

# Floor response spectra – new proposal of a simplified methodology to define seismic force on equipment

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## Abstract

The main requirement of actual seismic building codes is the preservation of human lives and the limitation of damage. These requirements are obviously applied to structural elements, but work has to be done in order to adapt the building codes for non-structural elements. Indeed, feedbacks from past earthquakes reminds us that, if not properly connected to the main building, the non-structural elements or equipment can be heavily damaged or become deadly weapons (and even block the emergency process).

However, for these non-structural elements, a global analysis of the whole structure with structural and non-structural elements is rarely possible, for three main reasons: (1) the equipment or/and non-structural element is barely known when the structure is designed, (2) there is a lack of knowledge of physical and mechanical characteristics for non-structural element or equipment (or of the existing building) and (3) to include all the non-structural elements or equipment in a model will make it much too complex.

Nevertheless, the interaction between the equipment or the non-structural element and the structure exists. This paper aims at: (1) presenting the specific issues of the design of such elements (including the business continuity), (2) explaining the physical phenomena, (3) proposing different types of calculation / model according to the type of structure and the study's level. At least, the formulation of Eurocode 8 is presented and discussed as it seems not appropriate for the design of equipment. A new simplified formulation is proposed as an alternative to calculate the lateral force applied to the non-structural element or equipment.

The general methodology is presented at first with its domain of validity. Then this formulation is compared to an analytical study and finally, to foreign regulations. The main objective is to provide a simplified formulation which will be easily applicable by engineers as well as "owners" if they need to add an equipment later.

Keywords: non structural element, simplified formulation, floor response spectra,



# 1. Introduction

Even if avoiding the structural collapse is the main purposes of earthquake standards (preservation of lives), the collapse of non structural elements is an important issue in order to reach the goal of life preservation. Indeed, life preservation and rescue service circulation during and after earthquake depend mainly of the resistance of the non-structural elements and their connections. These criteria (regarding nonstructural elements) are included in current seismic codes [1], [2], [3][4]. The main difficulty, when studying non-structural elements, lies in the diversities of the phenomena to take into account (type of equipment / non-structural element, building behavior, knowledge regarding the support or the building, nonlinear mechanical behavior...).

This issue concerns all types of structures, including typical residential buildings, schools or administrative offices as well as industrial buildings. Indeed, this study aims to propose a simplified formulation of the lateral force applied to a non-structural element or equipment (including architectural element / nonstructural elements / equipment). Thereafter, we will use for all the non-structural elements or equipment the generic term "*elements*". At first, this study presents the usual requirements for non structural elements, in terms of actions, strength criteria, applicability, level of knowledge or not on mechanical characteristics in building design process [5]. In a second time, the general approach of such a study is described and justified. This study can be performed by including a non-linear behavior of the structure [6] or more commonly considering a linearized behavior coefficient for the structure (through a spectral analysis), which is considered in this study. This approach is applied to a 3, 5 and 10-level structure with an equipment localized on the top or any other story of the building. For few configurations results are compared to analytical results. Finally, the proposed formulation is compared to proposals or requirements of various guidelines and standards, particularly the requirement of Eurocode 8 [1] which is currently open to comments.

# 2. Background and Objectives

The acceleration undergoing by the element inside a building during an earthquake corresponds to the soil acceleration amplified by two main phenomena:

- funct1, amplification of the acceleration between the ground and the floor on which is fixed the element,

- *funct2*, amplification of the acceleration between the floor and the acceleration perceived by the element. The possible combinations of these functions and their parameters are quite numerous and it is therefore necessary in order to develop a generic formulation, to specify the scope.

