**Canadian Conference - Pacific Conference on Earthquake Engineering 2023**
**Vancouver, British Columbia**
**June 25th – June 30th, 2023**

# Seismic Retrofitting of RC Bridge Piers using Ultra-High-Performance Concrete Jacketing: State-of-the-art Review

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## Abstract

Reinforced concrete (RC) bridges are critical infrastructure elements that are vulnerable to deterioration due to various factors, including steel corrosion, aging, poor maintenance, and natural disasters such as earthquakes. Effective techniques and materials are therefore required for the timely rehabilitation of these structures. Recent studies have demonstrated the potential of Ultra-High-Performance Concrete (UHPC) for seismic retrofitting of RC elements due to its superior strength, high ductility, and enhanced durability. This paper presents a critical review of the seismic performance of UHPC retrofitted RC columns, through the collective review of a comprehensive database of published experiments on UHPC retrofitted columns. Finally, the paper identifies the progress made and future research needs for retrofitting deficient RC columns using UHPC.

**Keywords**: UHPC; Seismic; Retrofit, Bridge Pier; Jacketing

## Introduction

Reinforced concrete (RC) is one of the most commonly used structural systems in civil engineering. We have been relying on RC structures for many decades due to the mechanical properties that concrete provides, such as workability, compressive strength, service life, high quality, access to the aggregates and cost-efficiency benefits. However, most of RC bridges today have serious damages in their elements such as piers, beams, and slabs, due to lack of maintenance, extreme environmental conditions or because they have endured catastrophic events such as earthquakes. Bridge piers are the vulnerable component to dissipate ground energy input through damage occasionally escalating to failures with catastrophic results [1]. Several novel materials and techniques with supporting experimental research have been developed worldwide in the last few years that enhance RC properties, creating new alternatives to deal with different types of damages in RC structures by retrofitting and rehabilitation. When it comes to repairing methods of damaged bridge columns, using column jackets is one of the most widely adopted approaches, which can be further categorized in terms of different jacketing materials. Nowadays we can work with reinforced concrete (RC) jacket, steel jacket, carbon fiber-reinforced polymer (CFRP) and steel wire mesh in mortar matrix [2]. RC jackets usually have greater strength, but the jacket thickness is generally greater than 100mm which creates a new cross section and new mass and dead load of the pier [3]. Steel jackets are not recommended for a pier with a rectangular cross-section mainly due to the reduced efficiency and the risk of localized corrosion at the corners in aggressive environmental exposure [4]. CFRP wraps have very small jacket thickness because of the great tensile strength, which is provided by the fibers, making CFRP wrapping suitable for circular piers [5]. For a rectangular shape pier retrofitted with CFRP wraps, rupture of the CFRP fibers generally occurs at the corners of the pier and this is followed by great strength loss and brittle failure load [6]. In either case, CFRP wrapping is only suitable as a local intervention (enhancing deformability of the column, but neither stiffness nor strength). Recently, an advanced new material has emerged, with very high compressive strength, high ductility, excellent impermeability and sustained tensile strength up to high levels of tensile strain known as Ultra High-Performance Concrete (UHPC) [7]. UHPC emerges as an attractive alternative option for the seismic bridge pier retrofitting [8] in the form of jacketing. Because of its high tensile strength, thin layers are adequate to provide confinement and durability to the encased concrete. As a result, UHPC jacketing has become a promising alternative for both newly-built and rehabilitation projects, and may be considered a mild global intervention due to its improvement in the seismic performance of RC elements in many aspects, including axial load capacity, deformation capacity, shear strength, and mild increase in stiffness and flexural strength [9].

## Description of the Database of Experimental Evidence

This study is aimed to conduct a literature review on the use of UHPC jacketing for rehabilitation/retrofitting RC bridge piers, based on collected experimental results for both circular and rectangular cross-section columns. Different characteristics were considered in the various experimental studies, such as the value of the axial load ratio (ALR) and end column testing conditions. A comprehensive database of experimental results on UHPC jacketed columns have been complied from published literature [2], [8]–[16]. The database comprises 79 specimens, 21 of which had a circular cross-section (identified henceforth as C-specimens) and 58 had rectangular cross-sections (identified henceforth with the letter R). Table 1 summarizes the key properties of the C-specimens.

