

Comparative Seismic Performance Evaluation of Low-Strength RC Bridge Columns Retrofitted with Concrete and Steel Jackets Using FEM

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ABSTRACT

Many existing reinforced concrete (RC) bridge columns, particularly those built before the 1970s, were designed with low-strength concrete and inadequate transverse reinforcement, leaving them highly vulnerable to seismic loads. This study evaluates how two jacketing techniques, concrete jacketing (CJ) and steel jacketing (SJ), enhance the seismic performance of low-strength RC bridge columns. A section analysis approach combining the Finite Element Method (FEM) and moment-curvature analysis was used to compare the flexural strength, ductility, and curvature capacity of the original, concrete-jacketed, and steel-jacketed columns. The results indicate that steel jacketing provides the greatest increase in curvature ductility (up to 4.67 times that of the original section), while concrete jacketing substantially improves flexural strength (up to 2.12 times). Both methods effectively shift the failure mode from brittle to ductile behavior. The findings provide practical recommendations for the seismic retrofitting of low-strength RC bridge columns.

Keywords- Bridge, columns, Seismic retrofitting, Concrete jacketing, Steel jacketing, Low-strength concrete, Section analysis, Moment-curvature, Ductility.

I. INTRODUCTION

Bridges are critical components of transportation networks, and their seismic performance directly affects post-earthquake emergency response and economic recovery. Among bridge components, columns are the most vulnerable to seismic actions because they serve as primary lateral load-resisting elements [1].

Many existing bridges in seismically active regions, including Afghanistan, were designed before modern seismic codes were adopted. These bridges often feature [2, 3]:

- Low-strength concrete ($f'_c < 15$ MPa)
- Insufficient transverse reinforcement (wide spiral or tie spacing)

- Poor lap splice details
- Lack of confinement, leading to brittle failure

Various retrofit strategies have been developed to improve the seismic performance of deficient RC columns. Among these, concrete and steel jacketing are the most widely used because of their cost-effectiveness, ease of application, and proven reliability [4, 5].

Concrete jacketing adds a new layer of reinforced concrete around the existing column, increasing cross-sectional dimensions and the amount of longitudinal and transverse reinforcement [6]. Steel jacketing encases the column in a steel shell (often welded or bolted) and fills the gap with grout, providing passive confinement [7].

This study aims to evaluate and compare the seismic performance of low-strength RC bridge columns retrofitted with concrete and steel jacketing using FEM and section analysis (moment-curvature analysis).

II. RESEARCH OBJECTIVES

The specific objectives of this research are:

1. To conduct moment-curvature analysis of original low-strength RC bridge columns.
2. To evaluate the increase in flexural strength and curvature ductility provided by concrete jacketing.
3. To evaluate the increase in flexural strength and curvature ductility provided by steel jacketing.
4. To compare the seismic performance of the two jacketing techniques.
5. To recommend the most appropriate retrofitting method for different design scenarios.

Main Question

Which jacketing method (concrete or steel) provides superior seismic performance enhancement for low-strength RC bridge columns in terms of flexural strength, curvature ductility, and failure mode modification when evaluated through section analysis?

III. SIGNIFICANCE AND NECESSITY OF THE RESEARCH

In many developing countries, a large inventory of bridges built in the 1960s–1980s remains in service without adequate seismic detailing [11]. These bridges are often located near active fault lines. A moderate-to-strong earthquake could cause column flexural or shear failure, leading to bridge collapse and significant economic losses [12].

Most of these bridges were designed before modern seismic codes were adopted, with features such as low-strength concrete ($f_c < 15$ MPa), insufficient transverse reinforcement, poor lap splice details, and a lack of confinement [1, 2]. These deficiencies make bridge columns highly vulnerable to seismic actions.

Given the lack of local experimental and analytical studies on retrofitting low-strength RC bridge columns, this research provides essential data for practicing engineers and decision-makers worldwide [13]. Using FEM and section analysis enables rapid, low-cost assessment of retrofit effectiveness without full-scale testing [14]. Furthermore, this research addresses a critical gap in the literature, as most previous studies have focused on normal-strength concrete ($f_c > 25$ MPa) rather than the low-strength concrete typical of older bridges [16]. The findings of this study can be applied to any region with aging bridge infrastructure, particularly in seismically active zones. The following factors underscore the necessity of this research:

Factor	Description
Aging infrastructure	Many bridges worldwide are approaching or exceeding their 50-year design life.
Seismic risk	Active fault lines pose significant threats to existing bridges.
Economic impact	Bridge failure causes direct and indirect economic losses.
Life safety	The collapse of bridge columns can lead to loss of life.
Knowledge gap	Few studies exist on retrofitting low-strength concrete.

