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Numerical Study of the Effectiveness of Post-Seismic Structural Repairs on Reinforced Concrete Portal Frames

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Abstract: This paper presents a numerical study of the effectiveness of post-seismic repair procedures on Reinforced Concrete (RC) portal frames. Seismic occurrences often compromise the structural integrity of reinforced concrete frames, leading to significant damage and even collapse. The usefulness of post-seismic repair techniques for Reinforced Concrete (RC) portal frames is examined numerically in this research. The structural integrity of reinforced concrete frames is frequently compromised by seismic occurrences, which can result in considerable damage or even collapse. Post-seismic repairs vary in efficacy depending on the kind and degree of the damage, but they are required to restore structural function. In order to mimic seismic damage and the selection of repair techniques, such as increasing the section, an inertia reduction of the structure element was employed in this work. Commercial software was utilized to perform the numerical computations. To measure the improvements in structural behaviour, the results are compared with pre-damaged and unreinforced structures. The findings provide valuable insights into the best repair techniques, demonstrating that although some methods only marginally improve RC portal frame robustness, others significantly do so. This research contributes to the development of effective post-seismic repair methods by increasing structural safety and prolonging the service life of damaged reinforced concrete structures.

Keywords: *Post-seismic, Repairs, Reinforced concrete, Portal frames, Inertia reduction*

1. Introduction

In recent years, there has been a significant increase in the importance placed on evaluating and rehabilitating structures following seismic events. The performance of a structure after an earthquake can be heavily impacted by the repairs made to it. The ability of a structure to withstand seismic activity is greatly influenced by its ductility, stiffness, and strength. One of the main challenges faced by reinforced concrete structures after a major earthquake is the reduction in strength and stiffness as a result of inelastic damage. This damage, which occurs due to the development of plastic zones within the structure, could potentially be addressed through the use of well-designed composite materials. Extensive research has been conducted to assess the effectiveness of repair methods utilizing composite materials like concrete jacketing or mortar. These repair techniques are primarily aimed at either restoring lost capacity due to concrete crushing or enhancing the structure's capacity by reinforcing existing deficient

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elements. Post-seismic inspection and repair strategies can provide an additional level of safety and performance of existing structures after an extreme event; however, these strategies are under-studied in the literature. Most research has been focused so far on the development of suitable repair techniques for different structural components, such as beams, columns, or walls. Following the observation of the damage at specific structural components, building owners and practitioners apply standard or general repair strategies for retrofitting the entire building.

A study has conducted by [9]to assesses the reparability of buildings damaged by earthquakes, based on estimating the expected performance loss and repair costs. These tools utilize capacity curves and cost-PL relationships calibrated against an extensive database, providing critical insights for decision-makers and insurance companies. Another research, study the seismic vulnerability of medium-span RC bridges designed decades ago for low seismic forces. It focuses on assessing capacity, demand, and damage using dynamic nonlinear methods, specifically investigating the impact of RC jacketing on frame-type pier-supported bridges. Parametric analysis considers jacket thickness and reinforcement ratios, aiming to enhance seismic resilience through optimized retrofitting strategies[7]. Moreover, an reviews frameworks and case studies on seismic resilience, highlighting challenges like data access, financial resources, and cooperation were studied[2]. A research of [11]examines a clustered building in L'Aquila's historic city center, damaged by the 2009 earthquake, focusing on repair and seismic strengthening. It addresses challenges in surveying, damage interpretation, and structural modelling of interconnected masonry buildings. The method is applicable to similar clusters in L'Aquila and other historic city centers. The study evaluates the VecTor4 program's ability to assess seismic performance of concrete containment structures, focusing on stress, cracking, and failure mechanisms. It also examines post-seismic performance under increased pressure, considering time-dependent factors like creep and tendon relaxation. The findings highlight the significant impact of earthquakes on structural integrity [6]. [3] examines the seismic behaviour of old reinforced concrete beam-column joints and the effectiveness of fiber-reinforced concrete (FRC) jacketing for strengthening. Tests show that FRC improves shear strength by up to 50% and energy dissipation by 85%. Comparisons between as-built and strengthened joints, along with strain measurements, highlight the benefits of this innovative solution [3]. Moreover, a study assesses the seismic vulnerability of reinforced concrete (RC) buildings by combining numerical analysis with field monitoring data to improve risk evaluation accuracy. The methodology is demonstrated through time-building-specific fragility curves for a hospital, incorporating ambient noise measurements and dynamic analysis. Results show that considering the actual structural state, including aging and corrosion, significantly increases the building's seismic vulnerability [8]. A study was conducted for the Ibn Khaldoun housing city in Boumerdes, Algeria, experienced significant damage during the 2003 earthquake. This study evaluates the reliability of the applied retrofitting solutions through

