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Research Article

Assessment of pathological failures in reinforced concrete frames for seismic retrofitting guidance

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Abstract

When an earthquake strikes, engineering experts and technical teams are urgently mobilized to investigate the causes of reinforced concrete (RC) building failures, with the aim of preventing future collapses and improving seismic design codes. This study focuses on several common deficiencies—poor material quality, inadequate beam–column joints, soft-story mechanisms, and insufficient foundation restraint—and evaluates their impact through comparative numerical analysis against a code-compliant reference frame. The numerical modeling was performed in Robot Structural Analysis v2014 using modal and response spectrum analyses in accordance with the Algerian Seismic Code (RPA 99), incorporating variations in material properties and boundary conditions. The results revealed significant differences in seismic response: pinned-base supports lengthened the fundamental period and increased flexibility, soft-story and weak-column systems amplified drift demands, and low-strength concrete produced shorter periods with brittle dynamic behavior. The novelty of this work lies in its comparative parametric assessment of pathological cases, enabling the identification of quantitative performance gaps directly attributable to common design and construction errors. These findings contribute to engineering practice by providing practical guidance for prioritizing seismic retrofitting strategies and strengthening regulatory frameworks in earthquake-prone regions.

1. Introduction

The preservation and rehabilitation of reinforced concrete (RC) structures have become critical components of modern engineering practice, driven by sustainability goals and the principles of the circular economy. Rather than demolishing and rebuilding deteriorated infrastructure—an approach that demands high financial and environmental costs—contemporary strategies prioritize strengthening and repair techniques that extend service life while conserving materials and energy [1]. This perspective is especially relevant as large segments of global RC building stock approach or exceed their original design lifespans and exhibit deterioration due to environmental exposure, corrosion, and inadequate maintenance [2, 3].

One of the most pressing concerns in this regard is the structural vulnerability of aging buildings under seismic loading. Recent earthquakes such as those in L'Aquila, Lorca, Emilia, Cephalonia, and Boumerdes have tragically demonstrated the fragility of non-retrofitted RC structures [4]. Many of these buildings, designed under outdated codes, lack the ductility and detailing required to

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withstand strong ground motion, making them especially susceptible to brittle failure mechanisms such as shear cracking, column crushing, and out-of-plane infill wall collapse.

Experimental studies have played a vital role in understanding these failures. Bracci et al. [5] demonstrated through shaking-table testing that RC frames retrofitted with prestressed concrete jacketing exhibited improved seismic resistance. Similarly, Wasti and Ozcebe [6, 7] evaluated the performance of old-type RC columns under cyclic loads and confirmed that composite overlays, particularly CFRP, can enhance resilience—though risks of brittle collapse persist. These findings highlight the importance of both ductile detailing and reinforcement strategies tailored to existing deficiencies.

Complementary to experimental work, numerical studies have enabled more robust failure prediction. For instance, Shoraka [8] proposed system-level collapse criteria specific to non-ductile moment frames, while Mazza and Pucci [9] compared several formulations of member and joint shear capacities, emphasizing the need for accurate differentiation between ductile and brittle mechanisms in both retrofitted and unretrofitted structures. O'Reilly and Sullivan [10], through probabilistic seismic assessment of Italian RC frames, illustrated the importance of considering masonry infill and shear effects in collapse modeling.

Recent research has also emphasized advanced retrofitting and energy dissipation systems. For instance, Bohara et al. [11] demonstrated that the strategic placement of steel bracings in irregular RC buildings can effectively reduce inter-story drift and torsional irregularity. Wu et al. [12] highlighted the benefits of precast UHPC plates for retrofitting GFRP-reinforced concrete columns, while Di Trapani et al. (2024) [13] investigated refined micro-modeling approaches to capture local infill–frame interaction under seismic loads. Hadidi et al. [14] further explored innovative I-shaped shear dampers made of low yield point (LYP) steel to enhance the ductility and energy dissipation capacity of RC frames. More recently, Ghafar et al. [15] reviewed seismic isolation techniques for existing structures, and Kumar and Ghosh [16] investigated the seismic performance of RC buildings with FRP-reinforced concrete. These studies enrich the state of the art by demonstrating that a combination of advanced materials, innovative damping devices, and refined numerical approaches can provide effective seismic strengthening strategies for existing RC structures.

Innovative methods such as displacement-based nonlinear analysis [17] and full-scale shake table testing of infilled RC substructures [18] have deepened our understanding of how infill walls affect overall performance, especially in the case of out-of-plane failures. Recent advancements have also explored alternative systems, like concrete-filled double-skin steel tube (CFDST) frames with beam-only connections [19], offering new perspectives for both design and retrofitting.

At the same time, structural rehabilitation has evolved through the use of advanced materials, including externally bonded reinforcement (EBR), near-surface-mounted (NSM), and side near-surface-mounted (SNSM) techniques. These methods, combining high-performance fiber-reinforced polymers with practical on-site application, offer promising solutions—though long-term durability, bond behavior, and compatibility with existing materials remain critical challenges [20, 21, 22].

In this context, the present study investigates the failure mechanisms and performance deficiencies of existing reinforced concrete structures subjected to combined static and seismic actions. Particular attention is given to:

- Progressive collapse due to soft-story mechanisms;
- Shear failure and plastic hinge formation in columns and joints;
- Bursting and instability in nodal regions;
- Out-of-plane infill wall displacements and detachment.