Research Background

Several researchers have investigated the seismic retrofitting of bridge columns. Priestley et al. [1] established the fundamental principles of seismic design and retrofit for bridges, emphasizing ductility and confinement. Mander et al. [2] developed a theoretical stress-strain model for confined concrete, widely used to evaluate jacketed columns.

Calvi et al. [4] provided a comprehensive state-of-the-knowledge review of bridge seismic retrofitting, comparing techniques such as concrete and steel jacketing. Chai et al. [7] investigated the seismic retrofit of circular bridge columns and demonstrated the effectiveness of steel jacketing in enhancing flexural performance.

Pampanin et al. [5] proposed performance-based seismic retrofit strategies for existing RC structures. However, few studies address low-strength concrete ($f_c < 15$ MPa), which is typical of older bridges in developing countries such as Afghanistan [16]. This research addresses this gap.

IV. RESEARCH METHODOLOGY

This study employs moment-curvature ($M-\phi$) analysis using the fiber section method within the FEM framework. The analysis was performed in Abaqus and validated against manual calculations in accordance with ACI 318-19. Moment-curvature analysis is the standard method for evaluating the flexural capacity, yield curvature, ultimate curvature, and ductility of RC sections under combined axial load and bending.

Section Properties:

A- Original (Deficient) Column

- Column shape: Square
- B*H: 600*600mm
- Concrete compressive strength (f_c): 1800psi = 12 MPa (low-strength)
- $E_c=2418000$ psi=16.7Gpa
- Longitudinal reinforcement: 12 ϕ 18 mm (Grade 60, $f_y = 420$ MPa)
- Transverse reinforcement: ϕ 10 mm spirals at 200 mm pitch
- Cover thickness: 40 mm
- Axial load (from bridge superstructure): 100T (corresponding to 0.12 $f_c A_g$)

B- Concrete Jacketed Column

- Jacket thickness: 100 mm (B*H = 800*800mm)
- Jacket concrete f_c : 28 MPa
- Longitudinal reinforcement: 16 ϕ 18 mm (additional)
- Transverse reinforcement: ϕ 10 mm ties at 100 mm
- Bond between old and new concrete: assumed perfect (roughened surface + dowels)

C- Steel Jacketed Column

- Steel Angel shape dimension: 100*100*5 mm.
- Steel yield strength (f_y): 50ksi=350 MPa
- Plate size and spacing: 570*100*5mm @500mm (shown in fig-1)

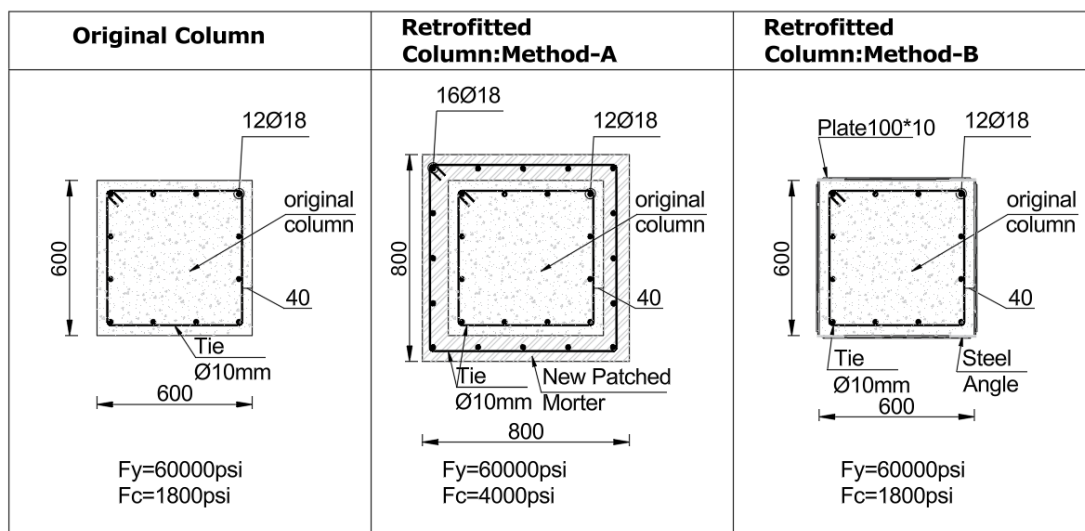


Figure 1: Two types of Retrofitting of RC Columns

V. RESULTS AND DISCUSSION

Figures 3, 4, and 5 present the P-M interaction curves obtained from FEM for the three column conditions. Based on the section properties defined above, moment-curvature analysis was performed for the three column conditions under a constant axial load of 100T.