Table 1. Summary of main properties for C-Specimens under study

| Reference # | Specimen ID | Diam. (mm) | Area ($mm^2$) | $f'_c$ of col. (MPa) | $f'_c$ of UHPC (MPa) | $L_S$ (mm) | ALR | TRR (%) | LRR (%) | $v_f$ (%) | $V_m$ (MPa) | $\theta_u$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [10] | A-U2-0-F | 305.00 | 73061.66 | 35.00 | 174.00 | 1320 | 0.10 | 2.17 | 2.17 | 2.0 | 113.00 | 6.36 |
| | A-U2-102- | 305.00 | 73061.66 | 35.00 | 174.00 | 1320 | 0.10 | 2.17 | 2.17 | 2.0 | 109.00 | 11.36% |
| | S-U2-102- | 305.00 | 73061.66 | 35.00 | 174.00 | 1320 | 0.10 | 2.17 | 2.17 | 2.0 | 102.00 | 9.85 |
| | S-U2-64- | 305.00 | 73061.66 | 35.00 | 174.00 | 1320 | 0.10 | 2.17 | 2.17 | 2.0 | 87.00 | 11.36% |
| | S-U2-64- | 305.00 | 73061.66 | 35.00 | 179.00 | 1320 | 0.10 | 2.17 | 2.17 | 4.0 | 86.00 | 13.64% |
| | S-U4-64-F | 305.00 | 73061.66 | 35.00 | 174.00 | 1320 | 0.10 | 2.17 | 2.17 | 2.0 | 96.00 | 8.71 |
| | S-U4-64-F | 305.00 | 73061.66 | 35.00 | 179.00 | 1320 | 0.10 | 2.17 | 2.17 | 4.0 | 89.00 | 7.58 |
| [11] | RC1 | 320.00 | 80424.77 | 29.30 | - | 1300 | 0.11 | 0.93 | 1.91 | 0.0 | 50.60 | 6.54 |
| | URC1 | 320.00 | 80424.77 | 29.30 | 110.60 | 1300 | 0.11 | 0.93 | 1.91 | 1.0 | 64.30 | 6.54 |
| | URC2 | 320.00 | 80424.77 | 29.30 | 110.60 | 1300 | 0.11 | 0.93 | 1.91 | 1.0 | 50.40 | 6.54 |
| [7] | URC2 | 320.00 | 80424.77 | 29.30 | 110.60 | 1300 | 0.11 | 0.93 | 1.91 | 1.0 | 50.40 | 6.54 |
| | URC4 | 320.00 | 80424.77 | 29.30 | 110.60 | 1300 | 0.11 | 0.93 | 1.91 | 1.0 | 50.75 | 6.54 |
| | URC5 | 32000 | 80424.77 | 29.30 | 110.60 | 1300 | 0.11 | 0.93 | 1.91 | 1.0 | 47.45 | 6.54 |
| | URC6 | 320.00 | 80424.77 | 29.30 | 110.60 | 1300 | 0.11 | 0.93 | 1.91 | 1.0 | 46.75 | 5.67 |
| [2] | LL-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1400 | 0.06 | 1.13 | 1.50 | 1.0 | 44.80 | 4.53 |
| | LLE-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1400 | 0.06 | 1.13 | 1.50 | 0.0 | 23.80 | 1.64 |
| | ML-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1800 | 0.07 | 1.13 | 1.50 | 1.0 | 21.60 | 4.92 |
| | MM-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1800 | 0.07 | 1.13 | 3.56 | 1.0 | 30.40 | 6.16 |
| | MME-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1800 | 0.07 | 1.13 | 3.56 | 0.0 | 43.80 | 6.31 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MH-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1800 | 0.07 | 1.13 | 5.63 | 1.0 | 45.50 | 8.03 |
| MHE-R | 240.00 | 45238.93 | 46.70 | 130.00 | 1800 | 0.07 | 1.13 | 5.63 | 0.0 | 38.10 | 5.20 |

The C-specimens collected were all retrofitted by applying UHPC Jackets with thickness ranging from 13 mm to 51 mm (Table 1). Fourteen of the 21 UHPC Jackets in the case of the circular cross-section specimens contained steel fibers with volume fraction ranging from 1% to 4%. In all cases, brass coated straight steel fibers were used, having length $l_f$ = 13 mm, diameter $d_f$ = 0.2 mm and an elastic modulus of elasticity of 200 GPa. The shear span ($L_s$) of the C-specimens was in the range of [1300 - 1800] mm. The shear span refers to the distance from the critical section to the point of inflection or location of zero moment; here, 18 columns in this group were tested as cantilevers so the shear span equals the deformable length of the column, while the other 3 columns had both fixed end conditions, resulting in shear spans of half the deformable length of the column). The sectional diameter, concrete cover, the distance from the centroid of the most extreme tension reinforcement to the compression zone (denoted here as $d$), and sectional area were within the ranges of [240 - 320] mm, [20 - 50] mm, [220 - 295] mm, and [45239 – 80425] mm$^2$, respectively. Longitudinal reinforcement bars varied in the range of [10 – 18] mm in diameter, arranged in a circular pattern that comprised [6 - 10] bars with varying mechanical properties. For a total of 19 C-specimens, the longitudinal reinforcement ratio ranged from 1.5% to 5.63%, , as listed in Table 1. The yielding stress and ultimate stress of longitudinal and transverse reinforcements collected for the specimens were in the ranges of [335 – 570] MPa and [637 – 779] MPa, respectively. Transverse reinforcement details for circular specimens included bar diameters of [6.00 – 9.50] mm spaced at [50 – 80] mm corresponding to transverse reinforcement ratios in the range of 0.9% to 2.20%.

