Enhancing Performance-Based Seismic Design through RC Column Jacketing: A Pathway to Improved Structural Safety

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Abstract:

In seismic-prone regions, improving the structural resilience of older buildings is critical for minimizing potential collapse and protecting lives. Concrete jacketing has emerged as a widely adopted retrofitting technique for enhancing the structural performance of columns in existing buildings. This study investigates the effectiveness of concrete jacketing in elevating the performance level of a building as defined by ASCE/SEI 17-41 **standards. Through pushover analysis, this research demonstrates that concrete jacketing substantially enhances plastic hinge rotation capacity, reduces story displacement, and decreases inter-story drift. The findings** highlight the critical role of column strengthening in seismic retrofitting **efforts, offering practical insights for engineers and architects aiming to bolster the safety of vulnerable structures.**

Keywords:

RC jacketing, retrofitting, performance based seismic design, plastic hinge, pushover analysis

1. Introduction

The resilience and safety of buildings, particularly in seismic regions, are critical to ensuring the protection of lives and property. The importance of rehabilitating existing structures, especially aging or seismically vulnerable buildings, has grown as urban populations expand and cities face increased seismic risks (Al-Safi et al., 2021 ;2020 **). Many older buildings were** designed according to outdated codes or without adequate consideration **for seismic activity, putting them at greater risk of damage or collapse during an earthquake. Rehabilitation of these buildings, therefore, has become a priority for engineers, urban planners, and policymakers to enhance public safety and protect the built environment (Bojanowski et al.,** 2021 **).**

Rehabilitation or retrofitting aims to upgrade a building's structural performance to meet current standards, increase resistance to seismic forces, and reduce the likelihood of catastrophic failure (Al-Safi, 2022). These upgrades range from minor structural reinforcements to comprehensive redesigns depending on the existing building's condition and the expected seismic demands. Among various retrofitting strategies, structural element strengthening—particularly for columns, beams, and joints—has shown to be highly effective. Columns are fundamental to a building's vertical load-bearing capacity, and their failure can lead to progressive collapse, emphasizing the need for reliable column strengthening techniques (Hakim & Booth, 2022).

Concrete jacketing is a prominent method for strengthening columns in reinforced concrete (RC) structures, widely regarded for its effectiveness and feasibility. It involves wrapping an existing column with an additional layer of concrete and reinforcing steel, thereby increasing the column's load-bearing capacity and improving its ductility. Concrete jacketing provides enhanced confinement, which is crucial for structures in seismic zones as it improves the column's ability to absorb and dissipate energy during seismic events (Priestley et al., 2007). Compared to other techniques, such as steel jacketing or fiber-reinforced polymer (FRP) wrapping, concrete jacketing has the advantage of compatibility with existing RC structures and is often more cost-effective in large-scale projects (Bingöl & Özmen, 2020).

The application of concrete jacketing has gained attention due to its straightforward implementation, durability, and ability to significantly improve structural resilience. Concrete jackets increase the cross-sectional area and moment of inertia of the column, resulting in enhanced flexural and shear strength. The technique also allows for a controlled increase in stiffness, thereby minimizing story drifts under lateral seismic loading. Moreover, concrete jacketing is a versatile solution, adaptable to varying column sizes and shapes, making it particularly beneficial for retrofitting irregularly shaped or slender columns that are commonly found in older buildings (Choi & Seo, 2019).

In recent years, research has focused on optimizing concrete jacketing techniques to further enhance their efficiency and cost-effectiveness. Ghannoum and Moehle (2014) demonstrated that jacketed columns experience improved performance in terms of plastic hinge formation, a critical factor for energy dissipation and inelastic behaviour during earthquakes. Their study showed that concrete jacketing allows for an extended plastic hinge zone, resulting in greater ductility and reduced chances of brittle failure. Additionally, studies have incorporated modern analysis tools, such as finite element modelling (FEM) and nonlinear dynamic analysis, to simulate the behaviour of jacketed columns under seismic loads more accurately (Mata et al., 2017). These simulations provide insights into the interactions between the original column and the jacket, aiding in the optimization of reinforcement details and jacket dimensions.

