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SEISMIC TESTS OF INTERACTING FULL-SCALE FUEL ASSEMBLIES ON SHAKING TABLE

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ABSTRACT

This paper presents tests performed on six full-scale fuel assemblies. Characterization tests allow frequency and damping to be determined as a function of the confinement with and without water and of the excitation amplitude. 300 seismic tests have been performed on a row of six assemblies using 30 different accelerograms. Several parameters have been investigated such as the gap between assemblies, the fluid (air or water with different confinement conditions) and the position of two different designs in the row. The full confinement in water has a notable influence on damping and decreases the values of the maximum impact forces. The scatter of the maximum impact force values for the same spectrum is about 20 %. The influence of the gap is not negligible, but the position of the assemblies with different designs and the generation method for the accelerograms do not have a significant effect.

1. INTRODUCTION

CEA, EDF and FRAMATOME have launched a large-scale research program on the behaviour of fuel assemblies under seismic loading. This paper presents seismic tests performed on six full-scale fuel assemblies.

The aims of these tests are:

- validation of the simulation models used for the assembly and core behaviours,
- study of the influence of :
  - the fluid on the response of the fuel assemblies (air/water with different confinement conditions),
  - the gap between assemblies,
  - the position of different assembly designs in the row,
  - the accelerogram.

The test program comprises:

- characterization tests with sine sweeps to measure resonant frequencies, snap-back tests (pull then release) without and with impact on grids to determine frequencies, damping ratios and impact stiffnesses,
- seismic tests on shaking table with one row of six assemblies.

2. MOCK-UPS

The six full-scale fuel assemblies correspond to two designs hereafter referred to as A (four assemblies) and B (two assemblies). These designs belong to the 12 ft with 17 x 17 rod array general design for 900 MWe reactors, with zircaloy grids. The differences, mainly relating to grid height and guide-thimble thickness, have a moderate but non-negligible influence on the dynamic behaviour.

3. CHARACTERIZATION TESTS

3.1. Characterization test set-up

Each fuel assembly has been tested separately. A steel frame (with a 1 m x 1 m base and 5 m high) fixed against a reaction wall maintains the fuel assembly in vertical position with a vertical compression load. Through a waterproof panel the fuel assembly can be excited by:

  - either an electrodynamic shaker located at the second grid level,

- or a winch which applies a horizontal force by means of a steel cable with load sensor.

Tests can be performed in air, in water without confinement or in water with lateral confinement (sides) and full confinement (sides and ends : gap of 1 mm)

3.2. Characterization test instrumentation

During tests the following parameters were recorded:

- excitation load applied to the assembly,
- displacement of each grid,
- impact force of each grid against the reaction wall.

3.3. Test program

The tests were performed in air, in water, and in water with full confinement. The assembly was fixed in vertical position at each end. The displacements and the impact forces of each grid level have been recorded. The tests have consisted of sine sweep tests and snap-back tests. For sine sweep tests, the shaker was controlled at constant force whose level was adjusted to obtain a given displacement at the grid #5 level. During the test series, the excitation level was increased to obtain a maximum grid #4 displacement of 3, 6, 9, 12, and 15 mm.

Snap-back tests were performed without impact, with impact on only one grid and on four grids. The amplitude at the grid #4 level was adjusted at the following values: 3, 6, 9, 12, and 15 mm.

3.4. Data reduction and investigated parameters

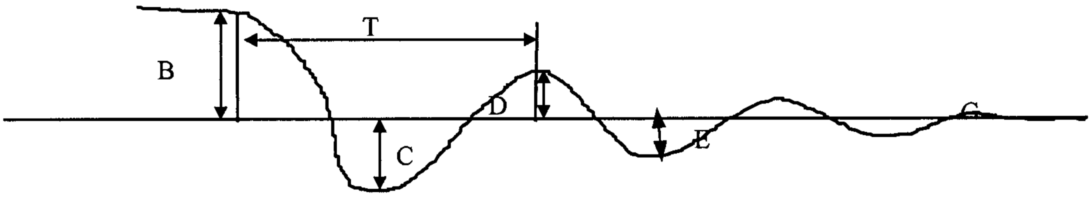
For each test series, trends versus maximum displacement were plotted for:

- first modal frequency,
- damping,
- maximum impact force,
- sum of the maximum impact forces,
- impact duration.

3.5. Characterization tests results

The first modal frequencies and damping values obtained from the sine weep tests are given in figures 3 and 4, for both designs. The frequencies decrease while the damping values increase when the excitation level and therefore the response amplitude increase, which corresponds to a typical behaviour of PWR fuel assemblies. In water, the frequencies and the damping values are decreased and increased, respectively, compared to those in air, reflecting the added mass effect and the friction forces from the fluid. Design B exhibits frequencies larger than design A by about 10 %, because of a larger lateral stiffness, but there are no significant differences in the damping values.

