Reducing the Sizes of Non-linear Impacting Models in Seismic Response Calculations for Graphite Moderated Reactors

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ABSTRACT

Advanced Gas-cooled Reactors (AGR) are large complex structures containing arrays of graphite brick columns that make up the reactor core. Clearances between the bricks and within a system of shear keys ensure that the columns are in little more than touching contact with each other during normal operations. During a significant seismic event, the columns will sway sufficiently for impacts to occur between them. This could be directly through contacts between bricks or indirectly through the shear key system. With the AGR cores in their current states, the seismic responses of the reactor cores are calculated using a pseudo-linear finite element representation of the core. Forward predictions indicate that, because of changes to the clearances in the cores resulting from normal reactor operations, this method of representing the reactor core will no longer be applicable, and must be replaced.

One alternative is to use a detailed model of the core in which each graphite brick is represented as a beam, and contact is modelled using combinations of non-linear discrete springs and dampers. It is relatively straightforward to generate these types of model using a bespoke computer program, *GCORE*, and to use proprietary non-linear dynamics solvers, such as *LS-DYNA*, to calculate their seismic response. However, the large number of bricks and potential impact locations mean that the models are large and complex, so that a seismic response computation for a complete core is predicted to take many days. As a significant number of response calculations is required to cover a range of modelling and physical parameters, the seismic assessment would become prohibitively long and expensive.

This paper describes the development of a method for reducing the size of the non-linear model for impacting between bricks in a single core layer, while retaining an acceptable degree of accuracy in the solution. This simplification is achieved by reducing both the number of masses and the number of impacting sites by combining the properties for individual bricks. The ability of the reduced size arrays to produce equivalent seismic responses is demonstrated by comparing them with the responses calculated for a full layer of bricks.

A major advantage of the method is that it can be used as part of a non-linear model of a complete reactor in which there might be components other than the graphite core that behave non-linearly.

INTRODUCTION

The Advanced Gas-cooled Reactor (AGR) is a type of UK designed, graphite moderated, nuclear reactor cooled by carbon dioxide. Its core is constructed from columns of graphite bricks, which provide vertical channels for fuel assemblies, control rods and coolant flow.

The details of the reactor core and restraint structures vary from station to station, but typically the core assembly consists of approximately 19,000 bricks, is roughly cylindrical in shape, and is surrounded by a steel restraint structure. The bases of the graphite brick columns are located by spigots in steel plates resting on a rigid grid supported by columns. There are 12 layers made up from two types of bricks – polygonal and interstitial – arranged on a square lattice with a pitch of 460 mm between the centres of the polygonal bricks. The bricks in each layer are keyed together at 0° and 45° in an arrangement of loose and integral keys that allows the graphite core to expand and contract radially to accommodate thermal movements of the steel restraint structure. The moderator is the central region of the core and contains channels in the polygonal brick columns for the fuel and channels in the interstitial brick columns for the control rods, monitoring devices and neutron sources. Around the radial periphery of the core is the reflector consisting of polygonal and interstitial brick columns that have only small central channels for cooling. This arrangement is illustrated in Figure 1 for a typical core.

A requirement for the operation of UK nuclear power stations is that the reactors can be safely shut down, held down and the decay heat removed in the event of an infrequent and severe earthquake. To demonstrate this seismic capability, it is necessary to show that the response of the reactor and its graphite core does not adversely affect either the ability of the safety systems to operate or the flow of coolant past the fuel.

The most recent AGR power stations were designed to withstand seismic events and a significant programme of calculations and tests was carried out to substantiate the final design and, in particular, that of the graphite core [1]. The individual bricks were modelled as rigid bodies with the contacts with neighbours represented by parallel combinations of linear springs and dampers. The models were implemented by bespoke computer programs, *AGRCOR* and *EXTAGR* [2], that drew extensively on the theoretical and experimental studies, undertaken in the USA [3] and Japan [4] on the seismic response of High Temperature Gas-cooled Reactors (HTGR).

