DYNAMIC CALCULATIONS USING A FRAMEWORK ANALOGY TO PREDICT THE SEISMIC RESPONSE OF A NUCLEAR REACTOR

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ABSTRACT

The feasibility of predicting the response of a nuclear reactor system to a spectrally defined earthquake is established in the context of a particular example. The associated dynamic calculations were carried out on FRAMES, which is a UKAEA Reactor Group program for the vibration analysis of skeletal structures. Although the pipework and framed structures could be represented quite directly in this way, further work was needed to simulate other components, such as the reactor vessel and core. The use of grid-framework methods in this connection is described, as is their application to the modelling of the ground strata supporting the reactor. The complexity of the combined system led to the use of physical partitioning, and full advantage was taken of a number of rationalisations which this technique suggested.

The analysis demonstrated that soil/structure interaction introduced significant extra degrees of freedom. The associated modal shapes involved simultaneous sideways movement and rocking of the raft, at frequencies which depended primarily on the values used for the soil moduli, thus emphasising the need for reliable data on the latter.

1. INTRODUCTION

The work described was aimed primarily at an assessment of seismic effects on a nuclear power station, with particular reference to the loads imposed on the core. Extensive use was made, in this assessment, of a general-purpose computer program (Jobson and Litherland [1]) which enables vibrating shapes and frequencies to be computed for skeletal structures. The need for a modal analysis arose from the form in which the earthquake data were presented. The latter were given in spectral terms (see Hudson [2]) and took the form of Housner-type response curves, normalised to a ground acceleration of 7% of g.

In the present study, attention was focussed on those features of the system which could influence the seismic response of the graphite core stack (see Figs 1 and 2) and these were judged to be:

(i) Soil/structure interaction.

(ii) Response of the diagrid and its support system, including the main vessel, ducts and heat exchangers.

(iii) Response of the core, including the support plates and the steel restraint structure.

2. SOIL/STRUCTURE MODES

The ground strata consisted of silty sand and clay, resting on soft rock. Beneath this was a thin layer of sand and then clay to a very great depth; the reactor raft was founded on the rock.

The application of spectral analysis first requires that the relevant natural frequencies and modal shapes of the system be found. If soil/structure interaction is ignored, there is no ambiguity as to what is meant by the "system". A relatively flexible building founded on solid bed rock extends only as far as the latter. The above method is obviously inadequate for situations where the raft and the biological shield are both massive and stiff, whereas the ground is relatively deformable. The boundaries of the "stress bulb" on which the reactor sits were based on the dead-weight stresses induced in the ground. These limits were chosen as the line beyond which the vertical stress felt by the soil was less than 10% of the mean vertical stress under the foundation and indicated that most of the enclosed soil volume was clay.

The above boundaries served as a conceptual convenience to limit the extent of the system for which modal analysis was required, see Figs' 3 and 4. They were supported in each reference plane by attaching horizontal and vertical springs to its boundary nodes. The spring stiffnesses were derived from finite element models of the ground lying beyond the boundaries considered. The inertia of the enclosed ground was modelled by a lumping procedure and the stiffnesses of each ground stratum were represented by equivalent elastic frameworks, (see Jobson [3]). The most important of the soil parameters was the Young's modulus for the clay. The considerable uncertainties in ascribing an effective value to the latter makes that used (4300 p.s.i.) a provisional figure which is subject to review. It was derived from fast undrained tri-axial compression tests, after making allowances for cyclic loading to a peak strain of 0·1%. The completed work showed that this was not significantly exceeded. The inertias of the foundation raft and the structures on it were similarly represented by lumped masses and the associated rigid body movements were found to be significantly larger than those induced by distortion of the concrete for the modal shapes plotted in Figs 5 and 6. Only relatively few of the many modal shapes found had any significant effect on lateral movement of the reactor. Strictly speaking, a complete computation of the modal shape at each of these frequencies required a modelling of the steel structures on the raft, together with the core. It was argued however that the dynamic effect of the latter in the 0-1 Hz range would have been negligible so far as the system considered was concerned. It followed that the modal shape at these frequencies could be "completed" by inferring the diagrid and core movements subsequently. The amplitudes of the raft followed from the spectral curves in the 0-1 Hz range. The associated spectral displacements (u_0) apply directly only to the motion of a single mass on a spring, see for example Biggs [4]. More generally each needs multiplying by the appropriate participation factor (Γ). For an earthquake oriented in the x and y directions respectively, Γ takes the form:

$$\Gamma_x = \frac{\Sigma_r m\varphi_x}{\Sigma_r m(\varphi_x{}^2 + \varphi_y{}^2 + \varphi_z{}^2)} \quad , \quad \Gamma_y = \frac{\Sigma_r m\varphi_y}{\Sigma_r m(\varphi_x{}^2 + \varphi_y{}^2 + \varphi_z{}^2)} \tag{1}$$

The summation is taken over all the r masses, each of which has component displacements φ_x, φ_y and φ_z respectively in that mode, relative to the reference axes Ox, Oy and Oz. Neglect of the relatively small masses of the steel and graphite features of the system in this calculation involved negligible error. The maximum displacements of the raft were obtained from u_o and the relevant Γ, together with the modal amplitude (φ_i) of the component considered. The spectral amplitudes ($u_o\ \Gamma\ \varphi_i$) of the raft so obtained are given in Table I. The tabulated values are spectral and not absolute displacements. Interpreted physically, they are the peak displacements of the raft, as seen from moving ground that is substantially uninfluenced by the presence of the reactor. As the methods described above are novel, they were compared with a conventional analysis of soil-structure interaction, using the method of Whitman [5]. Although there was a remarkably good agreement of frequencies, the modal shapes, see Figs 5 and 6, are much more complicated than could be derived from the Whitman analysis alone, and hence the responses are different.

3. DIAGRID, VESSEL AND DUCT SYSTEM

The 24 support legs for the spherical steel vessel are equally pitched round a circle which is approximately 45 ft in diameter. Their ends are so cradled that no bending is induced in them by radial expansion of the sphere. An equivalent system of six uniform pillars was devised, having the appropriate component stiffnesses. Similar simplifications were made for the pillars supporting the diagrid which was modelled structurally by reference to a smeared analysis.