Table 2. Summary of main properties for R-Specimens under study

| Reference | Specimen ID | h(mm) | b (mm) | Area (mm2) | $f'_c$ of col. (MPa) | f'c of UHPC (MPa) | Shear Span (mm) | ALR | TRR | LRR | $V_f$ (%) | $V_m$ (MPa) | $\vartheta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [12] | Specimen MN | 450.00 | 450.00 | 202500.00 | 40.60 | 104.00 | 1965.00 | 0.15 | 0.90% | 1.24% | 0.0 | 201.61 | 4.65% |
| | Specimen PC 1 | 450.00 | 450.00 | 202500.00 | 40.60 | 104.00 | 1965.00 | 0.15 | 0.90% | 1.24% | 2.0 | 223.77 | 4.38% |
| | Specimen PC2 | 450.00 | 450.00 | 202500.00 | 40.60 | 104.00 | 1965.00 | 0.15 | 0.80% | 1.24% | 2.0 | 224.25 | 3.95% |
| [9] | L-NC | 350.00 | 350.00 | 122500.00 | 45.00 | 0.00 | 600.00 | 0.11 | 1.25% | 3.31% | 0.0 | 432.00 | 2.00% |
| | L-UHPC | 350.00 | 350.00 | 122500.00 | 43.00 | 122.00 | 600.00 | 0.11 | 1.25% | 3.31% | 1.5 | 508.00 | 2.00% |
| | L-R/UHPC | 350.00 | 350.00 | 122500.00 | 44.00 | 125.00 | 600.00 | 0.11 | 1.25% | 3.31% | 1.5 | 632.00 | 5.00% |
| | H-NC | 350.00 | 350.00 | 122500.00 | 47.00 | 0.00 | 600.00 | 0.33 | 1.25% | 3.31% | 0.0 | 520.00 | 1.50% |
| | H-UHPC | 350.00 | 350.00 | 122500.00 | 44.00 | 122.00 | 600.00 | 0.33 | 1.25% | 3.31% | 1.5 | 598.00 | 2.00% |
| | H-R/UHPC | 350.00 | 350.00 | 122500.00 | 42.00 | 132.00 | 600.00 | 0.33 | 1.25% | 3.31% | 1.5 | 736.00 | 3.00% |
| | H-P/UHPC | 350.00 | 350.00 | 122500.00 | 50.00 | 138.00 | 600.00 | 0.33 | 1.25% | 3.31% | 1.5 | 755.00 | 4.00% |
| [13] | NPCC | 450.00 | 450.00 | 202500.00 | 40.60 | 0.00 | 1965.00 | 0.15 | 0.90% | 1.24% | 0.0 | 198.09 | 5.00% |
| | USPCC-1 | 450.00 | 450.00 | 202500.00 | 40.60 | 103.70 | 1965.00 | 0.15 | 0.90% | 1.24% | 2.0 | 188.73 | 5.00% |
| | USPCC-2 | 450.00 | 450.00 | 202500.00 | 40.60 | 103.70 | 1965.00 | 0.15 | 0.90% | 1.24% | 2.0 | 218.07 | 4.75% |
| | USPCC-3 | 450.00 | 450.00 | 202500.00 | 40.60 | 103.70 | 1965.00 | 0.15 | 0.00% | 1.24% | 2.0 | 192.29 | 2.75% |
| [14] | Specimen 1:4 | 1500.00 | 625.00 | 596250.00 | 42.50 | 136.30 | 5830.00 | 0.04 | 2.34% | 1.70% | 1.0 | 406.00 | 3.40% |
| [15] | C0-300-R | 200.00 | 200.00 | 40000.00 | 32.00 | 42.00 | 450.00 | 0.11 | 0.94% | 2.01% | 1,7[b] | 39.00 | 3.56% |
| | C0-500-R | 200.00 | 200.00 | 40000.00 | 32.00 | 42.00 | 450.00 | 0.15 | 0.94% | 2.01% | 1,7[b] | 51.00 | 4.00% |
| | C120-300-R | 200.00 | 200.00 | 40000.00 | 32.00 | 42.00 | 450.00 | 0.15 | 0.94% | 2.01% | 1,7[b] | 48.00 | 3.67% |
| | C120-500-R | 200.00 | 200.00 | 40000.00 | 32.00 | 42.00 | 450.00 | 0.15 | 0.94% | 2.01% | 1,7[b] | 52.00 | 4.00% |
| [8] | Pier UR | 500.00 | 450.00 | 225000.00 | 34.90 | 0.00 | 2650.00 | 0.08 | 0.67% | 0.71% | 0.0 | 110.60 | 4.20% |
| | Pier R400 | 500.00 | 450.00 | 225000.00 | 34.90 | 102.50 | 2650.00 | 0.08 | 0.67% | 0.71% | 2.0 | 126.40 | 4.90% |
| | Pier R850 | 500.00 | 450.00 | 225000.00 | 34.90 | 102.50 | 2650.00 | 0.08 | 0.67% | 0.71% | 2.0 | 149.90 | 3.90% |
| [18] | CT1-15M-R | 300.00 | 300.00 | 90000.00 | 20.4 | 172.5 | 1450.00 | 0.16 | 0.32% | 1.34% | 2.0 | 93.30 | 3.50% |
| | CT1-15M-S | 300.00 | 300.00 | 90000.00 | 20.4 | 172.5 | 1450.00 | 0.16 | 0.32% | 1.34% | 2.0 | 92.10 | 3.50% |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT2-20M-R | 300.00 | 300.00 | 90000.00 | 24.35 | 169.2 | 1450.00 | 0.14 | 0.32% | 1.34% | 2.0 | 95.30 | 2.00% |
