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Influence of Empirical and Dynamic Periods on the Seismic Responses of Reinforced Concrete Buildings Braced by L-Shaped Shear Walls

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Abstract
The Algerian Seismic Regulation of 1999, version 2003 (RPA99/v2003), presents ambiguities and a lack of thorough explanations in certain articles, which has led to a diversity of readings and interpretations among various stakeholders in the field, particularly the control offices. This situation has caused significant disagreements, especially during the approval of civil engineering files, thus resulting in a negative impact on project progress. To ensure adequate seismic protection of civil engineering structures, this work aims to unify the interpretations of certain passages of the regulation, with a particular emphasis on verifying the fundamental period of the structure, the shear forces at the base, and inter-story displacements using seismic calculation methods prescribed by the RPA. The comparative study demonstrates that no correlation between the period determined by the equivalent static method and that calculated by the spectral modal analysis method has been observed. This justifies the conclusion that adjusting between the empirical period and the dynamic period is not necessary.
Keywords: Reinforced concrete structures. L-shaped shear walls. Periods. Shear forces. Displacements.

1. Introduction

Seismic and active tectonic studies were initiated after the October 10, 1980 earthquake in El Asnam (Ms=7.3), located 200 km west of the Algerian capital, Algiers (Maouche *et al.*, 2019). This earthquake caused surface ruptures on a northeast-oriented thrust fault, spanning 30 km (Yielding *et al.*, 1981), destroying over 70% of buildings, while others suffered only minor damages (Boutaraa, 2019). This tragic event led to the development of the first version of seismic regulations, known as RPA 81 (DTR B.C2-48., 1981). This regulation was later revised and expanded in 1983 (DTR B.C2-48., 1983). The two previous regulations relied solely on the equivalent static method for seismic force calculation. In 1988, the spectral modal analysis method was introduced as an alternative for seismic force calculation, leading to the creation of RPA 88 (DTR B.C2-48., 1988). Following the experience gained and lessons learned from recent earthquakes in Algeria and other countries, a revision of the previous regulations was undertaken, resulting in the creation of RPA 99, where both the spectral modal dynamic method and the equivalent static method were placed on equal footing (DTR B.C2-48., 2000). The latest earthquake on May 21, 2003, in Boumerdès (Algeria), resulting in the loss of over 2300 lives and more than 10,000 injuries, led to a new revision of the regulation, resulting in the creation of RPA 99 version 2003 (DTR B.C2-48., 2003). This latest version of the regulation primarily encouraged the use of reinforced concrete shear walls.

For many years, various bracing systems have been developed to resist forces. However, the use of a combined column-beam and shear wall system has proved to be a more effective solution for ensuring shear resistance (Laissy., 2023). Shear walls contribute to the stability of reinforced concrete structures by reducing the effect of lateral forces, especially seismic forces (Wang *et al.*, 2024; Guan *et al.*, 2024; Aly and Galal., 2020). This result has been numerically and experimentally proven by several researchers (Tolou Kian and Cruz-Noguez., 2020; Epackachi and Whittaker., 2018). Ding *et al*. (2024) emphasize that these walls directly influence the seismic behavior of structures. Their thickness and the density of steel bars increase with the height of buildings and the intensity of the earthquake. Shear walls take various forms such as T-shaped walls (Wang *et al.*, 2023; Wang *et al.*, 2022; Liu *et al.*, 2023), U-shaped walls (Kim *et al*., 2023; Hoult and Beyer., 2021), and H-shaped walls (Silva *et al.*, 2023). However, numerous studies have been conducted on L-shaped reinforced concrete shear walls (Gu *et al*., 2022; Merabti *et al.*, 2023; Merabti and Bezari., 2023). Gu *et al*., (2022) researched stacked prefabricated L-shaped shear walls, while Liu *et al*., (2024) investigated the oblique seismic behavior of reinforced concrete L-shaped columns reinforced by carbon fiber polymer slabs. Similarly, Choi *et al.*, (2003) analyzed, both experimentally and numerically, the seismic behavior of unreinforced masonry L-shaped walls. Furthermore, previous works by Wood., (1990) and Gulec *et al.*, (2007) have emphasized that the behavior of shear walls depends on various factors such as concrete compressive strength, yield strength of reinforcements, shear wall thickness, and its specific shape. Interestingly, a study by Dabbagh., (2005) revealed a reduction in ductility when high-strength concrete is used in shear walls. These studies underline the crucial importance of considering several factors when designing shear walls, especially those in L shape.

