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Effect of the transverse reinforcement spacing in nodal zones on the seismic behavior factor of RC frames according to the Algerian seismic design code RPA99/version2003

Louzai A[1*], Abed A[2]

1 Department of civil engineering, Faculty of construction engineering, Geomaterials Environment and Development Laboratory (LGEA), University of Mouloud MAMMERI of Tizi-Ouzou, BP.17, RP 15000 Tizi-Ouzou, Algeria
2 Department of civil engineering, Faculty of construction engineering, University of Mouloud MAMMERI of Tizi-Ouzou, BP.17, RP 15000 Tizi-Ouzou, Algeria .
* Corresponding Author: amar.louzai@eummto.dz

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Abstract. The seismic behavior of reinforced concrete (RC) frames is significantly influenced by the confinement provided by transverse reinforcement. This study investigates the effect of transverse reinforcement spacing on the seismic behavior factor (R) of regular RC frames. The objective is to determine which spacing provides an R value in accordance with the Algerian seismic design code (RPA99/version 2003). To evaluate this effect, nonlinear pushover analysis is performed for each configuration. The confined concrete properties are defined using Mander's model, accounting for variations in compressive strength and strain capacity due to different stirrup spacings. The seismic behavior factor (R) is computed based on the overstrength factor (R_s) and the ductility factor (R_μ), derived from the capacity curves. The results of this study will provide insights into the influence of confinement on ductility and overstrength, allowing for the identification of an optimal stirrup spacing that ensures compliance with the RPA99/version 2003 seismic design code. The findings will help improve reinforcement detailing recommendations for enhanced seismic performance of RC frames.

Key words: RC frames, seismic behavior factor, transverse reinforcement spacing, overstrength, ductility.

1. Introduction

Reinforced concrete (RC) frames are widely used in seismic regions due to their structural efficiency and adaptability. However, their seismic performance is strongly influenced by the confinement provided by transverse reinforcement, which enhances the ductility and energy dissipation capacity of structural elements (Chang et al., 2025; Park & Paulay, 1975). Proper confinement prevents premature failure by delaying concrete crushing, improving post-peak behavior, and increasing overall structural resilience (Kyei & Braimah, 2017; Priestley et al., 1996)**.** In critical regions of RC frames, such as nodal zones (beam-column joints and plastic hinge zones in beams and columns), the role of transverse reinforcement is even more crucial, as these areas experience high stresses and inelastic deformations during earthquakes (Moehle et al., 1991).

One of the key parameters in seismic design is the seismic behavior factor (R), which accounts for the structure's ductility, overstrength, and energy dissipation capacity (Krawinkler & Nassar, 1992). This factor allows for the reduction of elastic seismic forces in design calculations, as prescribed by various seismic codes, including the Algerian seismic design code RPA/version 2003 (2003). The value of R depends on multiple factors, including structural system, material properties, and reinforcement detailing (Fardis, 2009). In particular, the transverse reinforcement spacing in nodal zones plays a crucial role in governing the level of confinement and, consequently, the overall seismic response of RC frames (Mander et al., 1988).

The Algerian seismic design code provides specific limitations on the maximum allowable spacing of transverse reinforcement in seismic regions. These limits vary according to the seismic zone considered to ensure adequate confinement in critical zones. However, the effect of different spacing values on the seismic behavior factor (R) is not always explicitly defined in design codes, making it essential to evaluate this influence through numerical simulations.

This study aims to evaluate the influence of transverse reinforcement spacing in nodal zones on the seismic behavior factor (R) of regular RC frames, considering four different spacing configurations: 20 cm, 15 cm, 10 cm, and 5 cm**.** The confined concrete properties for each case are determined using Mander's model**,** which provides a realistic representation of stress-strain behavior under confinement (Mander et al., 1988)**.** Nonlinear pushover analysis is performed to assess the overstrength and ductility characteristics of the frames, allowing for the computation of the behavior factor. The ultimate goal is to determine which reinforcement spacing provides an R value in compliance with the RPA99/version 2003 (2003)**.**

The findings of this study will contribute to a better understanding of the role of confinement in seismic design**,** offering practical recommendations for optimizing transverse reinforcement detailing in nodal zones to achieve enhanced ductility, energy dissipation, and overall seismic performance of RC frames.

2. Transverse reinforcements according to the RPA99/version2003

The maximum spacing for transverse reinforcement in nodal zones for columns and beams is established as follows:

2.1. For column structural elements

The maximum spacing for transverse reinforcement is fixed as follows:

$S_t \leq Min\ (10\emptyset_l, 15cm)$ in zone I et II_a

$S_t \leq 10\ cm$ in zone II_b et III

where $\emptyset_l$ is the minimum diameter of the column's longitudinal reinforcements.

2.2. For beam structural elements

The maximum spacing for transverse reinforcement is fixed as follows:

$$S_t \leq Min\left(\frac{h}{4}, 12\emptyset\right)$$

where h is the section depth of the beam element. The diameter $\emptyset$ of the longitudinal reinforcements should be set to the smallest diameter that is utilized.

3. Case study description

3.1. Geometry and structural configuration

A planar, three-bay, six-story RC frame is considered in this study. The frame is assumed to be located in a building that is symmetrical in both directions. The plan view of the building and an overview of the considered frame are presented in Figures 1 and 2. The building is assumed to be fixed at its base.

3.2. Data assumed for the studied frame

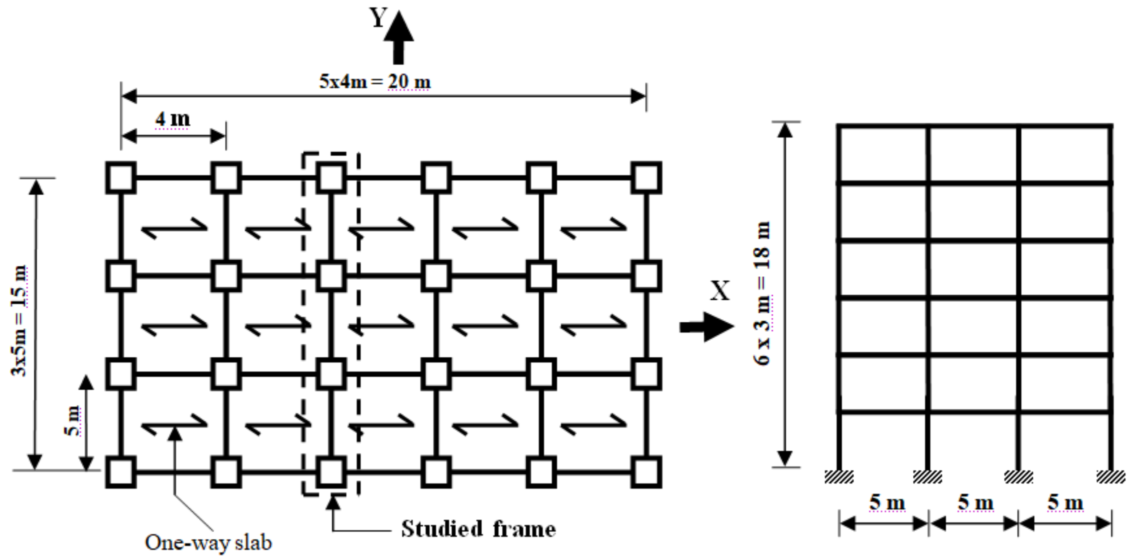

Fig 1. Plan view of the building and the studied frame.

