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Intercomparison of LMFBR seismic analysis codes -CEA contribution-

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ABSTRACT
Sophisticated methods have been developed to study the seismic response of LMFBR cores. These methods, mainly based on FEM beam models take into account non linearities and fluid structure interaction. The associated numerical techniques consist essentially in the computer code CASTEM 2000, developed by CEA/DMT. In order to validate these methods, a long series of experiments were performed on core mock-ups loaded by seismic excitations. Several tests, performed in air and in water (simulating sodium) were applied on Rapsodie and Monju cores. The aim of this paper is to present and to compare the experimental results and calculation through assembly displacements and shock forces.

1. INTRODUCTION

The fast reactors are made of several hundred flexible beams embedded in a diagrid, separated by small gaps and immersed in a fluid. So to study the dynamic response of a core to an earthquake, we need a non-linear model which takes into account the shock between assemblies and the fluid-structure interaction. The shock forces are simulated by systems of non-linear springs and dampers. These springs must take into account two aspects : the local stiffness of ovalisation due to local deformation of the beam and the stiffness due to neglected modes. The inertial effects due to fluid-structure interaction have been taken into account through different ways :

- distributed mass added to assembly models : this kind of modelization has been applied to Rapsodie [1], Phenix and SuperPhenix cores [2],
- modelization with finite elements of fluid and structures [3],
- homogeneization : this method consists in replacing the physical heterogeneous medium (the assemblies and the surrounding fluid) by an homogeneous equivalent medium [4].

In order to validate these methods and to determinate some physical parameters, tests were performed on shaking tables. The main experimental programs are Rapsodie and Symphony programs [5]. The aims of these tests are principally the experimental determination of the lessening of assembly frequencies due to fluid, the fluid coupling between assemblies, the influence of the input direction [6], and the design of an equivalent linear model in order to introduce a core model in a reactor vessel calculation [7].

2. COMPUTER CODE DESCRIPTION

For this type of study, CEA/DMT has developed the computer code CASTEM 2000. The equation of motion which is used in CASTEM 2000 is the well known Bernoulli-Euler beam equation. In order to avoid too small integration time step which may be required in an explicit integration scheme, CASTEM 2000 allows the use of modal analysis. The basic beam equation is projected on the eigenmodes of the beam. Then we have to calculate the modal coefficients which are the solutions of an harmonic type equation. The generalized force in the second member of this equation takes into account the seismic excitation and the shock forces.

3. REACTOR CORE MOCK-UPS EXPERIMENTS AND CODE VALIDATION

3.1. *Rapsodie tests*

The RAPSODIE core mock-up, already described in Ref. [1] is presented on the figure 1. It is composed by 91 fuel assemblies (figure 2) located at the center of the mock-up (1 central and 5 rings) surrounded by 180 neutronic shield elements (figure 3). The mock-up is surrounded by a stiff cylindrical vessel (diameter : 1.1 m) in order to perform tests in water. The vessel is assumed to be stiff enough in order to induce no amplification of the table motion (in the seismic frequency range). The non-linear seismic behaviour of this mock-up is due to impacts which occure between assemblies. The impacts between the subassemblies are supposed to be located at the pad level where the gaps are small and at the top where the displacements are important. Because the subassemblies are represented with only four modes (in the range 0 - 200 Hz), the shock stiffnesses are corrected by neglected modes stiffness. The values of damping used for calculations for fuel assemblies and neutronic shield elements are respectively 3% and 1% in air and 5% and 3% in water.

The time histories of the seismic accelerations of the shaking table are presented in figures 4 and 5. To limit CPU time but in keeping a representative response, time duration for analysis will be the most intensive 2.5 seconds of the input motion.