| | CT2-20M-S | 300.00 | 300.00 | 90000.00 | 24.35 | 169.2 | 1450.00 | 0.14 | 0.32% | 1.34% | 2.0 | 87.70 | 3.50% |
| | CS3-15M-R | 300.00 | 300.00 | 90000.00 | 27.30 | 142.35 | 850.00 | 0.12 | 0.32% | 1.34% | 2.0 | 165.80 | 5.00% |
| | CS3-20M-R | 300.00 | 300.00 | 90000.00 | 27.30 | 152.5 | 850.00 | 0.12 | 0.32% | 1.34% | 2.0 | 155.70 | 5.00% |
| [19] | RC | 250.00 | 250.00 | 62500.00 | 47.90 | 0 | 1100.00 | 0.40 | 1.60% | 1.29% | 0.0 | 94.16 | 2.22% |
| | URC1-a | 250.00 | 250.00 | 62500.00 | 47.90 | 127.4 | 1100.00 | 0.40 | 1.60% | 1.29% | 1.0 | 122.33 | 2.78% |
| | URC1-b | 250.00 | 250.00 | 62500.00 | 47.90 | 127.4 | 1100.00 | 0.40 | 1.60% | 1.29% | 1.0 | 135.02 | 2.86% |
| | URC2-a | 250.00 | 250.00 | 62500.00 | 47.90 | 127.4 | 1100.00 | 0.40 | 1.60% | 1.29% | 1.0 | 131.11 | 2.17% |
| | URC2-b | 250.00 | 250.00 | 62500.00 | 47.90 | 127.4 | 1100.00 | 0.40 | 1.60% | 1.29% | 1.0 | 130.25 | 2.63% |
| | URC3-a | 250.00 | 250.00 | 62500.00 | 47.90 | 127.4 | 1100.00 | 0.40 | 1.60% | 1.29% | 1.0 | 123.23 | 2.22% |
| | URC3-b | 250.00 | 250.00 | 62500.00 | 47.90 | 127.4 | 1100.00 | 0.40 | 1.60% | 1.29% | 1.0 | 122.23 | 2.17% |
| [20] | RC1 | 300.00 | 300.00 | 90000.00 | 32.40 | 0 | 700.00 | 0.37 | 1.01% | 1.40% | 0.0 | 168.31 | 3.21% |
| | U2-RC1 | 300.00 | 300.00 | 90000.00 | 33.40 | 140.1 | 700.00 | 0.15 | 1.01% | 1.40% | 2.0 | 237.51 | 4.01% |
| | RC2 | 300.00 | 300.00 | 90000.00 | 34.40 | 0 | 700.00 | 0.46 | 1.01% | 1.40% | 0.0 | 170.43 | 2.27% |
| | U1-RC2 | 300.00 | 300.00 | 90000.00 | 35.40 | 129.3 | 700.00 | 0.20 | 1.01% | 1.40% | 1.0 | 262.5 | 2.50% |
| | RU2-RC2 | 300.00 | 300.00 | 90000.00 | 36.40 | 129.3 | 700.00 | 0.20 | 1.01% | 1.40% | 1.0 | 261.59 | 4.00% |
| | U2-RC2 | 300.00 | 300.00 | 90000.00 | 37.40 | 140.1 | 700.00 | 0.19 | 1.01% | 1.40% | 2.0 | 259.52 | 3.91% |
| | U2RC3 | 300.00 | 300.00 | 90000.00 | 38.40 | 140.1 | 700.00 | 0.24 | 1.01% | 1.40% | 2.0 | 282.46 | 2.62% |
| [21] | C50 | 300.00 | 300.00 | 90000.00 | 52.60 | 0 | 1000.00 | 0.30 | 1.40% | 1.34% | 0.0 | 224.00 | 3.50% |
| | U50 | 300.00 | 300.00 | 90000.00 | 52.60 | 133.1 | 1000.00 | 0.30 | 1.40% | 1.34% | 1.0 | 243.30 | 2.98% |
| | U50H | 300.00 | 300.00 | 90000.00 | 52.60 | 133.1 | 1000.00 | 0.55 | 1.40% | 1.34% | 1.0 | 288.00 | 1.98% |
| | U20H | 300.00 | 300.00 | 90000.00 | 52.60 | 133.1 | 1000.00 | 0.55 | 3.50% | 1.34% | 1.0 | 334.40 | 2.01% |
| [22] | F_0.1 | 300.00 | 300.00 | 90000.00 | 15.00 | 0.0 | 1500.00 | 0.10 | 0.52% | 1.70% | 0.0 | 86.10 | 6.40% |
| | F_0.1R | 300.00 | 300.00 | 90000.00 | 15.00 | 125.0 | 1500.00 | 0.10 | 0.52% | 1.70% | 2.1 | 78.80 | 7.60% |
| | S_0.1 | 300.00 | 300.00 | 90000.00 | 15.00 | 0.0 | 900.00 | 0.10 | 0.26% | 4.22% | 0.0 | 159.60 | 2.90% |
| | S_0.1R | 300.00 | 300.00 | 90000.00 | 15.00 | 125.0 | 900.00 | 0.10 | 0.26% | 4.22% | 2.1 | 316.20 | 6.40% |
| | S_0.2 | 300.00 | 300.00 | 90000.00 | 15.00 | 0.0 | 900.00 | 0.20 | 0.26% | 4.22% | 0.0 | 147.00 | 3.50% |
| | S_0.2R | 300.00 | 300.00 | 90000.00 | 15.00 | 125.0 | 900.00 | 0.20 | 0.26% | 4.22% | 2.1 | 337.90 | 4.80% |