The novelty of this study lies in its comparative parametric analysis of different pathological configurations of RC frames against a code-compliant baseline. By systematically quantifying the impact of base fixity, soft-story mechanisms, strong-beam–weak-column hierarchy, and low concrete strength, the research not only advances understanding of seismic deficiencies but also provides practical guidance for prioritizing retrofitting interventions.

The outcomes of this research are expected to contribute to the development of more reliable and efficient rehabilitation techniques that align with both structural integrity and sustainability objectives.

2. Factors Influencing the Behavior of Portal Frame Structures

2.1. Masonry Infill

Self-supporting portal frames, whether or not infilled with rigid masonry, are often analyzed while neglecting both the stiffness of the masonry and the effects of its interaction with the structural frame. In most seismic analyses, the presence of infill masonry is accounted for solely through its mass contribution, while its role in enhancing the global lateral stiffness is considered negligible. However, it is important to highlight those current regulatory provisions concerning infill masonry and finishing works are frequently ignored. In fact, according to building codes, rigid infill masonry should consist of two layers of hollow bricks—10 cm and 5 cm thick, respectively [23, 24]. In practice, however, various non-standard combinations have been observed, including:

- 10 cm (brick) + 5 cm (gap) + 10 cm (brick)
- 10 cm (brick) + 10 cm (gap) + 10 cm (brick)
- 10 cm (brick) + 20 cm (gap) + 10 cm (brick)
- 15 cm (brick) + 10 cm (gap) + 15 cm (brick)

Such inconsistencies result in significant variability in the stiffness and mass of infill panels, potentially altering the seismic response of the entire structure.

2.2. Seismic Design: Strong Columns and Weak Beams

One of the key design principles in earthquake-resistant structures is the formation of plastic hinges in beams rather than in columns—a strategy known as the strong column–weak beam concept. Unfortunately, this principle is often disregarded in practice, leading to premature failure mechanisms initiated in the vertical members.

Ensuring that plastic hinges form in beams away from nodal regions is critical for preserving overall structural integrity during seismic events. Advanced nonlinear modeling approaches allow engineers to simulate the inelastic behavior of structures and assess their seismic response using simplified relationships between deformation and internal forces [25, 26].

2.3. Rigid Joints

Beam-to-column connections are among the most critical components in reinforced concrete frame structures under seismic loading. The performance of these joints significantly influences the structure's overall deformation capacity and failure mechanism [27].

To ensure a ductile response, joints must be stronger than the elements they connect. Ideally, plastic hinges should form in the beams rather than at the joints or in the columns. Unfortunately, this requirement is often neglected, and the following deficiencies are frequently observed in practice:

- Segregation at the base of columns, creating dual discontinuity planes at the top and bottom due to poor concreting;
- Inadequate transverse reinforcement in critical joint regions;
- Poor workmanship during joint execution.

2.4. Seismic Joint Width

One effective measure to prevent the transmission of seismic forces between adjacent building blocks is the implementation of properly designed seismic separation joints. These joints must be free of all materials and remain continuous and flush in both plan and elevation [28, 29].

Seismic codes require a minimum joint width of 4 cm. However, this requirement is rarely fulfilled, particularly in existing buildings or ongoing construction. The absence of inadequacy of separation joints is further compounded in structures with irregular floor levels, where differential displacements often result in column shear failures at interfacial zones.

2.5. Concrete Quality

The quality and nature of the materials used in construction play a pivotal role in the structural response to seismic loading. While no material can be deemed inherently "earthquake-proof," framed systems made of reinforced concrete or steel tend to exhibit superior seismic performance compared to unreinforced masonry or lightweight paneling [30, 31, 32].

Concrete strength, in particular, directly influences the stiffness and load-bearing capacity of a structure. Design calculations typically assume a compressive strength (fc28) of at least 25 MPa. However, results from conformity testing and specimen crushing often reveal actual strengths below this threshold. In Algeria, the seismic design code (RPA 99) mandates a minimum concrete strength of 20 MPa, though even this level is not consistently achieved in practice.

3. Numerical Analysis: Presentation and Comparison of Results

This section presents a numerical analysis aimed at identifying key parameters that influence the behavior of portal frame structures. The primary goal is to investigate the critical factors contributing to failure in self-stabilizing structural systems through a parametric study of the following variables:

- Type of support conditions (e.g., fixed, pinned)
- Flexible ground floor configurations
- Improper "strong beam–weak column" design
- Low concrete quality (fc28 < 25 MPa)

3.1. Numerical Modeling Approach

To ensure reproducibility and transparency, the numerical modeling framework adopted in this study is described below. All simulations were performed using Robot Structural Analysis v2014, applying the Algerian Seismic Design Code (RPA 99). Modal analysis was first conducted to determine the fundamental periods and mode shapes, followed by response spectrum analysis. Nonlinear pushover or time-history analyses were not included, and this limitation is acknowledged in the conclusion.

Beams and columns were modeled as frame elements, while slabs were represented by shell elements to capture diaphragm action and mass contribution. Concrete was modeled as linear elastic with compressive strengths of 16, 20, and 25 MPa, while reinforcing steel was defined as Fe400, bilinear elastic–perfectly plastic. The elastic modulus of concrete was automatically generated by the software according to Eurocode 2 provisions, ensuring consistency with international standards.

