columns. These local interface measurements of rigid-body translations and rotations are combined into accumulative global node displacement, relative to the fixed base of the column, to create the channel profiles. Given their accumulative nature, the node displacements are very sensitive to error propagation phenomena. Thus, the displacements on the top layer from the channel profiles are compared with the direct measurements of the vision system, to validate the internal measurement system. The brick interface data is stored as MATLAB structure files. Each test has a separate structure file that contains either all lattice brick interfaces or interstitial column interfaces.

2. THE CHALLENGE

Earthquakes have dynamic time dependent inputs, and the inputs into the quarter scale rig are no different; this leads to problems in displaying the measured data because time adds an additional dimension. With time dependent 6DOF data there are 7 different variables to plot at just one brick interface. In addition, seven (7) and thirteen (13) independent interface measurements are added to produce a lattice and an interstitial column profile, respectively (see Figures 7 and 9). Therefore,

producing representative figures for the whole core quickly becomes overwhelming, and traditional plotting methods fall short for thoroughly examining the dynamic response of the whole array.

2.1 Traditional Methods

Traditional data viewing methods may look at the measured variables separately to try to piece together a coherent understanding of the underlying dynamics of the whole array. Simple but quantitative plots may look at the maximum enveloped displacement in a certain direction for the peak spectral acceleration of the shaking table (Figure 7). These can give an idea of what may be considered the worst case scenario but they do not inform on the dynamic aspect of the dataset. In particular, the deflected shape presented in Figure 7 can be misleading regarding the dynamic response MLA columns, as it is resemblant to that of a "first mode" shear beam response, which might not be the case for the real, time dependent deflection of the column (see dashed line on Figure 7).
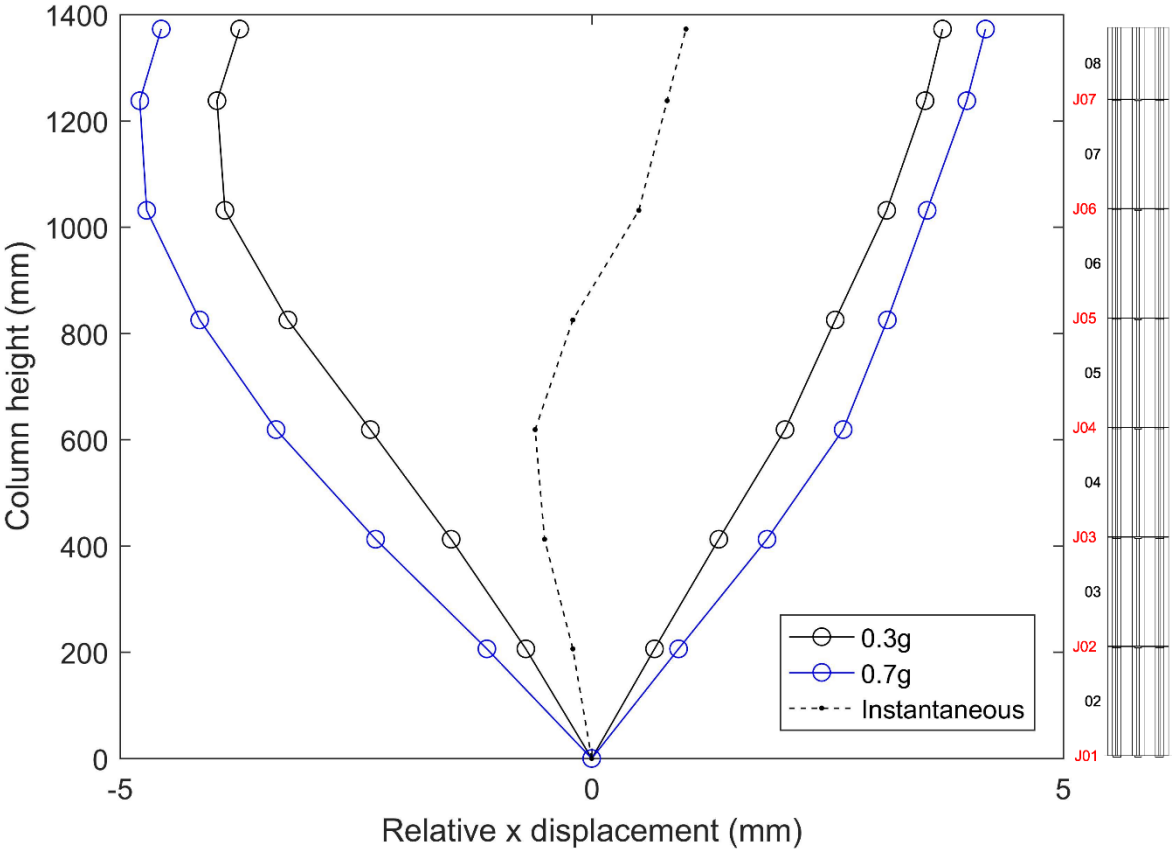

