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Simulations of column load-bearing capacity using Screening and ANOVA methods

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Abstract

In this work, we are interested in exploiting the various parametric sensitivity analysis methods for its application to a circular reinforced concrete column subjected to a centered compression force. The equilibrium equations governing the structure are prescribed by the French BAEL 91 rules as a function of input variables linked to the loads on the structure, to the mechanical properties of the materials, and variables linked to the geometry of the part under study. On the one hand, the Morris or screening method enabled us to extract the sensitivity matrix of the physical model studied. After reading and interpreting Mohr's diagram, we saw that the diameter of the column is a highly influential parameter, and that the characteristic strength of the concrete has a linear influence on the load-bearing capacity of the column.
On the other hand, methods based on analysis of variance or ANOVA enabled us to carry out a more in-depth analysis and quantitative evaluation in order to study the behavior of each model input variable and rank them in order of influence on the output. By interpretation of the Fourier spectra, post diameter is the most important variable, with a spectral amplitude of 66.68 dB/Hz, i.e. a degree of influence of around 61.04% on load-bearing capacity. In conclusion, sensitivity analysis is a very formidable and reliable mathematical tool, demonstrated throughout this work. Its application is highly recommended to engineers when predimensioning reinforced concrete structures.

Keywords

Reinforced concrete, simple compression, spectral density, buckling, Morris method, EFAST, Sobol, Mohr diagram

1- Introduction

Today, reinforced concrete is a material widely used in construction engineering. Numerous studies and research studies on concrete have been carried out by various researchers around the world, but there are still a number of questions surrounding behavior, evaluation methods and parameter sensitivities. It is for this reason that this work has been undertaken.

In this work, we have chosen a reinforced concrete column, as this is an essential element in ensuring the stability of a structure and the transmission of forces to the foundation.

Parametric sensitivity analysis is a mathematical modeling tool for determining, quantifying and analyzing how the outputs of a physical model react to perturbations in its input variables [1].

The introduction of parametric sensitivity analysis methods into the design of reinforced concrete structures is considered an essential and inescapable step in the proper dimensioning of future structures. This step is also of interest during pre-dimensioning, as it takes into account the degree of influence of all input parameters, especially those related to the geometry of the structure.

The aim of this work is to develop a computer and mathematical tool to classify the input variables according to their degree of influence on the load-bearing capacity of a reinforced concrete column, in order to analyze the behavior of the physical model with regard to elastic instability phenomena.

2- Methods

2.1. Formulation of load-bearing capacity

In this work, let's consider a circular reinforced concrete column shown in Figure 1 The design rules governing the structure are prescribed by the French BAEL 91 rules [2].

The column is considered to be in central compression if :

- the maximum value of the straightness imperfection given in article B.8.4.1 is : $e < \max(1cm, L_f/500)$ with L_f = buckling length ;
- the moment at the head of the column (embedding of the beams) causes only a slight eccentricity: article B.8.2.1 of the BAEL 91 rule.

Reinforced concrete structural elements subjected to simple compression loading will be considered as columns under centered loading, provided the above conditions are met. This is the usual case for standard buildings.

The slenderness λ of a column is the ratio of its buckling length L_f to the radius of gyration i of the straight concrete section alone, calculated in the buckling plane.

For a circular column of diameter D, we have : $\lambda = \frac{4\,L_f}{D}$ (1)

The buckling length L_f is determined from Figure 2 for an insulated column and from Figure 3 for a reinforced concrete-frame building.

Table 1. shows the different types of column compression as a function of slenderness.

The BAEL 91 rule (art.B.8.4,1) provides us with a fixed formula giving the ultimate normal force that a BA column with a slenderness of less than 70 can support.

$$\boldsymbol{N_{u\,lim} = \alpha\left[\frac{B_r\,f_{c28}}{0{,}9\,\gamma_b} + \frac{A_s\,f_e}{\gamma_s}\right]} \qquad (2)$$

Where $B_r = \frac{\pi\,(D-0.02)^2}{4}$ is the concrete section reduced by deducting 1 cm from the circumference of the straight section of a circular column with diameter D ;

A_s is the longitudinal steel cross-section ;

α is a coefficient that takes into account the slenderness λ of the column :

$$\alpha = \frac{0{,}85}{1+0{,}2\,(\lambda/35)^2} \quad if\ \lambda \le 50 \qquad (3)$$

$$\alpha = 0{,}6\left(\frac{50}{\lambda}\right)^2 \quad if\ 50 < \lambda \le 70 \qquad (4)$$

Figure 4 shows the crushing at the top of a reinforced concrete column subjected to axial compression.

According to article A.4.3, 41 of BAEL 91, γ_b is the partial safety coefficient for concrete, which is 1.5 for fundamental combinations (A.3.3,21) and 1.15 for accidental combinations (A.3.3,22).

2.2. Parametric sensitivity analysis

2.2.1. Generality

Consider a mathematical model, formed by a set of random input variables aléatoires $X = (X_1, \ldots.. X_p)$ and a set of random output variables (or responses) Y. We write this model in the following form:

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$$\boldsymbol{f} : |\mathbf{R}^{\mathbf{p}} \rightarrow |\mathbf{R}$$
$$\boldsymbol{X} \rightarrow \mathbf{Y} = \mathbf{f}(\mathbf{X}) \quad (4)$$

Sensitivity analysis studies how disturbances on the model's input variables X generate disturbances on the response variable Y.

Sensitivity Analysis can therefore be said to be a mathematical tool for studying the influence of parameters on the model: influential parameters, non-influential parameters and parameters that interact with each other [3] [4] [5].

Sensitivity analysis methods can be grouped into three classes:

- **Screening methods** : which consist of a qualitative analysis of the sensitivity of the output variable to the input variables;
- **o local sensitivity analysis methods** : which quantitatively assess the impact of a small variation around a given input value;
- **o global sensitivity analysis methods** : which look at the variability of the model's output over its entire range of variation.

2.2.2. Sreening methods

Screening" methods qualitatively analyze the importance of input variables on the variability of model response. The aim of these methods is initially to isolate the parameters that have the greatest influence on the results, and thus to reduce the number of parameters to be analyzed using more sophisticated and/or more expensive methods.

The MORRIS method or screening method is a qualitative one, it only identifies influential parameters. In other words, it does not allow factors to be ranked in order of importance, but on the other hand it requires little simulation.

The various stages of this method are as follows:

- Factor standardization : $xi \in [-1:1]$;
- Choice of k values for each factor xi ;
- Choice of r factor sets: $r \leq k-1$;
- Calculation of d_i^j which is an estimate of $\left.\frac{\partial Y}{\partial x_i}\right|_{x=x_{(j)}}$

$x_{(r)} = \{x_n \dots x_m\}$ $r^{ème}$ standardized factor sets

With :

$$d_i^{(j)} = \frac{Y(x_{j1},\dots x_{ji} + \Delta x_i^j,\dots x_{jn}) - Y(X_j)}{\Delta x_i^j} \qquad \text{Where} \qquad \Delta x_i^j = x_i^{j+1} - x_i^1$$

- Evaluation of the sensitivity matrix (dim : r x p) : d = $\begin{bmatrix} d_1^1 & \cdots & \cdots & d_p^1 \\ d_1^2 & \cdots & \cdots & d_p^2 \\ \cdots & \cdots & \cdots & \cdots \\ d_1^n & \cdots & \cdots & d_p^n \end{bmatrix}$
- calculation of the mean and standard deviation of the di for each factor ;
- Drawing in the MOHR plane of $\{\mu(i), \sigma(i)\}$ following Figure 5

The graph can be interpreted as follows :

- If μ is high, the parameter is linearly very influential;
- If σ is high, the parameter is very important non-linearly;
- If μ and σ are low, the parameter is non-influential;

- If μ and σ are high, the parameter is influential.