If the fuel assemblies are assumed to be pinned at their contact points with the diagrid, and the neutronic shield elements clamped on the dummy diagrid, the first eigenfrequencies are 8.13 Hz for the fuel assemblies, and 20.7 Hz for the neutronic shield elements. But because of the gaps which exist between the spike of the fuel assemblies and the diagrid the behaviour of fuel assemblies are typically non linear and their frequencies depend on the excitation level. In figure 6 is shown the evolution of the first eigenfrequency versus the maximal displacement at the top. In water, the added mass effect due to fluid-structure interaction was introduced by lessening (about 15 %) the in air eigenfrequency, and by increasing the modal masses and displacements with an added mass ratio (30 %).

- *In air seismic calculation*

Since the experimental responses were only measured on the central row of the mock-up, the core model used for in air calculation was the single row model (model A). In figure 7 are shown the maximum and minimum assemblies top displacements versus their position in the core. The profile of displacement obtained from calculation is very close to the experimental one. In figure 8 are compared the displacement time histories of the central fuel assembly issued from calculation and tests : the calculated displacement is very similar in magnitude to the measured one. The synchronization between the two curves is also very good. The figure 9 represents the displacement of one external fuel assembly. The impacts against neutronic shield elements is responsible for the dissymmetry. The calculation is also in good agreement with the experimental result. Concerning the neutronic shield element displacements, we can observe in figure 10 a discrepancy between calculation and test. The reason of this discrepancy is not very clear : it is possible that the contact between the element and the diagrid is not well modeled. The profile of impact forces in the core at pad level and at top level are shown in figure 11.

- *In water seismic calculation*

To take into account the fluid-structure interaction, only added mass effect was first applied on the assemblies, i.e. without coupling effect with the vessel. Consequently, the frequencies were lessening and the generalized displacement q_g(1) and generalized mass m_g(2) were modified in the same ratio (30 %). Since the water was carried with the vessel, buoyancy effects were observed on the assemblies during the tests. This phenomenon tends to decrease the effect of seismic acceleration. To model it, the modal displacements of the assemblies were lessening in a second phase, in order to introduce the coupling between the assemblies and the vessel :

$$q_{water} = q_{air} + q_a - q_c \qquad (1)$$

with :q_a (= q_{air} x 0.3): contribution due to added mass effect,
q_c: contribution due to vessel coupling effect.

The value of q_c, generally higher than q_a, depends on the distance between the assemblies and the vessel, but is considerably modified by the free surface effect. In Rapsodie case, the η ratio between the generalized displacement in water and in air was fitted from tests and estimated close to 0.9 (i.e. a little lower in water than in air). The results of three calculations with different participation ratios (η = 0.6 or 0.9 or 1) are compared with the experimental measures in figure 10. We can notice that the displacements calculated with no coupling effect (η = 1.3) would certainly be much higher than the experimental ones. When this coupling is taken into account, the magnitudes of displacements issued from calculation decrease to be in better agreement with the tests. In figure 13 is shown the profile of maximum impact forces at pad level in the core (η = 0.9). The higher values are also located between neutronic shield element and fuel assemblies.

3.2. *Monju tests*

The problem data used in the calculation (assemblies characteristics and seismic input) are issued from reference [8].

In the single row layout, twenty-nine mock-up assemblies, i.e. 17 fuel assemblies (F/A), 4 radial blanket assemblies (R/A), and 8 neutronic shield assemblies (N/S) were arranged in a single row layout to represent a diagonal row of MONJU core, as schematically shown in figure 14.1. It is important to note that the core is restrained. The assemblies were installed in a rectangular tank and subjected to horizontal excitations in the direction of the row on a shaking table. The acceleration time history used in the tests was a response of the core support structure obtained in seismic analysis of the reactor-block. The tests were carried out both in air and in water.

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(1) $q_g = X^t M U$, *where M is the mass matrix, X the modal shape and U a unit vector in the direction of the seismic acceleration.*

(2) $m_g = X^t M X$.

