Axial Load Behaviour Repaired Piers with Ultra High Performance Concrete Jacket

Khandaker M. Anwar Hossain, PhD, PEng – Professor, Toronto Metropolitan University, Toronto, Department of Civil Engineering, ON, Canada, Email: ahossain@torontomu.ca

Ali E. Yeganeh, PhD – Researcher, Department of Civil Engineering, Toronto Metropolitan University, Toronto, ON, Canada, Email: ali.ehsaniyeganeh@torontomu.ca

Philip Loh, M.Eng., P.Eng. (corresponding author) - Structural Engineer/Design Build Lead, Facca Incorporated, Ruscom, Ontario, Canada, Email: philip@facca.com

Abstract

Rehabilitation of bridge and other infrastructures damaged by continuous wear, as well as time-dependent and environmental effects, is a major concern. Every year, worldwide billions of dollars are spent to repair and maintain a large number of reinforced concrete (RC) bridges. Recent developments on ultra high performance concrete (UHPC) significantly made these materials feasible and convenient to use for repair of damaged and deficient piers. UHPC can protect the existing core pier against aggressive environmental agents and increase strength and durability of the piers as the confinement material. This paper presents an investigation on the performance of repaired damaged RC circular bridge piers using HPC jacketing technique. Jackets made of UHPC having different thicknesses with same reinforcement configuration were used to repair damaged RC core piers and analyze their behavior. Reinforced core piers were axially loaded to 60% of their ultimate load to induce damage before being repaired with HPC jackets. Jacketed pier specimens were tested to failure under concentric axial load applied through the core pier. Test results indicated performance enhancement of UHPC jacketed repaired piers in terms of improved ductility, energy absorbing capacity and strength recovery. The jacket confining effect and overall ductility characteristics of repaired piers were influenced by jacket thickness to core pier diameter ratio which needs to be optimized.

Keywords: Ultra high performance concrete; Reinforced concrete pier; Repair; Jacketing technology; Axial strength

1. Introduction

Traditionally Reinforced Concrete (RC) has been extensively used to repair damaged and deficient RC piers and other types of structures by jacketing method. RC jacketing is time-consuming and costly due to low strength, brittle materials and required large quantities of concrete materials (Raza et al. 2019). Common durability related issues such as the susceptibility of confining reinforcement to corrosion remain significant problems in RC techniques. though FC jacketing reduces the size and dead load remarkably. Jacketing using fibre-reinforced polymer (FRP) has addressed some limitations on the RC jacketing. However, effective confinement in the circumferential direction in the FRP repair systems is always a concern (Chellapandian et al. 2019; Mohammed et al. 2019) and with an increase of the damage percentage, the effectiveness of the FRP jacketing is significantly reduced (de Diego et al. 2019; Fanaradelli et al. 2019). Partially use of steel jacket and concrete-filled steel tube to enhance the strength and improve the deformability of concrete columns was previously studied (Wang et al. 2020; Hossain et al. 2021). RC columns wrapped externally with steel tubes have shown high compressive strength and substantially improved the ductility (Olmos et al. 2019). Due to poor bonding and complex construction methods, efficiency of the steel jacket method reduced significantly (Wang et al. 2020).

Fibre reinforced UHPC is a special class of high performance concrete designed to exhibit high strength, post-cracking strain hardening, good crack control and superior durability properties which make it useful for repairing and repair of damaged and deficient piers (Cho et al. 2018; Farzad et al. 2019; Hossain et al. 2021). With having low porosity UHPC jacket can protect the existing core pier aggressive environmental and increase the durability of the pier as the confinement material (Ali Dadvar et al. 2020; Xie et al. 2019). The use of UHPC in repairing of deteriorated bridge and building components is an emerging technology and gaining popularity worldwide. Every year, worldwide billions of dollars are spent to repair and maintain a large number of RC bridge structures. A lack of research studies warrants research investigations on UHPC-strengthened/repaired components of bridge/building structures (Hossain et al. 2012, Farzad et al. 2019).

