Basrah Journal for Engineering Sciences, Vol. 25, No. 2, (2025), 61-74

BJES Basrah Journal for Engineering Sciences

Original Article

Journal homepage: https://bjes.edu.iq/bjes
ISSN (Online): 23118385, ISSN (Print): 18146120

Bond Performance Evaluation for Members Cast with Reinforced Normal-Strength Concrete Strengthened by Slurry-Infiltrated Fiber Concrete Jacket

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Article Info

Article history:
Received: 11 July 2025
Revised: 25 August 2025
Accepted: 11 September 2025
Published: 31 December 2025

Keywords:
Bond,
Interface,
SIFCON,
Overlay,
Direct Shear Test,
Jacketing,
Dowel, Strengthening.

https://doi.org/10.33971/bjes.25.2.7

Abstract

In recent decades, the need for strengthening and repairing reinforced concrete structures has increasingly arisen. One common method is the use of concrete jackets. Slurry Infiltrated Fiber Concrete (SIFCON), a newly developed material, offers superior mechanical properties, making it a preferred choice for strengthening and repairing concrete structures. However, there is limited understanding of its bonding performance when used as an overlay on a Normal Strength Concrete (NSC) substrate. This study conducted a direct Shear Test (DST) to evaluate the bond performance using reinforced NSC cubes externally bonded with SIFCON jackets subjected to direct shear. Eighteen reinforced cubes were strengthened with various bonding systems to investigate how different factors affect the bond performance between the NSC substrate and SIFCON overlay. The parameters studied included surface preparation methods, binder types, jacket configurations, bonding conditions (fresh overlay on hardened substrate and hardened overlay on hardened substrate), dowel placement, and bonding mechanisms. The results show that using bonding agents significantly improved bond strength, with epoxy proving more effective than latex. Specimens prepared by chipping showed better bonding performance compared to those prepared through diamond cutting. Chipping increased bond strength by 8.91% to 13.84% over diamond cutting in the case of fresh SIFCON overlay on hardened substrate. Using dowels in the bonding systems also improved bond performance by 10.89% to 16.97%. Applying jackets to three sides instead of two increased the ultimate failure load by 31.76% when dowels were used in both the two-sided and three-sided strengthened samples, and by 35.45% in the absence of dowels in both types of strengthened specimens. The cast-in-situ specimens demonstrated superiority over those strengthened with precast jacket layers.

1. Introduction

In recent decades, many buildings have required strengthening and repairing specific structural members. The urgent need for strengthening can arise from various factors, such as flaws in structural design, construction errors, changes in the applied loads due to alterations in the structure's intended function, and the necessity to meet design requirements after updates to specifications and codes. Structural repair needs often result from exposure to harsh environmental conditions or loads that exceed design limits, which can lead to failures in certain structural members [1-4].

One common method for strengthening and repairing reinforced concrete beams is using concrete jackets. In this technique, the cross-section of the structural member is enlarged by adding a layer of concrete to its original cross-section. This method has several advantages and disadvantages. Among the benefits are significant strength enhancement, homogeneity with the substrate concrete layer, strong bonding, good debonding resistance, high resistance to temperatures, the capability to assess the structural member and monitor cracks after strengthening, high resilience to environmental conditions, and notable durability. It can also be applied to deteriorated concrete surfaces. The disadvantages can be summarized as the enlargement of the cross-sectional dimensions of the strengthened member, increased weight, implementation challenges, and requiring more time and effort compared to traditional methods [5-7].

Several commonly used types of concrete are employed in jacketing to strengthen structural members, especially those containing fiber, such as Fiber-Reinforced Concrete (FRC) and Ultra-High-Performance Concrete (UHPC). The inclusion of fiber significantly enhances the mechanical properties of concrete. The fiber content in these concrete types does not exceed 3% because they are produced by adding fiber while mixing the concrete ingredients. Due to issues associated with a higher fiber volume fraction, such as reduced workability and fiber balling in these mixes, the maximum fiber content that can be added to the mixture has become limited [8-11]. A new type of concrete called Slurry Infiltrated Fiber Concrete SIFCON has been developed in recent decades. Lankard was the first to produce this type of concrete in 1979 [12,13]. Due to its high fiber content, SIFCON outperforms FRC and UHPC in various mechanical properties, including flexural strength, shear strength, toughness, and impact load resistance. The fiber content in SIFCON ranges from 4% to 30%, depending on the fiber geometry. The capability to use this high fiber volume fraction in this type of concrete results from preplacing the mold with fiber during its production, after which a slurry is poured to infiltrate and fill the spaces between the fibers [14-16]. Many previous studies have examined the factors that affect the mechanical properties of SIFCON [17-19], but only a few researchers have utilized SIFCON to strengthen structural members in concrete structures [20,21].