Figure 7. Contours of maximum relative x displacement for lattice bricks at two different peak table accelerations. The dashed line shows an instantaneous column profile, indicating why maximum displacements may be misleading

More ambitious plots may place multidimensional data side-by-side to aid comparisons. Figure 8 shows a comparison between MLA (experimental) and GCORE (analytical) data in the upper layer. This figure allows the user to see how the surface vectors change with seismic input, and allows the comparison of numerical and physical models. The figure is however limited by selection of time stamps, in addition it gives no information as to what is happening in lower layers in the array.
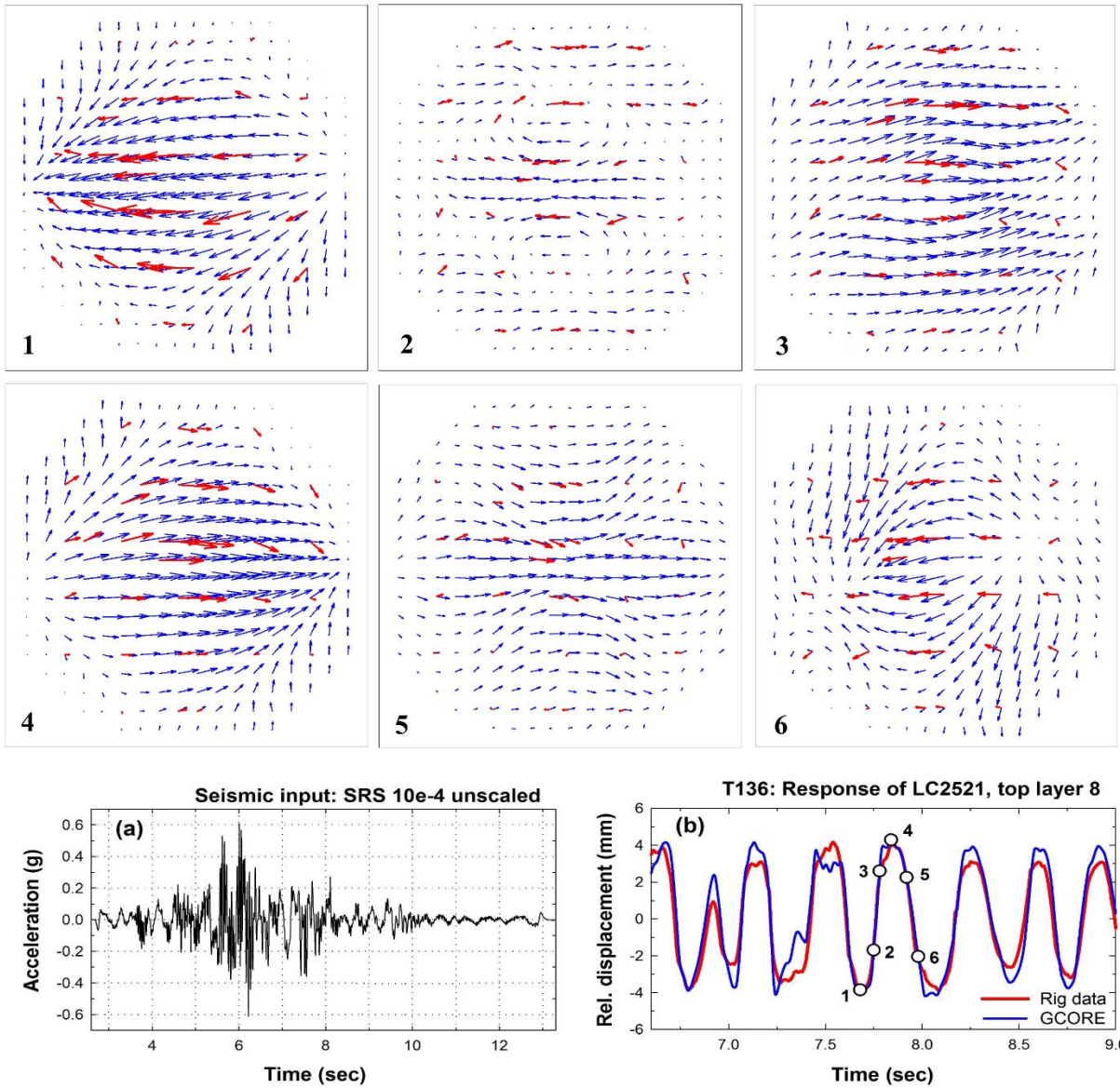
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Figure 8. GCORE vs MLA1 vector surface map. Rig data in red and GCORE numerical calculations in blue