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nonlinear static and dynamic analyses, revealing non-compliance with minimum seismic design criteria. However, the retrofitting enhanced structural performance by reducing seismic damage risks [1].In another way,[4] study, examines the vulnerability of mid-20th-century concrete infrastructure to seismic events, focusing on outdated design codes and reinforcement corrosion. Modifications to current guidelines were proposed to incorporate corrosion damage, with expressions for residual material and mechanical properties based on reinforcement mass loss. The study demonstrates the effectiveness of Ultra-High-Performance Concrete (UHPC) in mitigating corrosion and enhancing the strength and ductility of corroded lap-spliced columns, both before and after seismic activity. [5], Their study develops a building monitoring framework to assess changes in vibration frequency caused by seismic damage and repairs. Monitoring of University of Ferrara buildings after the 2012 Emilia earthquake revealed a permanent drop in vibration frequency due to damage, with partial recovery following repairs. A low-cost real-time monitoring system effectively provided insights for preliminary damage assessment. In the same way, improving the design and detailing of non-structural components—such as partition walls, ceilings, and piping—to reduce damage and simplify post-earthquake repairs. It emphasizes the importance of addressing reparability during the conceptual design phase to minimize future repair costs and disruptions [13]. A tools for assessing the reparability of existing reinforced concrete (RC) buildings after an earthquake by estimating two key metrics: Performance Loss (PL) and Repair Costs (Cr) are defined, these tools estimate two main indicators: Performance Loss (PL): A measure of how much the building's performance has degraded due to seismic damage, Repair Cost (Cr): The associated financial cost required to restore the building to its pre-earthquake condition. [10].

2. Objective

The main objective of the study presented in this paper is to investigate the effectiveness of different repair alternatives applied to frame structures damaged by earthquakes. A final goal was to choose a simple repair design that can be used to increase in initial stiffness and distribution of plastic hinges. The repair selected for investigation is based on the use of the concrete walls to increase the rigidity and decrease the total displacement.

3. Methodology

For this study, it is proposed to analyse a building braced by a self-stabilizing reinforced concrete portal system. The portals are theoretically subjected to seismic loading, modelled using a function available in ROBOT STRUCTURAL ANALYSIS software. This function enables the consideration of damage by reducing the moment of inertia for each column and beam." Three configurations were considered: the initial structure (without damage), the damaged structure, and the retrofitted structure. The Retrofitted Structure (RS) was reinforced using concrete walls as presented in the Fig1.

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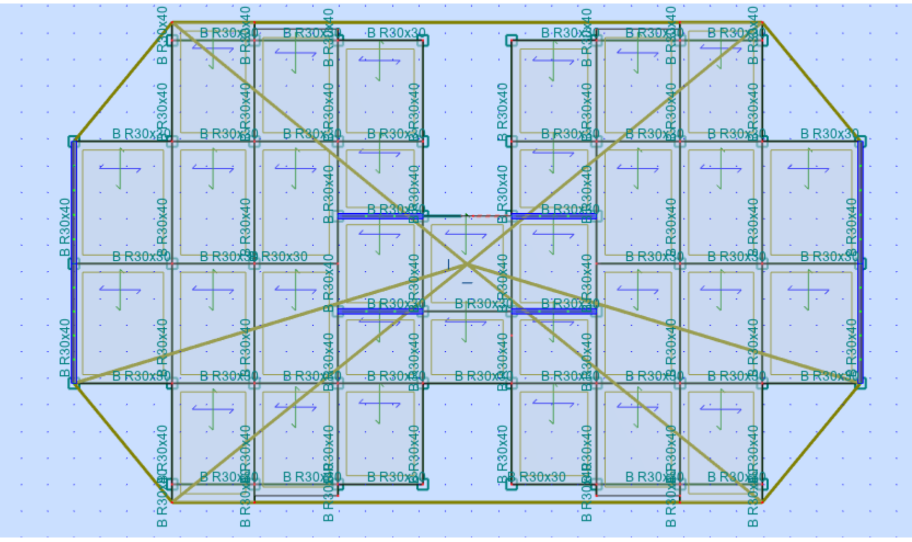

Figure 1. Position of the Reinforced concrete walls in (RS).