The total dead and live loads on the floor slabs are assumed to be 5.1 and 1.5 kN/m^2, respectively, and for roof slab, they are assumed to be 5.8 and 1.0 kN/m^2. The frame is designed according to reinforced concrete code BAEL 91 (1992) and Algerian seismic code RPA 99/version2003 (2003) with the following parameters: zone of medium seismicity, **zone IIa**, importance class **groupe 1b,** soil type **S_3** (soft soil)**,** quality factor **Q=1.15** and viscous damping ration **ξ = 6%.** The analysis will be performed for the zone acceleration factor **A= 0.20**. A seismic behavior factor of ***R*** **= 5** was taken into account for reinforced concrete frames without masonry infill.

A characteristic cylinder strength of 25 N/mm^2 for concrete and yield strength of 500 N/mm^2 for steel are utilized. The member cross-section sizes and steel bars are given in Figure 2. It should be noted that the steel bars presented in this figure are those concerning the extremity zones of beam and column member elements, zones which are the more solicited in case of seismic loading and are consequently the seat of formation of plastic hinges.

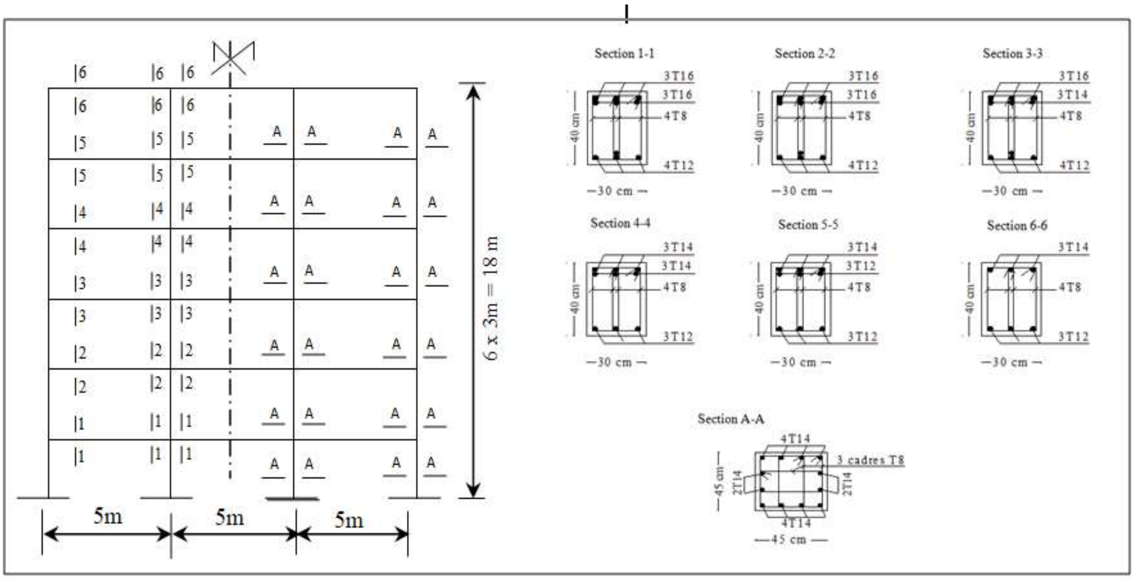

Fig 2. Dimensions and reinforcement details at both ends of the beams and the columns in the frame.

4. Modeling approach for inelastic analyses

Analyses have been performed using SAP2000 program (2009), which is a general-purpose structural analysis program for static and dynamic analyses of structures. In this study, SAP2000 Nonlinear Version 14 has been used. A description of the modeling details is provided in the following.

A two-dimensional model of the frame structure is created in SAP2000 to carry out nonlinear static pushover analyses. The nonlinear behavior of beams and columns was described according to the lumped plasticity approach, introducing moment and shear plastic hinges, in which all nonlinearity is concentrated at the end sections of the elastic beams.

For moment plastic hinges, the moment-rotation relationship shown in Figure 3 was used. It was assumed an elastic-plastic flexural response, where θ_y and θ_u are respectively the yield and ultimate rotations, θ_p is the plastic rotation capacity, M_y and M_u are respectively the yield and ultimate moment capacity of concrete members. The definition of a bilinear moment-rotation relationship requires moment-curvature analysis according to the prescriptions of ATC-40 (1996). The Mander model for unconfined and confined concrete (Mander & Priestley, 1988) and the Park model for steel reinforcement (Park & Paulay, 1975) are implemented in moment-curvature analysis.

For each column, moment-curvature analyses are carried out, considering section properties and constant axial loads on the elements (Intel & Ozmen, 2006; Rozman & Fajfar, 2009). On the beams, axial forces were assumed to be zero; on the columns, they were assumed to be constant and equal to dead loads (G) plus 20% of the live loads (Q) on the columns: G+0.2Q according to RPA 99/version2003 (Louzai & Abed, 2015). For this study, the moment-curvature analysis is obtained from SAP2000 (SD-Section) (2009). Saiidi and Sozen (1981) and Park and Paulay (1975) employed a strategy to establish moment-rotation relationships of elements based on moment-curvature relationships. In this approach, the moment is considered to change linearly along the beams and columns, with a contraflexure point in the center of each. Using this assumption, the relationship between curvature and rotation at yield, θ_y, is obtained as follows:

$$\theta_y = \phi_y \frac{L}{6} \tag{1}$$

where L is the element length and ϕ_y is the curvature at yield.

The ultimate rotation (θ_u) is obtained by adding plastic rotation to the yield rotation, where the plastic hinge rotation (θ_u) of elements is estimated using the equation 4 proposed by ATC-40 (1996). Thus,

$$\theta_u = \theta_y + \theta_p \tag{2}$$

and

$$\theta_p = \left(\phi_u - \phi_y\right). L_p \tag{3}$$

where ϕ_u is the ultimate curvature and L_p is the plastic hinge length.

