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INFLUENCE OF SUPERIOR VIBRATION MODES ON THE SEISMIC RESPONSE OF REINFORCED CONCRETE STRUCTURES WITH EIGEN-PERIODS NEAR CODE CONTROL PERIODS

Savu Adrian-Alexandru, Assistant Lecturer, PhD, Technical University of Civil Engineering Bucharest, Romania, e-mail: adrian.a.savu@utcb.ro

Rezumat

În prezenta lucrare se studiază efectul modurilor de vibrație superioare asupra răspunsului seismic al structurilor de beton armat cu perioade proprii în apropierea perioadelor de control prevăzute în codurile de proiectare. Deși calculul structural este bazat pe codurile de proiectare seismică din România ("P100-1/2013 - Cod de proiectare seismică - Partea 1 - Prevederi de proiectare pentru clădiri" și "SR-EN 1998/2004 - Proiectarea structurilor pentru rezistența la cutremur"), acesta are o anumită importanță și pentru alte țări cu spectre de proiectare seismică similare.

În calcul au fost considerate douăzeci și patru de modele de structuri variind locația (prin perioadele de control din cod), regularitatea în plan și elevație, dimensiunile totale și regimul de înălțime al acestora.

Comparațiile rezultatelor și concluziile sunt bazate pe valorile procentuale ale deplasărilor relative de nivel și a forței tăietoare de bază.

Cuvinte cheie: Structuri de beton armat, Moduri de vibrație superioare, Perioade de control

Abstract

The current paper studies the effect of superior eigen-modes on the seismic response for a series of reinforced concrete structures having eigen-periods near code control periods. Although the structural design is based on Romanian seismic design codes ("P100-1/2013 - Seismic design code - Part 1 - Design provisions for buildings" and "SR-EN 1998/2004 - Design of structures for earthquake resistance"), it carries some importance for other countries with similar seismic design spectra.

A total of twenty-four models for structures were considered by varying their location (through control period values), three-dimensional regularity, overall dimensions and height regime.

Results were compared and conclusions were drawn based on percentage values of relative displacements (storey drifts) and base shear forces.

Keywords: Reinforced Concrete Structures, Superior Eigen-Modes, Control Periods

1. INTRODUCTION

In current practice, the design of structures starts with the structural modelling of the building, considering its behaviour to both vertical and horizontal loads such as dead, live, snow, wind, seismic etc. In Romania, in the majority of cases of medium to tall buildings, the horizontal load that produces the most important effect is the seismic load.

As per P100-1/2013 & SR-EN 1998/2004, the seismic action and the structural model may be simplified depending on the regularity of the building, both in-plane and on the vertical. Based on the same considerations, the value of the behaviour factor may be reduced.[8][9]

Due to modern architecture requirements and plot layouts in crowded urban areas, regularity criteria cannot be fulfilled, requiring that the model of the structure must be a spatial one and the seismic action must be modelled through modal response spectrum analysis, rather than through lateral force method analysis.

For the modal response spectrum analysis, a very important requirement is that all modes of vibration contributing significantly to the global response are taken into account. This condition is considered fulfilled as long as the sum of the effective modal masses amounts to at least 90% of the total mass of the structure and all modes with an effective modal mass greater than 5% are considered. [8][9]

The purpose of this paper is to estimate the effect of superior eigen-modes on the seismic response for a series of reinforced concrete structures having eigen-periods near code control periods.

In the acceptance of this paper, superior eigen-modes are the modes of vibration that either have periods lower than the code control periods, or the modes of vibration that are not necessarily taken into account by following the code provisions.

2. SEISMIC ACTION MODELLING USING RESPONSE SPECTRA [8]

When using response spectra for seismic action modelling, the base shear force applied on the direction of the action of seismic motion in vibration mode *k* is determined as:

$$F_{b,k} = \gamma_{I,e} S_d (T_k) m_k \qquad (1)$$

where: $\gamma_{I,e}$ = importance factor;

T_k = vibration period in vibration mode *k*;

$S_d(T_k)$ = ordinate of the design spectrum corresponding to period T_k;

m_k = effective modal mass associated with vibration mode *k*.

The design spectrum for horizontal components of the seismic motion is the inelastic spectrum of absolute accelerations (measured in m/s^2), defined by relations (2) and (3):

$$0 < T \le T_B \quad S_d(T) = a_g \left[1 + \frac{\frac{\beta_0}{q} - 1}{T_B} T \right] \tag{2}$$

$$T > T_B \quad S_d(T) = a_g \frac{\beta(T)}{q} \ge 0.2 a_g \tag{3}$$

where: a_g = peak ground design acceleration, according to (Figure 1);

$\beta(T)$ = the ordinate of the normalized elastic response spectrum of absolute accelerations for horizontal components of the seismic motion corresponding to period *T*;

β_0 = maximum dynamic amplification factor for horizontal ground acceleration for a system with one dynamic degree of freedom;

q = behaviour factor of the structure - the factor of elastic to inelastic response modification.