For each configuration, the forces (M, N, and T) on structural elements (beams and columns) were calculated. A comparison was conducted between all force values to assess the variation in forces across the different configurations. It noted that the damaged structure is considered using the reduction inertia available in commercial software.

4. Selection of Portal Frame Parameters for a case study

The structural parameters that define the reinforced concrete (RC) portal frames are as follows:

The building which is the subject of this study is a R+3 building for residential use, located in Bejaia in the north of Algeria on firm with soil class S2, classified in zone Ⅱ-a according to Algerian seismic regulations (RPA 99/2003) [12].

The geometric characteristics are summarized in Table 1

Elevation dimensions	Total height of the building (m)	12.64
	Height of the ground floor (m)	3.06
	Height of the current floor (m)	3.06
Plan dimensions	Width (m)	18.06
	Length (m)	29.65

The floors are hollow-core slabs (16+4 cm), Main beams: 40 × 30 cm, Secondary beams: 30 × 30 cm, Columns: 40 × 40 cm across all levels and the terrace is inaccessible (Fig. 1).

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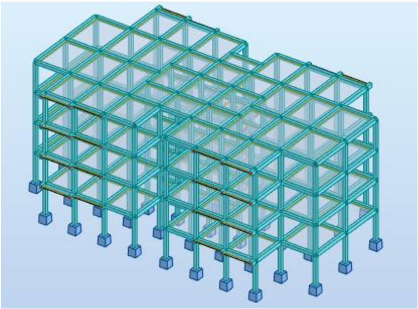

Figure 1. 3D view of the model.

5. Results and discussions

To account for seismic forces on the self-stabilizing reinforced concrete frames, the results obtained using ROBOT STRUCTURAL ANALYSIS software represent the variation in values forces (M, N, T) for the structural elements in the three cases: initial structure, damaged structure, and reinforced structure. The results are presented as a comparison between these three cases.

5.1.Axial and bending moment

5.1.1. Axial and Bending moment for Initial structure/ damaged structure/Reinforced structure (ELU and ELS states)

The Fig.2 present the variation of axial load for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS) in the ELU state. The Fig.3 show the evolution of the bending moment for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS).

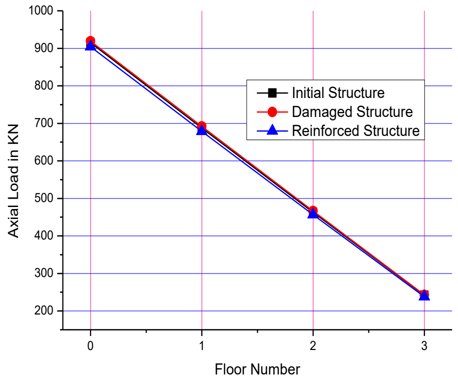

Figure 2. Axial load in columns for the three configurations (IS, DS, RS) ELU

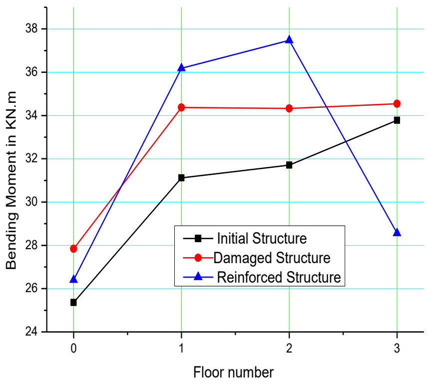

Figure 3. Bending Moments in columns for the three configurations (IS, DS, RS) ELU

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The Fig.4 present the variation of axial load for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS) in the ELS state. The Fig.5 show the evolution of the bending moment for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS).

