A SEISMIC POST ELASTIC BEHAVIOR OF SPHERICAL TANKS

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Introduction

French regulation for seismic verification of structures is separated in two parts :

* the "normal risk" for a structure which affects only it's surrounding when it collapses,
* the "special risk" for a structure which could be dangerous for persons at long distances

The first category includes all buildings. The calculation methods are in general static and the post elastic behavior is taken into account by a reduction factor. This factor allows to divide seismic stresses by a factor, function of the type of structure. For reinforced concrete and steel structures, values of this factor can be found in literature and codes (PS92 in France).

The second category concerns the nuclear field and SEVESO's industrial sites (petrochemical industry for example). For the "special risk", the calculation method is a modal spectral analysis, which is an elastic calculation method too. The ability of a structure to have a ductile post elastic behavior is also taking into account by "reduction factors". The spectrum to be considered is regulatory where the seismic level is low (95% of French territory) and must be calculated elsewhere (taking into account site effects).

If we consider industrial equipments, only a few values of this reduction factor exist, and they are not specified in codes. The engineer has to define and justify the values he chooses. To find a solution to this problem, the French Ministry of Environment decided in 1997 to make a comparison of French and US approach for this problem. This document gives values for some equipments but concludes anyway that some more calculations are necessary to be sure of these reduction factors.

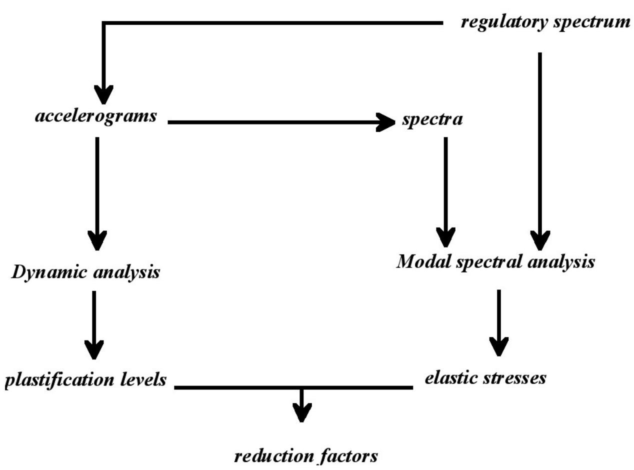
In 1999, The Ministry of Environment decided to undertake specific calculations for some equipments. This paper presents the first calculations performed for this project.

Presentation of the study

The study concerns existing pressurized spherical tanks.
This equipment was chosen for many reasons :

1. spherical tanks contain important masses of dangerous products (volumes of 300 to 3.000 m^3). If the equipment collapses, the dangerous distance is more than many hundred meters,
2. this equipment can be found everywhere in France (over 200 units),
3. reduction factor is very important for existing structures because elastic calculations lead generally to "the death" of the equipment,
4. existing equipments are similar everywhere in France and not initially calculated for seismic loads.

The approach was a comparison between modal spectral analysis and dynamic nonlinear calculations. It can be summarized in this chart :



Spherical tank

The study is performed for an existing equipment with a volume of 1000 m3 containing 85% of LPG. The middle diameter of the sphere is 12.50 m, its thickness varies from 36.2 mm to 36.8 mm taking into account the corroded thickness.

The sphere is supported by seven cylindrical columns equidistant of 5.4 m. Each column has two parts: the higher part on which the sphere is welded and the lower part fixed on the foundation. The middle radius of the columns is 25 cm and their thickness is 8 mm.

Fourteen reinforcement bars (bracing bars) with a section of 8 cm2 and a length of 7.45m are fixed on the columns. They have been designed to resist wind loads.

Regulatory spectrum

The regulatory spectrum chosen is presented here (this spectrum is for horizontal accelerations; in vertical direction, the spectrum is 2/3 of this one.).

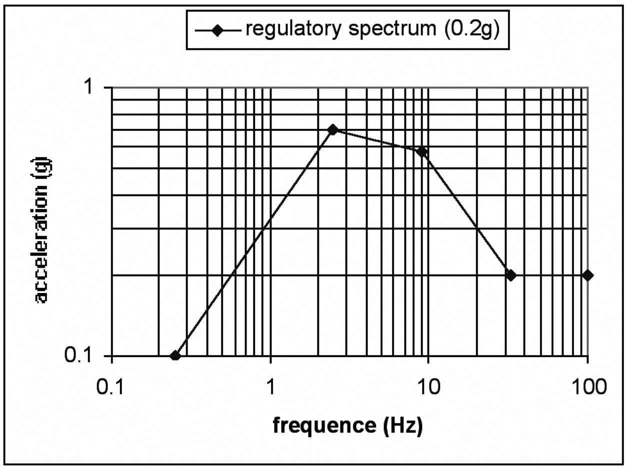


Figure 1 : regulatory spectrum

Accelerograms and spectra

It was decided to use real accelerograms for this study. Three seismic accelerograms were chosen : LOMA PRIETA, IRPINIA, and SAN FERNANDO. The comparison between LOMA PRIETA spectra and the regulatory spectrum is presented here after. Frequency of interest for spherical tanks is between 0.7Hz and 2 Hz.

