Influence of the angle of incidence of the earthquake on the seismic response of a regular building' shape.

Saddika Mohamadi[1], Malika Boumaiza[2], Belaid Amrane[3], Ouafa Ziane [4], Maroua Naoui[5],

[1]PhD Student, Civil engineering department, University of Bouira, Algeria
E-mail : s.mohamadi@univ-bouira.dz
[2]PhD Student, Civil engineering department, University of Bouira, Algeria
E-mail : m.boumaiza@univ-bouira.dz
[3]Associate Professor, Civil engineering department, University of Bouira, Algeria
E-mail : am_belaid@yahoo.fr
[4.5]Master Student, Civil engine ering department, University of Bouira, Algeria
E-mail : ouafagc07@gmail.com

ABSTRACT

Reinforced concrete structures are generally stressed by a three-dimensional seismic movement (two horizontal components and one vertical component). In most cases and respecting the seismic regulations in force, the dynamic analysis of these structures is carried out by considering only the two orthogonal components of the horizontal seismic movement (0° and 90°).
In this work, the influence of earthquake direction on the seismic response of regular buildings will be examined. A building of six stories of a regular rectangular shape braced by reinforced concrete shear walls located in average seismicity zone is invested for the analysis of critical incidence.
The response spectrum acceleration is calculated using the Algerian seismic code RPA 2003 following directions with an angle varying from 0 to 90° with a step of 10° from the principal horizontal x axis. The spectral modal analysis of the building is made using the ETABS software.
The various response parameters studied are the reaction at the base of the structure, its maximum horizontal displacement, the stresses (axial force, shear force, bending moment) in the horizontal and vertical elements and the normal stresses in columns and walls.
The results obtained demonstrate that the maximum seismic response of the examined structure as a function of the angle of incidence coincides with the main orthogonal axes (0° and 90°). It is observed in this study that the behavior of the examined structure varies according to the angle of incidence of the earthquake applied.

Keywords: Angle of incidence, regular building, shear walls, seismic response, RPA 2003.

INTROCUTION

Earthquakes are one of the most destructive "natural" disasters, unlike floods, cyclones or volcanic eruptions. Earthquakes, with their unexpected appearances, strike within seconds, causing enormous damage and often numerous victims. They affect several countries in the world, notably Algeria which was shaken on May 21, 2003 in Boumerdes city by an earthquake of magnitude Mw=6.8 and which caused 2,266 deaths in addition to the 10,261 injured and 200,000 homeless people recorded. This poses a final challenge to earthquake engineers and civil engineers to design buildings, bridges and dams capable of withstanding the devastating forces caused by earthquakes.
In most seismic regions, the adoption of construction techniques designed to reduce earthquake risk is aimed at increasing the resistance of structures. But the question is how and by what means structures can be strengthened under varying earthquake direction.
Several researchers have investigated the effect of horizontal earthquake direction on building behaviour. They have always posed the question in relation to the most unfavourable directions of the earthquake, which result in the maximum responses or stresses required for seismic design [1-3].

The Algerian seismic code, RPA99/2003 [4], does not allow to study the effect of the direction of the earthquake other than those of the main axes of the building. The direction of the earthquake is defined as perpendicular to the dimensions of the building (along x and y). In recent years, however, considerable progress has been made in research into the influence of the angle's incidence of earthquake on the dynamic behaviour of structures.

The main objective of this work is to evaluate the influence of the earthquake incidence angle on the dynamic response of a regular-shaped building. This will be achieved by its application to a six-storey portal frame building braced by shear walls, which will be invested for critical incidence analysis with a variation in earthquake direction from 0° to 90° with a 10° step.

DESCRIPTION OF THE STRUCTURE

The structure under study is a regular, six-storey residential building braced by frames and shear walls. It is located in the wilaya of Bouira, which is classified as a medium seismicity zone (zone IIa) according to the Algerian seismic code RPA 99 /2003.

The building is classified as a standard structure of medium importance (use group 2), as its height does not exceed 48m. The site is considered a soft site (S3).