2.2.3. Global sensitivity analysis

Local analysis can be distinguished from global analysis in the following way: local analysis is based on the derivative of the output with respect to the factors and focuses on the value of the response, while global analysis is based on analysis of variance (ANOVA) and focuses on its variability.

In this work, we are specifically interested in variance-based methods that calculate global sensitivity indices to quantify the influence of different input parameters on the variability of a numerical model's response.

a. Classic FAST method

FAST stands for *Fourier Amplitude Sensitivity Test*, and uses the multidimensional Fourier transform of f to obtain a variance decomposition of Y.The principle of this method is to replace the multidimensional decompositions with one-dimensional decompositions along a curve traversing the input space $[0,1]^p$.

This curve is defined by a set of parametric equations :

$$X_i(s) = G_i[\sin(f_i\, s)] \qquad s \in [-\pi, \pi] \tag{10}$$

f_i : set of linearly independent integer frequencies ;

G_i : functions to be determined, allowing uniform overlap of $[0,1]^p$ and verifies the differential equation :

$$\pi\sqrt{1-u^2}\, P_i \frac{dG_i(u)}{du} = 1 \tag{11}$$

With $\epsilon\, [-1,1]$ and Pi is the probability density of Xi.

- **Number of simulations**

To avoid spectrum aliasing, the minimum number of simulations for sensitivity index evaluation is given by the **Nyquist-Shannon** condition:

$$N \geq 2\, M \max(f_i) + 1 \tag{13}$$

In other words, a periodic signal whose spectrum admits a maximum frequency must be sampled at a frequency strictly greater than twice the maximum frequency.

- **Variance estimation**

If we assume that $f_1 \leq f_2 \ldots \leq f_k$. Also in this case, the variance estimated for Y by Parseval's relation is :

$$V(Y) = \frac{1}{2}\sum_{n=0}^{N}(A_n^2 + B_n^2) \tag{14}$$

Where A_n et B_n are the Fourier coefficients defined by :

$$A_n = \frac{2}{N}\sum_{j=1}^{N} Y(si) * cos\,(2n\pi s_j) \tag{15}$$

$$B_n = \frac{2}{N}\sum_{j=1}^{N} Y(si) * \, sin\,(2n\pi s_j) \tag{16}$$

With $s_j = \frac{2j\pi}{N}$ et j=1,…,N

- **Principal effects**

The first-order sensitivity index defined by $S_i = \frac{V[E(Y|X_i)]}{V(Y)}$ measures the proportion of variance due to Xi alone.
The numerator is calculated by the classic FAST method as the sum of the harmonics :

$$V_i = \sum_{n=1}^{M} (A_{nfi}^2 + B_{nfi}^2) \quad (17)$$

So :

$$S_i = \frac{2\sum_{n=1}^{M}(A_{nfi}^2 + B_{nfi}^2)}{\sum_{n=1}^{N}(A_n^2 + B_n^2)} \quad (18)$$

The advantage of this method is that it allows all the main effects to be determined in a single set of N simulations.

b. Sobol method

Let be the function $Y = f(X)$
Generate a base sample X_b of N factor combinations, then calculate the base output variable Y_b

- **Principal effects**

To calculate the main effects, we generate another sample X_{pi} of N factor combinations by modifying all the factors except the one under study with respect to the base sample, thus obtaining an output variable Y_{pi}
The principal effect is given by the following relationship:

$$S_{pi} = 1 - \frac{\mathrm{var}[(Y_{pi} - Y_b)/\sqrt{2}]}{\mathrm{var}(Y_b)} \quad (19)$$

- **Total effects**

To calculate the total effects, we generate another sample X_{Ti} of N factor combinations, keeping the initial combinations of values for all factors except the one under study, to obtain the output variable Y_{Ti}
The total effect is given by the following relationship:

$$S_{Ti} = \frac{\mathrm{var}[(Y_{Ti} - Y_b)/\sqrt{2}]}{\mathrm{var}(Y_b)} \quad (20)$$

- **Sobol function**

The Sobol benchmark is defined as follows:

$$Y = \prod_{j=1}^{p} \frac{|4\,X_j - 2| + a_j}{1 + a_j} \quad (21)$$

With $a_j \in [0 : 99]$ is a (Sobol) parameter associated with the factor X_j

The Sobol function can be used to check the sensitivity index values calculated using the various sensitivity analysis methods. For the Sobol function, the sensitivity index values can be calculated numerically. Generally speaking, the higher the value of a_j, the less influential the corresponding parameter.

c. EFAST method

One disadvantage of the classical approach is that it does not allow the effects of interactions between factors to be determined. This can distort the analysis in cases where a factor is not influential on its own, but only through interaction with other factors. To overcome this drawback, Saltelli et al. have extended the FAST method to the calculation of the total sensitivity index.

EFAST stands for *Extended Fourier Amplitude Sensitivity Test*, and is used to determine the total effect of a factor on the output of a model...

- How the method works

To achieve this, the authors propose to assign a very high frequency f_i to X_i compared with those assigned to the other factors $X_{\sim i}$.
Thus, the spectrum of the output shown in Figure 6 will have two distinct parts:

- the low frequencies containing the frequencies generated by $X_{\sim i}$,
- the high frequencies containing the frequencies due to X_i

⇛ As the spectra are symmetrical, the $E\left(\frac{N}{2}\right)$ simulations are sufficient to carry out the sensitivity study. (E: integer part)
⇛ If the frequency is found in the spectrum of the output, the factor is influential.

- Total effects

Once the N simulations have been carried out, the total contribution of X_i (whose associated frequency is f_{max}) to the variance of the model response is calculated using the following formula:

$$S_{Ti} = \frac{2\sum_{n=2(k-1)M+2}^{N/2}(A_n^2+B_n^2)}{\sum_{n=1}^{N}(A_n^2+B_n^2)} \qquad (22)$$

2.3. Mathematical modelling

In the following, the column bearing capacity formula will be modelled as a physical model with one (01) output and five (05) input variables, with the ranges of variation of each input variable summarised in Table 2.

3- Results

3.1. Calculation of the load-bearing capacity

Let's consider the following assumptions for calculating the column's load-bearing capacity:
- diameter of the column: **D = 0.25 m** ;
- free length of column: **Lo = 3.50 m** ;
- longitudinal reinforcement: **6 HA 10** ;
- characteristic strength of concrete: **fc_{28} = 25 MPa** ;
- yield strength of steel: **fe = 400 MPa** ;
- design combinations : **fundamental combination** ;

The bearing capacity of the column in centred compression is given by formula 2. Figure 7 shows the calculation program on an Excel sheet.

With the above parameters, the load-bearing capacity of the column is 57.67 tonnes. To avoid elastic instability, the ultimate load at the top of the column should be less than this value.

3.2. Simulation using the sreening method

We have already seen that the Morris method is a qualitative method, which does not allow factors to be ranked in order of importance. Furthermore, it only identifies influential factors.
We run the program « poteau_morris.m » with a number of values k = 6 for each factor Xi. Figure 8 shows the sensitivity matrix of the model:

⇛ We have a sensitivity matrix with **r** rows and **p** columns.
Where r = k-1 = 5 is the number of factor sets ;
p = 5 is the number of factors.
So a square matrix of order n = 5.