In the hexagonal cluster layout, thirty-seven mock-up fuel assemblies were to represent the inner fuel region of MONJU core, as schematically shown in figure 14.2. The assemblies were installed in a circular tank and subjected to horizontal excitations on the shaking table, using the same input as in the 29 assembly test. The tests were carried out both air and in water. Like RAPSODIE mock-up, the seismic behaviours of MONJU cores are non linear because of impacts between assemblies.

The theoretical acceleration time history and its response spectra, issued from [8], are shown in figures 15 and 16. This acceleration time history was scaled to different levels, and then used as the command signal to the shaking table for each test. Note that this is not a measured acceleration at the shaking table during the tests, but the input signal to the shaking table. The excitation levels applied in this study are for the single row layout 0.2g and 0.3g and for the hexagonal cluster layout 0.2g, 0.3g, 0.4g and 0.5g.

A linear analysis was first done to determine the in-air eigenfrequencies of the assemblies. In order to avoid the rigid body motion of the assembly due to the gaps at diagrid level, the assembly was assumed to be pinned at this contact. The first eigenfrequencies obtained for the fuel assemblies, the radial blankets and the neutronic shield elements were respectively 3.6 Hz, 4.4 Hz and 3.3 Hz. Because of the small clearances which exist between the entrance nozzle and the core support plate, the frequencies of each assembly depend on the excitation level : in figure 17 is shown the evolution of the fuel first natural frequency versus the maximal displacement of the head. It can be noted that the asymptotic frequency is equal to 3.6 Hz and is obtained for a displacement upper than 20 mm.

- *Single row analysis*

The maximum displacements calculated at the head level, which are functions of the input level, are compared to the experimental results (see figure 18). Because the calculation was not performed with the real acceleration of the shaking table, and because only the maximal values of displacements were studied, the comparison must be interpreted with care. One can notice in this figure that the calculation results for 0.3 g are in rather good agreement with the experimental results. Concerning the calculation, it can be noted that the internal assemblies (D7 and D6) have a more important displacement than the external, phenomenon which has not been observed during the tests. For 0.2 g level the differences between the first and the last subassemblies and the restraint rings, are shown in figure 19. The values for the upper pad are comparable to the experimental results, however the forces at lower pad level are higher in calculation than the measured ones. These differences can be explained by the over-estimated stiffness of the restraint or the lack of modeled impact damping.

- *Hexagonal cluster layout*

For this calculation an hexagonal mesh was developed. The impacts of each subassembly with its six neighbours and the possibility of displacement in the orthogonal direction of the excitation were taken into account. The agreement between calculation and experiment is rather good for the displacements. For high level (0.4 g and 0.5 g), the scattering of maximum displacements measured during the tests is confirmed by the calculation. As for the single row test, the external assemblies seem to have greater displacements than the internal ones.

The calculated impact forces are much higher than the measured ones. One can actually notice a ratio of two between the calculation and the measures. The explanation of that difference may be, as for the single row layout, an over-estimation of the stiffness of the restraint or the lack of impact damping. Moreover, the differences between real and theoretical acceleration can considerably modify the maximal values of impact forces.

4. CONCLUSION

CEA/DMT has performed with CASTEM 2000 calculations in order to analyse the seismic behaviour of RAPSODIE and MONJU mock-ups. The aim of these calculations was to demonstrate the quality of the core models used in LMFBR core, through the determination of shock forces between assemblies and in water behaviour. Concerning MONJU tests, calculations were performed with two layouts : single row and hexagonal mock-up. The agreement with the test results are rather good for the displacements. The impact forces at upper pad level are comparable to the tests in the case of the single row layout but the agreement is not so good for the hexagonal cluster. In order to ameliorate the results, an introduction of damping and a better estimation of stiffness of the restraint can be envisaged. Moreover, the comparison would be more accurate if the time histories of forces and displacements were studied and not only their maximal values and if the calculation was performed with the real acceleration of the shaking table. To analyse RAPSODIE tests, calculations performed with single row model and half core model were compared with in air and in water experimental tests. In air, the calculation results (maximal values and time-histories) and measures are in rather good agreement. In water, there are some differences between tests and calculation when the coupling effect with the vessel is not correctly taken into account. So the coupling mass ratio as the added mass ratio must be accurately estimated in order to take into account correctly the fluid-structure interaction in FBR core calculations.