Figures 5 to 10 present the main results obtained in snap-back tests without impact (i.e. for the free lateral response), for design A. Frequencies and damping values are determined between C-D, C-E and C-G (see schematic below). The trends in frequency and damping versus amplitude are similar to those observed in sine sweep tests. In water, the most significant result is that the increase in damping is enhanced with full confinement; damping can reach values of about 40 % of critical under confined conditions, even without axial flow.



4. SEISMIC TESTS

4.1. Seismic test set-up (figures 1-2)

The test frame, with a mass of 25 tons and a height of 5 m, restrains the assembly ends vertically in the desired configuration similar to the core plates. Two configurations have been tested: A B A A B A (1) and B B A A A A (2). The gap between assemblies is set at 2 mm or 1.5 mm and hold-down springs at the top nozzle are compressed as in the reactor. The frame is sufficiently stiff to introduce no spurious frequencies. At the row ends, instrumented uprights simulate the core baffles against which the assemblies impact at the grid levels. A device also enables lateral confinement of the row during in water testing, with the same gap as between the assemblies. The gap between this device and the frame can be closed for full confinement tests.

4.2. Seismic test instrumentation

The instrumentation comprises:

- leaktight displacement sensors especially designed for these tests (compact size), for measuring the shift at each grid relative to the set-up,
- resistive force sensors, which are located in the uprights at each end of the assembly row to measure the impact forces at each grid location,
- accelerometers to measure the table acceleration and the acceleration at the top of the frame.

4.3. Test program

A response spectrum used in the French nuclear program was taken as a reference to generate synthetic accelerograms applied to the shaking table. Each partner of the research program generated ten accelerograms using its own method. According to test configuration, 3x10 or 3x5 accelerograms were applied. The excitation level (ZPA) was increased from 0.1 g to 0.4 g (SSE level), yet limited if necessary in order to prevent the maximum impact force from significantly exceeding 1000 daN (about 50 % of the crush limit). Tests were performed:

- in air and in water with full confinement with the configuration # 1 and gap of 2 mm,
- in water with full confinement with the configuration # 1 and gap of 1.5 mm,
- in water with full confinement with the configuration # 2 and gap of 2 mm.

4.4. Main seismic test results

Three hundred tests have been performed. In this paper, we limit the interpretation to the comparison of the effects of different parameters on the maximum impact force and the sum of the impact forces for all grid positions. Although the latter has no direct physical significance, it provides a more global estimate of the response level than a single maximum force; an average impact force could also be used, yet it might be misleading because of the substantial and systematic difference between the forces obtained at different grid levels. Except when otherwise stated (effect of the gap or of the row configuration), the test results correspond to the larger 2 mm gap and configuration 1 (A B A A B A).

Figures #11 and 12 show the evolution of the maximum impact forces and of the sum of the impact forces versus the table acceleration obtained with the 30 different accelerograms, in water with lateral confinement. The forces increase with the acceleration level. We can observe a scatter of the results, corresponding to ± 20 % of the mean value.

Figure # 13 illustrates the maximum impact forces obtained with different runs of the same time history. We can observe at 0.4 g, when two tests were performed one after the other, that the difference is small. At 0.28 g the tests were not performed one after the other and the difference reaches 10 %.

Figure # 14 shows that the type of generation (software used, envelope of the signal) has no significant effect on the result. Also, the variations of the maximum impact forces for different test conditions are similar for CEA, EDF and FRAMATOME accelerograms.

Figure #15 shows that the effect of the configuration (position of the assembly types in the row) is not very significant.

Figures # 16 and 17 show that the impact forces (and the sum of the impact forces) are higher with a gap of 1.5 mm than with 2 mm. The difference is about 20 %.

Figures # 18 and 19 display the effect of the fluid and of the confinement. The largest maximum impact forces are obtained in air. In water the impact forces decrease (-30 %) especially with full confinement (-50 %). Therefore, the effect of the confinement is very significant.

Figure #20 shows the distribution of the impact forces along the assemblies in water (full confinement). The maximum impact force is obtained at the grid #5 level, near mid assembly, which reflects the predominant mode 1 in seismic response.

Finally, it may be noted that the maximum impact force limit chosen for these tests (1000 daN) has been reached at 0.25 g in air and at 0.4 g in water with lateral confinement.

5. CONCLUSION

The tests provide a large amount of data on the dynamic lateral behaviour of either a single assembly, or of interacting assemblies under seismic loads.

Using a relatively large number of accelerograms generated from the same response spectrum allows an estimation of the scatter range of the maximum impact forces to be performed, which represents about 40 % of the mean value for given test conditions. Also, this leads to an increased confidence in the trends observed in the test results.

The decrease of impact forces in water, even larger with full confinement, is consistent with the damping values determined in the characterization tests under similar conditions. The effect of the gap between assemblies is not completely negligible. The influence of the position of the different assembly designs is not significant.

The extensive data base now available can be used for relevant benchmarks in the development and validation of the models used in seismic analysis of PWR reactor cores.