6DOF data for a single interface can be combined into a single figure (e.g. Figure 9), giving an insight on to what is occurring at one particular interface during a shake, but the MLA rig contains such an interface in-between each instrumented brick, meaning that several hundred such plots would be needed to show even a small proportional of the full array behaviour. Questions also arise as to how one interface interacts with another above/below/beside it, and it is not clear how data from multiple individual interfaces such as this can be combined.
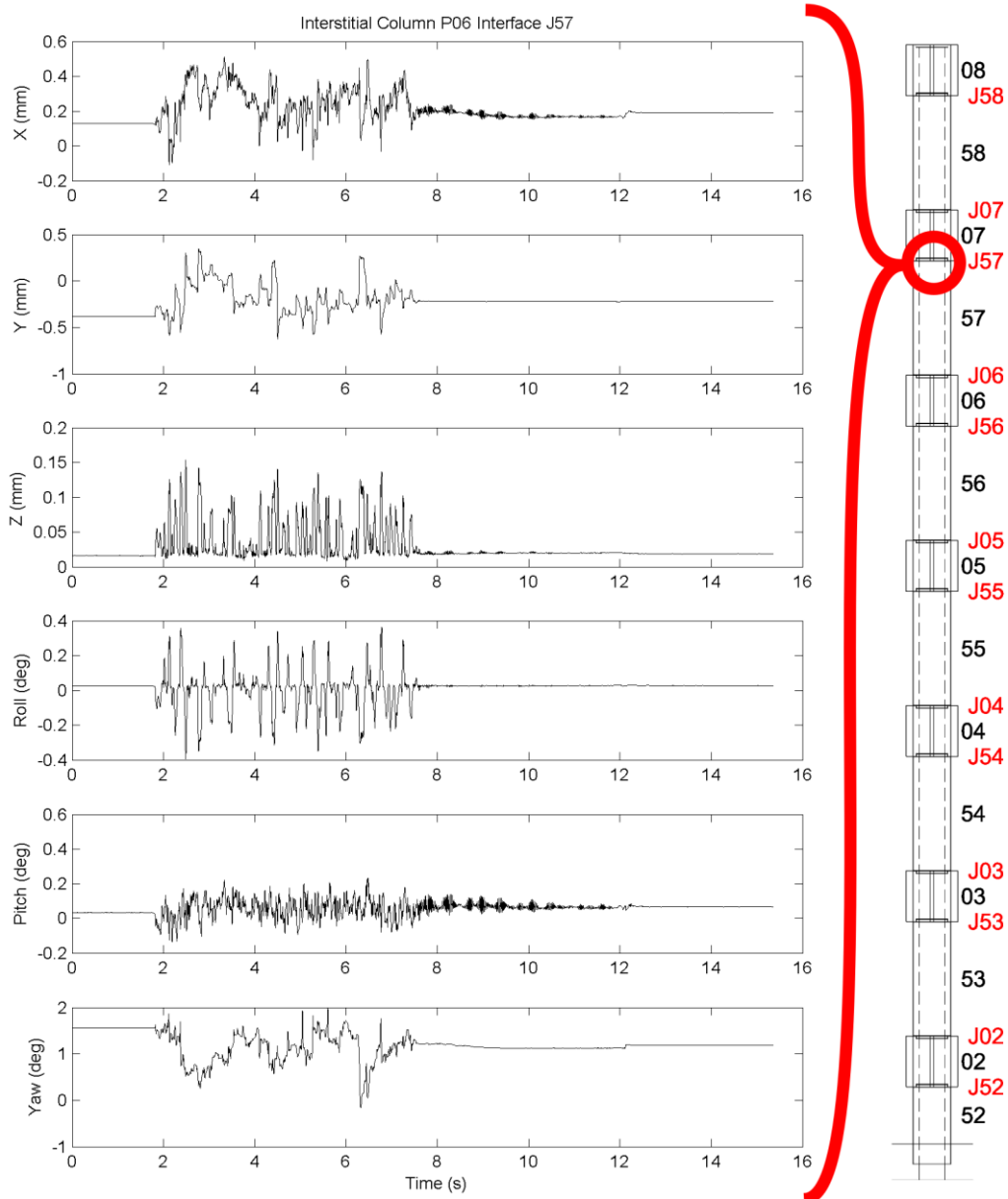
Figure 9. Six degree of freedom movement at one interface of an interstitial brick. On the right is a schematic of an interstitial column, with the interface corresponding to the data circled in red