Two boundary conditions were analyzed: fully fixed bases and pinned-base supports. Seismic input was modeled using the RPA 99 design spectrum, with modal responses combined through the Complete Quadratic Combination (CQC) method and 5% Rayleigh damping. All seismic input parameters (design spectrum, damping ratio, seismic weight calculation, and diaphragm assumptions) were kept identical across all structural configurations, ensuring that differences in the results are solely attributable to the considered structural pathologies.

Story height assumptions: the typical story height adopted in the models was 2.80 m for all cases, except in the flexible ground floor configuration, where the ground story was modeled with a height of 4.20 m to reflect the intended flexibility assumption. For clarity, the modeling assumptions are summarized in Table 1, and the member dimensions with reinforcement details are reported in Table 2.

Table 1. Summary of numerical modeling assumptions

Aspect	Description
Software	Robot Structural Analysis v2014
Analysis type	Modal analysis + Response Spectrum Analysis (RPA 99)
Solver	Eigenvalue solver (modal extraction) + response spectrum combination
Element types	Beams and columns: Frame elements; Slabs: Shell elements
Material models	Concrete: Linear elastic (fc = 16, 20, 25 MPa); Reinforcing steel: Fe400, bilinear elastic–perfectly plastic
Elastic modulus	Automatically generated by Robot according to Eurocode 2 provisions
Boundary conditions	Case 1: Fully fixed bases; Case 2: Pinned-base supports
Seismic input	Algerian Seismic Design Code (RPA 99) spectrum (Zone III, soft soil (S3))
Modal combination	Complete Quadratic Combination (CQC)
Damping model	5% Rayleigh damping
Seismic weight	Self-weight + superimposed dead loads (consistent across cases)
Diaphragm assumption	Rigid diaphragm (applied to all models)
Member dimensions	As per design assumptions (beam–column dimensions and reinforcement layouts provided in Table 2)
Modal mass participation	First mode > 90% of total mass (values reported in results section)

Table 2. Member dimensions and reinforcement details

Structural member	Dimensions (cm)	Concrete strength (fc)	Reinforcement type	Notes
Columns	35 × 35	16, 20, or 25 MPa	Fe400 (longitudinal & transverse) 8Ø16 bars	Used in both baseline and strong-beam–weak-column cases
Beams	35 × 40	16, 20, or 25 MPa	Fe400 (longitudinal & transverse) 6Ø16 bars	For strong-beam–weak-column case, beam flexural capacity > column capacity
Slabs	Thickness = 20	Same fc as beams	Fe400 reinforcement	Modeled as shell elements, diaphragm action + mass contribution

3.2 Support Types (Embedded vs. Pinned Supports)

In liquefiable soils, structures supported by shallow footings may experience excessive settlement and tilting [33]. While structural models often assume perfectly fixed base conditions during design, this assumption is frequently invalid in practice. To evaluate the influence of base conditions, this study analyzes a structure modeled with double-pinned supports at the base and compares its behavior to that of a properly designed earthquake-resistant structure with fixed supports.

3.2.1 Inter- story Drift and Lateral Displacement

Fig. 1 and Table 3 present the relative horizontal displacements and inter-story drifts for each level of the two structural configurations: one with Fixed-Base (Pinned-Base) supports and proper seismic design, and the other with double-pinned supports. These results are compared against the permissible drift values, calculated as 1% of the story height (h = 2.80 m).

Table 3. Inter-story Displacements and Horizontal Drifts

Level	Fixed-Base Frame		Pinned-Base Frame		Permissible Drift (Δ_{adm}, cm / %)
	Relative Displacement (Δ, cm)	Drift Ratio (%)	Relative Displacement (Δ, cm)	Drift Ratio (%)	
3rd Floor	1.9	0.68	3.1	1.11	2.8 cm (1.0 %)
2nd Floor	1.4	0.50	2.8	1.00	2.8 cm (1.0 %)
1st Floor	0.8	0.29	2.3	0.82	2.8 cm (1.0 %)
Ground Floor	0.3	0.11	1.5	0.54	2.8 cm (1.0 %)

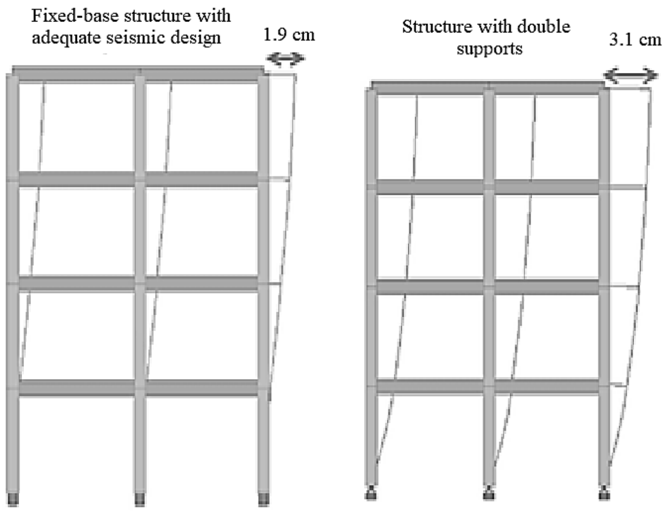

Fig. 1. Inter-story displacements of the fixed-base structure and the pinned-base frame

These results clearly show that relative displacements are significantly higher in the structure with double-pinned supports, exceeding 1% of the story height. In contrast, the Fixed-Base Frame demonstrates a 38.70% reduction in lateral displacement. To ensure proper structural embedding and enhance seismic performance, the following considerations should be taken into account:

- Ensure that the structure is embedded in suitable, non-liquefiable soil;
- Select the most appropriate type of footing based on geotechnical conditions;
- Avoid excessive mass excavation or unbalanced stripping around the foundation;
- Construct backfill in successive layers with adequate compaction at each stage;
- Avoid placing foundations on unstable or poorly compacted ground.