Figure # 1 – Top view of the assembly row

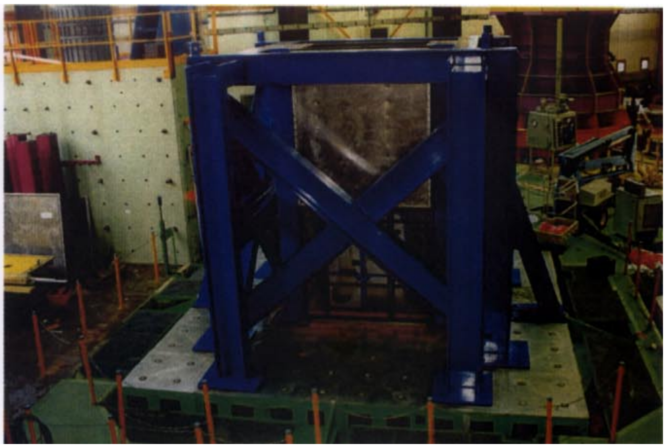


Figure # 2 – General view of the set up

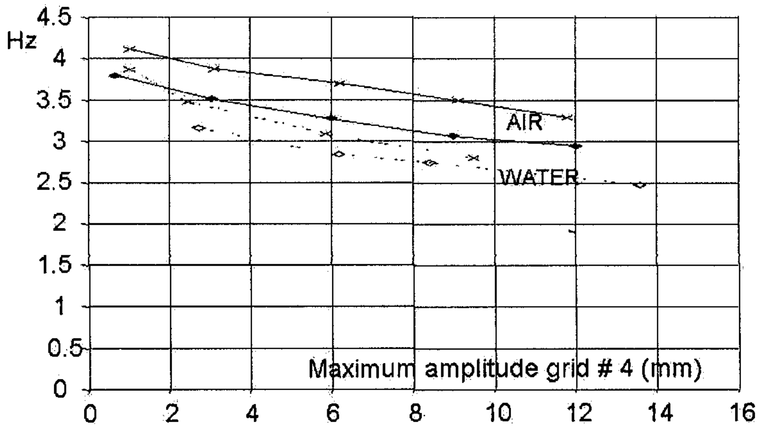


Figure # 3: First modal frequency – Sine sweep test – Comparison AIR/WATER

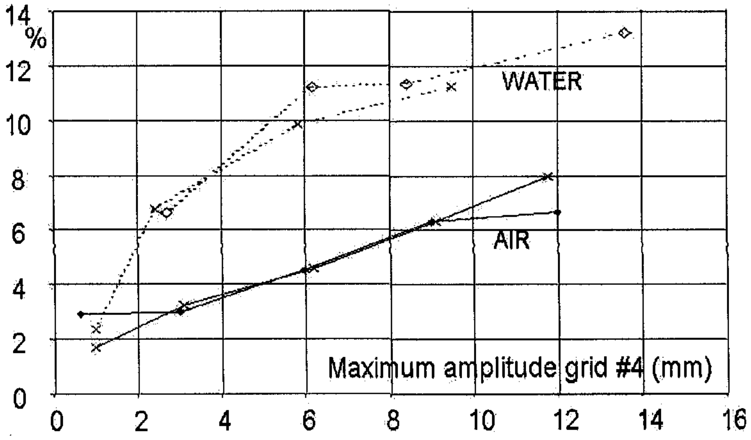


Figure # 4 : First modal damping – Sine sweep test – Comparison AIR/WATER

