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First Experimental Validation of the Core Equilibrium Code HARMONIE

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ABSTRACT

The code HARMONIE calculates the mechanical equilibrium of a fast reactor core. An experimental program of deformation, in air, of groups of subassemblies, was performed on a mock-up, in the Super Phenix 1- geometry, in order to achieve a first experimental validation of the code. This program included three kinds of tests, all performed without and then with grease : on groups of 2 or 3 rings of subassemblies, subjected to a force acting upon flats or angles ; on groups of 35 and 41 subassemblies, subjected to a force acting on the first row, then with 1 or 2 empty cells ; and on groups with 1 or 2 bowed subassemblies or 1 enlarged one over flats.

A preliminary test on the friction coefficient in air between two pads showed some dependance upon the pad surface condition with a scattering factor of 8.

Two basic code hypotheses were validated : the rotation of the subassemblies around their axis was negligible after deformation of the group, and the choice of a mean Maxwell coefficient, between those of 1st and 2nd slope, led to very similar results to experimental.

The agreement between tests and HARMONIE calculations was suitable, qualitatively for all the groups and quantitatively for regular groups of 3 rings at most (the highest relative difference was less than 20 %). But the difference increased for larger groups of 35 or 41 subassemblies, specially in the presence of empty cells (up to 37 %) : friction between pads, neglected by HARMONIE, seems to be the main reason. Generally, its influence is the following one : to restrain the central rows in the direction of the force ; to prevent the lateral ones to move aside, inwards or outwards ; and to push forward the lateral ones in the direction of the force.

Other reasons for these differences are : the influence of the loading order on the mock-up, and the initial contacts issued from the gap between foot and diagrid-insert, and from manufacture bowings.

1./ INTRODUCTION

HARMONIE code calculates the mechanical equilibrium in hexagonal and 3-dimensional geometry of a fast reactor core. From such data as the pattern pitch, the distances over flats, the elastic Maxwell coefficients, the compression spring constants of contacts and the free bowings at each contact level, the code yields equilibrium displacements and contact forces at each contact level. In order to achieve a first experimental validation of the code, a program of tests of deformation in air of groups of several subassemblies was performed by the CEA on the R106E mock-up, composed of 106 seatings, in Super Phenix 1 geometry at Cadarache. It led also to a better understanding of phenomena which rule the mechanical equilibrium of a group of subassemblies : stiffness of the subassemblies, friction between contacts, and geometry of the group mainly.

2./ BASIC HYPOTHESES OF THE CODE :

2.1.- Stiffness of the subassemblies :

It is represented by elastic flexibility coefficients of subassemblies, named Maxwell coefficients. If friction is neglected at the seat of the subassembly foot, preliminary tests and calculations showed the bilinear nature of the graph "force vs.deformation" (fig. 1) : the change of slope, and thus of Maxwell coefficient, comes from the arrival of a third contact level between the subassembly foot and the diagrid insert.

The code HARMONIE only uses one constant Maxwell coefficient for each subassembly. It was hence necessary to define a mean fictitious Maxwell coefficient between these of first and second slope : its definition is described in fig. 1.

2.2.- Friction between pads :

Friction between pads is not taken into account in the code. So, preliminary tests were defined to evaluate friction coefficient between two pads. Tests on the groups of subassemblies were performed without grease between pads first, and then with grease in order to decrease friction.

2.3.- Gap between foot and diagrid-insert :

The code only accounts for two supports for each subassembly : a pin at the level of the subassembly foot seat, and a sliding bilateral support between foot and diagrid-insert at the bottom of the foot. Actually, gap between bottom of the foot and diagrid-insert allows some free displacements at the head level (as a matter of fact, a small force is enough to overcome friction at the subassembly foot seat). To get rid of these displacements which prevented any comparison, the head displacements, after deformation of the group of the subassemblies, were measured from a zero position, with the gap closed and the group unloaded. These head displacements, corrected by substracting the displacements due to a slight diagrid tilting due to the force, could then be compared to the head displacements yielded by HARMONIE, corrected too by substracting manufacture bowings to obtain only the elastic parts of displacements.

But, neglecting the gap between foot and diagrid-insert, the code modifies the real diagram of the initial equilibrium : so it could consider initial contacts, due to manufacture bowings, contacts which do not exist in reality because of the gap between foot and diagrid insert, or vice-versa. Hence, some discrepancies between test and calculation, that can reach 1 to 2 mm.