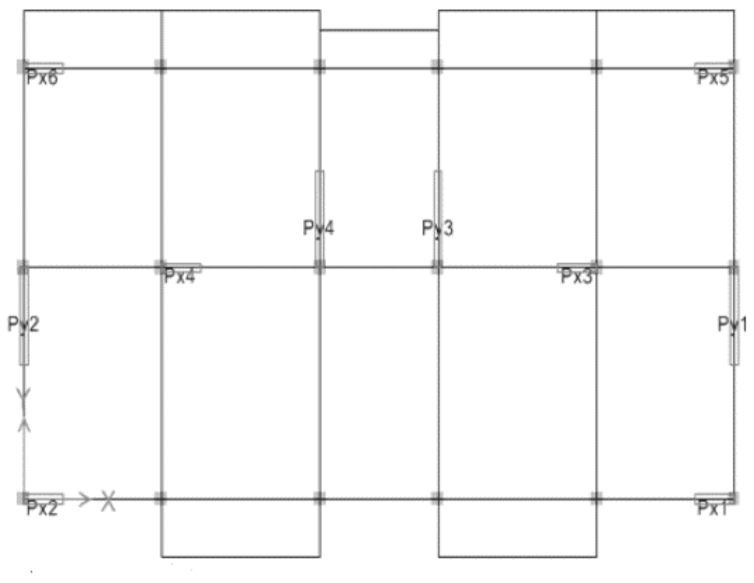


Fig. 1: Plan view of the structure.

The geometric characteristics of the structure are given in Table 1.

Table 1: Geometric characteristics of the structure studied.

	Designation	Value (m)
Total length	**L**	18.4
Total width	**l**	11.65
Total height	**H**	19.38
Ground floor height	h_{rdc}	4.08
Current storey height	h_{ec}	3.06

The dimensions and cross-sections of the building's structural elements (columns, beams, shear walls, slabs) are shown in Table 2. The columns, beams, shear walls and slabs (balcony) of the structure were considered to be made of reinforced concrete with linear elastic behavior. The material proprieties are summarized in Table 3 [5], The behavior of the structural elements was considered as linear elastic. A structural Rayleigh damping ratio of 8.5% [4], was assigned for all the elements in the concrete frame-shear wall building.

Table 2: Structural sections considered in the building

Section	Notation	Sections (cm x cm)	Thickness (cm)
Columns story 1	C1	45x45	
Columns story 2	C2	40x40	
Columns story 3	C3	35x35	
Columns story 4-6	C4	30x30	
Shear wall along X	SW1	100X0.2	
Shear wall along Y	SW2	0.2x200	
Beam	PB	30x40	
	SB	30x35	
Balcony slab	BS	/	15
Slab (Hollow body)	HBS		20 (16+4)

Table 3: Material proprieties considered for the structural elements in the building

Parameter	Notation	Columns, beams and shear walls
Young modulus (GPa)	E (GPa)	32
Shear Modulus (GPa)	G	12,5
Volumic Weight (kg/m^3)	ρ	2500
Poisson Ratio	ν	0,2
Damping Ratio	ξ	0,085

ANALYSIS OF THE EFFECT OF THE EARTHQUAKE'S ANGLE OF INCIDENCE ON THE DYNAMIC RESPONSE OF THE STRUCTURE

In order to study the effect of the angle of incidence of the earthquake on the dynamic response of the structure, the seismic action is defined by two components in the x and y directions, as shown in Figure 2. The seismic action is introduced using a design response spectrum.

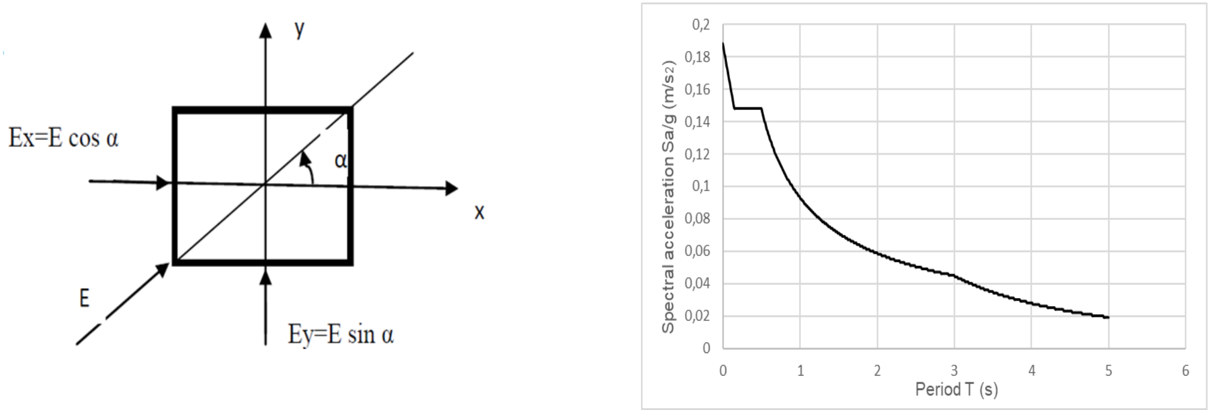


Fig. 2: Components of the seismic load and design response spectrum.

