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CORE SEISMIC BEHAVIOUR : LINEAR AND NON-LINEAR MODELS

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ABSTRACT

The usual methodology for the core seismic behaviour analysis leads to a double complementary approach : to define a core model to be included in the reactor-block seismic response analysis, simple enough but representative of basic movements (diagrid or slab) ; to define a finer core model, with basic data issued from the first model. This paper presents the history of the different models of both kinds.

The inert mass model (IMM) yielded a first rough diagrid movement.

The direct linear model (DLM), without shocks and with sodium as an added mass, let to two different ones : DLM1 with independant movements of the fuel and radial blanket subassemblies, and DLM 2 with a core combined movement.

The non-linear model (NLM) "CORALIE" uses the same basic modelization (Finite Element Beams) but accounts for shocks. It studies the response of a diameter on flats and takes into account the fluid coupling and the wrapper tube flexibility at the pad level. Damping consists of one modal part of 2 % and one part due to shocks. Finally, "CORALIE" yields the time-history of the displacements and efforts on the supports, but damping (probably greater than 2 %) and fluid-structures interaction are still to be precised. The validation experiments were performed on a RAPSODIE core mock-up on scale 1, in similitude of 1/3 as to SPX 1.

The equivalent linear model (ELM) was developed for the SPX 1 reactor-block response analysis and a specified seismic level (SB or SM). It is composed of several oscillators fixed to the diagrid and yields the same maximum displacements and efforts than the NLM.

The SPX 1 core seismic analysis with a diagrid input spectrum which corresponds to a 0,1 g ground acceleration, has been carried out with these models : some aspects of these calculations are presented here.

INTRODUCTION

The analysis of the core seismic behaviour is an important part of the design studies of a nuclear reactor. These studies consist briefly of :

- defining the SMHV (maximum likely historic earthquake) in terms of intensity from the study of the historic earthquakes in the region of the facility, or in terms of an accelerogramm or a response spectrum defined by setting an upper bound to real accelerogramms or response spectra.

- accounting for the problem of soil-foundation interaction

- defining two earthquake analysis levels : SB (basic earthquake) for an economical warrant and SMS (safety earthquake) for a safety warrant. The SB level is usually chosen as the SMHV one, and the SMS one as the SMHV one plus 1.

Then, the engineer has to analyze the direct earthquake consequences on the structures and the indirect ones on the accidental running of the facility, for these two earthquake levels.

The reactor core needs an important effort of fine modelization because of the prime importance and the complexity of its specific problems (control rods kinetics, reactivity problems).

This paper describes the methodology of the reactor-block seismic response analysis, and then, the different models developed for the core seismic analysis, from the linear ones to the non-linear ones with shocks.

1./ METHODOLOGY OF THE MECHANICAL ANALYSIS

The arrival of seismic waves on the site of the reactor starts moving every structure, and especially the core which is subjected to forced vibrations which are to be analysed.

A direct method would be to finely modelize every reactor structure, and to perform a direct dynamic calculation with the help of the soil (or bed-rock) accelerogramm. This method would not be very realistic from the point of view of its performance.

So it leads to isolate the core from the rest of the reactor by defining the reactor-block core intermediary with data such that imposed forces or displacements, which correspond to a transfer function of the reactor-block with respect to the soil data. This usual methodology leads to a double complementary approach :

a) To define a first core model to be included in the calculations of the seismic response of the reactor-block. This model would be simple enough not to overload already complicated calculations, but representative enough to obtain realistic basic movements (grid, plate, core coverplug) and support reactions.

b) To define a second core model for the finer analysis of its mechanical behaviour, with basic data issued from the first model.

This methodology allows to do in relative independence the core studies and the reactor-block ones.

2./ CORE MODELIZATION

In the vertical direction, the modelization consists of an inert mass, equal to the core mass : the core may be considered as infinitely rigid in this direction, because its resonance frequencies stand far beyond the seismic amplification zone.

In the horizontal direction, the modelization is more delicate, because one of the characteristics of the French fast cores is the high horizontal flexibility. The absence of constraint, other than "natural", lets the subassemblies horizontally free, except their clamping into the grid. This high flexibility means low resonance frequencies located in the amplification zone of the seismic spectra, filtered or no. The modelization of one subassembly by a beam with variable inertia moment and section is sufficient because the internal sodium, set in motion, acts as an added mass.

