Journal of Materials and Engineering Structures

Research Paper

Investigation of the angle formed in irregular structures on their seismic behavior

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ARTICLE INFO

Article history :

Received : 7 July 2022

Revised : 19 November 2022

Accepted : 14 December 2022

Keywords:

Re-entrant corner

Seismic incident angle

Irregular structure

Response spectrum analysis

Pushover analysis

ABSTRACT

The design of structures with re-entrant angle is often the consequence of the functional, architectural or urbanistic requirement. With any form building, the engineer has full responsibility to ensure the safety of the users and the structure in the case of the earthquake. However, re-entrant angle structures have geometric dissymmetry and limited choice in the disposition of rigid structural elements. The objective of this work is to evaluate the effect of the angle formed between the two wings of an L-shaped building, softened by a transition on their dynamic behavior. Different variants were considered by taking several angle values (45°, 60°, 75°, 90°, 105°, 120° and 135°). In order to evaluate the impact of the analyzed parameter, a study of the linear and non-linear dynamic behavior of the different structures was executed by the spectral modal analysis method and the non-linear static analysis. According to the atypical geometrical configuration in the plan of the various structures, six principal seismic directions were considered Ex, Ey, Ex', Ey', Ex" and Ey". The results show that seismic excitation applied on the transition zone of a building with projected parts occurs a higher deformability. In addition, along this seismic direction, the progressive pushing of a uniform lateral loading applied on the structure with a projections opening angle of 90° assures a better nonlinear behavior in terms of base shears bearing capacity, deformation ductility and damage level.

1 Introduction

Generally, the building attributed to the engineering field has always been one of the most important economic sectors. In effect, during an earthquake, the appropriate behaviour of a seismic design depends on several factors such as stiffness, adequate lateral strength, and ductility, simple and regular configurations [1-6]. However, with the evolution of technology, irregularly shaped structures are usually unavoidable. In addition, the evaluation of their seismic performance is one of the most important sources of serious damage [5, 7-10].

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e-ISSN: 2170-127X,

RESEARCH REVIEW of Sciences and Technologies

The literature shows that among the irregularities in structures the most confronted are represented by configurations with extensions or wings in the plan[11]. In this context, several researches [12-23] have been performed on the study of seismic behaviour under the effect of irregular shape with re-entrant corner. Furthermore, the problems caused by this irregularity can be summarized in two types[24]. Firstly, at the corner stress concentration occurs due to the different stiffness and movements of these parts of the building [7, 25]. The second problem is that of torsional forces whose resulting eccentricity between the centre of mass and the centre of rigidity tends to deform the structure and provokes torsional forces that are very difficult to analyse [7, 8, 26, 27]. To minimize the damage in the intersection of the projecting parts, which must have the capacity to resist and dissipate the effects of torsion adequately; several solutions have been proposed to improve the dispositions to achieve the best seismic performance. Fajari and Sumarsono [28] studied horizontal irregular buildings while eliminating the problem by employing seismic joints where two systems were adopted by using double columns and console beams. The results obtained show that the separation by a system of console beams reduces the horizontal irregularity.

Other researchers [24, 29-31] suggest the installation of resistance elements to reduce torsional movement. Mazza et al.[32] have evaluated the torsional effects of the superior modes of an existing structure with an L-shaped plan reinforced by the addition of hysteretic damper braces system, in order to reach the performance levels imposed by the Italian seismic code (NTC08) in a high-risk zone. The results obtained show that the incorporation of hysteretic dampers is very effective to reduce local structural damage, in terms of maximum curvature ductility demand at the column end sections.

In addition, Arnold et al. [7] present another proposal for the re-entrant corner problem; this solution consists of creating transitions between the two wings. However, the assessment of the seismic performance of this architectural typology has rarely been made in evidence. However, in order to understand and respond to the need for the survivability of these structures, more research is needed. To this purpose, the aim of this work is to evaluate the effect of the angle created between the two projecting parts of a five-storey reinforced concrete building braced by a resisting frame system containing a re-entrant corner smoothed by transition, built on a low seismicity zone in Algeria.