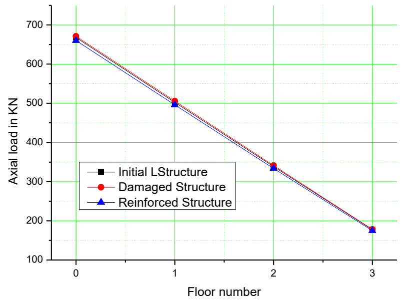

Figure 4. Axial load in columns for the three configurations (SI, DS, RS) ELS

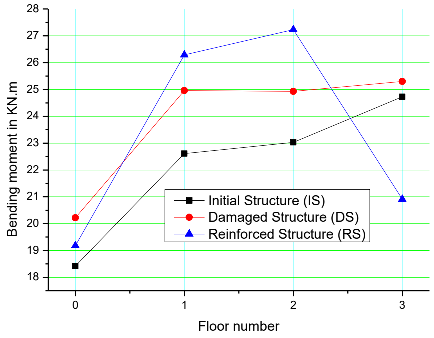

Figure 5. Bending Moments in columns for the three configurations (SI, DS, RS) ELS

According to Figs. 2 and 3, there is no significant variation in the axial forces in the columns across the three configurations: Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS). This is because the vertical loads remain constant across the three cases. According to the results in Figs. 4 and 5, the bending moment increases from the Initial Structure (IS) to the Damaged Structure (DS), but decreases from the Damaged Structure (DS) to the Reinforced Structure (RS). This can be explained by the fact that the bending moment depends on the inertia of the structural element(columns): when the inertia decreases, the bending moment increases. This observation demonstrates the benefits of inserting reinforced concrete walls in the reinforced structure.

Another observation was that the bending moment decreased significantly for the Reinforced Structure (RS) compared with the Initial Structure (IS) and the Damaged Structure (DS), particularly on the third floor. This can be explained by the fact that the bending moment decreases in the case of the (RS) because the presence of reinforced concrete walls increases the inertia of the columns. It is also noted that the bending moment decreases significantly by 18% at the level of the third floor when passing from the damaged structure (IS) to the reinforced structure (RS). This is due to an increase in the inertia of the columns. In light of these findings, it is advised that the width of the reinforced concrete walls for the posts on the third floor be varied.

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5.1.2. Initial Structure (IS) / Damaged Structure (DS)/ Reinforced Structure (RS) (ELA)

The Fig.6 present the variation of axial load for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS) in the ELA state. The Fig.7 show the evolution of the bending moment for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS). The ELA state concerns the combination taking into account the earth quake solicitation.

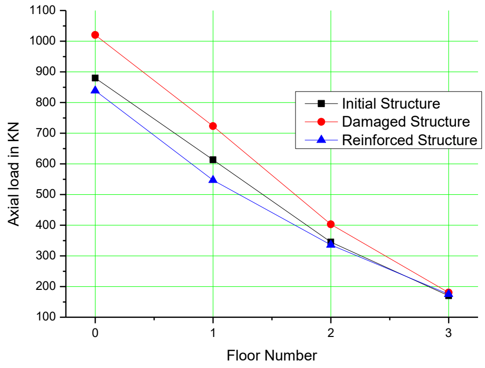

Figure 6. Axial load in columns for the three configurations (SI, DS, RS) ELA

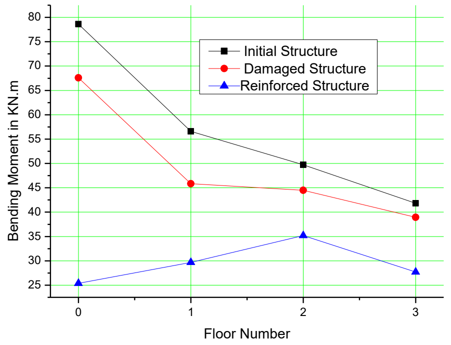

Figure 7. Bending Moments in columns for the three configurations (SI, DS, RS) ELA

According to the results in Fig. 6, there is a significant variation in the axial forces in the columns for the three configurations. This variation shows an increase from the Initial Structure (IS) to the Damaged Structure (DS), which can be explained as follows: this is due to the redistribution of the normal forces in the damaged structure, whereby the healthy columns take up the axial forces of the earthquake-damaged columns. However, the variation decreases from the damaged structure (DS) to the reinforced structure (RS). This can be explained by the redistribution of normal forces in the damaged structure, whereby the healthy columns (in this case, the reinforced columns) take up the additional axial forces of the earthquake-damaged columns (damaged to reinforced). It should be noted that this is clear for the ground floor, the first floor and the second floor. This is due to the reduction in axial forces from the ground floor to the third floor.