The main problem of the core modelization concerns the group of hexagonal subassemblies. More precisely, the critical problems to solve are the following ones :

a) the contacts between subassemblies are unilateral (the subassemblies may push each other, but not hold back each other)

b) the distribution of the contacts is hard to calculate in statics, and almost impossible to determine in dynamics and 3.D.

c) the presence of shocks

d) the fluid-structures interaction due to sodium between the subassemblies and around the core.

e) the damping characteristics are only available from tests and not from theory.

3./ THE DIFFERENT MODELS :

3.1.- Inert Mass Model (IMM) (1975)

This model of an inert mass yielded a first approximation of the grid movements.

3.2.- Direct Linear Model (DLM) (1977-1979)

This model developed a linear modelization with bilateral contacts, without shocks, accounting for sodium as an equivalent added mass and damping as an external parameter.

The modelization of the contacts led to two different models. As a matter of fact, there are two types of contacts between the subassemblies in the core : at the pad level, the contact is functionnally set (the gaps are closed at nominal power : problems of instantaneous reactivity) ; at the head level, there is a gap of some mm about between the possible contact surfaces (problem of the core constraining).

The first model DLM1 only takes into account the first kind of contacts (pads) : so, the fuel and fertile core and the radial blanket subassemblies (steel and NLP, i.e. neutronic lateral protection subassemblies) are independent.

The second model DLM2 (Fig. 2) accounts for the two kinds of contacts (pads and heads) and leads to a combined movement of the whole core ; these two approaches were used to encompass the real value of the first core resonance frequency, the first model giving the lower bound, and the second one the upper bound (fig. 1).

In these models, each type of subassembly is represented by one subassembly, whose the characteristics are multiplied by the number of subassemblies of this type in the core.

Although succint, these models achieved a first evaluation of the maximal displacements and forces by the modal method with quadratic combination of the modes from the response spectra of the grid.

3.3.- Non-Linear Model (NLM) : "CORALIE" (1980)

The basic modelization in finite elements beams is the same than DLM, but it accounts for shocks. In its present state of development, it studies the response of a main diameter on flats with the help of the modes of each type of subassembly (the validation tests showed that one file of subassemblies seemed to be representative of the seismic behaviour of the whole core).

It simulates shocs by springs, and computes interaction forces in an iterative way. The fluid-structure interaction, due to an added mass effect and mainly to fluid coupling and porosity effects between fuel and radial blanket subassemblies, is taken into account by decreasing the resonance frequencies with the help of the Young modulus. The damping coefficient is composed of a modal part of 2 % (standard value) and a part due to shocks, taken into account by the model to represent the energy dissipation during the impact.

This last model NLM is the core reference model. It allows to describe, with respect to the time, from the grid accelerogramm, the time-history of the displacements and support reactions of the subassemblies of each core ring. To know precisely the core motion may yield some important informations for safety analysis, specially as to kinetics of the introduction of the control rods in the core.

The theory of "CORALIE" is developed in a separate paper.

3.4.- Equivalent Linear Model (ELM) (1980)

This model is defined to be included in the reactor-block calculations. The participation coefficients of the modes issued from theNLM, are determined to obtain, from the grid accelerogramm, the same maximal displacements and support reactions than those of the NLM. Finally, this model consists of several oscillators, fixed to the diagrid, each one corresponding to one mode.

But this model ELM may represent the model NLM in a reactor-block calculation, only if the whole (reactor-block model including ELM, grid movement, equivalence between ELM and NLM for this movement) is consistent. This consistensy may need an iterative process (table II).

This ELM was determined for the SPX 1 reactor-block response analysis, and for a specified seismic level (SB, i.e. basic earthquake or SMS, i.e. safety earthquake).

4./ VALIDATION TESTS :

They were performed on a core mock-up in RAPSODIE geometry at scale 1, and in similitude of 1/3 as to SPX 1 (Fig. 3). The core mock-up was composed of 91 fuel subassemblies and 4 rings of radial blanket subassemblies. It was used on a shaking table, in air and in water. The tests consisted of harmonic and seismic ones. The experimental validation of "CORALIE" is not developped in this paper, but, in summary, the comparison between RAPSODIE tests and "CORALIE" results showed a good agreement.

5./ SEISMIC ANALYSIS OF THE SPX 1 CORE :

The SPX 1 core seismic analysis was carried out with the three models listed before, from a diagrid input spectrum which corresponds to a ground acceleration of 0.1.g, i.e. the basic earthquake level (Fig. 1).

5.1.- DLM models :

In these studies, the grid movement was supposed to be little sensitive to the core model, because there was no consistensy between the model used in the reactor block study and the one used in these studies.

* DLM 1 : it led to relative displacements of the heads of the subassemblies, which were inconsistent with the existing gaps.