2 Description of structures

A comparative study is conducted considering seven reinforced concrete structures with different opening angles (45°, 60°, 75°, 90°, 105°, 120° and 135°) (Fig. 1). The variants to be studied are structures composed of a five floor. These structures have the same number of spans in both longitudinal and transverse directions with the same spacing of 4 m, and a fixed storey height at all levels of 3.06 m (Fig. 1-h). It is supposed to be located in a seismic zone class IIa (low seismicity), implanted on a soil of type S3 according to the Algerian seismic rules [33]. The bracing is provided by a resisting frame system (columns and beams). The geometric cross-sections of the elements constituting the structures studied are indicated in Table 1. The material characteristics considered are 25 MPa for the specified concrete compressive strength f_{ck} and Fe-400 MPa for the reinforcement yield stress.

Table 1 – Geometric data of the studied structures elements.

Structures		
Number of storeys	5	
Geometrical of the structures elements	Storey height	3,06m
	Beams	300x400 mm²
	Columns	400x400 mm²
	Slabs	200 mm

2.1 Unification of total weight

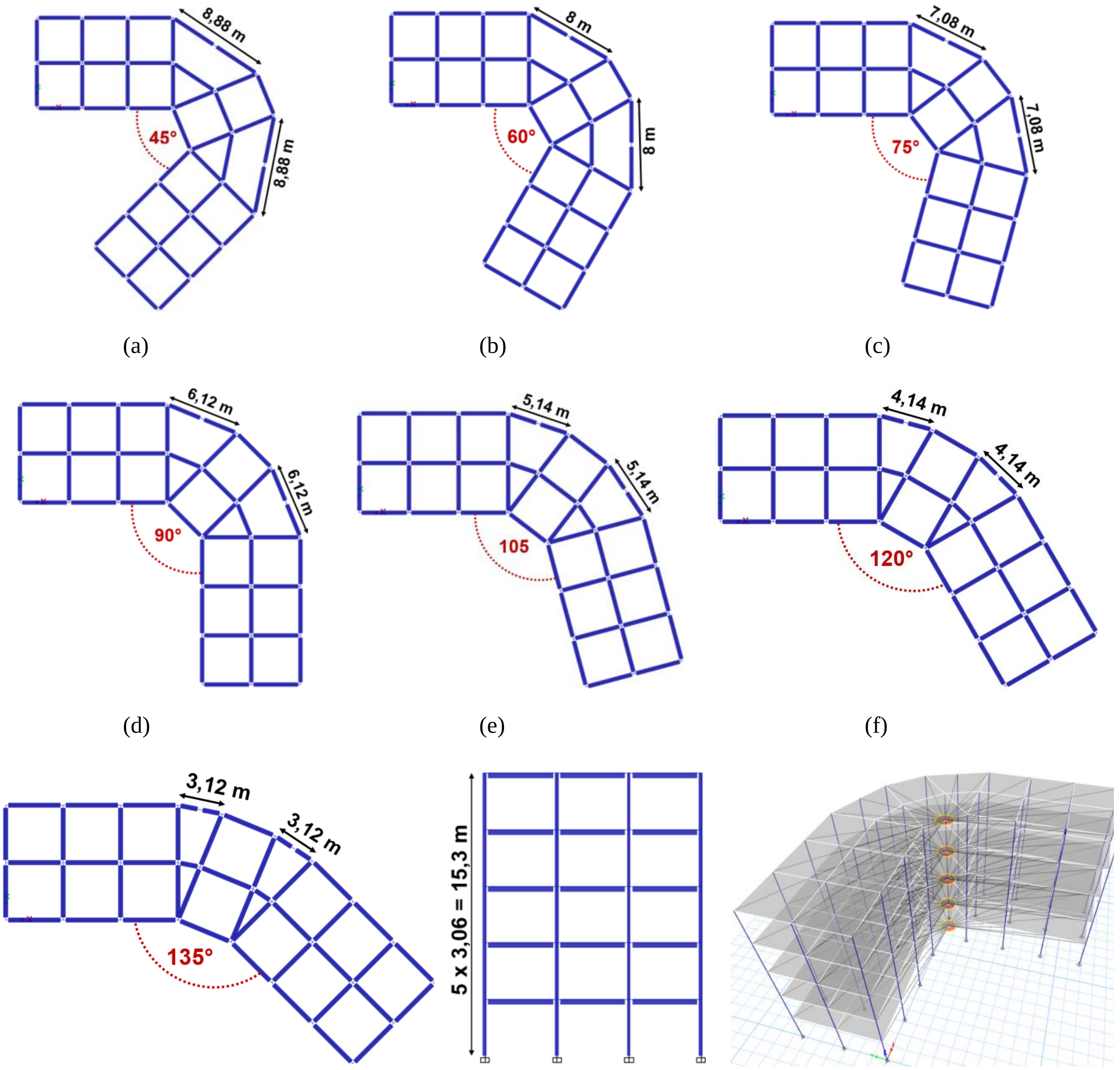
According to the Algerian Seismic Rules [33] the total weight of a residential use building is determined by the Formula (1).