## 2.1 Field of study

The cases where the *element* is fixed at a single point (or several points close enough to be considered with a same displacement) are taken into account here. The structural deformation compatibility problem between multi-fixed *element* and structure is out of the scope of this paper. The problem is therefore limited to the definition of the element acceleration named  $S_a(T_e)$ . For a response spectrum approach, this acceleration can be expressed as following:

$$S_{a}(T_{e}) = funct I(T_{b}, \zeta_{b}, \Phi_{b}, z / H) x funct 2(T_{e}, T_{b}, \zeta_{e}, \zeta_{b}) x a_{g}$$
(1)

These functions depend on eight main parameters: the fundamental period of the building -  $T_b$ , the period of the element -  $T_e$ , the fundamental mode of the building -  $\Phi_b$ , the position (height) of the *element* in the building - z, the total height of the building - H, the damping ratio of the building -  $\zeta_b$  (conventional value), the damping ratio of the element -  $\zeta_e$ , and finally the ground acceleration -  $a_g$ .

The large number of parameters, the difficulties to obtain mechanical properties (principally) of *elements* conduct, in order to simplify the problem, to find classification of elements and to take simplifying assumption (mono-modal approach, linearization of the first Eigen mode...). For such structures, it is possible to simplify the interaction problem with stick models completed with an additional mass and its mechanical support. AFPS in 1990's propose in their earthquake requirements, in regard of the mass ratio and the fundamental period ratio, domains where the problem can be simplified considering that "an additional mass does not affect the global dynamic behavior of the structure" [7], cf. Figure 1.



Fig 1 – AFPS Proposal on the possibility to neglect the interaction of an element on the global dynamic behavior of a structure [AFP 90].

## 2.2 Methodology of the proposed method

Considering now this simplified model, illustrated in Figure 2, mechanical parameters can be named. Index "b" is reserved for the building and index "e" is linked to the *element*. M<sub>e</sub>, the *element* mass, is small enough to consider a non interaction on the global behavior of the building.  $\zeta_{ie}$ , the damping ratio of the element, is independent of  $\zeta_{b}$  the conventional value of the building damping ratio.



Fig 2 – Simplified model considered in the study

With these assumptions it is possible to transform equation (1) by equation (2) with five  $\phi$  i functions [8]

 $Sa(Te) = \phi 1.x \phi 2.x \phi 3.x \phi 4.x \phi 5$ 

with:  $\phi$ 1, the dynamic response of the structure (amplification due to the position of the element in the building),

(2)

 $\phi$ 2, the position of the equipment in the structure

 $\phi$ 3, the number of fixing points of the *element* (in this case, considered to be one point, therefore = 1) equal to 1),

 $\phi$ 4, the number of fixing points of the *element* (in this case, considered to be one point, therefore = 1)

 $\phi$ 5, the resonance factor between the *element* and the structure f ( $\zeta_e, \zeta_b$ )

Now, we consider a building with a single or several *element*(s) punctually connected to this building with the following assumptions:

- The *element* is not attached to a flexible floor, so the vertical acceleration is not taken into account,

- The *element* is fixed to a primary element;

- The structure is assumed to be regular in elevation and can be properly modeled by a single mode behavior with a first mode displacement which can be defined by  $\phi(z) = (z / H)^{\alpha}$  for the horizontal displacement, with  $\alpha = 1$  for the method of lateral forces [1], ( $\phi(z) = 0$  for the vertical displacement);
- Three types of *elements* can be considered; in this study, only the first one is taken into consideration: rigid elements, the answer will depend mainly on the fasteners,



Flexible *elements* require a modeling with several degrees of freedom (pipes, wide panels...)

Hanging elements: pendulum type behavior (lighting ...)

- The stiffness of the element and its fixing is very low compared to the stiffness of the structure. Therefore, there is a high probability that the natural frequencies of the element are close to those of the structure (risk of resonance the seismic force to be considered can be quite large);
- The damping ratio of the element can be low;
- Values of mechanical parameters of element and structure allow us to neglect interaction of element on the global behavior of the building.

These assumptions may seem restrictive, but they correspond to a large number of cases for usual buildings.