Based on the conventional value for viscous damping ratio ($\xi = 0.05$) and with respect to the control periods T_B, T_C and T_D, the normalized elastic response spectrum of absolute accelerations for horizontal components of the seismic motion is defined by relations (4), (5), (6), (7):

$$0 \le T \le T_B \quad \beta(T) = 1 + \frac{\beta_0 - 1}{T_B} T \tag{4}$$

$$T_B < T \le T_C \quad \beta(T) = \beta_0 \tag{5}$$

$$T_C < T \le T_D \quad \beta(T) = \beta_0 \frac{T_C}{T} \tag{6}$$

$$T_D < T \le 5s \quad \beta(T) = \beta_0 \frac{T_C T_D}{T^2} \tag{7}$$

where: T_B = lower limit of the period of the constant spectral acceleration branch;

T_C = lower limit of the period of the constant spectral acceleration branch and the upper limit of the period of the constant spectral velocity branch;

T_D = lower limit of the period of the constant spectral velocity branch and the upper limit of the period of the constant spectral displacement branch;

The peak ground design acceleration and the control periods vary with respect to the location of the structure due to ground conditions influencing the frequency content of the seismic motion (Figure 1 and Figure 2).

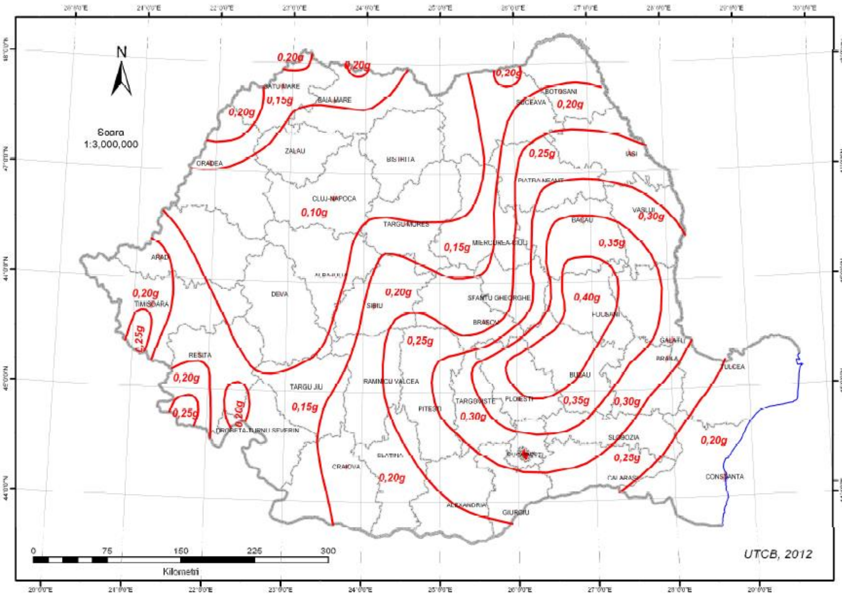

Figure 1. Zoning of Romanian territory in terms of peak ground design acceleration for Mean Recurrence Interval = 225 years [1]

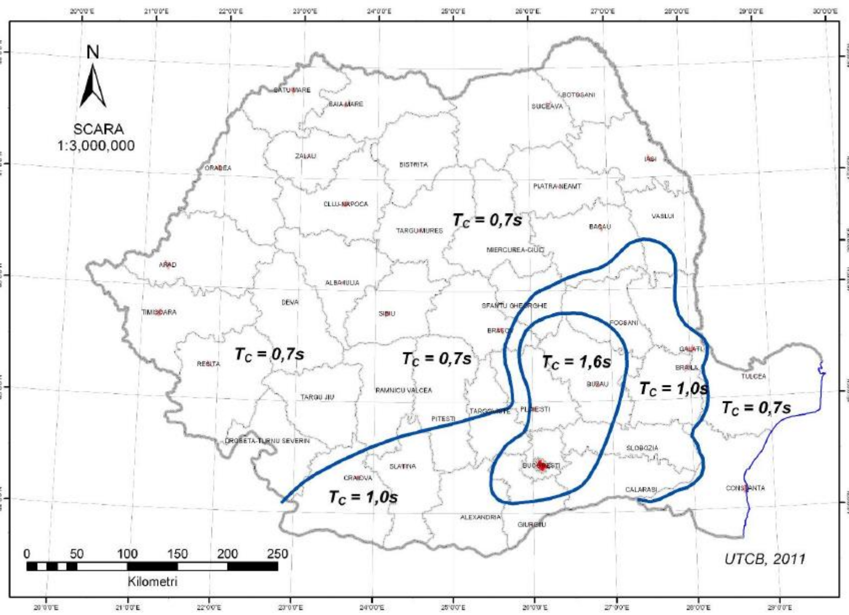

Figure 2. Zoning of Romanian territory in terms of control period T_C [1]

Based on the values from Table 1, three different response spectra must be considered (Figure 3).

