ON THE SEISMIC LOADING OF LARGE ENVIRONMENTAL CONTROL EQUIPMENT

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Abstract. *In recent years, the Brazilian Mechanical Engineering Community has been in charge of the design and manufacturing of large Environmental Control Equipment deployed in the Latin American Countries of the Pacific Coast. In such sites, seismic excitation is a foremost concern in the structural analysis of those machines.*

In this paper, we analyze a few national codes of those countries, usually intended for high-rise buildings analysis, not for mechanical equipments, and offer some guidelines on how to apply them to this class of structural problems.

One special interest is on whether to perform full-fledged dynamic structural analysis via Finite Element Codes or to use pseudo static loadings. This is of special interest in the preliminary phases of those projects when quick technical and business decisions must be taken.

Keywords*: structural dynamics, seismic excitation, environmental control equipment*

1. INTRODUCTION

In recent years, the Brazilian Mechanical Engineering Community, as is the case of the authors, has been in charge of the design and manufacturing of large Environmental Control Equipment deployed in the Latin American Countries of the Pacific Coast. In such sites, seismic excitation is a foremost concern in the structural analysis of those machines.

The considered equipments are usually Electrostatic Precipitators, ESP's, dedicated to capture and disposal of particulate materials present in industrial gaseous effluents.

In this paper, we present the relevant theoretical background and analyze a few national codes of the aforementioned countries, usually intended for high-rise buildings analysis, not for mechanical equipments, and offer some guidelines on how to apply them to this class of structural problems, as well as suggest some devices to mitigate the effects of strong seismicmotions.

One special interest is on whether to perform full-fledged dynamic structural analysis via Finite Element Codes or to use pseudo static loadings. This is of special interest in the preliminary phases of those projects when quick technical and business decisions must be taken.

We organized this paper as follows: in the second section we present the relevant theoretical background on structural dynamics; next, we present an overview of some Latin American seismic design codes; the forth section presents our comments and proposals on how to apply the subject to large environmental control equipment; in the end we make some final remarks and conclusions.

2. THEORETICAL BACKGROUND

The dynamic analysis of structures subjected to strong seismic motions, discretized as *n*-degrees-of-freedom mathematical models, can be put in matrix form, see e.g. Clough and Penzien (1976), as:

$$\mathbf{M}\ddot{\mathbf{u}}(t)+\mathbf{C}\dot{\mathbf{u}}(t)+\mathbf{K}\mathbf{u}(t)=\mathbf{f}(t) \tag{1}$$

where **M**, **C** and **K**, are, respectively, the *n* x *n* mass, damping and stiffness matrices, and $\mathbf{u}(t)$ is the *n* x *1* vector of generalized coordinates, superposed dots indicating successive derivation with respect to time. The applied force vector $\mathbf{f}(t)$, in this case of support motions, is given by

$$\mathbf{f}(t)=-\mathbf{M}1\ddot{u}_g(t) \tag{2}$$

where **1** is a *n* x *1* vector containing the number 1 in all entries and $\ddot{u}_g(t)$ is the adopted scalar ground acceleration time history of the seismic motion.

The problem is: what should be the time history to be adopted in project? The analysis is obviously one of random vibrations and no such choice among available past earthquakes would be a completely valid one.

As a short cut to the solution of this situation, most building codes adopt the so-called Elastic Response Spectra approach. A one-degree of freedom vibratory system is put in the form:

$$\ddot{u} + 2\xi\omega\,\dot{u} + \omega^2 u = -\ddot{u}_g \tag{3}$$

where ξ is the damping ratio, ω is the natural frequency of undamped vibrations of the system, and $\ddot{u}_g$ is an adopted acceleration time history, usually an averaged one from several previous earthquakes in the studied area.