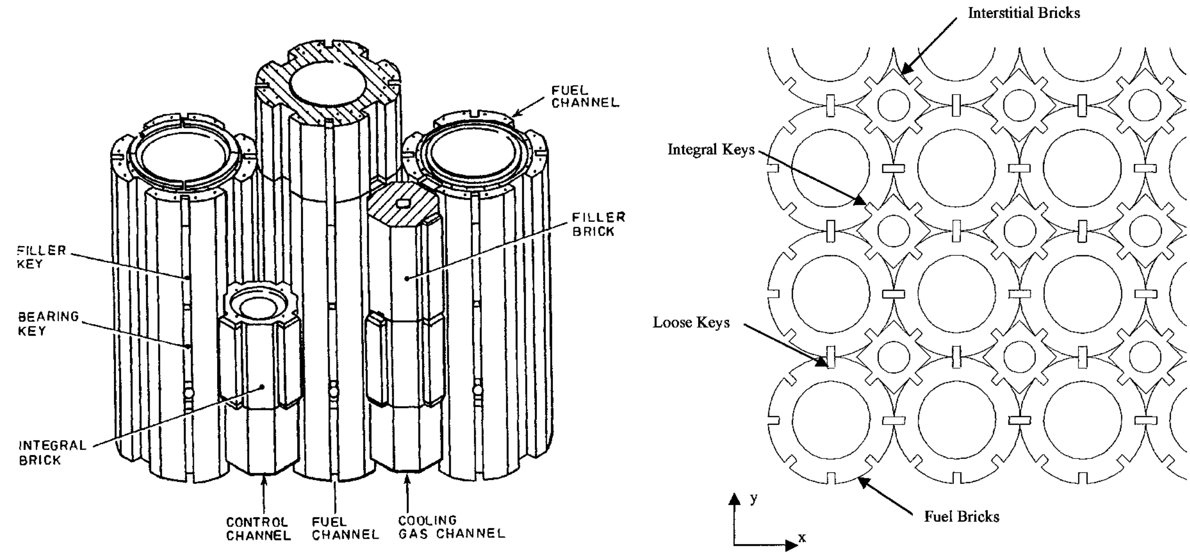

Figure 1 – Core Components and Plan of Keying Arrangement in a Brick Layer

The designs of earlier AGR power stations did not consider seismic loads, but have been the subjects of a programme of seismic assessments that used linear, structural dynamic, finite element models to represent the reactors. The relative sizes of the clearances between bricks and those within the shear keying system mean that all contacts between bricks in the same layer will be through the shear keys. This allows the non-linear effects of the keyways to be linearised using an equivalent linear oscillator formulation, and the networks of bricks and keys to be represented by elastic continuum layers [5]. The computational efficiency of this method enables the effects of non-linear responses in components of the restraining and supporting structures to be investigated [6].

Long-term predictions of graphite core behaviour indicate that the clearances within the shear key system will increase and once more allow direct impacts between bricks. Under these conditions, the linearised continuum layer representations cannot be used, and an alternative approach that includes brick-to-brick interactions is required. A review showed that the methods used for the HTGR and most modern AGR cores would be appropriate, and that *LS-DYNA* [7] has the required modelling representations and can provide solutions with acceptable accuracy and efficiency. To facilitate the economic and accurate production of detailed models of the reactor core, a modelling pre- and post-processor tool, *GCORE*, was developed to create *LS-DYNA* models from geometrical and structural data for the core stored in a database. These models are described in *Detailed Core Models*, below.

The size and complexity of detailed models for complete cores place significant demands on computing resources, and merging the core representation with a model of the rest of the reactor would increase these demands even further. To accommodate the significant number of sensitivity studies required to address the uncertainties inherent in seismic assessments, a reduced size model is required. It should be able to capture the dynamic behaviour of the detailed models whilst using significantly smaller computer resources and being capable of use in full reactor models similar in size and configuration to that described in [6].

DETAILED CORE MODELS

To adequately capture the non-linear impacting behaviour of the graphite bricks, the individual components of the core, i.e. the bricks and keys, and their interactions, are modelled in detail using combinations of beams, masses, springs, dampers and gaps. Standard non-linear structural analysis programs are capable of solving such models, but explicit finite element codes such as *LS-DYNA* are particularly well suited for these types of problem in which there is considerable contact and other forms of non-linearity.