2.4.- Subassemblies rotation around their axis :

The code neglects the subassemblies rotation, so it was necessary to check experimentally that, after deformation, there was no considerable rotation around their axis : this was done by comparing rotation angles with respect to a fixed coordinate system, first after closing the gap, then after deformation, and by checking that their difference was smaller than a value θ, function of measure uncertainties of the coordinates.

3./ DESCRIPTION OF THE TESTS :

3.1.- Mock-up description :

The R106E mock-up is composed of a diagrid of 106 seatings, in actual geometry Super Phenix 1, which represents 1/6 of the actual diagrid (Fig. 2). Subassemblies are dummy ones, of three kinds (fuel, fertile and control rods), without the bundle of pins, but representative as to stiffness. The thrust device consists of two jacks, acting on flats or angles of the group, and a jaw for thrust on larger groups.

All the tests take place in air at ambient temperature.

3.2.- List of the tests :

The experimental program may be split into three parts :

3.2.1.- Deformation of groups by a force acting on the pads of one subassembly. A constant force is applied by a jack so that it acts axially.

The groups consist of 7 subassemblies upon flats, then 8 upon angles, 19 upon flats and at last 19 upon angles.

All these tests are performed with and without grease between pads. The groups of 7 or 8 subassemblies are deformed by forces, either such that all the subassemblies are deformed on the 1st slope of the graph of the Maxwell coefficients, or such that only the central rows are deformed on the 2nd slope. The groups of 19 subassemblies were first used without any empty cell, then with one (corresponding to the absence of one subassembly), and then with two (corresponding to the absence of two adjacent subassemblies).

3.2.2.- Deformation of groups by a force applied on the pads of the 1st row : this kind of test presents two purposes : to validate the code on larger groups, and to study equilibrium in peripheral areas (for instance, the border core I-core II) and especially the problems related to the handling of normal (group with one empty cell) or special (group with empty adjacent cells) subassemblies. The groups consist of 41 subassemblies, thrust upon the flats of the 1st row (fig. 3) and 35 subassemblies, thrust upon the angles, first without any empty cell, then with 1 or 2 ones.

3.2.3.- Deformation of groups with bowed or enlarged across flats subassemblies

These tests are used to validate the code with 2 contact levels between the subassemblies (generally, head and pads), which is consistent with the actual running of the reactor.

The first tests include 1 bowed subassembly (upon flats then upon angles), then the following ones include 2 bowed subassemblies in different directions, and the last ones include 1 subassembly whose distance overflats was artificially increased.

4./ PRECISION OF THE TESTS

The main factors which govern the precision of the tests are :

- the precision of the measure system of the coordinates.
- friction in the subassembly foot seat, that could involve small residual displacements at head or pads levels.
- the dynamometer precision of 1 %.
- the precision of the metrological surveys of the subassemblies.
- the manufacture tolerances of the subassemblies and of the mock-up.

Comparisons between analytical calculations and test on a group of 3 subassemblies, then between HARMONIE calculations and test on a row of 5 subassemblies in very similar conditions of those of a HARMONIE calculation (no friction, no gap between foot and diagrid-insert, no initial contacts due to manufacture bowings) show little difference : about from 1 % to 15 %, according to the subassembly.

But the highest uncertainty comes from the last two factors listed before : metrological surveys and tolerances.

Finally, the uncertainty on the experimental displacements may be roughly estimated to 1 to 3 mm, according to the test. Besides, the reproductibility of the measures was confirmed by checking that the scattering of the measures, performed several times in succession, either after closing the gap or after deformation, was smaller than the scattering due to friction at the subassembly foot seat.

5./ ANALYSIS OF THE TESTS :

5.1.- Stiffness of the subassemblies :

The comparison between the results of tests, where some subassemblies are deformed on the 2nd slope of the graph of the Maxwell coefficients, and the results of the HARMONIE calculations with mean Maxwell coefficients, yielded a good agreement. As a matter of fact, these mean coefficients give to the subassembly a higher flexibility than in reality, but, in the same time, for a specified value of the force acting on the group, they increase the free bowing, which is the actual input of the code : the two contrary effects are balancing themselves.