2.2 The Dimension Problem

Traditional 2D plotting methods can generally give a good quantitative understanding of 'Big Data' challenges, but as the numbers of dimensions in the data increases, the ability to scrutinize all aspects of a problem becomes exponentially harder. One solution is to develop techniques that can quantitatively assess large dimensionality data. Another solution is to develop a system that can help inform where the interesting aspects of a large dataset lie, allowing quantitative methods to be targeted efficiently.

3. VIRTUAL REALITY MODELLING LANGUAGE

Virtual Reality Modelling Language (VRML) is a programming language used to describe 3D image sequences with the added ability for interactivity. VRML can be used to create models that can be rotated, moved and manipulated. MATLAB has a built in VRML manipulation tool in the form of Simulink 3D animation; using this, a 3D model can be produced that can be externally manipulated mathematically through both Simulink and MATLAB. This can become a powerful tool because 3D dynamic problems can be analysed using MATLAB in an intuitive, visual and interactive way.

3.1 The VRML Model

A model for the undamaged MLA1 has been produced to probe whether VRML could be useful for analysis of complex 3D dynamic systems. The model uses an initial MATLAB code to generalize all test data and convert it into the required format, this is then fed into the Simulink model, which takes this data and produces the required movements for each component. These movements are then passed to the VRML model, which contains blocks representing instrumented bricks (Figure 10). The sparsity of bricks shown in Figure 10, compared to the full array (Figure 1) shows that even though a huge number of sensors were installed in the array, these still only allowed eight columns of bricks to be instrumented.
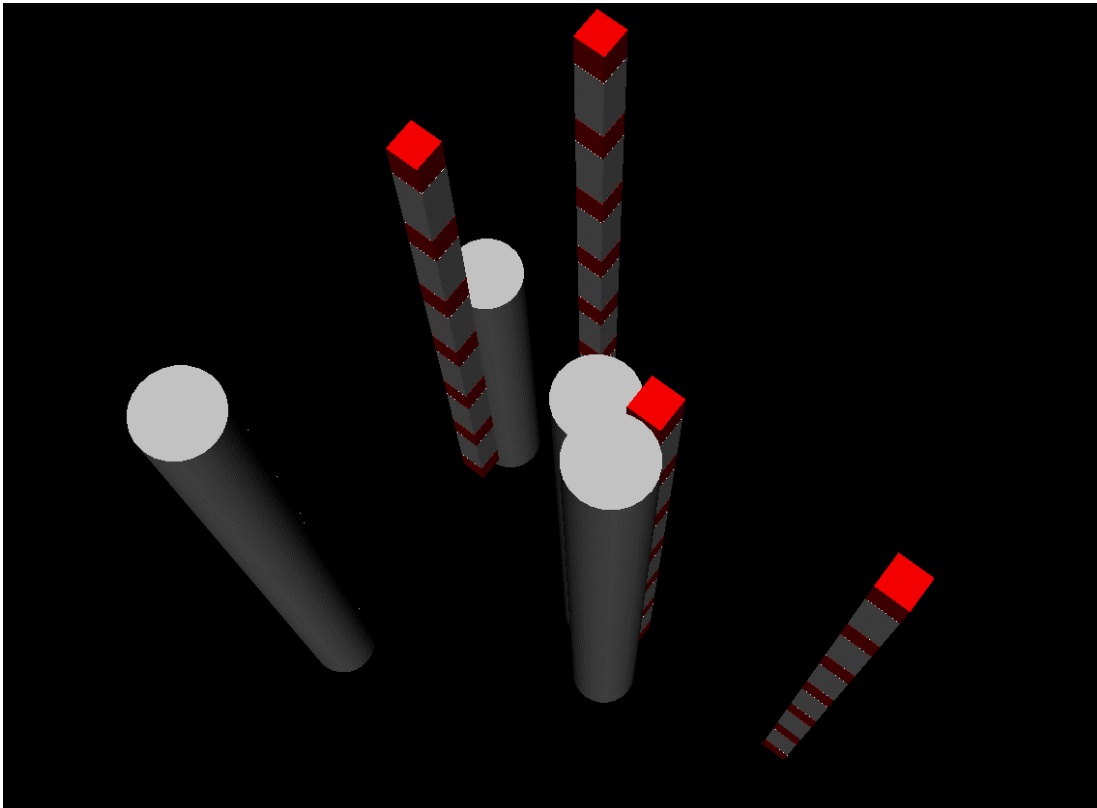