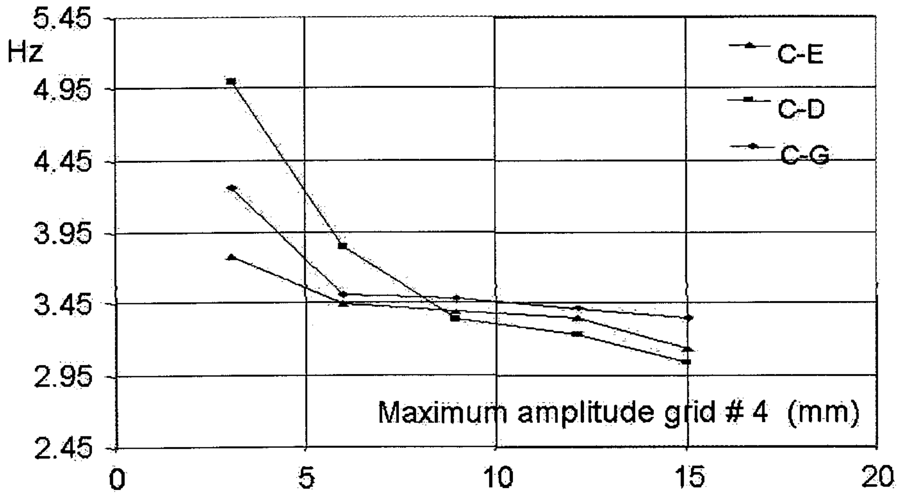


Figure # 5 : Frequency, design A – Snap-back tests en AIR

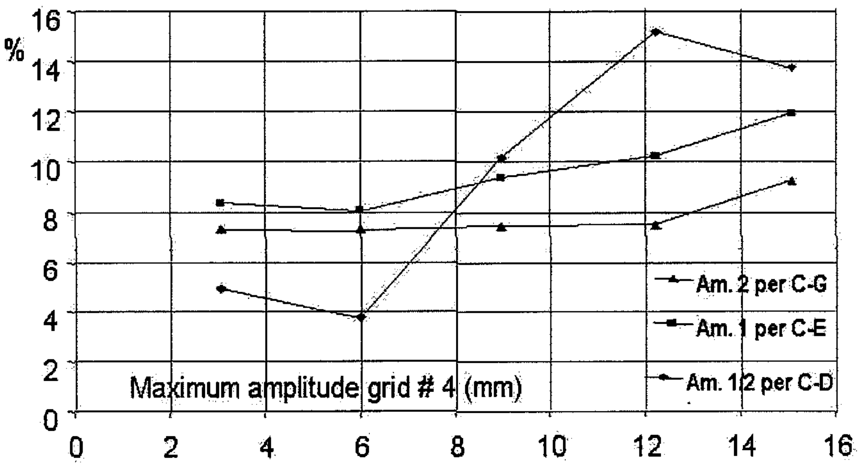


Figure # 6 : Damping, design A – Snap-back tests in AIR

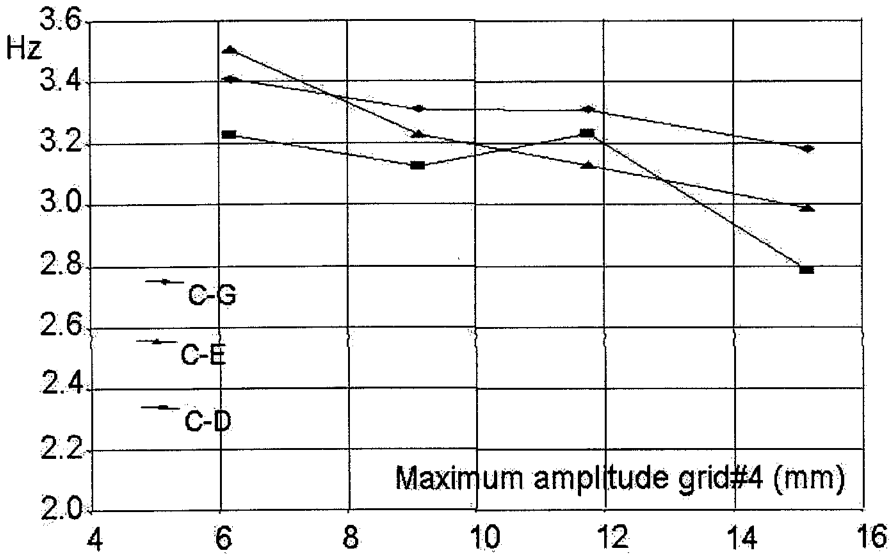


Figure # 7 : Frequency, design A – Snap-back tests in WATER

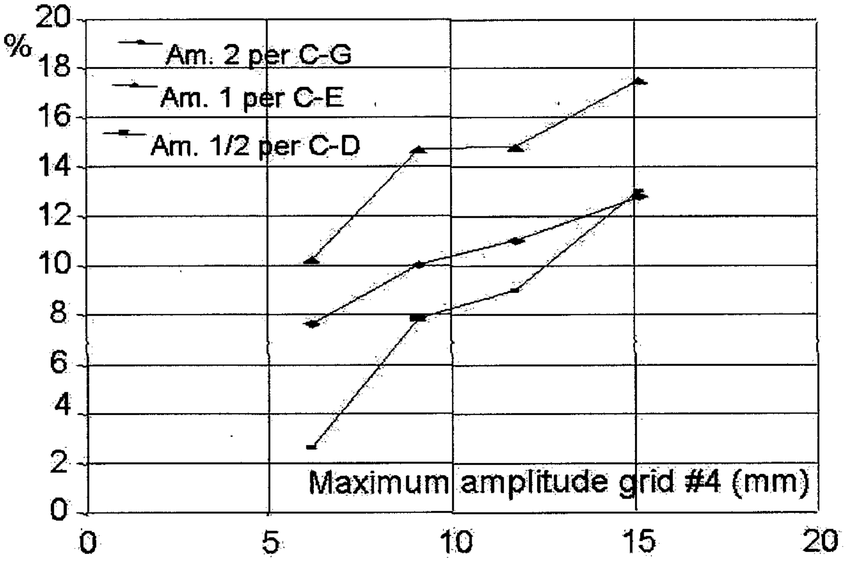


Figure # 8 : Damping, design A – Snap-back tests in WATER