3.2.2 Shear Force

The shear forces for each level are given in Table 4 for both structures. The results indicate that the base shear is slightly higher in the structure with double supports, reaching 14020 KN, compared to 13990 kN in the perfectly fixed-base structure.

Table 4. Shear force comparison between the fixed-base structure and the structure with double supports

Levels	Fixed-base structure with seismic design	Structure with double supports
Base shear force V (KN)	13990	14020

Although the difference is minimal (≈0.21%), this variation is attributed to numerical sensitivity rather than a real physical effect. In principle, pinned supports reduce global stiffness and should not lead to higher base shear. Therefore, the fixed-base configuration remains the stiffer system, consistent with structural dynamics theory [34].

3.2.3 Period and Angular Frequency

The table below (Table 5) presents the fundamental periods and Angular frequency obtained for the two types of structures. The results indicate that the fixed-base structure exhibits a shorter fundamental period of 0.44 s, reflecting its higher global stiffness due to the full restraint at the base. In contrast, the structure with double supports has a longer period of 0.63 s, consistent with lower stiffness and more flexible behavior caused by partial rotational freedom at the supports. This corresponds to a 30.15% shorter fundamental period for the fixed-base structure compared to the double-support configuration.

Table 5. Period and angular frequency of the fixed-base structure and pinned-base frame

Structure Type	Mode	Period (s)	Agular Frequency (rad/s)
Fixed-base structure with seismic design	1	0.44	2.25
Structure with double supports	1	0.63	1.60

This sensitivity of dynamic characteristics—particularly the relationship between stiffness and fundamental period—to boundary conditions is well documented in the literature. As emphasized by Chopra (2017), increasing base fixity enhances stiffness and reduces the fundamental period, which in turn improves seismic performance by reducing displacement demands [34].

3.3 Designing a Flexible Ground Floor

The need for large open spaces often leads to the use of portal frame construction, with the ground floor typically having a greater height than the upper levels. As a result, the first level is often designed as a flexible floor, meaning it has significantly lower stiffness compared to the stories above. This configuration was frequently observed during the Boumerdes earthquake, where ground floors, typically intended for commercial use, exhibited a higher floor height than the upper stories, leading to increased lateral flexibility. According to RPA99, a story is considered flexible if its lateral stiffness is less than 70% of the stiffness of the story directly above, or less than 80% of the average lateral stiffness of the three stories above.

3.3.1 Inter-Story Displacement

The Fig. 2 and Table 6 present the maximum relative displacements and inter-story drifts recorded at various levels for the two structural configurations. These results are compared against the permissible drift values, calculated as 1% of the story height (h = 2.80 m, except for the flexible ground floor configuration where h = 4.20 m).

Table 6. Inter-story displacements of the fixed-base structure and pinned-base frame

Level	Seismically Designed Structure		Pinned-Base Frame		Permissible Drift (Δadm, cm / %)
	Relative Displacement (Δ, cm)	Drift Ratio (%)	Relative Displacement (Δ, cm)	Drift Ratio (%)	
3rd Floor	1.9	0.18	4.6	0.18	2.8 cm (1.0 %)
2nd Floor	1.4	0.21	4.1	0.32	2.8 cm (1.0 %)
1st Floor	0.8	0.18	3.2	0.43	2.8 cm (1.0 %)
Ground Floor	0.3	0.07	2.0	0.48	4.2 cm (1.0 %)

These results indicate that relative displacements are significantly higher in the structure with a soft story, exceeding 1% of the story height. In contrast, they are reduced by approximately 58.69% in the structure with an adequate earthquake-resistant design, primarily due to increased stiffness and better energy dissipation.

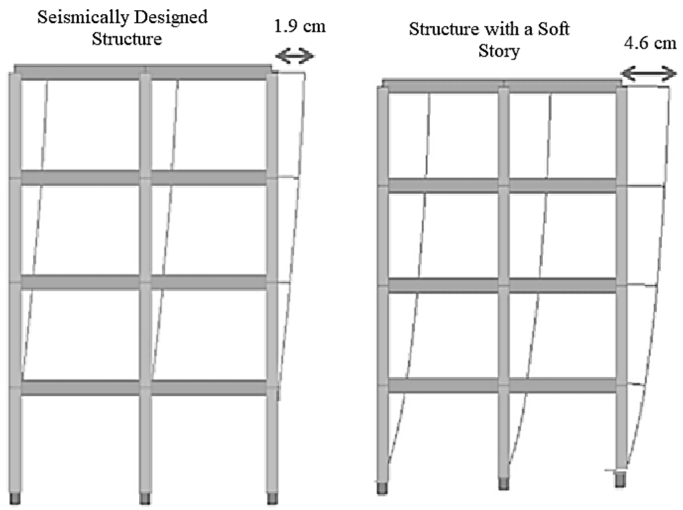

Fig. 2. Inter-story displacements of the seismically designed structure and the structure with a soft story

To mitigate this vulnerability, the following recommendations should be considered:

- Avoid designing floors with empty panels, i.e., without rigid masonry infill.
- Avoid excessive use of transparent façades, particularly large glass surfaces, which lack stiffness.
- Avoid abrupt changes in the plan geometry of load-bearing elements, as they create discontinuities in structural response.
- Ensure maximum regularity in both plan and elevation to promote uniform seismic behavior and reduce torsional effects.