Table 1. Control periods of the response spectrum for horizontal components of the seismic motion [1]

T_C	0.70s	1.00s	1.60s
T_B	0.14s	0.20s	0.32s
T_D	3.00s	3.00s	2.00s

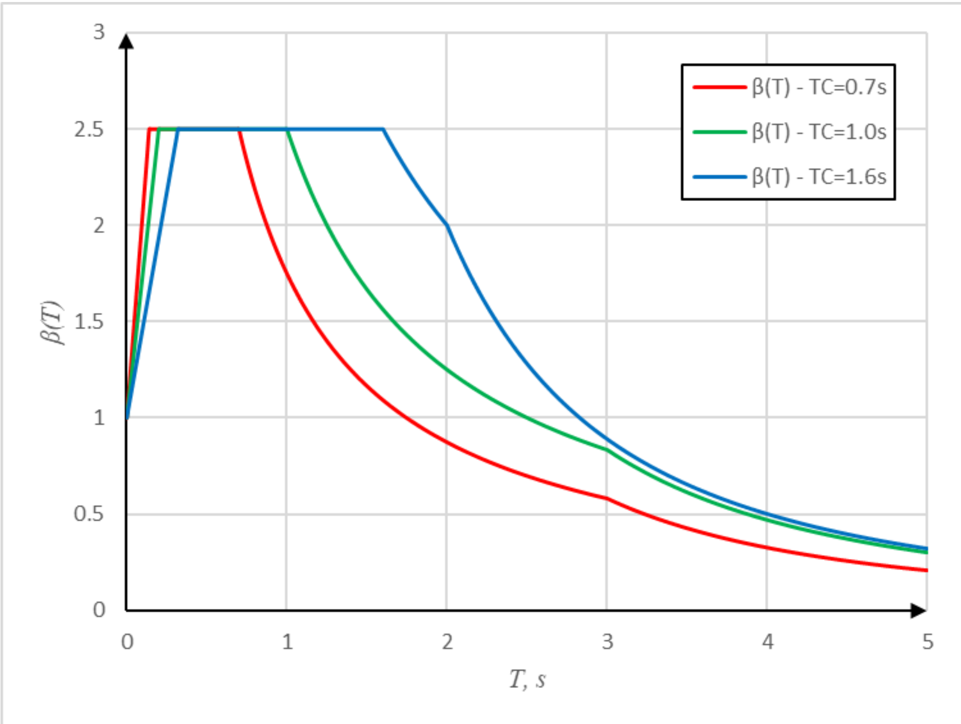

Figure 3. Normalized elastic response spectra of absolute accelerations for horizontal components of the seismic motion, in zones characterized by control periods T_C=0.7s, T_C=1.0s and T_C=1.6s

3. STRUCTURAL ANALYSIS

1.1. Model generalities and simplifications

The analysis was performed at the Technical University of Civil Engineering Bucharest, Structural Mechanics Department and the software used was ETABS.

A total of twenty-four models for structures were considered. The models vary with respect to the following criteria:

a) location - the structures were considered located in the three different zones specified by P100-1, with respect to the control period T_C:
   - zone 1, with $T_C = 1.60s$;
   - zone 2, with $T_C = 1.00s$;
   - zone 3, with $T_C = 0.70s$.

b) three-dimensional regularity:
   - structures with regularity both in-plane and on the vertical (abbreviated REG-ALL);
   - structures with plane regularity and vertical irregularity (abbreviated REG-PL);
   - structures with vertical regularity and plane irregularity (abbreviated REG-VERT);
   - structures with both plane and vertical irregularity (abbreviated IRREG).

c) proximity of the fundamental period to the control periods:
   - near T_C, with $T_1 \approx 0.9 \cdot T_C$;
   - near T_D, with $T_1 \approx 0.9 \cdot T_D$.

For simplification and comparison purposes, a series of seismic parameters were considered constant throughout the computed models:

a) peak ground design acceleration - $a_g = 0.4g$ for MRI = 225 years;
b) importance factor - $\gamma_{I,e} = 1.00$;
c) structural system - three-dimensional frames (columns, beams, slabs) fixed at ground level, with a behaviour factor - $q = 6.75$.

Due to these simplifications, the inelastic (design) spectra of absolute accelerations for horizontal components of the seismic motion, $S_d(T)$ - measured in m/s^2) are the ones depicted in Figure 4.

Also for simplification and comparison purposes, a series of structural parameters were considered constant throughout the computed models:

a) structural material - concrete C20/25 with $E = 30GPa$, $G = 12.5GPa$, $\gamma \approx 25kN/m^3$ and $\nu = 0.2$;
b) structural layout - 4x4 grid of 6m/6m with storey height 3m;
c) beam sections - rectangular - 30x50cm;
d) slab -shell, height = 15cm, mesh elements ≤ $1.00m^2$, rigid diaphragm;
e) slab loads:

   i. permanent loads - element weights + 2.50kN/m^2;
   ii. variable loads - live load = 2.00 kN/m^2.

f) load combinations - in accordance with CR 0/2012 and P100-1.

As per P100-1 provisions and for this article, the beams and columns were considered cracked by halving their elasticity (Young) modulus.