⇛ From each column of the matrix, we derive the means and standard deviations of each input variable.

Thus, Table 3. above allows us to establish Mohr's diagram by putting the mean μ(i) on the abscissa axis and the standard deviation σ(i) on the ordinate axis as in Figure 9.

Interpretation: On the one hand, the Mohr diagram shows that parameter X1 has a fairly high mean and a very high standard deviation, so it has a strong influence. On the other hand, parameter X5 has a very high mean and a very low standard deviation, so it has a linear influence on the output. But here, we can't yet classify the parameters according to their order of influence. So, in the future, we will have to use ANOVA methods.

3.3. Simulation using ANOVA methods

In what follows, the EFAST and Sobol methods will be used to calculate sensitivity indices for each input variable in order to rank these parameters in order of importance on the output of the model under study.

3.3.1. Using the EFAST method

The simulation parameters are :

M = 4: interference order ;
k = 5: number of parameters;
fe = 2 x 4 x (5-1) = 32: the highest frequency used;
Low frequencies vary from 1 to $\frac{fe}{2M} = 4$
N = 2 x 4 x 32 + 1 = 257: minimum simulation required (Shannon criteria)

We run the « poteau_efast.m » program with 257 simulations, assigning a high frequency equal to 32 to the parameter we want to study and low frequencies varying from 1 to 4 for the other factors.
After simulation, the output spectra for each sampled parameter are shown in the following figures:

- **Sampling of variable X1**

In Figure 10, two peaks are observed in the frequency zone generated by sampling the variable X1. The first is at a frequency of 1.988 Hz with a high amplitude of 66.68 dB/Hz. The second peak is at a frequency of 3,977 Hz with a low power of 2,705 dB/Hz.
As an interpretation, the first peak indicates a significant influence of the X1 variable on the model output and the second peak shows a significant interaction effect of the X1 factor with the other factors.

- **Sampling of variable X2**

In Figure 11, a single peak is observed in the frequency zone generated by sampling variable X2. It is located at a frequency of 1.988 Hz with a fairly high amplitude of 24.55 dB/Hz, which indicates a significant influence of the X2 variable on the model output.

- **Sampling of variable X3**

In Figure 12, a weak peak is observed at the frequency of 1.988 Hz with a low amplitude of 7.634 dB/Hz, which indicates a non-negligible influence of the variable X3 on the model output.

- **Sampling of variable X4**

In Figure 13, no peak is observed in the frequency zone generated by sampling the X4 variable. This means that this variable has no significant influence on the model output.

- **Sampling of variable X5**

In Figure 14, a single peak is observed at a frequency of 1.988 Hz with a low amplitude of 8.075 dB/Hz, indicating that the X5 variable has little influence on the model output.

3.3.2. Using Sobol method

The « poteau_sobol.m » program was run with 1000 simulations, and the sensitivity indices were calculated using the Sobol method. Table 4. shows the sensitivity indices calculated:
From Table 4. shows that parameter X1 has a strong influence on the output, both on its own, with a main sensitivity index of 0.54, and through interaction with the other parameters, with a total sensitivity index of 0.67. Figure 15 shows the Sobol graphs for the column bearing capacity.

In the graphs in Figure 15, the space (yellow) between the main effect and the total effect of a parameter represents the interaction effect. Thus, we can see a significant interaction between the parameters X1, X2 and X5, which are the variables related to the geometry and strength of the

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column. The Sobol method also confirms that parameter X1 has a strong influence on the model output.

3.3.3. Classification of inputs variables

From the results of the ANOVA simulations, the parameters can be ranked in order of their influence on the output, which is the load-bearing capacity of the column, as shown in Table 5.

From Table 5. above, we can deduce that the diameter of the column represents 61.04% of the influence on its load-bearing capacity.

4- Discussions

Previously, simulations on the load-bearing capacity formula (formula 2) were carried out with a type of fundamental combination (A.3.3,21) and a coefficient K=1.10 for an application of half the loads before 90 days (B.8.4,1). In order to seek a maximum spectral amplitude, we will interchange the various coefficients involved in the load-bearing capacity of the column by referring to the power spectral density of the output Y for the sampled variable X5.

4.1. Bearing capacity of the column according to combinations of actions

According to article A.3.3,2 of BAEL 91, the loads to be considered result from the following combinations of actions, the most unfavourable of which are retained:
- for the fundamental combinations (article A.3.3,21), in durable or transitional situations, the coefficients $\gamma b = 1.5$ and $\gamma s = 1.15$ should be considered;
- for accidental combinations, prescribed by article A.3.3,22 of the BAEL, the coefficients are $\gamma b = 1.15$ and $\gamma s = 1$.

Figure 16 shows the spectral density of the output Y according to formula (2) after sampling the variable X5 with respect to the different combinations of actions.
On the logarithmic scale $100*\text{Log}_{10}$, we can clearly see that the spectrum with an accidental combination represents a much higher amplitude than that of the fundamental combination with a difference of 20.22%. We can deduce from this that, in order to achieve maximum spectral amplitude, it would be better to use the **accidental combination** type.

4.2. Load-bearing capacity of the column according to the duration of the loads applied

According to article B.8.4.1 of BAEL 91, the values of the coefficient α (formula 3 and 4) are to be divided by 1.10 if more than half of the loads are applied before 90 days.
The values given for the coefficient were chosen taking into account the hardening of the concrete between 28 and 90 days as well as the reduction in the susceptibility to creep in the case of late loading. An additional reduction should be applied when the majority of the loads are applied before 28 days (the stress fc is taken instead of fc_{28} and the reduction coefficient is 1.20 instead of 1.10).

We run the simulation again on the spectral density of the output Y for the sampled variable X5, keeping the type of accidental combination and varying the coefficient K. Figure 17 shows the results.
For an accidental combination of loads, here are the results found:
- K = 1.00 amplitude over 100Log_{10} : 82.43 dB/Hz
- K = 1.10 amplitude over 100Log_{10}: 90.71 dB/Hz
- K = 1.20 amplitude over 100Log_{10}: 97.91 dB/Hz

We conclude that for the load-bearing capacity of the column, the maximum value of the spectral amplitude is found with a type of accidental combination of loads with a coefficient K=1.20 for an application of the major part of the loads before 28 days.

5- Conclusion

In conclusion, the screening and ANOVA methods have demonstrated their effectiveness and reliability throughout this work. Its application to the load-bearing capacity of a circular reinforced concrete column confirms the strong influence of column diameter and the interaction effects with the model's other input variables. The results once again justify the BAEL rules' assumption that concrete resists compression very well. It is therefore sufficient to consider a good pre-dimensioning ratio between the geometry and the buckling length of the column to ensure its stability. Thus, the reinforcement cross-section reflects very little sensitivity.

In this work, we are limited to the use of sensitivity analysis on an element subjected to compression. It would also be interesting to investigate structural elements subjected to much more complex loads (compound bending, biaxial bending, tilting, buckling, etc.).