The novel aspect of this investigation was the study of the effect of different types of HPC materials of two different thicknesses used as jacket to repair damaged RC piers/columns. The performance of the repaired HPC jacketed self-consolidating concrete (SCC) columns subjected to concentric monotonic loading through the core to failure is described based on jacket thickness (t) to core diameter (D) ratio (t/D), failure modes, streel/concrete strain development, strength enhancement due to confinement effect of UHPC jackets, energy absorbing capacity and overall axial strength. The recommendations of this study will help, engineers, builders, and local authorities to understand and apply UHPC-based repair technology.

2. Experimental Investigation

An experimental program had been conducted to study the behavior of reinforced UHPC jacketed repaired circular Self-Consolidating Concrete (SCC) piers under concentric axial compressive loading to the failure. The variables in the study included: type of pier specimens (virgin, repaired with UHPC jacket), two UHPC jacket thicknesses and jacket thickness (t) to core pier diameter (D) ratio (t_r% =25% and 33.4%).

2.1 Material Properties and Concrete Mix Design

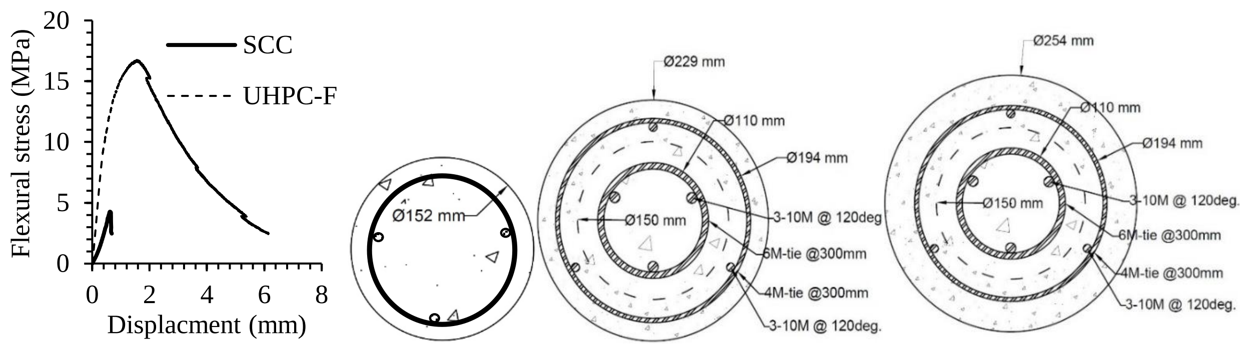
A commercial SCC mixture made of 10 mm (0.4 inch) maximum size coarse aggregates, crushed sand, Portland cement and admixtures were used to cast core piers. A UHPC (designated as UHPC-F) was used for jacketing the SCC core piers. UHPC-F consisted of general-purpose cement, silica fume, water, natural grain silica sand, steel fibers (13 mm (0.51inch) in length, 0.2 mm (0.008 inch) diameter, tensile strength of 2160 MPa (313.3 ksi) and melting point of 800^{o}C) and a high range water reducer (HRWR). UHPC-F had water to cementitious ratio of 0.16 and a steel fiber content of 158 kg/m^3 (1.69 lb/yd^3). Details of the mix designs are provided in Table 1.

Table 1: Mix design of concrete

	Cement	Silica fume	Silica Sand	Steel fiber, kg/m^3	HRWR, kg/m^3	w/b
UHPC-F	1	0.26*	1.42*	158	24	0.16

w: water; c: cement; b: binder; *by mass of cement; 1 kg/m^3= 1.686 lb/yd^3

The mean concrete compressive strength (f_c') was determined from minimum of three 100 mm (4 inch) x 200 mm (8 inch) cylindrical specimens tested at the same time of testing the pier specimens as per ASTM C39 (2018). Four-point bending test was performed on concrete prism specimens at 28-days as per ASTM C78 (2018). Typical flexural stress to mid-span deflection responses of SCC and UHPC-F are presented in Figure 1a. The mean 28-day compressive and flexural strengths of SCC are 75 ± 2 MPa and 4.7 ± 0.2 MPa while 148 ± 3 MPa and 16.6 ± 0.3 MPa, respectively for UHPC-F. The properties of reinforcing steels were obtained based on the tension test performed on three randomly selected coupon specimens for each bar size. The mean yield stress and yield strain were 485 MPa and 2110 microstrain, respectively for 10 mm bar, 466 MPa and 2354 macrostrain for 6 mm bar and 473 MPa and 2291 microstrain for 4 mm bar.