The dynamic characteristics of the structure according to RPA 99/2003 [4] are shown in Table 4.

Table 4: Dynamic proprieties of the building

Behavior coefficient R	Acceleration coefficient of the zone A	Dynamic amplification factor D	Quality factor Q
3.5	0.15	Dx=1,96 Dy=1,20	Qx=1,25 Qy=1,20

Numerical analysis of the dynamic response of the structure

To study the influence of the direction of the earthquake on the dynamic response of the structure, we carried out a spectral modal analysis [6] using ETABS 2016 software based on the finite element method (FEM), varying the angle of incidence of the earthquake from 0° to 90° with a step of 10°. The columns and beams were modelled with frame elements. The slab floors were modelled with deck elements. The shear walls and balcony slabs were modelled by shell elements [6]. beam structural elements were two-noded, straight, finite elements with six degrees of freedom per node, including three translational components and three rotational components. The shell structural elements were four-noded, flat finite elements with 20 degrees of freedom. Soil-structure interaction is not considered in the model and base are restraints in all three X, Y and Z directions. For the Response Spectrum Analysis RSA, SSRS (square root of the sum of square) and CQC (Complete quadratic Combination) are considered [7]. A sufficient number of modes (16 modes) are considered in the analysis such that to get the sum of mass for all modes assumed 90% of the total seismic mass, according to the RPA 99/2003 [4]. The mesh size used is the default mesh size in the ETABS software.

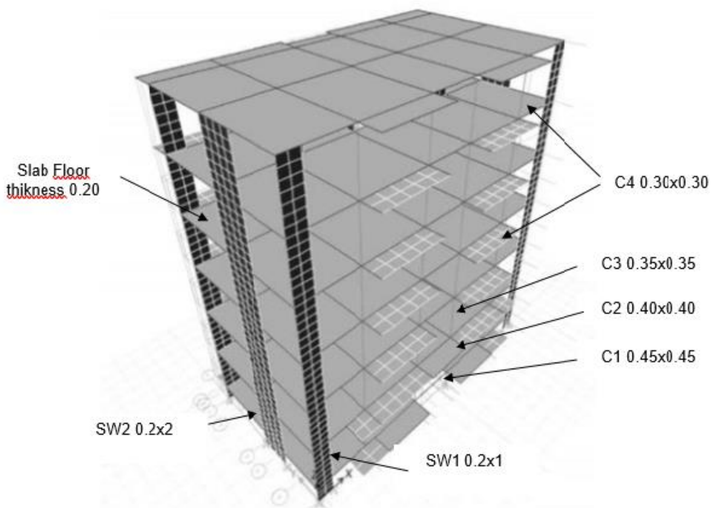


Fig. 3: Numerical simulation of the structure by ETABS 2016.

The arrangement of the braced walls was made in such a way that the first and second modes of vibrations are translations along X and Y and the third mode is a rotation around Z.
The regularity of the building was checked by calculating the eccentricity between the center of mass and the center of rigidity [8]. at each floor (e_x=0.0027m and e_y=0.017m).
The first vibration mode is translation along X with a period T_1= 0.577s, the second vibration mode is translation along Y with a period T_2= 0.528s, while the third mode is rotation around Z with a period T_3= 0.497s.
The response of the structure is calculated in both directions for the most unfavourable load combination:

$$G+Q+E \qquad (1)\ [4]$$

Where:
G: Dead loads.
Q: Live loads
E: Seismic Load.
The values of G and Q for the various elements are given in the following table:

Table 5: Dead and Live Loads

Element	Terrace floor	Current floor	Balcony
G (KN/m^2)	6.83	5.09	5.31
Q (KN/m^2)	1	1.5	3.5

The variation in response studies the following parameters: reaction at the base of the structure, maximum displacement and maximum solicitations in columns, beams and shear walls.