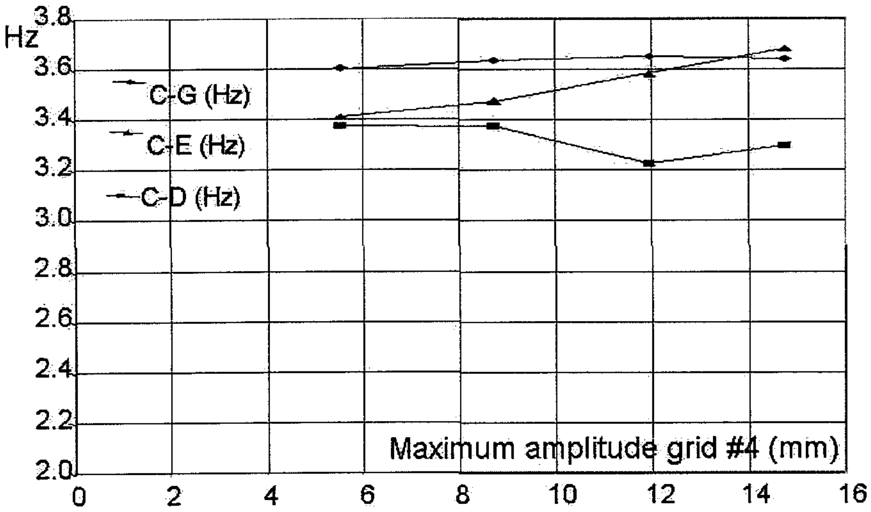


Figure # 9 : Frequency, design A – Snap-back tests in WATER – Full confinement

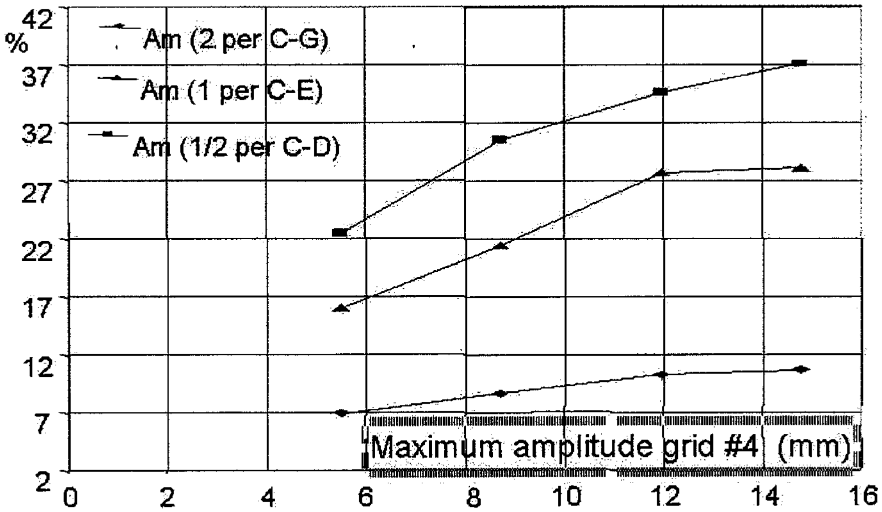


Figure # 10 : Damping, design A – Snap-back tests in WATER – Full confinement

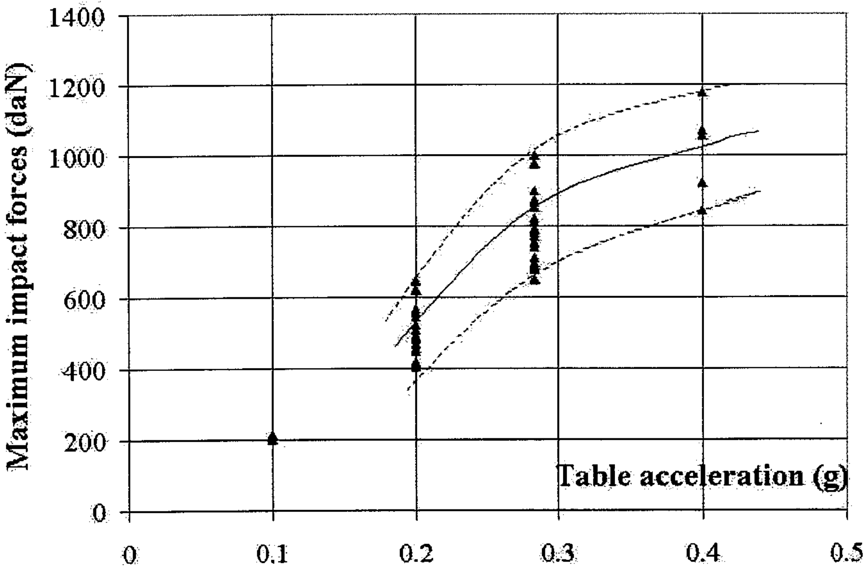


Figure # 11 : Maximum impact forces with 30 accelerograms – – Water with lateral confinement –