The equivalent static and spectral modal analysis methods have been employed to simulate the seismic response of reinforced concrete buildings during any earthquake represented by a regulatory design spectrum. However, the calibration of the fundamental period was extensively discussed in the section concerning the equivalent static method, but no indication of this parameter in the spectral modal analysis method was discussed (DTR B.C2-48., 2003). This study aims to examine the relationship between the period obtained by the equivalent static method and that derived from the spectral modal analysis method, as well as their impact on verifying the base shear force and inter-story displacements, in the case of regular buildings braced by L-shaped shear walls.

2. Research studies program

Seismic analyses were conducted on five reinforced concrete structures with varying heights but fixed geometry (see Figure 1). These analyses were performed using the ETABS simulation software, version 2018. The buildings, with heights of 6m, 9m, 12m, 15m, and 18m, and fixed plan dimensions (Dx = 9m and Dy = 12m), were modeled. L-shaped shear walls, each with a length of 2m and a thickness of 15cm, were placed at the corners of the buildings. They were excited by a single response spectrum, with parameters introduced into the simulation software according to the Algerian Seismic Regulation (DTR B.C2-48., 2003).

- High seismicity zone: Zone III,
- Occupancy group: 1B,
- Loose soil: S3,
- Behavior coefficient : R = 3.5,
- Quality factor: Q = 1.2.