The enclosing pressure vessel was simulated by a lattice structure, based on an equatorial ring and a parallel set of six horizontal small circles, together with a perpendicular set of six meridians. They were rigidly jointed at their intersections and a curvilinear rectangular element of the shell was notionally associated with each of these nodes, see Fig. 7. By suitably lumping the membrane, bending and torsional stiffnesses of each element so defined, an equivalent skeletal grid-framework (Hrennikoff [6] and Jobson [7,8]) was derived. Corresponding values were similarly determined for the members forming the equilateral lattice in plan round each of the poles and these were further adjusted to take account of the fairing lying within the bottom of the vessel. The inertia of the vessel, as well as that of the diagrid and support system, was represented by a set of lumped masses, distributed as symmetrically as possible. Associated problems of core storage and machine time required that the number of inertial degrees of freedom in each sub-system be limited to 78. It was therefore decided to neglect the obliquity of the side-ducts in plan and define equivalent top and bottom ducts, disposed on each side of the vessel, along the major axis of the foundation raft. The restrictions on flexibilities were far less severe and each length of heat exchanger vessel and duct was represented by an appropriate prismatic member. The component stiffnesses of each bellows was assessed and combined with those of the tongues lying within them. The guides which prevent lateral motion of the ducting presented no difficulties since the program allowed imposition of appropriate component restraints.

The lowest natural frequency of this combined system was found at 1·99 Hz and the next critical was found at 3·02 Hz. Neither of these modes induced any substantial diagrid movement however, such as that seen at the next critical (3·39 Hz, see Fig. 8). Although there were uncertainties about the behaviour of the heat exchangers, subsequent computer runs showed that the core movements were not in general sensitive to their response. Only an unlikely synchronism between the natural frequency of a heat exchanger and one of the modes of the main system could substantially modify the top duct movement and its interaction with the main modes of the vessel. The dynamic modelling and characteristics of the core, together with its associated restraint structure will be considered in the next section.

4. GRAPHITE CORE STACK AND RESTRAINT STRUCTURE

Figure 9 shows the graphite core construction in which, at the assembly stage, each brick is separated in plan from its neighbour by a small gap (exaggerated for clarity in the figure), the individual columns of bricks being stabilized by keys to those surrounding it.

A layered model was used to simulate this structure, each node of the latter being supported vertically by columns having a stiffness derived from tilting tests on a model core stack. The octagonal bricks are arrayed on a square pitch with clearance between each, and an interlinking system of mutually perpendicular keys. The further interstitial bricks, which are loosely fitted between them and are similarly interlinked by sliding keys, thus give rise to what is equivalent to a cross-braced lattice pattern. Reference has already been made to the studies which have been made of lattice systems of this kind. In smeared terms, if $\underset{\sim}{\sigma} = \{\sigma_x, \sigma_y, \tau_{xy}\}$ is a column vector of stress components in the plane of the lattice and $\underset{\sim}{\varepsilon} = \{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}$ similarly denotes the corresponding engineering strains as conventionally defined, then to a first order:

$$\underset{\sim}{\sigma} = \underset{\sim}{C}\,\underset{\sim}{\varepsilon} \qquad (2)$$

For each graphite layer it was found that:

$$\underset{\sim}{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} = \begin{bmatrix} G & -G & 0 \\ -G & G & 0 \\ 0 & 0 & G \end{bmatrix} \qquad (3)$$

which is unusual in that it corresponds to an isotropic lattice that has been so designed as not to resist all-round tension. Its elastic constant (G) was inferred from tests on keyed connections and the flexural characteristics of each lattice member were so chosen as to reproduce $\underset{\sim}{C}$.

The enclosing restraint structure is plated towards its base and is diagonally braced towards the top. A rationalised system having 12 sides was devised and the section constants for the plated portion were so chosen as to reproduce the elastic constants of the material it replaced, again by the use of grid-framework methods. Advantage was taken of symmetry and only one half of the core and the restraint structure was modelled. The mass was distributed over four layers and the response to harmonic excitation at the level of the diagrid obtained for the frequency range 0–6 Hz at intervals of 0·25 Hz. The otherwise "free-free" system was located positively by dummy springs which were sufficiently light as to introduce negligible errors above 0·1 Hz. These runs demonstrated that, in the range 0–1 Hz, rigid body displacements were much larger than any distortion of the core shape in response to either unit force or to unit moment. It was concluded that in this frequency range, the interactive effect, or receptance of the core on the diagrid would be substantially the same as that for a rigid body. An equivalent dynamical system was thus devised, consisting of two lumped masses, lying on the centre-line of the core.

The forced responses further showed that there was negligible straining of the cross-section of the core due to excitation by alternating forces and moments at the base of the core in the range 0-5 Hz. Core distortion could therefore be represented in this frequency range simply by flexing of its centre-line and led to the use of a flexible "dumb-bell" for computations in this range. Such a simple model could not adequately represent the core at higher frequencies, where its behaviour became increasingly complex. In the 3-5 Hz range it was difficult to decide whether a rudimentary modelling of the core, with a fairly complete representation of the vessel and associated circuits, would yield better results than a sophisticated modelling of the supported core, with a crude modelling of the vessel/duct and heat exchanger system. It was judged that the latter would certainly be more appropriate above 5 Hz and it was finally decided to analyse the 3-5 Hz range by a combination of both models.

5. RESPONSE OF CORE/VESSEL COMPLEX

Modelling of the vessel/duct and heat exchanger system, together with the definition of a rigid dumb-bell to represent the core enabled the modal profiles of the complete system to be inferred at each of the soil/structure natural frequencies given in Table I. The associated core accelerations were found from the known spectral movements of the foundation raft about its virtual pivot position for each mode, and it was found that deformation of the support pillars increased the core movements, see Table II. The natural frequencies and modal shapes of the vessel/duct system were also found for the above model in the 1-5 Hz range using the flexible dumb-bell representation of the core. The presence of the latter reduced the frequency at which substantial diagrid movement was felt from 3•39 Hz down to 2•95 Hz. Further frequencies were found, again involving diagrid movement parallel to the longitudinal axis of the raft at 3•61 Hz and 4•03 Hz. Only one significant mode was found in the 1-5 Hz range for diagrid oscillation parallel to the transverse axis, which was attributed to the additional lateral restraints on the ducts. The corresponding frequency was 3•77 Hz and in all of these cases the diagrid movement was substantially horizontal. The associated profiles of the core stack at each natural frequency were deduced from its harmonic responses to excitation of the base.