To generate an Elastic Response Spectrum, we must fix a certain damping ratio and make the natural frequency vary in a step-by-step fashion along a certain band of values of interest. For each such value, we must numerically integrate Eq. (3) for the whole adopted acceleration time history. The resulting spectrum is just a plot of the maximum obtained structural acceleration for each run against the natural frequencies. The basic idea is: for a certain real structure we compute its natural frequency and get the correspondent maximum amplitude of structural acceleration $\ddot{U}$ from the spectrum graphic. If we suppose the response motion to be harmonic at the same frequency of the structure we will have:

$$\dot{U} = \frac{1}{\omega} \qquad U = \frac{1}{\omega^2}\ddot{U} \qquad F = M\ddot{U} \tag{4}$$

for the amplitude of the structural velocity, displacement and elastic force, respectively.

For *n*-degrees-of-freedom mathematical models, the same approach may be applied to each of the *n* vibration vector modes $\boldsymbol{\phi}_r$ with their frequencies ω_r (r = 1,…,n). The usual mode superposition technique is applied. First, modal masses and modal loads are computed:

$$M_r = \boldsymbol{\phi}_r^T \mathbf{M} \boldsymbol{\phi}_r = \sum_{i=1}^{n} m_i \phi_{ir}^2, \qquad r = 1,\ldots n$$

$$P_r = \boldsymbol{\phi}_r^T \mathbf{p} = -\ddot{u}_s \sum_{i=1}^{n} m_i \phi_{ir} \qquad r = 1,\ldots n \tag{5}$$

Next we write the *n* uncoupled equations of motions for de modal dynamics:

$$\ddot{y}_r + 2\xi_r\omega_r\dot{y}_r + \omega_r^2 y_r = P_r / M_r \qquad r = 1,\ldots n \tag{6}$$

that, for seismic loading is

$$\ddot{y}_r + 2\xi_r\omega_r\dot{y}_r + \omega_r^2 y_r = -\ddot{u}_s \frac{\sum_{i=1}^{n} m_i\phi_{ir}}{\sum m_i\phi_{ir}^2} \tag{7}$$

The modal maximum acceleration for each mode is then obtained from the adopted Elastic Response Spectrum and the maximum modal displacement will be:

$$U_r = \frac{1}{\omega_r^2}\ddot{U}_r \frac{\sum_{i=1}^{n} m_i\phi_{ir}}{\sum_{i=1}^{n} m_i\phi_{ir}^2} \tag{8}$$

Modal superposition is then applied to compute maximum displacements in the original physical coordinates. It is a well-known fact that only a very small number of lower modes, usually only the first one, must be kept in the analysis. Further, it is not reasonable to expect that all the considered modes will reach their maximum amplitude at the same time, leading to the use of some method to take this into account such as the Square Root of the Sum of Squares of the maximum amplitudes:

$$U = \sqrt{\sum_{r=1}^{k} U_r^2} \tag{9}$$

3. AN OVERVIEW OF SOME LATIN AMERICAN DESIGN CODES

In this section we present an overview of the proposed Elastic Response Spectra of two Latin American design codes: a recently proposed Brazilian seismic structural analysis code, ABNT (2006) and the Venezuelan seismic design national code, FUNVISIS (2001).

The seismic excitations given in such codes is a product of the weight (mass times the acceleration of gravity) of the considered part of the structure by a factor that is a function of several characteristics of the problem, as follows.

a) Importance of the building

Classification is made in groups (usually 3): first the very important ones, such as hospitals, power plants, telecommunications centers, etc; second, the common buildings, such as commercial, industrial and residential ones; next the others.

b) Intensity of seismic activity in the region of the structure

Given by maps displaying zones (usually 4) of seismic activity for each country. We present sample maps for Brazil (Fig. 3.1) and Venezuela (Fig. 3.2). The graphs have captions in the original languages, Portuguese and Spanish, respectively.

c) Soil characteristics

Classification is usually made in 3 types, according to the stiffness and damping characteristics of the several soils.

d) Strength and ductibility characteristics of the structure

In this classification the codes list the several kinds of structural systems, taking into account: the materials they are built of and their capacity to dissipate energy; the presence of stiffeners such as portal frames, walls, etc.