* DLM 2 : in this model, the hypothesis of an identical displacement of every head overestimated the effect of stiffening by the radial blanket subassemblies.

The first resonance frequency was much increased, and the maximal displacement at the head level was much decreased (table I).

5.2.- NLM and ELM models :

The NLM, from 4 different modes (one for each kind of subassembly) yielded a maximal head displacement intermediate between the results of DLM1 and DLM2. The graph of the displacements at the two contact levels is shown in Fig. 4.

Moreover, it yielded the shock forces at the two contact levels (Fig. 5) : the maximal forces are observed for shocks between subassemblies of different kind and, hence, of different frequencies.

A low value of the time step, equal to 2 ms, was used for a correct integration of the forces during each shock.

As to the shock stiffnesses :

- at the head level, they correspond to the stiffness due to the modes which are neglected in the calculation.

- at the pad level, they were determined by tests, and they allowed to neglect the effect of the highest modes.

The tests on the RAPSODIE mock-up showed a relative scattering of the first frequencies, due to shocks, and a slight decreasing of 15 %, due to fluid coupling with a porosity effect.

All these observations and results of the NLM led to define the ELM for SPX 1 : it is composed of 6 oscillators plus one static term.

The 6 oscillators refer to :

- the internal fissile subassemblies
- the external ones + control rods
- the fertile ones
- the steel reflector ones, much influenced by fuel ones
- the NLP moved by fuel ones
- the NLP, laterally located whose the frequency is influenced by the fuel one.

6./ CONCLUSION

In the seismic design of the different components of the reactor-block of a French fast reactor, a peculiar importance was given to a fine and isolated core modelization, due to its specific problems and its complexity.

The evolution of the core models led to a non-linear model with shocks, which allows a fine analysis of its behaviour and an equivalent linear model which may be included in the seismic calculations of the reactor-block. All the developed models were applied to the SPX 1 core seismic calculations.

This most recent non-linear model, developed in the code "CORALIE", yields the time histories of the displacements and efforts on supports, but some parameters are still to be precised : damping and fluid-structures interaction.

TABLE .I.

COMPARISON OF SPX 1 RESPONSE ANALYSIS

MODELS	FIRST CORE FREQUENCY	MAXIMAL HEAD DISPLACEMENTS
DLM 1/ DLM 2	0,39	3,06
DLM 1/ NLM	0,96 to 1,15	1,15
DLM 2/ NLM	2,42 to 2,94	0,38

TABLE .II.