According to the results in Fig. 7, Significant variations are observed in the three configurations. This is due to a reduction in the bending moments when moving from the initial structure to the damaged structure, and then to the reinforced structure. This can be explained by the fact that the bending moment depends on the ratio of the two reduced inertias of the column and the beam due to the damage. In the same context, Significant variation in bending moments can be seen (a reduction from initial to damaged), especially on the ground and first and second floors. This is due to the formation of plastic hinges.

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In conclusion, it can be seen also from the results in Fig. 7, there is a significant reduction in the normal column forces for the three configurations. This can be explained by the redistribution of normal forces in the reinforced structure, since reinforced columns allow normal forces to be redistributed (i.e. initial, damaged and reinforced). For the bending moments, a significant variation is observed (a reduction from the damaged state to the reinforced state) for all the columns. In our opinion, this is due to the reinforcement levelling the building.

The Figs provide an in-depth analysis of the performance of columns, main beams and secondary beams under various conditions (initial structure, damaged structure and reinforced structure). For Ultimate Limit States (ELU), Service Limit States (ELS) and Accidental Limit States (ELA), the following can be noted:

- For each of the ELU and ELS, under all conditions, there is a significant increase in the stress values (N, M and T).
- For ELA, there was a significant increase in the load values (N, M and T).
- The fluctuations in stresses are attributable to the impact of the reduction in inertia on the load distribution and the addition of reinforcement.

5.1.3. Stress results for the columns (ELU, ELS)

The Fig.8 present the variation of the stress in columns for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS) in the ELU and ELS states. The Fig.9 show the evolution of the bending moment for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS).

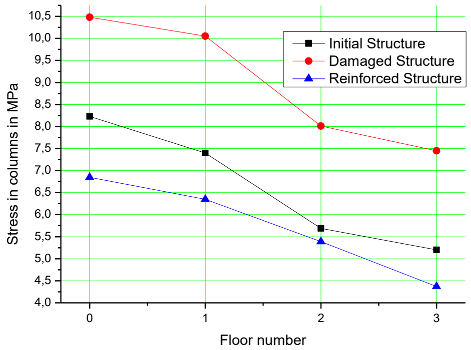

Figure 8. Stress in columns for the three configurations (SI, DS, RS) ELU

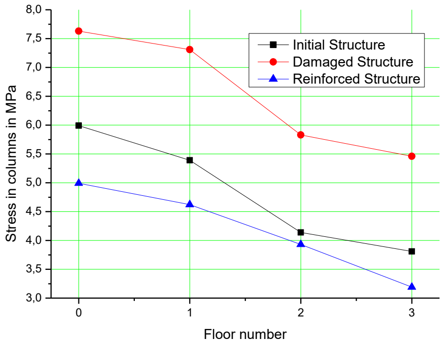

Figure 9. Stress in columns for the three configurations (SI, DS, RS) ELS

From the results in Fig.8, it can be seen that there is a significant increase in the stresses in the columns for the three configurations (IS, DS and RS), Furthermore, this variation results in an

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increase in stresses of around 22% when transitioning from the initial structure to the damaged structure. This is due to the reduction in column section size caused by seismic action. Conversely, this variation results in a 35% decrease in stresses in the columns when transitioning from the damaged structure to the reinforced structure. This is due to the columns' increased sectional area resulting from the addition of reinforced concrete walls. The same constatations were confirmed for the Fig.9 (ELS state).

5.1.4. Stress results for the columns (ELA)

The Fig.10 present the variation of the stress in columns for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS) in the ELA state. The Fig.11 show the variation of the stress in beams for the three configurations, Initial Structure (IS), Damaged Structure (DS) and Reinforced Structure (RS) in the ELA state.