(a) **(b)** **(c)** **(d)**

Figure 1: (a) Stress-deflection responses of SCC/UHPC and dimensions and reinforcement details of piers (b) core, (c) with 38 mm (1.5 inch), (d) 51 mm (2 inch) jacket layer (1 inch = 25.4 mm; 1 MPa = 145 psi)

2.2 Pier Specimens' Dimensions and Reinforcement Details

Table 2 provides the details of specimens, jacketing materials, thickness of the jacket, and loading scheme and specimen's designations. First letter in the specimen designation of repaired jacketed specimens represents the type of UHPC used in the jacket and 1st numeric represents the thickness of the jacket in inches and numeric 60% represents the load in % of axial strength of virgin core applied to cause damage. Circular core pier specimens were constructed with SCC having 152.4 mm diameter and 1000 mm length. The cross-section of the SCC core pier (S-C) without jacket is shown in Fig. 1b. SCC core piers were then loaded to 60% of their axial strength to cause damage and then repaired with UHPC-F using two different jacket thicknesses of 1.5 inches (38 mm), and 2 inches (51 mm) as shown in Fig. 1(b-c). Reinforcement details of piers are also shown in Fig. 1(b-d). Three 10 mm and 6 mm diameter steel rebars at 150 mm c/c were used as vertical and tie reinforcement, respectively in SCC core pier. The jacket layer was reinforced with three 10 mm diameter steel rebars as vertical reinforcement and 4 mm diameter bar as ties at 100 mm c/c.

Table 2: Details of pier specimens with designations

Core material	Jacket material & their abbreviations	Jacket thickness (inch)	Jacket thickness (mm)	Specimen notation
SCC	-	-	-	S-C (control with no jacket)
Repaired SCC core pier specimens with jacket: axial load applied through SCC core - pier core dimeter: 152.4 mm; pier height: 1000 mm				
SCC	UHPC-F (U-F)	2	51	UF-2-60%
SCC	UHPC-F (U-F)	1.5	38	UF-1.5-60%

2.3 Construction, Damage and Repair of Core Pier Specimens

SCC core pier specimens were constructed first by using a high shear concrete mixer and water cured for 3 days before being demolded at 7 days and then air cured in the lab at 23 ± 2^{o}C. Control specimens in the form of cylinders and prisms were also casted at the same time and cured under similar conditions as pier specimens. Virgin (control) SCC core pier specimen (S-C) was loaded to failure to determine the axial strength and other companion specimens were loaded to 60% of the axial strength to induce damage at the age of 28 days. Damage induced S-C pier specimens were then repaired/rehabilitated by UHPC-F jacketing of different thickness. The jacketing reinforcement, placement of jacket, damaged SCC core pier and formworks are shown in Figure . Self-flowing UHPC mix was produced using high shear mixture and poured into the tube formwork without consolidation. Repaired pier specimens were water cured for 3 days in the laboratory and demolded after 7 days. Then, all repaired pier specimens (Fig. 2c) were air cured in the lab at 23 ± 2^{o}C along with control cylinder and cube specimens and tested at the age of 28 days (at the age of 56 days from the SCC core casting).