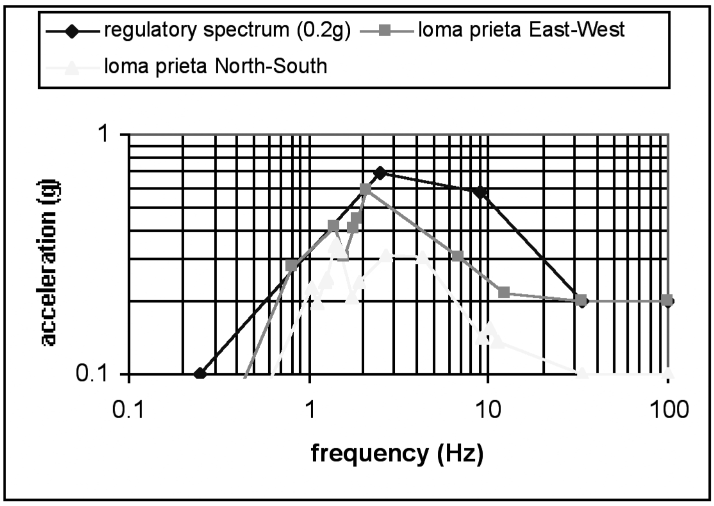


Figure 2 : LOMA PRIETA spectra vs regulatory spectrum

Finite element analysis with LS-DYNA

Model

Meshing

The sphere and the columns are completely meshed with the belytschko-Tsay shell elements with three integration points through thickness.

The mesh of the central part of the sphere is finer than the others parts in order to increase the precision at the connection between the sphere and the columns.

Reinforcement bars are modeled using fully integrated beam elements. Fifteen elements are used for each bar in order to represent correctly their buckling in case of compression.

The LPG is represented by lumped mass elements assigned to nodal points corresponding to the volume of the sphere.

The model contains 12956 shell elements and 210 beam elements.

The model is presented on figure 4.

Material models

The sphere and the columns are modeled using the LS-DYNA material MAT_PLASTIC_KINEMATIC (material type 3). An isotropic hardening behavior of this material was considered for the most of the calculations. However, the kinematic hardening option has been also tested.

The material used for the reinforcement bars is the material MAT_PLASTIC_KINEMATIC (material type 3) with a null tangent modulus.

The connection of the reinforcement bars to the columns is modeled using rigid wings to avoid stress concentrations.

A Rayleigh damping coefficient (stiffness damping) is defined for all the structure in order to obtain 4% of critical damping for the main frequency of vibration.

Boundary condition and Loading

The base of all columns is assigned to a rigid material which has all the rotation and translation degrees of freedom constrained.

The columns are tied to the sphere using CONTACT_TIED.

In a first step, gravity and internal pressure loads are applied to the structure. A mass damping is used for all the structure parts for the stabilization of the response.

After this static loading, the three components x, y, z of each seism are applied as a prescribed displacement via the rigid body attached to the base of columns.

Numerical simulations have been performed on the duration of each accelerogram : from 15 s to 30 s.

Parametric Analysis

In order to justify the validity of results, a parametric study was carried out to determine the influence of a number of parameters for which uncertainties exist. Three primary parameters have been extracted :

I. *Seismic accelerogram* : three real earthquakes have been studied :

1. Loma Prieta seism with a duration of 30 s,
2. Irpinia seism with a duration of 26 s,
3. San Fernando seism with a duration of 15 s.

Figures 5 6 7 show the accelerograms and spectra for the three components of each seism.

II. *Hardening behavior* of the sphere and columns : isotropic or kinematic,

III. *Yield stress*, σy, for the sphere and columns.

In order to check if the reinforcement bars act upon the structure behavior, another run has also been performed without the reinforcement bars for the Loma Prieta seism.

The following table presents the list of runs performed for the parametric study:

Run	Seism	Hardening behavior	σy	Reinforcement bars
1	Loma Prieta	isotropic	initial	yes
2	Loma Prieta	isotropic	+10%	yes
3	Loma Prieta	isotropic	+20%	yes
4	Loma Prieta	Isotropic	+30%	yes
5	Loma Prieta	isotropic	+50%	yes
6	Loma Prieta	kinematic	initial	yes
7	Loma Prieta	isotropic	initial	no
8	Irpinia	isotropic	initial	yes
9	Irpinia	isotropic	+20%	yes
10	San Fernando	isotropic	initial	yes

Table 1 : parametric study runs

Results

* The following table shows the results obtained for different earthquakes :

	f (Hz)	Maximum Plastic strain (%)			Maximum relative displacement of the top of the sphere (mm)			Bars lengthening (mm)
		Column parts higher	Column parts lower	Sphere	Along X	Along Y	Along Z	
Run 1: Loma Prieta	0.9	3.3	1.8	0	85	43	4.5	13→46
Run 8: Irpinia	0.9	6.4	3.8	0	84	78	7	13→46
Run 10: San Fernando	1.00	0.6	0.4	0	48	12	1	5→25

Table 2 : Results obtained for different earthquakes

Higher levels of displacement and deformation are obtained for the Loma Prieta and Irpinia seisms. This is due to the fact that the acceleration level is higher on their spectra, in the range of the principal frequency of the structure (0.9-1.0 Hz).

* The following table shows the results of the two calculations with and without the reinforcement bars:

	f (Hz)	Maximum Plastic strain (%)			Maximum relative displacement of the top of the sphere (mm)			Bars elongation (mm)
		Column parts higher	Column parts lower	Sphere	Along X	Along Y	Along Z	
Run 1	0.9	3.3	1.8	0	85	43	4.5	13→46
Run 7	0.8	3.8	2.1	0	116	32	4.5	-

Table 3 : Results with and without the reinforcement bars

The reinforcement bars seem to have a small effect on the behavior of the structure. This shows that the bars are under-dimensioned for the applied seismic loads. Even, the failure of all bars would not affect significantly the dynamic response of the sphere.