ATC-40 (1996) suggests that plastic hinge length equals to half of the section depth in the direction of loading is an acceptable value which generally gives conservative results. This suggestion was adapted to calculate plastic hinge length in this study. Thus,

$$L_p = 0.5\, h \tag{4}$$

where h is the depth of the element, beam or column.

The shear failure of structural elements should be considered in a RC frame structure with no special considerations for seismic lateral loading, particularly the insufficient spacing of the transverse stirrups in critical regions (i.e., element ends). For this purpose, shear hinges are assigned for beams and columns. As a consequence of the brittle failure of concrete in shear, ductility is not considered for this type of hinge. Shear hinge properties are defined so that when the shear force in the element reaches its maximum strength, it fails instantly (Inel & Ozmen, 2006). The shear strength of each structural element, V_u, is calculated according to UBC 97 (1997), as follows:

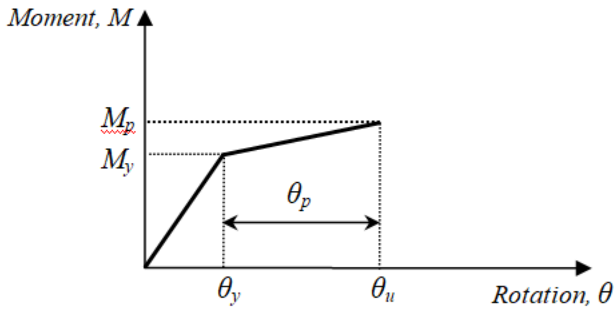

Fig 3. Moment – Rotation relationship (ATC-72-1, 2010).

$$V_u = V_c + V_s \tag{5}$$

where V_c and V_s are shear strength provided by concrete and transverse reinforcement in accordance with Eqs. (6) and (7), respectively:

$$V_c = 0.182 a d_e \sqrt{f_c}\left(1 + 0.07\frac{N}{A_c}\right) \tag{6}$$

$$V_s = \frac{A_{sh} f_{yh} d_e}{s} \tag{7}$$

where a is the section width, d_e is the effective depth, f_c is the unconfined concrete compressive strength, N is the axial load on the section, A_c is the concrete area, and A_{sh}, f_{yh}, and s are the area, yield strength, and spacing of transverse reinforcement, respectively.

5. Nonlinear static pushover analysis

Nonlinear static pushover analyses of the studied frame with different spacing of transverse reinforcements are performed to estimate their ductility and overstrength factors which are required for computing R factor for each configuration.

The method consist of applying gradually increasing the lateral loads appropriately distributed over the stories, to obtain the relationship between the base shear and the top story displacement, which is generally called pushover curve or capacity curve. There can be many alternatives for the distribution pattern of the lateral loads, and it may be expected that different patterns of lateral loads result in pushover curves with different characteristics and different sequence of plastic hinge formation. In a recent study done by Mwafy and Elnashai (2001), it is shown that the inverted triangular distribution pattern of the lateral loads produces better estimates of the maximum drift and R factor compared with uniform and multi-modal distributions. In this study, the pushover curves of the frame with different spacing of transverse reinforcement are obtained using the inverted triangular distribution pattern of the lateral loads.

6. Computation of behavior factors

The ATC-19 (1995) proposed simplified procedure to estimate the response modification factors, in which the seismic modification factor, R, is calculated as the product of the three parameters that profoundly influence the seismic response of structures. Thus,

$$R = R_\mu \cdot R_s \cdot R_R \tag{8}$$

where R_μ is the ductility factor which is the measure of the global nonlinear response of a structure, R_s is the overstrength factor to account for the observation that the maximum lateral strength of a structure generally exceeds its design strength and R_R is a redundancy factor to quantify the improved reliability of seismic framing system that use multiple lines of vertical seismic framing in each principle direction of a structure. In this study the redundancy factor is assumed to be 1 (table 2 from ATC-19), and then the seismic behavior factor is determined as the product of the ductility factor and the overstrength factor, as shown in Fig. 4. Thus,

$$R = R_\mu \cdot R_s \tag{9}$$

Figure 4 illustrate also the global ductility, μ, of the structure which is defined as the ratio between the ultimate top storey displacement (d_u) corresponding to the collapse limit state of a structure and the yield top storey displacement (d_y). Thus,

$$\mu = \frac{d_u}{d_y} \tag{10}$$

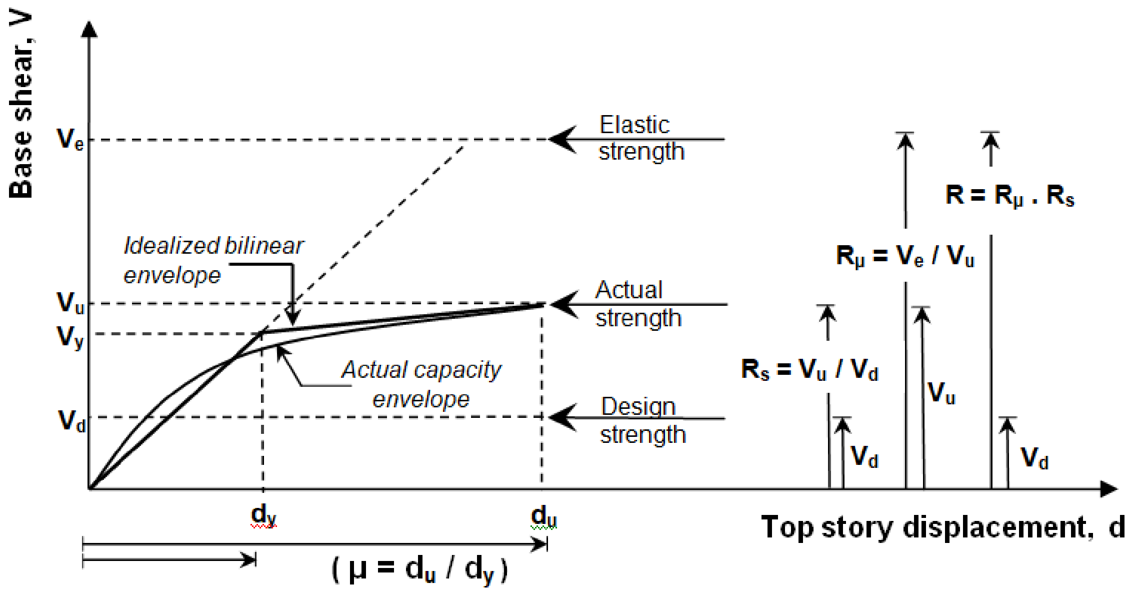

Fig 4. Relationship between seismic behaviour factor (R), overstrength factor (R_s), ductility factor (R_μ) and global ductility, μ (Mwafy and Elnashai, 2002).