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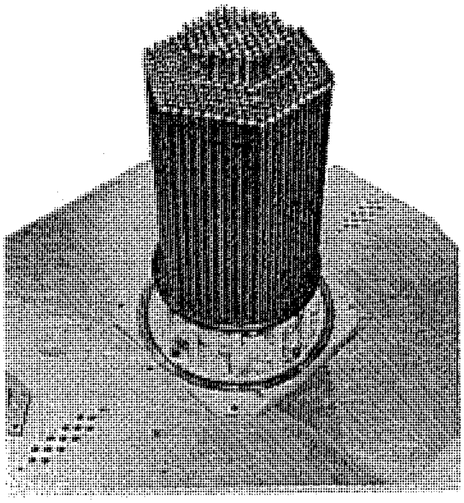


Fig. 1 : RAPSODIE mock-up

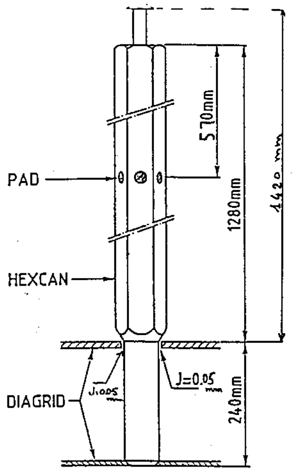


FIGURE 2

FUEL ASSEMBLY

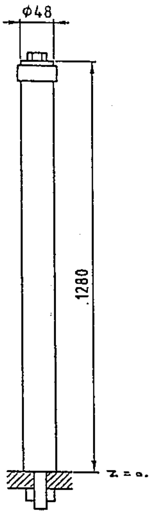


FIGURE 3

NEUTRONIC SHIELD ELEMENT

