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Research Article

Repairing and Strengthening of Damaged RC Columns Using Thin Concrete Jacketing

Bassam A. Tayeh, Mohammed Abu Naja, Samir Shihada, and Mohammed Arafa

Civil Engineering Department, Islamic University of Gaza, Gaza, State of Palestine

Correspondence should be addressed to Mohammed Arafa; marafa@iugaza.edu.ps

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This research aims to investigate the efficiency of repairing damaged concrete columns using thin concrete jacketing. The experimental program included casting of nine reference 300 mm long reinforced concrete column specimens: three specimens had a cross-sectional dimension of 100 mm × 100 mm, three specimens had a cross-sectional dimension of 150 mm × 150 mm, and three specimens had a cross-sectional dimension of 170 mm × 170 mm. A total of 36 identical column cores were cast with similar cross sections of 100 mm × 100 mm and a height of 300 mm. These cores were damaged by loading them with approximately 90% of their actual ultimate axial load capacities. Then, the columns were repaired and strengthened by applying two jacketing materials, which were 25 and 35 mm thick, on all four sides. Group 1 consisted of 18 column cores jacketed by normal strength concrete with a maximum aggregate size of 4.75 mm and steel reinforcement, whereas Group 2 consisted of 18 column cores jacketed using ultrahigh-performance fibre-reinforced self-compacting concrete with steel reinforcement. The experimental program showed that the Group 1 specimens had ultimate load capacities more than twice those of the unjacketed reference columns and the same axial capacity as the monolithically cast reference columns. The Group 2 specimens showed a significant increase in ultimate load capacity, which was approximately 3 times that of the unjacketed reference column and 1.86 times that of the monolithically cast reference columns. Moreover, using the shear studs was found to be the most effective among the three surface preparation techniques.

1. Introduction

The repair and rehabilitation of existing structures are major construction activities. Meanwhile, reinforced concrete (RC) is used widely as a construction material in most parts of the world. Structures made with this material often suffer damages due to overloading, natural disasters (e.g., earthquake and flood), fire, environmental effects (e.g., corrosion), or changes in building usage before reaching their intended design life. These damages may cause the structural elements to fail to meet the functional requirements within their designed service life. If proper attention is not paid in this regard, structures could fail to carry their design load and disasters could occur [1].

The failure of the most important structural elements, i.e., columns, may lead to the total collapse of frame-structured buildings because they are the only structural elements that convey the total vertical loads of buildings to the soil. These members can lose their strength and stiffness due to damages during their service lives. Therefore, repair or reconstruction is necessary in case of noticeable cracks to ensure that loads are further carried and transmitted to the soil [2].

Strengthening methods depend on the type of structure and loading. Regarding structures subjected primarily to static loads, increasing flexural and axial compressive strength is essential. Regarding structures subjected primarily to dynamic loads, increasing flexural and shear strength is crucial. Improving column ductility and rearranging column stiffness can also be achieved with strengthening methods. Damages to RC columns may include slight cracks without damage to reinforcement, superficial damage in concrete without damage to reinforcement, concrete crushing, reinforcement buckling, or tie rupture. On the basis of the degree of damages, techniques such as injections, removal and replacement, or jacketing can be applied [3–8]. Three principal techniques are available for strengthening RC columns: concrete jacketing, steel jacketing, and composite jacketing (FRP) [1].

The susceptibility of existing buildings to structural damages largely depends on the quality of the design, detailing, and construction. Engineers in many cases can extend the life span of buildings by utilising simple repairing or strengthening techniques. The choice of repairing or strengthening techniques becomes, therefore, the decisive factor because high costs may prevent many building owners from executing essential repair works [9–13].

Experimental investigations into strengthened or repaired columns are generally conducted on unloaded original columns, although having unloaded strengthened columns in the field presents a challenge. In studying the behaviour of strengthened columns with preloading, the original column is important but difficult to apply experimentally [3, 14–16].

Ersoy et al. [17] studied the repairing and strengthening of columns by jacketing. They tested four basic columns with identical dimensions and reinforcement under monotonic axial loading. After the test, they jacketed and retested these basic columns. They called the intervention either a repairing or strengthening jacket depending on whether the basic specimens had been loaded to a damaged level.

Fukuyama et al. [2] investigated jacketing with RC steel plates and carbon fibre sheets. This method has been widely used to repair or strengthen the RC columns damaged by the Hyogoken-Nanbu earthquake in 1995. To investigate the shear strength and ductility of RC columns repaired or strengthened by jacketing, they tested eight column specimens under constant axial compressive load and cyclic shear forces.

Meda et al. [7] studied the possibility of strengthening existing RC columns with a technique based on the application of a high-performance fibre-reinforced concrete jacket with 170 MPa compressive strength.

The ultrahigh-performance fibre concrete with a compressive strength of more than 100 MPa and improved durability marks an advancement in the concrete industry. This high-performance material offers various interesting applications. It allows the construction of sustainable and economic buildings with an extraordinary slim design. Its high strength and ductility make it the ultimate building material, e.g., for bridge decks, storage halls, thin-walled shell structures, and highly loaded columns. Aside from its improved strength properties, its outstanding resistance against all kinds of corrosions is an additional milestone on the way towards zero-maintenance construction [18–21].

Many researchers have investigated the bond strength between two concrete layers and different techniques for increasing the roughness of the substrate surface [22–28].

Nowadays, repairing techniques suitable in terms of low cost and fast execution time should be identified. Hence, the current research studied the repairing and strengthening of square RC columns by applying two concrete jacketing types: using ultrahigh-performance fibre-reinforced self-compacting concrete (UHPFRSCC) and normal strength concrete (NSC) as jacketing materials with three methods of surface roughening, i.e., mechanical wire brushing, mechanical scarification, and using shear studs. Moreover, the effects of jacket thickness on ultimate load-carrying capacity and axial displacement were studied. The obtained results were compared with those of the reference columns. The bonding among the column cores with their jacketing was investigated to decide on the best surface preparation technique.

2. Experimental Program

The experimental work herein aims to investigate the bonding among the column cores and their jacketing and the ultimate load-carrying capacity and axial displacement of uniaxial loaded square RC columns repaired and strengthened using two jacketing types with three methods of surface roughening. The obtained results are compared with those of the reference columns. Figure 1 presents the experimental plan of column specimens' fabrication.

2.1. Fabrication of Column Specimens. The current study includes the fabrication of 45 column specimens: 9 column specimens are reference columns, whereas 36 column cores are repaired and strengthened by applying two jacketing types using NSC-4.75 and UHPFRSCC with three methods of surface roughening. All column specimens are designed according to ACI 318 code requirements [25]. The longitudinal reinforcement ratio of all column specimens is not less than 1%. The details of the fabricated column specimens are as follows:

(1) Three square column specimens (UC) are cast monolithically to act as unjacketed reference columns (similar to the column core). These reference columns have cross-sectional dimensions of 100 mm × 100 mm and a height of 300 mm with 4Ø8 mm longitudinal steel reinforcement and 3Ø2.5 mm steel reinforcement ties, as shown in Figure 2.

(2) Six square column specimens (MC1 and MC2) are cast monolithically as reference columns. These reference columns have cross-sectional dimensions of 150 mm × 150 mm and 170 mm × 170 mm and a height of 300 mm with 4Ø8 mm longitudinal steel reinforcement and 3Ø2.5 mm steel reinforcement ties (Figure 3).

(3) All the column specimens which are jacketed are loaded with approximately 90% of their actual axial capacity and are associated with appearing hairline cracks without reaching failure.