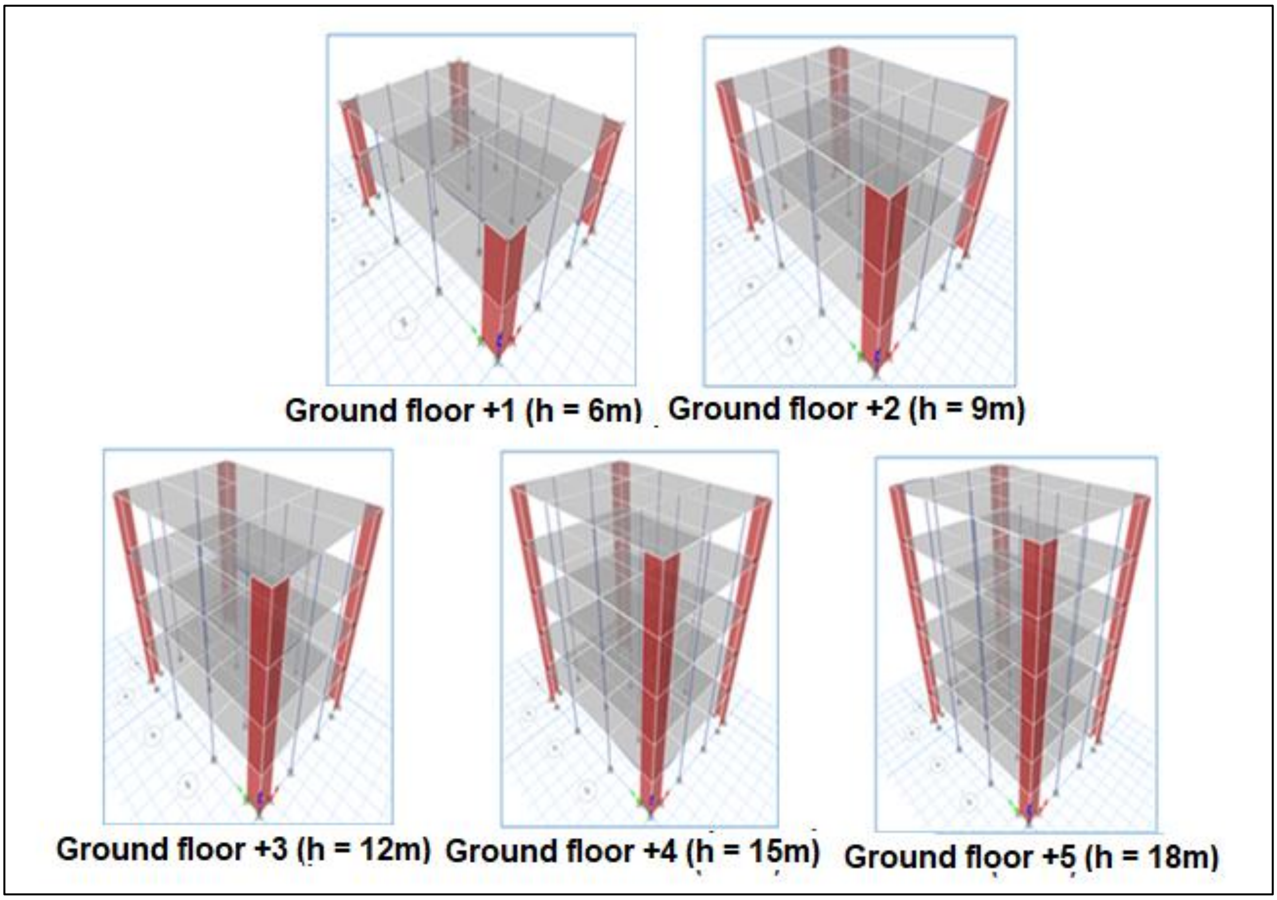

Figure 1. Modelling of the five buildings.

The empirical periods, seismic forces, and inter-story displacements were determined following the RPA 99/v2003 (DTR B.C2-48., 2003).
The two empirical periods are calculated using the following formulas:

$$T = C_t h_N^{3/4} \tag{1}$$

$$T = 0.09 h_N / D \tag{2}$$

Where:
h_N: Height measured in meters from the base of the structure to the topmost level (N).
C_t: Coefficient, dependent on the bracing system and the type of infill.
D: Dimension of the building measured at its base in the direction of the considered calculation.

According to the equivalent static method, the values of T obtained from Rayleigh's formulas or numerical methods must not exceed those estimated from the appropriate empirical formulas by more than 30%."

$$T < 1.3 T_{numeric} \tag{3}$$

The seismic force from the equivalent static method is given as follows:

$$V = \frac{A\,.\,D\,.\,Q}{R}.W \qquad (4)$$

Where:
A: Zone acceleration coefficient is given according to the seismic zone and the building occupancy group.
D: Mean dynamic amplification factor, dependent on the site category, damping correction factor (η), and the fundamental period of the structure (T).
Q: Quality factor.
W: Total weight of the structure.
R: Overall behavior coefficient of the structure.

Verification of the inter-story displacement of the different buildings is also studied, with the following relationships:

$$\delta_k = R.\delta_{ek} \qquad (5)$$
$$\Delta_{ky} = \delta_k - \delta_{k-1} < 1\%h \qquad (6)$$

Where:
δ_{ek}: Displacement due to seismic forces Fi, including torsional effects.
R: Behavior coefficient (R = 3.5).
h: Storey height

3. Results and analysis

3. 1. Verification of periods

Figure 2 illustrates the relationship between the empirical period and the dynamic period as a function of the height of the different buildings in both the X and Y directions. The results obtained indicate that increasing the height of the building contributes to an increase in both periods. This can be attributed to the decrease in flexural rigidity with height and the increase in the mass of the structure. It is also noted that the values of the periods T, calculated using the spectral modal analysis method (dynamic), are lower than those estimated from empirical formulas for buildings with heights less than 9m, for both the X and Y directions (formula 3). However, for heights ranging from 12 to 18m, the values of the dynamic periods are lower than 1.3 times the static periods for the X direction. In contrast, for the Y direction, the values of the static periods are higher than 1.3 times the dynamic periods. However, the dynamic period exceeds that calculated by the equivalent static method by more than 30% for the building with a height of 18m. The results highlight a reduction in both periods in the Y direction for heights ranging from 6m to 9m, thus indicating a direct correlation between empirical and dynamic periods and the dimensions of the structure, namely the height and plan dimensions of the buildings. Notably, the empirical period appears more significant in the Y direction, while a less pronounced dynamic period is observed in the X direction.