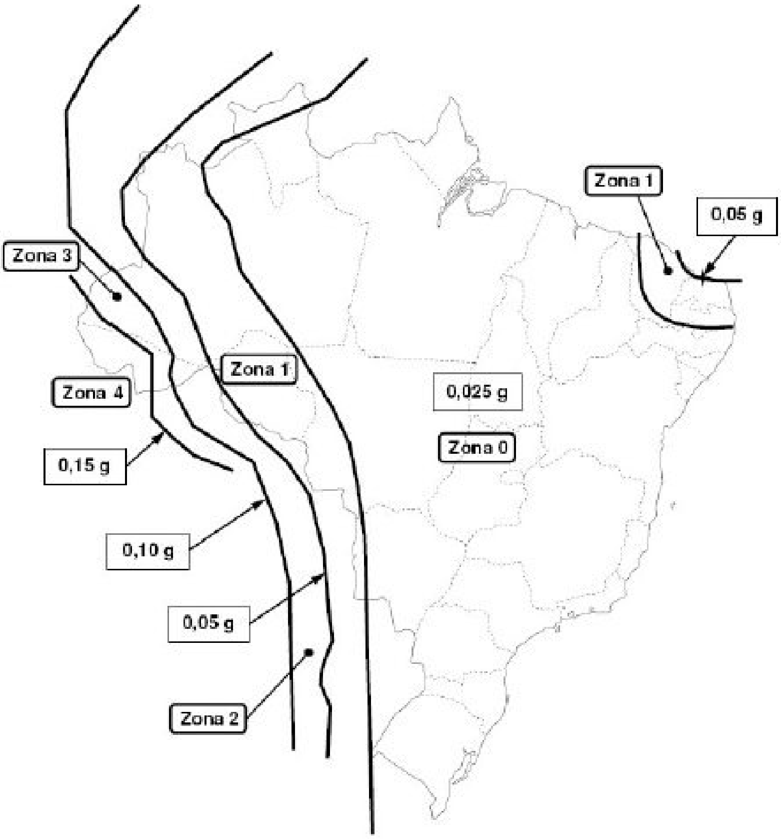
e) Vibration period or frequency of structure or considered mode.

All these aspects are reflected in the provided Response Spectra. We present sample Spectra for Brazil (Fig. 3.3) and Venezuela (Fig. 3.4). The graphs have captions in the original languages, Portuguese and Spanish, respectively.

About the methods of analysis, the design codes usually suggest the use of four different schemes, as follows.

- Simplified method, for low rise structures, admissible up to 13m, usually;
- Static method, for medium rise structures, between 13 m and 60 m;
- Spectral dynamic analysis, for all kinds of structures of linear behavior;
- Step-by-step time history integration, for all kinds of structures, linear or non-linear.

In our view, for the class of structures we deal with, it is enough to apply simple static analysis using equivalent loading resulting from the multiplication of the factors given by the Elastic Response Spectra by the acceleration of gravity and the mass of the analyzed part of the equipment or to the overall bulk of the ESP as a lumped mass mounted on a support structure, as we comment and explain in the next section of this paper. We do not find it necessary to apply to this class of structures a full dynamic Finite Element analysis, neither a spectral one nor a step-by-step time history integration one, linear or non-linear.



Zona sísmica	Valores de a_g
Zona 0	$a_g = 0{,}025g$
Zona 1	$0{,}025g \leq a_g \leq 0{,}05g$
Zona 2	$0{,}05g \leq a_g \leq 0{,}10g$
Zona 3	$0{,}10g \leq a_g \leq 0{,}15g$
Zona 4	$a_g = 0{,}15g$