A proper evaluation of the R factor can be undertaken by evaluating the two components contributing it. These can be obtained from the force-displacement relationship, capacity envelope of a structure, which can be obtained from inelastic nonlinear static pushover analyses.

6.1. Ductility factor, R_μ

Ductility factor R_μ is a function of both characteristics of the structure including ductility, damping and fundamental period of vibration (T), and the characteristics of earthquake ground motion. In the last three decades, significant work has been carried out to establish the ductility factor on single degree of freedom (SDOF) systems subjected to various types of ground motions. In this study, the R-μ-T relationship developed by Newmark and Hall (1982) is used to calculate the ductility factor. Thus,

$$R_{\mu} = 1 \qquad for \qquad T < 0.2\ s \tag{11}$$

$$R_{\mu} = \sqrt{2\mu - 1} \qquad for \qquad 0.2 < T < 0.5\ s \tag{12}$$

$$R_{\mu} = \mu \qquad for \qquad T > 0.5\ s \tag{13}$$

where μ is the global ductility of the structure and T the fundamental period of vibration of the structure.

6.2. Overstrength factor, R_s

It is observed that structures usually possess a considerable amount of reserve strength. This extra strength is known to be one of the key characteristics, which influence seismic response of building structures (Annan et al., 2009). Many sources of overstrength can be easily identified but not all can be readily quantified. Sources that have been reviewed by Uang (1991), Mitchell and Paultre (1994), Rahgozar and Humar (1998), Bruneau et al. (1998), and Mitchell et al. (2003) include: material effects caused by higher yield stress compared with the nominal value; effect of using discrete member sizes and practical considerations that require provision of bigger sections for some elements; strain hardening behavior in steel; redistribution of internal forces in the inelastic range; difference between nominal and factored resistances; as well as code requirements for considering multiple loading combinations and contribution of non structural elements.

The analytical definition of overstrength factor, R_s, considering a typical structural response envelope in Figure 4, showing the relationship between base shear and top storey displacement, the structural overstrength accounting for all possible sources can be defined by the following equation:

$$R_s = \frac{V_u}{V_d} \tag{14}$$

7. Failure criteria

To evaluate the R factor, a number of response criteria are needed to define the collapse limit states of a structure. In this study, only one failure criterion is taken into consideration and it is defined based on the limitation of plastic hinge rotation of different elements (beams, columns) to the ultimate rotation, θ_u, as in Ciutina Liviu Adrian (2003) and Mwafy and Elnashai (2001).

8. Results and discussion

In this section we present and discuss the results obtained from inelastic static pushover analyses carried out on the RC frame with different transverse reinforcement spacing. The results investigated here are related to the evaluation and comparison of the following parameters: the global ductility, μ, by which the ductility factor, R_{μ}, is calculated, the over strength factor, R_s, and the seismic behavior factor, R.

8.1. Pushover curves

The figure 5 presents a series of pushover curves that illustrate the relationship between base shear force and top story displacement for RC frames with different levels of concrete confinement. The confinement is varied by adjusting the spacing of transverse reinforcement (stirrups), ranging from unconfined concrete to confined concrete with stirrup spacings of 20 cm, 15 cm, 10 cm, and 5 cm.

In the case of unconfined concrete, the frame exhibits a base shear capacity of approximately 400 kN and reaches a maximum top story displacement of around 22 cm. The curve displays a steep initial slope followed by a short plateau, reflecting limited ductility. While there is no sudden drop in strength, the structure shows reduced deformation capacity and limited ability to dissipate seismic energy. When the concrete is confined with stirrups spaced at 20 cm, the performance slightly improves. The maximum base shear to around of 390 kN, and the top displacement reaches about 40 cm. The curve shows a smoother transition from elastic to inelastic behavior, indicating a modest enhancement in ductility compared to the unconfined case. With 15 cm stirrup spacing, the structural performance becomes noticeably better. The maximum strength remains similar (around 395 kN), but the top displacement increases beyond 40 cm. The curve flattens more gradually, suggesting greater energy dissipation capacity and improved post-yield behavior. In the case of 10 cm stirrup spacing**,** both strength and top story displacement are enhanced. The base shear reaches approximately 420 kN, and the displacement extends to nearly 60 cm. The response curve shows a broad and stable post-peak plateau, which is indicative of strong confinement and a ductile structural behavior suitable for seismic applications. Finally, the frame with 5 cm stirrup spacing demonstrates the most favorable response. It reaches a base shear of around 415 kN and sustains top displacements exceeding 70 cm. The curve features an extended plateau after yielding, indicating excellent ductility, superior energy dissipation, and stable post-peak performance. This configuration clearly provides the best seismic resistance among all the cases studied. In order to better highlight the effect of decreasing transverse spacing on displacement capacity, figure 6 has been purposefully incorporated. It is also essential to note that the base shear capacity (resistance) does not vary significantly with the level of confinement; it is primarily the top story displacement of the structure that is affected. As the stirrup spacing decreases and confinement increases, the ability of the structure to undergo large inelastic deformations and dissipate energy improves markedly. This highlights the essential role of transverse reinforcement in enhancing seismic ductility, which is a critical parameter for the performance of reinforced concrete frames under earthquake loading. These different observations will be more detailed in the subsequent results.

8.2. Maximum inter-story drift

The figure 7 illustrates the distribution of inter-story drift (expressed as a percentage) over the height of the RC frame structure, for various configurations of concrete confinement. Also, the figure shows three vertical reference lines which mark the performance thresholds defined by FEMA 273 (1997)**:** Immediate Occupancy~1% inter-story drift, Life Safety~2% inter-story drift, and Collapse Prevention~ 4% inter-story drift. The results show that the inter-story drift increases significantly with improved confinement (i.e., tighter stirrup spacing):

In the case of unconfined concrete, the drift values remain relatively low across all levels, generally within or just above the Immediate Occupancy threshold. This reflects the limited deformation capacity of unconfined concrete and its tendency toward brittle behavior under lateral loading. For confined concrete with ST = 20 cm, drift values increase modestly, sometimes approaching or slightly exceeding the Life Safety limit at certain levels. However, this level of confinement still appears insufficient to ensure robust ductile behavior, especially in critical stories. As the confinement improves (ST = 15 cm, 10 cm, and especially 5 cm), a notable increase in drift capacity is observed. With ST = 10 cm and ST = 5 cm, most stories reach or exceed the Life Safety threshold and, in some cases, approach the Collapse Prevention limit, particularly in lower stories where lateral demands are greatest. The configuration with ST = 5 cm demonstrates the highest inter-story drift across all levels, indicating excellent ductility and energy dissipation capacity**.** This level of performance is ideal in seismic design, as it shows the ability of the structure to undergo large deformations without loss of integrity or collapse.