## 3. General approach

3.1 Elastic response spectrum of an elastic single degree of freedom structure

The equation of motion of a single degree of freedom, undergoing inertial forces through motion of its base is written in the form of equation (3). Depending on the type of motion of its base,  $\gamma$  (t) can be expressed in different ways (harmonic excitation, random excitation...). For earthquakes,  $\gamma$  (t) is often available as an accelerogram.

$$M\ddot{X}_r + C\dot{X}_r + KX_r = -M\gamma(t) \tag{3}$$

The projection on modal base allows to write this equation as equation (4) where the pseudo-acceleration Ar considers all the modes [9]:

$$A_{r} = \left[ \left( \sum_{i=1,N} \Gamma_{i} \phi_{i} S_{a}(T_{i}) \right)^{2} + \overline{\gamma}^{2} \left( 1 - \sum_{i=1,N} \Gamma_{i} \phi_{i} \right)^{2} \right]^{1/2}$$

$$\tag{4}$$

with  $\overline{\gamma}$ , the value of the spectrum to zero period,

 $\phi_i$ , the eigen mode i,

 $\Gamma_i$ , the modal participation factor i,

N, the number of degrees of freedom of the structure.

In this expression, the first term corresponds to the combination (by the SRSS method) of modes with frequency below the spectrum cutoff.

3.2 Special case of quasi-modal structures

In the case of a single mode type structure, this formula is simplified and can be written as (5) [8]

$$A_{r} = \left[ \left( \Gamma_{1} \phi_{1} Sa(T_{1}) \right)^{2} + \bar{\gamma}^{2} \left( 1 - \Gamma_{1} \phi_{1} \right)^{2} \right]^{1/2}$$
(5)

Integrating the resonance phenomena, the acceleration to be applied to the mass of the *element* can be expressed by the simplified formula (6). This formula is based on the assumption of a single-mode behavior of the building.

$$a_{H} = \frac{A_{r}(T_{b})}{q_{b}} \times \varphi\left(\frac{T_{e}}{T_{b}}\right) = \frac{A_{r}(T_{b})}{q_{b}} \times K_{T}$$
(6)

with  $a_H$ ,

the horizontal acceleration applied to the *element*;

 $A_r(T_b)$ , the absolute acceleration for Tb period and  $\zeta_b$  the damping of the building. This acceleration is a function of *z* (height of the element implantation) and H (the total height of the building);  $q_b$ , the behavior factor of the building. The  $q_b$  value will be equal to 1,5 unless a different value

 $f_b$ , the behavior factor of the building. The  $q_b$  value will be equal to 1,5 unless a different value can be justified;



 $\phi$   $(T_e / T_b) \equiv K_T$ , the function defining the amplification factor is related to the ratio between the natural period of the element  $T_e$  and the natural period of building  $T_b$ . This amplification coefficient is noted  $K_T$ . It depends in particular of the damping ratio of the *element*.

Assuming the general shape of the fundamental mode of building as  $\phi = z / H$  (unimodal linear form), the coefficient of participation  $\Gamma$  participation is calculated by the formula (7):

$$\Gamma = \frac{\int_{0}^{H} \rho \, \Phi \, dz}{\int_{0}^{H} \rho \, \Phi^2 \, dz} = \frac{\rho \int_{0}^{H} \left(\frac{z}{H}\right) \, dz}{\rho \int_{0}^{H} \left(\frac{z}{H}\right)^2 \, dz} \frac{3}{2}$$

$$\tag{7}$$

From equation (4) the acceleration Ar (Tb) is expressed as (8) and by developing the expression (9) is obtained.

$$A_{r}(T_{b}) = \left[\Gamma^{2} S_{a}^{2}(T_{b})\left(\frac{z}{H}\right)^{2} + a_{g}^{2}\left[1 - \Gamma\left(\frac{z}{H}\right)\right]^{2}\right]^{1/2}$$
(8) 
$$A_{r}(T_{b}) = \sqrt{a_{g}^{2} + \Gamma^{2} S_{a}^{2}(T_{b})\left(\frac{z}{H}\right)^{2}}$$
(9)

If the spectral acceleration is unknown, and for conservative reasons, it is possible to retain the maximal value of the spectral acceleration spectrum.  $K_T$  is given by the following formulas (10) [9]:

$$\frac{T_e}{T_b} < \frac{1}{2} \quad \Rightarrow K_T = 1 \qquad \qquad \frac{2}{3} \le \frac{T_e}{T_b} \le \frac{3}{2} \quad \Rightarrow K_T = 5\sqrt{\frac{50}{\zeta_b(\zeta_b + \zeta_e)}} \qquad \qquad 2 \le \frac{T_e}{T_b} \quad \Rightarrow K_T = 1 \tag{10}$$