Despite being composed of only a small number of different components, the models quickly become extremely large and complex, with the change of a single parameter often requiring considerable re-modelling. It is this complexity that mitigates against the use of proprietary finite element graphical pre-processors, and favours a customised system designed specifically for this class of problem. The computer program *GCORE* was developed to generate *LS-DYNA* models from structural and geometrical properties of the core stored in a relational database. *GCORE* is fully interactive, and provides facilities for the graphical display of models and *LS-DYNA* results as a core structure, as opposed to the graphical representation as element types provided by a standard pre- and post-processor.

The standard *GCORE* graphite brick elements are represented by a combination of linear elastic beam elements and rigid body definitions (Figure 2). The body of the brick is modelled by two vertical linear elastic beam elements that represent its bending behaviour, while a horizontal plane of nodes is defined at the intersection of the beam elements to allow the interactions between horizontally adjacent bricks to be modelled by non-linear contact spring elements. The horizontal plane of nodes, including the node at the centre of the beam elements, is defined as a rigid body. Damper elements are used in parallel to these springs to represent energy dissipation at impact. The bricks can rock about their bases where spherical joints are defined to connect the degrees of freedom and define the rocking stiffness with the bricks in the layers above and below. In this standard definition the brick has 18 degrees of freedom enabling it to bend and rock independently.

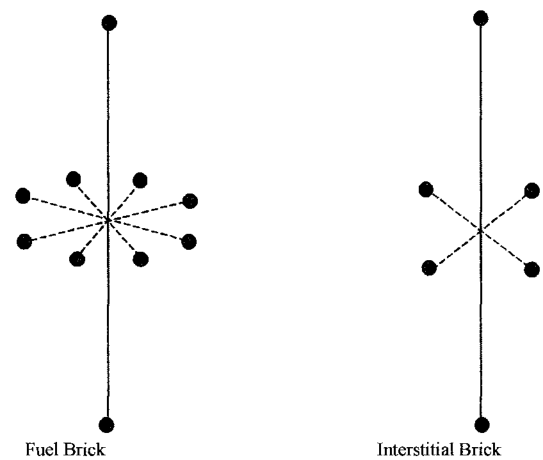

Figure 2 - *GCORE* Brick Representation

An AGR core consists of approximately 19,000 bricks in 12 layers. The representation of the interstitial bricks is simplified in *GCORE* so that a model would contain around 10,500 brick elements with 190,000 degrees of freedom. With the maximum practical time step of 50μs and using a Silicon Graphics Origin 2000 computer, it is estimated that the model would take over a week to run. This is not practical for seismic assessments in which a range of parameter variations is considered. Ideally, the analyses should be completed overnight with run-times no greater than 16 hours and this suggests that models should be no greater than about 10,000 degrees of freedom.

REDUCTION METHOD

The reduction method works at two levels. First of all at the brick element level where the number of degrees of freedom of each brick element is reduced, and then at the brick array level where the number of brick elements in the array is reduced.

Brick Element Level

The standard *GCORE* representation of a brick is a combination of linear elastic beam elements and rigid body definitions giving 18 degrees of freedom in total. In models of single layers, the bending degrees of freedom for the brick are removed by making the brick representation fully rigid along its entire length. This reduces the degrees of freedom by a factor of three.

Brick Array Level

The objective is to represent the dynamic behaviour of the core using fewer masses, and thus fewer degrees of freedom. The full core layer has a repeatable pattern of cells containing contact sites at both 0° and 45° to the cardinal axes of the reactor. This cellular structure can be exploited by superimposing an identical pattern of brick and contact representations over several cells in the core layer as shown in Figure 3 for a half layer. This gives a factor of 3 reduction in each direction.