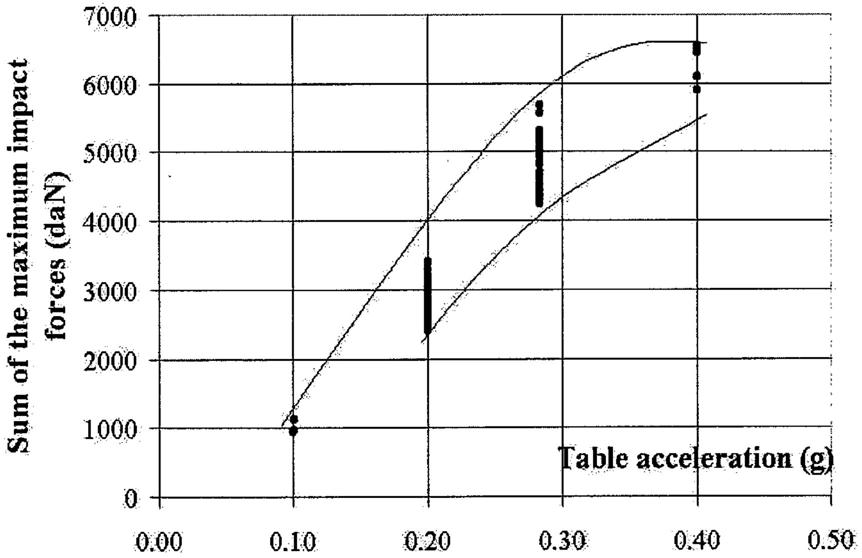


Figure # 12 : Sum of the maximum impact forces with 30 accelerograms – – Water with lateral confinement –

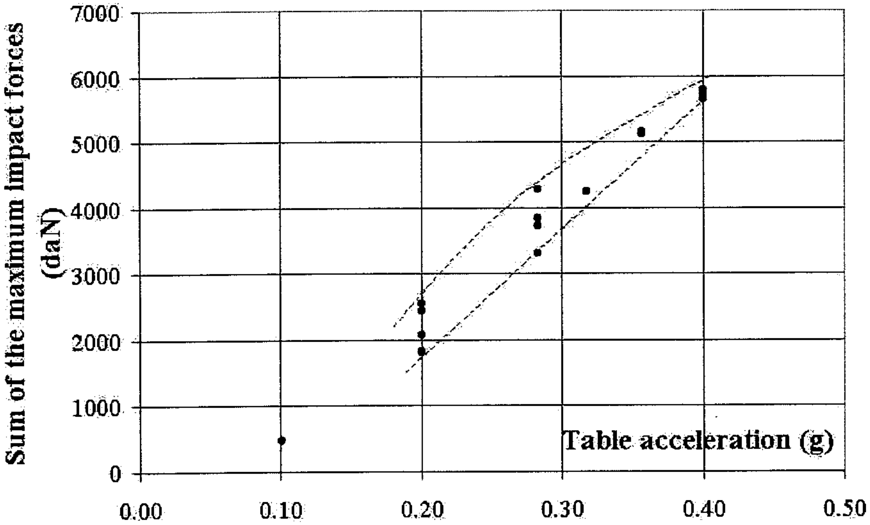


Figure #13 : Different runs with the same accelerogram
-Water with full confinement-

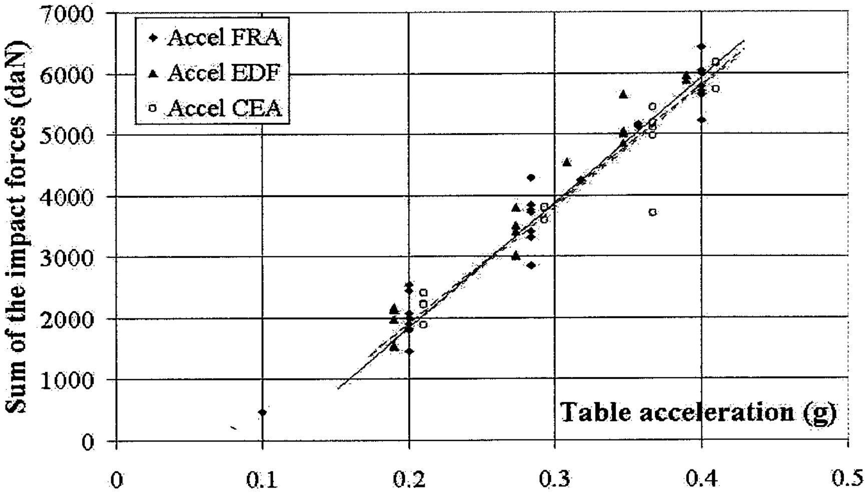


Figure # 14 : Sum of the maximum impact forces – Water with full confinement – Effect of the type of accelerogram –