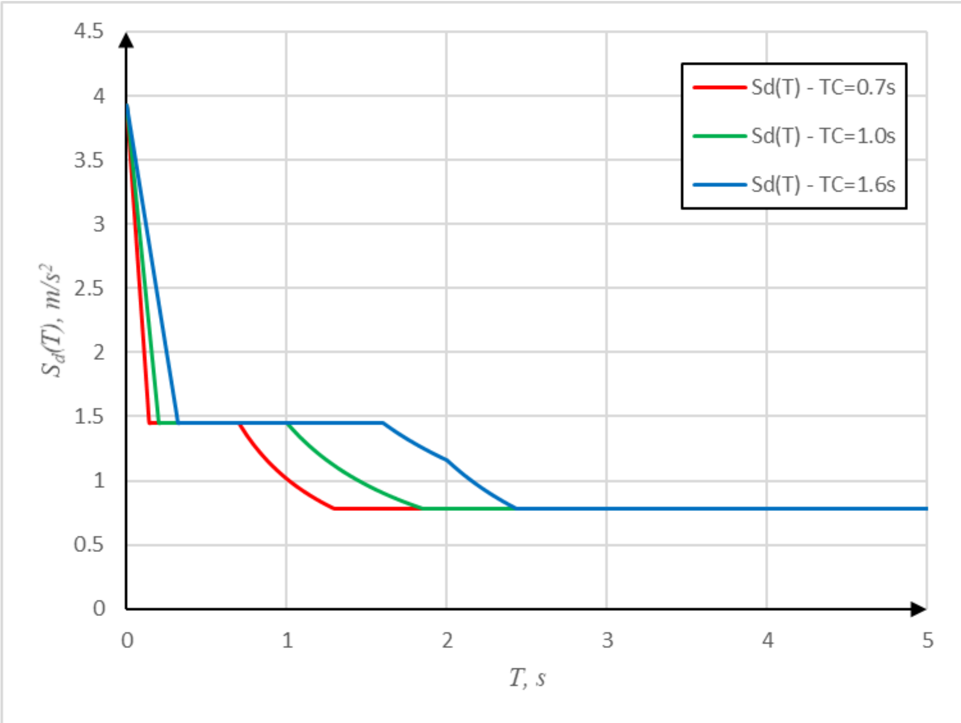

Figure 4. Inelastic (design) response spectra of absolute accelerations for horizontal components of the seismic motion, in zones characterized by control periods T_C=0.7s, T_C=1.0s and T_C=1.6s, for the chosen seismic parameters

The combination of modal responses was done by "Complete Quadratic Combination" and the combination of effects of the components of seismic action on the horizontal was done by "Square Root of the Sum of Squares" of the value of the action effect due to each horizontal component.

The vertical component of the seismic action was not considered as it is not necessary for the selected models, all of them satisfying the code criteria.

The number of vibration modes was considered such that the sum of the effective modal masses amounts to at least 98%.

1.2. Developed models

The developed models are depicted below (Figures 5-16), for the structures with a fundamental period close to T_C. The structures that have fundamental periods close to T_D have a similar shape and result from increasing the number of storeys and / or the dimensions of the columns.