RESULTS AND DISCUSSION

Influence of the seismic angle of incidence on the seismic reaction at the base of the structure

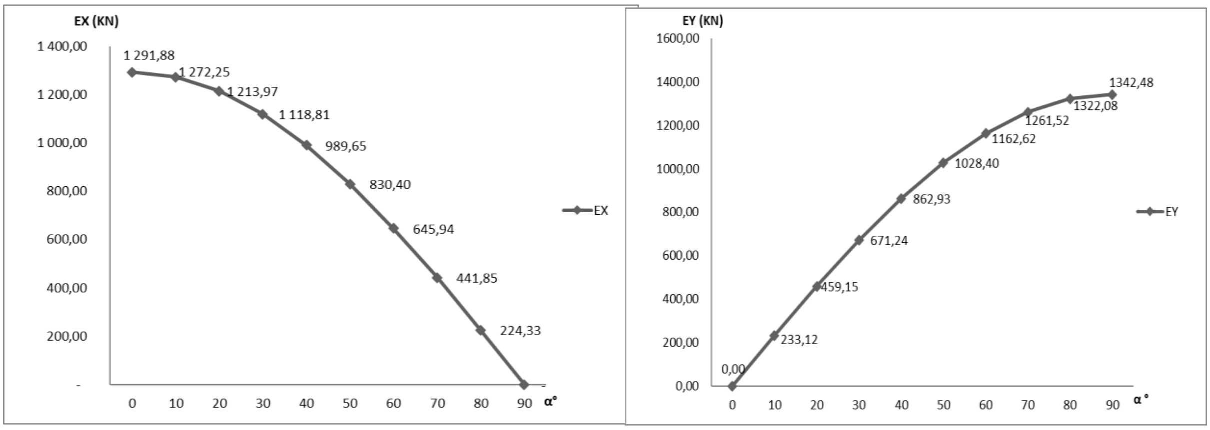


Fig.4: Seismic reaction at the base as a function of the angle of incidence of the earthquake

The seismic reaction at the base in the x direction has a maximum value of Ex=1291.87 KN at angle α=0°, then decreases until it reaches a zero value at angle α=90°. On the other hand, the seismic reaction at the base in the y direction varies from Ey=0 KN at angle α=0° to reach a maximum value of Ey=1342.47 KN at α=90°.

Influence of the angle of incidence of the earthquake on the horizontal displacement of the structure

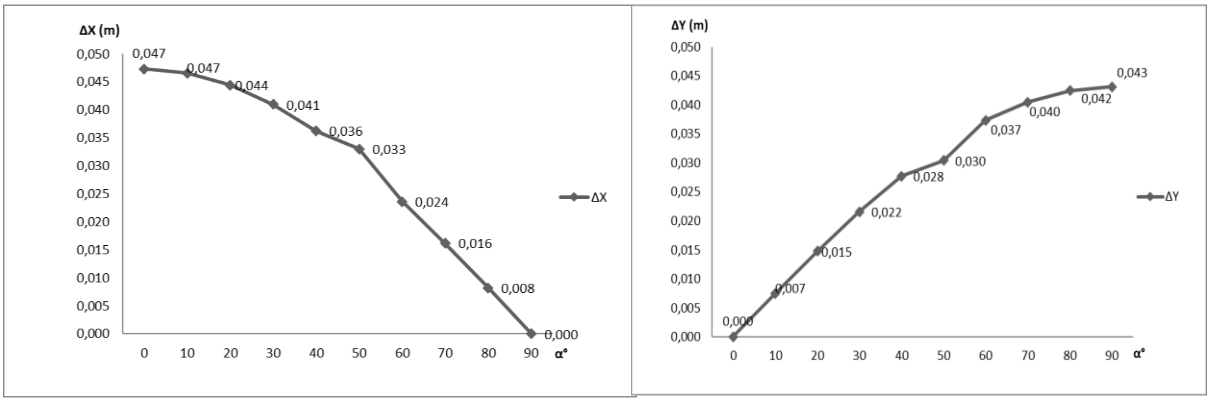


Fig.5: Horizontal displacement of the structure as a function of the seismic angle of incidence

We observe that the maximum displacement in the x direction is ∆x =0.047m at angle α= 0°, then it decreases until reaching a zero value at angle α=90°. On the other hand, the displacement following the direction y varies from Δy = 0m at the angle α=0° until reaching a maximum value Δy = 0.043m at α=90°.

Influence of the angle of incidence of the earthquake on the stresses in the columns

The aim of this analysis is to study the dynamic behaviour of columns under the effect of the variation in the seismic angle of incidence. The results obtained for the most heavily loaded column are shown in Figure 6,7 and 8.