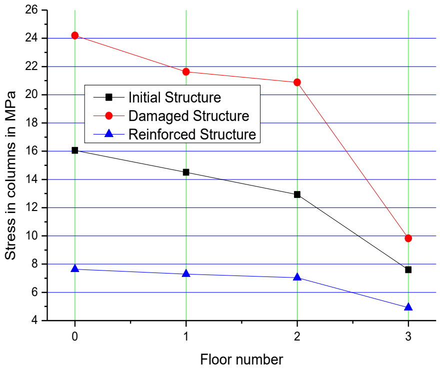

Figure 10. Stress in columns for the three configurations (SI, DS, RS) ELA

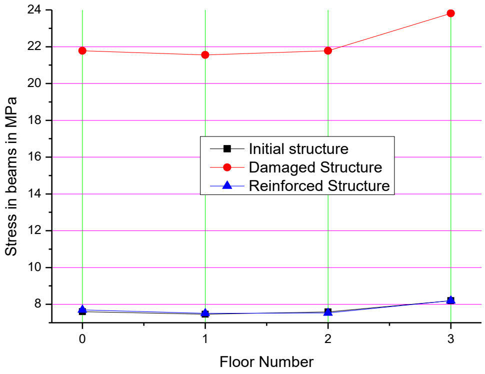

Figure 11. Stress in beams [MPa] for the three configurations (SI, DS, RS) ELU

From the results in Fig.10, it can be seen that there is a significant increase in the stresses in the columns for the three configurations (IS, DS and RS), Furthermore, this variation results in an increase in stresses of around 34% when transitioning from the Initial structure (IS) to the Damaged structure (DS). This is due to the reduction in column section size caused by seismic action. Conversely, this variation results in a 70% decrease in stresses in the columns when transitioning from the Damaged Structure (DS) to the Reinforced Structure (RS). This is due to the columns' increased sectional area resulting from the addition of reinforced concrete walls

Figure 11 shows how compressive stresses in the beams vary for the three configurations. This variation is almost zero when transitioning from the initial structure to the reinforced structure. This demonstrates the effectiveness of the adopted reinforcements, as the structure returns to its initial stress state once reinforced. Conversely, a significant increase in compressive stresses of around 67% is observed in the beams when transitioning from the initial structure to the damaged structure. This indicates the formation of plastic hinges in the beams rather than the columns, which aligns with the recommendations for good seismic design in RPA 99 V2003[12].

 The figures provide a detailed analysis of the stresses observed for the columns, main beams and secondary beams under different conditions: initial structure, damaged structure and reinforced structure for Ultimate Limit States (ELU), Service Limit States (ELS) and Accidental Limit States (ELA).

- After the transition from the initial to the damaged structure, the stresses decrease and then increase after strengthening, indicating the success of the strengthening method, which demonstrates improved load capacity and resistance to permanent deformation.

6. Conclusions

A case study was conducted on an R+3 building located in seismic zone II-a in the North of Algeria, designed as a self-stable reinforced concrete portal frame. To carry out this study, three structural configurations were modelled using ROBOT Structural Analysis software:

- Initial Structure (IS) (pre-seismic)
- Damaged Structure (DM) (using the inertia reduction option in the software to account for cracking)
- Reinforced Structure (RS) (strengthened by the addition of bracing walls)

These three configurations were analysed, and the results are summarized. The key findings are as follows:

1. When transitioning from the initial to the damaged structure, a decrease in stresses is observed due to the loss of stiffness from cracking. After reinforcement, the stresses increase again, indicating the effectiveness of the strengthening method and improved load-bearing capacity and resistance to permanent deformation.
2. A significant increase in column stresses is observed when comparing the initial and damaged structures. This increase is due to seismic effects. However, a notable decrease in stresses occurs after reinforcement, confirming the structural benefit of the added bracing walls.
3. A marked reduction in axial (normal) forces is observed when moving from the damaged to the reinforced configuration. This can be attributed to the redistribution of internal forces in the strengthened structure, as the reinforced elements help better distribute the loads.
4. Regarding bending moments, a significant reduction is noted across all cases when transitioning from the damaged to the reinforced structure. This reduction is likely due

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to the improved alignment and stiffness introduced by the bracing walls, contributing to a more balanced and levelled structural response.

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