$$W_i = W_{Gi} + 0{,}2W_{Qi} \tag{1}$$

with

W_{Gi} : Represents the weight due to dead loads and those of any fixed equipment linked to the structure;

W_{Qi} : Represents the weight due to live loads;



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 1 – Variants studied: (a) Structure A45°; (b) Structure A60°; (c) Structure A75°; (d) Structure A90°; (e) Structure A105°; (f) Structure A120°; (g) Structure A135°, (h) Elevation view, (i) 3D view.

In order to evaluate the effect of the angle formed between the two wings of the structure, it becomes more interesting to find a weighting coefficient that keeps the same total weight of the A45° structure, which has the most weight compared to the other variants. Based on several correlations, the improvement of Formula (1) was stopped, and which is expressed by the following equation:

$$W_i = \alpha\, W_{Gi} + 0{,}2W_{Qi} \tag{2}$$

α: Represents the ponderation coefficient to unify the total weight.

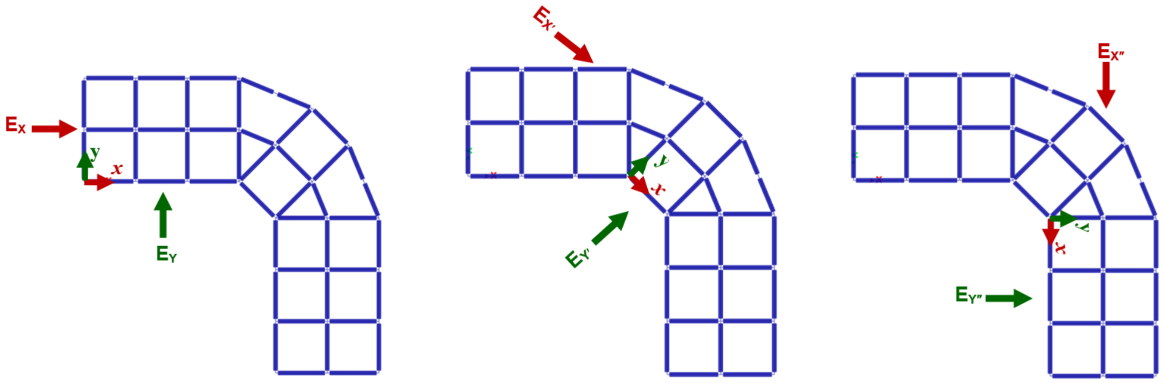
The values of the ponderation coefficients obtained for each variant considered are shown in Table (2).

Table 2 - Ponderation coefficient to unify the weight of the different variants.

Variants	Initial mass (t)	Ponderation coefficient (α)	Resulting mass (t)	Weight (KN)
A45°	1412,95	/	/	13861,07
A60°	1396,28	1,01218861	1412,953	13861,07
A75°	1376,23	1,02724080	1412,953	13861,07
A90°	1353,08	1,04516676	1412,953	13861,07
A105°	1327,18	1,06596208	1412,952	13861,06
A120°	1298,91	1,08959854	1412,951	13861,05
A135°	1268,70	1,11601847	1412,948	13861,02

2.2 Earthquake directions

In general, for regular shapes, two principal seismic directions are considered in the global frame [34-36]. In contrast, for irregular shapes, the direction of the earthquake takes several seismic directions [2, 5, 37-39]. For this study, three landmarks were considered and each landmark has two seismic directions (horizontal part Fig. 2 a, inclined part Fig. 2 b and vertical part Fig. 2 c). Table 3 shows the rotation angle of each landmark of the different variants relative to the landmark of the horizontal part.