We not that the axial force in the most stressed column varies from N=815.77 KN at angle α=0° to a maximum force of N=876.36KN at angle α= 90°. The normal stress varies from σ =4028.49 KN/m2 at an angle of incidence of 0° until reaching the maximum value σ =4327.73 KN/m2 at the angle 90°.

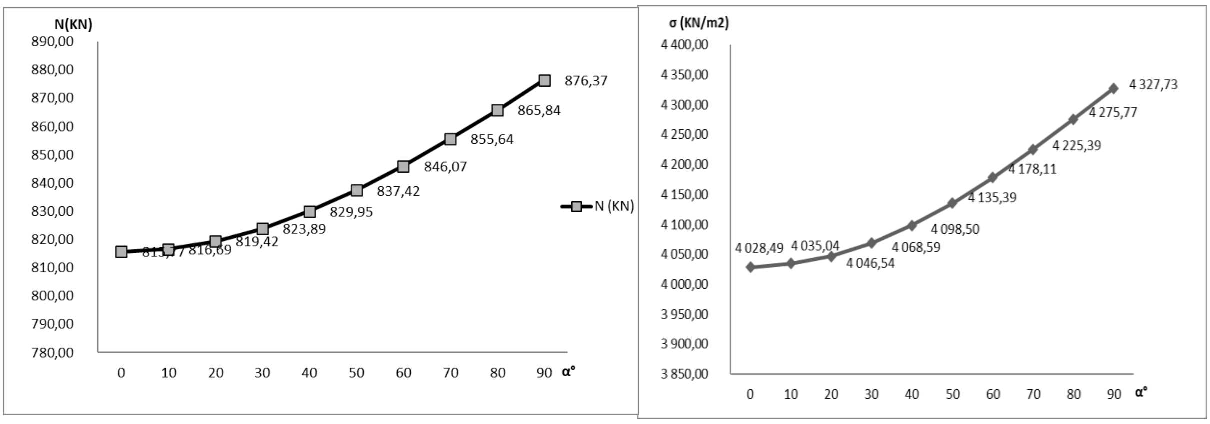


Fig.6: Axial force in the most stressed column as a function of the seismic angle of incidence.

As for the shear force, the maximum value along axis 2.2 V2=32.36 KN is obtained at angle α=0° and decreases until reaching a value of V2=-2.21 KN at angle α=90°. The maximum shear force along axis 3.3 V3=32.36 KN itself is obtained at angle α=0° and decreases until reaching a value of V3=14.81 KN at angle α=90°.

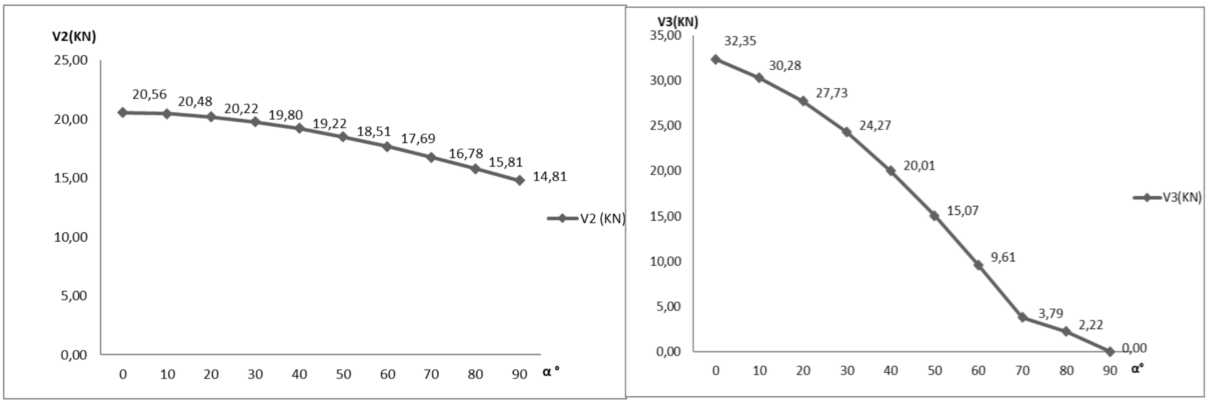


Fig.7: Shear force in the most stressed column as a function of the seismic angle of incidence.

Regarding the influence of the angle of incidence of the earthquake on the bending moment, we note that the most unfavourable value along axis 3.3 M3=45.36 KN.m is obtained at angle α=0° then it decreases until reaching a minimum value of M3=0.72 KN.m. The variation of the moment along axis 2.2 presents an approximately constant curve but always the maximum and minimum values are obtained at angles 0° and 90° respectively.