(a) (b) (c) (d) (e) (f) (g)

Figure 2: (a) Jacket reinforcements, (b) damaged SCC core pier in tube form, (c) repaired piers, (d) test setup with instrumented and failure pattern of piers (e) core (S-C), (f) jacketed UF -1.5-60%, (g) UF-2-60%

2.4 Test setup, Instrumentation and Testing

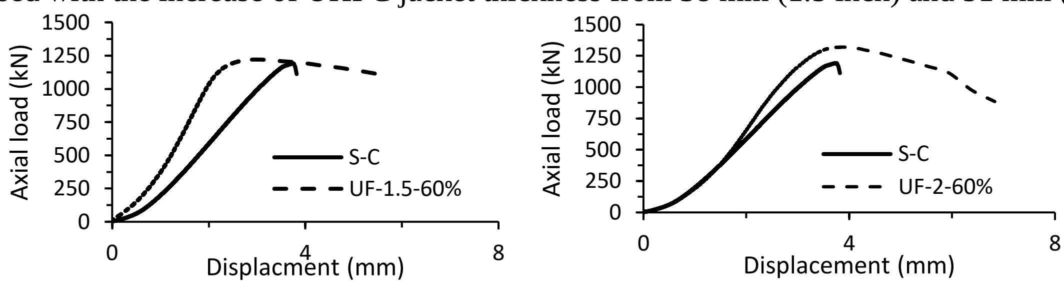
An MTS machine was used to test the pier specimens under concentric monotonic axial loading applied through the SCC core at a rate of 0.2 MPa/s (29 psi/s) until failure of control (S-C)/repaired specimens and up to 60% of axial strength to induce damage before being repaired. The test set-up with an instrumented pier specimen is shown in Figure 2(d). One concrete gauge was attached horizontally to the outer surface of the SCC core pier at 200 mm from the bottom to measure the radial/hoop strain while a steel strain gauge was installed at the same height to measure the axial strain development in vertical reinforcement as shown in Fig. 2(d). After repair, one concrete gauge was installed horizontally to outer surface of the UHPC jacket at mid-height to monitor the radial (hoop) strain development Fig. 2(d). During loading, axial load-displacement response and steel/concrete strains were recorded through a data acquisition system while observing cracking, crack propagation and failure modes (Fig. 2e-g).

3. Experimental Results and Discussions

Tests results are analyzed based on axial load-deflection responses, crack formation and propagation, ultimate/peak load, failure modes, UHPC jacketing characteristics, ductility, energy absorption capacity, and steel/concrete stress-strain developments.

3.1 Load-Displacement Responses of Repaired/Jacketed Core Pier Specimens

Figures 3(a-b) present the axial load-displacement responses of repaired piers. All repaired piers exhibited higher axial load capacity with ability to allow larger displacement/ductility before failure, compared to S-C control pier. The axial load capacity and ductility of repaired piers increased with the increase of UHPC jacket thickness from 38 mm (1.5 inch) and 51 mm (2 inch).

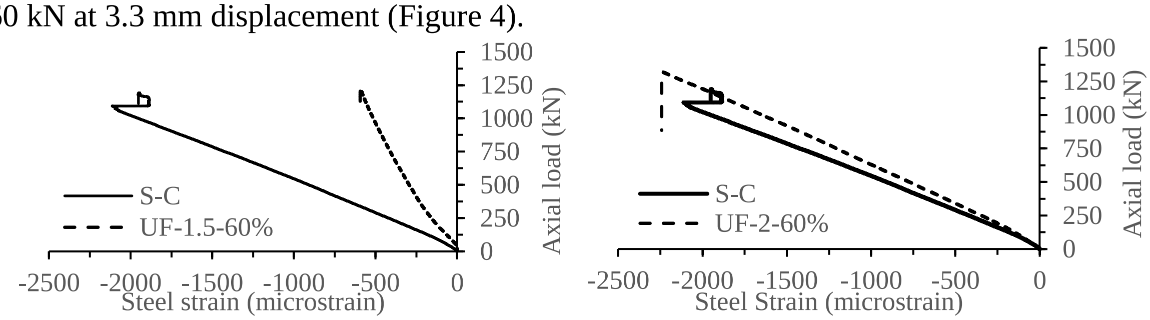


(a) **(b)**

Figure 3: Load-displacement responses of piers -jacket thickness (a) 1.5 inch (38mm) and (b) 2 inch (51 mm)

3.2 Concrete and Steel Strain Development

Longitudinal steel strain development of UHPC jacketed piers is compared with those of S-C control pier in Figures 4(a-b). The longitudinal steel strain at 60% of axial strength of control S-C core pier (715 kN) was 1356 microstrain (about 68% of yield strain) and reached yield strain at 1060 kN at 3.3 mm displacement (Figure 4).