A linear interpolation is proposed for the transition zones,  $1/2 \le T_e / T_b \le 2/3$  and  $3/2 \le T_e / T_b \le 2/3$ , with respect to log  $(T_e / T_b)$ . If the  $T_e / T_b$  ratio is not known,  $K_T = 5$  (with a damping ratio equal to 5%) [9]. In a general and unspecified case, on the base of formula (9), formula (11) can be used [9].

$$S_{a}(T_{e}) = fonct_{1} (T_{b}, \zeta_{b}, \Phi_{b}, z/H) \cdot fonct_{2} (T_{e}, T_{b}, \zeta_{e}, \zeta_{b}) \cdot a_{g} = 5 [a_{g}^{2} + 1.5^{2} S_{a}^{2}(T_{b})]^{0}, \qquad 5 \qquad (11)$$

## 4. Illustration and approach synthesis

To illustrate this approach, formulae are applied to a 3 multi degree of freedom unidirectional system. The *element* is located on the top of the structure. For this example, an analytical study can be carried out. A same mass and a same stiffness is considered for each storey, so the building is regular in elevation, which is an assumption of the present approach. The different stages of the analysis are presented below.



Fig. 3 – Example of a 3 Storey building with an *element* on the top.

The circular frequencies of the system are:  $\omega_1 = \sqrt{0.1981} \sqrt{k/M}$ ;  $\omega_2 = \sqrt{1.555} \sqrt{k/M}$ ;  $\omega_3 = \sqrt{3.247} \sqrt{k/M}$ The mode shape of this oscillator are  $\phi_1 = \begin{bmatrix} 1,00\\1,80\\2,25 \end{bmatrix}$   $\phi_2 = \begin{bmatrix} 1,00\\0,45\\-0,81 \end{bmatrix}$   $\phi_3 = \begin{bmatrix} 1,00\\-1,25\\0,56 \end{bmatrix}$ 



It can be noted that the first mode shape is  $\phi(z) = (z / H)^{\alpha}$ , with  $\alpha$  [0,55; 0,74].

The influence vector can be written as:  $\Delta = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ 

Modal participation factors are defined as:

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$$\Gamma_n = \frac{\Phi_n^T \underline{M} \ \Delta}{\Phi_n^T \underline{M} \ \Phi_n} \cdot \Gamma_1 = 0,54 \ ; \ \Gamma_2 = 0,35 \ ; \ \Gamma_3 = 0,11$$
with  $M_n = \Phi_n^T \cdot \underline{M} \cdot \Phi_n \cdot M_1 = 9,30M \ ; \ M_2 = 1,84M \ ; \ M_3 = 2,86M$ 

A SRSS combination with a constant response spectra  $S_a$  gives the following accelerations, which corresponds to the acceleration at the support of the equipment (no resonance phenomena included – funct 1):

$$\begin{aligned} A_{r\_step\_1} &= \left[0,54^2 S_a \, {}^2(T_1) + 0,35^2 S_a \, {}^2(T_2) + 0,11^2 S_a \, {}^2(T_3)\right]^{1/2} = 0,66 S_a \\ A_{r\_step\_2} &= \left[0,97^2 S_a \, {}^2(T_1) + 0,16^2 S_a \, {}^2(T_2) + 0,13^2 S_a \, {}^2(T_3)\right]\right]^{1/2} = 0,99 S_a \\ A_{r\_step\_3} &= \left[1,22^2 S_a \, {}^2(T_1) + 0,28^2 S_a \, {}^2(T_2) + 0,06^2 S_a \, {}^2(T_3)\right]\right]^{1/2} = 1,25 S_a \end{aligned}$$

In order to compare our results to floor response spectra defined with the knowledge of the whole of mechanical parameters, this (3+1) multi degree of freedom structure is studied with FSG software [10]. On the assumption of a unitary spectrum (1g), acceleration amplifications compared to design spectrum are presented in figure 4 for different set of damping ratios. In terms of maximum amplification, table 1 shows the comparison between results obtained with the proposed method and those issued to the complete 4 mdof study.