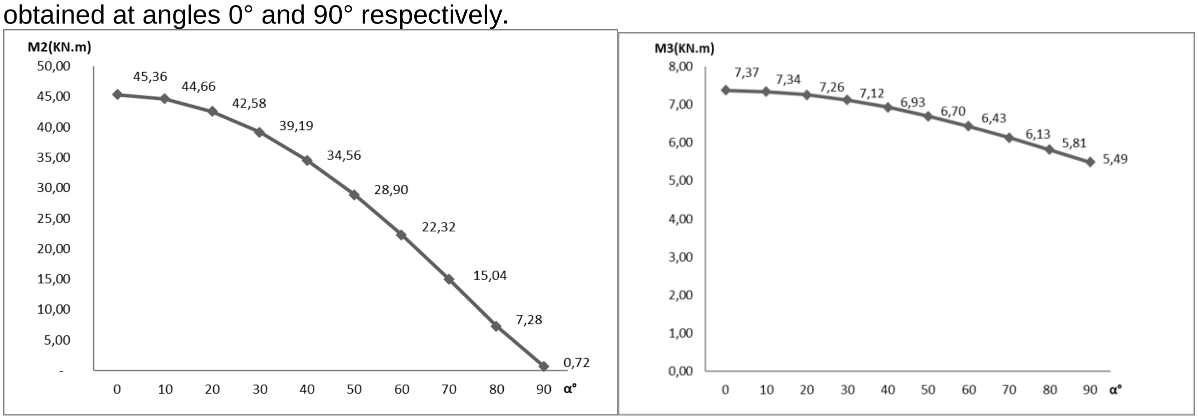


Fig.8: Bending moment in the most stressed column as a function of seismic angle of incidence

Influence of the angle of incidence of the earthquake on the stresses in the beams

Beams are among the horizontal load-bearing elements that distribute seismic loads in the structure to the vertical elements (columns and walls). For this purpose, we studied the effect of the angle of incidence of the earthquake on the bending moment and shear force in beams.

- The principal beam

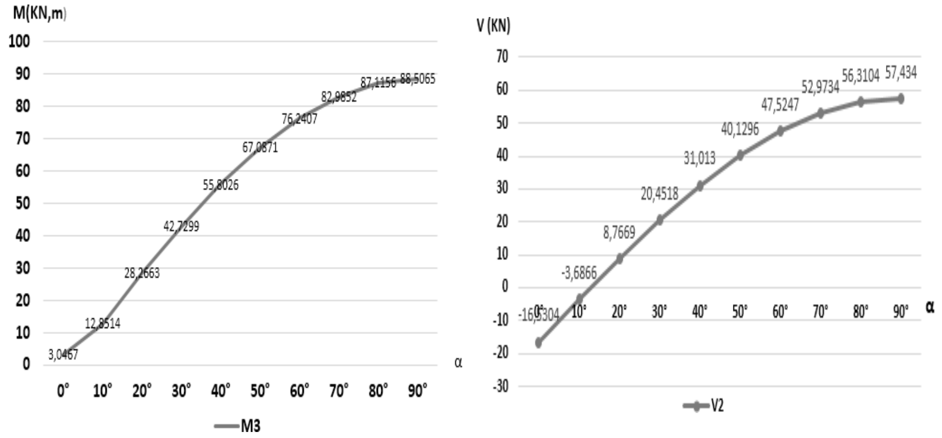
The variation of bending moment and shear force as a function of the angle of incidence of the earthquake in the most stressed principal beam is shown in Figure 7.

The bending moment increases from M=3.05 KN.m at angle α=0° to reach a maximum of M=88.51 KN.m at angle α=90°. As for the shear force, it varies increasingly from V=-16.53 KN at angle α=0° to reach a maximum value of V=57.43 KN at angle α=90°.