*Note: ALR = axial load ratio, TRR= transverse reinforcement ratio, LRR= longitudinal reinforcement ratio and the superscript ($^b$) in fiber content is for where PVA fibers were used.*

A summary of the key properties of the R-specimens is presented in Table 2. As listed in this table, a total of 58 R-Specimens jacketed with thin UHPC layers with jacket thickness $t_f$ in the range of [25 - 50] mm were reported in the literature. Two types of fibers were used for the R-jackets: Steel fibers were used in 42 of the cases, four contained polyvinyl (PVA) fibers and twelve did not contain any fiber reinforcement. The volume fraction of the PVA fiber for the four experiments were 1.7%, whereas the steel fiber content was in the range of 1.0% to 2.1%. Compared with the C-specimens, a wider range of fiber mechanical properties were used. The PVA fibers had a tensile strength of 1600 MPa and a modulus of elasticity of 43 GPa, while the steel fibers had a tensile strength of 2800 MPa and a modulus of elasticity of 205 GPa. A cantilever test setup for the application of the combined axial and lateral loads was considered for half of the specimens; in all other cases columns were fixed at the base and connected to a stiff cap beam at top which prevented rotation enforcing a fixed-fixed sway condition. In most cases $L_s$ was in the range of [900 – 5830] mm, however, one test was conducted on a 1:4 scale single column with a hollow, 1.5 m long section, having a total height of 7000 mm and a shear span of 5830 mm [15]. The total longitudinal reinforcement ratio for R-specimens was [0.7 – 4.2] %, having yielding and ultimate stress in the ranges of [413.3 – 536.0] MPa and [576.0 – 649.0] MPa, respectively. Transverse reinforcement comprised bars with diameters ranging from 6 mm to 10 mm with varying spacing in the range of 80 mm to 100 mm, resulting in transverse reinforcement ratio in the range of [0.65 – 3.5] %.

It is noted that a few more specimens (24 R-Specimens) were found in recent literature [19]–[22] testing the efficacy of various modifications to the basic concept of an UHPC jacket such as: (a) addition of wire reinforcement in the jacket; (b) prefabricated components that serve as permanent placement formworks or are externally attached by adhesive; (c) The material used in many cases seems to have been strain softening and results are presented either without mention of the material properties, or giving little (if at all) information of how the material was characterized. An additional 19 specimens were found where either the entire column comprised UHPC or the plastic hinge region was cast with this class of materials – so there was no retrofitting or jacketing but monolithically cast components containing UHPC.

The axial load ratio applied on the specimens was defined as $ALR = P/(f_c'/A_g)$, where $P$ is the applied axial load and $A_g$ is the gross area of the column cross section. All of the specimens, circular and rectangular, were first built with Normal Strength Concrete (NSC) ($f_c'$ in the range of 29 – 50 MPa) and then retrofitted with UHPC Jackets. Mechanical properties of the jacketing material were: compressive strength, tensile strength and flexural at 28 days after casting being in the range of $f'_c$ = [102.0 – 180.0] MPa, $f'_t$ = [5.00 – 5.45] MPa and $f'_{ff}$ = [22.00 – 25.00] MPa, respectively. All the C-specimens were tested under lateral load reversals with a combined ALR less than 0.15. On the other hand, the R-specimens had ALR in the range of [0.04 – 0.33]. Lateral load and drift ratio coordinates at milestone points of the response curves were collected of all the specimens for reported yielding ($V_y$, $\theta_y$), at peak ($V_m$, $\theta_m$), and at ultimate ($V_u$, $\theta_u$), which is defined at the post-peak point in the envelope that corresponds to 80% of the peak load (or 20% drop in the peak load).