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7- Tables

Table 1. Types of compression as a function of slenderness

slenderness	Types of compression
$\lambda \leq 35$	Simple compression
$35 < \lambda \leq 50$	Simple compression probable
$50 < \lambda \leq 70$	Possible simple compression (to be verified)
$70 < \lambda \leq 150$	Possible buckling
$150 < \lambda$	Buckling

Table 2. Variation range of input variables

Variables	Designations	Variation ranges
X1	column diameter *D (m)*	[0.10 : 0.60] m
X2	buckling length *Lf (m)* ;	[1.00 : 10.00] m
X3	longitudinal reinforcement section *As (cm²)*	[0.192 : 108.11] cm²
X4	guaranteed steel yield strength *fe (MPa)*	[400 : 600] MPa
X5	characteristic strength of concrete f_{c28} (MPa)	[16 : 60] MPa

Table 3. Mean and standard deviation of input variables

Variables	X1	X2	X3	X4	X5
Mean μ(i)	1.95	0.01	0.51	1.65	3.54
Standard deviation σ(i)	0.81	0.00	0.00	0.00	0.00

Table 4. Sensitivity indices by Sobol method

Variables	X1	X2	X3	X4	X5
Total effect	0.6703	0.3105	0.1044	0.0060	0.1426
Principal effect	0.5400	0.2115	0.0668	0.0022	0.0641

Table 5. Classification of input variables by degree of influence on output

Variables	Designations	Percentage of influence	observations
X1	column diameter *D (m)*	61.04%	Strong influence
X2	buckling length *Lf (m)* ;	23.91%	Medium influence
X3	longitudinal reinforcement section *As (cm²)*	7.55%	Low influence
X5	characteristic strength of concrete f_{c28} (MPa)	7.25%	Low influence
X4	guaranteed steel yield strength *fe (MPa)*	0.25%	No influence

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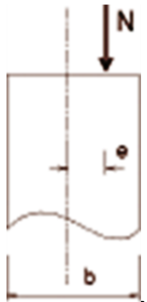
8- Figures

Figure 1. Modelling of simple compression



$$e = \frac{M}{N} < \frac{b}{12}$$

Figure 2. Buckling length for different connection conditions

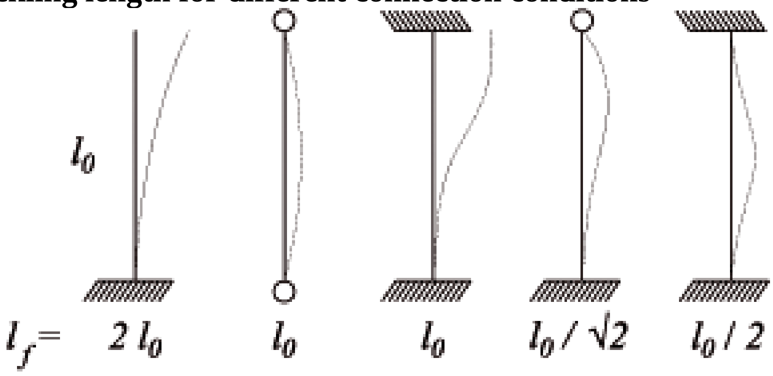


Figure 3. Buckling length of building columns

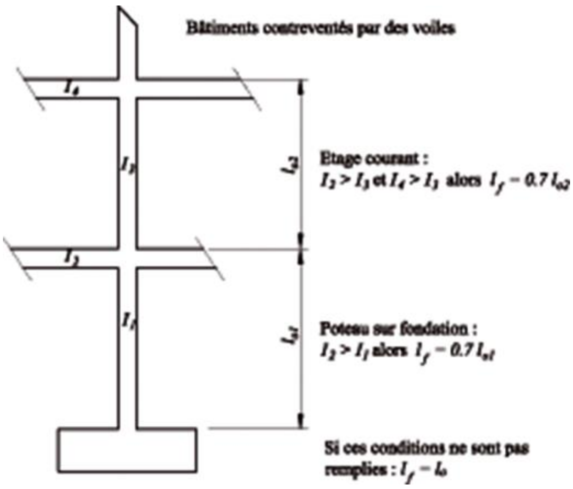


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Figure 4. Crushing of the head of a reinforced concrete column