More recent investigations have explored alternative materials and **techniques to enhance the performance of concrete jacketing; Khoury et al. (**2021 **) analysed the use of high-performance concrete and self-compacting concrete for jacketing applications, which reduced construction time and improved confinement effectiveness. Furthermore, hybrid jacketing methods incorporating both concrete and fibre-reinforced polymers (FRP)** have been studied to achieve higher stiffness and reduce the overall weight **added to the building. These developments reflect a continuous advancement in retrofitting methodologies, aimed at making buildings safer, more resilient, and less intrusive to occupants (Teng et al.,** 2022 **).**

Despite these advancements, there remain critical gaps in understanding the overall influence of concrete jacketing on building performance levels. Existing research often focuses on individual performance indicators, such as moment capacity or ductility, but lacks a holistic approach to assessing performance across different levels, particularly under seismic conditions. Building performance levels, as outlined by the American Society of Civil Engineers (ASCE), provide a systematic way to evaluate how a structure will perform under seismic loads—from "Operational" to "Collapse Prevention." Concrete jacketing's potential to elevate a building's performance from "Collapse Prevention" to "Life Safety" is particularly valuable, as it implies a significant reduction in the risk of collapse while allowing controlled **deformation and energy dissipation (ASCE,** 2017 **).**

The importance of this study lies in bridging the gap between column strengthening at a local level and the overall improvement of building **performance levels. By focusing on how concrete jacketing can enhance performance from "Collapse Prevention" to "Life Safety," this research highlights a practical and widely applicable solution for seismically vulnerable buildings. The findings of this study can provide engineers and policymakers with data-driven insights into the effectiveness of concrete jacketing, supporting informed decisions on retrofitting approaches that prioritize occupant safety and structural resilience.**

This study employs a case-study approach to examine a five-story RC building initially classified at a "Collapse Prevention" level. The building's seismic performance is analysed before and after the application of concrete jacketing to its columns. Key performance indicators, including plastic hinge formation, story displacement, and inter-story drift ratios, are evaluated to quantify the improvements brought by the jacketing. The results demonstrate the potential of concrete jacketing to elevate **performance to "Life Safety," thereby contributing to a safer building** environment and providing a model for similar structures in need of seismic **retrofitting.**

2. Methodology

2.1 Building Information

The case study building is a five-story reinforced concrete (RC) structure located in Sana'a, Yemen, an area classified within a moderate risk zone. The seismic design parameters are based on a peak ground acceleration **(PGA) of approximately 0.20**g to **0.30g. The building has a total height of** 15 **meters, with each story measuring** 3 **meters. It is designed in a rectangular layout with four bays along both the X and Y directions, each bay spanning** 5 meters in length as shown in figure 1**. The concrete used has a** compressive strength of 25 **MPa, while the steel reinforcement has a yield** strength of 280 **MPa. Site soil investigations indicate that the building rests on a moderately stiff soil profile, classified as Site Class D. For finishing loads, the building was designed with an additional 1.9 kN/m^2, and the live** load is **2.0 kN/m^2, reflecting typical residential use in Sana'a. These load specifications, along with non-structural component considerations, are incorporated into a detailed pushover analysis - a non-linear static technique used to assess a structure's capacity to withstand seismic forces by applying gradually increasing lateral loads - to simulate the building's behaviour under lateral seismic loads.**

The building's structural system consists of a two-way slab floor system supported by beams. Each slab is 130 **mm thick, designed to accommodate typical residential live loads. Beams are** 250 mm x 500 **mm. The building's columns, which are initially** 300 mm x 300 **mm in cross-section.**

The RC jacketing of columns is designed to strengthen the columns passed to CP level only to enhance their performance to LS level. Each column jacket adds a 100 **mm layer of high-strength concrete around the original column, effectively expanding the column's dimensions to** 500 mm x 500 **mm. Additional main and transvers reinforcement with a yield strength of** 280 MPa and the concrete in the jacket has a compressive strength of 30 **MPa, slightly higher than the original concrete, to ensure compatibility and increase overall durability. The jacket is anchored to the original column using dowels and shear connectors, ensuring composite action between the new and existing materials. This RC jacketing is expected to enhance the columns' ductility, shear strength, and flexural capacity, thereby improving the building's overall seismic resilience and performance level.**