(a) **(b)**

Figure 4: Steel strain of piers-jacket thickness (a) 38 mm (1.5 inch) and (b) 51 mm (2 inch) (1 kN = 224.8lb)

Longitudinal reinforcements of jacketed pier UF-1.5 yielded but UF-2 did not reach yielding. This could be attributed to the crushing of top concrete before yielding of longitudinal reinforcements in UF-2. Development of radial/hoop strain in UHPC jacket is shown in Figure 5 and repaired piers (UF-2) with higher jacket thickness of 51 mm (2 inch) had higher hoop strain compared to their (UF-1) lower jacket thickness (38 mm) due to providing higher confinement. The UF-2-60% pier (with 51mm jacket) had shown higher jacket concrete radial/expansion strains (ε_c) of approximately 1800 microstrain compared to 626 microstrain of its 38 mm counterpart (Figures 5a-b). From higher strain, it can be concluded that the jacket had higher ability to undergo expansion before failure and therefore withstanding larger axial displacement.

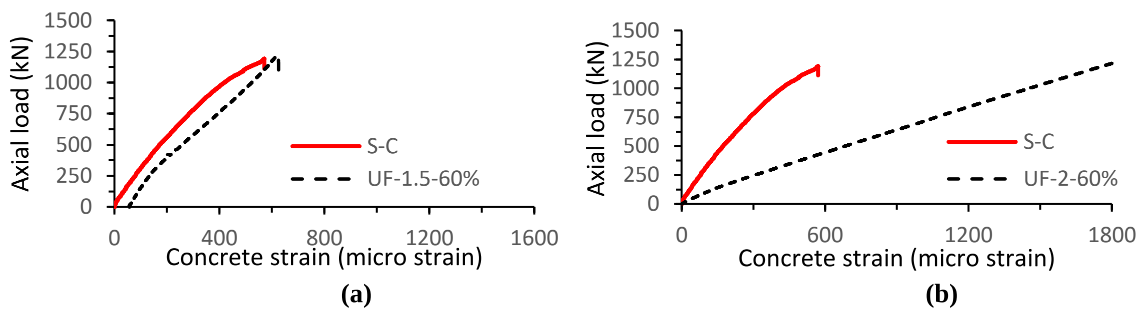


Figure 5: Axial load versus jacket concrete hoop strain of piers with jacket thickness of (a) 31 mm (1.5 inches) and (b) 51 mm (2 inches) (1 kN = 224.8lb)

3.3 Crack Pattern and Failure Modes

Failure mode of SCC core pier specimen (S-C) was by top concrete bearing through mobilizing reinforcement exhibiting a cone shape, concrete spalling and longitudinal reinforcement buckling (Figure 3e). In general, failure of repaired UHPC jacketed piers was associated with crushing of SCC core pier associated radial expansion of core/jacket, formation of radial and vertical cracks in jacket, core pier-jacket separation with extension and widening of vertical cracks from the top to the bottom. Two types of failures (Table 3, Figures 3f-g) are identified. Type 1: brittle crushing failure at the top with spalling of UHPC jacket (not desired) and Type 2: ductile failure due to extension/widening of vertical cracks in jacket from the top engaging confinement effect to greater height of the pier. Piers repaired with UHPC jacket of higher thickness (UF-2) exhibited type 2 brittle crushing failure at the top while those thickness (UF-1.5) exhibited type 1 ductile failure generating confining effect along the height.