Figure 10. Wide view of VRML model. Only instrumented columns are displayed. Missing bricks in columns are due to missing data

4. APPLICATION OF VRML FOR TEST DATA

The VRML model allows rotation and movement of the camera while it is operating. Time snapshots can be taken as the model progresses, and by the use of ghosting (overlaying transparent data) comparisons can be made between different test sequences. The quarter scale rig keying system is so rigid that there is relatively little movement of the blocks during large shakes, but the displacements can

be easily amplified so as to: a) highlight any interesting behaviour; this can direct more quantitative and traditional methods of what are the most interesting and valuable parts of the dataset to explore, or b) highlight any particularly problematic nodes, affecting the whole column profile through error propagation; So the method can be used for a faster and more efficient "sanity check" of the experimental results, as opposed to a detailed scanning of the whole dataset for problematic measurements/sensors.

4.1 Results

The VRML model camera can be manipulated as the model is running; this allows the user to pan, rotate and zoom on interesting features. Figure 11 gives an example of a rocking interface during a dynamic test. The grey column is a lattice brick column with the rocking occurring at the interface between layers 4 and 5. The white and red bricks in the background are filler and interstitial bricks respectively.
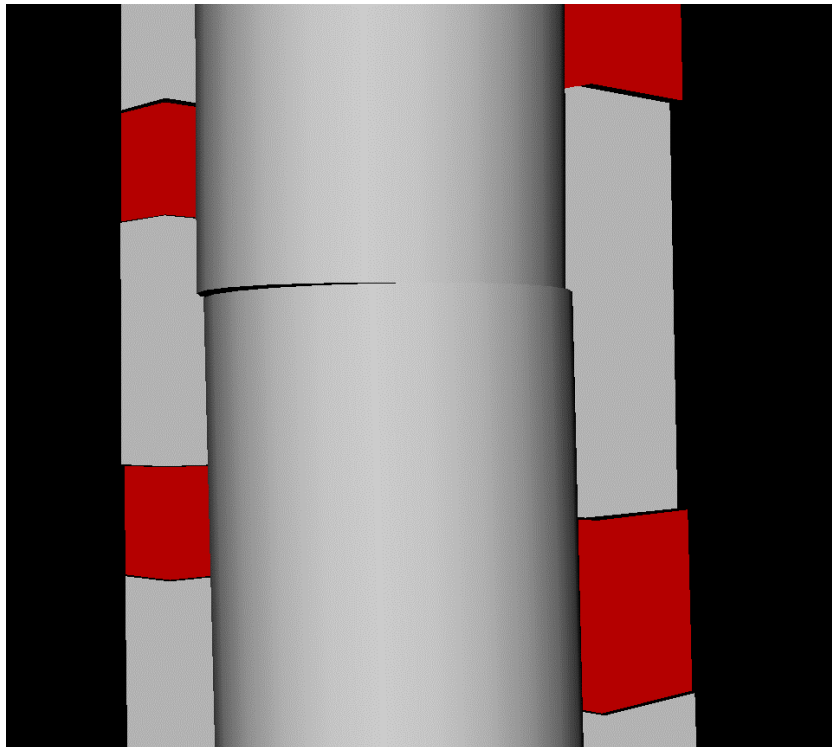