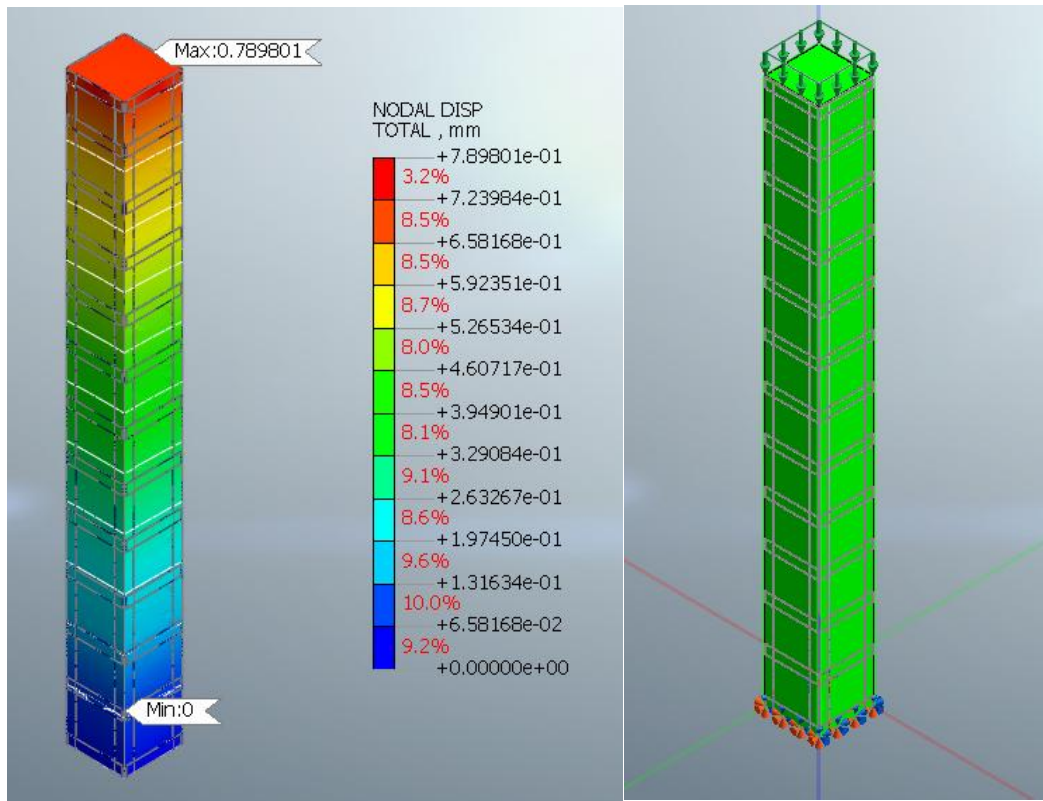
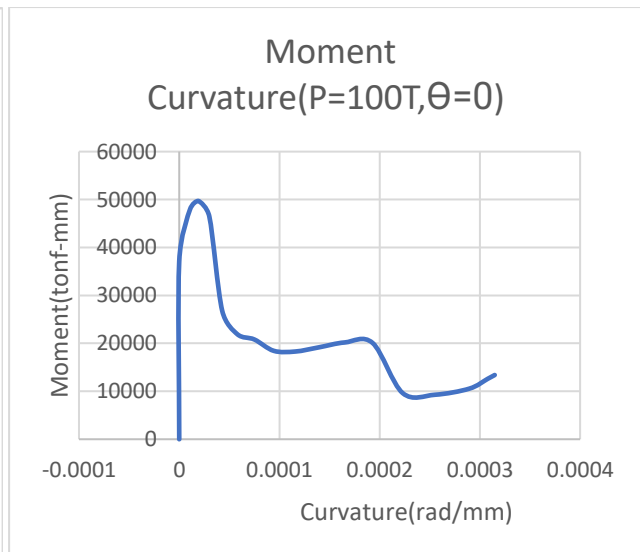
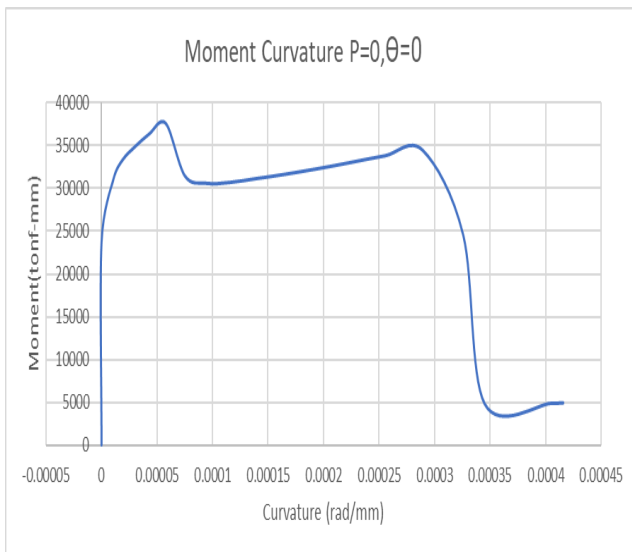