3.3.2 Shear Force

The shear forces at each level are presented in Table 7 for both structures. The results show a substantial difference: the base shear in the structure with a flexible floor reaches 26290 KN, while it is significantly lower (13990 kN) in the seismically designed Fixed-Base Frame. This corresponds to a 46.78% reduction in base shear when proper seismic design measures are implemented. This significant increase in base shear in the flexible-floor structure can be attributed to the dynamic amplification caused by planar irregularities, which are known to exacerbate seismic demands. A flexible floor acts less effectively in distributing inertial forces uniformly among vertical structural elements, leading to concentration of shear forces in certain areas—particularly at the base. Moreover, the lack of stiffness continuity in the horizontal diaphragm introduces undesirable torsional effects and vertical irregularities, increasing the global seismic response.

Table 7. Shear forces for the Fixed-Base Frame and the structure with double support

Levels	Fixed-Base Frame with Seismic Design	Structure with a Flexible Floor
Shear Force at Base (V, KN)	13990	26290

Numerous studies have highlighted the detrimental effects of floor flexibility on seismic behavior. For instance, Tena-Colunga [35] demonstrated that when diaphragm flexibility is considered, lateral displacements can increase by a factor of 2.1 to 3.4 compared to the rigid diaphragm assumption, significantly impacting dynamic properties and seismic design parameters in buildings with plan irregularities [35]. Similarly, Chopra also discusses how lateral-force-resisting systems are greatly affected by diaphragm flexibility, which can undermine overall seismic performance [34].

3.3.3 Period and Agular Frequency

Table 8 below shows the fundamental periods and Angular frequency obtained for the two types of structures. As shown in Table 8, the structure with a flexible floor exhibits a longer fundamental period compared to the Fixed-Base Frame designed with proper seismic detailing. Specifically, the period of the seismic-resistant structure is reduced by approximately 20%, reflecting greater global stiffness and improved dynamic performance. Furthermore, the dominant pulse frequency of the flexible structure is lower, indicating a more compliant response to seismic excitation.

Table 8. Periods and angular frequency

Structure Type	Mode	Period (s)	Angular Frequency (rad/s)
Fixed-Base Frame with Seismic Design	1	0.44	2.25
Structure with a Flexible Floor	1	0.55	1.81

3.4 "Strong Beam – Weak Column" Design

According to Article 7.6.2 of the RPA (Algerian Seismic Code), it is required to verify the sum of the ultimate resisting moments at the beam–column joint zones. To ensure that plastic hinges develop in the beams rather than in the columns, this article recommends that the resisting moment capacity of the columns should exceed that of the beams by at least 25%. This approach is aligned with what is conventionally referred to as the “strong column–weak beam” philosophy in ductile seismic design.

In this study, the opposite configuration was deliberately analyzed—namely, a "strong beam–weak column" system. The aim was to assess the structural behavior resulting from this inverse design scenario. The outcomes of this analysis are presented and discussed in the following sections.

3.4.1 Inter-story and Global Displacements

Fig. 3 and Table 9 summarize the maximum inter-story drifts and relative displacements at each level for both structural models. The results presented in Table 9 clearly indicate that the structure with a weak column–strong beam configuration exhibits significantly higher inter-story displacements compared to the seismically designed structure. This finding aligns with established seismic design principles, which emphasize that insufficient column strength relative to beams leads to excessive drift and early hinge formation at beam–column joints [36]. In particular, the relative displacements for the flexible configuration reach or even exceed the permissible drift limits defined as 1% of the story height at several levels. Notably, the ground and first floors record values of 1.2 cm, matching or surpassing the allowable threshold of 1.2 cm and 2.8 cm, respectively. According to seismic codes, inter-story drift ratios should not exceed approximately 1–1.5% to prevent damage to structural and non-structural elements.

Table 9. Inter-story displacements and drifts for the seismically designed structure and the structure with a weak column–strong beam configuration

<table>
<tr><th rowspan="2">Level</th><th colspan="2">Seismically Designed Structure</th><th colspan="2">Structure with Structure with a Weak Column–Strong Beam</th><th rowspan="2">Permissible Drift (Δadm, cm / %)</th></tr>
<tr><th>Relative Displacement (Δ, cm)</th><th>Drift Ratio (%)</th><th>Relative Displacement (Δ, cm)</th><th>Drift Ratio (%)</th></tr>
<tr><td>3rd Floor</td><td>1.9</td><td>0.18</td><td>3.8</td><td>0.18</td><td>2.8 cm (1.0 %)</td></tr>
<tr><td>2nd Floor</td><td>1.4</td><td>0.21</td><td>3.3</td><td>0.32</td><td>2.8 cm (1.0 %)</td></tr>
<tr><td>1st Floor</td><td>0.8</td><td>0.18</td><td>2.4</td><td>0.43</td><td>2.8 cm (1.0 %)</td></tr>
<tr><td>Ground Floor</td><td>0.3</td><td>0.07</td><td>1.2</td><td>0.43</td><td>2.8 cm (1.0 %)</td></tr>
</table>