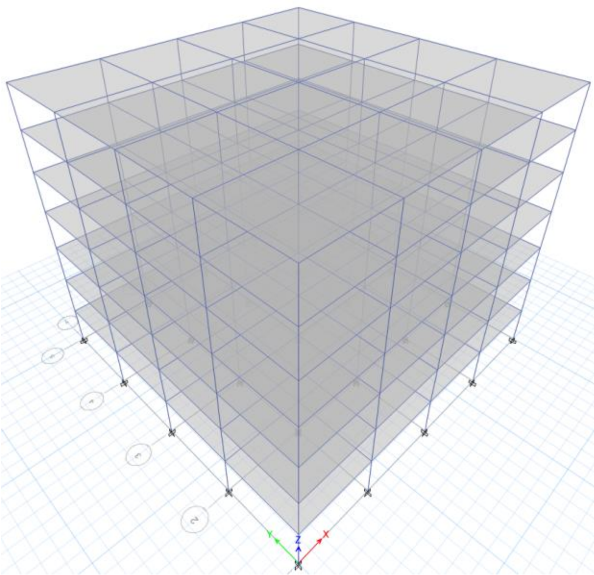

Figure 5. Zone 1 - REG_ALL

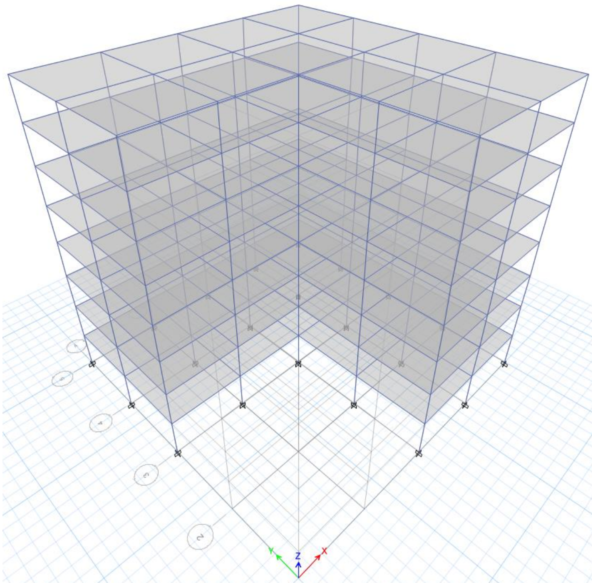

Figure 6. Zone 1 - REG_VERT

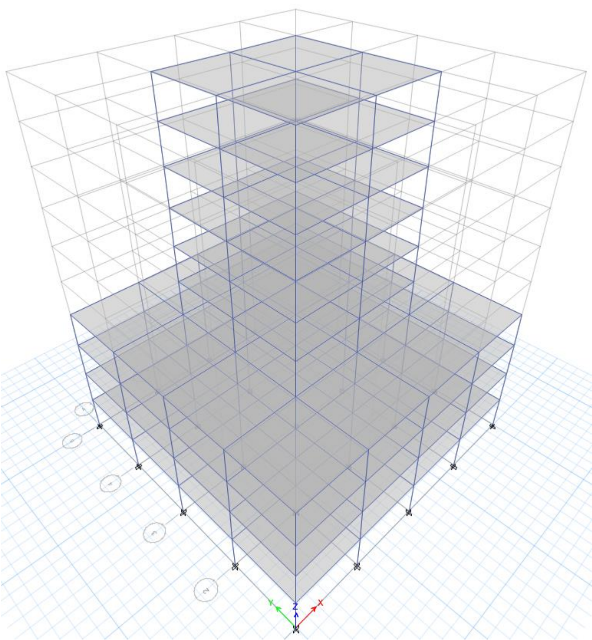

Figure 7. Zone 1 - REG_PL

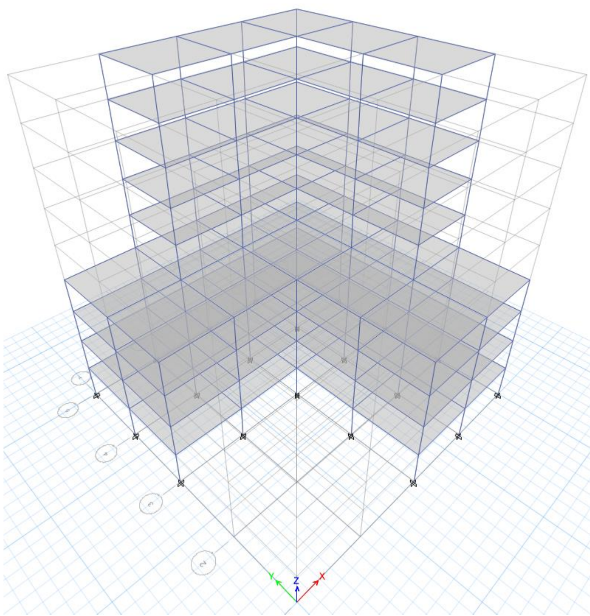

Figure 8. Zone 1 - IRREG

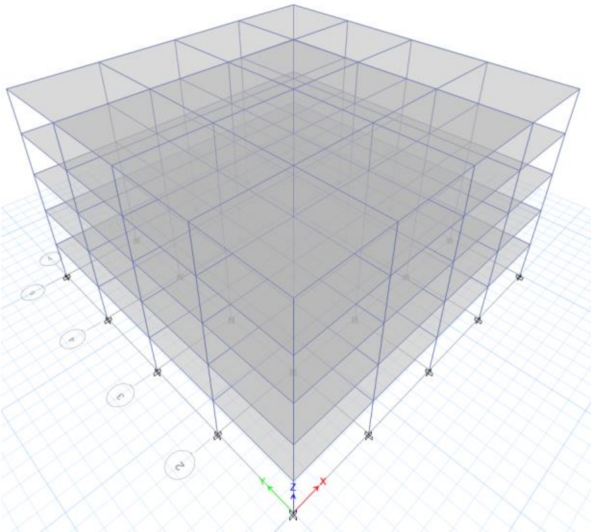

Figure 9. Zone 2 - REG_ALL

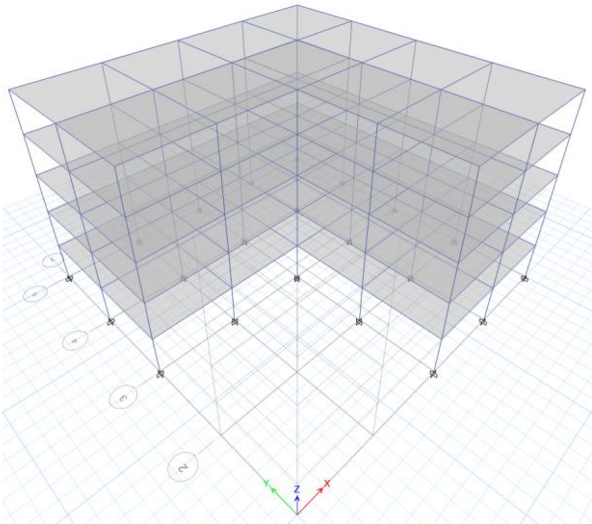

Figure 10. Zone 2 - REG_VERT

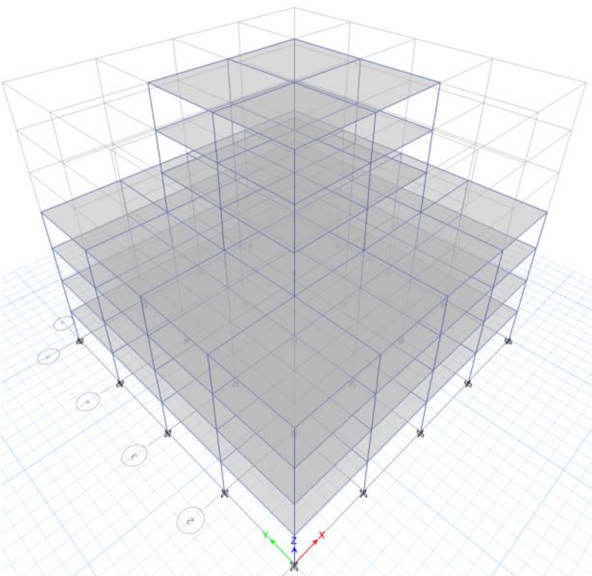

Figure 11. Zone 2 - REG_PL

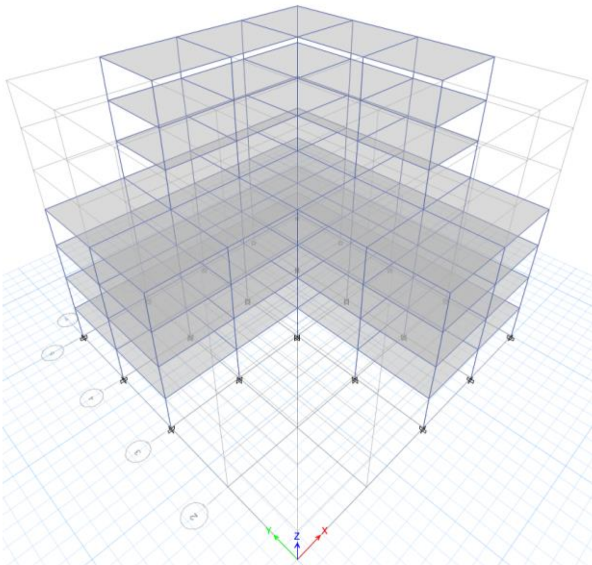

Figure 12. Zone 2 - IRREG

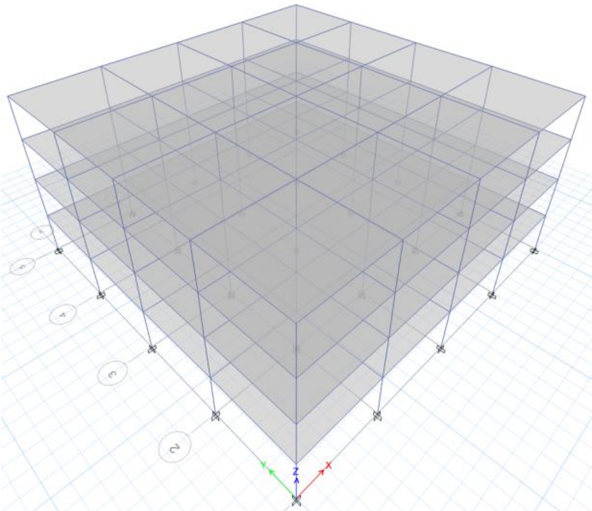

Figure 13. Zone 3 - REG_ALL

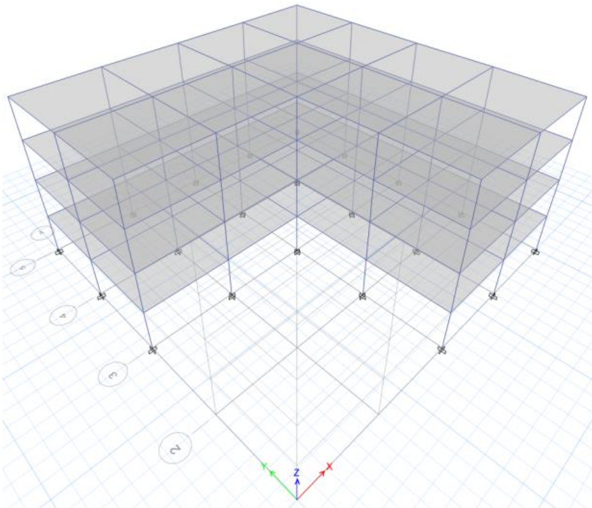

Figure 14. Zone 3 - REG_VERT

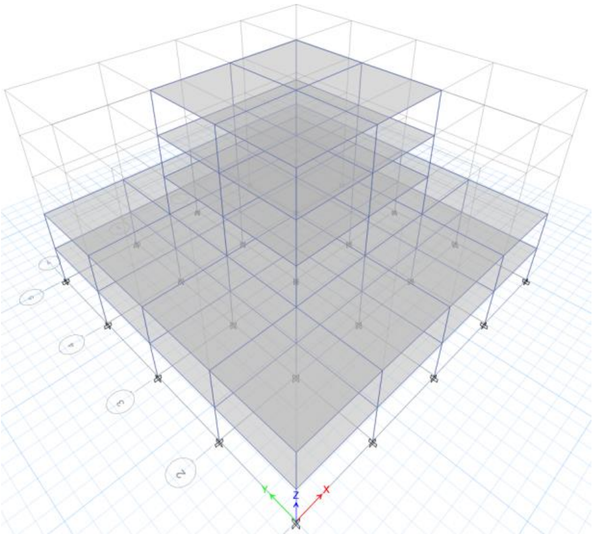

Figure 15. Zone 3 - REG_PL

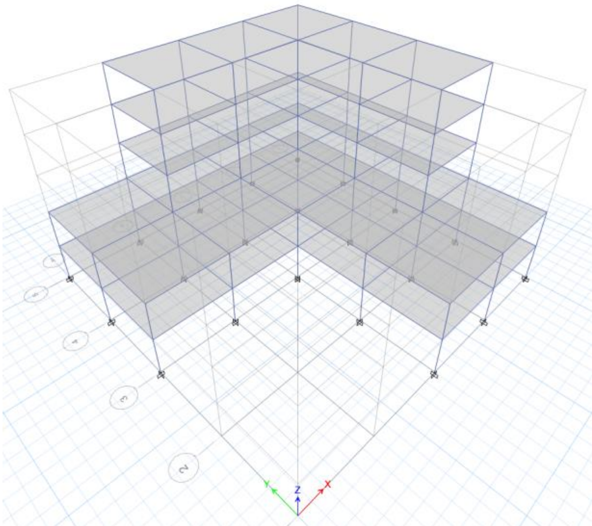

Figure 16. Zone 3 - IRREG

1.3. Analysis results

The analysis results are presented in the tables below (Tables 2-5) in terms of maximum storey drifts and base shear forces with/without considering the influence of superior eigen-modes. All results are determined in the seismic combination (STR/GEO), considering the effect of both horizontal components.

Although storey drifts were computed for the selected models, a lateral drift check (according to P100-1, Annex E) was not performed as it exceeds the purpose of the current paper.