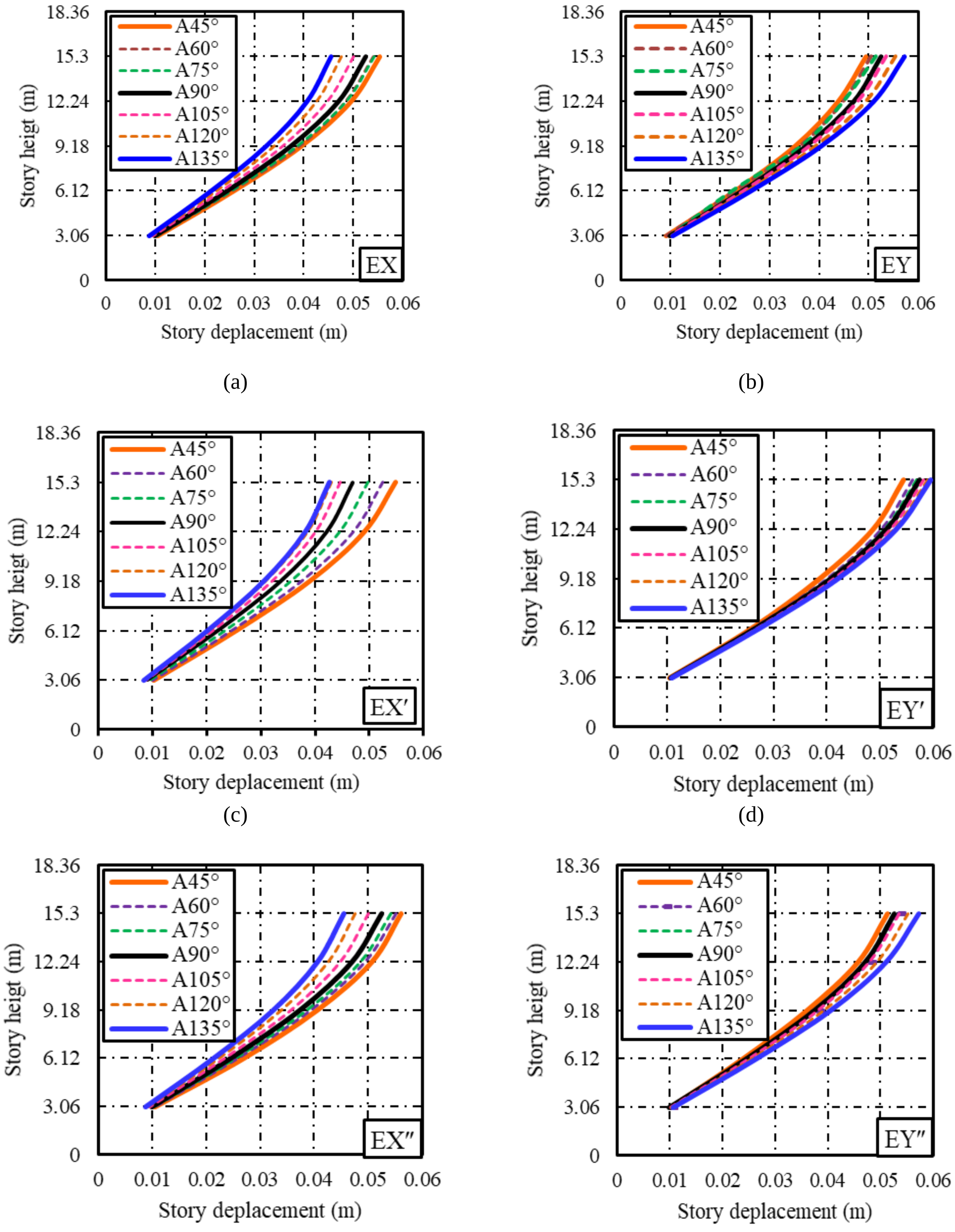


(a) (b) (c)

Fig. 2 – Representation of the dominant earthquakes for each benchmark considered of the A90° structure: (a) horizontal part; (b) inclined part; (c) vertical part.

Table 3 - Rotation angle of each part of the different variants.

Variants	Horizontal part	Inclined part	Vertical part
A45°	0	67.5°	135°
A60°		60°	120°
A75°		52,5°	105°
A90°		45°	90°
A105°		37.5°	75°
A120°		30°	60°
A135°		22,5°	45°



(a) (b)