But, in the reality of a core equilibrium calculation, the data are the free bowings, and not the forces. Here, there is no more balancing, but, as shown by the analysis of the 2 tests with one bowed subassembly, on flats or on angles, the code results stand close to the experimental ones (Fig. 4).

On the other hand, some calculations were done with only one mean Maxwell coefficient for the group : it was defined as the average of all the mean coefficients, computed for each subassembly. The results of these calculations being near those done with one mean coefficient for each subassembly, it proves that, in a complete core calculation, only some coefficients need to be used : they would be defined from a mean value of deformation "a priori" evaluated.

5.2.- Friction coefficient :

Preliminary tests showed a large dependence upon the surface condition of the pads : a scattering factor of a 8 was observed. The smallest values were measured on pads smoothed by the file and the emery-cloth.

When pads were covered with grease, the values were less scattered and gathered around a mean value. But grease showed little influence upon the experimental results : the experimental results with grease were slightly nearer the code results than the ones without grease.

5.3.- Subassemblies rotation around their axis :

Considering the measure uncertainties on the displacements, there was no appreciable rotation of the subassemblies around their axis, after deformation.

5.4.- Deformation of the groups :

A comparison between the results of the HARMONIE calculations and those of the tests, shows that, roughly, in the test :

- the contact forces are smaller.
- the centrifugal or centripetal displacements are smaller in the perpendicular direction to the force acting on the group.
- the lateral rows are moving further in the direction of the force acting on the group.
- the central rows, located before the jack, are more restrained in the direction of the force acting on the group.

These conclusions are illustrated by the figures 5 and 6 which represent respectively the deformations from the test and the code for a group of 7 subassemblies, thrust on flats, and for a group of 8 ones, thrust on angles.

The conclusions of a comparison between the experimental results of a test with grease between pads, and the ones of a test without grease, would be identical.

They are probably related to the phenomenon of friction between contacts.

The deformation of a group, thrust on angles, is larger than the one of a group, thrust on flats with the same force, because of the wedge type of the thrust in the 1st case. The differences between the calculations and the tests are larger on angles than on flats : it comes from friction which increases in the same time than the relative displacements between the subassemblies. On the contrary, in groups with 1 or 2 empty cells, the differences between the calculations and the tests are larger on flats than on angles : this is illustrated by fig. 7 and 8 which represent the deformations of the groups, either on flats or on angles, in the area of the empty cells. As a matter of fact, in the case of the thrust on flats, the empty cell creates a discontinuity in the transmission of the thrust, and increases the relative displacements, and thus the friction forces : the difference between the calculations and the tests may reach more than 50 % of the experimental displacements in the direction of the thrust, for the subassemblies located before the jacks. In the case of the thrust on angles, the empty cell modifies in a little way the diagram of the transmission of the thrust through the group, with an angle of 30° with respect to the direction of the thrust, and therefore, increases only slightly the relative displacements between the subassemblies.

The tests on groups with 1 or 2 bowed subassemblies, or with 1 enlarged subassembly over the flats, displayed another phenomenon, which cannot be considered by HARMONIE : the loading order of the subassemblies on the mock-up. The final equilibrium for identical groups may be different according to the loading order : different contacts map, and different experimental displacements.

5.5.- Tests HARMONIE agreement

The main reasons for the differences between the experimental results and the HARMONIE calculations results, are the following ones : on one hand, the uncertainty on the experimental data and measures, and on the other hand friction. The part due to the uncertainty on data may be roughly estimated to some mm.

Quantitatively, the agreement between tests and calculations is suitable, as shown in table 1, which gathers the mean relative differences on the displacements in the direction of the thrust for all the tests (in the perpendicular direction to the thrust, the displacements are too small to obtain significant relative differences). The best results concern the regular groups of 3 rings at most, for which the maximum relative difference is 13 %. In presence of an empty cell, it reaches 20 %.

In larger groups of 35 or 41 subassemblies, the relative difference may reach 30% and, in presence of 2 empty cells, more than 50 %. These last values, observed in the area of the empty cells or before the jacks, can be explained mainly by friction which modifies greatly the equilibrium of the deformed group.

Qualitatively, the almost full coherence between the tests and calculations results must be noticed : the map of the contacts, the direction of the displacements, the evolution of the displacement values along the group.