METHODOLOGY OF THE SEISMIC BEHAVIOUR ANALYSIS

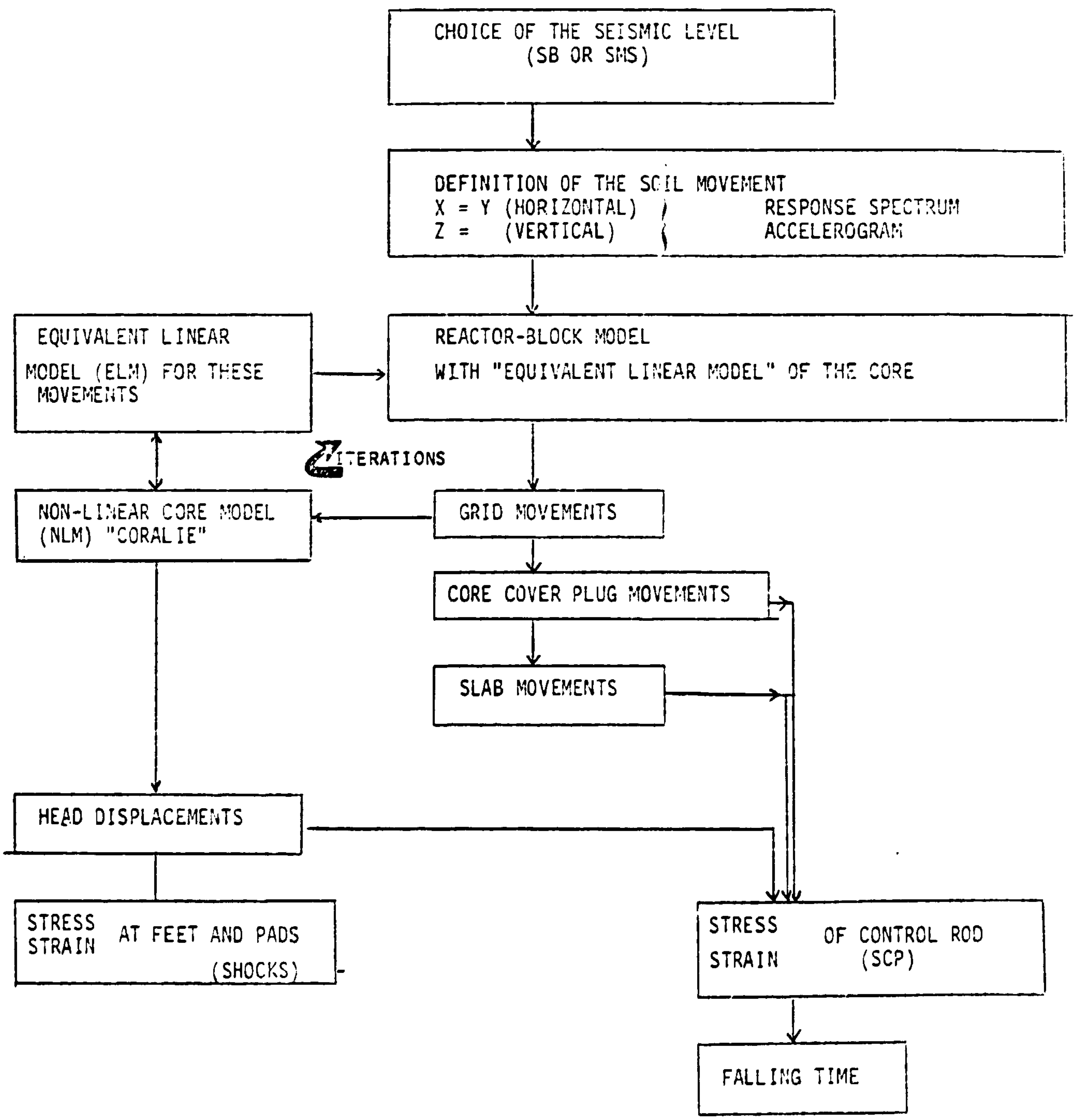


FIGURE 1. : GRID ACCELERATION RESPONSE SPECTRUM FOR SPX 1
FREQUENCIES FOR THE DLM 1 and DLM 2 MODELS

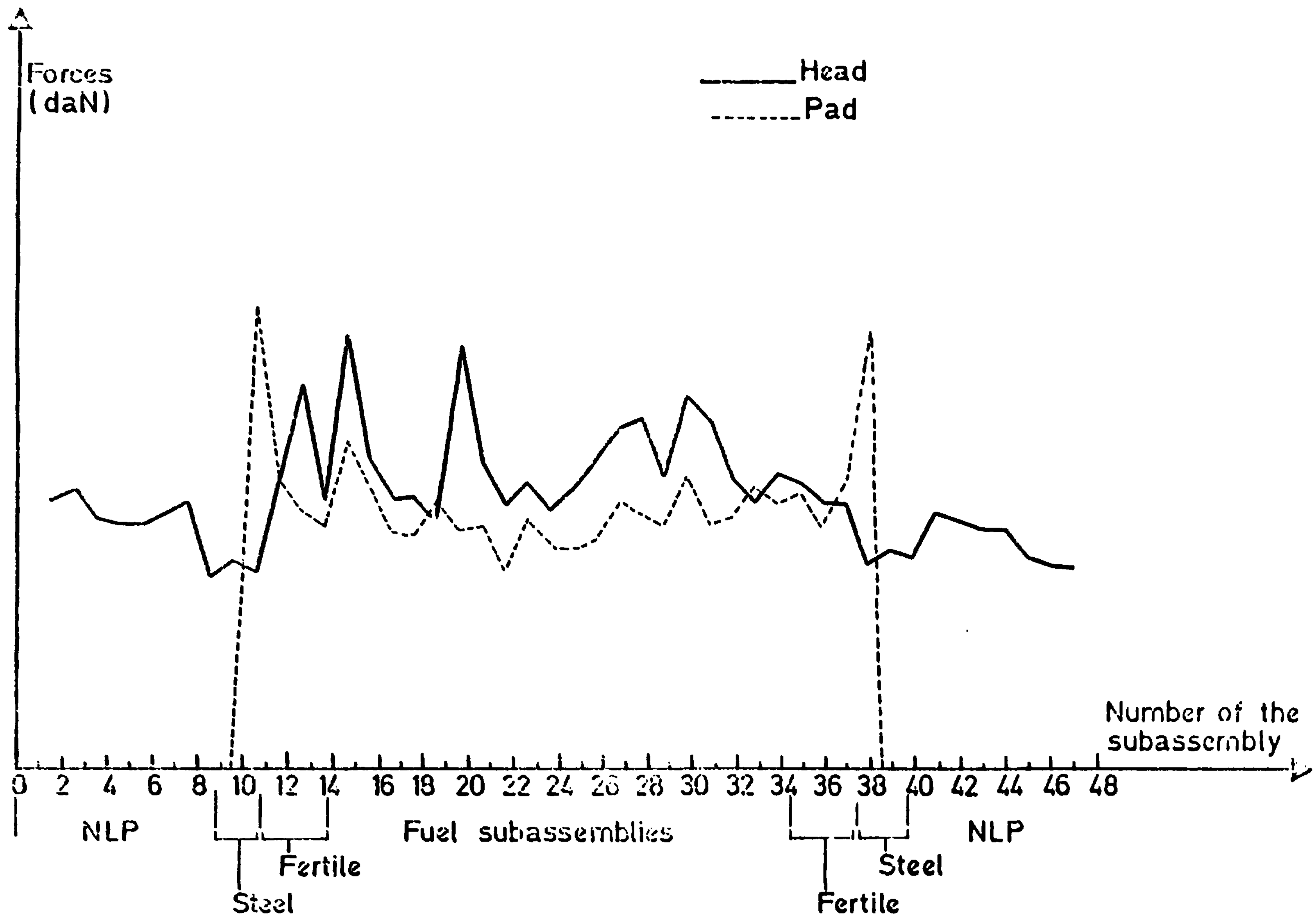