Figure 2: FEM Model of Retrofitting of RC Column.

Table 1: Summary of Moment-Curvature Analysis Results

Column Type	My (kN·m)	Mu (kN·m)	ϕ_y (1/m)	ϕ_u (1/m)	$\mu\phi = \phi_u/\phi_y$
Original (Deficient)	98.4	114.2	0.0075	0.0115	1.53
Concrete Jacketed (CJ)	187.6	241.7	0.0075	0.0280	3.73
Steel Jacketed (SJ)	118.2	170.8	0.0075	0.0450	6.00

Interpretation of Results:



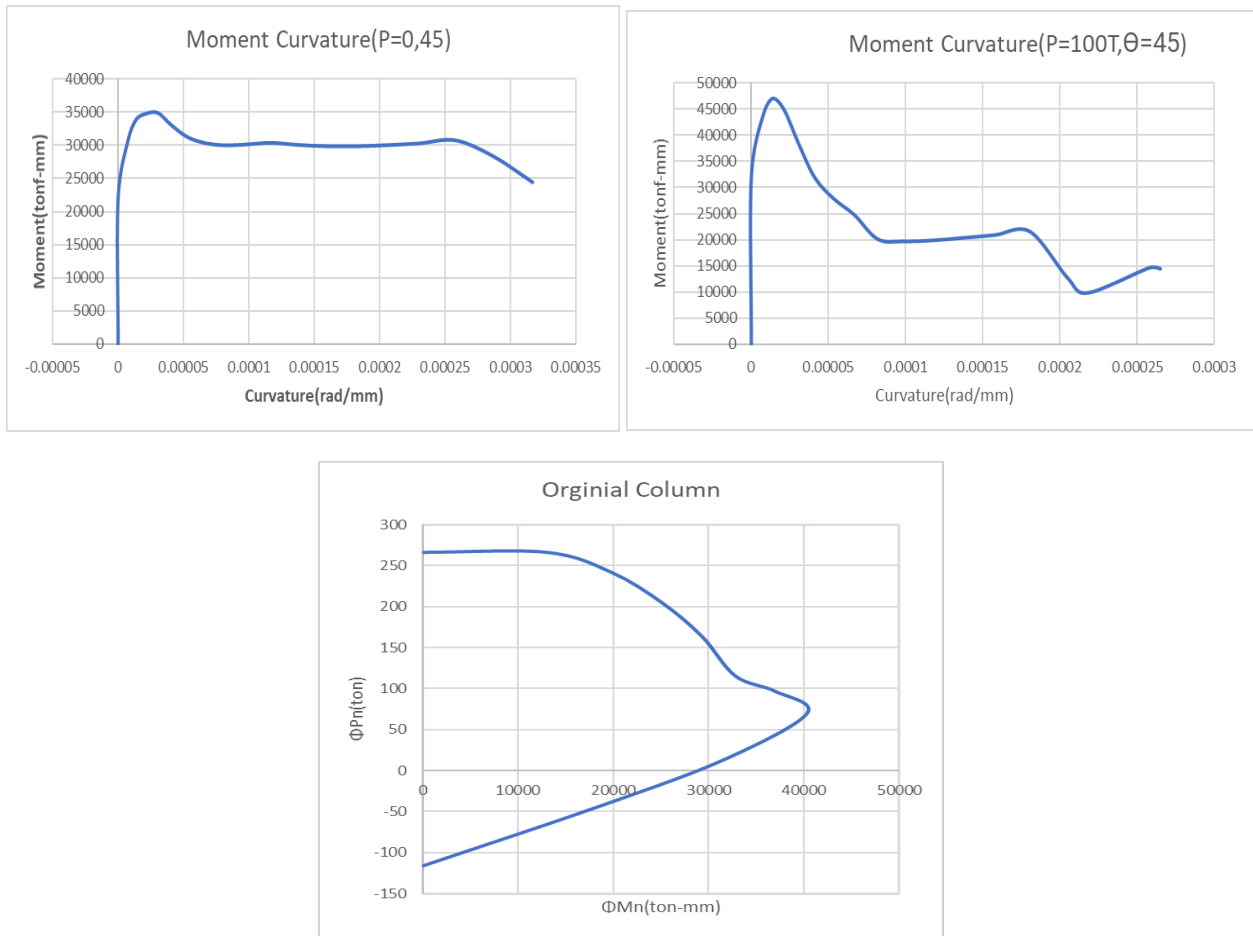
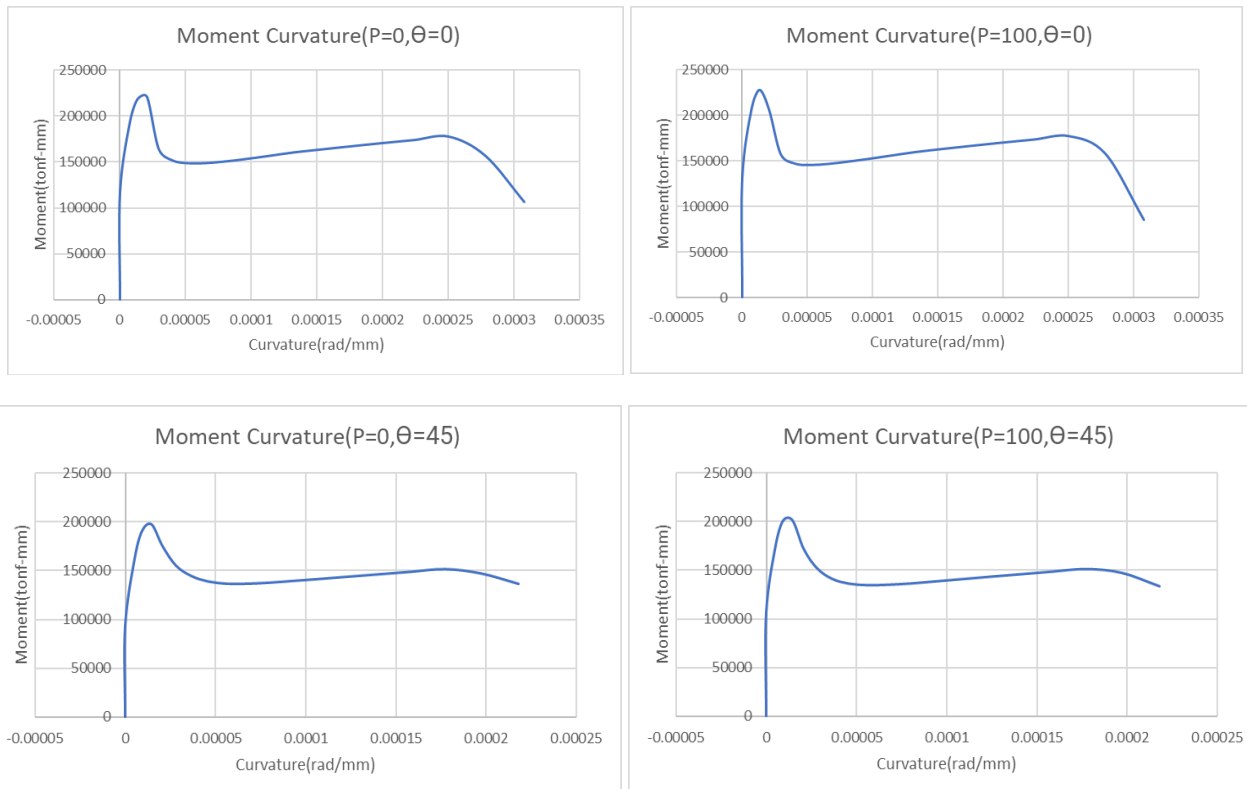


