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Computational Modelling of the Response of the Advanced Gas Cooled Reactor Graphite Moderator Core under Static Loading

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ABSTRACT

Continuing work performed by British Energy Generation Ltd. is described which investigate the 3D mechanical behaviour of the AGR reactor core, with the aim of demonstrating undue pessimisms in current basic assessments. An approach developed with the ABAQUS finite element code is described, where individual bricks are represented by rigid bodies, and horizontal key/keyways and vertical joints represented by systems of non-linear orthogonal springs. The models permit a range of configurations to be investigated, including those constrained by the core geometry and those constrained additionally by gravity and restoring forces, some of which are illustrated, confirming the conservative nature of current methods.

INTRODUCTION

British Energy Generation Ltd. (BEGL) operates all five twin Advanced Gas-cooled Reactor (AGR) power stations in England. The functionality of the AGR graphite moderator core is based on the requirements for un-impeded movement of both control rods and fuel, and adequate cooling of the fuel and moderator. This is dependent on the geometry of displaced channels formed from columns of hollow bricks which are subject to restoring moments under their own weight, irradiation deformation and external loadings, and also constrained by an interlocking horizontal keying system. BEGL are developing computational models of the geometry of the graphite cores of their gas cooled reactors which aim to demonstrate undue pessimisms in current basic assessments of functionality, and have pursued a simplified Finite Element representation capable of modelling the entire core. Studies to verify and validate the modelling are ongoing, see [1], using alternative models and test rigs respectively.

The models are currently used in two distinct fashions, one being to examine cases where the resulting geometry is limited solely by the geometric nature of the core components, which gives the most onerous changes in path geometry and therefore functionality, and the other including the effects of gravity and restoring forces, more representative of reality.

DESCRIPTION OF THE AGR GRAPHITE MODERATOR CORE

The AGR graphite core, which moderates fast neutrons to promote the thermal fission of fuel and acts as a structure to locate fuel assemblies and control rods, consists of a cylindrical graphite moderator, surrounded above, below and at the sides by a graphite reflector, built from 13-15 layers of bricks with ~450-630 "round" bricks per layer, depending on the station (see Fig. 1 of [1]). This structure, which is approximately 11m tall by 11m diameter and weighs 1500te, rests on steel plates over a steel support system, and is connected to a surrounding steel restraint system by adjustable links attached to the outermost bricks. The round bricks are laid on a square lattice with smaller "square" bricks filling interstitial locations, and are hollow in the moderator region to form vertical channels which accommodate fuel and control rods respectively.

During the life of the reactor, the core is subject to internal loading as irradiation by fast neutrons causes the graphite bricks to deform, and also peripheral external loading which arises due to differential movements of the surrounding support and restraint steelwork as a result of non-uniform thermal response during temperature transients. In order to accommodate shrinkage of bricks arising from irradiation ageing and maintain the channel geometries under these loadings, the round bricks have eight axial keyways machined all or part way along their length (Fig. 1 of [1]) to accommodate either loose keys (between round and round) or integral keys (attached to the interstitial bricks) to form a horizontal interlocking network of connections. In addition, the round and square bricks are connected to their vertically adjacent neighbours by orthogonal axial keys or spigots/recesses which resist horizontal shear of layers and ensure continuity of columns and channels.

ABAQUS MODEL OF THE AGR GRAPHITE MODERATOR CORE

As whole core displacements are constrained mechanically by the horizontal keying system and energetically by the restoring moments of displaced columns a capability of modelling the entire 3D core is required. The ABAQUS Finite Element code [2] was chosen because of its wide use in the nuclear industry. Each major component is modelled discretely to allow rotation about horizontal and vertical axes, and associated kinking of columns. As the interactions between components are not considered to deform bricks significantly, it is adequate to model the core as a system of rigid bodies connected by non-linear springs representing gaps, with nodes only at the points of interaction. Furthermore, since such sites are approximately coincident on adjacent rigid bodies, JOINTC elements are used, and the springs have bi-linear stiffnesses with values representative of either the translation of the brick-to-brick and key/keyway gaps at the horizontal key/keyways, or the rotational restoring moments at axial connections as appropriate. The joint definitions (eg. non-linear characteristic) are unique to each joint and may be changed to reflect the values at a given time, allowing irradiation induced geometry changes to be incorporated.