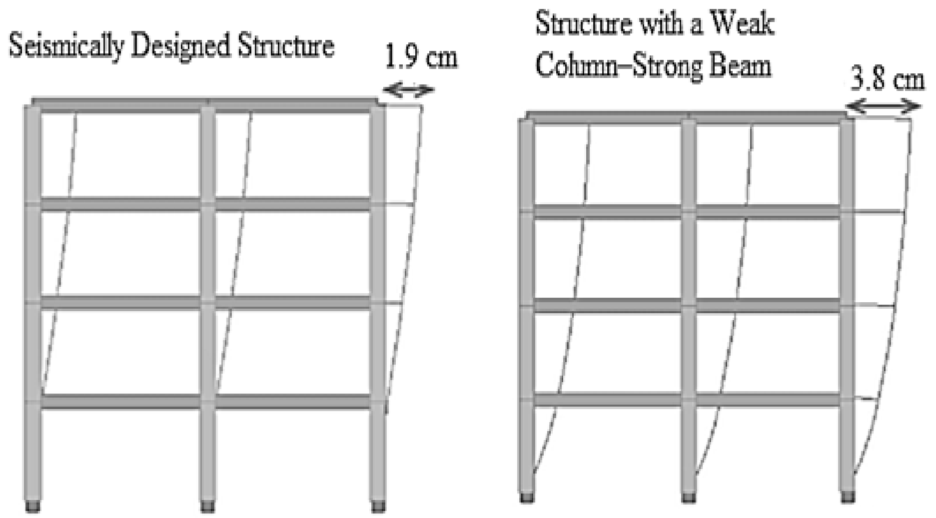

Fig. 3. Inter-story displacements of the Fixed-Base Frame and the structure with a weak-column–strong-beam design

The excessive drifts observed in the weak-column system confirm its vulnerability to lateral instability and potential deformation under seismic loading. By contrast, the seismically compliant structure maintains drift values well below these critical limits, with reductions of up to 50% across all stories compared to the weak-column system. This significant improvement illustrates how appropriate stiffness distribution and seismic detailing effectively control lateral displacement, in agreement with ductile design methodologies. The observed divergence in behavior arises from a pronounced loss of stiffness and the concentration of drift demand at beam–column intersections in the weak-column configuration [37]. Such failure mechanisms are symptomatic of frames that contravene the "strong column–weak beam" philosophy, a core tenet for achieving ductile seismic performance and ensuring that energy dissipation occurs predominantly in beams rather than in columns.

3.4.2 Shear Force Distribution

The shear forces at each level for both structural configurations are presented in Table 10. These results reveal that the base shear force in the seismically designed structure is considerably higher than in the structure with a weak column–strong beam configuration. Specifically, a reduction of approximately 19.97% is observed in the latter case. This difference can be attributed to the increased global flexibility and reduced lateral stiffness of the weak-column structure, which absorbs less seismic energy through inertial base shear transfer. The stiffer frame in the properly designed configuration leads to higher seismic demand at the base, consistent with seismic design theory [38].

Table 10. Shear force at the base for the two structural configurations

System	Seismically Designed	Weak Column–Strong Beam Structure
Base Shear Force Structure (V in kN)	13990	11195

3.4.3 Fundamental Period and Dominant Angular Frequency

The fundamental periods and dominant Angular frequency of the two structural systems are provided in Table 11. According to the data in Table 11, the structure with a weak column–strong beam configuration exhibits a longer fundamental period, indicating lower lateral stiffness and greater flexibility under seismic excitation. By contrast, the period for the seismically designed structure is shorter by approximately 38%, confirming its superior dynamic response and stiffness characteristics. The reduced angular frequency in the flexible frame reflects slower vibrational behavior, which is typically associated with higher displacement demand and less effective energy dissipation under dynamic loading.

Table 11. Fundamental periods and angular frequency of the two structures

Structure Type	Mode	Period (s)	Angular Frequency (rad/s)
Seismically Designed Structure	1	0.44	2.25
Weak Column–Strong Beam Structure	1	0.71	1.40

These observations align with the inter-story drift behavior discussed earlier in Table 9, where the weak-column system showed excessive displacements. The dynamic characteristics (longer period and lower base shear) further validate the vulnerability of the weak-column design and reinforce the need to adhere to the strong column–weak beam principle in ductile seismic design.

3.5 Structural Performance with Low-Strength Concrete (fc28 = 16 MPa)

The quality of materials used in structural design plays a crucial role in seismic performance. In particular, the compressive strength of concrete directly influences the stiffness of the structure, as it is related to the Young's modulus through the empirical relationship $E = 22000\sqrt[3]{F_C/10}$ (MPa). A lower concrete strength thus results in a lower elastic modulus and reduced lateral rigidity.

In this analysis, we modeled a structure using concrete with a compressive strength of fc28=16MPa, which is below the minimum requirement set by the Algerian Seismic Code (RPA). The results are compared with those of a seismically designed structure using standard concrete quality.