(4) Two jacketing types are applied to two groups of column cores (A-B and X-Y). The first group (A-B) consists of 18 column cores jacketed with NSC-4.75

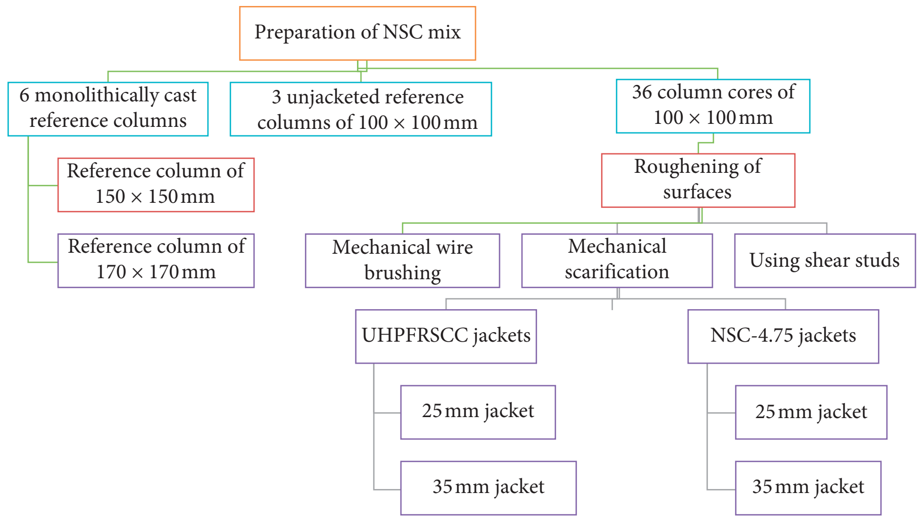

Figure 1: Experimental program.

using additional longitudinal and transverse steel reinforcement. The contact surfaces between the old and new concrete are roughened by three methods, i.e., mechanical wire brushing, mechanical scarification, and using shear studs. The second group (X-Y) consists of 18 column cores jacketed with UHPFRSCC using additional steel reinforcement. The surfaces are roughened in a similar way to the first group.

(5) Two jacket thicknesses of 25 and 35 mm are applied to the two groups of column cores (A-B and X-Y).

(6) The overall cross-sectional dimensions of the A-B and X-Y jacketed column specimens become 150 mm × 150 mm and 170 mm × 170 mm with jacket thicknesses of 25 and 35 mm, respectively, and fixed heights of 300 mm.

(7) The test result for the column specimens is considered the average of the three samples (S1, S2, and S3). Table 1 shows the details of the 45 column specimens considered in the experimental program.

2.2. Types of Concrete Mixes. In this research, the following concrete mixes are designed on the basis of the targeted concrete compressive strength.

2.2.1. NSC. The NSC mix is prepared and used to cast the UC reference columns, MC reference columns, and the column cores of the two groups A-B and X-Y. Table 2 shows the NSC mixing proportions.

2.2.2. NSC-4.75. The NSC mix with a maximum aggregate size of 4.75 mm (NSC-4.75) is prepared and used to cast the jackets of the A-B column specimens. The absolute volume method recommended in [29, 30] is used to compute the quantities of concrete materials required for the NSC-4.75 mix. Table 3 shows the mixing proportions of NSC-4.75.

2.2.3. UHPFRSCC. The UHPFRSCC mix is used to cast the jacket of the X-Y column specimens. It is prepared using the ingredients detailed in Table 4 [31]. The UHPFRSCC mix is designed to obtain a target standard cylinder compressive strength of approximately 120 MPa. The UHPFRSCC mix is prepared at IUG Soil and Materials Laboratory. All required amounts of constituent materials are weighed accurately and mixed properly using a tilting revolving drum mixer to produce homogeneous concrete. The mixing procedures are based on the study in [32].

2.3. Preparation of UC and MC Reference Columns and Column Cores. The NSC mix is prepared to obtain a targeted standard cylinder compressive strength of approximately 25 MPa. The low targeted strength represents the real status of most damaged RC columns. The absolute volume method recommended in [29] is used to compute the quantities of concrete materials required for the NSC mix.

The UC and MC reference columns and A-B and X-Y column cores are reinforced with two types of steel-reinforcing bars. High tensile strength steel with a yield stress of 360 MPa is used for longitudinal steel reinforcement, whereas steel reinforcement ties with a yield stress of 240 MPa are used. Tests are carried out for each bar size: three steel specimens with a diameter of 8 mm and length of 300 mm and another three steel specimens with a diameter of 2.5 mm and length of 280 mm. All steel samples are obtained from randomly chosen bars. Table 5 shows the testing results of the main longitudinal and transverse steel reinforcements.

2.4. Preparation of Jackets. Two jacketing types are applied to the two groups of column cores, i.e., A-B and X-Y. The A-B group represents the 18 column cores jacketed by NSC with a maximum aggregate size of 4.75 mm (NSC-4.75); the steel reinforcement cage is placed in the jacket. The X-Y group represents the 18 column cores jacketed by UHPFRSCC; the steel reinforcement cage is placed in the jacket.

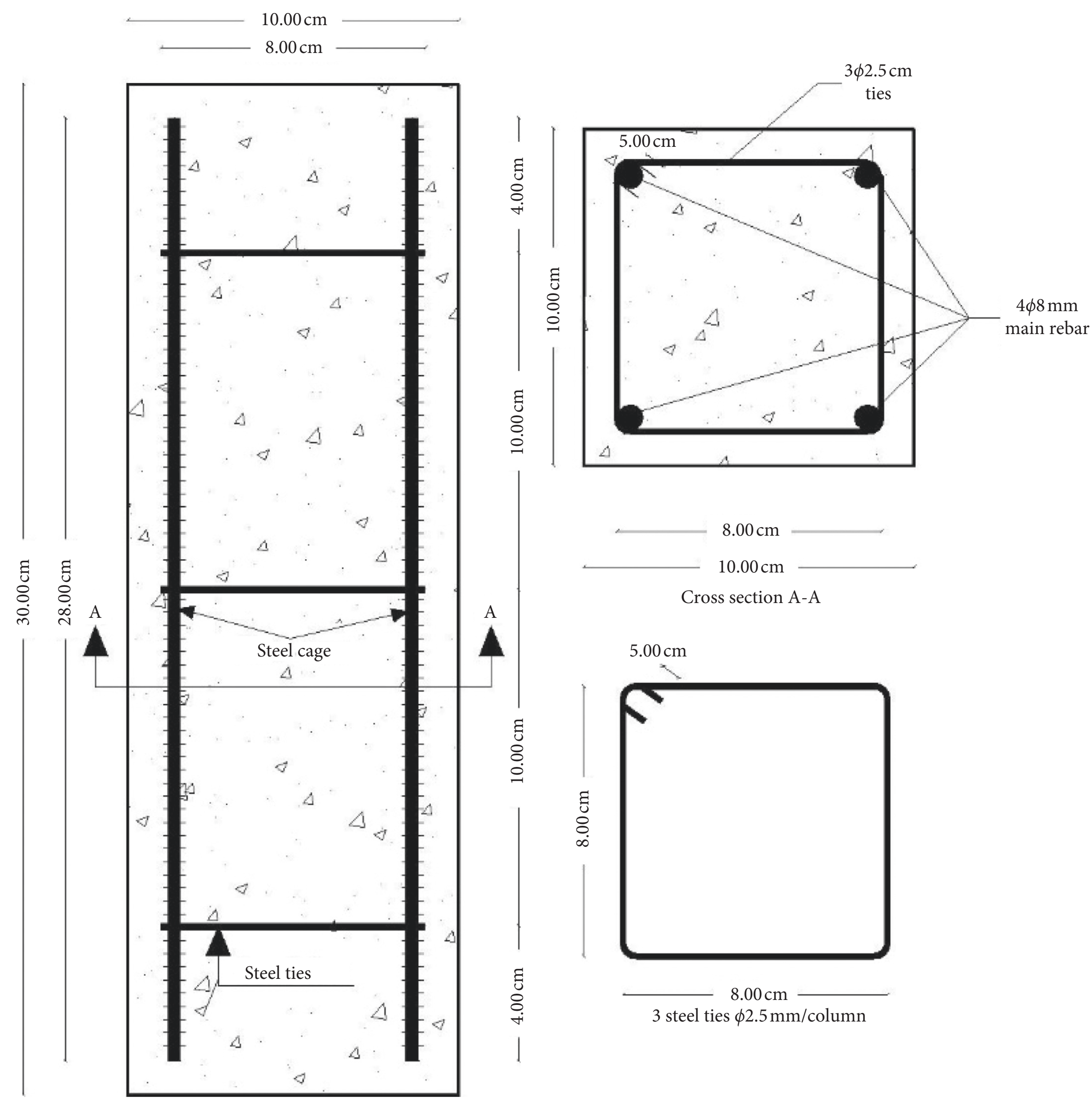

Figure 2: Geometry and reinforcement details of UC unjacketed reference columns.