For joints representing an axial connection between adjacent fuel bricks rotations about the horizontal axes represent the opening of a gap between vertically adjacent bricks, and the associated restoring moments are assumed to build up over a small angle, and then remain approximately constant over further displacements, see Fig. 1. The magnitude of the restoring torque is chosen to be the product of the weight of all bricks, etc. above the joint and the radius of the rocking diameter. The effects of irradiation deformation between brick end features may be introduced by "shifting" the rotational stiffness characteristic origin by the same angle, giving non-zero a restoring moment when the axes of vertically adjacent bricks are co-linear. The nature of the joints representing a key/keyway between adjacent fuel or interstitial bricks are similarly bilinear and have been described in [1].

VERIFICATION

The rigid body/spring model pursued by BEGL is being verified by comparison of results obtained from alternative modelling techniques. One approach has been the use of alternative FE models, restricted to a horizontal section of the fuel brick array of 5x5 size, and is described in [1]. Another approach has been comparison with a distinctly different program based on a Linear Programming (LP) solver, which has the ability to treat key/keyway clearances as mathematically perfect gaps rather than low stiffness entities. Early calculations using this alternative LP solver are reported in [3], and subsequent (as yet) unreported work has shown that satisfactory agreement can be obtained between the two techniques, not only for two dimensional models with geometric restraints, but also in three dimensions where energetic constraints and restoring forces are significant, and both of a size comparable to the real core.

VALIDATION

There are four fundamentally different sources of validation of the rigid body/spring model. Firstly there is the direct evidence obtained by BEGL from ongoing monitoring of the fuel channel shapes arising in its AGR cores, which lie well within the enveloping movements established using the geometrically constrained models. Secondly there is comparison with the experimental results arising from the 5x5 array horizontal section of the full size fuel bricks, as described in [1], complementing the verification work described above. Thirdly, to validate the three dimensional behaviour of the model, including force calculations, a rig which can house up to 48 full size fuel bricks arranged in three layers of 4x4 has been constructed, which can impose a wide range of displaced profiles on peripheral bricks, and is instrumented to measure loads arising in connecting key/keyways, as well as interior channel shapes, see Fig. 2. Finally, to complement these experiments which employ a relatively small number of real AGR bricks, an ⅙th scale plastic model of representations of fuel and interstitial bricks is planned, with similar numbers of components as AGR moderator cores, see Fig. 3. This will be used initially as a 2D horizontal section through the core to validate geometrically constrained movements, and ultimately in 3D with either externally imposed loads, eg. by tilting, or internal loads arising from perturbations associated with simulated brick deformations, when meta-stability of the deformed core can be investigated.

APPLICATIONS CONSTRAINED BY THE HORIZONTAL KEYING SYSTEM

Two applications will be illustrated which are constrained by the horizontal keying system alone. As these are geometrically constrained, and are not influenced by the effects of the third direction which include gravitational restoring forces as well as the requirement for compatibility of brick rotations in one layer with those in adjacent layers, these result in the most onerous core movements and challenge to core functionality for the chosen form of core loading. The loadings chosen tend to take a global form, and although theoretically larger individual brick maximum horizontal displacements could be obtained by isolated perturbing forces, the existence of a physical source of such loadings is thought unlikely.

Diametral Core Loading

A 2D representation a typical AGR graphite core "middle" layer and adjacent steel restraint system was generated, with stiffness characteristics of the joints chosen to be sufficiently representative of rigid body/gap behaviour consistent with the magnitude of imposed loading, and is illustrated in Fig. 4. The model was modified to reflect irradiation deformation, ie. shrinkage of brick radii and key/keyway clearances, to give results corresponding to the irradiated core at the time when maximum constraint due to shrunk horizontal keyways is expected.

The model was subject to an arbitrary horizontal (translational) body force (consistent with joint stiffnesses), sufficient to take up all the keyway clearances, applied parallel to the cardinal 'x' axes (0°), in which case the integral key/keyways are expected to constrain displacements and transmit the load. This fictitious global horizontal perturbing force has been chosen to give an indicative result of the likely upper bound to whole core movement.