Figure 5. MOHR diagram

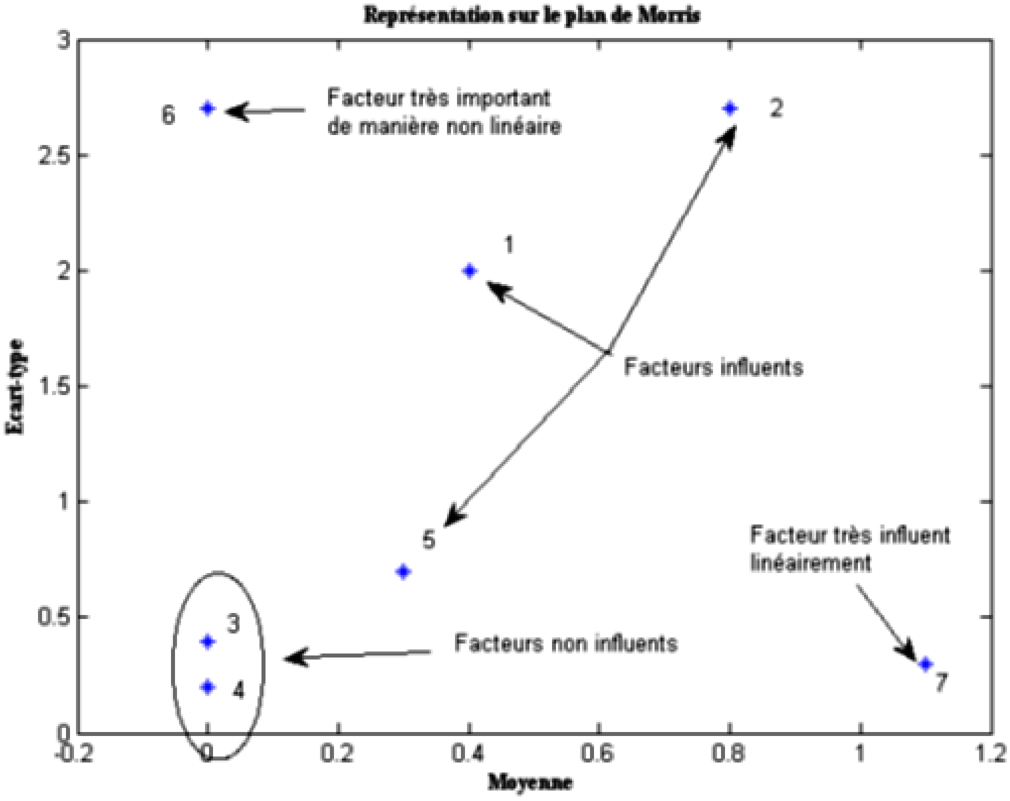

Figure 6. EFAST spectrum output

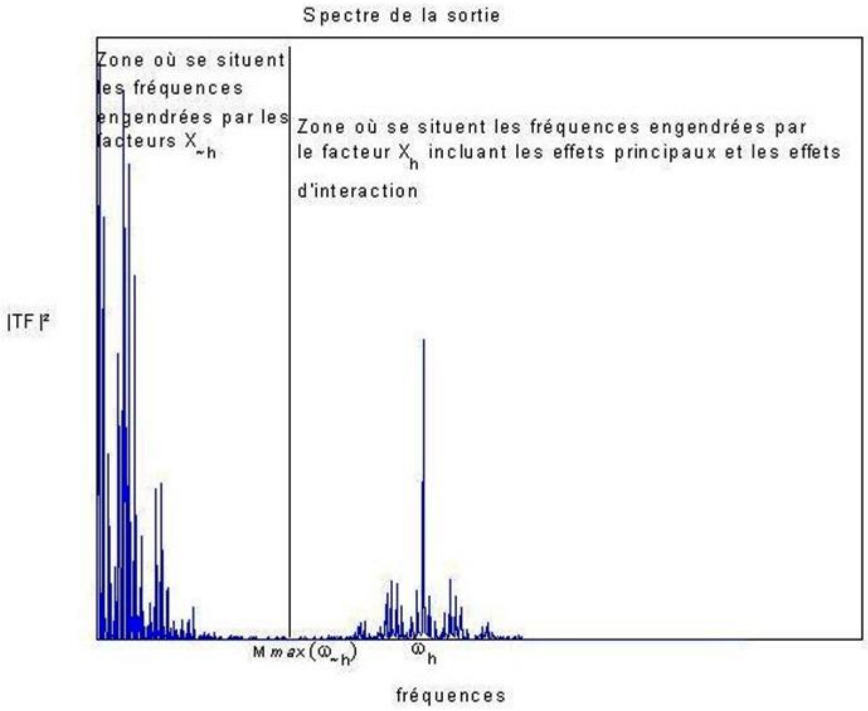

Figure 7. Calculation of load-bearing capacity on Excel sheet

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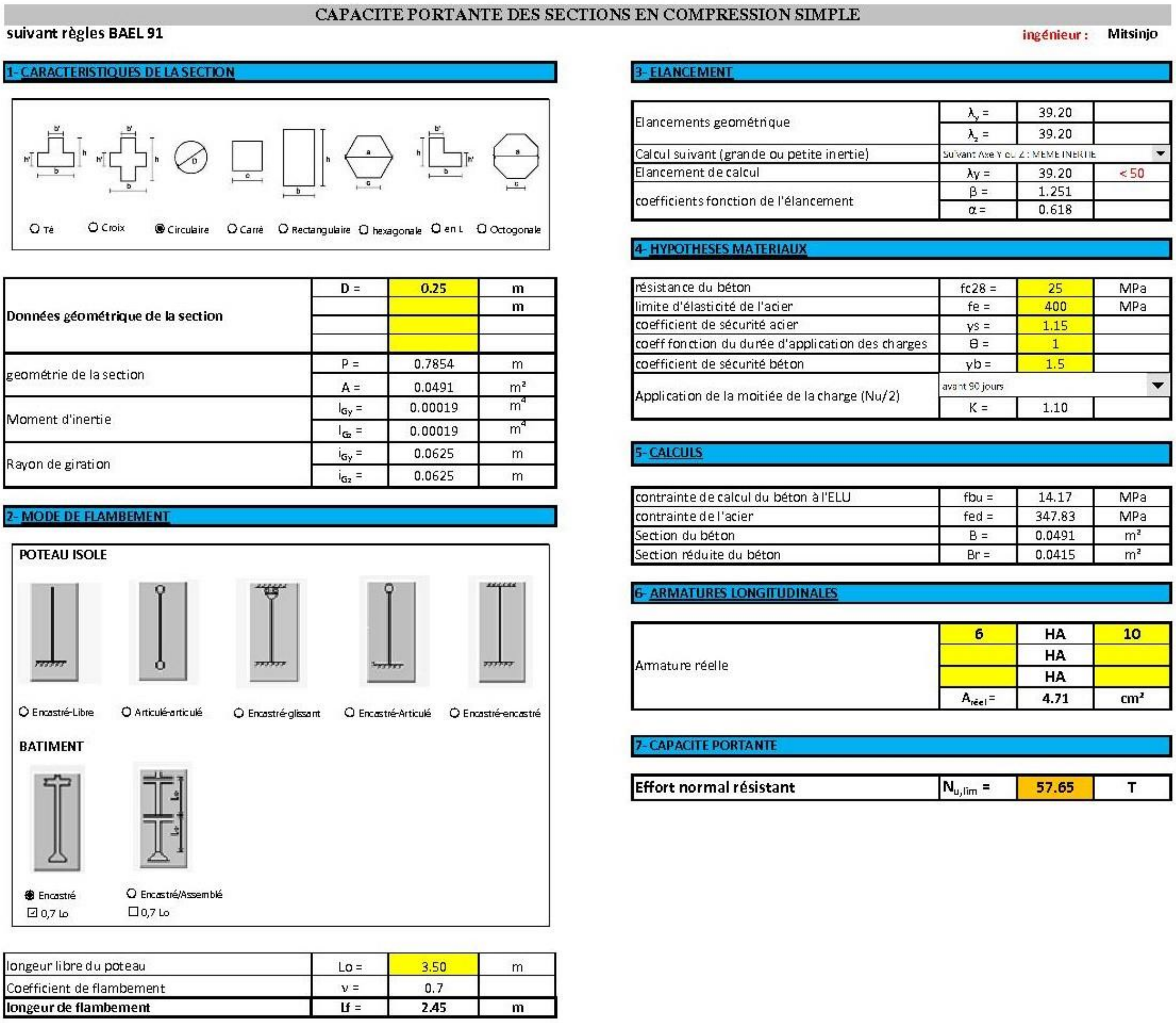

CAPACITE PORTANTE DES SECTIONS EN COMPRESSION SIMPLE

suivant règles BAEL 91 — ingénieur : Mitsinjo

1- CARACTERISTIQUES DE LA SECTION

Données géométrique de la section	D =	0.25	m
			m
geométrie de la section	P =	0.7854	m
	A =	0.0491	m²
Moment d'inertie	I_{Gy} =	0.00019	m^4
	I_{Gz} =	0.00019	m^4
Rayon de giration	i_{Gy} =	0.0625	m
	i_{Gz} =	0.0625	m

2- MODE DE FLAMBEMENT

longeur libre du poteau	Lo =	3.50	m
Coefficient de flambement	ν =	0.7	
longeur de flambement	**Lf =**	**2.45**	**m**

3- ELANCEMENT

Elancements geométrique	λ_y =	39.20	
	λ_z =	39.20	
Calcul suivant (grande ou petite inertie)	Suivant Axe Y ou Z : MEME INERTIE		
Elancement de calcul	λy =	39.20	< 50
coefficients fonction de l'élancement	β =	1.251	
	α =	0.618	

4- HYPOTHESES MATERIAUX

résistance du béton	fc28 =	25	MPa
limite d'élasticité de l'acier	fe =	400	MPa
coefficient de sécurité acier	γs =	1.15	
coeff fonction du durée d'application des charges	θ =	1	
coefficient de sécurité béton	γb =	1.5	
Application de la moitiée de la charge (Nu/2)	avant 90 jours		
	K =	1.10	

5- CALCULS

contrainte de calcul du béton à l'ELU	fbu =	14.17	MPa
contrainte de l'acier	fed =	347.83	MPa
Section du béton	B =	0.0491	m²
Section réduite du béton	Br =	0.0415	m²

6- ARMATURES LONGITUDINALES

Armature réelle	6	HA	10
		HA	
		HA	
	$A_{réel}$ =	4.71	cm²

7- CAPACITE PORTANTE

Effort normal résistant	$N_{u,lim}$ =	**57.65**	**T**

Figure 8. **Sensitivity matrix for load-bearing capacity calculation**

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matrice d

0.73364	-0.001195	-0.50702	1.6501	3.54
1.6057	-0.003979	-0.50702	1.6501	3.54
2.3033	-0.005859	-0.50702	1.6501	3.54
2.3033	-0.007142	-0.50702	1.6501	3.54
2.8274	-0.009878	-0.50702	1.6501	3.54

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Figure 9. MOHR plan for load-bearing capacity calculation