Table 2. Analysis results - maximum storey drifts for structures with fundamental periods close to T_C

Zone	Regularity	Maximum storey drift (mm/m)	
		With superior eigen-modes	Without superior eigen-modes
Zone 1 $T_C = 1.60s$	REG_ALL	8.748	8.745
	REG_PL	10.305	10.297
	REG_VERT	8.536	8.532
	IRREG	8.173	8.159
Zone 2 $T_C = 1.00s$	REG_ALL	4.653	4.653
	REG_PL	4.154	4.149
	REG_VERT	5.091	5.090
	IRREG	4.270	4.264
Zone 3 $T_C = 0.70s$	REG_ALL	2.834	2.834
	REG_PL	3.384	3.383
	REG_VERT	3.046	3.046
	IRREG	2.782	2.780

Table 3. Analysis results - maximum storey drifts for structures with fundamental periods close to T_D

Zone	Regularity	Maximum storey drift (mm/m)	
		With superior eigen-modes	Without superior eigen-modes
Zone 1 $T_C = 1.60s$	REG_ALL	10.322	10.293
	REG_PL	11.177	11.061
	REG_VERT	9.928	9.890
	IRREG	9.832	9.730
Zone 2 $T_C = 1.00s$	REG_ALL	8.778	8.671
	REG_PL	9.160	8.952
	REG_VERT	9.699	9.557
	IRREG	8.518	8.436
Zone 3 $T_C = 0.70s$	REG_ALL	8.731	8.729
	REG_PL	9.160	9.011
	REG_VERT	9.646	9.639
	IRREG	8.518	8.440

Table 4. Analysis results - Base shear force for structures with fundamental periods close to T_C

Zone	Regularity	Base shear force (kN)	