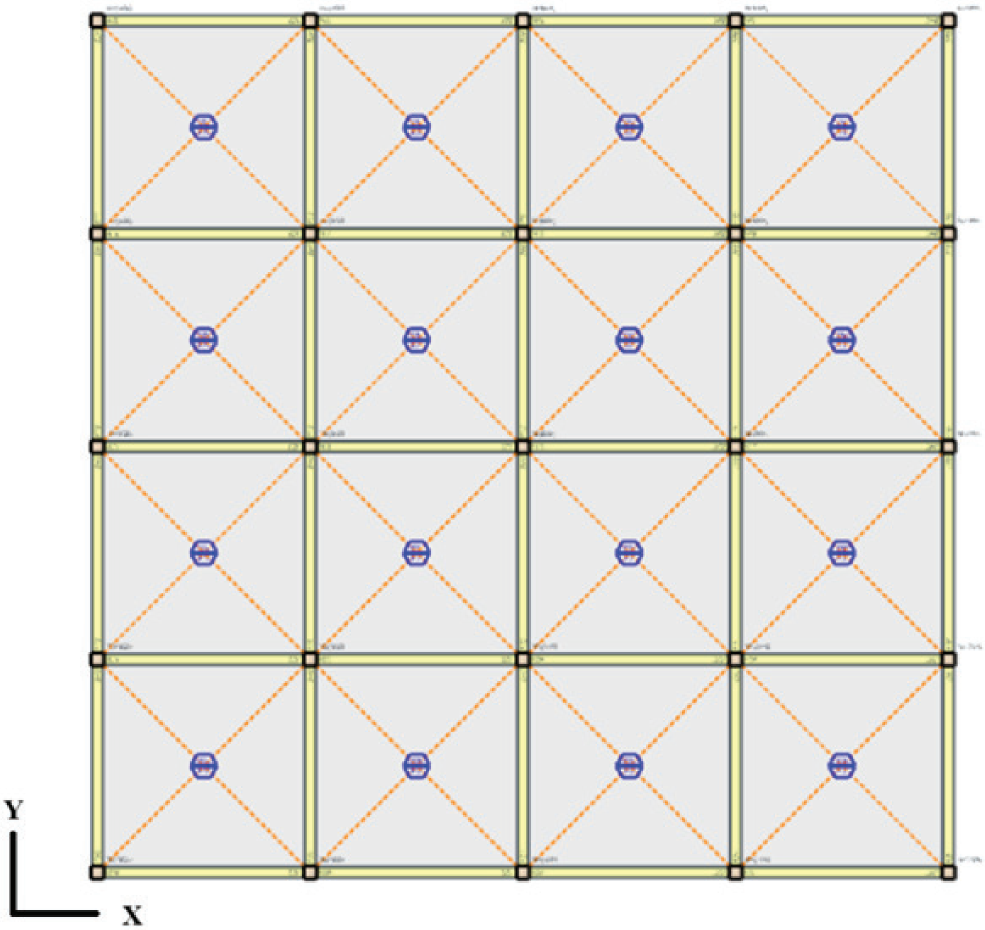

Figure 1 Plan view of the building

2.2 Procedure

The seismic evaluation procedure for the building commenced with a primary assessment using pushover analysis, which progressively applies lateral loads to identify the building's load-bearing and deformation capacities. Plastic hinge limits, as per Federal Emergency Management Agency (FEMA 356 **and FEMA** 440**) guidelines, as shown in Figure** 2 were set according to **defined performance levels for concrete members: "Immediate Occupancy" (IO), "Life Safety" (LS), and "Collapse Prevention" (CP). For concrete columns,** allowable hinge rotation and maximum drift limits for each level according to **FEMA** 356 **and FEMA** 440 were summarized in table 1**.**