3.4 Performance Evaluation of UHPC Jacketed Repaired Piers

A summary of ultimate/peak axial load (P), peak displacement (Δ), energy absorbing capacity, load or displacement or energy ratios with respect to control SCC non-jacketed pier (S-C), maximum longitudinal steel strain ($\boldsymbol{\varepsilon_s}$) and jacket concrete hoop strain ($\boldsymbol{\varepsilon_c}$) at peak load are presented in Table 3. Energy absorbing capacity was calculated based on area of the load-displacement curve up to 85% post peak load. A summary of axial load capacity increase/decrease with the increase of jacket thickness and failure modes of specimens are also presented in Table 3. All the repaired damaged pier specimens developed higher axial strength than the control SCC core pair (S-C) and the increase in strength increased with the increase of UHPC jacket thickness. The axial load capacity increased from 3% to 11% compared to S-C control core pier as jacket thickness ratio (t_r%) increased from 25% to 33.3% (Table 3). For each 13 mm increase of jacket thickness, the axial load capacity was increased by approximately more than 10%. Jacketed repaired pier specimens also exhibited 1.01 to 2.86 times higher energy absorbing capacity than the unjacketed SCC core pier (Table 3). Repaired UHPC jacketed pier's (UF-2) brittle type 2 failure was a cause of concern that needs to be avoided. Longitudinal reinforcement strain (ε_s) of all repaired piers did not reach yielding (Table 3). The axial strength can be increased by controlling jacket layer thickness, jacket reinforcement and UHPC strength, to generate yielding of main steel in SCC core and type 1 ductile failure. Investigations are necessary on these aspects.

Table 3: Summary of maximum load, displacement, strains and energy absorbing capacity

Pier Specimen	Jacket thickness (t) (mm)	t_r (%)	P (kN)	Δ (mm)	ε_s microstrain	ε_c microstrain	Energy (kNmm)	P ratio*	Δ ratio*	Energy ratio*
S-C	0	0	1192	3.71	580	2092	2075	1.00	1.00	1.00
UF-1.5-60%	38	25	1222	3.17	626	585	5152	1.03	0.85	2.48
UF-2-60%	51	33.3	1320	5.53	1798	2242	5937	1.11	1.49	2.86

Summary of enhancement comparison of repaired piers

Jacket material	Pier specimen	t (mm)	t_r (%)	Axial load increase with respect to core pier (S-C) (%)	Displacement increase/decrease with respect to core pier (S-C) (%)	Failure modes
UHPC-F	UF-1.5-60%	38	25	3	-15**	Type 1
	UF-2-60%	51	33.3	11	49	Type 2

Thickness ratio (t_r %): ratio of jacket thickness to core diameter (%); *P ratio, Δ ratio, Energy ratio: ratio of peak load, displacement and energy, respectively of repaired piers to those of core pier; **decrease; (1 kN = 224.8lb, 1 mm = 0.0394 inch)

4. Conclusions

The axial load behavior of repaired reinforced circular Self-consolidating Concrete (SCC) piers with reinforced jacket made of Ultra-High Performance Concrete (UHPC) of different thickness had been investigated. The following conclusions are drawn from the test results of piers loaded axially through the SCC core to failure:

- Two types of failures were identified. Type 1: brittle crushing failure at the top with spalling of UHPC jacket (not desired) and Type 2: ductile failure due to extension/widening of vertical cracks in jacket from the top engaging confinement effect to greater height of pier.
- UHPC jacketed repaired pier specimens exhibited 2.48 to 2.86 times higher energy absorbing capacity and higher strength than their control virgin SCC core pier counterparts.
- UHPC jacketed piers of greater thickness of 2 inch (58 mm) exhibited type 1 brittle crushing failure at the top while those with lower jacket thickness of 1.5 inch (38 mm) exhibited type 2 ductile failure. UHPC jacket thickness to SCC core pier diameter ratio of more 25% can lead to type 1 brittle failure.
- Brittle failure of piers with UHPC jacket of higher thickness is a cause of concern and such concerns can be resolved by selecting proper combination of pier dimeter, jacket thickness and UHPC strength to ensure type 2 ductile failure.