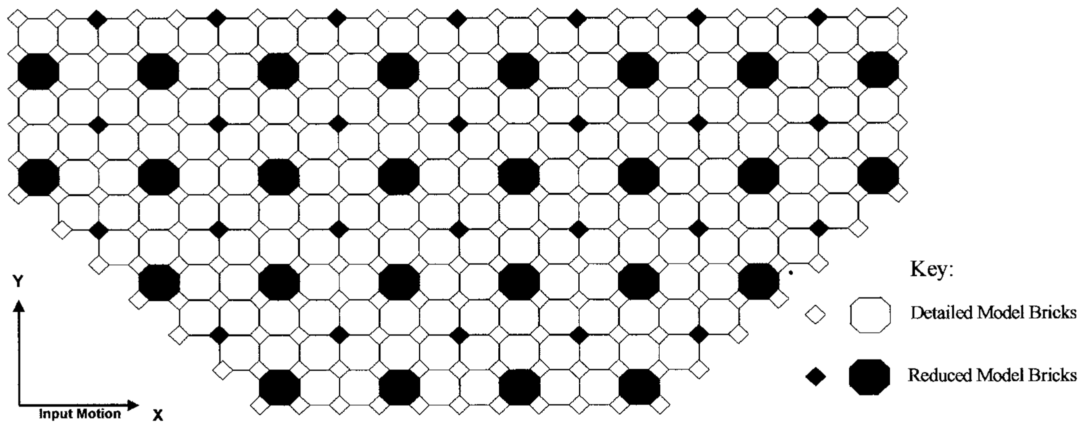

Figure 3 - Sub-Division of an AGR Reactor Core Layer

Combining the reductions of the model at brick level and array level produces an overall reduction in degrees of freedom for the full core by a factor of 27 to around 7,000, which is practical for non-linear seismic response calculations.

Reduced Size Array

As the arrangement of brick and contact elements in the reduced array cell is identical to that in the detailed array, it is expected that it will behave in the same manner. Therefore, the effort in developing the reduced models was centred on deriving suitable lumped stiffness, damper, gap and inertia values that would accurately model the response of the cell within the detailed array.

There are three parts to the reduction process and these are described below. It should be noted that, whilst the reduction factor n is described as an integer in the example, this is only for clarity of presentation. This method may also be applied to reduced arrays with non-integer reduction factors, as might be necessary when developing combined core and buildings models.

Inertia Properties

For each cell in the reduced array, the total inertia of the fuel and interstitial bricks is calculated, and then divided equally between the equivalent fuel and interstitial bricks in the reduced array. Using this formulation, the dynamic mass in the reduced model is less than in the detailed model because the mass of the bricks close to the boundary is added to constrained nodes. It is possible to reduce this effect by increasing the amount of dynamic (unconstrained) mass in the reduced model by an appropriate amount. It should be noted that the results presented below are from models created using the basic formulation, and with no re-distribution of dynamic mass.

Contact Springs and Dampers

The spring stiffness and impact damper properties are combined in the same way although the example describes the method only in terms of the contact springs.

Considering a line of contact sites in the detailed model, as shown in Figure 4, the stiffness values of the intermediate arrangement of contacts were obtained by combining the stiffness of the detailed springs in parallel. For contacts of the same stiffness and with a reduction factor of n, the intermediate stiffness values are given by:

$$K_{Int} = n \times K_{Det} \qquad (1)$$

The lines of intermediate contacts are then combined in series using the same reduction factor to obtain the final set of reduced contact stiffness values:

$$K_R = \frac{K_{Int}}{n} \qquad (2)$$

For the case considered where contact stiffness values are constant throughout the array, Eq. (1) and Eq. (2) show that $K_R = K_{Det}$, i.e. the contact stiffness in the reduced array is the same as that in the detailed array. Where stiffness values vary throughout the detailed layer, the use of the normal series and parallel spring combination techniques will produce reduced stiffness values, K_R, which will vary across the array.

This procedure is applied independently to each set of contact sites, whether representing direct impacts between bricks or transverse impacts in the shear key system.