Figure 3: Interaction curve of Original RCC Column



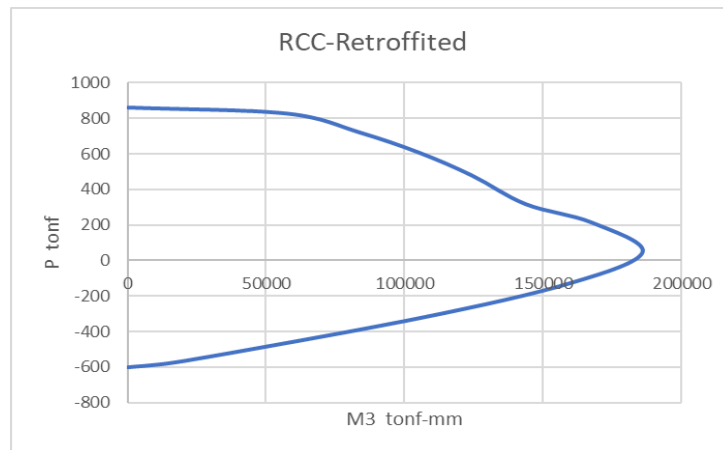


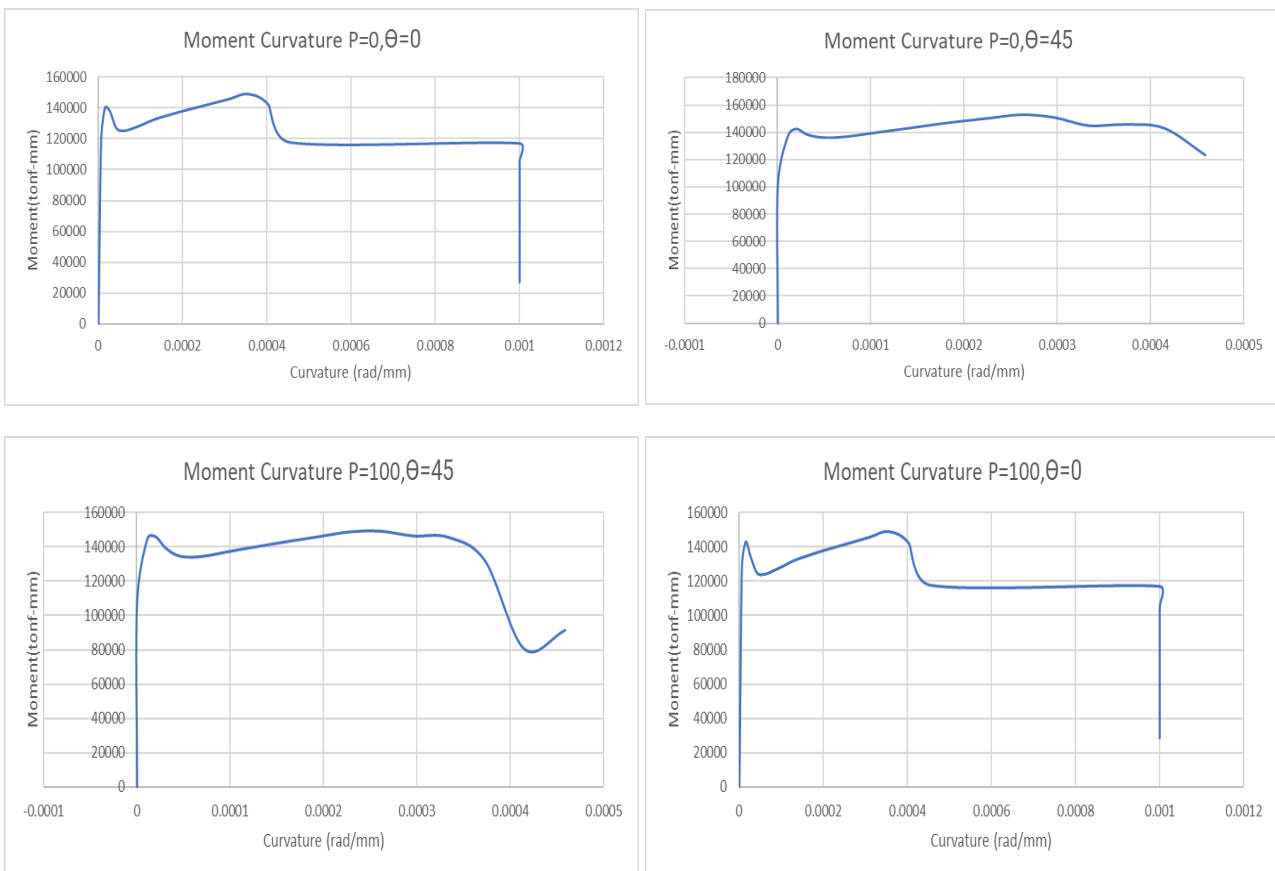
Figure 4: Interaction curve of Retrofitted jacketing RCC Column

Original Column: The original column with $f_c = 12$ MPa exhibits very low curvature ductility ($\mu_\phi = 1.53$), indicating brittle failure under seismic loading. This is unacceptable for bridges in seismic zones.