* The following table shows the results obtained for different values of yield stress, sy, of the sphere and columns :

	F(Hz)	Maximum Plastic strain (%) Column parts higher	lower	Sphere	Maximum relative displacement of the top of the sphere (mm) Along X	Along Y	Along Z	Bars elongation (mm)
Run 1	0.9	3.3	1.8	0	85	43	4.5	13→46
Run 2, σ_y+10%	0.9	3.4	1.7	0	85	46	4	16→47
Run 3, σ_y+20%	0.9	4.4	1.6	0	85	48	3.5	21→46
Run 4, σ_y+30%	0.9	5.7	2.1	0	84	51	3	22→44
Run 5, σ_y+50%	0.9	6.3	2.5	0	87	50	2	21→46
Run 8	0.9	6.4	3.8	0	84	78	7	13→46
Run 9, σ_y+20%	0.9	4.8	2.3	0	69	57	4	15→38

Table 4 : Results for different values of yield stress

Variations of the yield stress change the post-elastic stiffness and behavior of the global structure in different directions. Local plastic strains obtained at the top and the base of the columns change according to yield stress values, but the maximum values (about 6%) are rather small comparing to the failure limits of materials.

No plastic strain is obtained in the sphere in all cases.

* The following table shows the results obtained for different hardening options:

	f (Hz)	Maximum Plastic strain (%) Column parts higher	lower	Sphere	Maximum relative displacement of the top of the sphere (mm) Along X	Along Y	Along Z	Bars elongation (mm)
Run1 Isotropic behavior	0.9	3.3	1.8	0	85	43	4.5	13→46
Run 6 Kinematic behavior	0.9	4.0	2.0	0	86	43	4.5	14→46

Table 5 : Results for different hardening options

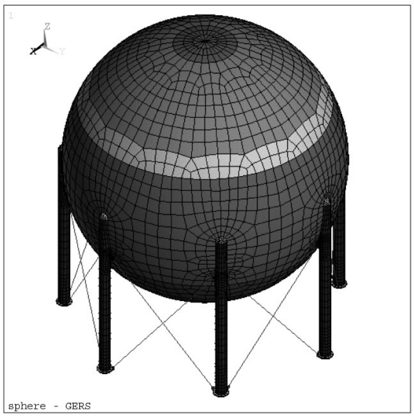
The hardening behavior has not significant effects on the structure because of small level of plastic strains obtained in all the columns and the sphere.

The results obtained for the run 1 (reference case) are shown in the following figures:

- Plastic strain of the lower and higher parts of the columns; Figure 8
- Total displacements of the top of the sphere compared to the ground displacements; Figure 9
- Time plots for the maximum plastic strain obtained in the columns; Figure 10
- Time plots for axial stress obtained in a reinforcement bar; Figure 11

Modal Spectral Results and Reduction Factors

Modal spectral analysis was conducted for the regulatory spectrum and for all Loma Prieta spectra.



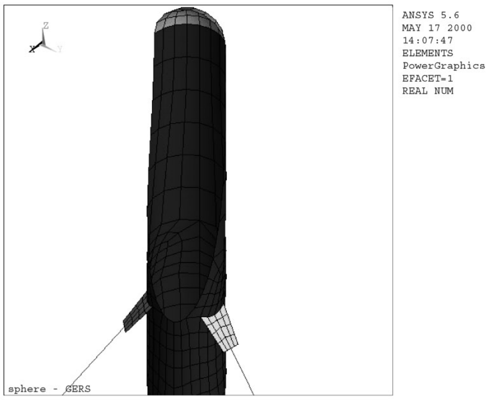


Figure 3 : Finite element model for modal spectral analysis

The table here after summarizes the main results :

Element	Elastic limit	Loma Prieta spectrum	Regulatory spectrum
Braces	225 Mpa	749 Mpa	893 MPa
Columns (top)	320 Mpa	483 Mpa	570 MPa
Columns (bottom)	235 Mpa	377 Mpa	440 MPa
Sphere	320 Mpa	272 Mpa (1)	318 MPa (1)
Displac.		60 mm	75 mm

(1) values without internal pressure

In terms of reduction factor, we should use for each element the following values :

Element	Loma Prieta spectrum	Regulatory spectrum
Braces	3.3	4.0
Columns (top)	2.0	2.4
Columns (bottom)	2.3	2.7
Sphere	2.6	3.0

Conclusion

In dynamic nonlinear analysis, the plastic strain levels obtained in the columns are small in a general manner in all simulations. The maximum values are about 6%, under the failure limits of the steel (between 21% and 26%). No plastic strain is observed in the sphere in all cases. The equipment resists very well to the applied seismic loads by generating small plastic strains in local regions.

On the other hand, the modal spectral analysis shows that a reduction factor of 2.3 should be used to find acceptable stresses in columns (2.7 for regulatory spectrum). To have acceptable stresses in the sphere, a value of 2.6 is necessary (3.0 for regulatory spectrum). For braces, necessary values of reduction factor are 3.3 or 4.0.

Looking at plastic strain levels obtained by dynamic nonlinear analysis, it is easy to conclude that the needed reduction factors after the modal spectral analysis are minimum values that we can consider to justify the seismic behavior of the equipment. Higher values could be probably proposed for this type of equipment.

These calculations were performed for a specific equipment. To define general values of reduction factor for spherical tanks, it is needed to perform other calculations for several equipments having different types and sizes.