5. Acknowledgement

The authors acknowledge the financial support provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada and Facca Inc. Canada.

6. References

ASTM C39/C39M (2018). "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." *ASTM International*, West Conshohocken, PA.

ASTM C78/C78M (2018). "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." *ASTM International*, West Conshohocken, PA.

Ali Dadvar, S., Mostofinejad, D., and Bahmani, H. "Repairing of RC Columns by Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) Jacketing." *Construction and Building Materials*, Vol. 235, 2020, 117485.

Chellapandian, M., Prakash, S. S., and Sharma, A. "Experimental and Finite Element Studies on the Flexural Behavior of Reinforced Concrete Elements Repaired with Hybrid FRP Technique." *Composite Structures*, Vol. 208, 2019, p. 466–478.

Cho, C. G., Han, B. C., Lim, S. C., Morii, N., and Kim, J. W. "Repairing of Reinforced Concrete Columns by High-Performance Fiber-Reinforced Cementitious Composite (HPFRC) Sprayed Mortar with Repairing Bars." *Composite Structures*, Vol. 202, 2018, p.1078–1086.

de Diego, A., Arteaga, Á., and Fernández, J. "Repairing of Square Concrete Columns with Composite Materials - Investigation on the FRP Jacket Ultimate Strain." *Composites Part B: Engineering*, Vol. 162, 2019, p. 454–460.

Fanaradelli, T., Rousakis, T., and Karabinis, A. "Reinforced Concrete Columns of Square and Rectangular Section, Confined with FRP – Prediction of stress and strain at failure." *Composites Part B: Engineering*, Vol. 174 (June 2019), 107046.

Farzad, M., Shafieifar, M., and Azizinamini, A. "Retrofitting of Bridge Columns Using UHPC." *Journal of Bridge Engineering*, Vol. 24, No. 12, June 2019, p.1–13.

Hossain, K.M.A., Chu, K., Anwar, M.S. "Axial Load Behavior of Ultrahigh Strength Concrete-Filled Steel Tube Columns of Various Geometric and Reinforcement Configurations", *Infrastructures*, Vol. 6, No. 5, 2021, 66.

Hossain, K.M.A., Mak, C. and Ametrano, D. "GFRP Reinforced UHPC Composites for Sustainable Bridge Construction. *Canadian Civil Engineer*, Vol. 29, No. 1, 2012, p. 12-15.

Mohammed, A. A., Manalo, A. C., Maranan, G. B., Zhuge, Y., Vijay, P. V., and Pettigrew, J. "Behavior of Damaged Concrete Columns Repaired with Novel FRP Jacket." *Journal of Composites for Construction*, Vol. 23, No. 3, 2019, p.1–14.

Olmos, B., Jara, J. M., Gómez, G., and Martínez, G. (2019). "Influence of Steel Jacket Thickness on the RC Bridges' Seismic Vulnerability." *Journal of Traffic and Transportation Engineering (English Edition)*, Vol, 6, No. 1, 2019, p.15–34.

Raza, S., Khan, M. K. I., Menegon, S. J., Tsang, H. H., and Wilson, J. L. "Repairing and Repair of Reinforced Concrete Columns by Jacketing: State-of-the-Art Review." *Sustainability (Switzerland)*, Vol. 11, No. 11, 2019.

Wang, H., Zhou, X., Liu, J., Wang, X., and Chen, Y. F. "Seismic Behavior of Steel Tube Confined Reinforced Concrete Double-Column Bridge Bents." *Journal of Constructional Steel Research*, Vol.166, 2020, 105919.

Xie, J., Fu, Q., and Yan, J. B. "Compressive Behaviour of Stub Concrete Column Repaired with Ultra-High Performance Concrete Jacket." *Construction and Building Materials*, Vpl. 204, 2019, p. 643–658.