It is possible to repeat the above process by computing the actual receptances of the distorting core at each natural frequency and correcting the receptances of the flexible dumb-bell in a subsequent recalculation. There are, however, indications to suggest that the modes of the gas circuit are not sensitive to the receptance of the core in this frequency range and the modal shapes of the vessel/core complex were obtained without iteration. They were used to compute the corresponding participation factors and hence the spectral accelerations, see Table III. These results are the same as would have been obtained had soil/structure interaction effects been ignored completely and this is a point which will be reconsidered subsequently.

In an alternative representation, particularly aimed at computation of the higher modes of the core (above 5 Hz), the core and restraint structure were modelled in full detail. This allowed only a crude simulation of the vessel and attached ducts. Lumped masses were used to represent each of the latter, based on the total mass of the vessel, plus a nominal allowance for the attached ducts.

It followed that such a model would give the same fundamental frequency in each of the two principal planes, and this came out at 3·09 Hz. It corresponds to 2·95 Hz (longitudinal) and 3·77 Hz (transverse) obtained from the previous model. A further limitation was that no other frequencies were found in this range to correspond to the different ways in which the ducts could participate in core motion.

Further significant core modes were found at 5·9 Hz and 13·3 Hz, see Fig. 10(a), (b) and (c). Computation of the modal participation factors, again ignoring any reactive effect on the foundations, led to the results given in Table IV. Negligible distortion of the cross-section of the core was found for the frequency range covered by Tables II, III and IV. This was attributed not only to the effectiveness of the lattice layers in preserving their shape, when account is also taken of the stability of the graphite columns and of the restraint structure, but also to the absence of any excitation of the 'breathing' modes of the core found at 6·4, 9·4 and 14·2 Hz (see Fig. 11(a), (b) and (c)).

6. REACTIVE MOTION DUE TO SOIL/STRUCTURE INTERACTION

The analysis presented so far suggests that soil/structure interaction had two effects:

(i) It introduced additional low-frequency modes which did not interact strongly with those of the reactor structure because of the low value assumed for the soil modulus.

(ii) By obtaining the structural modes of the system with the implied assumption that the foundation and the soil did not participate in the <u>modal</u> motions, these frequencies and amplitudes came out the same as if soil/structure interaction effects had been ignored entirely.

It is the second assumption that leads to results which are in conflict with current views about soil/structure effects. The latter are known not to be wholly deleterious, particularly for heavy stiff structures [9]. This can be illustrated by reference to a very simple model in which the mass m_1 representing the "foundation" is much larger than the "structural" portion of the system. The spring constants are such that the natural frequency of the large mass is very much lower than that of the smaller one. With the above provisos, the frequencies of the coupled system are virtually the same as those of each mass on its own spring i.e. $\omega_a = \sqrt{(k_1/m_1)}$ and $\omega_b = \sqrt{(k_2/m_2)}$. The modal participation factor for the first of these two frequencies is virtually:

$$\Gamma_a = \frac{\Sigma mX}{\Sigma mX^2} = \frac{m_1X_1}{m_1X_1{}^2} = \frac{1}{X_1} \tag{4}$$

since at this frequency $X_1 = X_2$ and $m_1 \gg m_2$. The corresponding spectral displacements of m_1 and m_2 are thus substantially equal at the lower (soil/structure) frequency:

$$d_1 = d_2 = \frac{1}{X_1} X_1 \; u_a = u_a \tag{5}$$

The modal participations for the higher (structural) frequency require however that account be taken not only of the relatively large movement of the small structural mass m_2 at this frequency, but also the relatively small movement of the much larger foundation mass m_1. An approximate analysis shows X_1 to be very nearly, $-X_2m_2/m_1$. It follows that the modal participation factor at the higher frequency is virtually zero since $\Sigma mX \simeq 0$. Physically it implies that the higher mode is such that the mass-centre of the combined system remains virtually stationary. These conditions appear to be well satisfied for the reactor considered and require that the participation factors for the structural modes be reduced by taking into account the reactive effect on the foundation. Using m, φ and M, Φ to denote the "structural" and "foundation" masses respectively, the modified modal participation factor corresponding to Γ_x is:

$$\Gamma_x{}' = \frac{\Sigma m\varphi_x + \Sigma M\Phi_x}{\Sigma m\varphi^2 + \Sigma M\Phi^2} \tag{6}$$

Since $\Phi^2 \ll \varphi^2$ the effect on the denominator of $\Sigma M\Phi^2$ is virtually negligible. It follows that the Reactive Factor (r) to be applied to Γ_x is approximately:

$$r_x \simeq \frac{\Gamma_x{}'}{\Gamma_x} \simeq \frac{\Sigma m\varphi_x + \Sigma M\Phi_x}{\Sigma m\varphi_x} = 1 + \frac{\Sigma M\Phi_x}{\Sigma m\varphi_x} \tag{7}$$

Similarly:

$$r_y = \frac{\Gamma_y{}'}{\Gamma_y} \simeq 1 + \frac{\Sigma M\Phi_y}{\Sigma m\varphi_y} \tag{8}$$

The second term in each expression comes out negative, as a result of the reactive shears and moments exerted by the structure on the foundation. The values of r have been found for each of the structural modes in this way and their effect is to reduce all predicted accelerations for the high frequency modes (above 1 Hz) to which they apply. It should be noted that they have no relevance to the soil/structure interaction modes. The diminished accelerations on the core support are given in Table V, and may be compared with the undiminished values given in Tables II, III and IV.

7. SUMMARY AND CONCLUSIONS

A seismic analysis of the vital components of a nuclear power station has been described in which the primary aim was to assess the loads imposed on the core restraint structure. It followed that the motion of any components which interacted with that of the core needed to be included. These were judged to be the core diagrid, its supporting pillars, together with those for the vessel and the vessel itself. It was found that allowance also needed to be made for the attached ducts, together with the heat exchangers to which they are connected. Seismic excitation of such systems must essentially be limited to displacements which can be accommodated by a substantially recoverable elastic response and the object of the study was to provide data to enable this to be checked.

Extensive use was made of FRAMES, which is a powerful general-purpose program for the dynamic analysis of skeletal structures. This was deployed in conjunction with grid-framework methods, which enable elastic continua to be represented by equivalent lattices.

Modal analyses were carried out by means of an eigenvalue/eigenvector sub-routine, which was based on the use of a matrix deflation method that determined each frequency in turn from the lowest value upwards. Dynamic interaction between sub-systems was accounted for by modelling the dynamic flexibilities of the attached system at each interface.