FIGURE 2 : DLM 2 : CORE MODELIZATION

LOCATION OF THE NODES	NUMBER OF THE NODES
Foot bottom	1, 23, 47, 68
Foot seat	8, 30, 52, 72
Pads	14, 38
Heads	22, 46, 67, 89

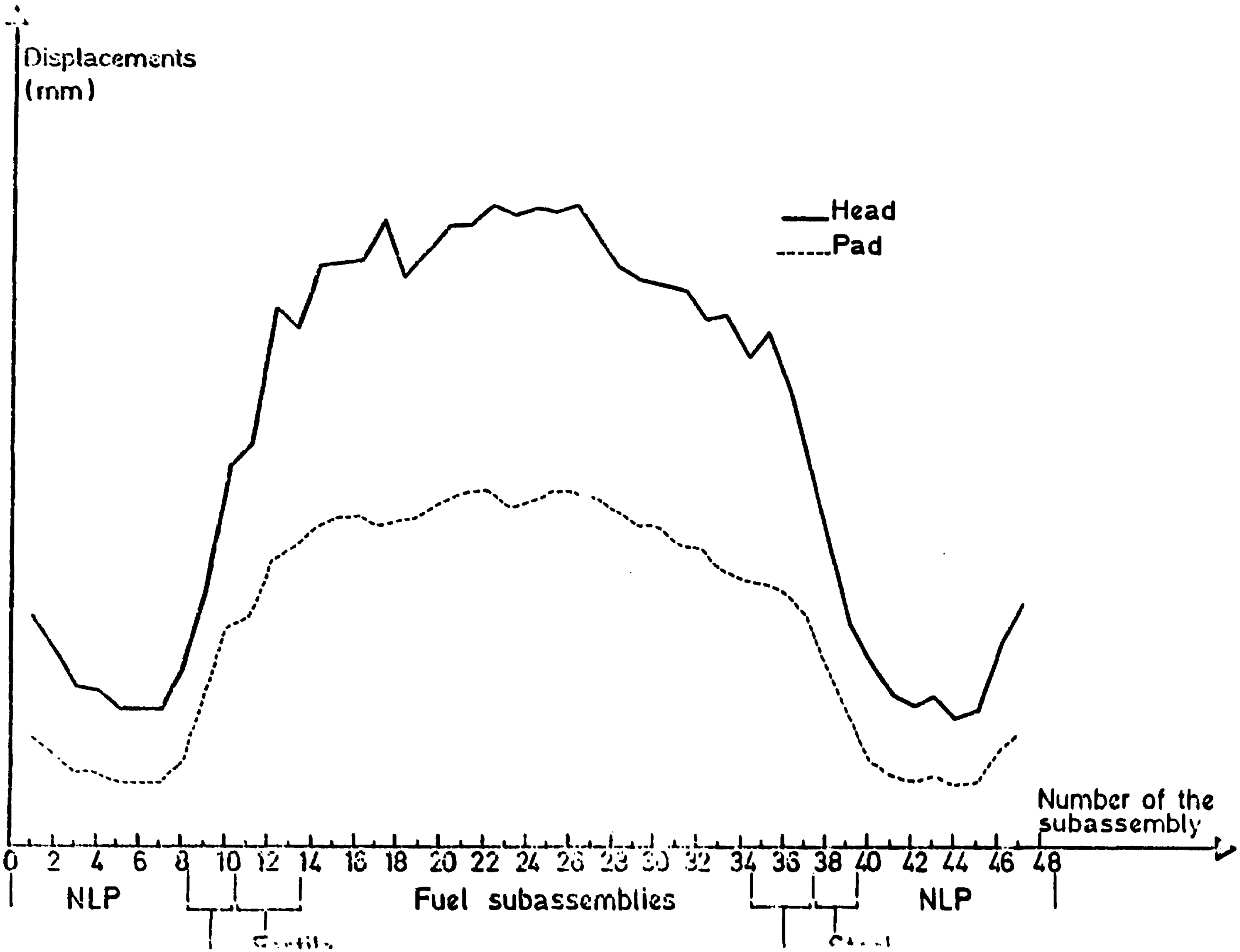
FIGURE 3 : RAPSODIE CORE MOCK-UP FOR THE "CORALIE" VALIDATION