A sufficient bond must be achieved at the interface between the original beam substrate and the new concrete jacket to ensure its effectiveness and that it will act as one. The contribution of the added concrete jacket in enhancing the reinforced concrete beam's carrying capacity depends significantly on the quality of the bonding system. So, it is significant to evaluate the bond strength between the substrate and the overlay layers [22] If the bond strength between the old concrete surface and the new jacket layer is greater than the concrete strength of the two layers, then when sufficient interface stresses are applied, failure will occur in the weaker concrete.

Based on the available literature, prior research has examined the factors influencing bond strength between old and new conventional concrete layers. Researchers have reported that the most critical factors affecting bond strength between the substrate and overlay layers include: the compressive strength of both layers, the roughness of the substrate's surface, the curing regime, the bonding agent type, the humidity of the substrate surface, and the content of pozzolanic materials in the overlay mixture [23-25].

Elbakry and Tarabia [26] studied the bond strength of RC columns strengthened through concrete jacketing. The research explored the impact of using dowels as shear connectors and stirrups in the jackets to enhance bond performance and the overall behavior of the columns. The study investigated the effects of different substrate preparation methods and a bonding agent. The concrete jacket was applied to two opposite sides of the column or all four sides to achieve complete confinement. The study concluded that the hand-chiseling surface preparation method yielded better results than grinding. Furthermore, while using dowels significantly improved bonding performance, using stirrups in the jacket was more effective in enhancing bond performance.

Bahraq et al. [5] investigated the structural behavior of shear-deficient beams strengthened with Ultra-High-Performance Concrete (UHPC) jacketing. The research conducted Slant Shear Test (SST) and tensile bond strength tests to evaluate the interfacial bond strength and compared the results with the recommended range in the ACI 546.3R-14 [27] to ensure the bonding method's suitability for repair purposes. The substrate surface of all specimens was prepared through sandblasting without the use of a bonding agent. In both tests, interfacial shear and partial substrate failure occurred. Comparing the slant shear and tensile bond strength test results with the permissible limits in the ACI 546.3R-14 [27] showed that they exceeded the minimum proposed limit. Therefore, the researchers concluded that sandblasting the RC beam surface without a bonding agent is sufficient to prevent jacket debonding. Indeed, the bond was excellent, and no separation occurred between the beam surface and the jacket in any of the tested specimens.

Julio et al. [28] examine the bond performance between the old concrete substrate and overlay concrete of varying ages, mixtures, and strengths. The surface of the substrate concrete was prepared through sandblasting. A slant shear test was performed to evaluate the bond strength. The study revealed that as the overlay to substrate resistance ratio increased, the bond strength improved, and the failure mode may shift from interfacial bond failure to monolithic. The research also conducted a numerical study and concluded that increasing the resistance of the overlay layer while keeping the substrate resistance constant leads to an increase in the normal stresses applied to the contact surface. In contrast, the shear stresses remain unchanged.

Yang et al. [29] investigated the bonding performance between the existing concrete substrate and a high-early-strength high-ductility concrete (HES-HDC) overlay. The study evaluated the effects of substrate roughness, silica fume content, curing age, and fiber content in the HES-HDC on bonding performance. The results indicated that the bond strength of all tested specimens at 2 hours exceeded 1.2 MPa. Furthermore, the bonding strength of all specimens at one day reached at least 60% of their strength at 28 days, demonstrating the material's effectiveness for rapid repair. The findings suggest that increased surface roughness positively influenced bonding resistance. The paper concluded that using 6% silica fume content in the HES-HDC is optimal for enhancing interfacial bond strength.

Previous research has yet to study the factors affecting the bond strength between an ordinary concrete substrate and an SIFCON layer. In the present study, several tests were conducted to understand the influence of factors affecting the bond strength between the normal concrete substrate surface and the SIFCON Jacket layer. Understanding the importance of these factors and their contribution to achieving connectivity plays a significant role in choosing the best connection system between the RC beam surface and the SIFCON Jacket layer.

2. Experimental program

This study examined the bond performance of normal-strength concrete reinforced cubes (NSC-RC cubes) strengthened with SIFCON jacketing under a direct shear test. The effects of various factors on bond strength were analyzed, including the binder type, surface preparation method, dowel placement, and the bond mechanism.