Figure 3.1. Seismic regions in Brazil

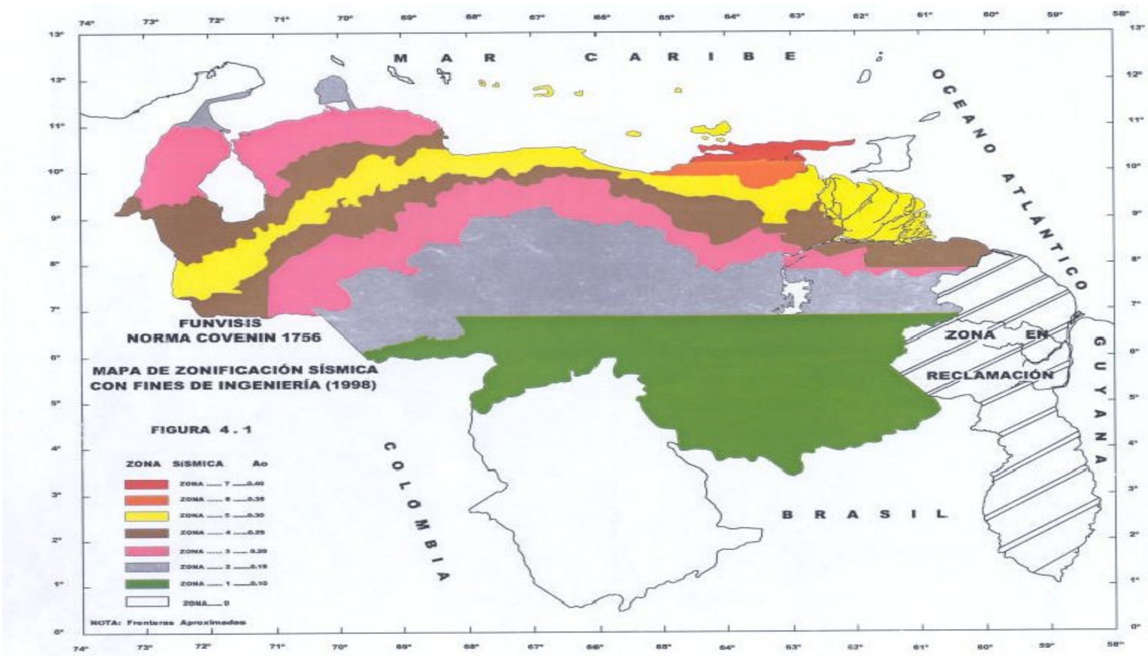


Figure 3.2. Seismic regions in Venezuela

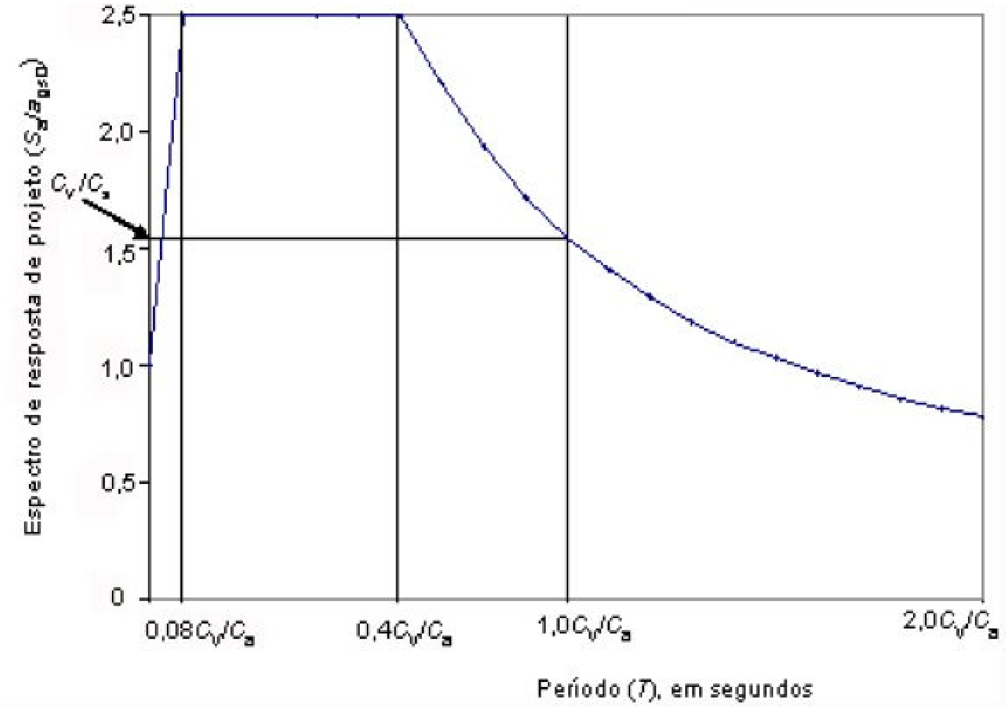


Figure 3.3. Elastic Response spectrum of Brazilian seismic design code

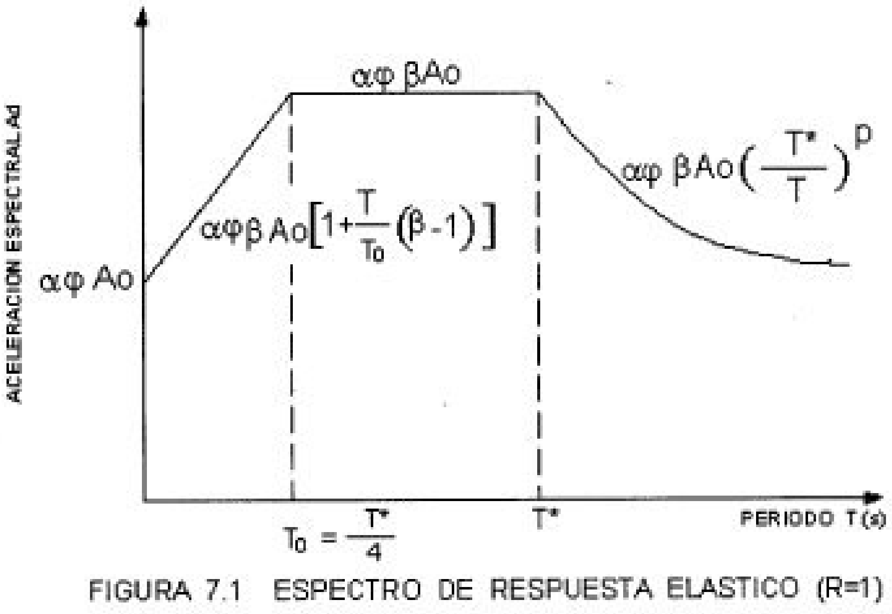


Figure 3.4. Elastic Response spectrum of Venezuelan seismic design code

4. APPLICATION TO ELECTROSTATIC PRECIPITATORS

In this section we present the usual structural models for Electrostatic Precipitators, ESP's, and our view on how to apply seismic codes recommendations to this class of mechanical structures.

Structurally, ESP's are basically large roughly cubic metal boxes to house a system of high-tension discharge and collection electrodes. Due to the so-called *corona effect*, the latter are in charge of capturing the particulate materials present in industrial gaseous effluents. Both systems hang freely from the ceiling beams of the boxes. This assemble of hanging electrodes have very low undamped free vibration frequencies, way out of the band of frequencies where significant energy is present in seismic excitation spectra.

In the other hand, the structure of the metal box is itself fairly rigid as the main concern in their design is to avoid large displacements that could impair the proper performance of the electrostatic process, as the *corona effect* is quite sensitive to very small changes in the distance between the electrodes. Typically, the resulting stresses are very low and relative displacements one order of magnitude smaller than the usually accepted values for Civil Engineering structures. That implies in very high frequencies, also reasonably out of the band of frequencies where significant energy is present in seismic excitation spectra.

Due to the usual input and output gas ducts lay out, the machines are usually built on relatively tall spatial portal frames. Thus, we usually have a considerable mass lumped at a high center of mass, as in an inverted pendulum. So, it is to the global structural model that one should apply the seismic codes dispositions.