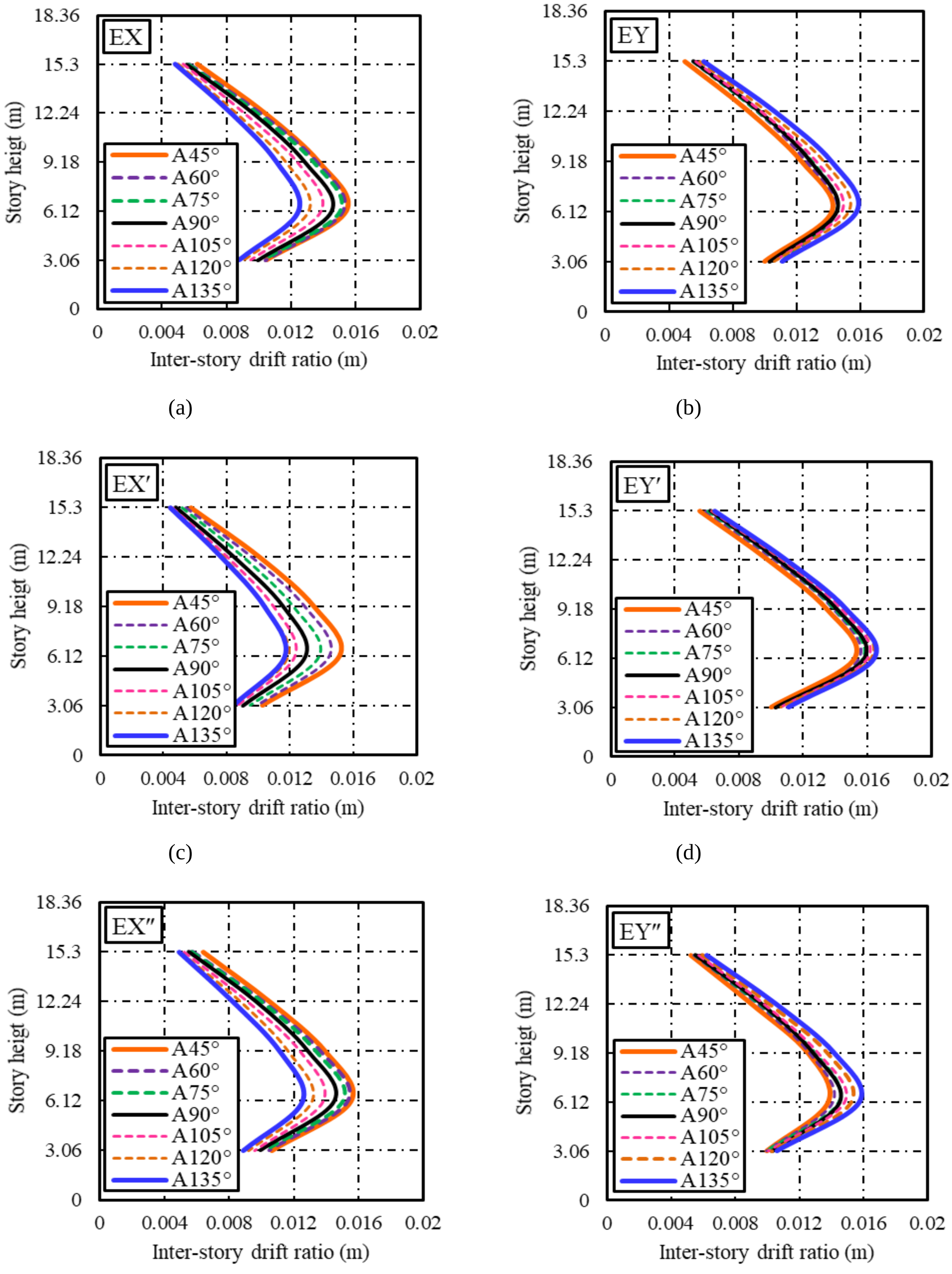
(c) (d)

(e) (f)

Fig. 3 – Global displacement of each variant studied and at each seismic direction considered.

2.3 Vibration modes

The overall response of a building is the resulting of the response of all vibration modes that must be considered in all models. Generally, for regular structures, the first two modes are purely translational and the third one is a torsional mode, however for irregular structures the modes become mixed translational and torsional. In this study, for the seven variants proposed, the first mode is purely translational; the second and third modes are both mixed between translation and rotation [40].



(a) (b)

(c) (d)

(e) (f)

Fig. 4 – Inter-storey drift of each variant studied and at each seismic direction considered.

3 Analysis and discussions

3.1 Linear Displacement

The overall lateral displacement (Fig. 3) and the inter-storey drift (Fig. 4) at each floor of irregular reinforced concrete buildings with re-entrant angles providing the different configurations, as detailed in Fig. 1, were evaluated. This assessment is based on a dynamic linear modal spectral analysis using a regulatory seismic action which is represented by the design seismic spectrum of the Algerian seismic regulations [33]. This seismic action is applied in all directions considered determinant for the calculation of the seismic forces, as illustrated in Fig. 2.