2.4.1. Preparation of Core Surfaces. Three methods are used to roughen the surfaces of column cores to investigate the method which can provide the best bond between column cores and their jacketing.

(1) Preparation of A-B-W and X-Y-W Groups. Using mechanical wire brushing, the specimens' surfaces are cleaned to remove the dust and ensure their roughness. Figure 4 shows the preparation of the A-B-W and X-Y-W groups [33]. 4Ø8 mm main steel-reinforcing bars with a length of 280 mm and a diameter of 8 mm are used at the four corners of the column cores. 3Ø2.5 mm transverse steel reinforcement ties are used and fixed to the longitudinal steel bars (not welded) with a vertical spacing of 90 mm.

(2) Preparation of A-B-C and X-Y-C Groups. In preparing the core surfaces of the A-B-C and X-Y-C groups, a concrete cutting diskette is used to scarify the specimens' surfaces. The scarification is approximately 3–6 mm wide and 5–7 mm deep for good roughening. Figure 5 shows the preparation of the A-B-C and X-Y-C groups [33]. 4Ø8 mm main steel-reinforcing bars with a length of 280 mm and a diameter of 8 mm are used at the four corners of the column cores. Figures 6 and 7 show the geometry and reinforcement detailing of the A-C and B-C groups, respectively. The geometry and steel detailing of the Y-W, B-C, and Y-C groups are discussed later. 3Ø2.5 mm transverse steel reinforcement ties are used and fixed to the longitudinal steel bars (not welded) with a vertical spacing of 90 mm.

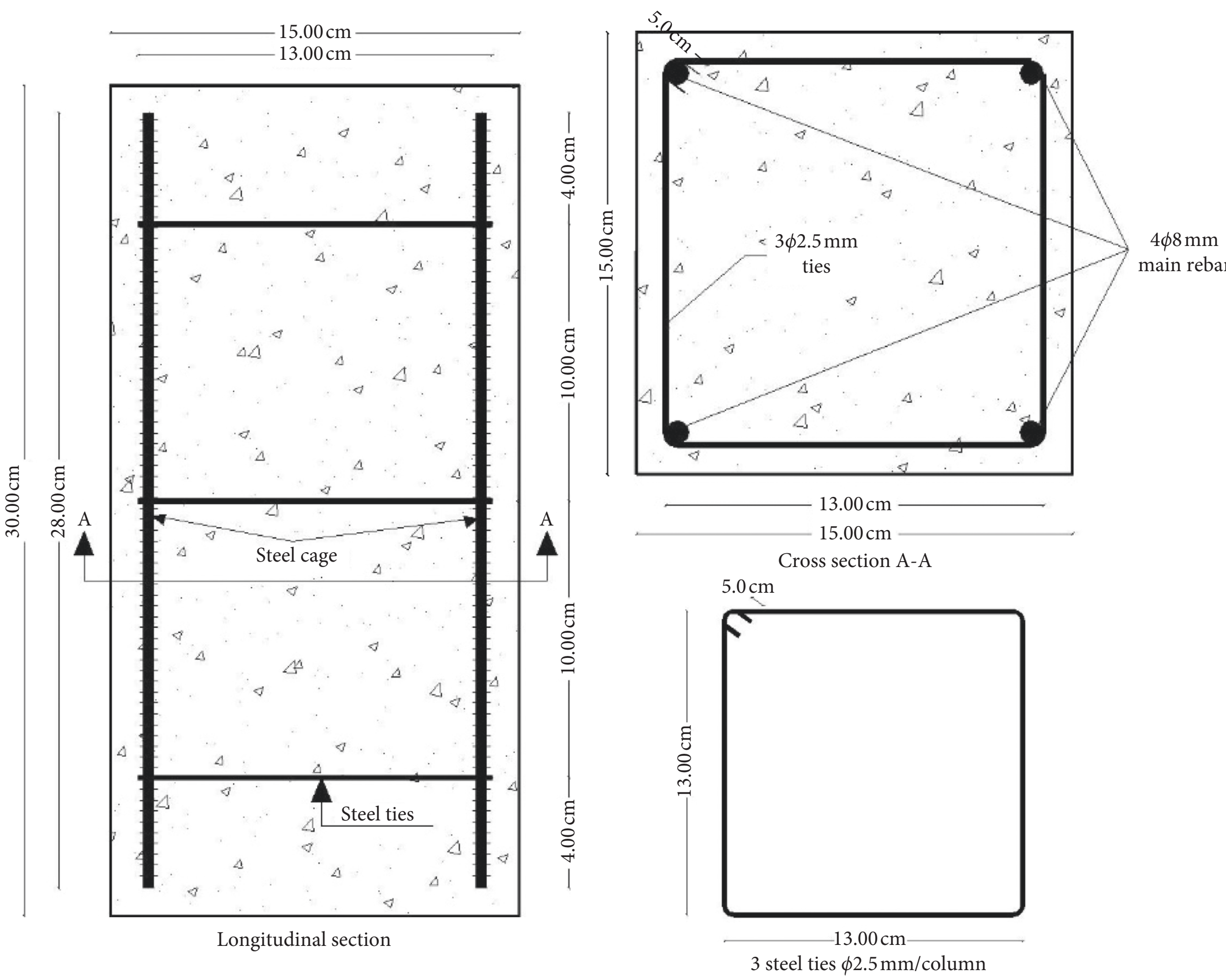

Figure 3: Geometry and reinforcement details of MC1 unjacketed reference columns.

Table 1: Details of column specimens.

#	Description		Notation	Column core (mm)	Overall cross section (mm)	Jacket thickness (mm)	Number of samples
1	UC unjacketed reference column		UC	100 × 100	Cross-sectional dimensions of UC and MC reference columns are fixed		3
2	MC monolithically cast reference columns		MC1	150 × 150			3
3			MC2	170 × 170			3
4	NSC-4.75 jacket, [A-B]	Roughening surface by mechanical wire brushing	A-W	100 × 100	150 × 150	25	3
5			B-W	100 × 100	170 × 170	35	3
6		Roughening surface by mechanical scarification	A-C	100 × 100	150 × 150	25	3
7			B-C	100 × 100	170 × 170	35	3
8		Bonding by using shear studs	A-S	100 × 100	150 × 150	25	3
9			B-S	100 × 100	170 × 170	35	3
10	UHPFRSCC jacket, [X-Y]	Roughening surface by mechanical wire brushing	X-W	100 × 100	150 × 150	25	3
11			Y-W	100 × 100	170 × 170	35	3
12		Roughening surface by mechanical scarification	X-C	100 × 100	150 × 150	25	3
13			Y-C	100 × 100	170 × 170	35	3
14		Bonding by using shear studs	X-S	100 × 100	150 × 150	25	3
15			Y-S	100 × 100	170 × 170	35	3

(3) Preparation of A-B-S and X-Y-S Groups. Mechanical drilling with a 6 mm diameter drilling bit is conducted to perforate a hole with a diameter of 6 mm and a depth of 25 mm in accordance with the ASTM A307 standards. The drilled holes are filled with the Sikadur-31 CF bonding material (SIKA Company) to ensure a good bond between

Table 2: NSC mixing proportions.