Another kind of tests could be very interesting to validate the code, because it would limit the influence of friction : a test with vibrations of the group during the deformation. Such a test was undertaken on 7 subassemblies, but it did not yield correct results, because of the excitation device, which is too weak, and of a maladjusted hanging system of this device. This test will have to be defined again with better experimental conditions.

6./ CONCLUSION

The aim of this experimental program of deformation of groups of several subassemblies was to achieve a first step of validation of the calculation code of the core mechanical equilibrium : HARMONIE.

Qualitatively, a suitable coherence between tests and calculations was observed, but quantitatively, if the agreement seems good for regular groups of 19 subassemblies at most (less of 20 % of relative difference), it is less good for larger groups, especially in presence of empty cells (in the last case, the maximum relative difference reaches more than 50 %). The influence of friction is probably mainly responsible for these differences, but also the loading order of the subassemblies on the mock-up and the initial contacts due to the gap between foot and diagrid-insert, and due to the manufacture bowings. In its present state of development, HARMONIE reglects friction and the gap between foot and diagrid-insert.

Two basic hypothesis of the code were validated : there is no appreciable rotation of the subassemblies around their axis after deformation, and the choice of a mean Maxwell coefficient between those of 1st and 2nd slope yielded results near the experimental ones.

An experimental study of the friction coefficient between two pads in air showed a great dependance upon the surface condition of the pads, with a scattering factor of 8 about. So, the main experimental efforts will concern in the future the tests under vibrations, and the tests in sodium on the friction coefficient. Theoretically, the development, of the code HARMONIE will be assured by introducing friction, the gap between foot and diagrid-insert and the double slope Maxwell coefficients.

TABLE .1.

'MEAN RELATIVE DIFFERENCES ON THE DISPLACEMENTS
BETWEEN HARMONIE AND TEST RESULTS

Number of the test	Number of subassemblies	Thrust force (kgs)	O/A:on angles O/F:on flats	Grease	Mean relative difference(%)	Number of the test	Number of subassemblies	O/A: on angles O/F: on flats	Mean relative difference(%)
1	7	small	O/F		15	17	41	O/F	34
2	7	small	O/F	G	16	18	40	O/F	32
3	7	large	O/F		9	19	39	O/F	37
4	7	large	O/F	G	8	20	35	O/A	17
5	8	small	O/A		12,2	21	34	O/A	16,8
6	8	small	O/A	G	12,3	22	33	O/A	19
7	8	large	O/A		8,2	23	7	1 bowed subassemblies on flats	20
8	8	large	O/A	G	7,8				
9	19		O/F		19	24	8	1 bowed subassembly on angles	26
10	19		O/F	G	13				
11	19		O/A		11	25	9	the 2 bowed subassemblies	26 (Y) 11 (X)
12	19		O/A	G	9				
13	18		O/F		24	26	19	1 enlarged subassembly across the flats	33 (X) 17 (Y)
14	18		O/F	G	20				
15	18		O/A		12				
16	18		O/A	G	11				