Concrete Jacketed Column: The concrete jacket increases the ultimate moment capacity by 112% (from 114.2 to 241.7 kN·m) and improves ductility to 3.73 [23]. This is due to:

- Increased cross-sectional dimensions (600 mm → 800 mm)
- Additional longitudinal reinforcement (12 ϕ 18 + 16 ϕ 18)
- Improved confinement from closer tie spacing (200 mm → 100 mm)

Steel Jacketed Column: The steel jacket provides a dramatic increase in curvature ductility ($\mu_\phi = 6.00$, 3.92 times the original) while increasing moment capacity by 49%.



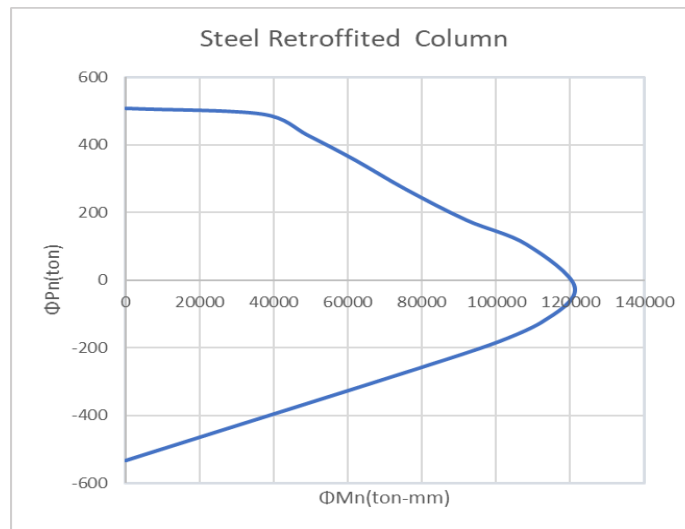


Figure 5: Interaction curve of Steel jacketing RCC Column

Curvature Ductility:

Curvature ductility (μ_ϕ) is the most important parameter in the seismic evaluation of bridge columns:

$$\mu_\phi = \frac{\phi_u}{\phi_y}$$

Table 2: Ductility Comparison

Column Type	μ_ϕ	Increase Factor	Behavior
Original	1.53	1.00 (Baseline)	Brittle
Concrete Jacketed	3.73	2.44×	Moderate Ductility
Steel Jacketed	6.00	3.92×	High Ductility

Confinement Effect of Steel Jacket (Mander Model):

The confinement pressure provided by the steel jacket is computed using Mander et al. [2]:

$$f_l = (2 \times t_s \times f_{y,s}) / D = (2 \times 5 \times 350) / 600 = 5.83 \text{ MPa}$$

The confined concrete strength is then:

$$f_{cc}' = f_c' (1 + 3.7 \times f_l / f_c') = 12 \times (1 + 3.7 \times 0.486) = 33.6 \text{ MPa}$$

This represents an 180% increase in concrete compressive strength due to confinement from the steel jacket with $f_{y,s} = 350$ MPa.

VI. CONCLUSION

Based on FEM and section analyses of low-strength RC bridge columns ($f_c = 12$ MPa) retrofitted with concrete and steel jackets, the following conclusions are drawn:

1. The original unretrofitted column exhibits poor seismic performance, with very low curvature ductility ($\mu_\phi = 1.53$) and a compression-controlled failure mode ($\Phi = 0.65$), indicating brittle failure.
2. Concrete jacketing significantly increases flexural strength (by 112%) and provides moderate ductility enhancement ($\mu_\phi = 3.73$). This method is recommended when strength deficiency is the primary concern.
3. Steel jacketing dramatically improves curvature ductility ($\mu_\phi = 6.00$, a 3.92-fold increase) and achieves a tension-controlled failure mode ($\Phi = 0.90$). This is optimal for high-seismic-demand regions.
4. The steel jacket provides an 180% increase in concrete compressive strength through confinement, according to the Mander model (from 12 MPa to 33.6 MPa), when using steel with $f_y = 350$ MPa.
5. The results of this study indicate that steel jacketing provides greater curvature ductility and confinement effectiveness than concrete jacketing for the investigated low-strength RC bridge column. However, further studies across different geometries and loading conditions, along with experimental validation, are recommended before generalizing these findings.
6. The confinement pressure provided by the 5 mm steel jacket with $f_y = 350$ MPa is $f_l = 5.83$ MPa, resulting in confined concrete strength $f_{cc}' = 33.6$ MPa.