Material	kg/m^3
Coarse aggregate	1317
Fine aggregate (sand)	658
Cement	300
Water	165

Table 3: NSC-4.75 mixing proportions.

Material	kg/m^3
Coarse aggregate	1316.8
Fine aggregate (sand)	658.4
Cement	300
Water	165
Superplasticizer	9

Table 4: UHPFRSCC mixing proportions [31].

Material	kg/m^3
Cement CEM I 42.5 R	900
Water	216
Silica fume	90
Quartz sand	1125
Superplasticizer	27
Steel fibres	36

the shear connectors and old concrete. L-shaped shear connectors with a diameter of 4 mm and a total length of 40 mm are used. The 25 mm straight portion of the shear connector is inserted in the drilled hole. Figure 8 shows the preparation of the A-B-S and X-Y-S groups. 4Ø8 mm main steel-reinforcing bars with a length of 280 mm and a diameter of 8 mm are used at the four corners of the column cores. Figures 9 and 10 show the geometry and reinforcement detailing of the A-S and B-S groups, respectively. The geometry and steel detailing of the X-S and Y-S groups are discussed later. 3Ø2.5 mm transverse reinforcement ties are used and fixed to the longitudinal steel bars (not welded) with a vertical spacing of 90 mm.

2.4.2. Jacketing Using NSC-4.75. The mixing procedure comprises the following steps [34]: The NSC-4.75 concrete is placed in timber moulds. Three standard test cylinders with a height of 300 mm and a diameter of 150 mm are used in compliance with the ASTM C470 standards. They are cast from the same batch of NSC-4.75 mix and compacted mechanically using a hand tamping rod to prevent segregation and honeycombing. The sides of the moulds are stripped away after being left for 24 h. All the specimens, i.e., UC and MC reference columns and A-B and X-Y column cores, are submerged in a curing water basin for 28 days. Figure 11 shows the A-B jacketed column specimens after curing, at which point they are ready to be tested.

2.4.3. Jacketing Using UHPFRSCC. After the UHPFRSCC is cast in the timber moulds, the surfaces are smoothed by trowelling. Three standard test cylinders with a height of 300 mm and a diameter of 150 mm are used in compliance with the ASTM C470 standards. They are cast from the same batch of UHPFRSCC mix without manual compaction (as it is self-compacting concrete). The sides of the moulds are stripped away after being left for 24 h. The X-Y jacketed column specimens are submerged in a curing water basin for 28 days. Three other standard test cylinders are cast with UHPFRSCC and submerged in a curing water basin for 28 days. Figure 12 shows the X-Y jacketed column specimens after curing, at which point they are ready to be tested.

2.5. Testing of Column Specimens. The UC and MC reference columns and the A-B and X-Y jacketed column specimens are tested using a high-capacity compression testing machine (with code number C109N and supplied by Matest Company for material testing). The machine configuration is changed to an elastic system to enable the testing of compressive strength versus the axial displacement in compliance with the ASTM C470 standards, as discussed in the following section.

2.5.1. Ultimate Load-Carrying Capacity of Column Specimens. After ending the curing period, the UC and MC reference columns and A-B and X-Y jacketed column specimens are kept in a dry place for 10–15 min to attain the surface dry condition. Loose sand grains or incrustations are removed from the contact faces with testing machine platens.

The column specimens are then located carefully in the testing machine to ensure the vertical concentricity (uniaxial) of the applied compressive load. Then, the test is performed by the hydraulic machine with 3000 kN compression testing capacity.

All column specimens are tested under a monotonically small loading rate of approximately 6 kN/s and a starting load of approximately 20 kN. The load is applied vertically at the top and bottom of the column specimens until failure and compression readings are recorded.

2.5.2. Axial Displacement of Column Specimens. The axial displacement of the UC and MC reference columns and A-B and X-Y jacketed column specimens is measured using the same compression testing machine. Three strain dial gauges with an accuracy of approximately 0.00254 mm are fixed at the midheight of the column (three faces) prior to testing. At each increment of 6 kN axial compression load, the readings of axial displacement are recorded using the machine data acquisition system.

3. Results and Discussion

3.1. Compressive Strength of Reference Specimens. The compressive strength of the NSC is obtained by testing three standard test cylinders (300 mm in height and 150 mm in diameter) at 28 days. Table 6 shows the average compressive strength of the three tested standard cylinders; the value is

Table 5: Steel reinforcement testing results.

Bar type	Diameter (mm)	Actual diameter (mm)	Yield stress (MPa)	Ultimate tensile strength (MPa)	% of elongation
Transverse steel reinforcement	2.5	2.5	240	276.8	31
Main rebar	8	8	360	414	20

(a) (b)

Figure 4: Preparation of the A-B-W and X-Y-W groups.

(a) (b)

Figure 5: Preparation of the A-B-C and X-Y-C groups.

almost equal to the targeted NSC cylinder compressive strength of 25 MPa.

The compressive strength of the UHPFRSCC is obtained by testing three standard test cylinders (300 mm in height and 150 mm in diameter) at 28 days. Table 6 shows the average compressive strength of the three tested standard cylinders. The value is close to the targeted UHPFRSCC cubic compressive strength of 120 MPa.

Figure 13 presents the obtained load-displacement diagrams of the UC, MC1, and MC2 column specimens. The UC, MC1, and MC2 reference columns reach their ultimate load-carrying capacities at an axial displacement of approximately 0.66 mm; they have almost equal axial displacements at rupture points of 0.972, 0.99, and 1.02 mm, respectively, possibly because they have similar steel reinforcement ratios and the same NSC mix.

3.2. A-B Jacketed Column Specimens (NSC-4.75 Jacket). The two jacket thicknesses of 25 and 35 mm result in a noticeable increase in the ultimate load-carrying capacity. The overall composite cross sections of the A-B jacketed column specimens are made of two different concrete mixes: the column cores are made of the NSC mix, whereas the outer jackets are made of the NSC-4.75 mix. Table 7 shows the effect of jacket thickness on the ultimate load-carrying capacity of the A-B group. The column cores are cast using the NSC mix with an unchanged cross section of 100 mm × 100 mm. Thus, the increase in cross-sectional area is obtained by applying the two jacket thicknesses.

The ratio of the jacket area of B-W/A-W is 1.51, whereas the corresponding ratio of ultimate load-carrying capacity is 1.38. This result shows a nearly direct proportional relation between jacket thickness and the ultimate load-carrying