		With superior eigen-modes	Without superior eigen-modes
Zone 1 $T_C = 1.60s$	REG_ALL	6497	6468
	REG_PL	4092	4037
	REG_VERT	5762	5726
	IRREG	3718	3681
Zone 2 $T_C = 1.00s$	REG_ALL	4734	4702
	REG_PL	4180	4131
	REG_VERT	3592	3572
	IRREG	3651	3553
Zone 3 $T_C = 0.70s$	REG_ALL	3857	3828
	REG_PL	2143	2094
	REG_VERT	2930	2912
	IRREG	2168	2102

Table 5. Analysis results - Base shear force for structures with fundamental periods close to T_D

Zone	Regularity	Base shear force (kN)	
		With superior eigen-modes	Without superior eigen-modes
Zone 1 $T_C = 1.60s$	REG_ALL	7384	7282
	REG_PL	3977	3052
	REG_VERT	6381	6278
	IRREG	3794	3462
Zone 2 $T_C = 1.00s$	REG_ALL	7256	7009
	REG_PL	3472	2256
	REG_VERT	5462	5276
	IRREG	3735	3179
Zone 3 $T_C = 0.70s$	REG_ALL	7924	7862
	REG_PL	3472	3077
	REG_VERT	5412	5373
	IRREG	3644	3431

3. CONCLUSIONS

From the comparative analysis of results (Figure 17 and Figure 18), the most affected seismic response when superior eigen-modes are not taken into account, in terms of both storey drift and base shear force, is for the structures with plane regularity and vertical irregularity that have fundamental periods close to T_D, having an increase in storey drift of 2.25% and an increase in base shear force of 35% if the structures are located in Zone 2 ($T_C = 1.00s$).