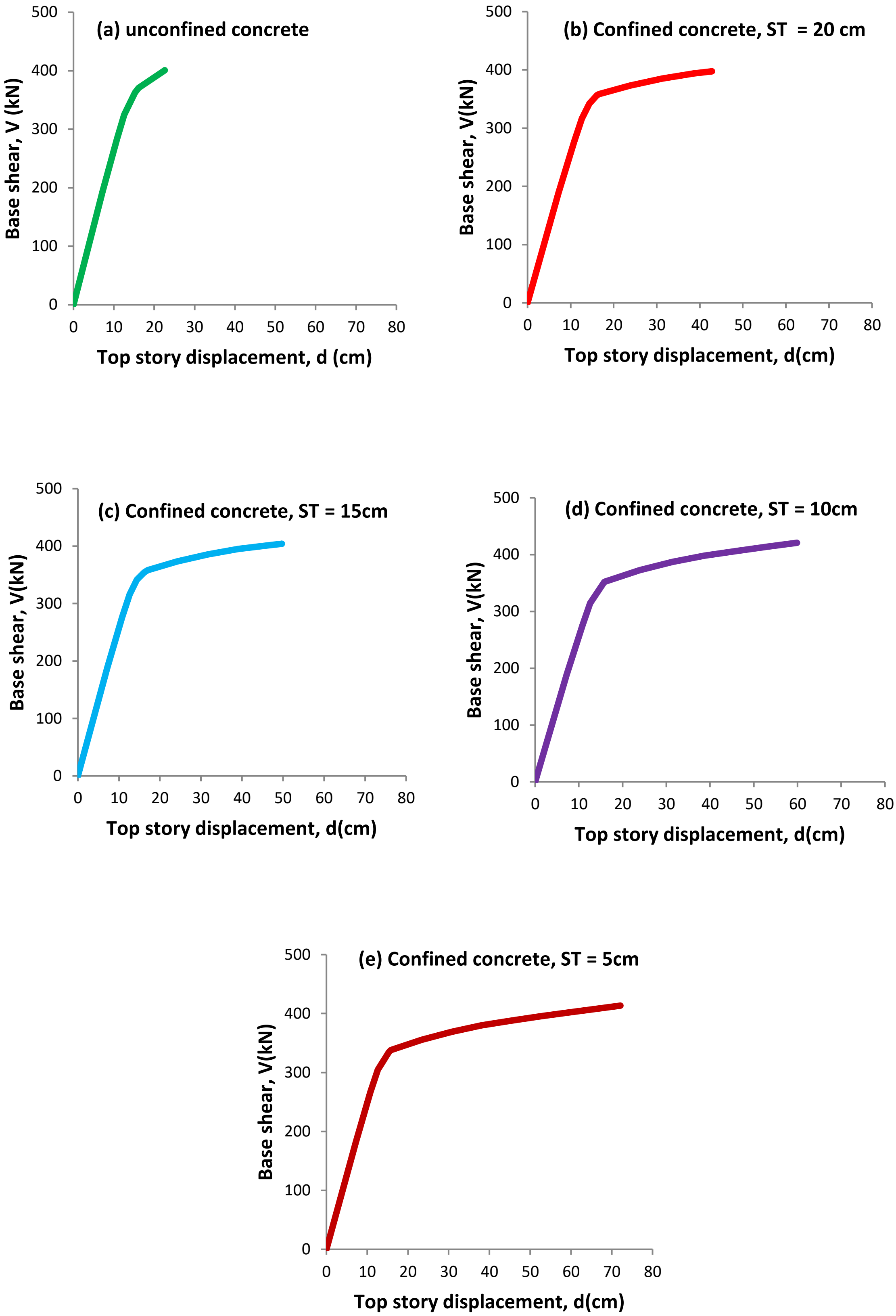

Fig. 5 Pushover curves of the studied frame with different transverse reinforcement spacing: (a) unconfined concrete, (b) confined concrete, ST = 20cm, (c) confined concrete, ST = 15 cm, (d) confined concrete, ST = 10cm, (e) confined concrete, ST = 5cm

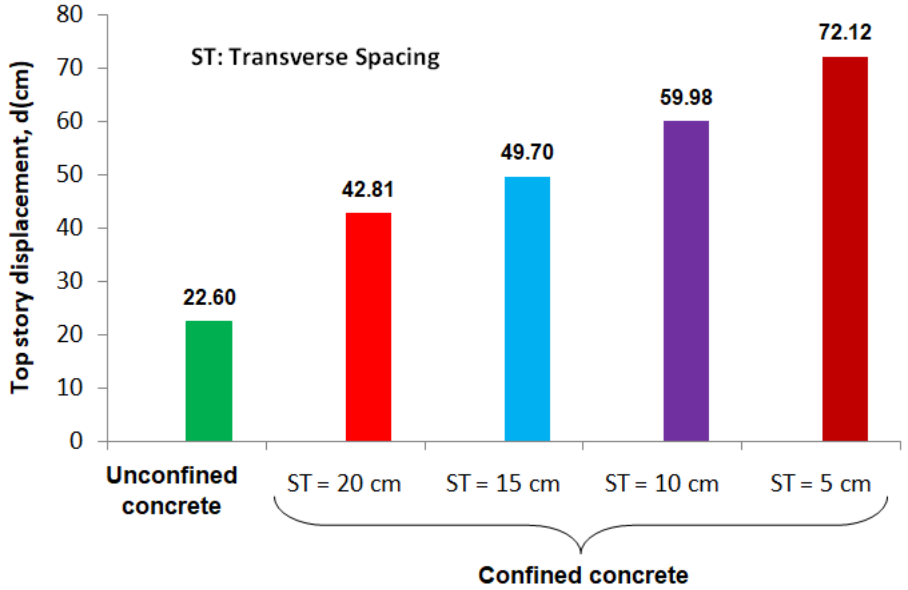

Fig. 6 Top story displacement capacity of the studied frame under different transverse reinforcement spacings