Internal parts of ESP's are usually modeled as point masses at their appropriate level under seismic excitation. Some seismic restrain devices for the internals of ESP´s must be added to keep the collecting plates in their right positions under these motions. The discharge elements cannot be supported in the same way due the electrical short cut, but the mass of these electrodes is rather small so there is no big damage expected if they should shock against collecting plates. There are usually around 100 mm free spaces between collecting and discharge electrodes so the possibility of this kind of collision is rather small.

Obviously, in case of earthquake, the precipitators need to be switched off, what normally happens automatically by the ESP's control units in order to avoid the short cuts and flashing that may occur if the spacing between collecting plates and discharge electrodes get smaller (as the process is based in high electric tension difference between these electrodes).

Internal parts must, of course, be checked for seismic actions and all necessary reinforcements for seismic resistance be designed. Some parts cannot be fully seismic resistant, so that some minor damages during major earthquakes can be expected. In general, the main components of precipitator, as collecting plates and discharge electrodes, cannot be designed so strong that they can support all seismic actions. The dimensions and necessary spacing due to high tension do not allow the use of any seismic stoppers at collecting/discharge system area. The collecting electrode shape must be also carefully chosen to guarantee perfect performance under the rapping and dust collecting so it can not be made any more strong. These collecting electrodes are not capable to support loads due to accelerations in excess of approximately 0.2 g. The discharge electrodes can not be fixed in such way that they can not move under of seismic action in order not to shock against the collecting electrodes, but as these discharge electrodes are relatively light components severe damages are not expected due this kind of collision. We present in Fig. 4.1 a sample detail of seismic stoppers that allow the rapping to freely work by guiding the upper and bottom support for collecting system. There are some small caps around these guides.

As seismic stopper are added to the collecting supports, the supporting main roof beam of the metal box of the ESP bottom flange will suffer some horizontal loads due the seismic actions. Those flanges are to be checked for these loads. The mass of one collecting system can usually be around 35 tons. That mass must be multiplied by the acceleration given by the adopted Response Spectrum. A sample detail of reinforcements is shown in Fig. 4.2

The high strength ceramic support insulators, from which the emission electrodes hang, are usually designed to carry only vertical forces, but due to their conical shape they are also capable of carrying considerable horizontal loads. We show, in Fig.4.3, a sample output of a Finite Element seismic analysis, using shell elements, of one such isolator.