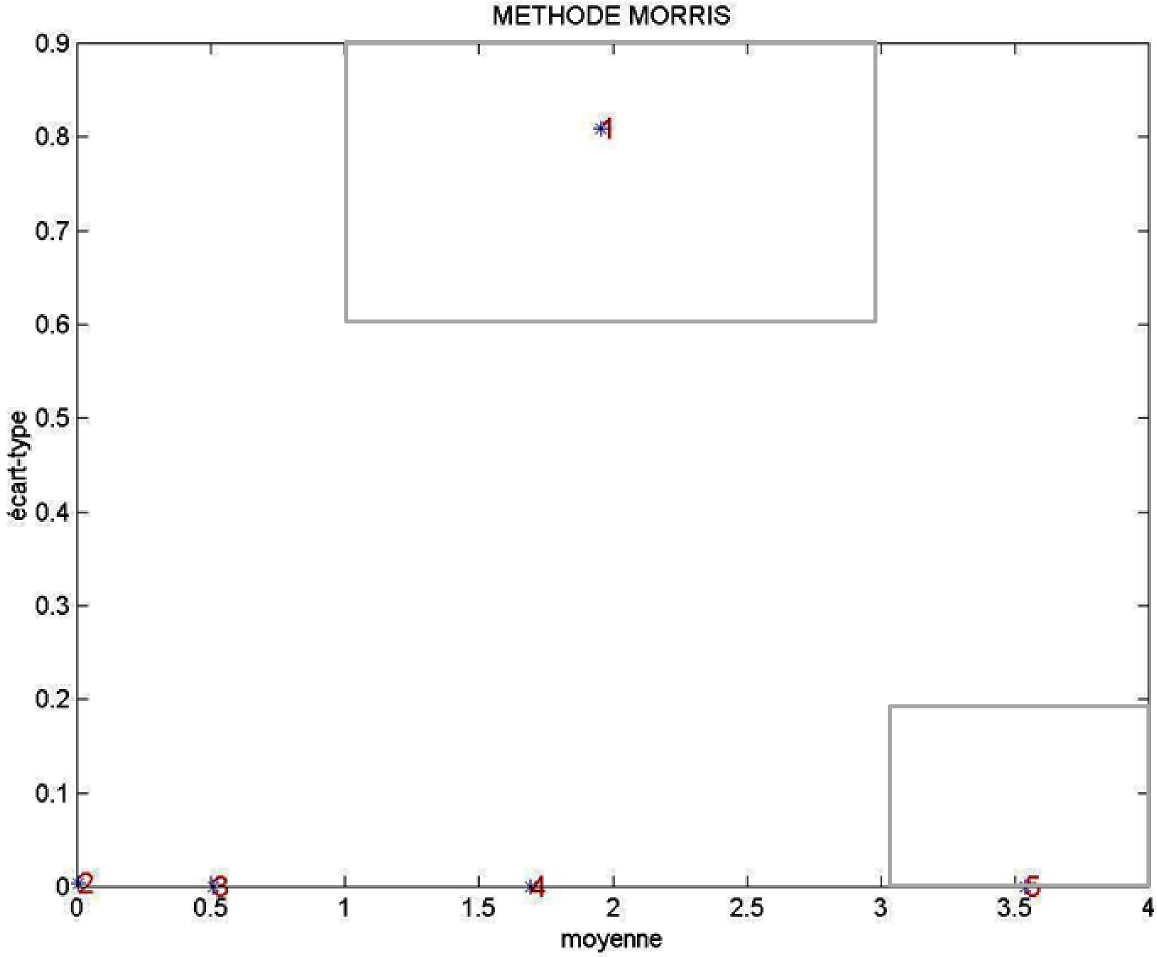

Figure 10. Output power spectral density for sampled X1

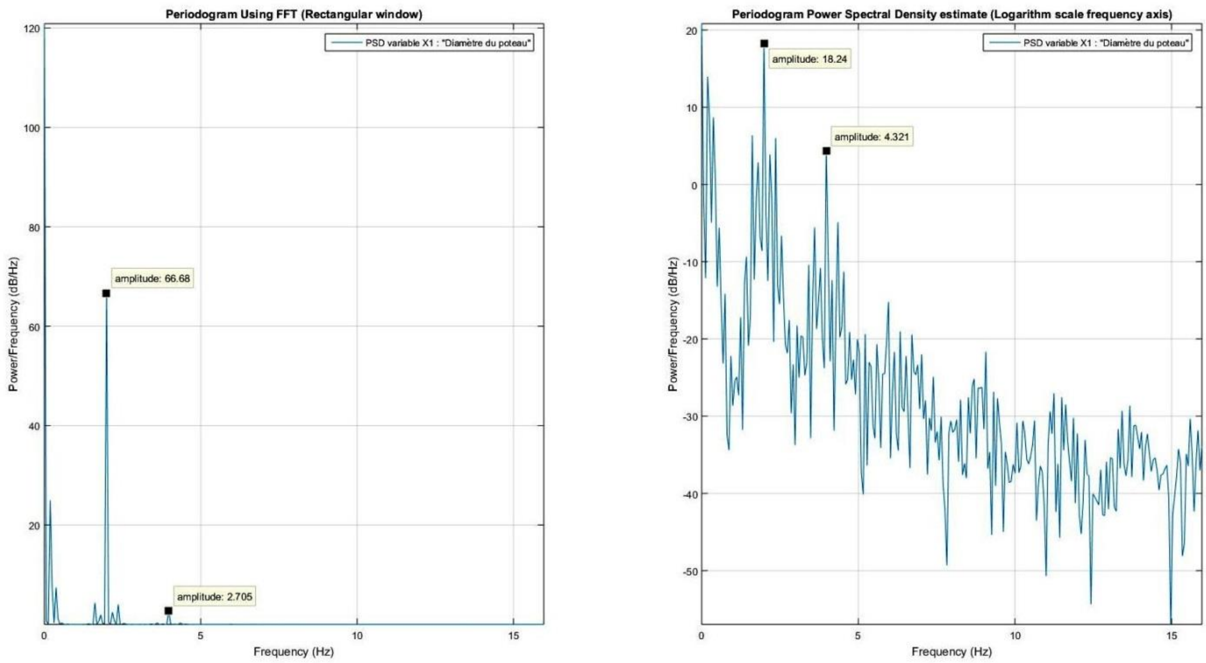

Figure 11. Output power spectral density for sampled X2

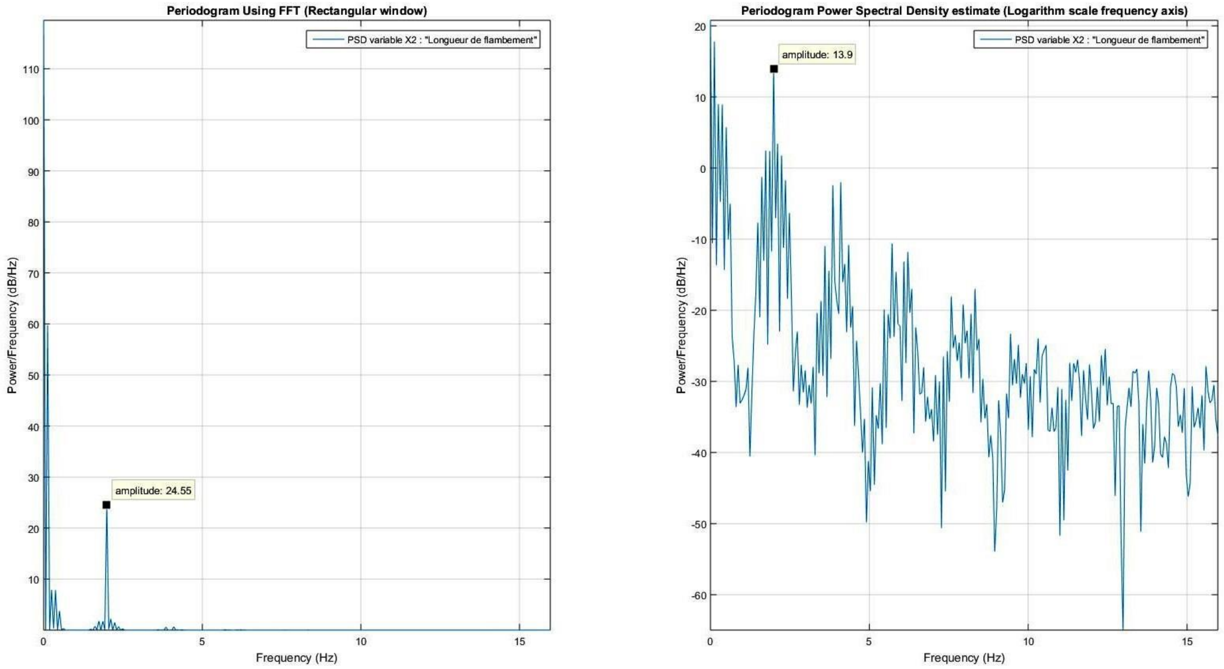