From the results obtained in Fig. 3, it can be seen that the increasing of the angle formed between the two projections from 45° to 135° decreases the displacements by a rate of 17,67%, 22,17%, and 17,86% in the seismic directions EX, EX′ and EX" respectively. And increases the displacements by a rate of 4,43%, 7,14% and 4,45% in the seismic directions EY, EY′ and EY" respectively. However, when the opening angle is greater than 90°, the displacements are greater in the EY, EY′ and EY" directions (Fig. 3 b-d-f) , while for structures where the angle is less than 90° the highest displacement values are in the EX, EX′ and EX" seismic directions (Fig. 3 a-c-e). Furthermore, the displacement of the A90° variant remains almost constant in the seismic directions EX, EX", EY, and EY" whatever the salient angle because the part I (horizontal) is perpendicular to the part III (vertical). On the other hand the part II represents higher displacement values in the EY′ direction compared to the EX′ direction this is due to the difference in inertia between the two directions. While the maximum displacement value is measured at the top of the structure with an opening angle of 135° which is 59.5mm in the EY direction.

From the results obtained in Fig. 4, it can be distinguished that the inter-storey drift of the different structures remains within the deformation domain limited by the admissible displacements (0.01he = 30,6 mm) according to the Algerian seismic rules [33]. Similarly, it can be seen that the rise in the value of the re-entrant angle from 45° to 135° also produces a linear decrease in the inter-storey drift in the seismic directions EX, EX′ and EX" (Fig. 4 a-c-e) and an increase in the seismic directions EY, EY′ and EY" (Fig. 4 b-d-f), where the maximum value of the inter-storey displacement is recorded in the second storey of the A135° structure which is 16,44 mm in the EY′ direction.

These results clearly indicate that the effect of the variation of the re-entrant angle on the linear deformability of the studied structures is significant for the different seismic directions considered. However, this effect becomes slight when the seismic action is applied perpendicular to the transition zone part of the architectural plane, while inducing the largest deformations. This is due to the volume and the important inertia of the projecting parts. Therefore, a more detailed analysis is required in the non-linear domain along the EY′ seismic direction to highlight the effect of the variation of the re-entrant angle of irregular reinforced concrete structures.

3.2 Capacity curves

Beams and columns are modelised by elements with linear elastic properties. However, the non-linear behaviour of the elements is translated by the introduction of plastic hinges at the level of the sections susceptible to plastification. In addition, modifications to the initial stiffness properties must be done. These guidelines are taken from the American regulations ATC40 [40]. In this study, a uniform monotonically increasing the pattern of lateral forces distribution that are proportional to masses was considered and determined by the Eurocode8 expression [41], so that each floor is submitted to a concentrated force in the seismic direction perpendicular to the part of the transition zone of the whole geometrical configuration of the different structures considered.

Fig. 5 shows a comparison of the pushover curves for the seven structures selected to evaluate the effect of the angle formed between the two projections of an irregular plan building smoothed by a transition. From this figure it can be seen that the curves obtained show several inclinations and collapses characterizing the progressive degradation of the stiffness of the structures, because the elements of the structure above the elastic limit start to yield, others are still stressed below this limit and may have a higher elastic limit. In fact, the results obtained show that A90° variant gives the highest capacity in terms of base shear resistance of the structure reaching the value of 4723,15 kN. Furthermore, increasing the angle between the two wings decreases the shear resistance by a rate of 3%, 6%, 9%, 14%, 16% and 18% for A45°, A60°, A75°, A105°, A120° and A135° variants respectively. In the same context, according to Fig. 5, it is clear that a right angle for the studied geometrical configuration (A90°) provides a higher deformability having a ductility μ=12.29 as shown in Table 4. Further, a building with an angle that nears a right angle, either for the lower or upper values, gives a lowering of the ductility compared to variant A90° by a variation of 21,5%, 22,3%, 22,7%, 27,5%, 23,3% and 18.8% for A45°, A60°, A75°, A105°, A120° and A135° variants respectively.

The pushover curves obtained show that the angle formed between the two projections, of the geometrical configuration studied, has a significant influence on the seismic performance in terms of base shear bearing capacity and corresponding roof displacement. From these results, it is clear that when the re-entrant angle is lower or exceeds 90° the global ductility of deformability is less important, this is due to the complex shape, which is composed of three different parts distributed according to three distinct coordinate systems. Consequently, when the re-entrant angle is right, the seismic performance of the structure is very high because the building form is not so complicated and is distributed in only two coordinate systems.