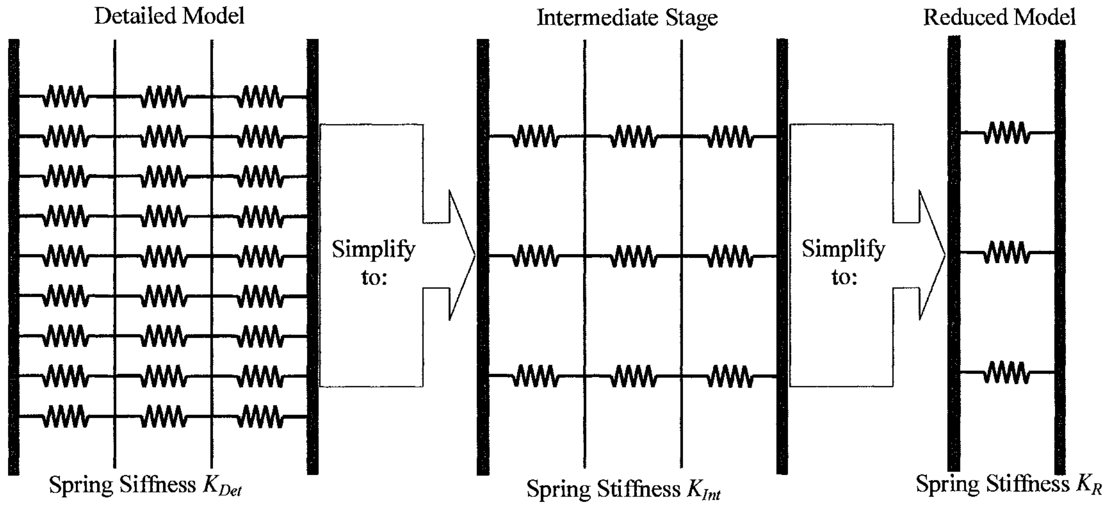

Figure 4 – Reduction Process for Contact Stiffness

Clearances

There is a small gap associated with each impacting site. Each gap is represented in the detailed model by a zone in the non-linear impact characteristics where there is zero contact stiffness and during which no damping acts. The equivalent gap in the reduced model is obtained by summing the values of the gaps in series and then taking the average of the gaps in the parallel array of intermediate contacts.

This procedure is applied independently to each set of contact sites, whether for gaps between bricks or for clearances in the shear key system.

PERFORMANCE

Comparing the responses of arrays calculated using the reduced model to those calculated using the detailed model enabled the performance of the method to be assessed. Two large arrays were used: a 16 x 16 array and a half of a single core layer with symmetry constraints along the diameter. In both cases, the seismic excitation was applied simultaneously to all boundary bricks.

As already noted, the detailed model representation is the same as those in earlier seismic studies for HTGR and AGR graphite cores, and the experimental array test results carried out for the AGR cores [1,2] were used to validate *GCORE* and its models during development. As these involved relatively small arrays, additional responses were calculated for large idealised arrays such as those reported in [5] and compared against responses obtained using other non-linear dynamic solvers.

To show equivalence between the reduced and detailed models, an extensive programme of computation was undertaken. First of all, the models were linearised by removing the gaps to confirm that the fundamental natural frequencies and mode shapes agreed, showing that the reduced model can reproduce the dynamics of the detailed model.

Then the gaps were re-introduced and non-linear seismic responses were calculated for a range of inputs covering both broad and narrow band frequency content, and variability in frequency phasing:

- Time History Characteristics – several independent time histories were generated to match the same target response spectrum.
- Input Magnitude – a time history was scaled to give time histories with a range of peak ground accelerations.
- Building Response – a time history was modified to represent the modal response of reactor buildings of different fundamental natural frequencies.

Key parameters were used to compare the results of the detailed and reduced models across a range of sensitivity studies. The two main parameters used were the total boundary force, because it is used in the assessment of the core restraint structure, and individual brick displacements, because these are used as part of the assessment of the capability of the shutdown and cooling systems. In each case, the peak values and the general response characteristics were compared. A selection of the results obtained is presented in Figures 5 to 10.