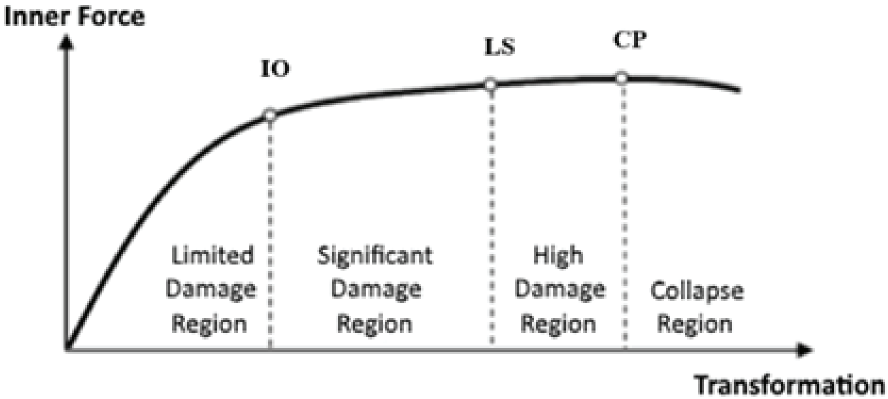

Figure 2 **Damage regions curve**

Table 1 Allowable hinge rotation and maximum drift limits

Performance level	IO	LS	CP
Allowable rotations (rad)	0.005	0.015	0.03
Max. drift limits (%)	1	2	4

The overall performance level of the building was determined by comprehensive plastic hinge counts in beams and columns, and the total count was compared to allowable limits per FEMA guidelines. According to FEMA 356 **standards, up to %**20 of plastic hinges in vertical members **(columns) are permitted to exceed the LS level and reach CP without impacting the overall building classification as LS. Furthermore, Performance points were calculated by finding the intersection between the structure's capacity curve (a plot of base shear versus displacement) and the seismic demand curve derived from expected ground motion.**

The procedure for this article was as follows

a)A pushover analysis of the existing building was performed using ProtaStructure software according to the ASCE/SEI 17-41 guidelines to **determine the actual performance level in terms of story displacement, and plastic hinge formation in columns and beams.**

b)Jacket thickness of 100 mm with additional steel reinforcement was **designed using interaction diagrams around columns passed to CP level only to enhance their performance to LS level as shown in figure** 3**. The jacket was designed to ensure compatibility with the existing structure and was anchored to improve composite action.**

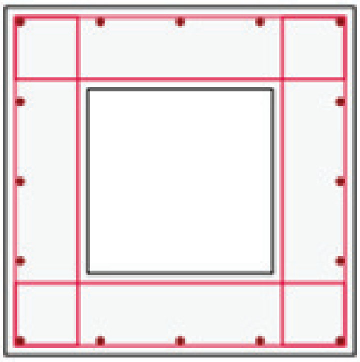

Figure 3 **RC jacketing of columns**

c)Concrete jacketing of columns was simulated by updating the column properties in the finite element analysis (FEA) model. The modulus of elasticity, section dimensions, and reinforcement details were modified to represent the retrofitted state.

d)After updating the model with retrofitted column properties, a second pushover analysis was conducted to determine the performance level of the retrofitted building.

3. Results

3.1 Plastic Hinge Formation

According to pushover analysis results calculated using ProtaStructure software, the damage levels of the members that occurred in beams and columns are summarized in Table 2 for the exiting and RC jacketing of columns buildings. The performance analysis of the existing building prior to retrofitting reveals significant vulnerabilities, particularly in the structural beams and columns. Before retrofitting, none of the beams were in the IO level, which would indicate the ability to sustain only minor damage in a seismic event. Instead, %100 of the beams were in the LS level, suggesting that they met minimum safety requirements but lacked resilience under higher seismic loads, potentially allowing moderate damage that could compromise functionality. The vertical members showed a similar need for improvement, with only %9.8 achieving IO level, %85.8 in the LS level, and %2.5 in the CP level, indicating severe limitations in their load-bearing capacity. Alarmingly, %1.9 of the vertical members were classified in the Collapse region, suggesting a risk of catastrophic failure under intense seismic loads. This distribution underscores the necessity of intervention to address the building's structural weaknesses, particularly in its columns, which are essential to overall stability.