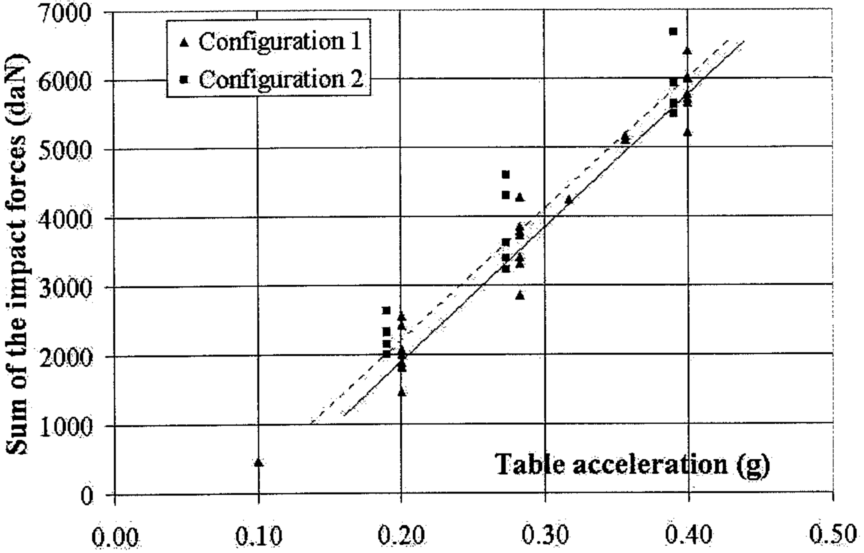


Figure #15: Sum of the maximum impact forces - Effect of the configuration – Water with full confinement -

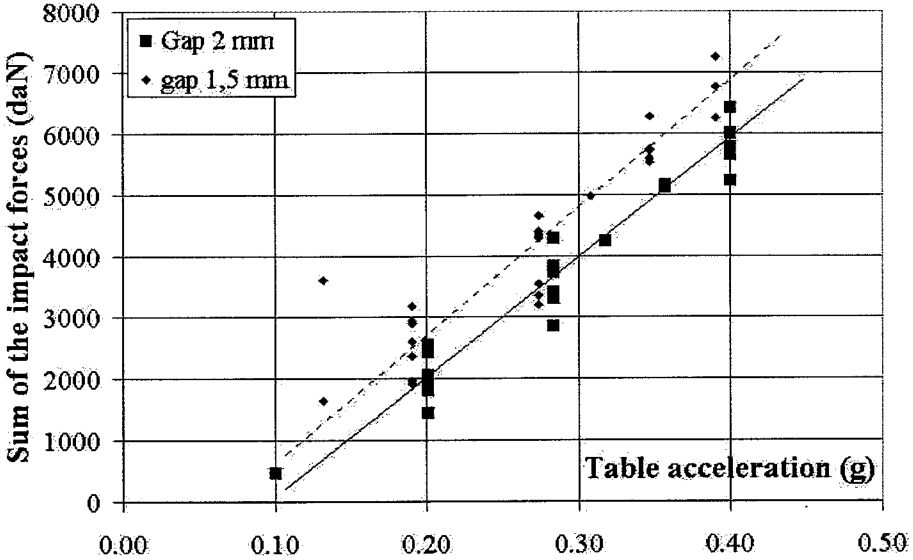


Figure #16: Sum of the maximum impact forces – Effect of the gap –
– Water with full confinement –

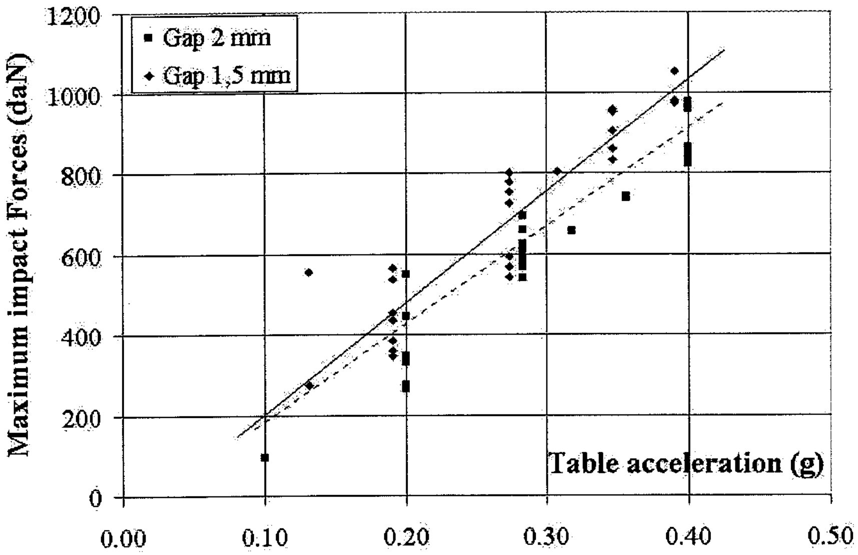


Figure #17: Maximum impact forces - Effect of the gap – Water with full confinement