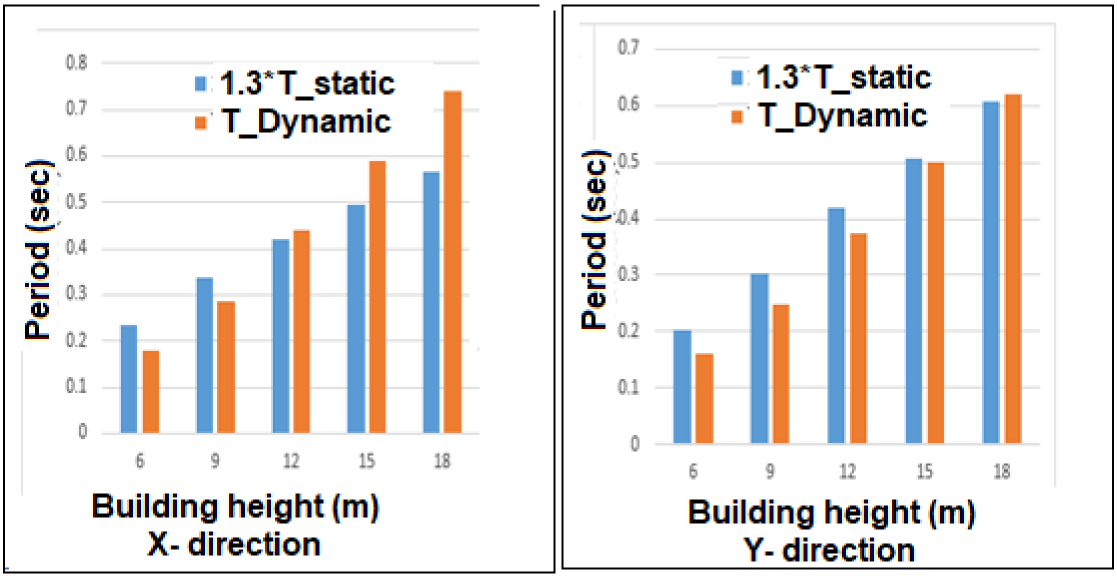

Figure 2. Relationship between the empirical period and the dynamic period as a function of the height "h" in both directions.

3.2. Shear force verification

The base shear forces calculated using the equivalent static method and the spectral modal analysis method for each type of building are illustrated in Figure 3. By comparing buildings with different heights but the same plan dimensions, a total agreement is observed between the two directions, where the relationship of the base shear force is not verified from the first level. This can be explained by the fact that the L-shaped shear walls were of reduced dimensions, which can also be attributed to the specific nature of the site (S3). Indeed, according to research conducted by Merabti and Bézari., (2023), the type of soil has a significant influence on the seismic response of buildings. It is worth noting that the ratio between $V_{dynamic}$ and 80% of V_{static} increases with the elevation of the building height, especially in the X direction. The results of this simulation show almost similar dynamic and static shear forces for heights ranging from 6m to 12m, regardless of the building direction. However, a predominance of dynamic shear forces is observed in the Y direction when the building height exceeds 12m. This explains the discrepancy between the forces at 80% of V_{static} and $V_{dynamic}$ in the X direction.