The displacement components along the two cardinal axes under the global body forces are summarised as an exaggerated displaced mesh in Fig. 4. The bricks shrink so that brick/brick contact cannot occur, and irradiation closure of the key/keyway system gaps limits both the contracting and expanding lattice, giving core displacements that are symmetric about the cardinal axes. Local longitudinal and transverse forces at the joints; corresponding to brick to brick contact and shear of the keys were recorded. The forces within the core separate into distinct regions, so that the loading transfers from integral keys in the sectors parallel to the loading to the loose keys in the sectors perpendicular to the direction of loading.

Circumferential Core Loading

As an alternative form of applied loading, the effect of a rotational corkscrew was investigated. Despite the lack of a third dimension, the fuel bricks were constrained so as not to rotate by more than a reasonable amount, recognising that ultimately their rotation is constrained by their positive location to the support plates via the brick end face keying system.

In this instance the displacement pattern found is illustrated in Fig. 5. The maximum displacement value is no greater than that found for diametral loading, above, although it clearly occurs on the oblique planes, and at roughly half the core radius, reflecting the a non-uniformity in the "rotational" strains that can be accommodated by the "loose" round/round and "integral" round/square keying systems. It was also observed that the keying system balancing the rotational load on the whole core is that which is locally parallel/perpendicular to the circumferential direction, which is consistent with a keying system undergoing shear rather than direct strain.

THE EFFECT OF THE VERTICAL DIMENSION AND GRAVITY - RADIAL LOADING

For the purposes of these calculations, a further form of core loading was considered, in this case radial loading. In both circumstances, a three dimensional model of a core was used, but restricted to a core quadrant using symmetry conditions to reduce computational overheads. The loading was restricted to a radial loading of the mid height layer.

Vertical Dimension Without Restoring Forces

In the first instance, the effect of gravitational restoring forces were omitted from the model to examine the effect of the third dimension geometrical constraint alone. In this case the bricks in adjacent layers must maintain at least a vertical rotation which is compatible with the adjacent layers, and, in principle, differences in relative translations can be accommodated by horizontal rotations.

The displacement obtained is illustrated for a vertical section through the core in Fig. 6, where it is seen that, consistent with expectations, the central and peripheral columns remain vertical, while the greatest displacement arises at approximately the middle radius. It can also be observed that the column deformation is restricted to the mid height, as there is little communication of force along the column height, and trivial forces used to stabilise the model behaviour maintain the column straightness. The displacements, and forces, in this case are indistinguishable from those obtained from 2D calculations with the same form of loading.

Restoring Forces

In this case gravitational forces were introduced to the model, so that restoring moments about the horizontal were activated between layers, and an additional energetic constraint applies. This means that lateral movements can now be communicated along the brick column height, and the columns and core will attempt to maintain a minimum energy configuration.

Now the displacements through the core, Fig. 6, are spread more uniformly along the core height, and, for a representative loading, the greatest displacement is considerably smaller than the geometrically bounded case, above.

CONCLUSIONS

Continuing work to analyse the 3D mechanical behaviour of the gas cooled AGR graphite core has been described, and a brief summary of ongoing verification and validation routes presented. It has been demonstrated this is a practical method able to analyse a significant volume of the core, and that the additional constraints of three dimensional modelling and more representative patterns and magnitudes of loading can lead to less onerous core configurations, as anticipated, indicating conservatism in current simplified approaches.

ACKNOWLEDGEMENT

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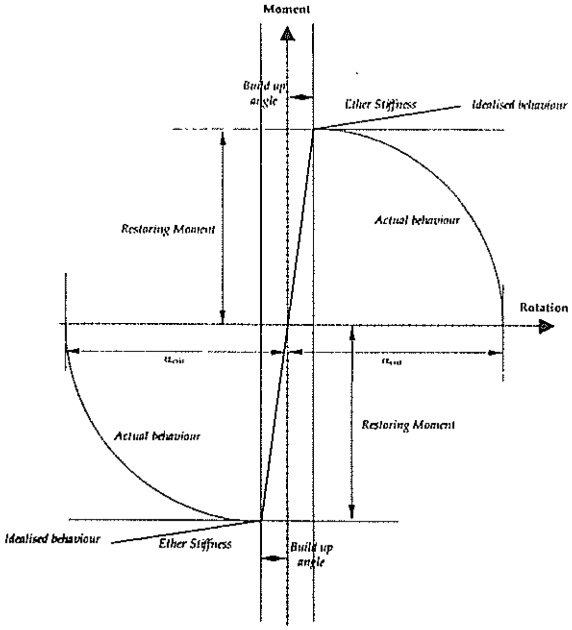