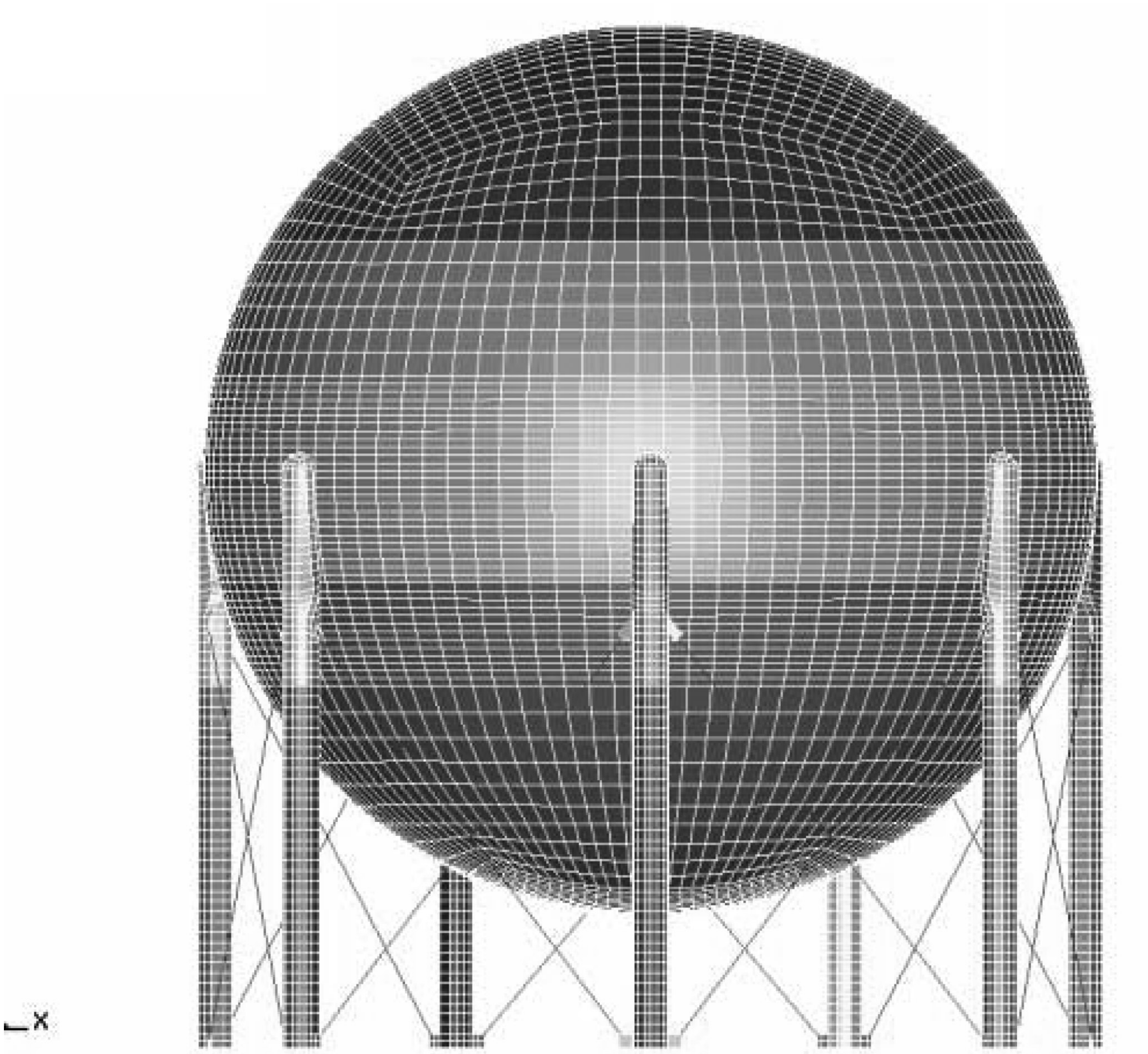


Figure 4 : Model

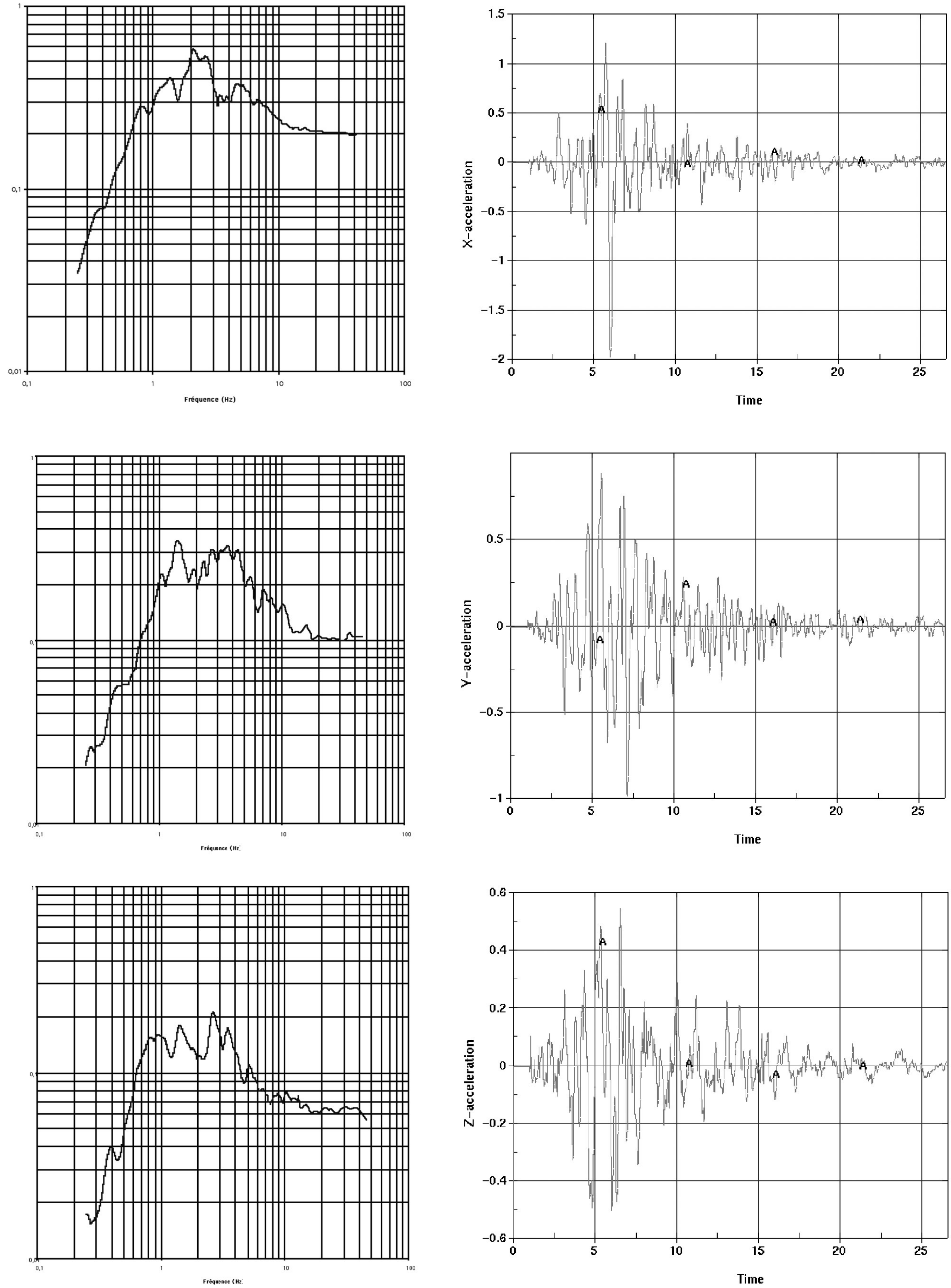


Figure 5 : Loma Prieta Seism ; accelerograms (m/s²) and spectra (g)

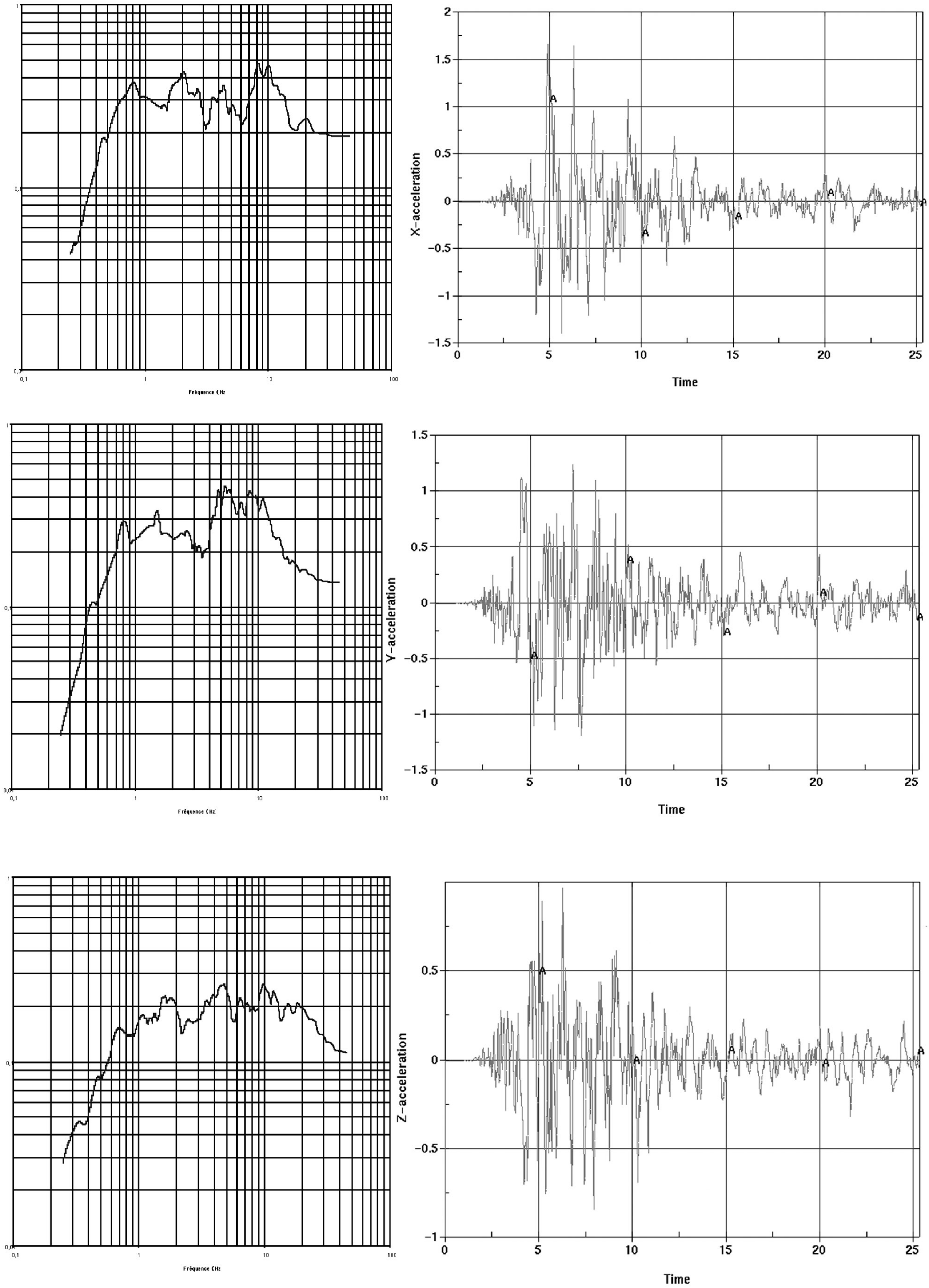


Figure 6 : Loma Irpinia Seism ; accelerograms (m/s²)and spectra (g)