Fig. 4 – Floor spectrum generated from the FSG software

 Table 1 – Comparison of amplification calculation on an *element* located on the top of a Three storey building regular in elevation

	amplification with proposed method damping ratio of the structure		amplificatioon with complete 4 DOF computation damping ratio of the structure		Overvaluation of the simplified method (%)	
					damping ratio of the structure	
	2%	5%	2%	5%	2%	5%
damping ratio of the element: 2 %	22,53	17,03	20,02	11,4	12,56	49,43
damping ratio of the element: 5 %	10,77	9,01	9,68	7,8	11,3	15,56



# **5.** Comparison with other formulations

In order to complete the scope of this proposed method, formulation and parameters are compared to other standard formulations or to requirements or recommendations proposed in different handbooks.

## 5.1 AFPS90 Recommendations (§23)

Two parameters are taken into account in AFPS90 approach. The first is the location of the element in the height of the building: z/H. The second,  $K_T$ , consider natural frequency ratio between the element and the building.

$$a_H = a_g \left( 1 + \frac{2}{q_b} \frac{z}{H} \right) K_T \tag{12}$$

with:  $a_g$ , ground acceleration;  $q_b$ , the building of the behavior factor;

 $K_T$  coefficient is defined on the set Te / Tb values we proposed, also with a linear transition in logarithmic scale. However,  $K_T$  values  $\neq 1$  is different ( $K_T = 35 / (2 + \zeta)$ ).

#### 5.2 EC8 requirements for non-structural elements (§4)

Number of criticisms exist on the "non structural elements" formula (4.25) of the EN 1998-1. Two independent terms are merged, the amplification induced by the building depending on the floor level (therefore the coefficient z/H), and the amplification due to the natural frequency ratio Te/Tb. EC8 is:

$$a_{H} = S_{a} \gamma_{a} \frac{1}{q_{a}} \qquad \text{with} \qquad S_{a} = \alpha S \cdot \left[ 3 \left( 1 + \frac{z}{H} \right) \right] / \left[ \left( 1 + \left( 1 - \frac{T_{a}}{T_{1}} \right)^{2} \right) - 0.5 \right] \qquad S_{a} > \alpha S \qquad (13)$$

 $a_H$  and  $S_a$  parameters is are:  $\alpha$ , the ratio between the ground acceleration for a soil class A; S, the soil parameter ;  $T_a$ , the natural period of the *element*;  $T_I$ , the period of the building;  $\gamma a$ , the coefficient of importance (as Ip FEMA 368 [EMF 368]);  $q_a$ , the behavior factor of the *element*.

#### 5.3 PS92 for non-structural elements (§7)

The formulation for the non-structural elements in the PS 92 (French standard before EC8) is close to the AFPS90 proposal. A coefficient of importance  $K_i$  is added. The coefficient  $K_T$  refers to the same set of  $T_e/T_b$  the same transition rules, but the value of  $K_T \neq 1$  is defined as a constant value equal to 5.

$$a_H = a_N \left( 1 + \frac{2}{q_b} \frac{z}{H} \right) K_T K_i$$
(14)

#### 5.4 FEMA 368 and FEMA369 comments [FEM369]

FEMA formulation is similar to the PS92 one also with the addition an important factor:

$$a_{H} = 0.4 S_{DS} \left( 1 + 2\frac{z}{H} \right) a_{p} I_{p} \frac{1}{R_{p}} \qquad \qquad 0.3 S_{DS} I_{p} < a_{H} < 1.6 S_{DS} I_{p} \qquad (15)$$

 $a_H$  parameters are:  $0, 4.S_{DS} \equiv a_N$ , the ground acceleration ( $S_{DS} \ge a_N = 2,5$ );  $a_p = K_T$ , an amplification factor according to ( $T_e / T_b$ );  $I_p$ , an important factor;  $R_p = q_e$ , a coefficient of performance of the *element*.  $K_T$  is set to five zones, two where  $K_T = 1$ , one with  $K_T = 2,5$  and two transition zones with linear interpolation with  $T_e / T_b$ . The singular values of  $T_e / T_b$  are approximately the same as the ones presented before.