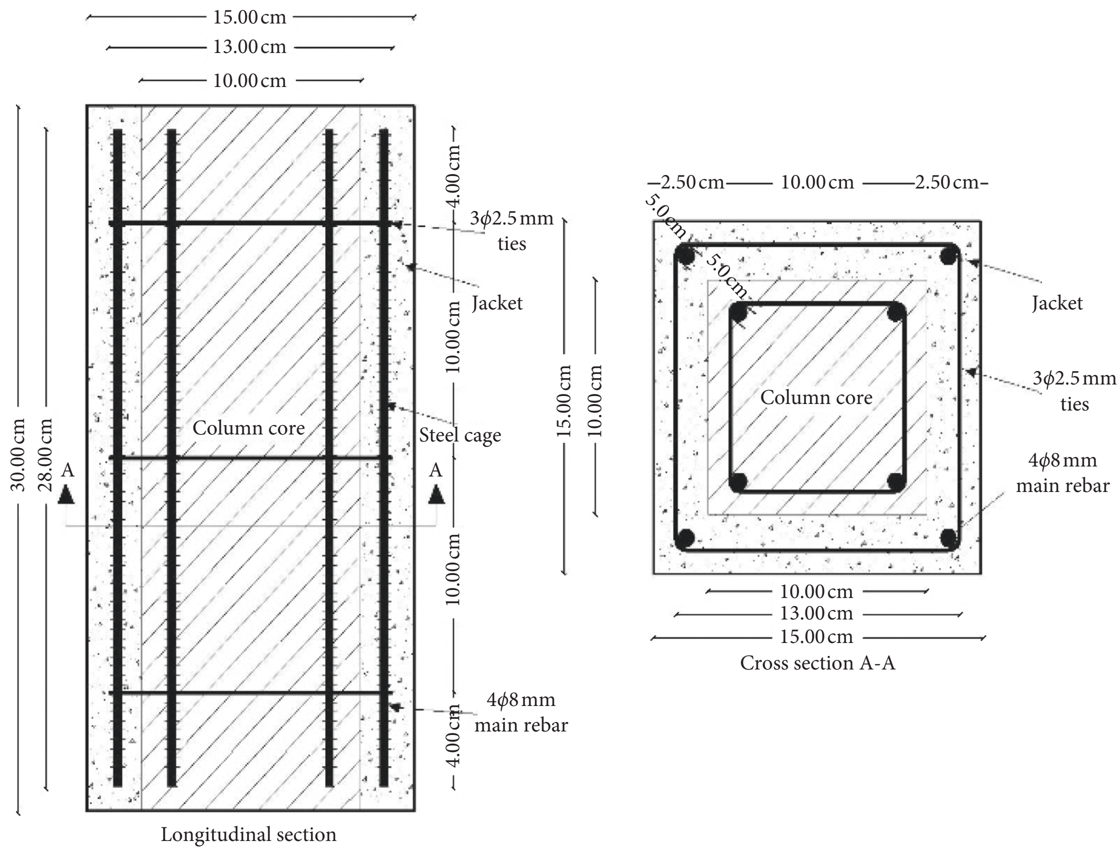

Figure 6: Geometry and reinforcement details of the A-W, X-W, A-C, and X-C groups.

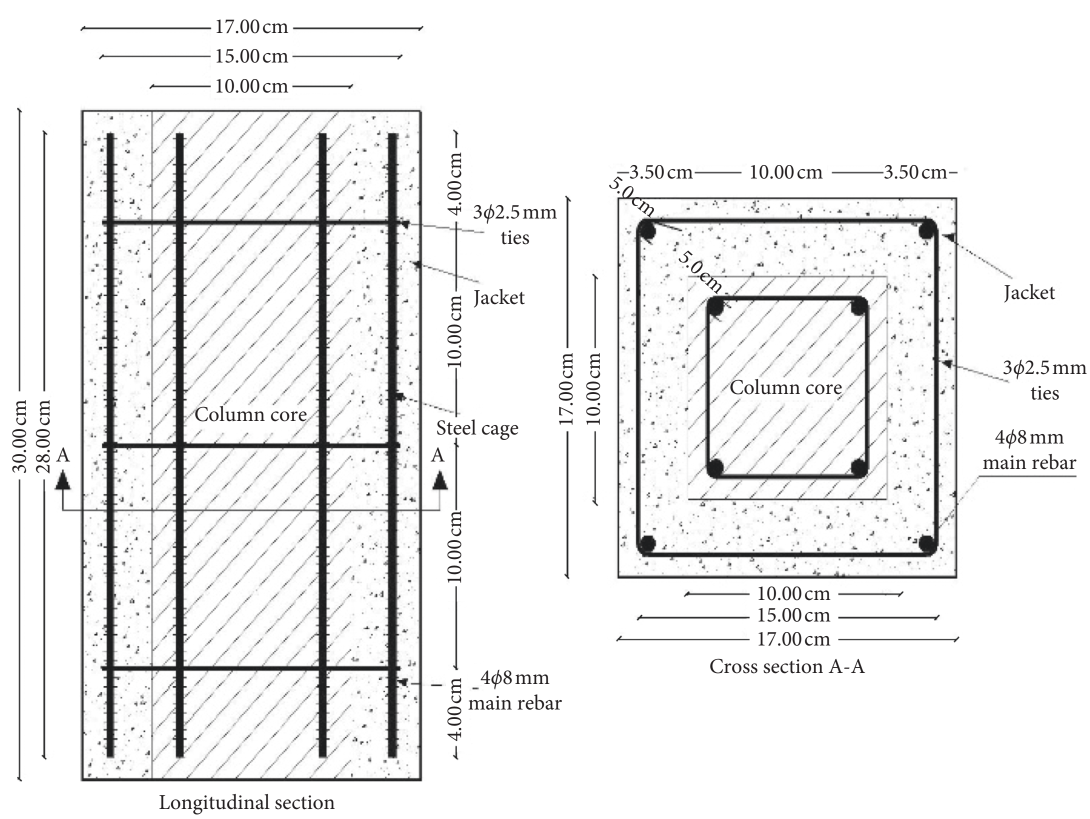

Figure 7: Geometry and reinforcement details of the B-W, Y-W, B-C, and Y-C groups.

Figure 8: Preparation of the A-B-S and X-Y-S groups.

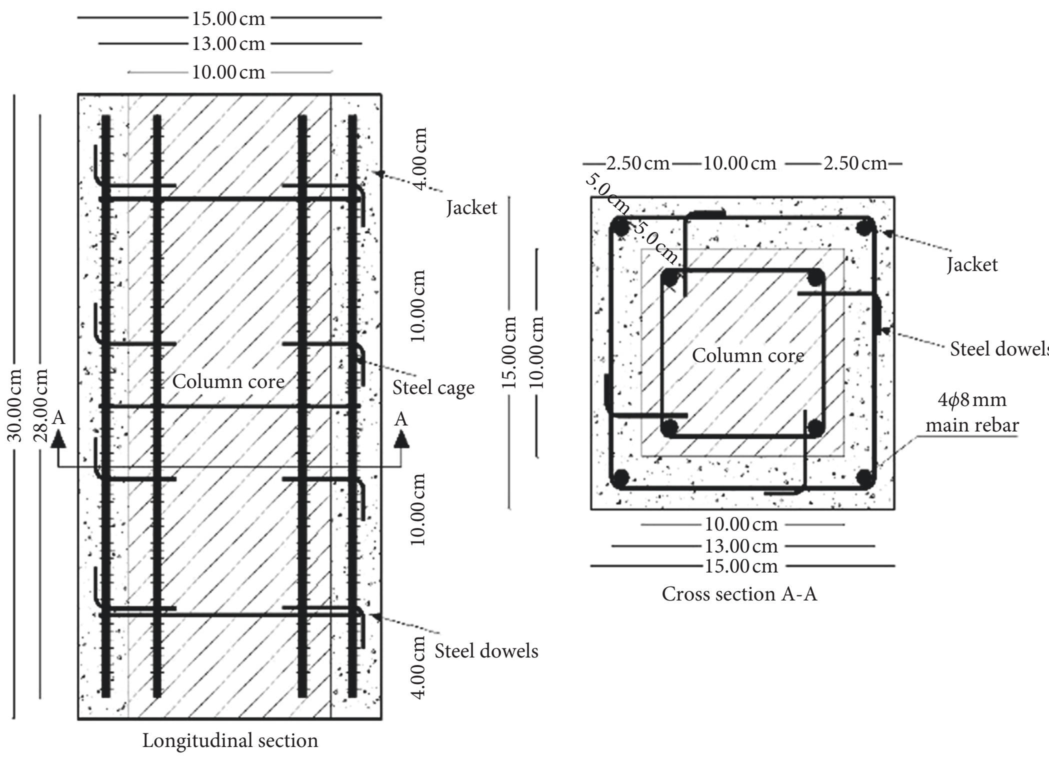

Figure 9: Geometry and reinforcement details of the A-S and X-S groups.

capacity of the A-B-W jacketed column specimens. The ratio of the jacket area of B-C/A-C is 1.51, whereas the corresponding ratio of ultimate load-carrying capacity is 1.26. This result shows a nearly direct proportional relation between jacket thickness and the ultimate load-carrying capacity of the A-B-C jacketed column specimens. The ratio of the jacket area of B-S/A-S is 1.51, whereas the corresponding ratio of ultimate load-carrying capacity is 1.32. This result shows an almost direct proportional relation between jacket thickness and the ultimate load-carrying capacity of the A-B-C jacketed column specimens.