**Analysis of the Collective Experimental Evidence**

A vast range of drift capacities were observed when perusing the database. The drift capacity and strength increase achieved over the nominal flexural strength of the columns prior to jacketing are used in the present study in order to gauge the effectiveness of the retrofit. Systematic evaluation of the experimental evidence points to the following observations:

(a) The thickness, $t_j$, and volumetric fiber content, $v_f$, of the UHPC jacket provide an estimate of the effective confinement and shear strength increase of the encased cross-section, and therefore these must increase proportionally with the effective sectional dimension; i.e., column diameter and effective section depth for C- and R-specimens, respectively. In fact, the confining pressure may be calculated from: $\sigma_{lat} = 2t_j f_{fu}/D\ (or\ h)$, where the jacket ultimate tensile strength $f_{fu}$ is proportional to $v_f$; it is evident that confinement achieved with a certain jacket thickness decreases with increasing section size. In the following evaluation of the data, a geometric jacket index, $JI$, is used to quantify this effectiveness defined as follows:

$$JI = 100 t_j v_f / D, \text{ for C-specimens} \quad (1)$$

$$JI = 100 t_j v_f / h, \text{ for R-specimens} \quad (2)$$

For example, an indicative value is obtained here for a 25 mm thick jacket containing 2% fiber on a 500 mm diameter cross section: $JI = 100\times25\times2/500 = 10$. (In reality, for a random distribution of fibers, the effective value of $JI$ may be halved, but as the method of casting is unknown and is considered a construction parameter in many studies, this index is taken at its nominal value.

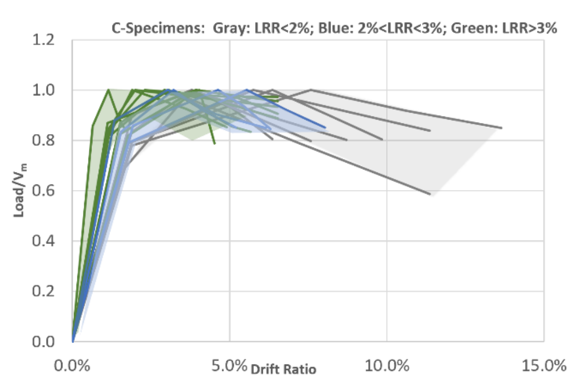
(b) Deformation capacity is compromised by three independent design variables that concern the original column design, i.e., large flexural demands (such as when the cross section is heavily over-reinforced); high axial load ratios; and low aspect ratio (defined as the ratio of $L_s/d$, where $d$ is the effective depth of the column cross section). Any other form of existing confinement prior to the application of the jacket enhances the ultimate deformability of the structural member. Similar is the effect of these parameters in the characteristics of the mode of column failure even after jacketing. In the present study, a composite index *CI* is defined to classify the data as follows:

$$CI = TRR \cdot AR \cdot (1 - ALR)/LRR \tag{3}$$

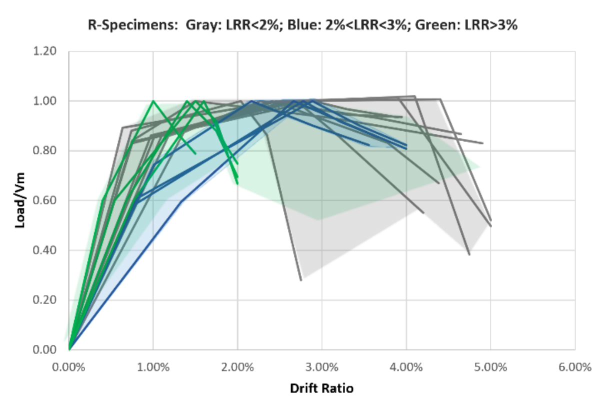
where *TRR* is the transverse reinforcement volumetric ratio (calculated over the volume of the confined core), *LRR* is the longitudinal reinforcement ratio (calculated over the gross cross-sectional area) and *AR* is the aspect ratio of the member.

(c) Attainment of the flexural strength that is provided by the combination of axial load ratio and longitudinal reinforcement is an indicator of retrofit success. Values of flexural moment that can be supported by the column considering flexural response are calculated in the present investigation considering the ultimate strength of longitudinal reinforcement; the attained values are then divided by the shar span in order to obtain the lateral force for flexure-dominated response, $V_{flex}$. This is compared against the maximum lateral force resisted by the specimen, $V_m$, in the test. Cases with $V_m/V_{flex} > 1$ indicate that the jacketing enhanced the column response, precluding any premature forms of failure (e.g., shear) and thereby securing flexural overstrength to the retrofitted component. Values of the ratio less than one indicate the occurrence of earlier forms of failure (often, in the anchorages of the repaired specimen, particularly if these have been compromised prior to retrofitting).