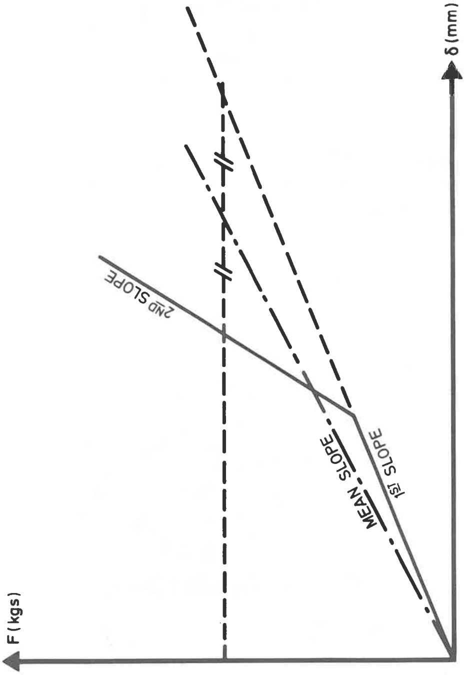

Figure 1 -
DEFINITION OF THE MEAN MAXWELL COEFFICIENT

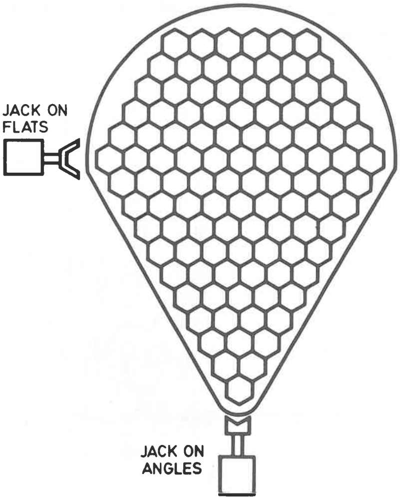

FIGURE 2 -
60° SECTOR OF MOCK-UP DIAGRID

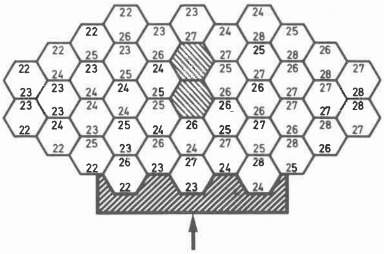

FIGURE 3 -
GROUP OF 41 SUBASSEMBLIES WITH 2 EMPTY CELLS

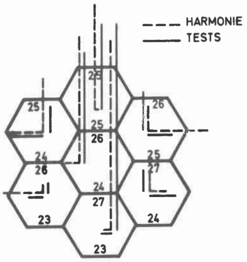

FIGURE 4 -
COMPARISON BETWEEN EXPERIMENTAL AND CALCULATED DEFORMATIONS OF A GROUP WITH ONE BOWED SUBASSEMBLY, LOCATED IN 27-23.

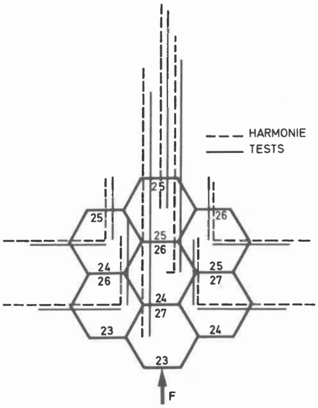

FIGURE 5 -
DEFORMATIONS OF A GROUP OF 7 SUBASSEMBLIES THRUST ON FLATS.

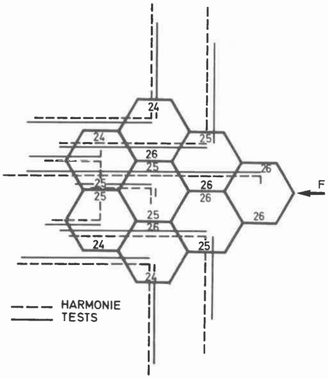

FIGURE 6 -
DEFORMATIONS OF A GROUP OF 8 SUBASSEMBLIES THRUST ON ANGLES.

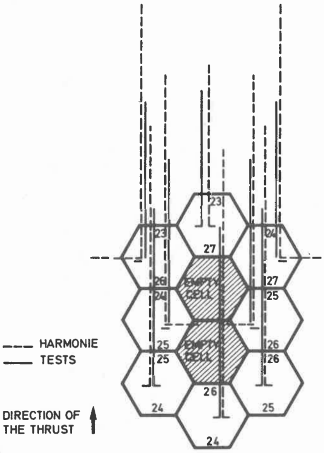

FIGURE 7 -
DEFORMATIONS OF A SUB-GROUP AROUND THE TWO EMPTY CELLS, WITHIN THE GROUP OF 41 SUBASSEMBLIES THRUST ON FLATS.

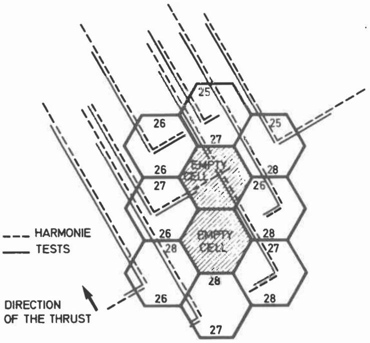

FIGURE 8 -
DEFORMATIONS OF A SUB-GROUP AROUND THE TWO EMPTY CELLS, WITHIN THE GROUP OF 35 SUBASSEMBLIES THRUST ON ANGLES.