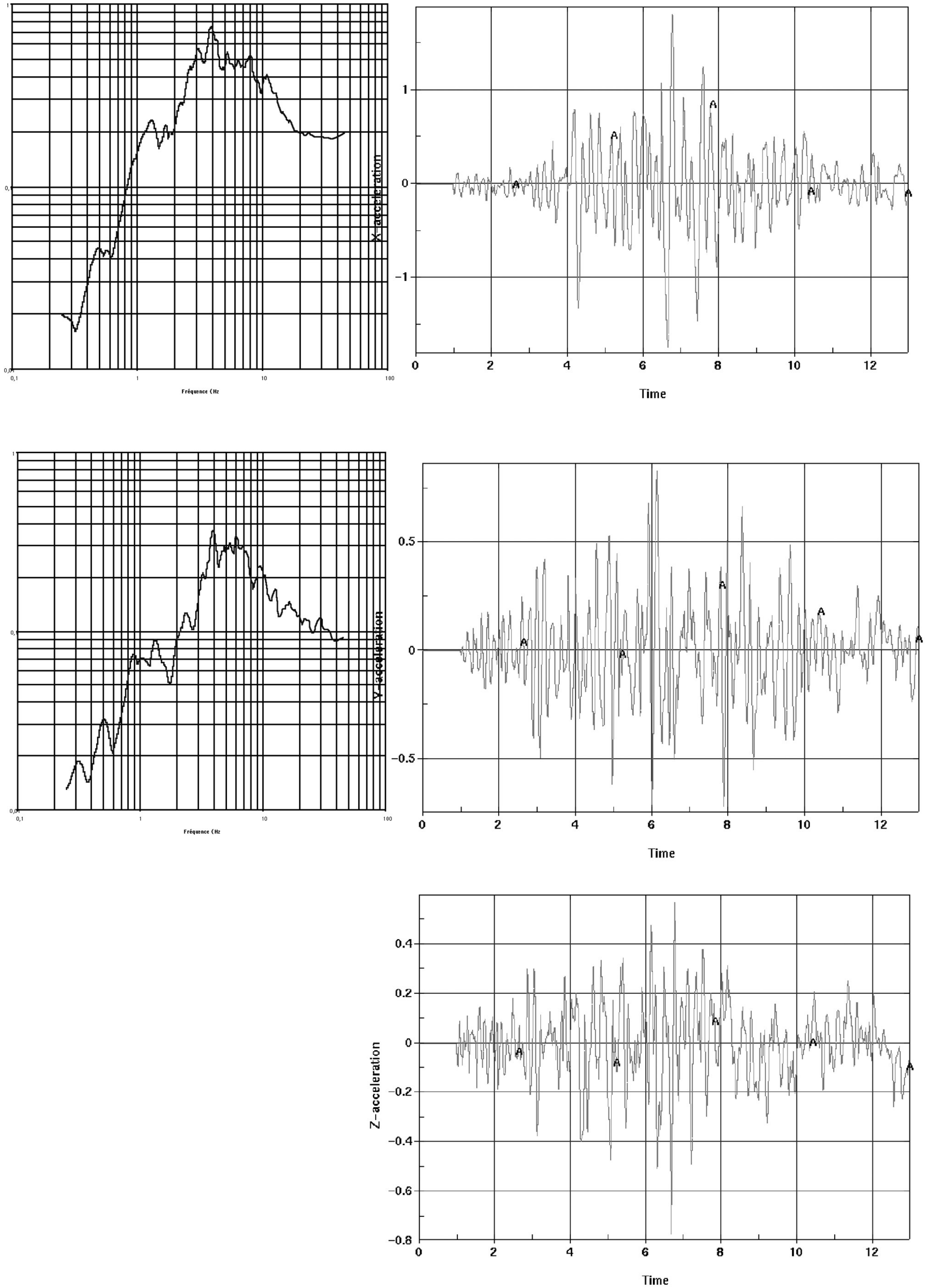


Figure 7 : San Fernando Seism ; accelerograms (m/s²) and spectra (g)