3.5.1 Inter-story and Global Displacements

Fig. 4 and Table 12 present the maximum relative displacements and inter-story drifts recorded at each level for both structural configurations. Table 12 illustrates that the structure built with low-quality concrete (fc28 = 16 MPa) exhibits significantly lower inter-story displacements compared to the seismically designed structure showing a reduction of approximately 68.4%. At first glance, this may seem advantageous; however, this is a misleading outcome, resulting from the reduced Young's modulus of the weaker concrete, which yields a more flexible yet less capable frame under seismic action.

Table 12. Inter-story displacements for the seismically designed structure and the structure with fc28 = 16 MPa concrete

Level	Seismically Designed Structure		Structure with fc28 = 16 MPa Concrete		Permissible Drift (Δadm, cm / %)
	Relative Displacement (Δ, cm)	Drift Ratio (%)	Relative Displacement (Δ, cm)	Drift Ratio (%)	
3rd Floor	1.9	0.18	0.6	0.036	2.8 cm (1.0 %)
2nd Floor	1.4	0.21	0.5	0.071	2.8 cm (1.0 %)
1st Floor	0.8	0.18	0.3	0.071	2.8 cm (1.0 %)
Ground Floor	0.3	0.07	0.1	0.036	2.8 cm (1.0 %)

Indeed, dynamic analyses confirm that lower-stiffness materials prolong the structural period, shifting mass participation to lower frequencies and decreasing seismic base shear, but at the cost of higher drift demands and reduced ductility. Studies have demonstrated that stiffness more than strength is the dominant factor governing seismic drift in reinforced concrete frames [39, 40]. These findings reaffirm that, while low-strength concrete may exhibit reduced drift in elastic analysis, it compromises seismic performance by decreasing energy dissipation capacity and promoting brittle failure modes [40].

Accordingly, although the measured displacement is lower in the fc28 = 16 MPa case, the structure lacks the resilience to withstand inelastic deformations during strong ground motions. This highlights the necessity of maintaining minimum concrete strength and stiffness requirements in seismic design to ensure adequate ductility and post-yield performance.

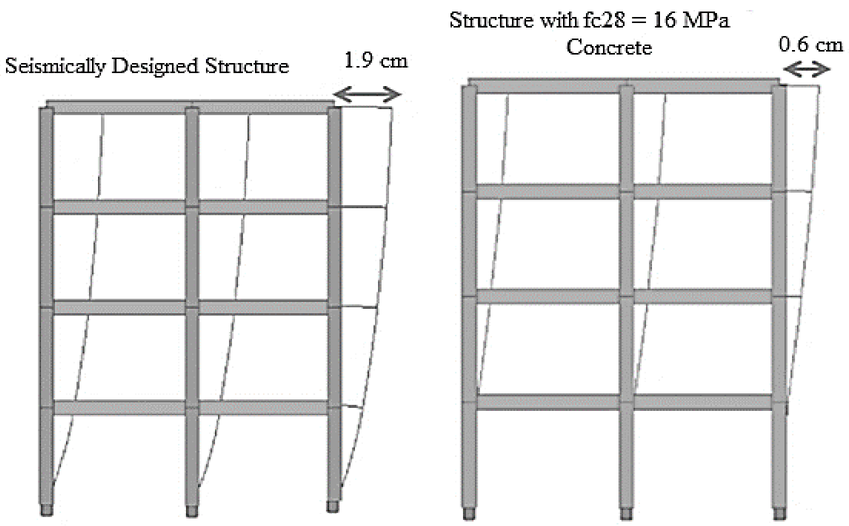

Fig. 4. Inter-story displacements of the seismically designed structure and the structure with concrete strength fc28 = 16 MPa

3.5.2 Shear Force Analysis

The shear forces at each level for both structural configurations are summarized in Table 13. The results indicate that the base shear in the structure using fc28 = 16 MPa concrete is reduced by approximately 12.5% compared to the seismically designed structure. This reduction can be attributed to the lower stiffness of the weak concrete, which alters the building's dynamic characteristics, notably by increasing its flexibility and reducing its ability to transfer seismic inertia forces to the base. However, this reduction in base shear should not be interpreted as improved seismic behavior. As confirmed in recent literature, low-strength concrete reduces stiffness and base force demand, but at the cost of energy dissipation capacity and post-elastic performance [41]. Structural elements designed with insufficient concrete strength may experience early cracking and brittle failure, undermining the principles of ductile design required for seismic resilience.

Table 13. Base shear forces for the seismically designed structure and the structure with fc28=16MPa concrete

Level	Seismically Designed Structure (V in KN)	Structure with fc28 = 16 MPa Concrete (V in KN)
Base	13990	12242

3.5.3 Fundamental Period and Angular Frequency

The fundamental periods and Angular frequency for both structural systems are presented in Table 14. According to the results in Table 14, the structure with low-strength concrete (fc28 = 16 MPa) exhibits a shorter fundamental period reduced by approximately 46%, and a correspondingly higher angular frequency. This inverse relationship, $\omega=2\pi/T$, indicates that the structure vibrates at higher frequencies, which is often characteristic of stiffer but more brittle systems [39].

Table 14. Fundamental Periods and Angular Frequency of the Two Structures

Structure Type	Mode	Period (s)	Angular Frequency (rad/s)
Seismically Designed Structure	1	0.44	2.25
Structure with fc28 = 16 MPa Concrete	1	0.24	4.09

The increased angular frequency and decreased period in this context are not signs of superior seismic behavior, but rather a reflection of altered dynamic response due to the reduced mass and stiffness contributions of low-quality concrete. In this case, the reduction in effective mass—

derived from the density of the weaker concrete and the associated self-weight—was proportionally larger than the reduction in stiffness. This explains why the fundamental period is shorter (0.24 s versus 0.44 s in the baseline), confirming that the result stems from modeling assumptions rather than any real improvement in seismic performance. As shown in experimental and numerical studies, such systems lack energy absorption capacity, and are more prone to brittle failure under strong seismic excitation [42].