Figure 12. Output power spectral density for sampled X3

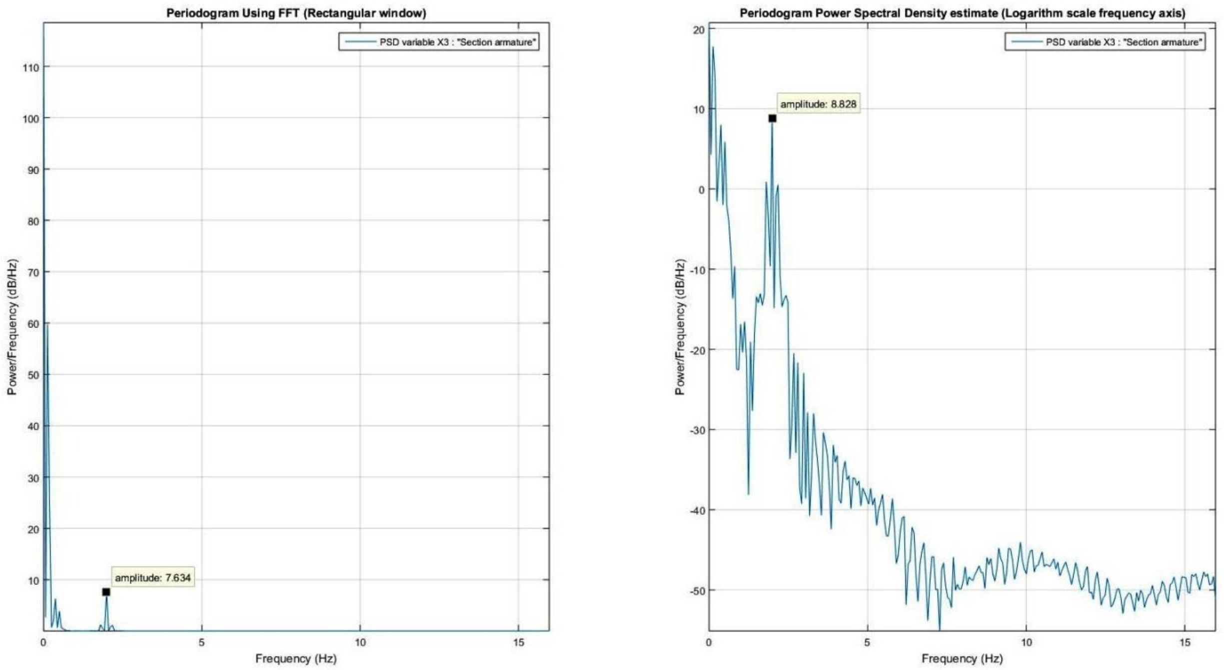

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Figure 13. Output power spectral density for sampled X4