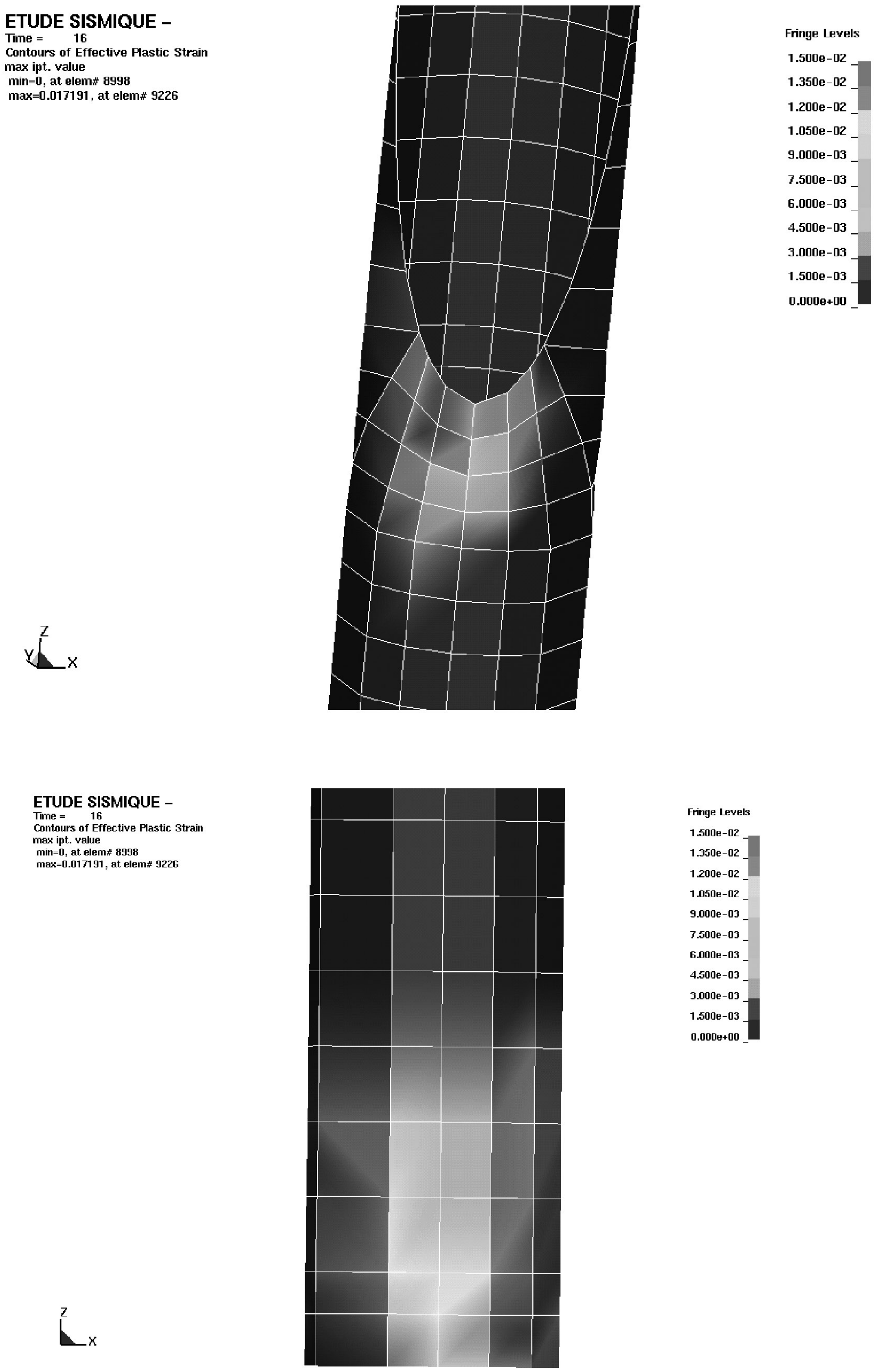


Figure 8 : Plastic strain of the lower and higher parts of the columns

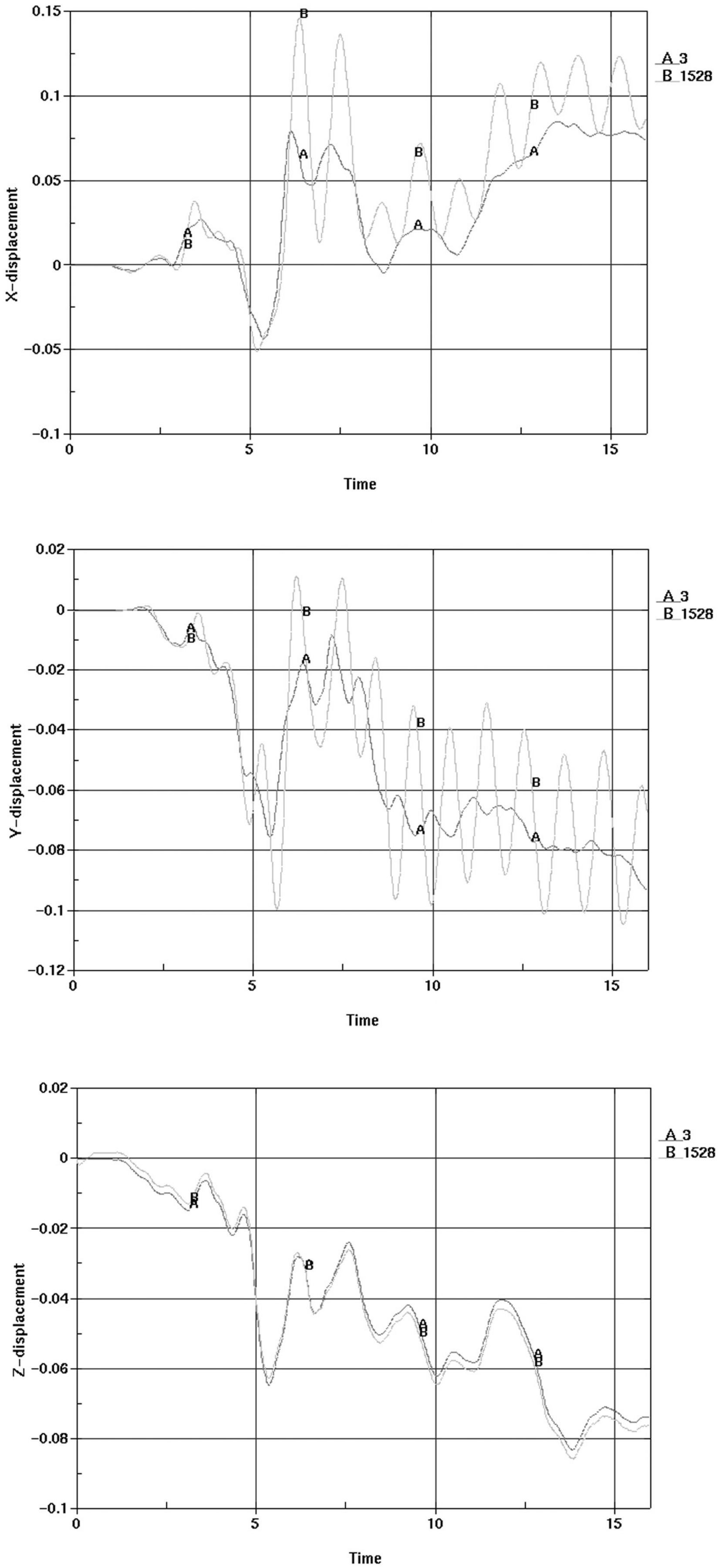


Figure 9 : Total displacements of the top of the sphere compared to the ground displacements (mm)