Deformable ground implied that the natural modes of the raft/structure needed to include that part of the sub-soil which participated significantly in the motion. In assessing the latter account also had to be taken of the fact that the ground properties depended on the associated bearing pressure. Definition of the boundary for modal analysis is to some extent arbitrary but is not judged to be critical. The various layers of ground within the supporting stress bulb were represented by an equivalent elastic framework and its distributed mass was lumped on the nodes of the latter. The boundary of the framework was anchored by equivalent springs having stiffnesses based on a finite element modelling of the surrounding ground. Subsequent analysis of the forced response of the structural features mounted on the raft showed that the sideways movement was amplified so far as the core was concerned by associated deformation of its support system.

One further significant effect resulted from including soil/structure interaction. Vibration of the structural features at each relevant natural frequency gave rise to reactive forces and moments on the foundation and ground. These, in turn, caused small displacements of the latter which were, nevertheless, significant in that the masses involved were relatively large. Consequently the participation factor for each of these modes due to excitation from the surrounding ground was reduced. As a result, the spectral accelerations of the higher frequency structural modes were less than would have been predicted had soil/structure interaction effects been ignored.

8. ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions made by his colleagues to the work described, and to thank the Managing Director of the Reactor Group, UKAEA, for permission to publish this paper.

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TABLE I

RESPONSE OF FOUNDATION

Mode	Frequency /(Hz)	Maximum spectral displacement of top of slab/(in.)	Maximum rotation /(rdn)
Longitudinal direction			
2	0·46	1·75	0·0010
3	0·50	0·15	0·0006
6	0·76	0·10	0
7	0·88	0·01	0
9	0·97	0·01	0
Transverse direction			
2	0·41	0·98	0·0011
3	0·57	0·27	0·0001
6	0·88	0·05	0
7	1·04	0·03	0·0001

TABLE II

LOW FREQUENCY RESPONSE OF CORE

	Frequency /(Hz)	Spectral displacement of core/(in.)		Lateral acceleration of core/(g)	
		Base	Top	Base	Top
Longitudinal axis	0·461	2·033	2·406	0·0441	0·0522
Transverse axis	0·409 0·571	1·272 0·248	1·666 0·223	0·0217 0·0083	0·0284 0·0074

TABLE III

INTERMEDIATE FREQUENCY RANGE UNDIMINISHED RESPONSE

Mode	Frequency/(Hz)	Lateral acceleration of core/(g)	
		base	top
Longitudinal axis	2·95 3·61 4·03	0·0118 0·0015 0·0058	0·0688 0·0102 0·0162
Transverse axis	3·77	0·0012	0·0065

TABLE IV

HIGH FREQUENCY RANGE UNDIMINISHED RESPONSE

Mode	Frequency/(Hz)	Lateral acceleration of core/(g)	
		base	top
Longitudinal and transverse	5·90 13·30	0·050 0·043	0·052 0·0026

TABLE V

DIMINISHED SPECTRAL RESPONSE

Frequency/(Hz)	$r(=\Gamma'/\Gamma)$	Lateral acceleration of core/(g)	
		base	top
Longitudinal axis			
0·461	1·0	0·0441	0·0522
2·953	- 0·017	0·0002	0·0012
3·606	- 0·006	0	0
4·025	- 0·043	0·0003	0·0007
5·90	- 0·001	0	0
13·30	- 0·040	0·002	0·0001
Root square value (L)		0·0441	0·0522
Transverse axis			
0·409	1·0	0·0217	0·0284
0·571	1·0	0·0083	0·0074
3·771	- 0·190	0·0002	0·0001
5·90	- 0·064	0·0032	0·0033
13·30	- 0·018	0·0008	0·0001
Root square value (T)		0·0235	0·0296
Resultant $\surd(L^2 + T^2)$		0·050	0·060