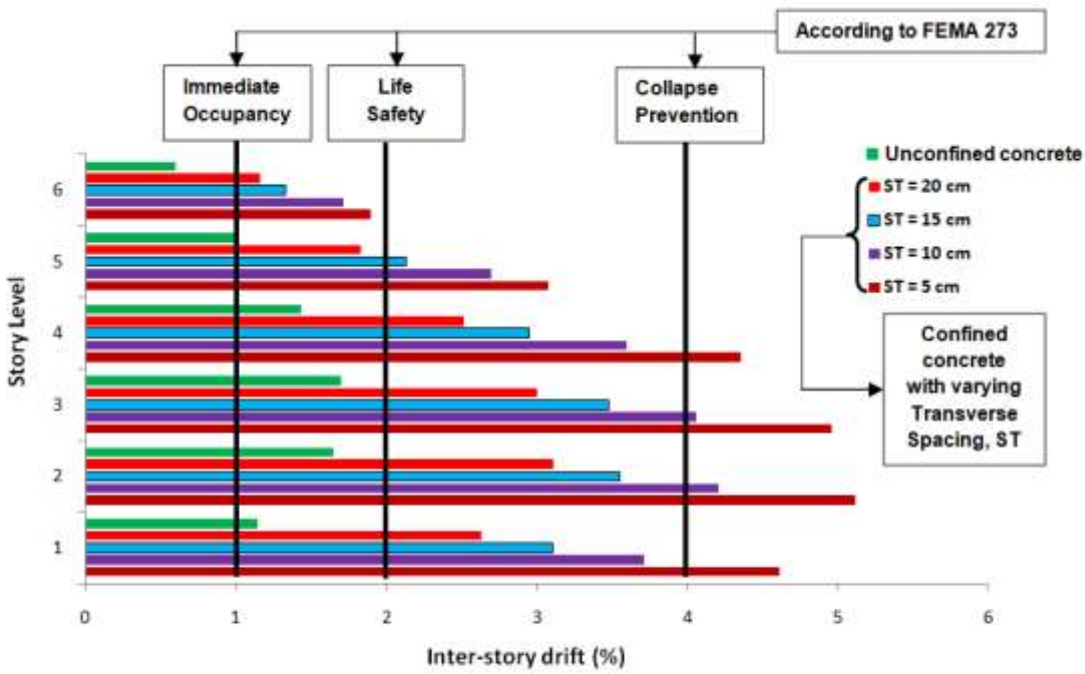

Fig. 7 Maximum inter-story drift over the height of the studied frame under different transverse reinforcement spacings

8.3. Local ductility in beam and column structural elements

The figure 8 presents the local ductility of beams ($\boldsymbol{\mu_\theta}$) for a RC frame, considering both positive ($\boldsymbol{\mu_{\theta(+)}}$) and negative ($\boldsymbol{\mu_{\theta(-)}}$) rotations at each story level. The different curves correspond to various levels of concrete confinement.

The results clearly demonstrate the influence of transverse reinforcement spacing on the ductility of beams. In fact, as the spacing of transverse reinforcement decreases, the local ductility of beams significantly increases. Beams with ST = 5 cm exhibit the highest ductility values, both in positive and negative directions, across all stories. In contrast, unconfined concrete results in the lowest ductility, with limited deformation capacity. Also, it can be seen that for confined concrete (especially ST ≤ 10 cm), ductility increases in the lower stories, where seismic demands are typically higher. This indicates good energy dissipation capacity and the ability to form plastic hinges at critical zones. In contrast, unconfined beams show a nearly uniform and limited ductility distribution, which is not favorable in seismic design.

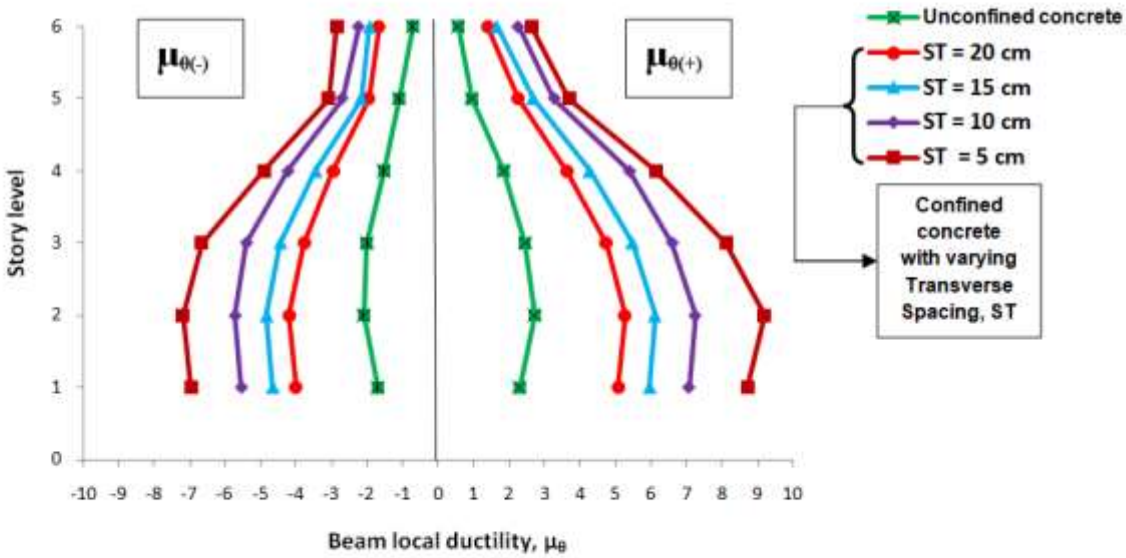

Fig. 8 Flexural local ductility in beam structural elements over the height of the studied frame under different transverse reinforcement spacings

The figure 9 illustrates the local ductility ($\boldsymbol{\mu_\theta}$) at the base of first-story columns, which are known to be the most solicited structural elements during seismic events due to their critical role in supporting vertical loads and resisting lateral forces. The results illustrate in the figure clearly show that as the spacing of the transverse reinforcement decreases, the local ductility of columns increases significantly. Columns with tighter stirrup spacing, especially ST = 5 cm, exhibit nearly five times the ductility of those without confinement. This behavior underscores the vital role of confinement in enhancing the deformation capacity of concrete columns, enabling them to withstand higher strains without losing their load-bearing capacity. Subsequently, when this behavior is compared to that of the beams, a similar trend is observed: improved confinement leads to increased ductility. However, the magnitude of improvement is more significant in columns, particularly at the first story, where seismic demands are highest. This difference can be attributed to the axial load effect present in columns, which makes them more sensitive to confinement detailing. Also, while beams contribute to energy dissipation and the formation of plastic hinges during seismic loading, it is the ductility of columns, especially at their bases, that is essential for preventing soft-story mechanisms and overall structural collapse as also reported by Ulutas (2024).