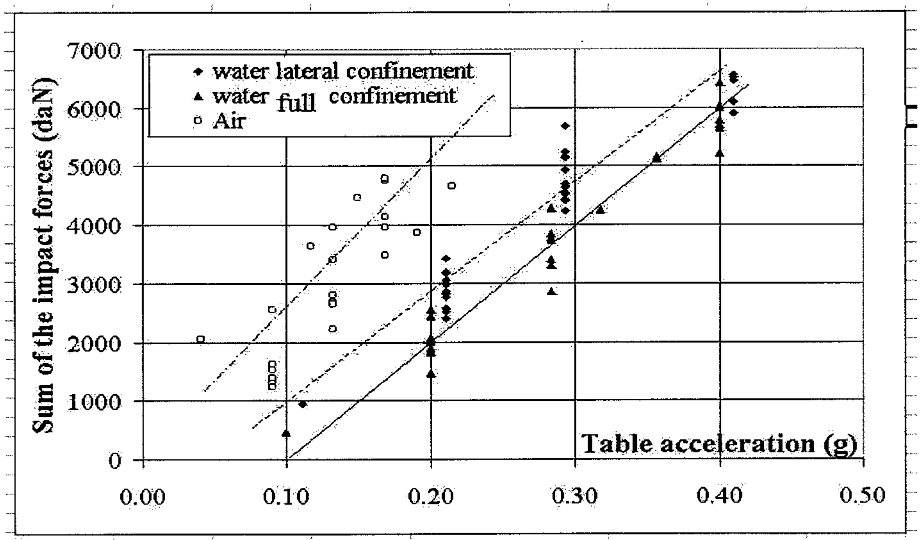


Figure #18: Sum of the impact forces – Effect of the fluid

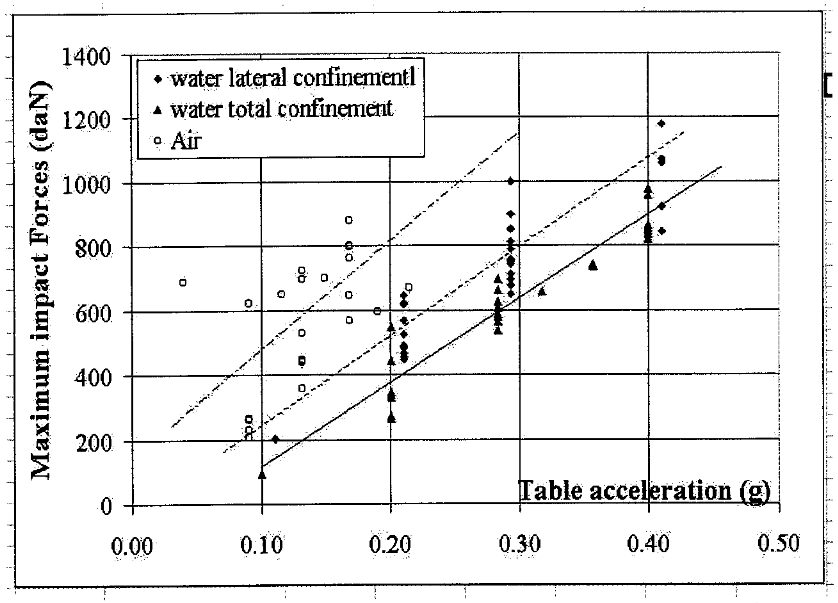


Figure #19: Sum of the impact forces – Effect of the fluid

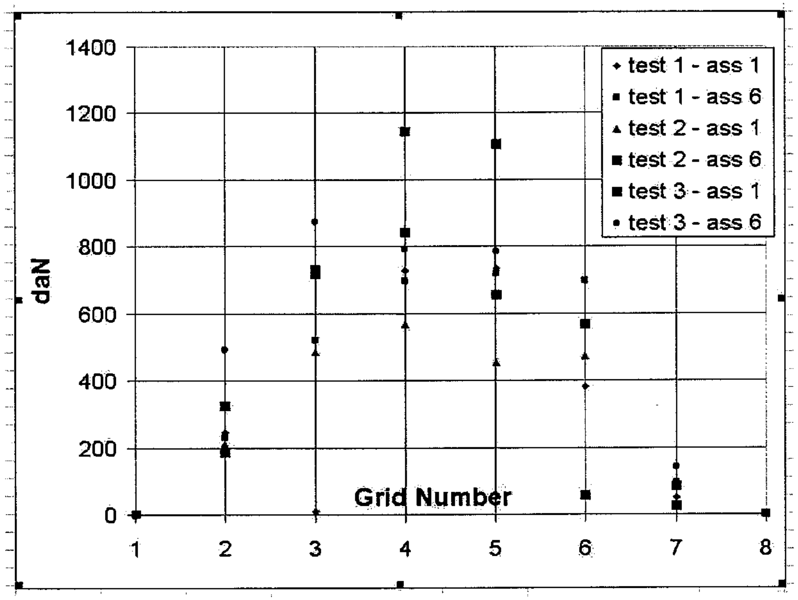


Figure #20 : Examples of the maximum impact forces distributions along the assemblies – (Water full confinement)