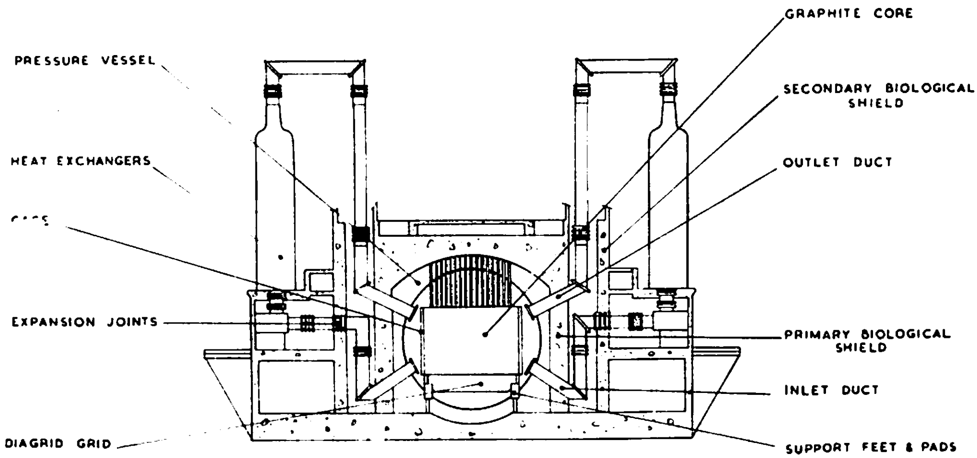


FIGURE 1 - The Reactor Building Elevation

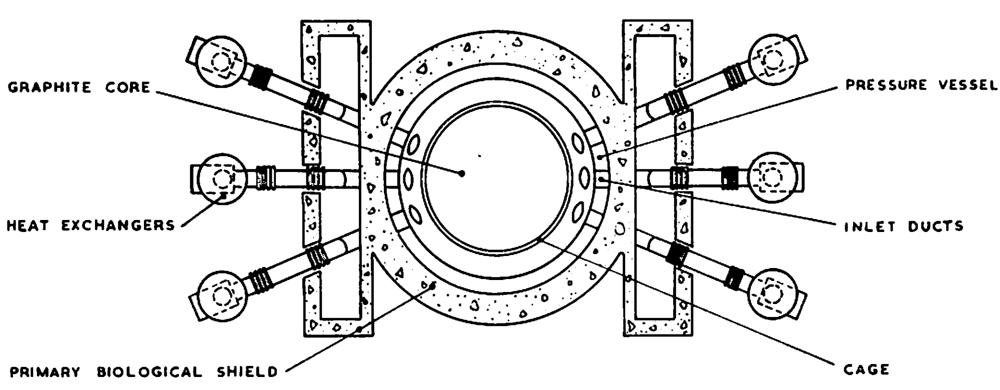
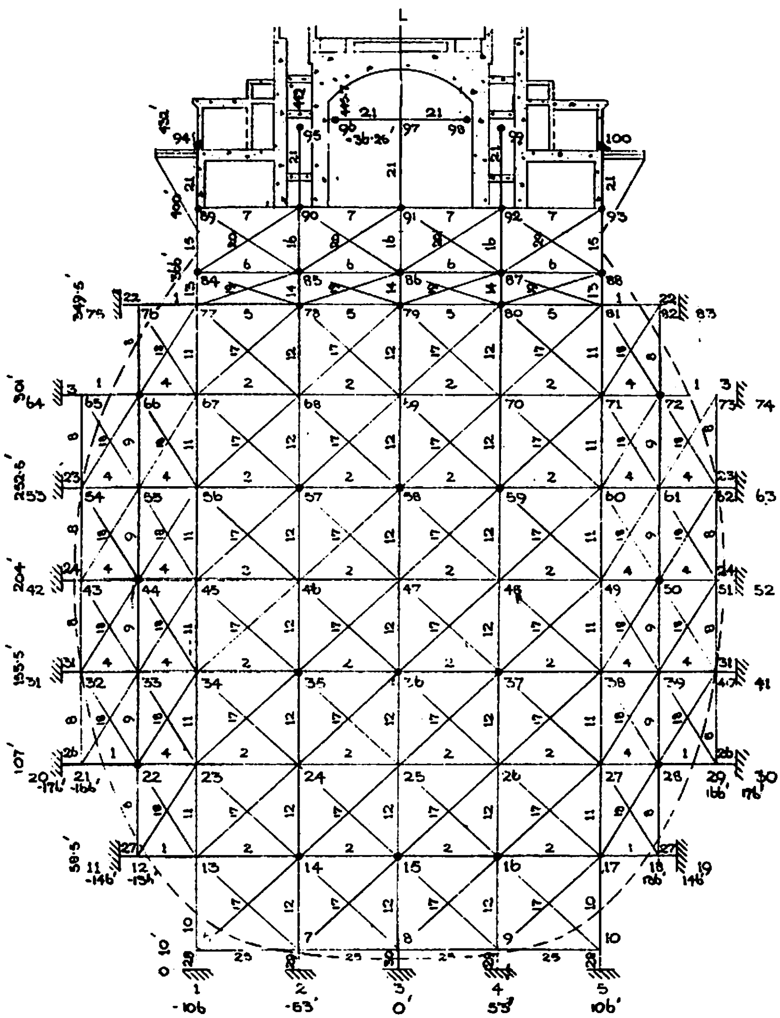