8.4. Global ductility of the studied RC frame

The figure 10 presents the global ductility (μ) of the structure for different levels of concrete confinement, defined by the spacing of the transverse reinforcement (ST). It can be clearly observed that the global ductility increases with the degree of confinement. In other words, as the spacing of transverse reinforcement becomes tighter (from 20 cm to 5 cm), the entire structure becomes more capable of undergoing inelastic deformations without significant strength degradation. The global ductility nearly triples from 1.5 (unconfined) to 4.24 (ST = 5 cm). In earlier figures, we saw that local ductility in columns increased substantially with improved confinement, especially at the base of the first story (from 2.08 for unconfined to 9.95 for ST = 5 cm). Similarly, beam local ductility also improved with decreasing stirrup spacing, although to a slightly lesser degree than in columns. These local improvements in both beams and columns translate directly into improved global ductility, as the capacity of each component to undergo plastic deformations without failure contributes to the overall energy dissipation and deformation capacity of the frame. Hence, the global ductility is closely linked to the local ductility of structural elements, particularly the columns, which play a critical role in maintaining structural integrity under seismic loading. While beams mainly contribute to energy dissipation, the ductility of columns prevents mechanisms like soft-story failures, which are often catastrophic.

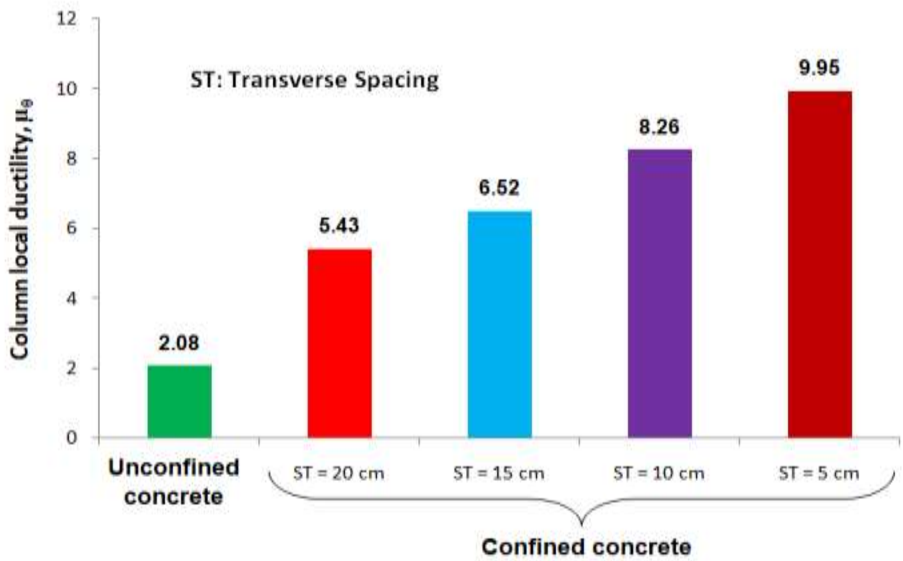

Fig. 9 Flexural local ductility in column structural elements over the height of the studied frame under different transverse reinforcement spacings

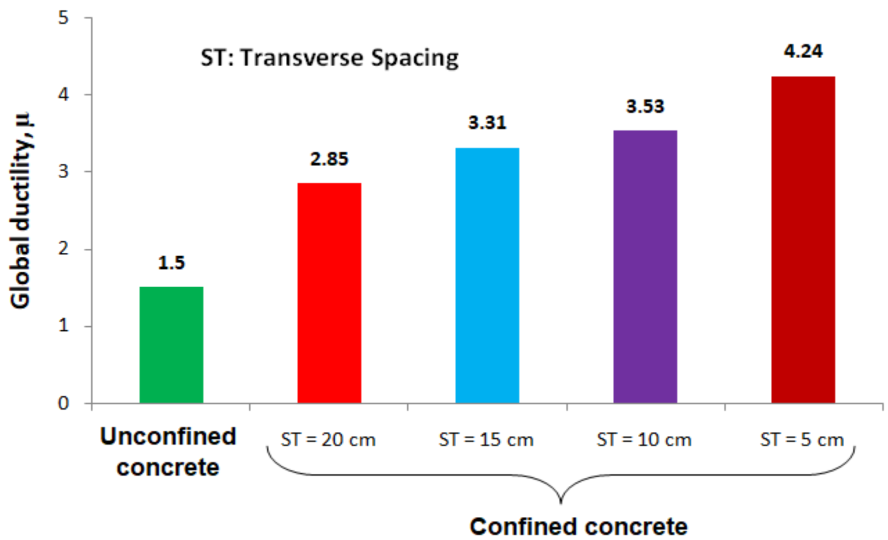

Fig. 10 Global ductility of the studied frame under different transverse reinforcement spacings

8.5. Overstrength factor of the studied RC frame

The figure 11 illustrates the overstrength factor (R_s) for structure with various levels of concrete confinement. This figure shows that the overstrength factor remains relatively stable across all configurations, with only minor variations. The values fluctuate slightly around 1.3 to 1.4, indicating that confinement of concrete does not significantly influence the strength of the structure. This result aligns perfectly with the findings from the pushover curves presented earlier. In those curves, we observed that the peak base shear (i.e., the strength) did not change substantially with decreasing stirrup spacing. All configurations, whether confined or unconfined, exhibited similar maximum strength values.

8.6. Seismic behavior factor of the studied RC frame

The evolution of the seismic behavior factor, R, with respect to the variation of the transverse reinforcement spacing is shown in Fig. 12 and Table 1. Also, the R values calculated from pushover analyses are compared to the reference value R = 5 prescribed by the Algerian seismic design code RPA99/version 2003. It can be seen that the unconfined concrete frame exhibits a very low behavior factor (R=2), which is far below the code-specified value. This indicates that such a frame has limited energy dissipation capacity and insufficient ductility under seismic loading. As the confinement improves (by reducing ST from 20 cm to 5 cm), the behavior factor increases progressively**.** This trend clearly shows that better confinement leads to improved seismic performance, mainly by enhancing the ductility of the structure. Subsequently, this increase in R is not due to a significant gain in strength, as shown in the earlier pushover curves and overstrength factor chart, where the base shear capacity and overstrength factor remained nearly constant across all cases. This confirms that the strength of the structure does not vary significantly with confinement, and the observed improvements in R are essentially attributed to the increase in ductility.

Also, the figure 12 confirms that, under the Algerian code's assumption of R=5, only well confined frames (ST ≤ 10 cm, and ideally ST = 5 cm) can safely achieve the intended reduction in design seismic forces**.** In other words, to legitimately use R_{RPA}=5, designers must detail transverse reinforcement tightly enough to ensure the ductility that underpins that behavior factor.