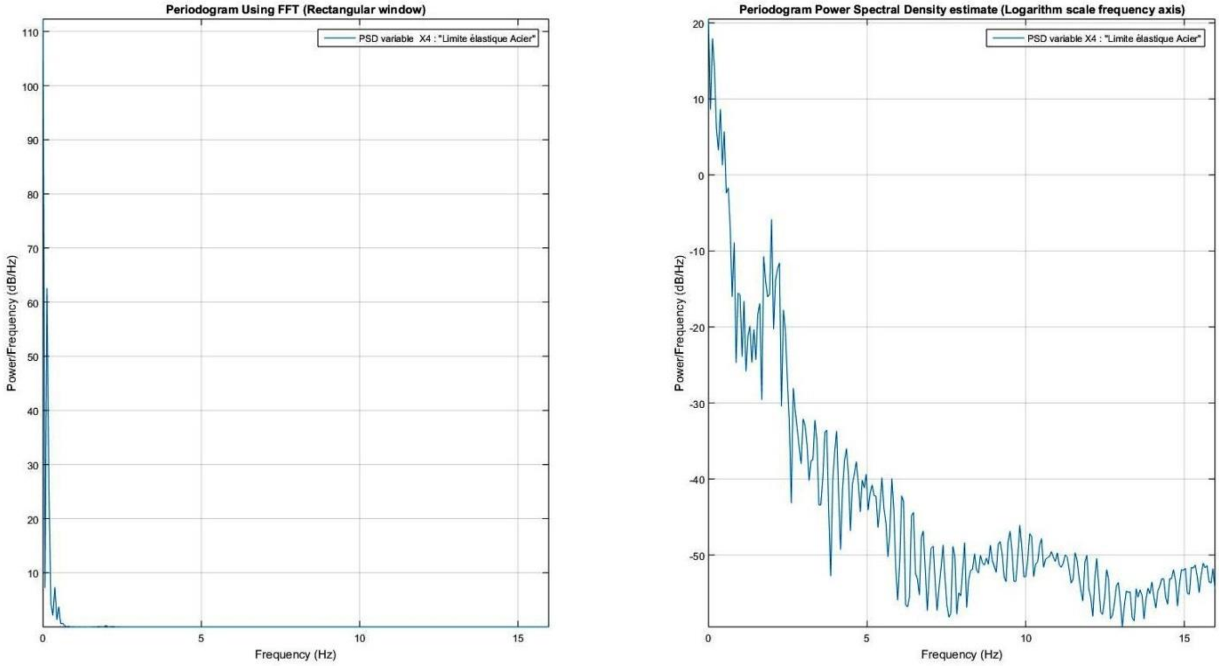

Figure 14. Output power spectral density for sampled X5

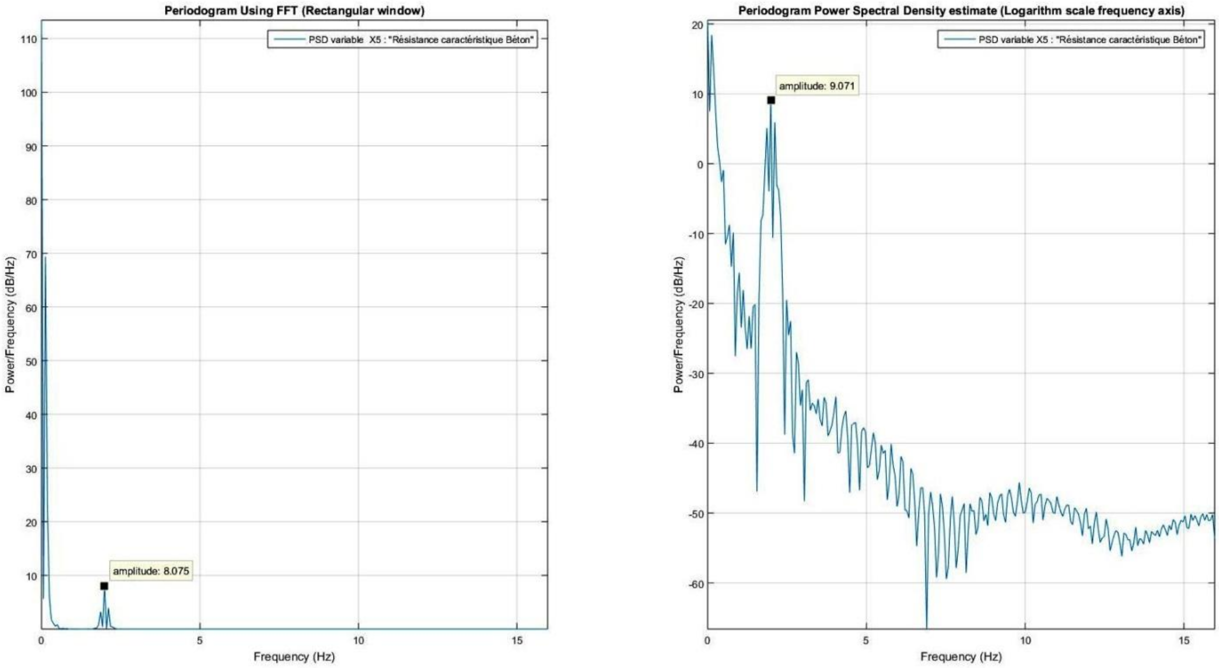

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Figure 15. Sobol graphs for load-bearing capacity

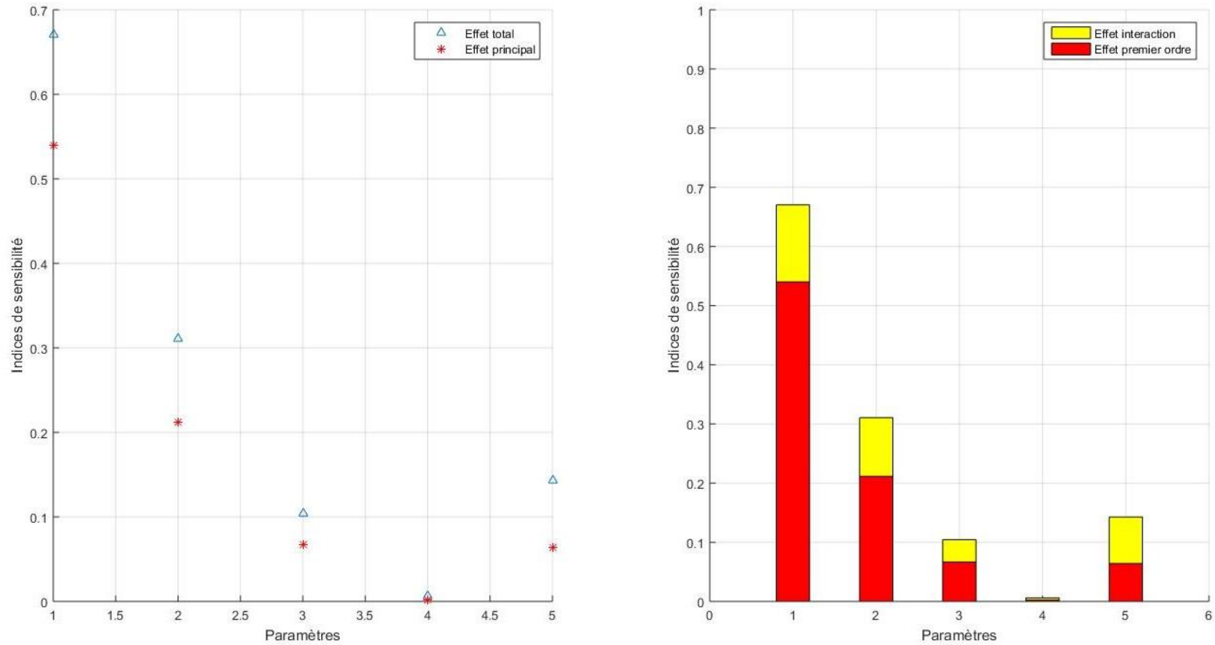

Figure 16. Output spectral density according to action combinations

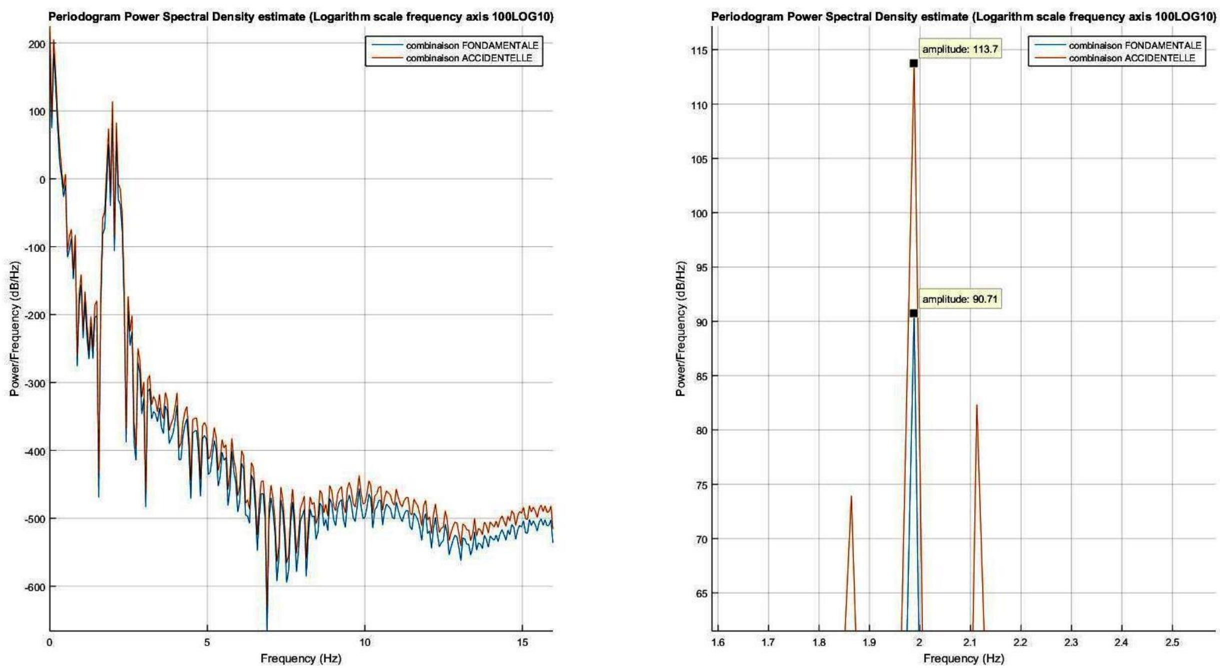

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Figure 17. Spectral density of output according to duration of load application