FIGURE 2 - The Reactor Building Plan



LONGITUDINAL SECTION

FIGURE 3 - Longitudinal Section of Supporting Ground

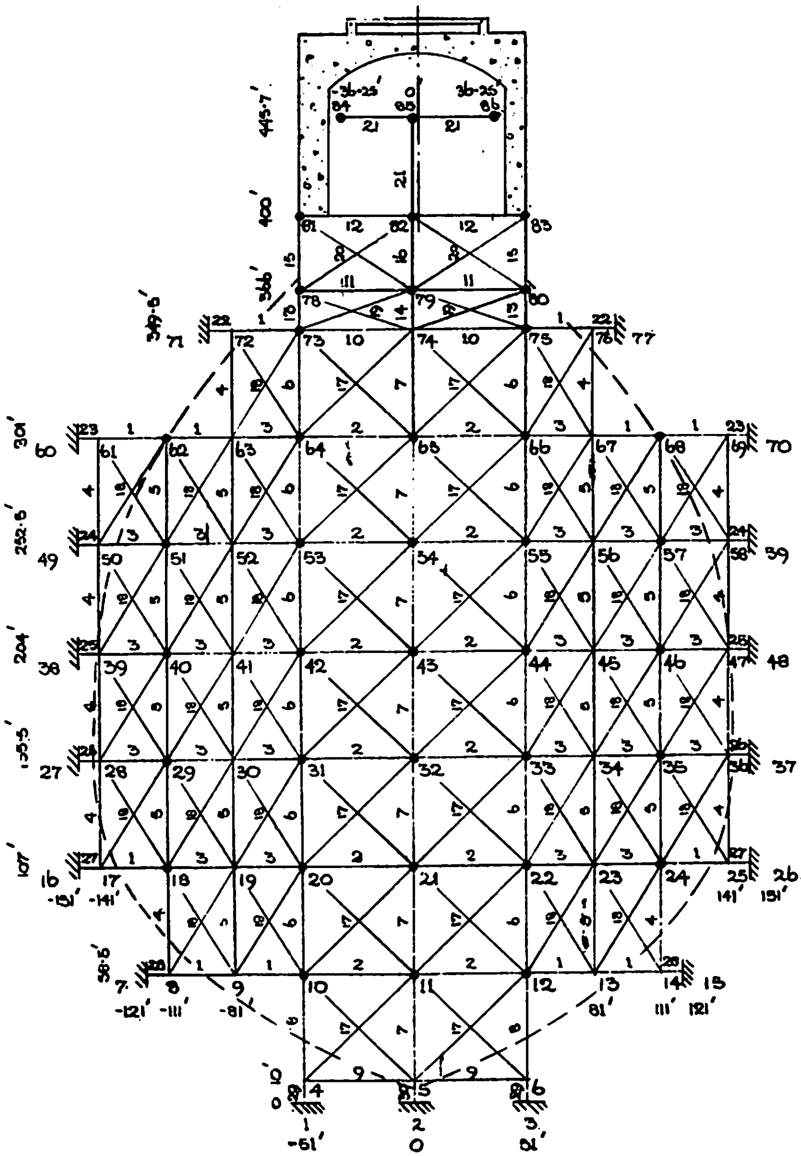


FIGURE 4 - Cross Section of Supporting Ground

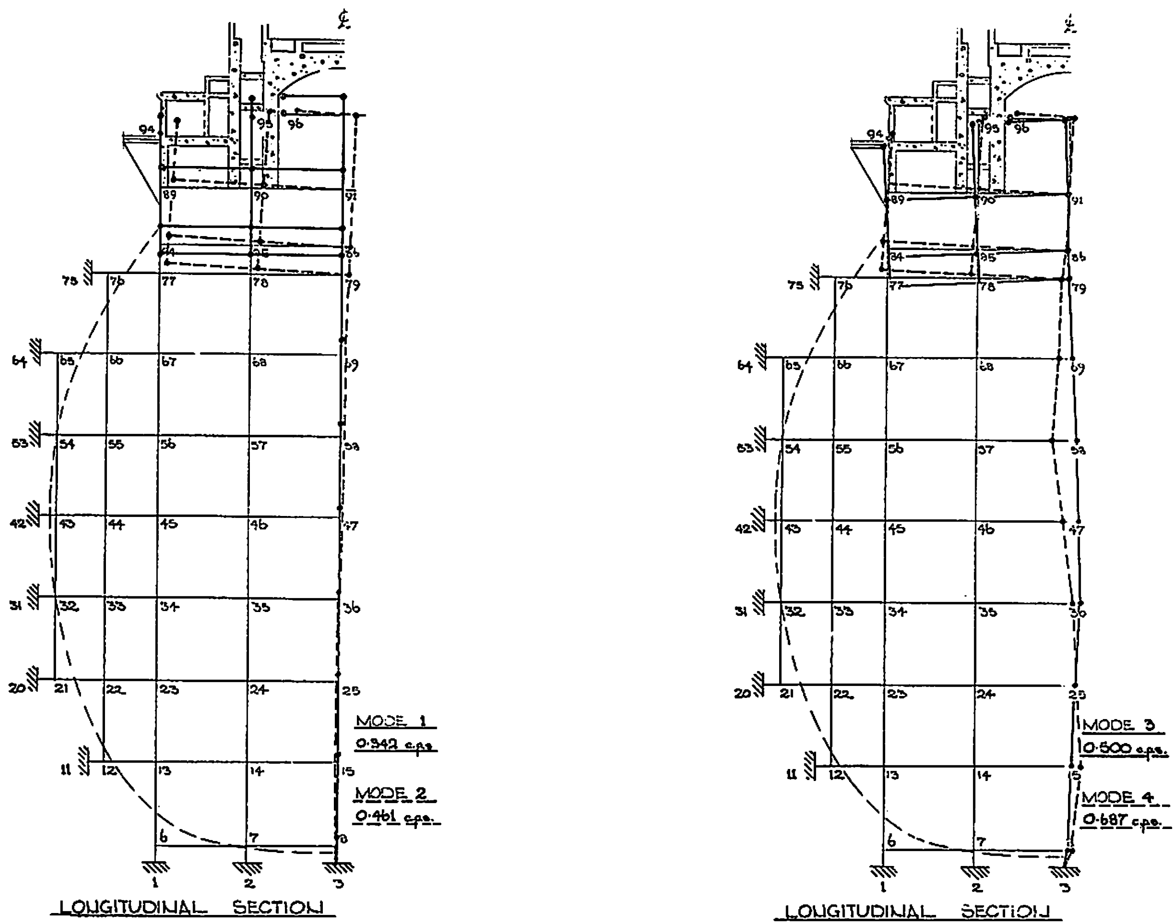


FIGURE 5 - Longitudinal Modes due to Soil-Structure Interaction

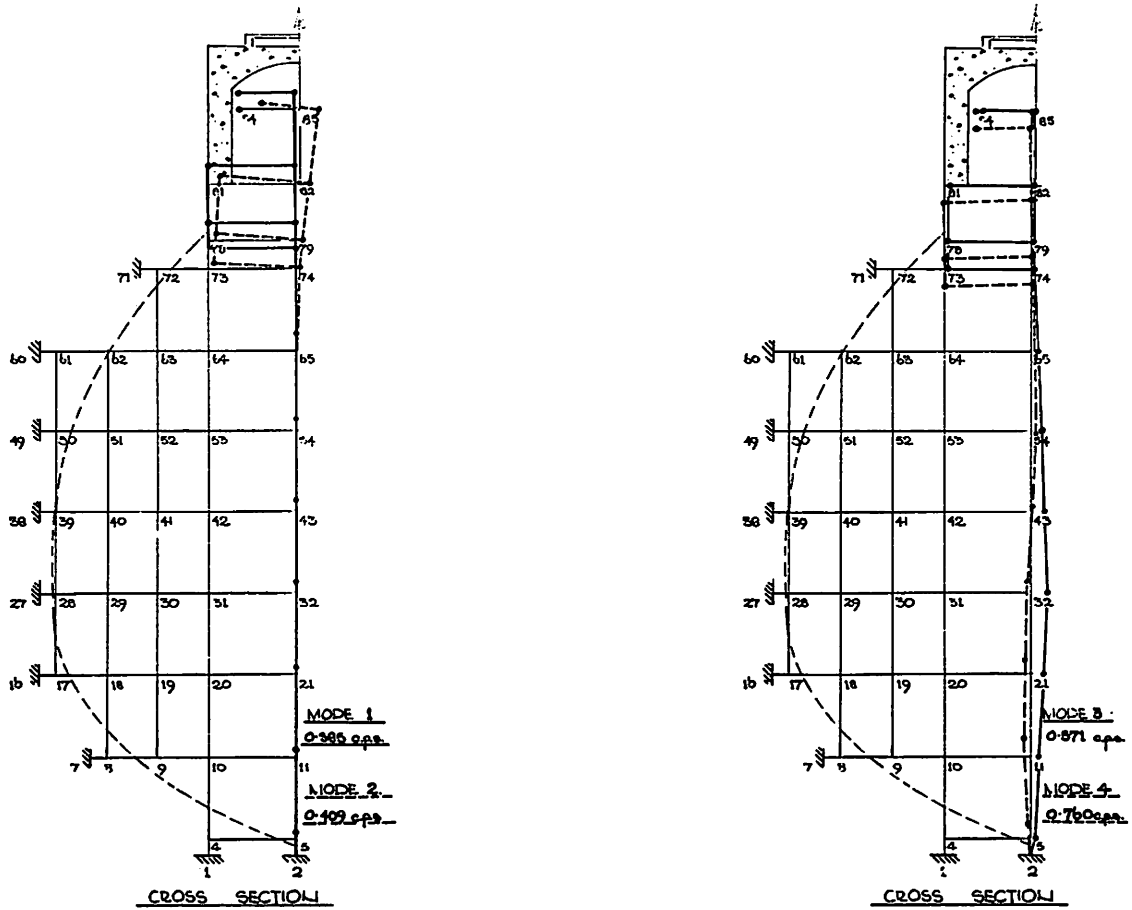


FIGURE 6 - Transverse Modes due to Soil-Structure Interaction

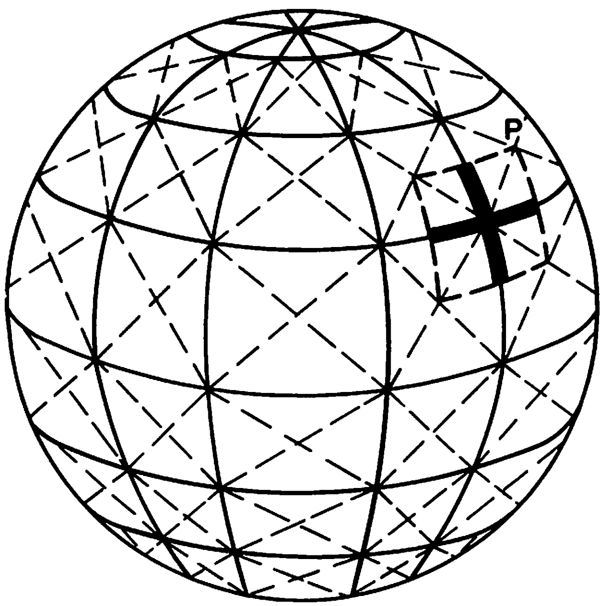


FIGURE 7 - Lattice Representation of Sphere

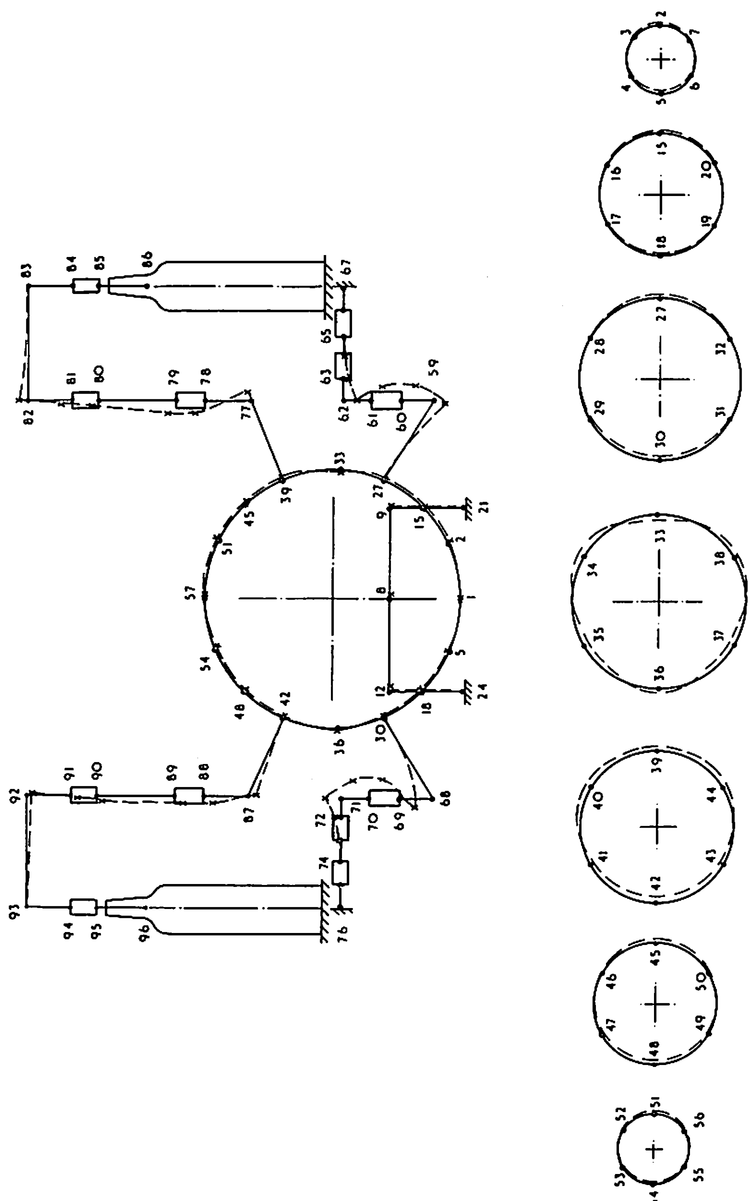


FIGURE 8 - Modal Shape of Vessel/Duct System at 3·39 Hz