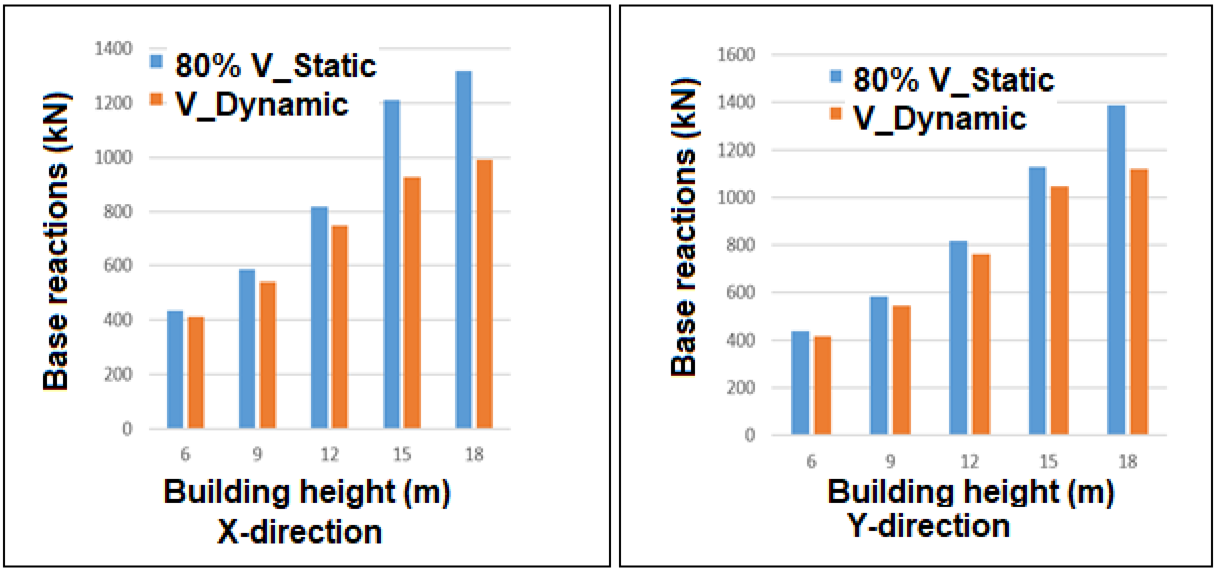

Figure 3. Verification of the shear force at the base as a function of the height "h" in the X and Y directions.

3.3. Inter-story displacements verification

The results of the inter-story displacements for each level of the five buildings studied, in the X and Y directions, are summarised in the following table 1.

Table 1: Verification of lateral displacements.

Type of building	Δ_{kx} (mm)	Δ_{ky} (mm)	1%h (mm)	Verification
	13.104	8.922		
	16.104	11.781		
Ground floor + 5	19.016	16.530	30	Verified
	20.097	18.230		condition
	17.591	14.774		
	8.148	7.168		
	12.877	9.118		
	15.593	11.862		Verified
Ground floor + 4	17.318	13.192	30	condition
	15.645	13.192		
	7.368	6.515		
	11.095	7.459		
	12.635	9.037		Verified
Ground floor + 3	11.859	8.971	30	condition
	5.712	4.550		
	7.070	5.040		
Ground floor + 2	7.105	5.411	30	Verified
	3.640	2.951		condition
	4.319	3.350		Verified
Ground floor + 1	2.391	1.960	30	condition

The results obtained indicate that inter-story displacements are verified for each direction of the building and each level, although the validation of the base shear force is not confirmed and the periods are not consistently verified in most cases. Inter-story displacements increase with the height of the building. The largest displacement is recorded for the 18m building, with a value of 20.097mm at the second-story level.

4. Conclusion

The analysis of the data collected in this study shows that there is no significant relationship between empirical and dynamic periods based on the height of the buildings. This suggests that calibration between these two periods may not be necessary. Therefore, it may not be appropriate to assess the seismic resistance of buildings using only empirical methods. At the same time, the increase in building height leads to a significant increase in both periods, mainly due to a decrease in building stiffness and an increase in their mass. The difference between dynamic and empirical periods is particularly pronounced for buildings between 12 and 18 meters in height, highlighting the importance of dynamic approaches in seismic assessment. Furthermore, for buildings taller than 12 meters, a predominance of dynamic shear forces is observed in the Y direction, while this predominance in the X direction is less pronounced. Finally, when examining the base shear forces, it is noteworthy that they do not depend on the modal behavior of the structure.

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