Fig. 1. Axial Joint & Characteristic

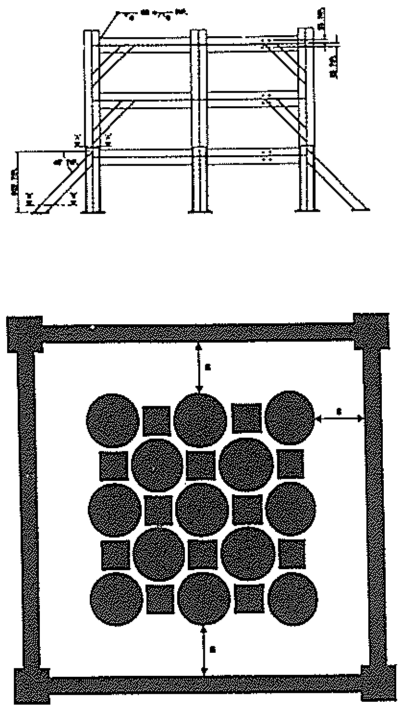


Fig. 2. 48 Full Size AGR Brick 3D Rig

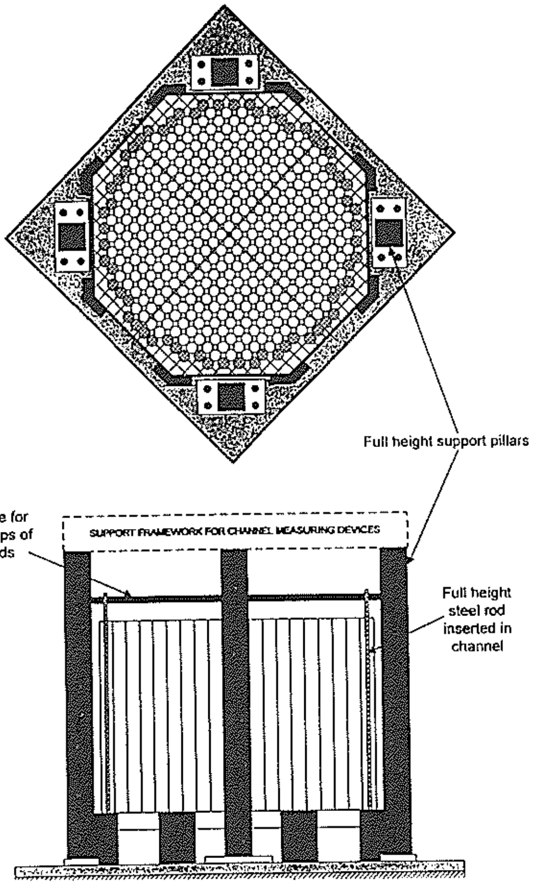


Fig. 3. ⅛ Scale AGR Core Rig

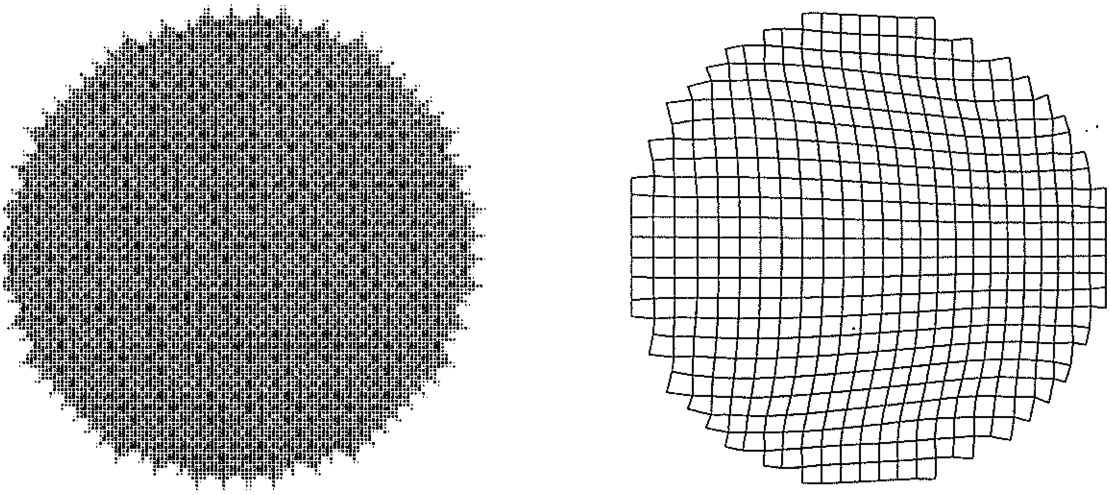