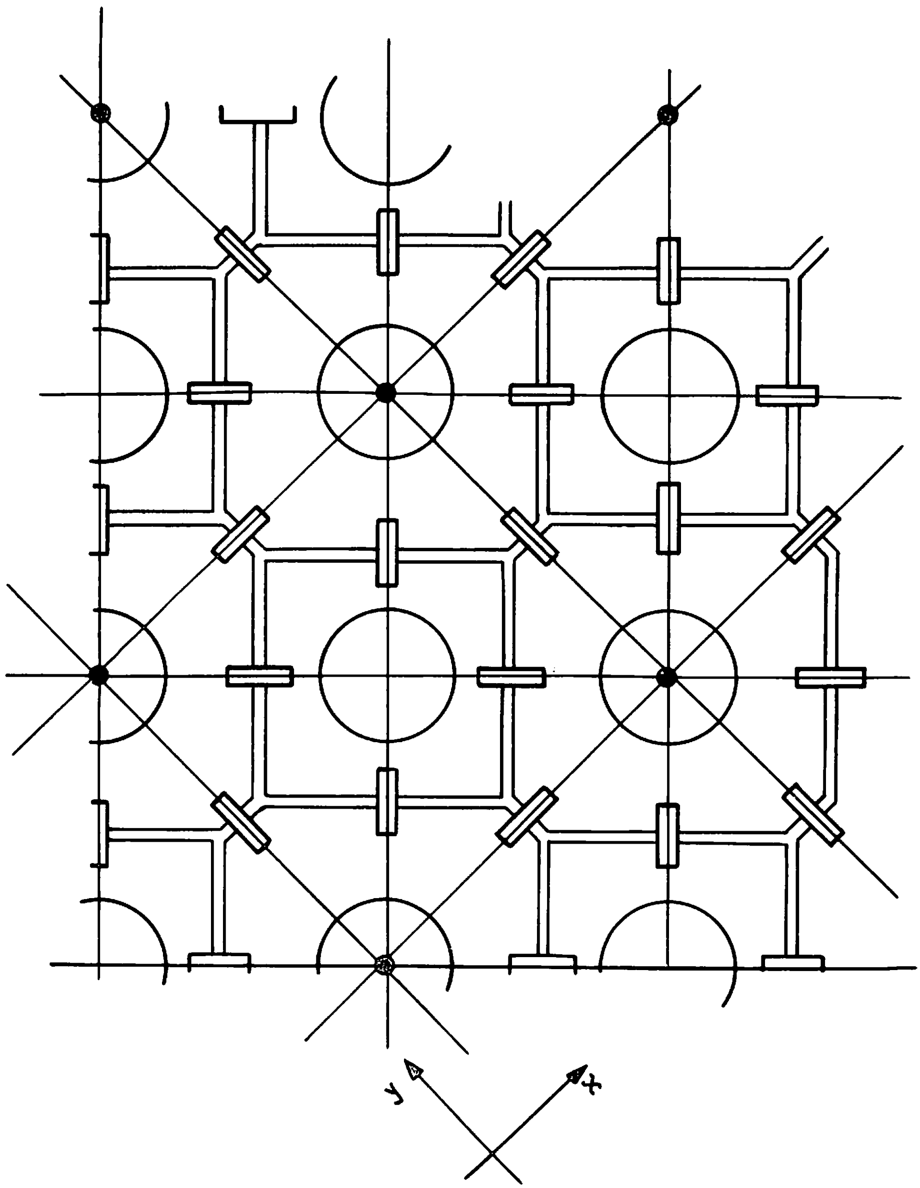


FIGURE 9 - Graphite Core Lattice

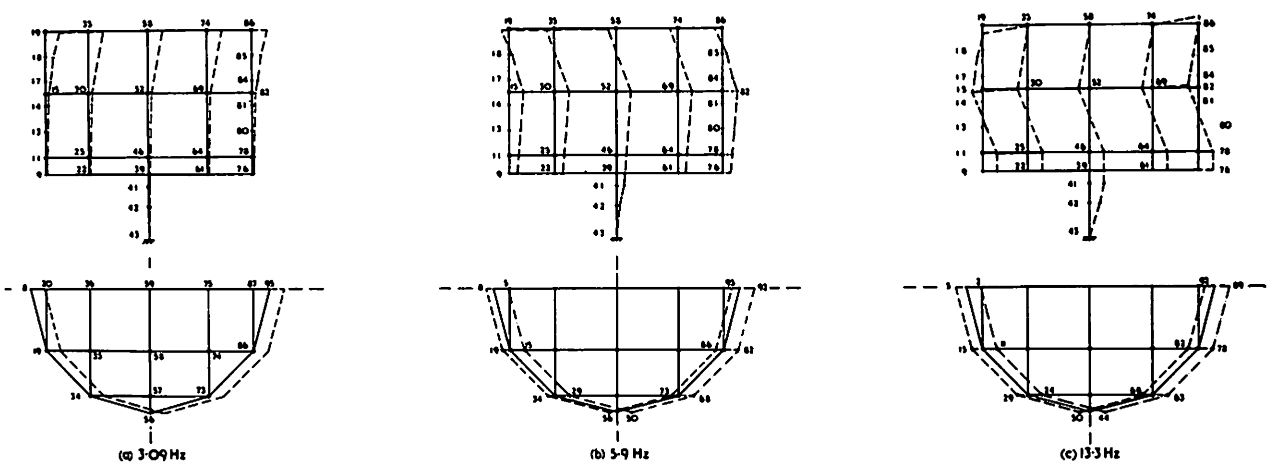


FIGURE 10 - Asymmetric Core Modes

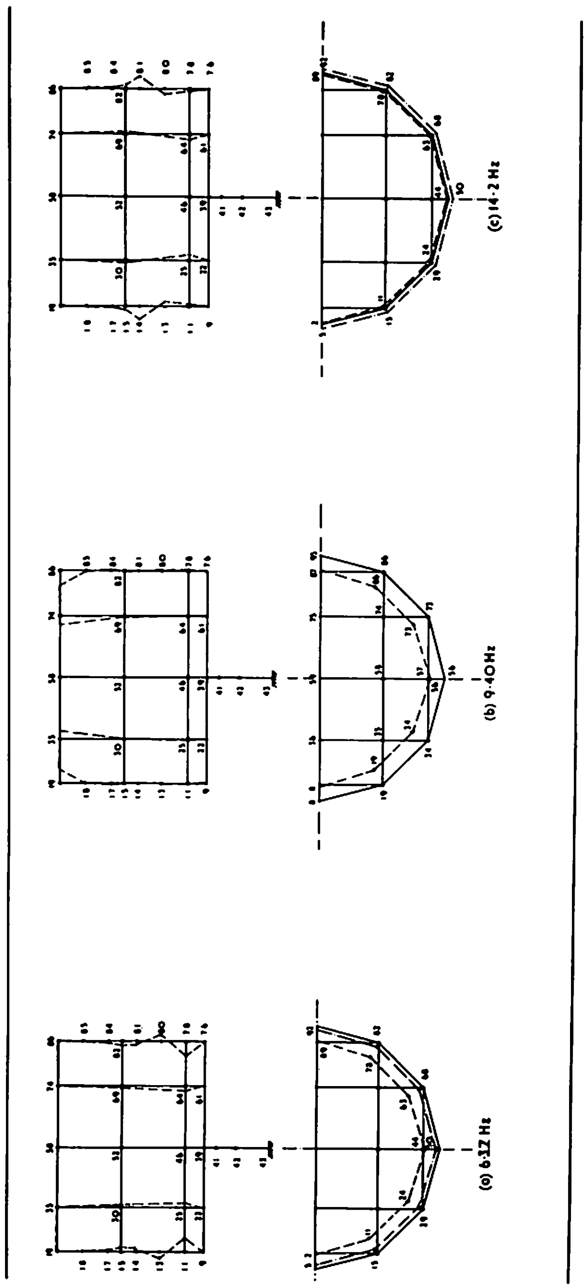


FIGURE 11 - Symmetric Core Modes

DISCUSSION

Q

K. AKINO, Japan

We carried out vibration test for the graphite shielding structure, and test results show us that the graphite pile-up structure does not have eigenvalues.

In your paper, you proposed the framework analogy including the graphite core structure and you stated natural period of the structure to be 6 cps. Do you have any experimental evidence concerning that figure ?

A

W. T. LAWTON, U. K.

The graphite core was simulated by a 3-dimensional array of damped masses and springs; the stiffnesses in the horizontal plane were calculated to reflect the freedom to particular horizontal movements permitted by the keyed construction, while the vertical springs were determined from experimental measurement of the lateral stiffness of a column of graphite bricks.

Measurements have been made of the response of a section of the core when excited on a vibrating table and clear evidence of eigenvalues observed. Checking of these natural frequencies against calculation is not yet complete.