3.6 Consolidated Numerical Results

To improve clarity and facilitate comparison across the different structural configurations, the key outputs of the numerical analyses are consolidated in Table 15. The summarized parameters include the fundamental period (s), base shear (kN), maximum drift ratio (%), top displacement (cm), and angular frequency (rad/s). This overview allows a direct evaluation of how each pathological case deviates from the baseline seismically designed structure.

Table 15. Summary of key numerical outputs for baseline and pathological cases

Configuration	Fundamental Period (s)	Base Shear (kN)	Maximum Drift Ratio (%)	Top Displacement (cm)	Angular Frequency (rad/s)
Baseline (Seismically Designed)	0.44	13990	0.50	1.9	2.25
Pinned-Base Frame	0.63	14020	0.80	3.1	1.60
Soft Story	0.55	26290	1.20	4.6	1.81
Weak Column–Strong Beam	0.71	11195	1.20	3.8	1.40
Low-Strength Concrete (fc28=16 MPa)	0.24	12242	0.2	0.6	4.09

4. Practical Retrofit Recommendations

This section summarizes targeted retrofit strategies for each identified structural pathology, linking the observed numerical weaknesses with practical engineering solutions. The recommendations are supported by previous studies and, where possible, by thresholds derived from our numerical results:

- Flexible ground floor → Addition of shear walls, steel bracing, or seismic isolation systems is recommended to reduce excessive lateral drift and enhance overall stability.
- Weak-column–strong-beam configuration → Column jacketing with CFRP or steel is suggested to restore the intended capacity hierarchy and prevent premature column failures.
- Low-strength concrete → FRP wrapping or steel encasement can be applied to improve axial load capacity, ductility, and shear resistance.
- Poor support conditions (pinned/embedded) → Foundation retrofitting, soil stabilization, or base isolation should be considered to mitigate risks of settlement, tilting, and loss of lateral resistance.

These retrofit measures provide a direct link between the identified structural pathologies and practical interventions, thereby strengthening the applicability of this study as a guide for seismic retrofitting of reinforced concrete frames.

5. Conclusion

Effective structural design is fundamentally about making deliberate and rational decisions. In this context, capacity-based design provides a robust and practical framework for seismic engineering

[43]. Given that it is neither economically feasible nor technically realistic to design structures that remain entirely undamaged under all earthquake scenarios, a certain level of controlled, repairable damage is generally accepted, provided it does not compromise human safety.

To this end, the engineer must intentionally locate potential plastic hinge zones and prescribe detailing strategies that ensure ductility in those regions. Simultaneously, the remaining structural elements, especially the primary load-bearing components that safeguard the building's global integrity, must be over strengthened and adequately protected by these sacrificial zones. When this design philosophy is rigorously implemented, the likelihood of unexpected or unaccounted structural failures is greatly minimized.

This study has focused on reinforced concrete portal frames, which are known to exhibit vulnerabilities under seismic action. Through comparative numerical simulations of multiple structural configurations, several key insights have emerged:

- Structures with design deficiencies, such as flexible ground stories or weak column–strong beam layouts, exhibit significantly larger relative displacements, with inter-story drift ratios exceeding 1% of the story height, a critical threshold known to induce damage to non-structural components.
- Shear force distribution varies notably among the configurations. The Pinned-Base Frame and the one with a flexible story transmit higher shear forces to the base, increasing demand on foundations and connections. Conversely, the weak column–strong beam system and the structure built with low-strength concrete (fc28 = 16 MPa) present reduced base shear, but this is misleading, as it stems from a lack of stiffness and energy dissipation capacity, not from improved performance.
- In terms of dynamic behavior, structures such as the weak column–strong beam and double-supported frames exhibit increased fundamental periods, exceeding those of the seismically compliant frame by more than 36%. This elongation of the structural period reflects greater flexibility, which, while reducing base shear, correlates with amplified lateral displacements and higher damage potential.

Overall, this study highlights the critical importance of structural hierarchy, material quality, and stiffness distribution in seismic design. The findings provide quantitative evidence supporting the enforcement of capacity design principles in engineering codes and demonstrate the risks associated with non-compliant configurations. This work contributes to the growing body of literature emphasizing performance-based approaches in seismic design and encourages further experimental validation and field calibration to strengthen the resilience of built infrastructure.

Despite its contributions, this study has certain limitations. The analyses were restricted to linear elastic and response spectrum methods, without explicit modeling of nonlinear plastic hinge formation or degradation of materials. Masonry infill panels, soil–structure interaction, and damping variability were not incorporated, which could influence the actual seismic response. Furthermore, no experimental validation was carried out to compare the numerical results with field or laboratory data. Future research should therefore extend the current framework by conducting nonlinear static (pushover) and time-history analyses, integrating full-scale testing and field observations, and exploring advanced retrofitting techniques such as CFRP jacketing, steel jacketing, and base isolation systems. Such developments would allow for a more realistic assessment of pathological RC structures and provide direct guidance for practical retrofitting applications.

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