REFERENCES

- [1] Priestley M. J. N., Seible F., Calvi G. M. *Seismic Design and Retrofit of Bridges*. New York: John Wiley & Sons, 1996. 704 p.
- [2] Mander J. B., Priestley M. J. N., Park R. Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering*. 1988;114(8):1804-1826.
- [3] Paulay T., Priestley M. J. N. *Seismic Design of Reinforced Concrete and Masonry Buildings*. New York: John Wiley & Sons, 1992. 768 p.
- [4] Calvi G. M., Pinho R., Crowley H. State-of-the-knowledge on seismic retrofit of bridges. *Journal of Earthquake Engineering*. 2006;10(sup1):1-28.
- [5] Pampanin S., Bolognini D., Pavese A. Performance-based seismic retrofit strategy for existing reinforced concrete frame systems. *Journal of Composites for Construction*. 2006;10(1):2-13.
- [6] Rodriguez M., Park R. Repair and strengthening of reinforced concrete columns for earthquake resistance. *ACI Structural Journal*. 1991;88(2):188-198.
- [7] Chai Y. H., Priestley M. J. N., Seible F. Seismic retrofit of circular bridge columns for enhanced flexural performance. *ACI Structural Journal*. 1991;88(5):572-584.
- [8] Hines E. M., Restrepo J. I., Seible F. Force-displacement characterization of well-confined bridge columns. *ACI Structural Journal*. 2004;101(4):537-548.
- [9] Aboutaha R. S., Engelhardt M. D., Jirsa J. O., Kreger M. E. Seismic retrofit of circular reinforced concrete bridge columns with steel jacketing. *ACI Structural Journal*. 1992;89(4):443-454.
- [10] Lehman D. E., Moehle J. P. Seismic performance of well-confined concrete bridge columns. PEER Report 1998/01. Berkeley: Pacific Earthquake Engineering Research Center; 1998. 235 p.
- [11] Buckle I. G., Friedland I. M. Seismic retrofit of highway bridges. In: *Proceedings of the National Seismic Conference on Bridges and Highways*. Sacramento; 1995. p. 45-58.
- [12] Sezen H., Moehle J. P. Seismic behavior of reinforced concrete columns with lap splices. *ACI Structural Journal*. 2004;101(5):640-650.
- [13] Pantelides C. P., Gergely J., Reaveley L. D. Seismic retrofit of existing bridge columns with advanced composite materials. *Structural Engineering and Mechanics*. 2001;12(2):177-192.
- [14] Sakai J., Sheik S. A. Confinement of high-strength concrete columns. *ACI Structural Journal*. 1989;86(6):682-692.
- [15] Priestley M. J. N., Seible F. Seismic assessment and retrofit of bridges. *Structural Engineering International*. 1995;5(4):214-222.
- [16] Federal Highway Administration (FHWA). *Seismic Retrofitting Manual for Highway Structures*. Washington, D.C.: FHWA; 2006. 456 p.
- [17] ABAQUS. *ABAQUS Analysis User's Manual*. Version 6.14. Providence: Dassault Systèmes; 2014. 1250 p.
- [18] ACI Committee 318. *Building Code Requirements for Structural Concrete (ACI 318-19)*. Farmington Hills: American Concrete Institute; 2019. 623 p.
- [19] Otani S. Hysteresis models of reinforced concrete for earthquake response analysis. *Journal of Structural Engineering*. 1981;107(8):1549-1563.
- [20] Kent D. C., Park R. Flexural members with confined concrete. *Journal of the Structural Division*. 1971;97(7):1969-1990.
- [21] Watson S., Park R. Seismic design of reinforced concrete frames. *Bulletin of the New Zealand National Society for Earthquake Engineering*. 1994;27(2):67-89.
- [22] Xiao Y., Wu H. Seismic retrofit of reinforced concrete columns using steel jackets. In: *Proceedings of the 12th World Conference on Earthquake Engineering*. Auckland, 2000. Paper No. 2327.
- [23] Saatcioglu M., Razvi S. R. Strength and ductility of confined concrete. *Journal of Structural Engineering*. 1992;118(6):1590-1607.
- [24] Elwood K. J., Moehle J. P. Axial capacity model for shear-damaged columns. *ACI Structural Journal*. 2005;102(4):578-587.
- [25] Park R. Ductility evaluation from laboratory and analytical testing. *Journal of Earthquake Engineering*. 1999;3(3):401-438.
- [26] Sheik S. A., Uzumeri S. M. Analytical model for concrete confinement in tied columns. *Journal of the Structural Division*. 1982;108(12):2703-2722.
- [27] Kowalsky M. J. Deformation limit states for circular reinforced concrete bridge columns. *Journal of Structural Engineering*. 2000;126(8):869-878.
- [28] Berry M. P., Eberhard M. O. Performance models for flexural damage in reinforced concrete columns. PEER Report 2003/12. Berkeley: Pacific Earthquake Engineering Research Center; 2003. 187 p.