Fig. 4. 2D Layer Mesh and Displaced Lattice under Diametral Loading

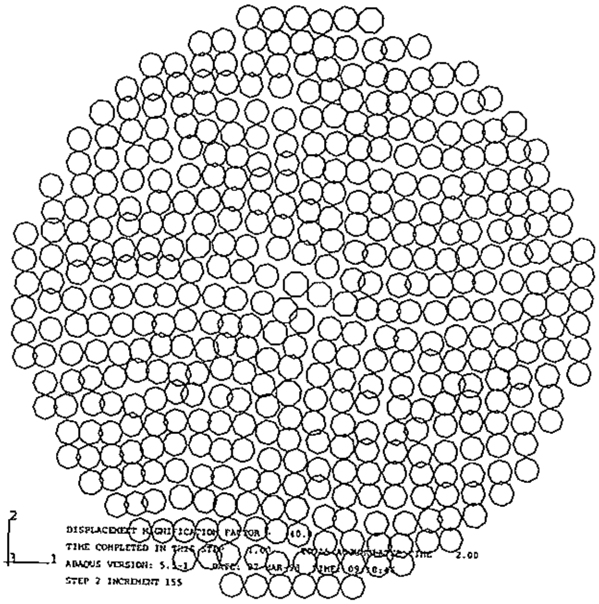
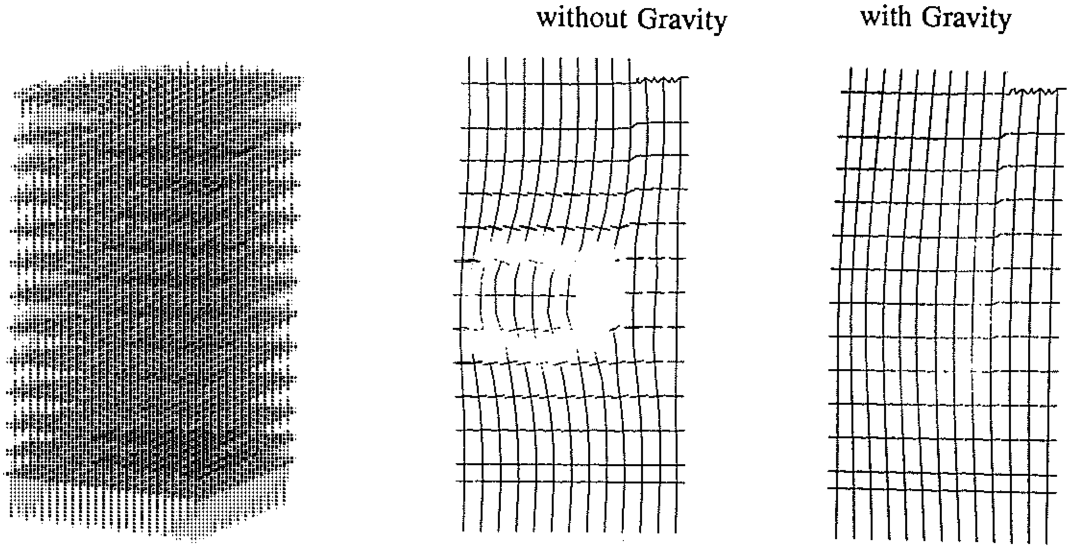


Fig. 5. Displaced 2D Lattice under Rotational Loading


without Gravity

with Gravity

Fig. 6. Displacement of 3D Mesh under Radial Loading