The observations reported above are illustrated in the following sequence of plots of the experimental data. The first two cases show the influence of longitudinal reinforcement ratio on drift capacity of all specimens (Fig. 1(a) for C-Specimens and Fig. 1(b) for R-Specimens); to facilitate comparison, the resistance curve each individual specimen has been normalized in the y-axis with the corresponding value of $V_m$. A cloud is used to better identify each group of specimens classified according to the value of LRR: gray for LRR < 2%; blue for 2% < LRR < 3%, and green for LRR >3%. It is noted that the higher the value of LRR, the smaller the range to which the graphs extend in the x-axis which plots the drift ratio. It is also noted that the range of maximum drift values to which the resistance curves extend is much higher in the case of circular as compared with the rectangular section specimens.



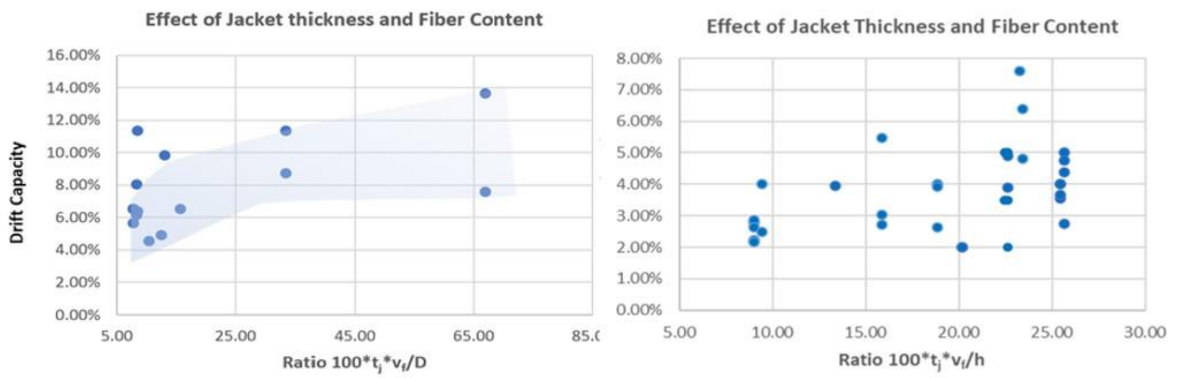

(a) C-specimens




(b) R-specimens

Figure 1: Resistance curves of all specimens normalized with respect to the maximum attained lateral load resistance, $V_m$.

One mechanism of the improvement of UHPC enhancing a RC pier is by confinement [21]. The confining effect of the jacket in enhancing the drift capacity of the columns is illustrated in Fig. 2(a) and (b) which organize the maximum attained drift ratios according with the geometric jacket index, JI, defined in Eq. (1) and Eq. (2). The use of UHPC shells generates greater concrete confinement than regular concrete, which contribute to a less disperse distribution of concrete cracking. This behavior is due to the bridging ability provided by steel fibers [11].

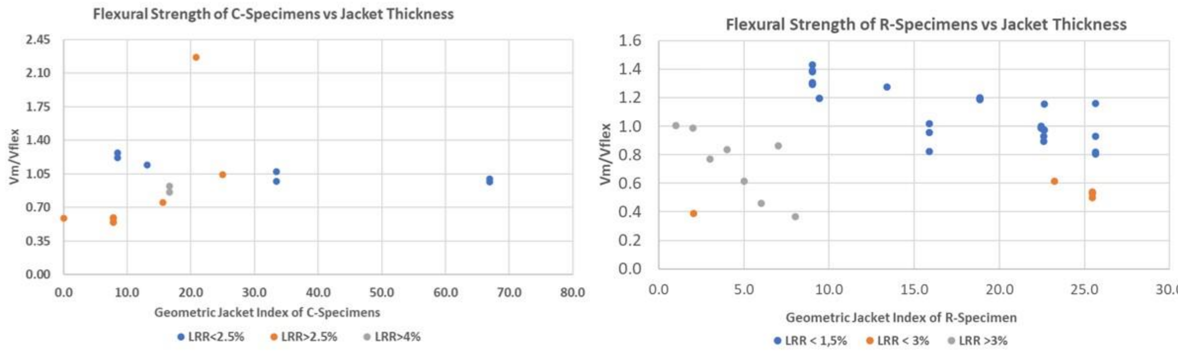



(a) C-specimens (b) R-specimens

Figure 2: Ultimate Drift capacity plotted against the geometric jacket index, JI. Note that the effect of Cross-sectional shape on drift capacity of retrofitted specimens is evident.

The scarcity of the data in the larger range of JI values in circular sections is notable; however, even in the lowest case the drift capacity for the C-specimens is much higher than what is achieved in the R-specimens, underscoring the fact that the confinement effectiveness obtained by UHPC jacketing is affected by the cross-section shape in the same manner as would occur with other forms of confinement (stirrups, FRP wraps, etc.). It is noted here that 3 R-specimens that had wire-mesh reinforcement in the jackets attained drifts in the range of 3-5%; however, these are excluded from Fig. 2(b) for clarity of comparison between specimens with UHPC jackets and other form of reinforcement.