Table 8 indicates that the A-W and B-W jacketed column specimens show an increase in ultimate load-carrying capacities of approximately 1.56 and 2.15 times those of the UC reference columns, respectively. Table 8 also shows that A-W and B-W have an increase in ultimate load-carrying capacities of 1.08 and 0.95 times those of the corresponding MC reference columns, respectively. The results obtained are less than those obtained by Meda et al. [7], who strengthened a concrete column of cross section (300 mm × 300 mm) with normal strength RC jacket that is 60 mm thick. Their results also showed that the ultimate capacities of the jacketed columns are more than 2.5 times those of the unjacketed columns. However, the results obtained are in good agreement with those obtained by Mourad and Shannag [16], who strengthened a concrete column of cross section (150 mm × 150 mm) with ferrocement jackets of 20 mm jacket thickness after preloading one of them to 100% of

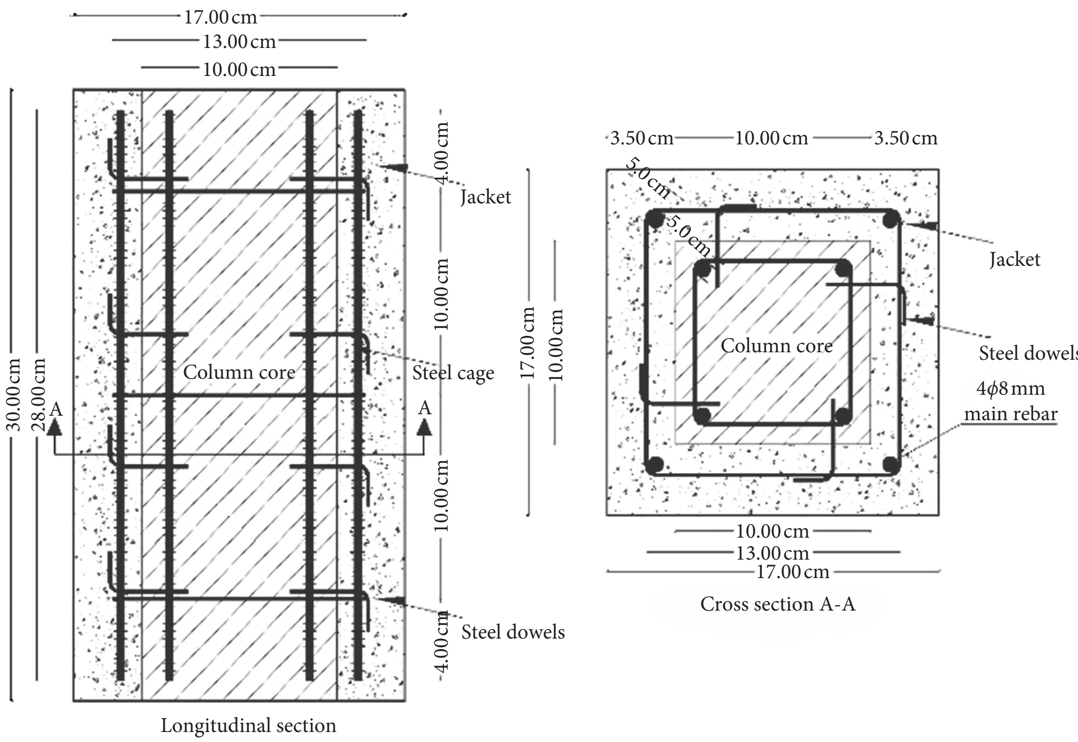

Figure 10: Geometry and reinforcement details of the B-S and Y-S groups.

Figure 11: The A-B jacketed column specimens ready for testing.

Table 6: Compression test results of NSC and UHPFRSCC.

Mix type	Notation	Cylinder compressive strength S (MPa)
NSC	S1	27.1
	S2	25.3
	S3	26.9
	Average	26.4
UHPFRSCC	S1	103.2
	S2	106.3
	S3	107.6
	Average	105.7

Figure 12: The X-Y jacketed column specimens ready for testing.

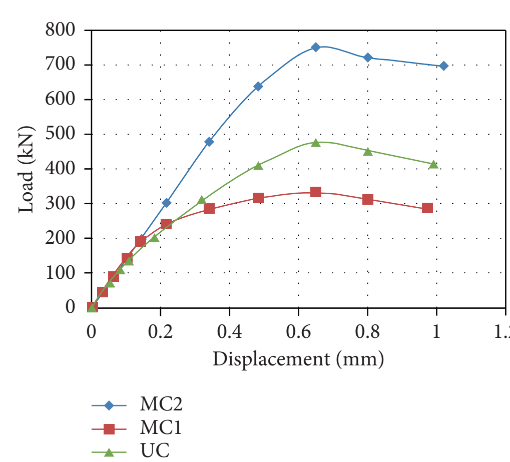

Figure 13: Load-displacement diagrams of UC, MC1, and MC2 reference columns.

their ultimate axial strength. Strengthening the failed column restored its original capacity with similar axial stiffness and minimal ductility.

Table 7: Ultimate load-carrying capacities for A-B jacketed column specimens.

Notation	P_u (kN)	Column sectional area	Column core area (cm^2)	Jacket area (cm^2)
A-W	517	(15 cm × 15 cm) 225 cm^2	100	125
B-W	713	(17 cm × 17 cm) 289 cm^2		189
B-W/A-W	1.38			1.51
A-C	642	(15 cm × 15 cm) 225 cm^2	100	125
B-C	812	(17 cm × 17 cm) 289 cm^2		189
B-C/A-C	1.26			1.51
A-S	653	(15 cm × 15 cm) 225 cm^2	100	125
B-S	859	(17 cm × 17 cm) 289 cm^2		189
B-S/A-S	1.32			1.51

Table 8: Increases in A-B ultimate load-carrying capacity with respect to UC and MC.

A	B		C		C/A	C/B
UC, P_u (kN)	MC	P_u (kN)	A-B	P_u (kN)		
331	MC1	478	A-W	517	1.56	1.08
	MC2	751	B-W	713	2.15	0.95
	MC1	478	A-C	642	1.94	1.34
	MC2	751	B-C	812	2.54	1.12
	MC1	478	A-S	653	1.97	1.37
	MC2	751	B-S	859	2.6	1.14

The results of the current research also indicate that the A-C and B-C jacketed column specimens show increases in ultimate load-carrying capacities of 1.94 and 2.54 times those of the UC reference columns, respectively. Table 8 also presents that A-C and B-C gain a significant increase in ultimate load-carrying capacities of 1.34 and 1.12 times those of the corresponding MC reference columns, respectively. The obtained results match those stated by Meda et al. [7] and Mourad and Shannag [16]; meanwhile, using scarification improves ultimate load-carrying capacity relative to mechanical wire brushing. The A-S and B-S jacketed column specimens show an increase in ultimate load-carrying capacities of 1.97 and 2.60 times those of the UC reference columns, respectively. Table 8 displays that A-S and B-S gain a significant increase in ultimate load-carrying capacities of 1.37 and 1.14 times those of the corresponding MC reference columns, respectively. These results are in good agreement with those obtained by Meda et al. [7] and Mourad and Shannag [16]; however, the current research indicates that using shear studs is the best method for improving ultimate load-carrying capacity.

The maximum measured axial displacements (axial displacements at rupture) of the UC and MC reference columns and A-B jacketed column specimens are compared in Table 9. The A-B-W jacketed column specimens gain a minimal increase in axial displacements at rupture relative to the UC and MC reference columns. This result is attributed to the use of NSC in jacketing, in addition to some enhancements to the concrete mix. Moreover, the A-B-C jacketed column specimens gain a minimal increase in axial displacements at rupture relative to the UC and MC reference columns. This result is attributed to the use of NSC in jacketing.