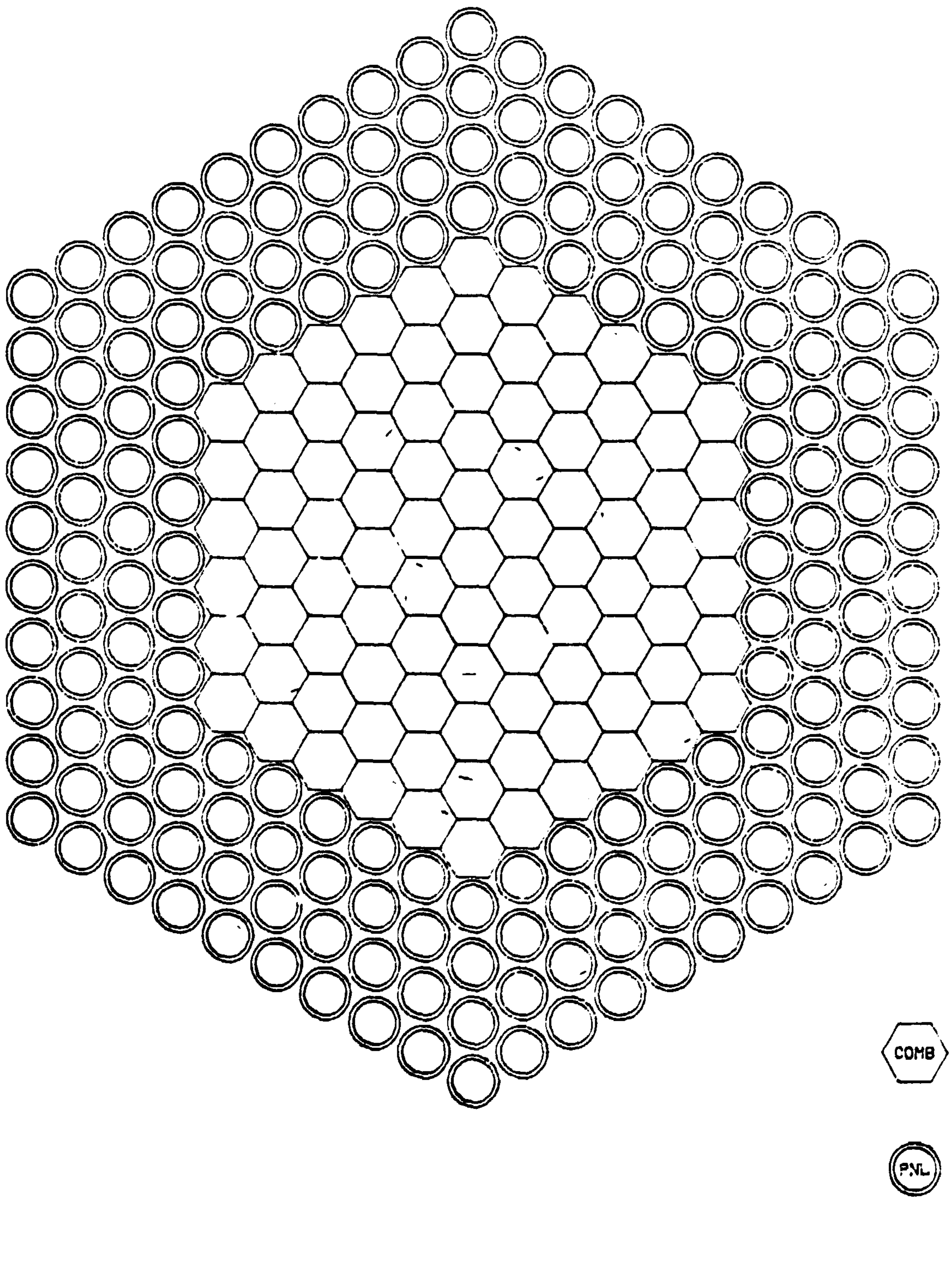
FIGURE 4 : MAXIMAL DISPLACEMENTS OF A FILE OF SUBASSEMBLIES SUBJECTED TO A SEISMIC EXCITATION