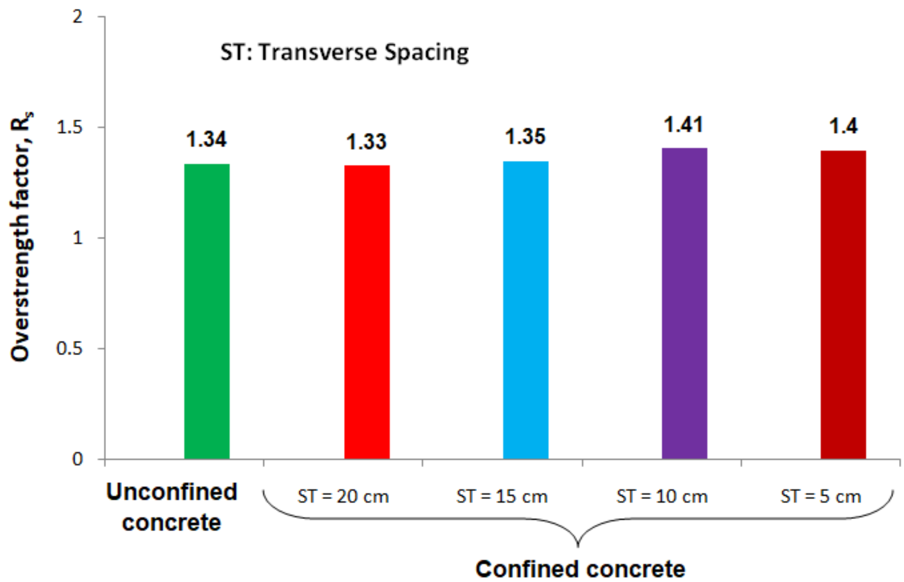

Fig. 11 Overstregth factor of the studied frame under different transverse reinforcement spacings

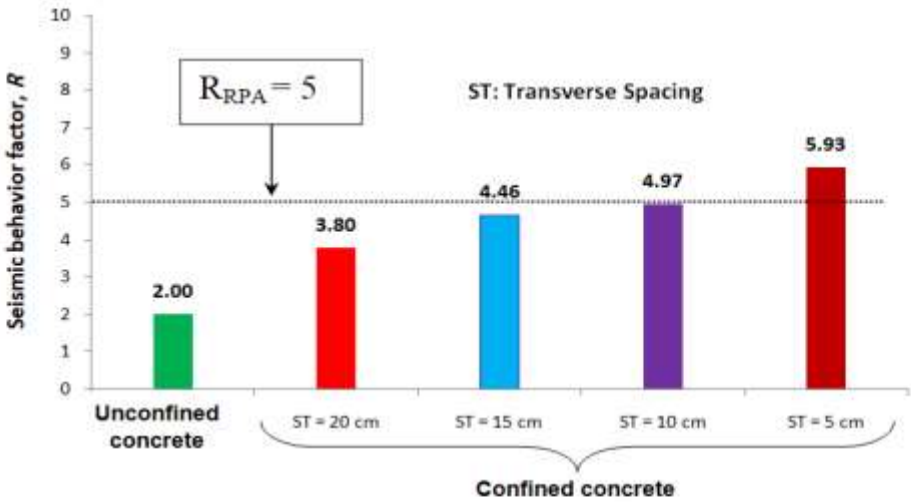

Fig. 12 Seismic behaviour factor of the studied frame under different transverse reinforcement spacings

Table 1. Ductility factor, R_μ, overstrength factor, R_s and behavior factor, R, for the sudied structure.

Transverse spacings (cm)	Ductility factor R_μ	Overstrength factor R_s	Behaviour factor R
Uncofined concrete	1.50	1.34	2.00
20	2.85	1.33	3.80
15	3.31	1.35	4.46
10	3.53	1.41	4.97
5	4.24	1.40	5.93

9. Conclusions

The seismic performance of RC frames critically depends on the ductility provided by transverse reinforcement in nodal zones. This study investigates how varying stirrup spacing (unconfined, 20 cm, 15 cm, 10 cm, and 5 cm) influences key seismic parameters. Nonlinear static (pushover) analyses were conducted on six-story RC frames to evaluate (1) base shear capacity, (2) local ductility of beams and first-story column bases, (3) global ductility, (4) inter-story drift demands, (5) overstrength factor, and (6) seismic behavior factor R. Performance was assessed against FEMA 273 drift limits and the Algerian code's reference behavior factor R_{RPA}=5. The following conclusions may be drawn from the results of this study.

- Reducing the spacing of transverse reinforcement (ST) leads to a substantial increase in both local (beam and column) and global ductility**.**
- The pushover curves and overstrength factor (R_s) show that the peak base shear capacity is not significantly affected by the level of confinement. This suggests that confinement has little influence on strength**,** and its benefits are primarily linked to enhancing ductility**.**
- The inter-story drift results show that tightly confined structures perform better across all stories, reaching higher performance levels (Immediate Occupancy, Life Safety, Collapse Prevention) according to FEMA 273**.** Unconfined structures exceed performance thresholds at lower drift values, indicating earlier damage and failure.
- The seismic behavior factor R combines overstrength and ductility into a single coefficient. Since overstrength barely changes with confinement, the observed increase in R is driven almost entirely by the enhanced ductility of the frame.
- To legitimately apply the code prescribed behavior factor R=5 and achieve the intended reduction in seismic design forces, an optimal stirrup spacing of 5 cm in nodal zones is

required. A spacing of 10 cm may be acceptable under conservative design, but only 5 cm consistently ensures full compliance with the RPA 99/version 2003 provisions.

This study has demonstrated the critical role of transverse reinforcement spacing in achieving the seismic factor prescribed by the Algerian seismic design code (RPA99/version2003). However, to further strengthen and generalize these findings, future research could explore the following directions:

- Extension to dynamic analyses: incorporating nonlinear time-history analyses using real earthquake records would help capture the full range of seismic demands, including cyclic degradation and energy dissipation mechanisms that are not fully addressed by static pushover analysis.
- Soil–Structure interaction effects: including the interaction between the structure and its foundation system could reveal additional influences on the required confinement levels, especially for taller or more flexible buildings.
- Application to irregular structures: studying the same confinement effects on vertically and plan-irregular RC frames would help determine whether the identified optimal spacing remains valid under more complex seismic responses.

By addressing these areas, future research can contribute to a more comprehensive understanding of confinement detailing and support the development of improved design recommendations for seismic-resistant RC structures.

10. References

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