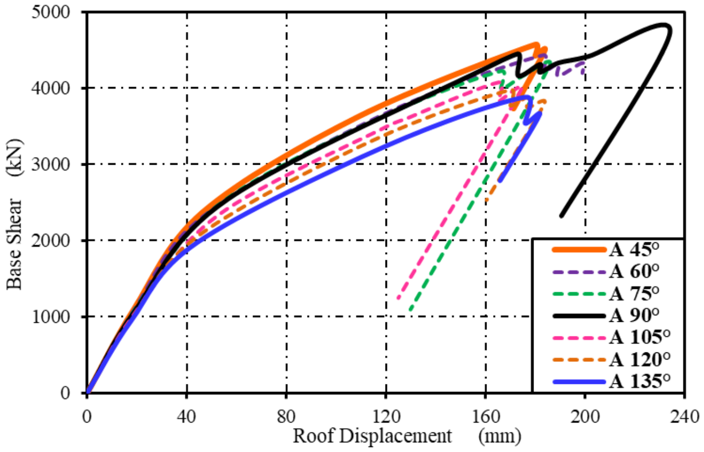


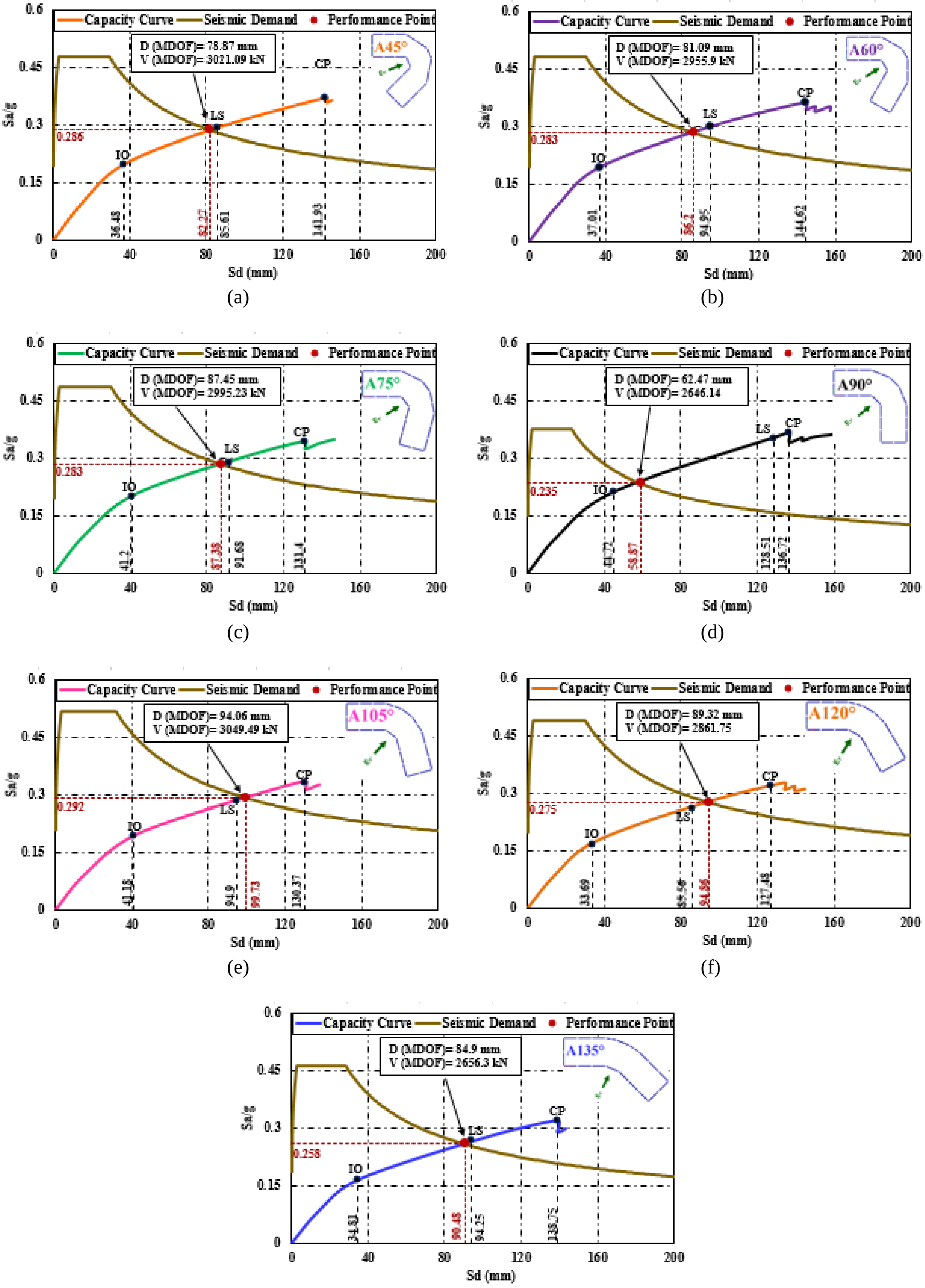
Fig. 5 – Capacity curves for the different variants studied.