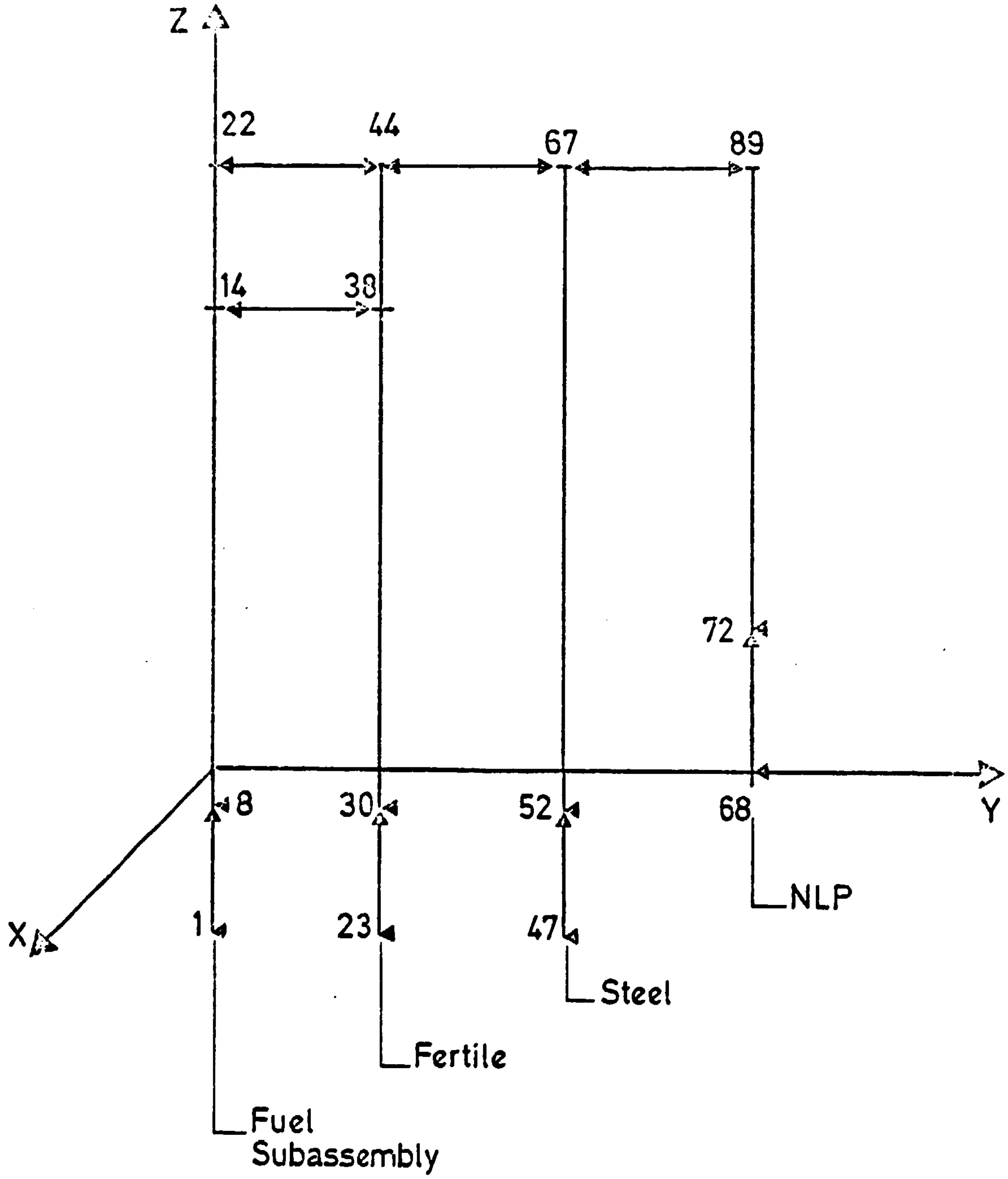
FIGURE 5 : MAXIMAL SHOCK FORCES OF A FILE OF SUBASSEMBLIES SUBJECTED TO A SEISMIC EXCITATION.