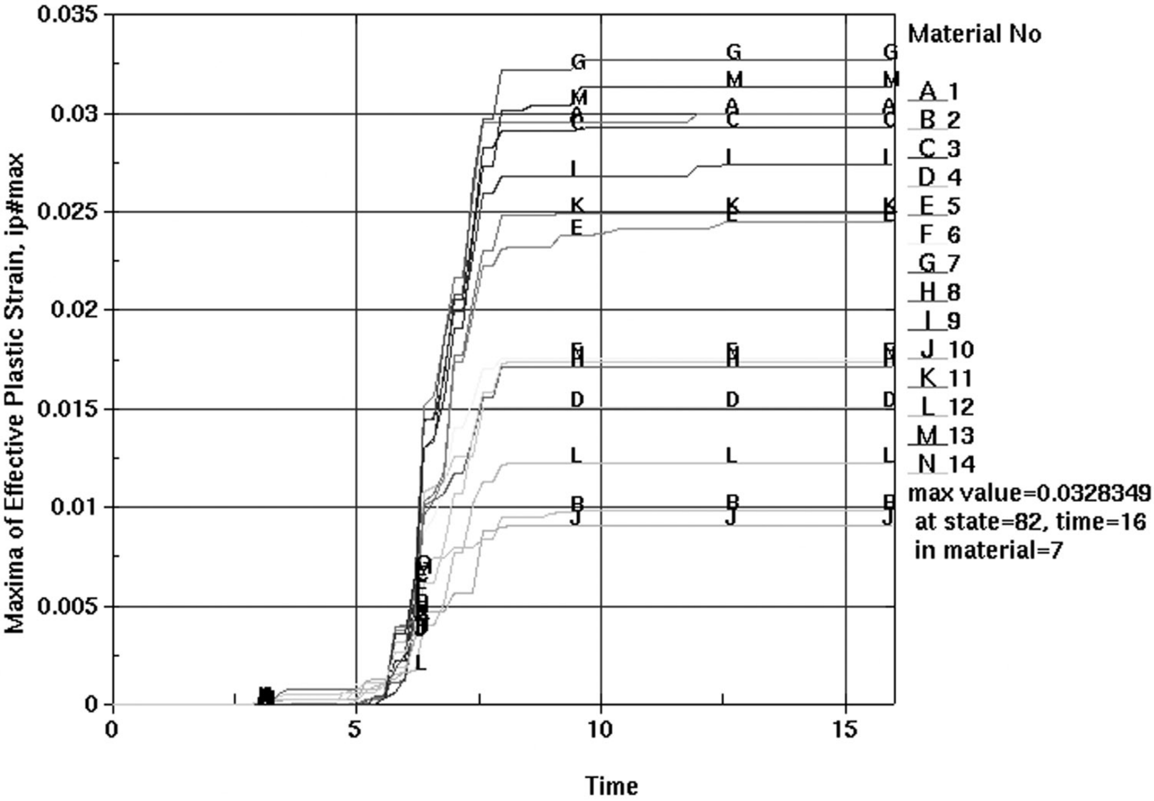


Figure 10 : Time plots for the maxima of effective plastic strain function obtained in the columns

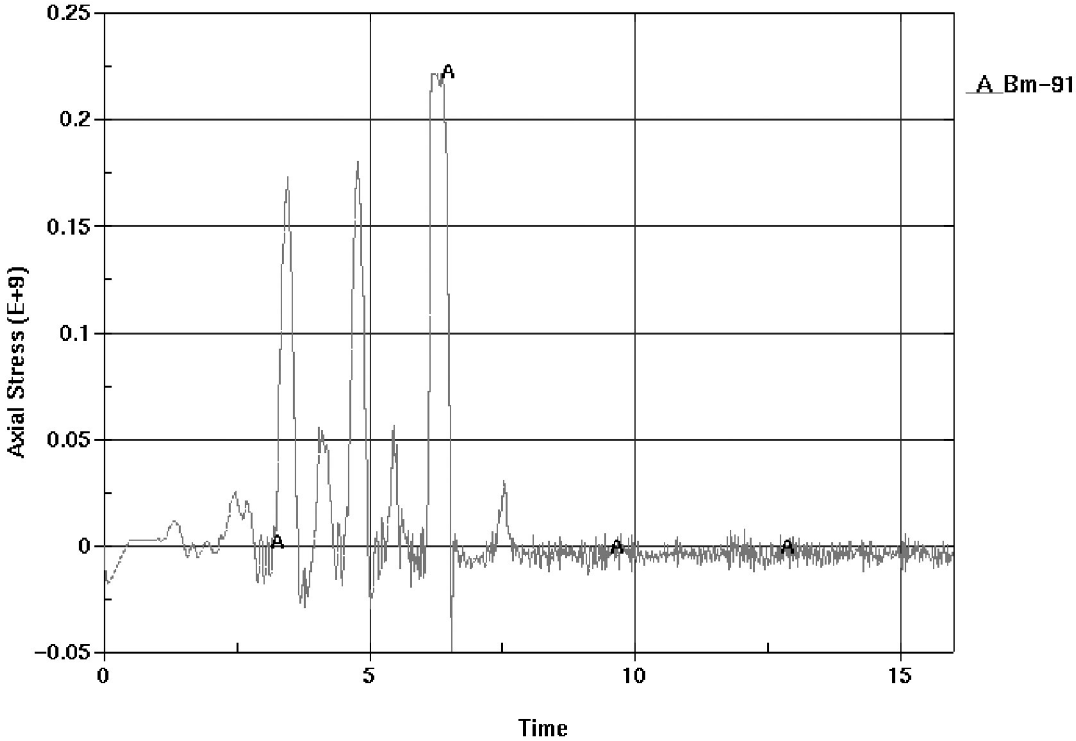


Figure 11 : Time plots for axial stress obtained in a reinforcement bar (Pa)