After the application of reinforced concrete (RC) jacketing of columns, the analysis indicates substantial performance gains across the structural components. The percentage of beams achieving IO level rose from %0 to %64.6, a significant improvement that indicates enhanced resilience. Meanwhile, %35.4 of beams remain in the LS level, a considerable improvement over the original scenario, and with none in the CP or Collapse regions. For the

now achieved IO level, while only %9.7 remain in the LS level. Importantly, no columns fall into the CP or Collapse categories post-retrofitting, indicating that all critical columns being capable of bearing seismic loads with a **significantly reduced risk of major structural damage or failure. This** transformation in performance status among both beams and columns **reflects the impact of RC jacketing in redistributing stresses and enhancing the overall resilience of the building structure.**

Table 2 Plastic hinge formation results

	Plastic hinges (%)	
	Existed building	RC Jacketing of columns
No. of Beams in IO	0	64.6
No. of Beams in LS	100	35.4
No. of Beams in CP	0	-
No. of Beams in C	0	-
No. of Vertical Members in IO	9.8	90.3
No. of Vertical Members in LS	85.8	9.7
No. of Vertical Members in CP	2.5	-
No. of Vertical Members in C	1.9	-

3.2 Story Drift

Comparative story drift in X-direction for existing vs. RC jacketing (in mm) is shown in figure 4**. The total building displacement at the roof level shows a slight reduction after applying RC jacketing to the columns, decreasing from 90.6**mm in the existing building to **82.6mm after retrofitting. This decreases, while modest (around %**9**), indicates an improvement in the building's lateral stiffness and overall structural stability. The reduction in displacement can likely be attributed to the RC jacketing's effect on enhancing the load-bearing capacity and rigidity of the columns.**