- The secondary beam

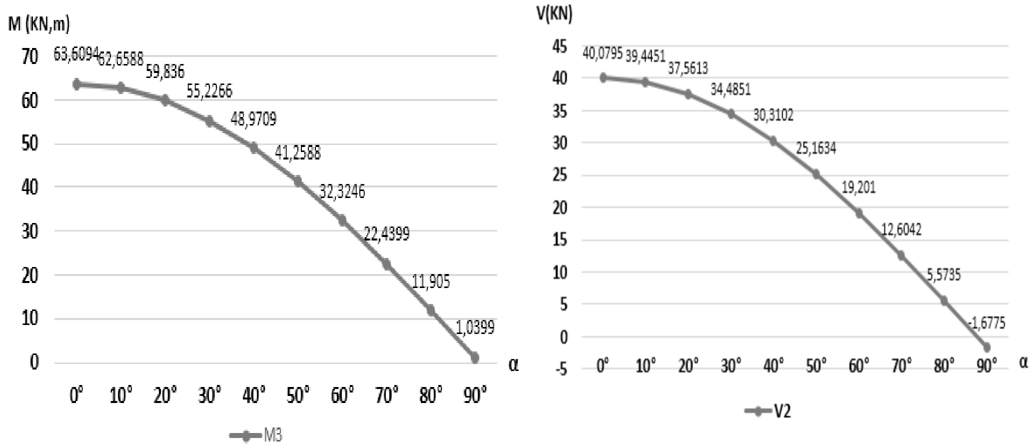
The variation of bending moment and shear force as a function of the angle of incidence of the earthquake in the most stressed secondary beam is shown in Figure 8.

The bending moment decreases from M=63.60 KN.m at angle α=0° to reach a minimum value of M=1.04 KN.m at angle α=90°. As for the shear force, it varies in a decreasing manner from V=40.08 KN at angle α=0° to reach a minimum value of V=-1.67 KN at angle α=90°.



(1) Variation of bending moment **(2)** Variation of shear force

Fig.9: Stresses in the principal beam as a function of the seismic angle of incidence



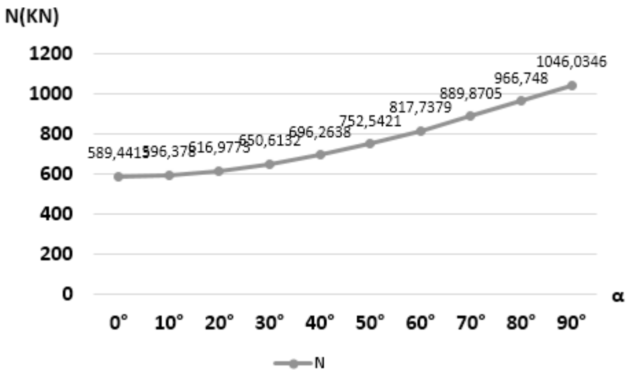
(1) Variation of bending moment **(2)** Variation of shear force

Fig. 10: Stresses in the secondary beam as a function of the seismic angle of incidence

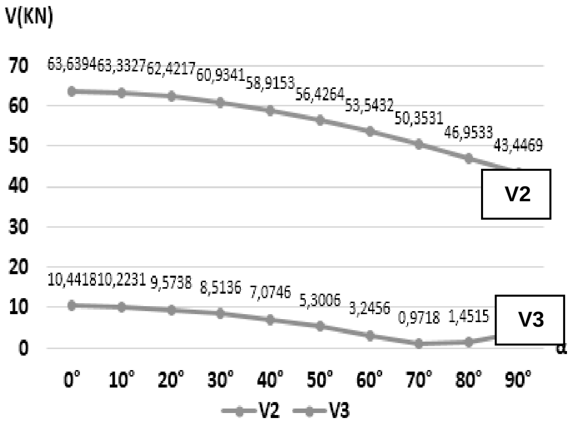
Influence of the angle of incidence of the earthquake on stresses in shear walls

In reinforced concrete frame structures braced by shear walls, the walls take up no more than 20% of the stresses due to vertical loads and all the stresses due to horizontal loads [4]. To this end, we