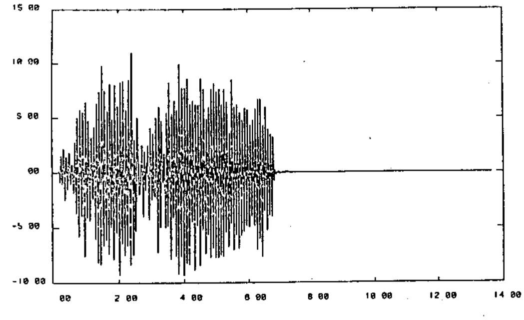


fig. 4

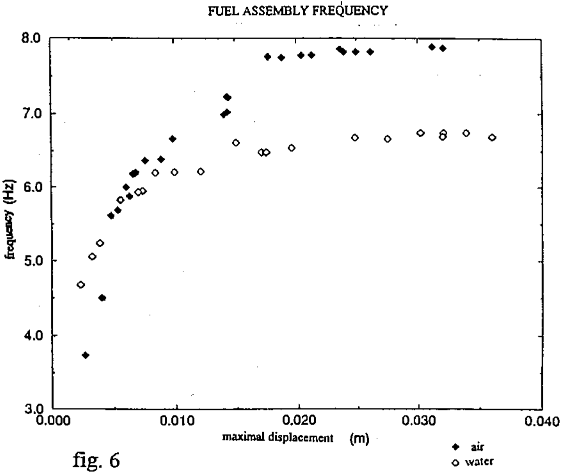


fig. 6

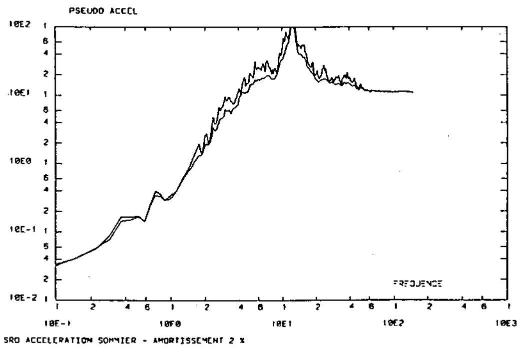


fig. 5

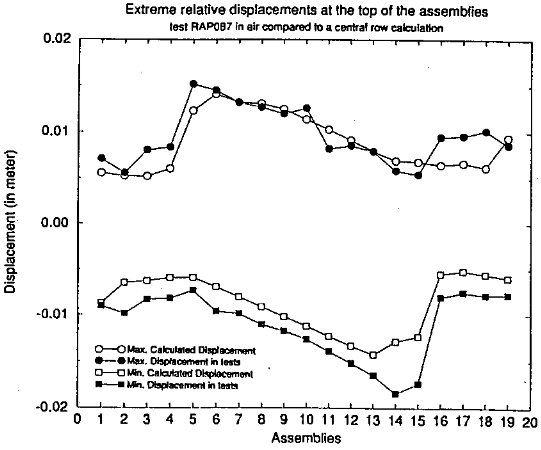


fig. 7

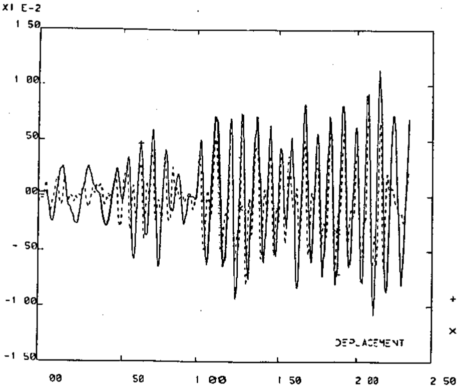


fig. 8