Table 4 - Ultimate shears and global displacement ductility for each variant.

Variants	Vu (kN)	Δe (mm)	Δu (mm)	$\mu = \frac{\Delta_u}{\Delta_e}$
A 45°	4566.73	18.66	180.05	9.65
A 60°	4430.79	19.14	182.75	9.55
A 75°	4292.74	19.55	185.70	9.50
A 90°	4723.15	19.01	233.70	12.29
A 105°	4078.41	18.51	165.06	8.92
A 120°	3976.16	18.05	170.05	9.42
A 135°	3883.93	17.61	175.90	9.99

3.3 Performance points

In this section, the target displacement (performance point) will be evaluated for the different structures according to the N2 method of Eurocode8 [41] considering only the contribution of the fundamental mode of vibration and using the capacity curves obtained by the uniform lateral loads pattern. The principle of this method consists in superposing a curve representing the capacity of the structure resulting from a nonlinear static analysis (pushover) with a curve representing the solicitation provided by the earthquake (inelastic response spectrum). Both curves (capacity and seismic demand) should be transformed into the format of the acceleration-displacement response spectrum (S_a-S_d). The intersection of these two evaluated curves represents a performance point for evaluating the maximum displacement that the structure can endure and subsequently its degree of penetration in the plastic domain [41, 42].



(a) (b)

(c) (d)

(e) (f)

(g)

Fig. 6 – Performance point coordinates under the inelastic Algerian Spectrum.

Fig. 6 shows the results obtained in terms of performance point in spectral coordinates (of the SDOF system with one degree of freedom) and indicates the coordinates of maximum displacement and corresponding base shear (of the MDOF system) for the different structures studied, considering the seismic demand of the inelastic spectrum appropriate to the Algerian seismic rules [33]. According to these results, the A90° variant remains largely safe in terms of deformability and shear strength with a maximum displacement of 62,47mm and base shear force of 2646,14 kN (Fig. 6 d) which are 61% and 38% lower than the displacement and shear corresponding to the appearance of life-safety plastic hinges (LS) [42]. However, a building with a salient angle that diverges from 90° amplifies the risk of yielding and the penetration of performance point to the plastic hinges of type "collapse prevention" (CP) [42] with an increase in deformability compared to A90° variant of 40%, 46%, 48%, 69%, 61% and 54% for A45°, A60°, A75°, A105°, A120° and A135° variants respectively.

From the coordinates of the performance points obtained, it is clear that the effect of the re-entrant angle on the seismic performance of the considered architectural form is very considerable. As a result, the level of damage is acceptable and the structure remains safe when the re-entrant angle formed by the two projections is less than or equal to the right angle. On the other hand, the seismic risk becomes more important with a level of damage that approximates to collapse when the salient angle is obtuse.

4 Conclusion

In this paper, the effect of the re-entrant angle formed between the two projections of an irregular architectural plan smoothed by a transition was evaluated. The seismic response in terms of lateral displacement and inter-storey drift was discussed using linear dynamic (spectral modal analysis). The seismic performance was assessed in terms of capacity curve and performance point using a non-linear static (pushover) method. According to the linear displacement obtained, it is noted that the response is significant when the seismic action is applied perpendicular to the transition zone of the geometrical configuration studied (EY'). In addition, the best non-linear response in terms of base shear bearing capacity and roof displacement as well as the overall ductility of deformability is recorded in the structure with the 90° wing-opening angle according to the most unfavourable seismic direction of the transition zone. In contrast, a building with an acute or obtuse angle formed between the two wings weakened the capacity compared to that of the structure with a right angle. In the same context, the damage level was assessed by determining the coordinates of the performance point by applying the regulatory seismic spectrum. When the salient angle is greater than the right angle, the safety level is challenged and an increase in plastification and significant penetration into the post-elastic domain exceeding the life safety damage level (LS) was observed.

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