The column cores are repaired and strengthened using NSC-4.75 jacketing by applying the three jacketing methods. A-B-W, A-B-C, and A-B-S show improved ultimate load-carrying capacities, especially when compared with the UC and MC reference columns. Figures 14 and 15 show no significant differences in the results of the ultimate load-carrying capacities of A-B-W, A-B-C, and A-B-S. The rate of increase in ultimate load-carrying capacity is almost similar to the increase in jacket thickness. The ultimate load-carrying capacities of A-B-W, A-B-C, and A-B-S increase to approximately twice those of the corresponding UC reference columns and have no significant increase relative to the MC reference columns. Figures 14 and 15 also show that A-S and B-S have the maximum axial displacement values, which indicate the best ductility.

The results of using the three methods of surface roughening for good bonding between the specimens' cores and jackets reveal that using shear studs is the best among the three methods.

3.3. X-Y Jacketed Column Specimens (UHPFRSCC Jacket). The overall composite cross sections of the X-Y jacketed column specimens are made of two different concrete mixes: the column cores are made of the NSC mix, whereas the outer jackets are made of the UHPFRSCC mix. Table 10 presents the average ultimate load-carrying capacity of X-Y.

The same table shows the effect of jacket thicknesses on X-Y-W's ultimate load-carrying capacity. The ratio of the jacket area of X-W/Y-W is 1.51, whereas the corresponding ratio of ultimate load-carrying capacity is 1.27. This result shows an almost direct proportional relation between jacket thickness and the ultimate load-carrying capacity of the X-Y-W jacketed column specimens. Table 10 shows the effect of jacket thicknesses on X-Y-C's ultimate load-carrying capacity. The column cores are cast using the

Table 9: Increases in A-B maximum axial displacement with respect to UC and MC.

A UC, axial displacement at failure (mm)	MC	B Axial displacement at failure (mm)	A-B	C Axial displacement at failure (mm)	C/A	C/B
0.972	MC1	0.99	A-W	0.99	1.02	1
	MC2	1.02	B-W	1.11	1.05	1.14
	MC1	0.99	A-C	1.02	1.05	1.03
	MC2	1.02	B-C	1.14	1.07	1.17
	MC1	0.99	A-S	1.05	1.08	1.06
	MC2	1.02	B-S	1.2	1.23	1.18

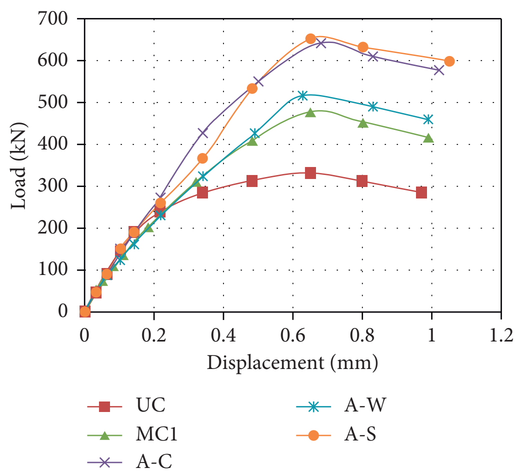

Figure 14: Average load-displacement diagram of A-(W-C-S) with respect to UC and MC1.

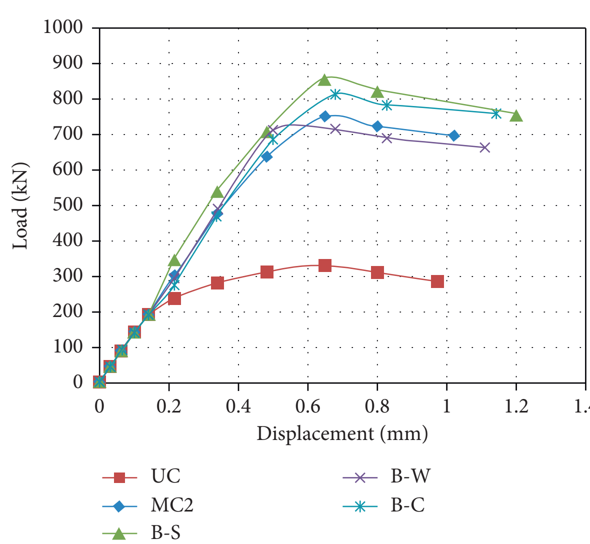

Figure 15: Average load-displacement diagram of B-(W-C-S) with respect to UC and MC2.

NSC mix with an unchanged cross section of 100 mm × 100 mm. Thus, the increase in cross-sectional area is obtained by applying several jacket thicknesses, almost similar to the obtained X-Y-W results. The ratio of the jacket area of X-C/Y-C is 1.51, whereas the corresponding ratio of ultimate load-carrying capacity is 1.34. This result confirms the almost direct proportional relation between jacket thickness and the ultimate load-carrying capacity of the X-Y-C jacketed column specimens; the same results are obtained with respect to the X-Y-W jacketed column specimens. The ratio of the jacket area of X-S/Y-S is 1.51, whereas the corresponding ratio of ultimate load-carrying capacity is 1.32. This result shows the almost direct proportional relation between jacket thickness and the ultimate load-carrying capacity of the X-Y-S jacketed column specimens; the same results are obtained with respect to the X-Y-W and X-Y-C jacketed column specimens.

Table 11 indicates that the X-W and Y-W jacketed column specimens show a substantial increase in ultimate load-carrying capacities of 2.67 and 3.70 times those of the UC reference columns, respectively. Table 11 also presents that X-W and Y-W gain a significant increase in ultimate load-carrying capacities of 1.85 and 1.63 times those of the corresponding MC reference columns, respectively. These results are less than those obtained by Meda et al. [7], who strengthened a concrete column of cross section (300 mm × 300 mm) with a high-performance fibre RC jacket with 30 mm thickness. This study found that the ultimate load capacities of jacketed columns are more than four times those of unjacketed columns. In the present study, adopting a UHPFRSCC steel-reinforced jacket enhances the lateral confinement of the column specimens and thus increases the ability to sustain additional compression loads. The X-C and Y-C jacketed column specimens show considerably large increases in ultimate load-carrying capacities of 2.89 and 3.87 times those of the UC reference columns, respectively. Table 11 also shows that X-C and Y-C almost double their ultimate load-carrying capacities relative to the corresponding MC reference columns. The obtained results are less than those obtained by Meda et al. [7], who strengthened a concrete column of cross section (300 mm × 300 mm) with a high-performance fibre RC jacket with 30 mm thickness. This study found that the ultimate capacities of the jacketed columns are more than four times those of unjacketed columns. These results are primarily attributed to the use of strengthening by the jacketing method instead of the repairing and strengthening jacketing method for predamaged RC columns. Meanwhile, using scarification improves ultimate load-carrying capacity relative to mechanical wire brushing. The X-S and Y-S

Table 10: Ultimate load-carrying capacities for X-Y jacketed column specimens.

Notation	P_u (kN)	Column sectional area	Column core area (cm^2)	Jacket area (cm^2)
X-W	883	(15 cm × 15 cm) 225 cm^2	100	125
Y-W	1224	(17 cm × 17 cm) 289 cm^2		189
Y-W/X-W	1.27			1.51
X-C	956	(15 cm × 15 cm) 225 cm^2	100	125
Y-C	1280	(17 cm × 17 cm) 289 cm^2		189
Y-C/X-C	1.34			1.51
X-S	1030	(15 cm × 15 cm) 225 cm^2	100	125
Y-S	1356	(17 cm × 17 cm) 289 cm^2		189
Y-S/X-S	1.32			1.51

Table 11: Increases in X-Y ultimate load-carrying capacities with respect to UC and MC.