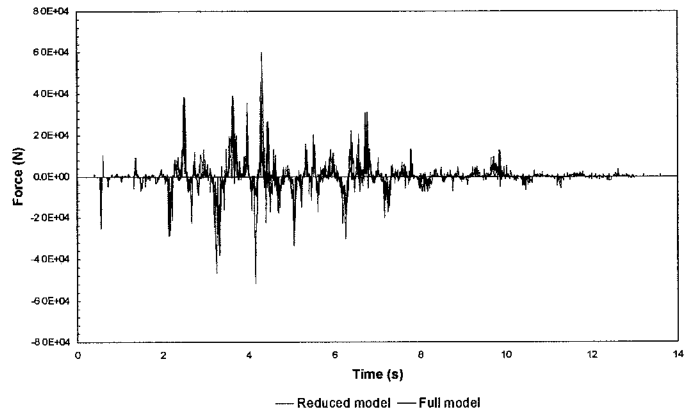

Figure 5 –Typical Total Boundary Forces

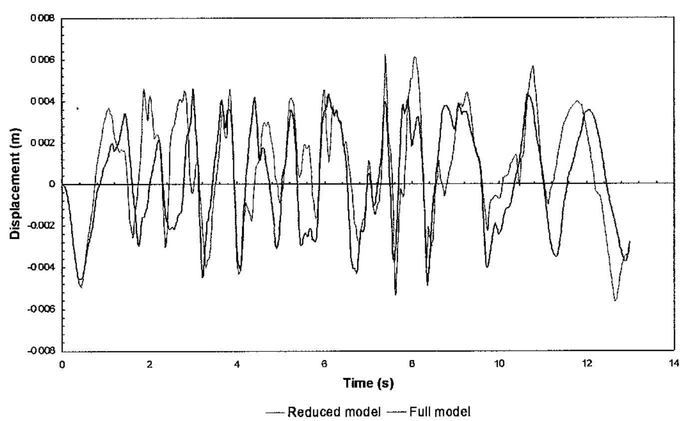

Figure 6 – Typical Mid-Array Brick Displacement

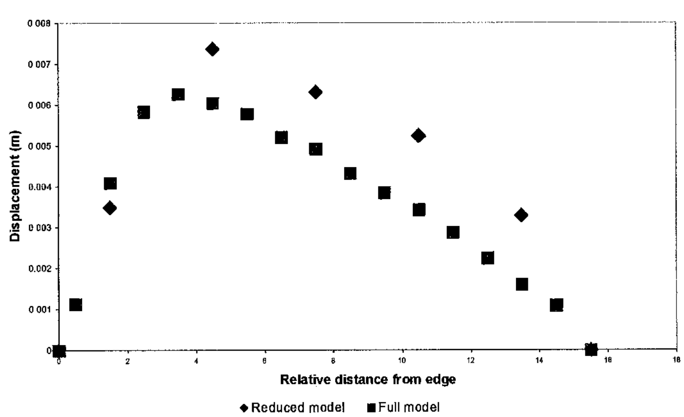

Figure 7 – Typical Profile of Maximum Displacement along Array Centre-line

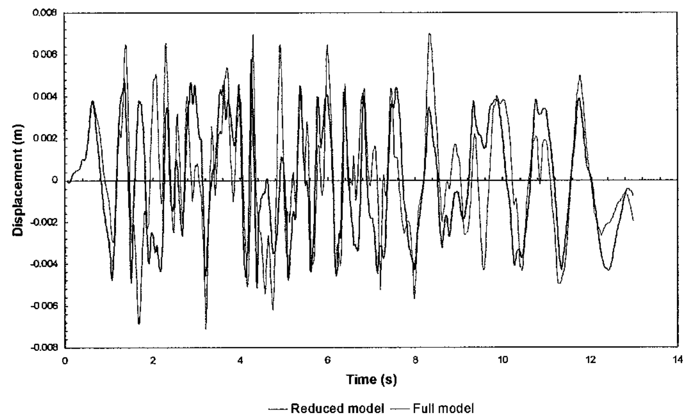

Figure 8 – Typical Mid-Array Brick Displacement at Higher Seismic Accelerations

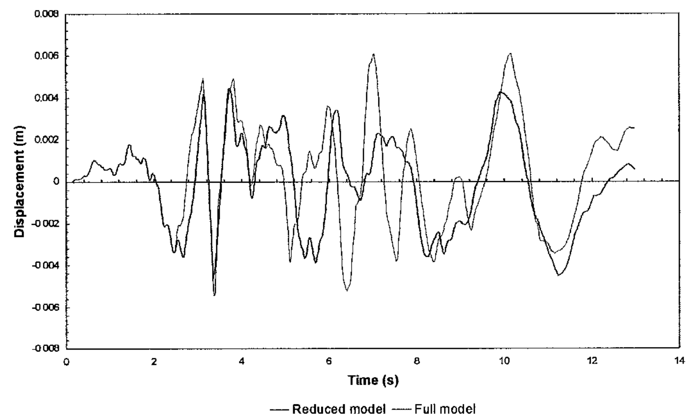

Figure 9 – Typical Mid-Array Brick Displacement at Lower Seismic Accelerations

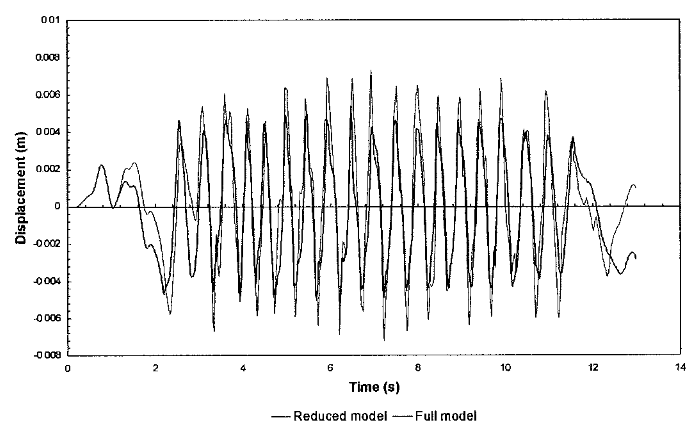

Figure 10 – Typical Mid-Array Brick Displacement for Simulated Building Mode Excitation at 2 Hz

The reduced model responses match well those of the detailed model both qualitatively and quantitatively. The results from the reduced model are generally conservative, as there is a tendency for it to predict slightly higher peak values of force and displacement.

The advantage of using the reduced model is, however, the ability to run a large number of sensitivity studies with acceptable accuracy. The run times were also recorded, and are shown in Table 1 for a single layer model. The reduction in run times achieved is of the order anticipated.

Table 1. Comparison of CPU Times (Single Layer Model)

Detailed Model CPU Time (Sec)	Reduced Model CPU Time (Sec)	Ratio (Detailed / Reduced)
26,162	1,459	17.9

Sensitivity studies enable a far greater understanding of the variability of the results around the best-estimate baseline, and thus provide significantly increased confidence in the full set of results. Such confidence is generally worth far more to the engineer than a single set of results that predict with greater resolution but with little indication of their variability.

CONCLUSIONS

A technique has been developed to reduce the size of non-linear dynamic models used for carrying out seismic assessments of AGR graphite cores. Simple and logical combinations of inertia, contact stiffness, contact damping and clearances for the individual core components have been used to obtain the properties of the elements in the reduced size arrays. The technique has been applied to brick arrays of the size of a single layer of graphite bricks in an AGR core, and seismic responses have been calculated for boundary excitations covering a wide range of earthquake magnitudes and characteristics, and reactor building natural frequencies. The reduced size array models have been shown to capture the dynamic behaviour exhibited by the detailed array models, and to predict loads and motions with an acceptable degree of accuracy for the full range of excitations considered, while achieving reductions in run-times by factors of around 18. Consequently, the reduced size arrays are judged to be suitable and practical to use in fully detailed non-linear structural dynamic models of AGR reactors for seismic assessments.

ACKNOWLEDGEMENT

This paper is presented with the permission of British Energy Generation Limited.

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