Figure 11. Lattice brick (grey) interface showing rocking during shaking. The interface shown is in between layers 4 and 5

Through the use of transparency, different seismic shakes can be compared by ghosting one on top of the other. This can qualitatively allow the user to see interesting changes between different shakes, and once again inform the user on where to best target their quantitative methodology. Ghosting can also be used to explore the difference in response to two different pulses in the same earthquake. This method can also be used to qualitatively compare the difference in response caused by difference in frequency and/or amplitude of the two pulses. The initial conditions of the array can also be explored at the start of each pulse. An example of this ghosting is shown in Figure 12.
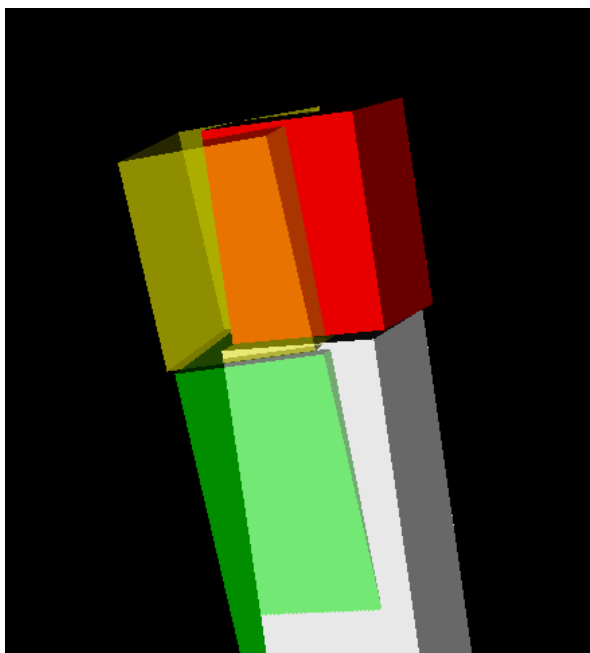
Figure 12. Different shakes can be compared through the technique of ghosting. A transparent block is overlain on top of the opaque block to allow comparison

Video capture is built into the Simulink system, allowing videos to be produced as the model runs. Frames can also be captured at any point during the run (Figure 13). This contrasts with other 3D visualization techniques such as ABAQUS that must run fully before they can be viewed.
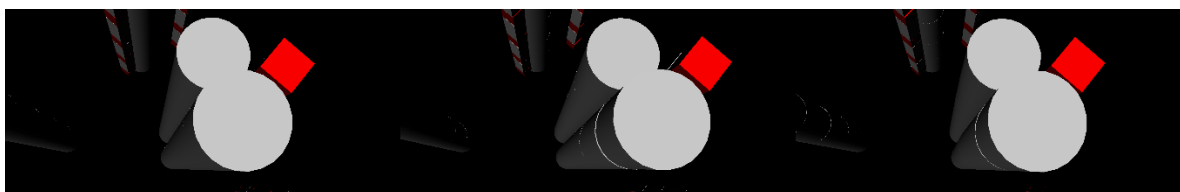

Figure 13. Successive time snapshots as the model runs

5. CONCLUSION

VRML is a promising technique for dealing with the visualization of high dimensional dynamic data. It provides a qualitative appraisal of large systems that can then help inform where resources should be spent on more quantitative methods. For this particular VRML model the keying system will be labelled in future versions before moving onto more damaged core configurations. Future work will also improve interactivity to allow quantitative methods to be accessed as the model is running. VRML visualisation techniques have proved to be an excellent way to study the dynamic response of the AGR core models and they also have applicability for interpretation of other large data sets that are present throughout engineering.

6. ACKNOWLEDGMENTS

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