A	B		C		C/A	C/B
UC, P_u (kN)	MC	P_u (kN)	X-Y	P_u (kN)		
331	MC1	478	X-W	883	2.67	1.85
	MC2	751	Y-W	1224	3.7	1.63
	MC1	478	X-C	956	2.89	2
	MC2	751	Y-C	1280	3.87	1.7
	MC1	478	X-S	1030	3.11	2.15
	MC2	751	Y-S	1356	4.1	1.81

jacketed column specimens show a huge increase in ultimate load-carrying capacities of 3.11 and 4.10 times those of the UC reference columns, respectively. Table 11 also reveals that X-S and Y-S gain significant increases in ultimate load-carrying capacities that are 2.15 and 1.81 times those of the corresponding MC reference columns, respectively. The obtained results are much better than those obtained by Meda et al. [7], who strengthened a concrete column of cross section (300 mm × 300 mm) with a high-performance fibre RC jacket with 30 mm thickness. This study found that the ultimate capacities of jacketed columns are more than four times those of unjacketed columns. These results are attributed to the use of shear studs for bonding the column cores and their jacketing; this approach significantly enhances load capacity. The current research validates that using shear studs is the best method for improving ultimate load-carrying capacities.

The average load-displacement diagram is plotted for the X-Y jacketed column specimens. The maximum measured axial displacements (axial displacements at rupture) of the UC and MC reference columns and X-W and Y-W jacketed column specimens are compared in Table 12. The X-Y-W jacketed column specimens gain almost a double increase in axial displacements at rupture with respect to the UC and MC reference columns. The axial displacements of the X-W and Y-W jacketed column specimens are 1.98 and 2.04 times those of the UC reference columns, respectively. Furthermore, the axial displacements of both the X-W and Y-W jacketed column specimens are 1.94 times those of the corresponding MC reference columns. As shown in Table 12, the X-Y-C and X-Y-S jacketed column specimens gain almost a double increase in axial displacements at rupture with respect to the UC and MC reference columns.

Column cores are repaired and strengthened using UHPFRSCC jacketing by applying three jacketing types. X-Y-W, X-Y-C, and X-Y-S show significantly improved ultimate load-carrying capacities, especially when compared with the UC and MC reference columns. Figures 16 and 17 also show no significant differences in the results of X-W, X-C, and X-S and in those of Y-W, Y-C, and Y-S in terms of ultimate load-carrying capacity. The rate of increase in ultimate load-carrying capacity is almost similar to the rate of increase in jacket thickness. The ultimate load-carrying capacities of X-Y-W, X-Y-C, and X-Y-S increase to about four and two times those of the corresponding UC and MC reference columns, respectively.

The results of using the three methods of surface roughness reveal that using shear studs is the best among the three methods.

Table 13 shows that the X-Y jacketing type significantly increases the ultimate load-carrying capacities and high ductility of the jacketed column cores because of the application of steel fibres and steel-reinforced UHPFRSCC jackets. The significant increase in the axial displacements of X-(W-C-S) and Y-(W-C-S) is attributed to the addition of 4% steel fibres in accordance with the weight of the UHPFRSCC mix; such a change results in improved material properties. The results of using the three methods of surface roughness also reveal that using shear studs is the best among the three methods.

4. Conclusion

The outcomes of the experimental study can be summarised as follows:

(i) Applying two jacket thicknesses of 25 and 35 mm with A-B and X-Y jacketing types considerably improves ultimate load-carrying capacity in almost a similar rate to the rate of increase in jacketing area.

Table 12: Increases in X-Y maximum axial displacements with respect to UC and MC.

A UC, axial displacement at failure (mm)	B MC	B Axial displacement at failure (mm)	C X-Y	C Axial displacement at failure (mm)	C/A	C/B
0.972	MC1	0.99	X-W	1.92	1.98	1.94
	MC2	1.02	Y-W	1.98	2.04	1.94
	MC1	0.99	X-C	1.92	1.98	1.94
	MC2	1.02	Y-C	2.01	2.07	1.97
	MC1	0.99	X-S	1.98	2.04	2
	MC2	1.02	Y-S	2.04	2.09	2

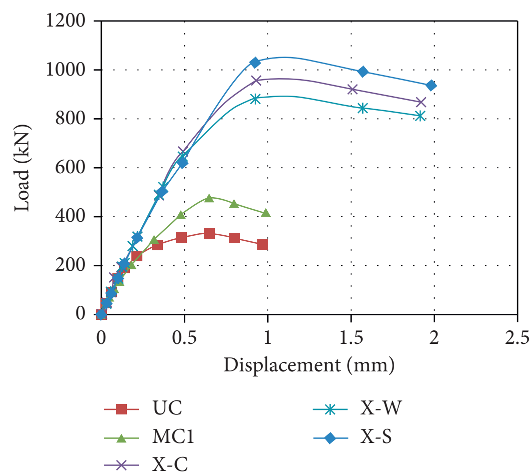

Figure 16: Average load-displacement diagram of X-(W-C-S) with respect to UC and MC1.

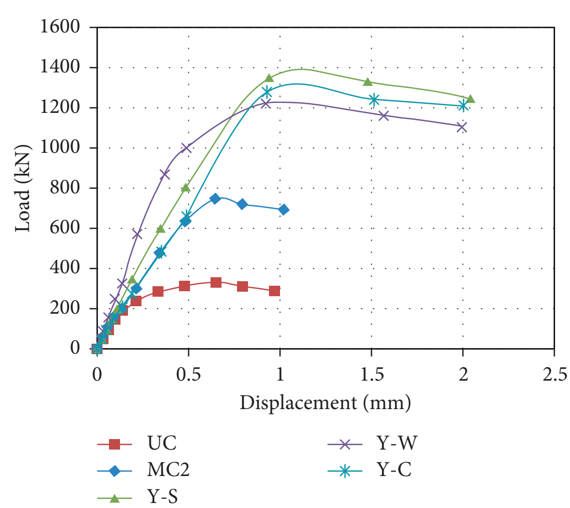

Figure 17: Average load-displacement diagram of Y-(W-C-S) with respect to UC and MC2.

(ii) Repairing and strengthening using UHPFRSCC and NSC-4.75 jackets significantly increases the ultimate load-carrying capacities and axial displacements of the specimens with respect to the UC and MC reference columns. The failure modes of the two jacketed column specimens are ductile and thus provide noticeable warning signs under loading before crushing and spalling.

(iii) Although repairing and strengthening RC columns using NSC-4.75 as a jacketing material is effective, UHPFRSCC is more effective due to the use of steel fibres. It also reduces the total strengthened column

Table 13: Summary of the results for all tested column specimens.

#	Description		Notation	P_u (kN)	Axial displacement (mm)
1	UC unjacketed reference column		UC	331	0.972
2	MC monolithically cast reference columns		MC1	478	0.99
3			MC2	751	1.02
4	NSC-4.75 jacket, [A-B]	Roughening surface by mechanical wire brushing	A-W	517	0.99
5			B-W	713	1.11
6		Roughening surface by mechanical scarification	A-C	642	1.02
7			B-C	812	1.14
8		Bonding by using shear studs	A-S	653	1.05
9			B-S	859	1.2
10	UHPFRSCC jacket, [X-Y]	Roughening surface by mechanical wire brushing	X-W	883	1.908
11			Y-W	1224	1.989
12		Roughening surface by mechanical scarification	X-C	956	1.92
13			Y-C	1280	2.001
14		Bonding by using shear studs	X-S	1030	1.98
15			Y-S	1356	2.04

sections. The UHPFRSCC can flow better than NSC-4.75 in narrow sections without segregation or honeycombing problems.

(iv) The relationships between the applied loads and axial displacements of the tested column specimens are almost typical: a linear behaviour up to one-third of the ultimate load-carrying capacity followed by a nonlinear behaviour until failure.

(v) The slopes of the first parts of the plotted load-displacement curves of the UC and MC reference columns are almost the same, ultimately becoming steep during repairing and strengthening with the two jacketing types. Steep slopes mean that the modulus of elasticity of strengthened columns increases.

(vi) Applying the three methods of surface roughening, i.e., roughening by mechanical wire brushing, mechanical scarification, and using shear studs, to bond column cores and their jackets reveals that using shear studs is the best among the three methods.

Data Availability

The experimental data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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