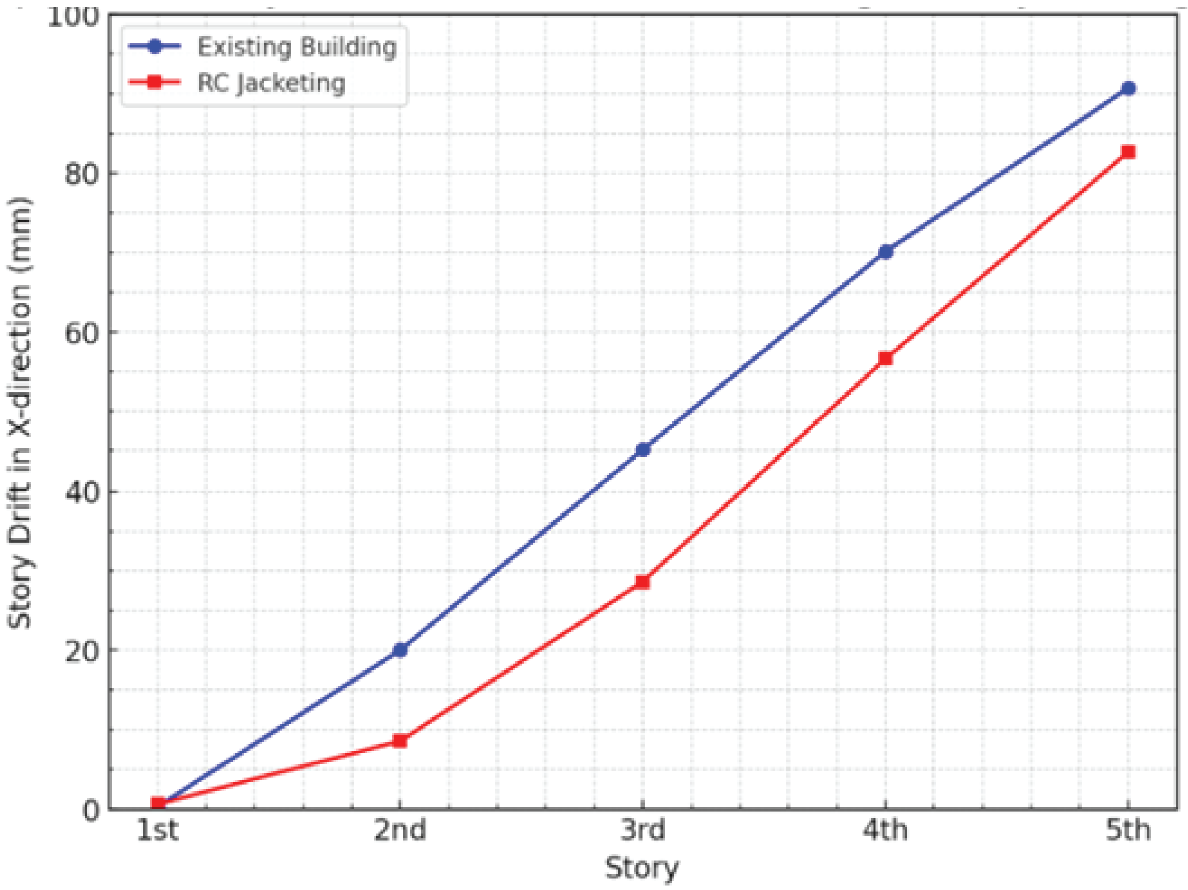

Figure 4**. Comparative story drift in X-direction for existing vs. RC jacketing (in mm)**

4. Conclusion

This study evaluated the structural performance of an existing building before and after the application of reinforced concrete (RC) jacketing to the columns and the main findings are summarized as follows:

-The application of RC jacketing to columns yielded marked improvements in performance across several parameters. Post-retrofitting, %64.6 of beams achieved IO level, and the remaining %35.4 were in the LS level, representing a significant shift toward higher resilience and minimal damage.

-In vertical members, the improvements were more pronounced: %90.3 of columns achieved IO level, and the CP and Collapse levels were entirely eliminated, enhancing the building's structural safety and stability under seismic stress.

-The slight decrease in total roof displacement further confirmed an increase in the building's lateral stiffness, indicating better control over structural movements during lateral load events.

Recommendations for Future Work

Future research could explore the following

▪The effectiveness of RC jacketing in combination with other retrofitting methods, such as the use of CFRP or base isolation techniques, to further reduce lateral displacement and enhance seismic performance level.

▪Evaluating the cost-benefit ratio of RC jacketing versus alternative retrofitting methods in various building types.

References

Al-Safi, S., Alameri, I. A., Badhib, R. A. M., & Kuleib, M. (2020). Evaluation of performance-based earthquake engineering in Yemen. Challenge Journal of Structural Mechanics, 10 ,(1)6.
https://doi.org/10.20528/cjsmec.2020.01.002

Al-Safi, S., Alameri, I. A., Ezzedine, S. A. N., & Alwalidi, M. Q. (2022). Performance-based seismic design of laterally braced steel frames. Challenge Journal of Structural Mechanics, 141 ,(4)8.
https://doi.org/10.20528/cjsmec.2022.04.002

Al-Safi, S., Alameri, I., Wasel, W. A., & Al-kadasi, A. B. (2021). Linear and Nonlinear Behavior of Steel Buildings with Different Bracing Systems. International Journal of Steel Structures, 486–475 ,(2)21.
https://doi.org/10.1007/s1-00450-020-13296

ASCE. (2017). ASCE/SEI 17-41: Seismic Evaluation and Retrofit of Existing Buildings. American Society of Civil Engineers.

Ghannoum, W., & Moehle, J. (2014). Behavior of lightly confined column longitudinal bars under cyclic loading. Journal of Structural Engineering, 12-1 ,(6)140.

Kappos, A. J., Lekidis, V. A., & Stylianidis, K. C. (2018). The effectiveness of RC jacketed columns in seismic retrofitting. Engineering Structures, 48-40 ,(10)50.

Priestley, M. J. N., Calvi, G. M., & Kowalsky, M. J. (2007). Displacement-based seismic design of structures. IUSS Press.

Sezen, H., & Whittaker, A. S. (2006). Seismic performance of structural walls in reinforced concrete buildings. Journal of Structural Engineering, 457-446 ,(2)132.