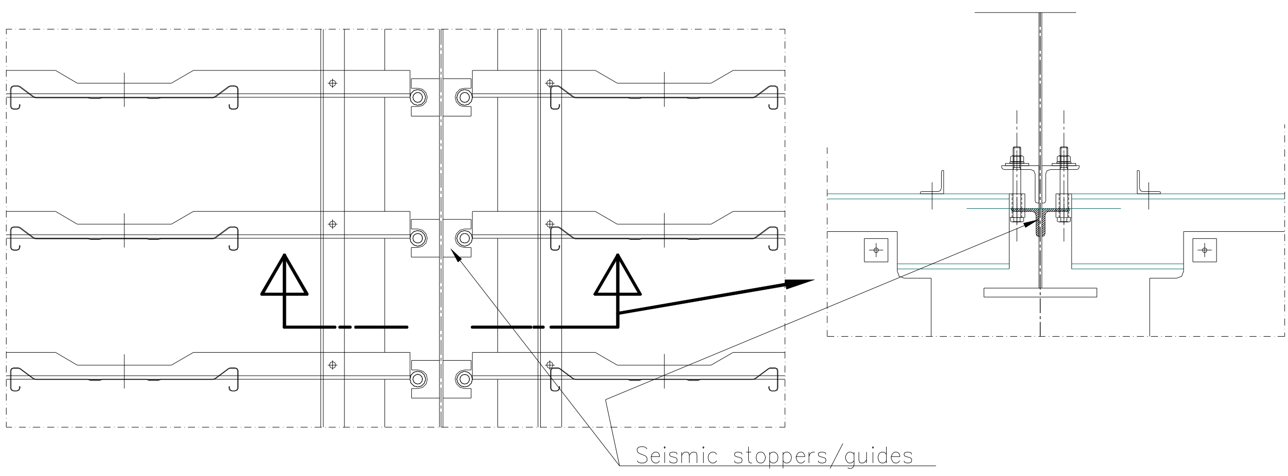


Figure 4.1. Sample detail of seismic stoppers/guides

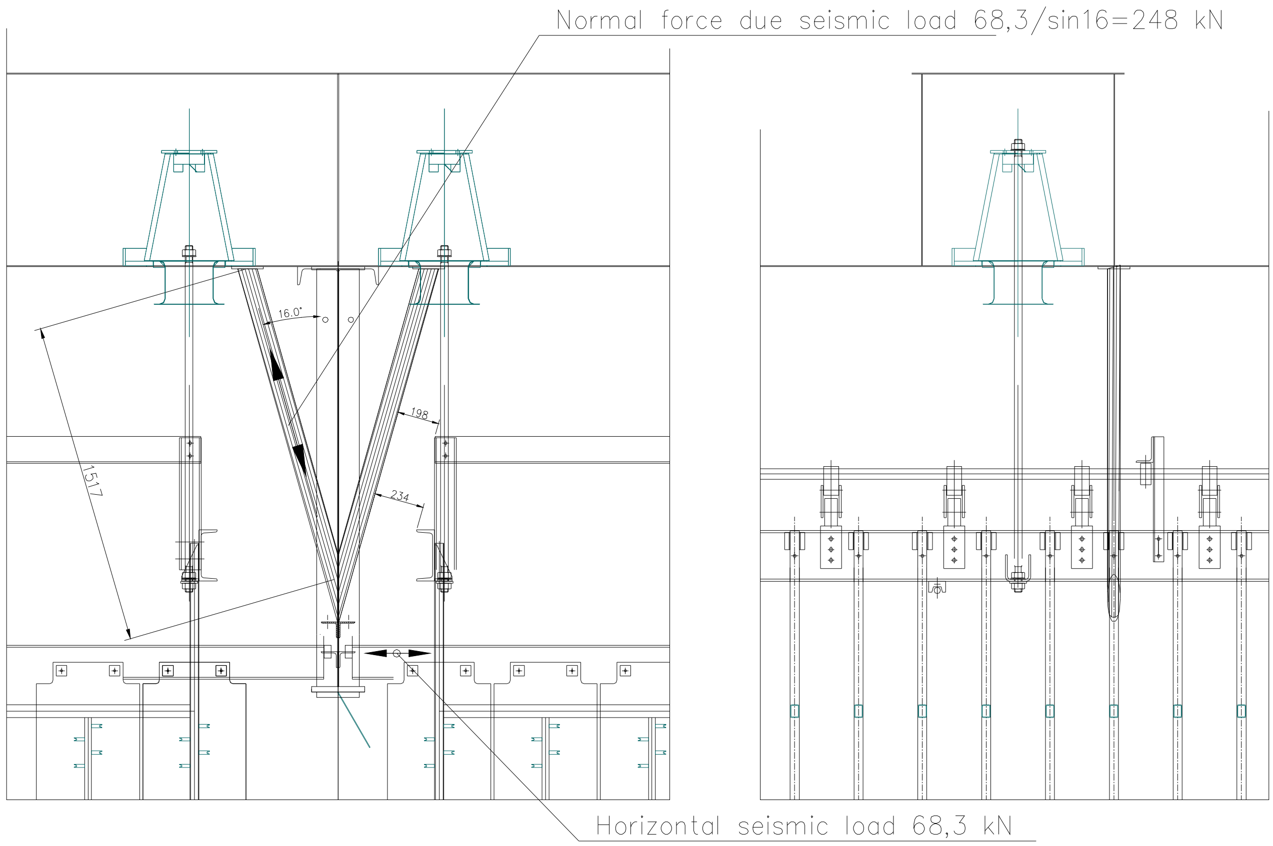


Figure 4.2. Typical detail of roof beam flange reinforcement

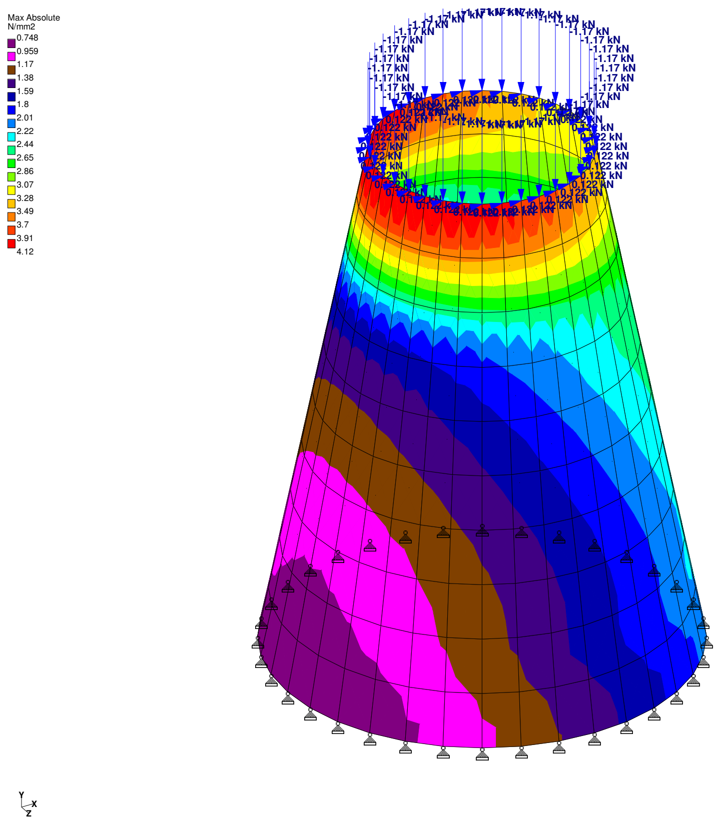


Figure 4.3. Sample output of seismic FEM analysis of ceramic isolator

5. FINAL REMARKS AND CONCLUSIONS

In this paper, the authors, professionally involved in the design of large Electrostatic Precipitators, ESP's, present their view on how to design such machines to seismic excitation, as required when they are to be deployed in Latin American countries where this kind of loading must be considered.

The national design codes are usually intended for high-rise buildings and not for this kind of equipments. They all prescribe the so-called Elastic Response Spectra that take into account: importance of the construction; geographic location; soil characteristics; structural characteristics; and fundamental periods of the structural system. Thus, these spectra are given as a function of these parameters. They provide a factor to be multiplied by the acceleration of gravity and the mass of the analyzed part of the structure to render an applied force to be used in a static structural analysis. No complete dynamic Finite Element analysis is considered necessary by the authors.

Structurally, ESP's are basically large roughly cubic metal boxes to house a system of high-tension discharge and collection electrodes. Due to the so-called *corona effect*, the latter are in charge of capturing the particulate materials present in industrial gaseous effluents. Both systems hang freely from the ceiling beams of the boxes. This assemble of hanging electrodes have very low undamped free vibration frequencies, way out of the band of frequencies where significant energy is present in seismic excitation spectra.

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In this paper we also suggest some devices that may be used to improve the structural performance of the internal parts of ESP's under strong seismic motions and mitigate their effect.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

ABNT, 2006, Projeto 02:122.15-001 " Projeto de estruturas resistentes a sismos - procedimento", ABNT, Rio de Janeiro, 2006.

Clough, R.W., Penzien, J. 1976, "Dynamics of Structures", McGraw-Hill, New York, 428 p.

FUNVISIS, 2001 "Edificaciones Sismorresistentes" , FONDORAMA, Caracas, 2001

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