#### 5.5 Summary

Table 2 summarizes all the formulations presented here. Independent of the coefficient values or the results of formulas, expressions extracted from the bibliography and proposed formula are consistent together except the formulation of Eurocode 8.



Parameters	PS92	PS90	Proposition	FEMA	EC8
Accélération du sol	$a_N$	$a_N$	$a_g$	0,4 S <sub>DS</sub>	αS
$\varphi\left(\frac{z}{H}\right)$	$\left(1+2\frac{z}{H}\right)$	$\left(1+2\frac{z}{H}\right)$	$\sqrt{a_g^2 + \Gamma^2 S_a^2(T_b) \left(\frac{z}{H}\right)^2}$	$\left(1+2\frac{z}{H}\right)$	$3\left(1+\frac{z}{H}\right)$
$K_T$ or $\varphi\left(\frac{T_e}{T_b}\right)$ $V_m$ : maximum amplification value	$K_T$ $V_m = 5$	$S_f = K_T$ $V_{m,5\%} = 5$ $V_{m,2\%} = 8,75$	$K_T$ $V_m = 5$	$a_p$ $V_m = 2,5$	$1 / \left[ \left( 1 + \left(1 - \frac{T_a}{T_1}\right)^2 \right) - 0.5 \right]$ $V_m = 2$
importance factor	$K_i$	/	$I_p$	$I_p$	$\gamma_a$
Behavior factor	$q_b$ and $q_e$	$q_b$ and $q_e$	$q_b$ and $q_e$	$q_b, R_p = q_e$	$q_a = q_e$

Table 2 - Comparison of different formulations and different approaches

## 5. Conclusion

The method proposed in this study for buildings regular in elevation is compared successfully to complete analytical approach. This method has been built on the basis of an approach by linear or linearized response spectrum. Its formulation is inspired by those present in the main current seismic codes or guidelines. This method is stills easy to apply and allows to take into account different mechanical phenomena. The example shows that the proposed formulation provides skeleton values from those obtained by more precise and heavier parametric approaches. The proposed method and the comparison with existing formulations also show that this formulation in the current version of Eurocode 8 is not relevant and should be revised.

To summarize the proposed method following successive stages can be pointed out.

1) a single shape mode is considered for the building with a simplified model:  $\varphi(z) = (z / H)$ .

$$A_r(T_b) = \sqrt{a_g^2 + \Gamma^2 S_a^2(T_b) \left(\frac{z}{H}\right)^2} = K_H a_g \quad \text{with} \quad \Gamma = \frac{3}{2} \quad \text{and} \quad K_H = \sqrt{1 + \Gamma^2 \frac{S_a^2(T_b)}{a_g^2} \left(\frac{z}{H}\right)^2}$$

2) The *element* is considered fixed in a single point, or in localized area defined by z/H.

3) The mass of the *element* compared to the building one allows to consider no influence of the *element* on the global behavior of the building. The design load to be taken into account for the *element* is:

$$F_{H} = \frac{K_{H} K_{T}}{q_{b}} a_{g} W_{e} \text{ with } W_{e}, \text{ the weight of the element and } K_{H} = \sqrt{1 + \Gamma^{2} \frac{S_{a}^{2}(T_{b})}{a_{g}^{2}} \left(\frac{z}{H}\right)^{2}} \leq \sqrt{1 + 14 \left(\frac{z}{H}\right)^{2}}$$
$$K_{T} = 1 \quad \text{if } T_{e}/T_{b} \leq \frac{1}{2} \text{ or } T_{e}/T_{b} \geq 2 \text{ and } K_{T} = 5\sqrt{\frac{50}{\zeta_{b}(\zeta_{b} + \zeta_{e})}} \quad \text{if } \frac{2}{3} \leq T_{e}/T_{b} \leq \frac{3}{2}$$

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