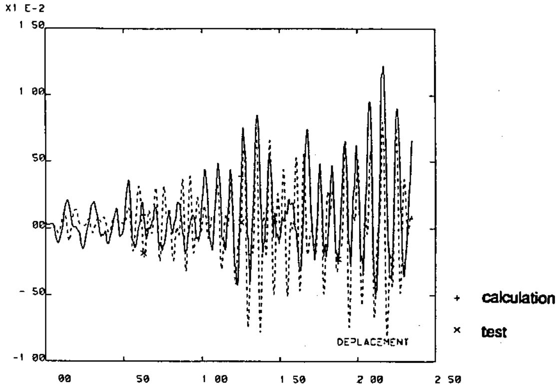


fig. 9

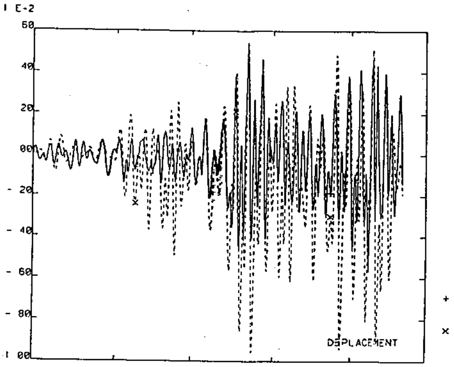


fig. 10

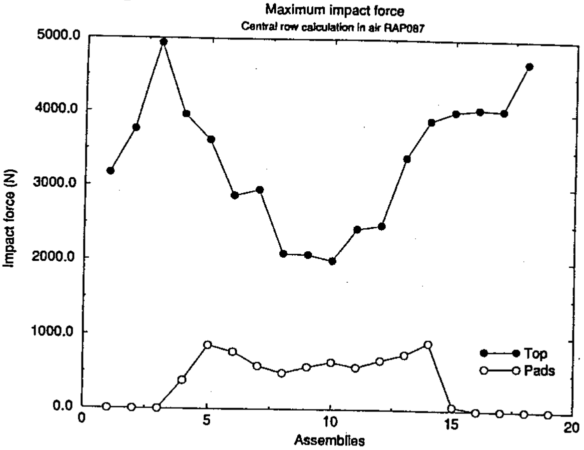


fig. 11

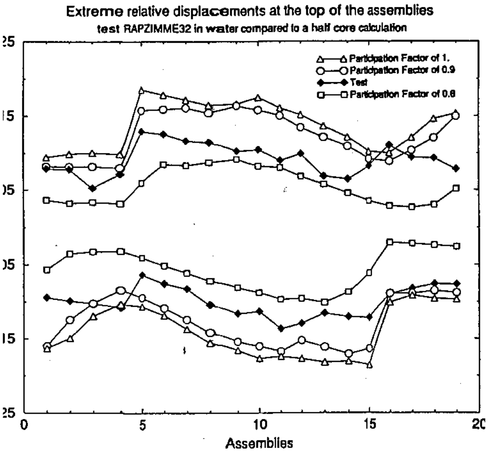


fig. 12

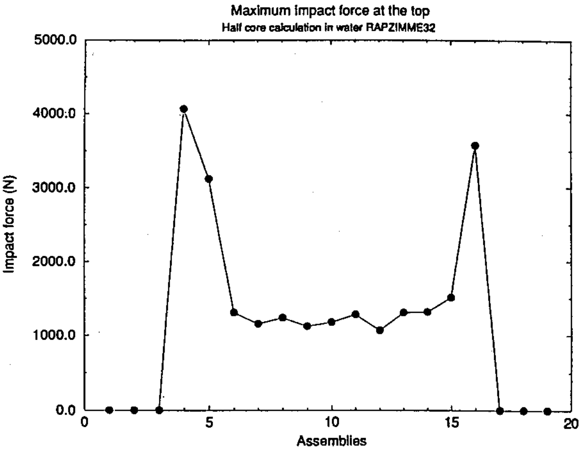
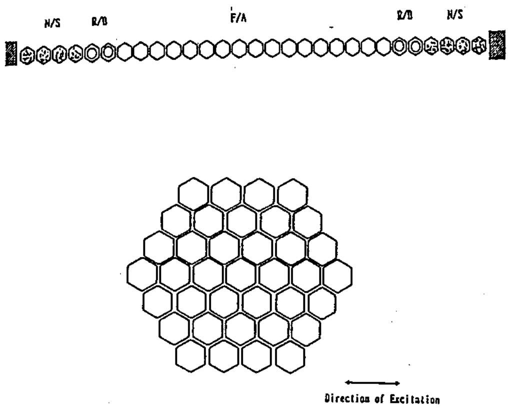