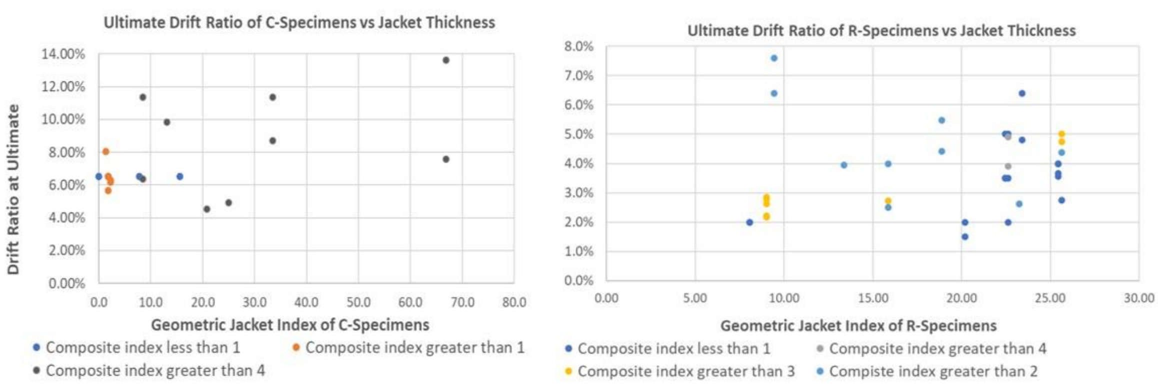
Figure 3 below plots the strength ratio, $V_m/V_{flex}$, for all specimens in the database, against the composite index, CI, defined by Eq. (3). It is observed that values of the $V_m/V_{flex}$ ratio less than 1 indicate that another form of failure other than extensive flexural yielding occurred limiting the effectiveness of the retrofit. Such values of the ratio occur in the lower range of the CI index. (By definition, CI is inversely proportional to the LRR and decays with increasing value of ALR.) more slender specimens, having a higher AR and more well confined (by means of embedded stirrups) specimens have higher CI and overall better performance in terms of attaining a strength ratio ≈1 (which would mean that the steel reinforcement at the critical section was able to develop its full capacity without other types of earlier failure). Orange markers correspond to specimens with lower effective confinement as the jacket comprised PVA fibers; it is noted that strength recovery is less effective in these cases.




(a) C-specimens (b) R-specimens

Figure 3: Behaviour of flexural strength as $V_m/V_{flex}$ of all specimens against the composite index CI.

Ultimate drift ratio ($\theta_u$) for all specimens in the database, against the composite index CI is shown in Figure 4. Results of the ratio are mostly grouped on *JI* ratios less than 15%, meanwhile only two C-Specimens experience *JI* ratios higher than 60%. On the other hand, R-Specimens are gathered on *JI* ratios between 22% to 25%. C-Specimens show higher ultimate drift capacities overall when compared to R-Specimens. This factor could be attribute to the fact that R-Specimens $v_f$ values were not higher than 2.0%. Another factor that could be interfering are other fiber mechanical properties, such as tensile strength, fiber length, fiber diameter or fiber modulus of elasticity. Further research to investigate these parameters must be conducted since they were not directly included in the discussion of this paper.




(a) C-specimens (b) R-specimens

Figure 4: Performance of all specimens by comparing the composite index CI at the ultimate drift capacity.

## Conclusions

In this paper, a critical review of the seismic performance of UHPC retrofitted RC columns with circular and rectangular cross-sectional shapes has been conducted. A total of 49 specimens were collected from published literature, with 21 being C-specimens and 28 being R-Specimens.

The following conclusions can be drawn:

- UHPC has superior mechanical properties and higher reinforcing confinement performances than NSC, which result high-quality and longer life-lasting retrofits when compared with NSC. However, a proper design of UHPC Jacket amount and retrofit section may help to achieve an efficient and cost-effective solution.
- Lower JI index ratios were common in experiments on C-Specimens than in R-Specimens, however they were more effective in providing higher ultimate drift capacities, highlighting the reduced confining effectiveness of the jacket in rectangular sections.
- The existing amounts of longitudinal reinforcement which control the flexural demand eventually control the deformation capacity and amount of strength enhancement that may be achieved by the jacket. Expected performance of the jacket may be gauged by a composite index that accounts for the favorable effect of confinement in existing transverse reinforcement and higher aspect ratio, and the unfavorable influence of higher axial load and higher amounts of longitudinal reinforcement on drift capacity of the repaired element as well as on the ability of the column to develop its ideal flexural strength.
- RC columns retrofitted using UHPC jackets reinforced with PVA fibers exhibited less efficient strength recovery compared to those retrofitted with UHPC jackets containing steel fibers.

Further research is needed to fully understand the effectiveness of UHPC jackets in the seismic retrofitting of RC columns. Additionally, further investigation is needed to explore the influence of different factors including the fiber types and mechanical properties thereof used in UHPC on the seismic performance of UHPC retrofitted RC columns.

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