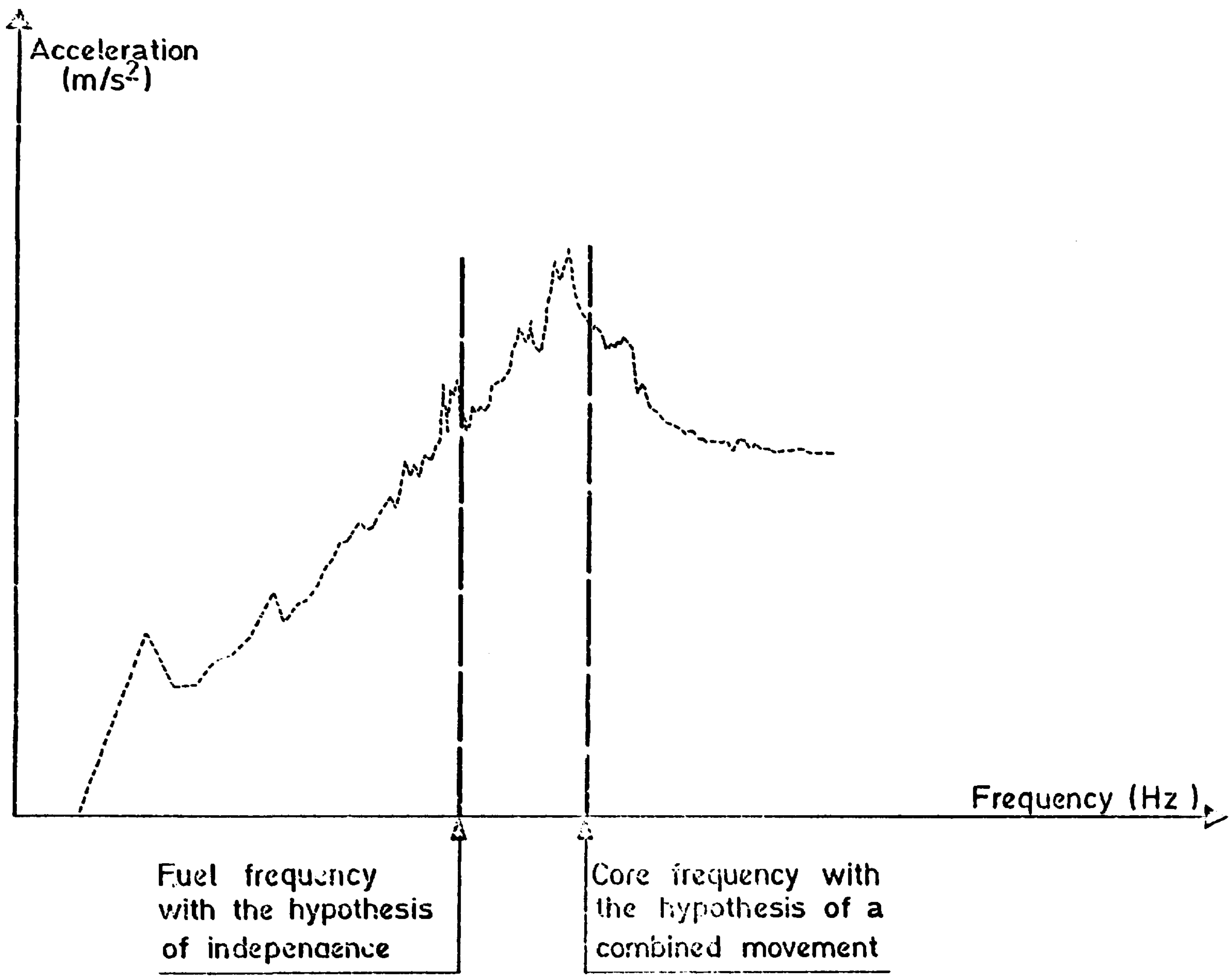
Forces
(daN)
Head
Pad
Number of the
subassembly
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
NLP
Fuel subassemblies
NLP
Steel
Fertile
Fertile
Steel


Displacements (mm)
Head
Pad
Number of the subassembly
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
NLP
Fuel subassemblies
NLP


COMB
PNL



Z
22
44
67
89
14
38
72
8
30
52
68
Y
X
1
23
47
NLP
Steel
Fertile
Fuel
Subassembly


Acceleration (m/s2)
Frequency (Hz)
Fuel frequency with the hypothesis of indepenaence
Core frequency with the hypothesis of a combined movement