fig. 13



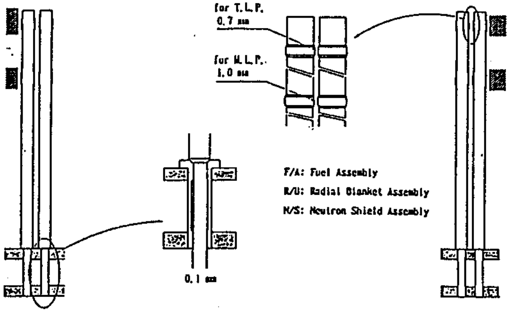


Fig. 14 : Geometrical description of a MONJU assembly

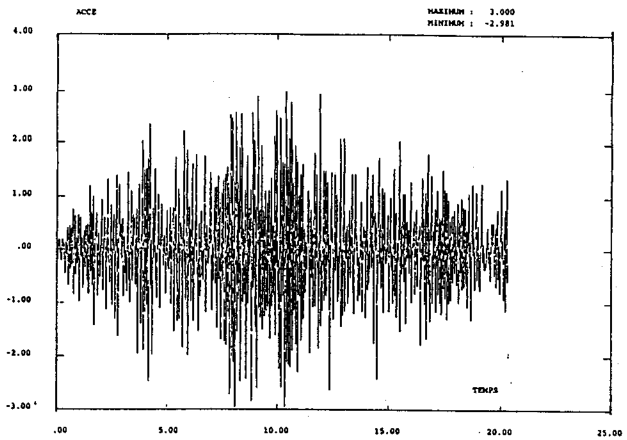


Fig. 15 : Acceleration time history

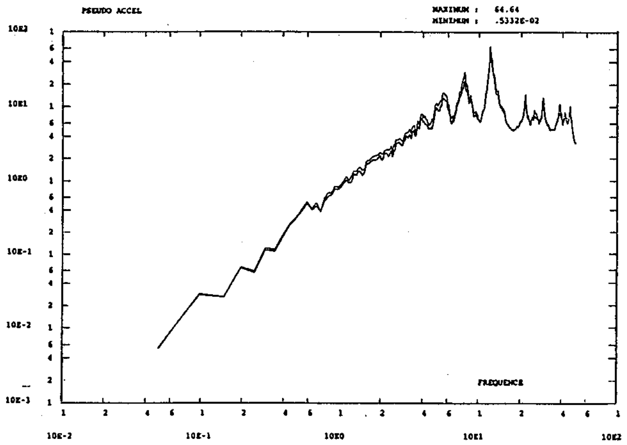


Fig. 16 : Response spectra (with 1 % and 1.5 % damping ratio)

Fig. 17: First natural frequency of fuel assembly

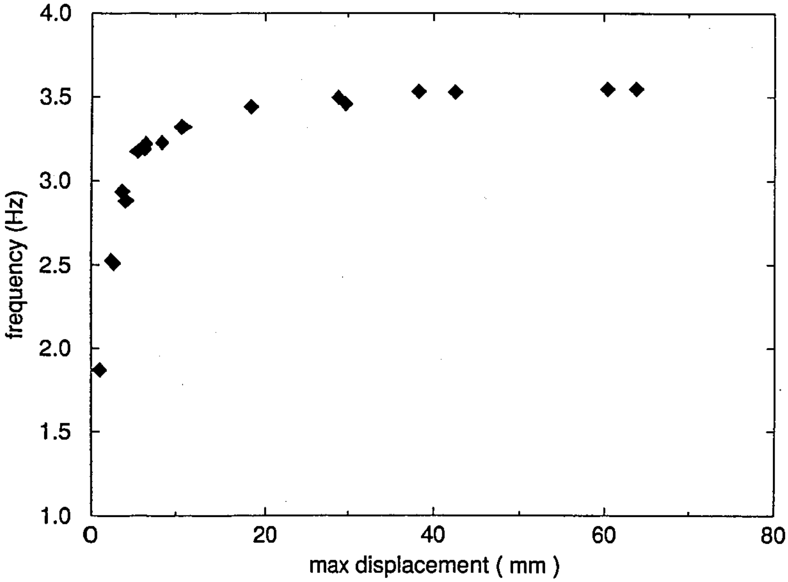


Fig. 18: Single row layout - displacements

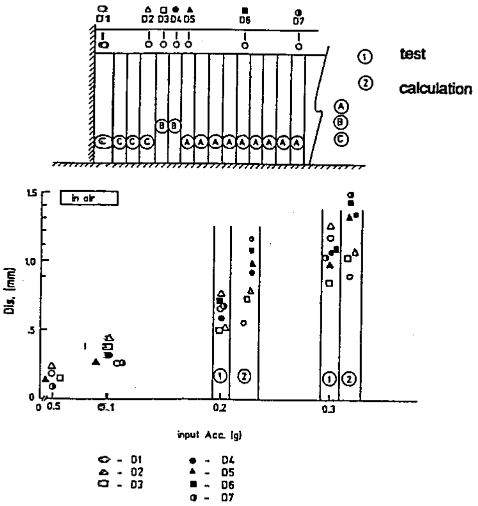


Fig. 19 : Single row layout - impact forces