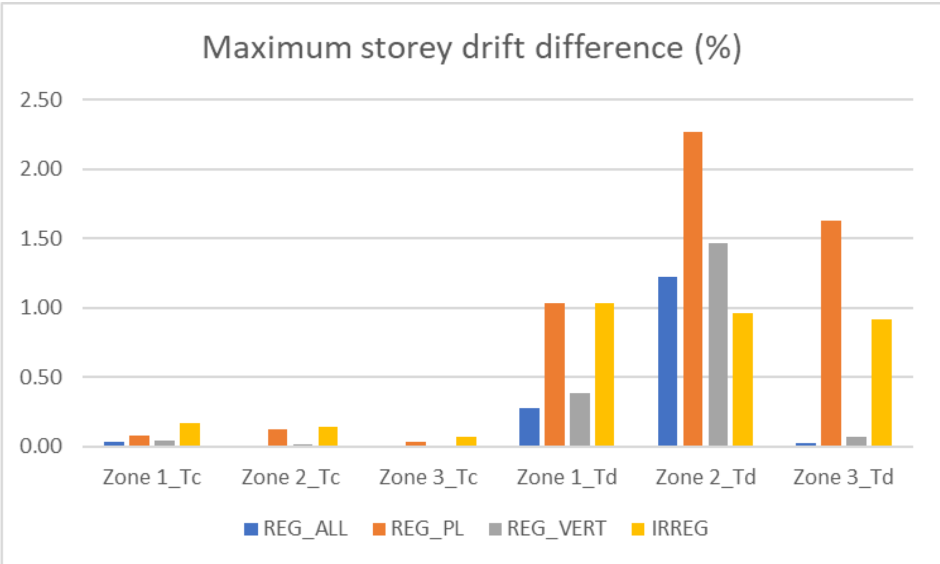

Figure 17. Maximum storey drift difference (% increase)

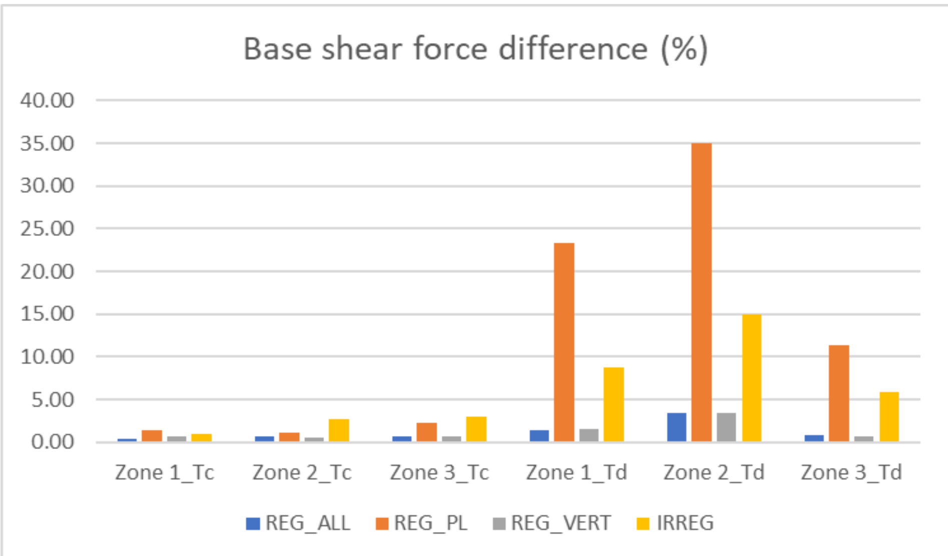

Figure 18. Base shear force difference (% increase)

The second most affected seismic response in terms of both storey drift and base shear force is for structures with plane and vertical irregularity that have fundamental periods close to T_D, having an increase in storey drift of 1% and an increase in base shear force of 15% if the structures are located in Zone 2 ($T_C = 1.00s$).

In the cases that showed a significant increase in seismic effect, it is mainly due to the vertical irregularity, both types of structures having large masses at the bottom and smaller masses towards the top.

For all analysed types of structures that have fundamental periods close to T_C, regardless of their shape, the effect of superior eigen-modes is negligible - under 0.2% for maximum storey drifts and under 4% for base shear force.

It was observed that for almost all analysed structures the superior eigen-modes that were not taken into account correspond to the modes that are excepted from code provisions (after the modal mass sum reaches 90%). There were some exceptions, but even in those cases, a maximum of two vibration modes was not considered.

In conclusion, even if code provisions allow the exception of superior eigen-modes, in some cases their effect might be significant.

It must be said, however, that the analysed cases that are the most affected are fringe cases (medium-rise structures with fundamental periods close to T_D, in highly seismic areas) that probably won't satisfy other code provisions, such as lateral drift checks. In these cases, an increase in structural rigidity is mandatory, causing a shift in fundamental period that will bring it closer to T_C and of course, a redistribution of masses to or from other vibration modes.

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