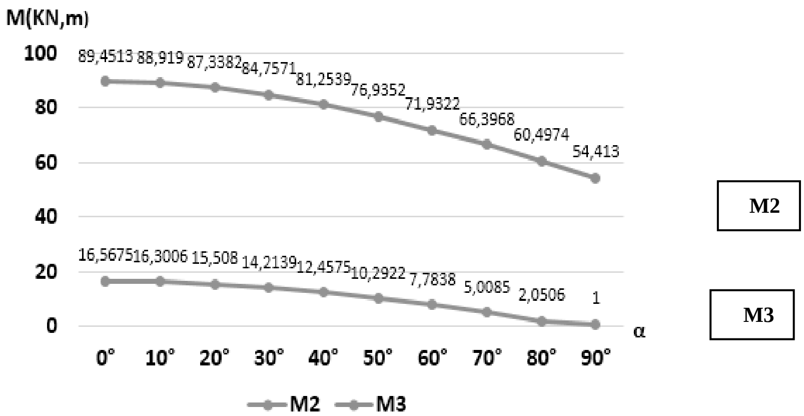
studied the effect of varying the angle of incidence of the earthquake on the stresses in shear walls. The results obtained for the most stressed wall are shown in Figure 9.
It can be seen that the axial force has a minimum value N=589.44 KN at angle α=0°, which increases as the angle of incidence varies, reaching a maximum value N=1046.03KN at angle α=90°.
With regard to shear force along axis 2.2, seismic action develops the most unfavorable value V2= 63.63 KN at angle α=0°, which then decreases to reach a minimum value V2= 43.44 KN at angle α=90°. The shear force along axis 3.3 itself varies from V3= 10.44 KN at angle α=0° to reach a minimum value V3=3.95 KN at angle α=90°.
For the bending moment along axis 3.3, the most unfavorable value M=89.45 KN.m is obtained at angle α=0° which decreases until reaching a minimum value M=54.41 KN.m at angle α=90. For the bending moment along axis 2.2, the maximum and minimum values always correspond to angles 0° and 90°respactively.



(1) Variation of axial force



(2) Variation of shear force.



(3) Variation of bending moment

Fig.11: Stresses in the shear wall as a function of the angle of incidence of the earthquake

CONCLUSION

In order to study the influence of the angle of incidence of the earthquake on the dynamic behaviour of regular shape buildings with regular frames braced by reinforced concrete shear walls, we analysed a six-storey building by varying the angle of incidence of the earthquake.
This analysis shows that the seismic reactions at the base (Ex and Ey) and the maximum horizontal displacements (Δx and Δy) are always along one of the building's principal directions x or y. This is due to the existence of the shear walls, which are arranged along the two principal directions and offer great rigidity to the structure.

Bending moments and shear forces in columns and shear walls are maximum at angles α=0° and 90°, depending on the direction in which the shear walls are positioned. Normal stress in columns and shear walls is highest at angle α=90°.
In the case of beams, we have seen that stresses are greatest at α=0° for secondary beams and at α=90° for principal beams, due to their stiffness along these axes.
Finally, we deduce that the angle of incidence of the earthquake has no influence on the dynamic response of this type of structure, so the most unfavorable direction of the earthquake coincides with the principal axes of the building.
On the basis of this limited study, we propose to carry out further studies or work on all structural typologies (regular, irregular, in plan, in elevation, with or without shear walls), taking into account the vertical component of the earthquake, and to see whether the seismic response of the structure can be different for angles of incidence of the earthquake different from the principal axes of the building.

REFERENCES

1. Anastassiadis, K., Directions sismiques défavorables et combinaisons défavorables des efforts. Annales de l'I.T.B.T.P. 512 (Mars/Avril), pp. 83-99, 1993.
2. Lopez, O.A., and Torres R., The critical angle of seismic incidence and the maximum structural response. Earthquake Eng. Struct. Dyn. 26, pp. 881-894, 1997.
3. M. Athanatopoulou, A. Tsourekas & G. Papamanolis, (2005) Variation of response with incident angle under two horizontal correlated seismic components, Earthquake Resistant Engineering Structures, vol 81.
4. Ministère de l'Habitat et de l'Urbanisme, Règles Parasismiques Algériennes RPA 99/Version 2003, Edition CGS,2003.
5. G. A. L. Jiménez et D. Dias, « Dynamic Soil–Structure Interaction Effects in Buildings Founded on Vertical Reinforcement Elements », CivilEng, vol. 3, no 3, p. 573-593, juin 2022, doi: 10.3390/civileng3030034.
6. A. K. Chopra, *Dynamics of Structures: International Edition*. Pearson Education Limited, 2015.
7. B. K. Bohara, K. H. Ganaie, M.Tech in Structural Engineering Sharda University, P. Saha, et Department of Civil Engineering, Sharda University, India, « Effect of position of steel bracing in L-shape reinforced concrete buildings under lateral loading », Res. Eng. Struct. Mater., 2021, doi: 10.17515/resm2021.295st0519.
8. S. E. Abdel Raheem, M. M. M. Ahmed, M. M. Ahmed, et A. G. A. Abdel-Shafy, « Seismic performance of L-shaped multi-storey buildings with moment-resisting frames », *Proc. Inst. Civ. Eng. - Struct. Build.*, vol. 171, n° 5, p. 395-408, mai 2018, doi: 10.1680/jstbu.16.00122.