2.1. Materials

In this study, type I Portland cement, conforming to ASTM C150-22 [30], was used to produce both normal-strength concrete (NSC) and SIFCON. The natural fine aggregate was sourced from the Al-Zubair area in Basra city. Natural sand, complying with ASTM C33-18 [31], was used to produce NSC. There are no standard specifications for the SIFCON mix design and its component requirements. Previous research indicates that the size of sand grains greatly influences the properties of SIFCON. The sand grains must be small enough to allow complete infiltration of the slurry into the dense steel fiber network without clogging, honeycombing, segregation, or bleeding. Many prior studies show that fine aggregate with a maximum size of 1.18 mm is suitable for SIFCON production [12,19]. Therefore, this study used sand with a maximum size of 1.18 mm to produce the slurry. Natural crushed gravel of 4 to 19 mm nominal size, conforming to ASTM C33-18 [31], was used to produce NSC. Figure 1 shows that the silica fume from the CONMIX company, conforming to ASTM C1240-20 [32], is used in the SIFCON production. The MasterGlenum 200 high-range water reducer (HRWR) from BASF is used in NSC and SIFCON production. Figure 2 illustrates the steel fiber used in the current study, which is a hook-ended steel fiber measuring 30 mm in length and 0.5 mm in diameter, with an aspect ratio (length/diameter) of 60 and a tensile strength of 1100 MPa, for SIFCON production. In this study, three types of epoxies were used. The first type bonds the hardened normal concrete substrate to the SIFCON in its fresh state. The second type connects the ordinary hardened concrete to precast SIFCON plates. The third type anchors steel rebars and bolts within the hardened concrete substrate. Sikadur-32 LP from SIKA was used to bond the hardened concrete with the SIFCON in its fresh state. A two-component epoxy-based material called Sikadur-31 CF Slow from SIKA was used to bond the precast SIFCON layers to the hardened concrete. Sika AnchorFix-2 Tropical was employed to anchor steel rebars and bolts within the hardened concrete. A synthetic rubber emulsion called SikaLatex-IQ was also used to bond the old, hardened concrete substrate with the new SIFCON.

Fig. 1 Silica fume

Fig. 2 Steel fibers

2.2. Mix proportions, curing regime, and evaluation

The mix proportions of the NSC were 400, 720, 1080, 168, and 3 kg/m³ for cement, sand, gravel, water, and superplasticizer. The mix proportions of the slurry were 882, 946, 98, 294, and 19.6 kg/m³ for cement, silica fume, sand, water, and superplasticizer. The maximum available fiber content of 7% was used in this study. The compressive strength of the NSC and SIFCON was tested using cylinders with a 75 mm diameter and 150 mm height. Their tensile and flexural strengths were evaluated according to ASTM C496−17 [33] and ASTM C78-18 [34]. The mechanical properties of the fresh slurry were examined through mini-slump flow and V-funnel tests. The NSC and SIFCON specimens were demolded after 24 h, cured for 28 days, and then tested. The NSC was cured in tap water at room temperature, while the SIFCON was cured in dry air at room temperature. The SIFCON was cured in dry air to simulate the curing regime of the strengthened RC cube, where, after applying SIFCON layers on the surface of the RC cube, the strengthened composite cannot be submerged in water to complete the chemical reactions of the binder. The compression, flexural, and tensile strengths of the NSC were 34, 3.9, and 2.3 MPa, respectively, while SIFCON had strengths of 69.6, 35.2, and 18.8 MPa. The test results for the slurry's mini-slump flow and V-funnel tests were a spread diameter of 360 mm and 10.1 seconds.

2.3. Experimental work

In this study, 18 NSC-RC cubes were strengthened by applying SIFCON jackets to their surfaces and tested under direct shear. Several bonding systems were used to attach the NSC substrate to examine the factors affecting bond strength. The study also compared the chipping (CH) and diamond cutting (DC) surface preparation methods. This research employed two different bonding agents (epoxy and latex). Additionally, the study investigated the effect of adding dowels as shear connectors to enhance the bonding strength between the old and new layers. The jacket layers were bonded to the surface in two different configurations. This study explored two different bond mechanism strategies. First, a fresh SIFCON overlay was applied onto the hardened NSC substrate. Hardened precast SIFCON layers were bonded to the RC cube surface in the second. Standard cube molds with a length of 150 mm were used to cast reinforced NSC cubes that represented the original member. The cubes were reinforced with 10 mm diameter bars, as shown in Fig. 3, to ensure they did not fail prematurely.

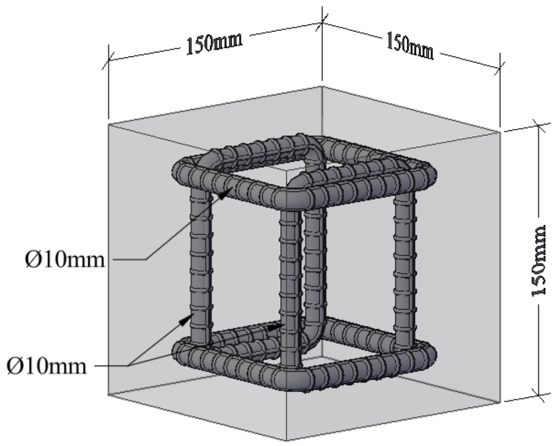

Fig. 3 Reinforcement details of the NSC-RC cube

The RC cubes were strengthened by applying 50 mm SIFCON jackets on either two opposite sides or three sides in a U-shape, simulating the practical and conventional configuration of concrete jacketing to strengthen RC beams. As shown in Fig. 4, the molds for casting these specimens were designed with a 25 mm difference between the cube level and the jackets. Consequently, the contact area between the cube surface and the surface of the SIFCON jacket for each face is a rectangle measuring 150 mm in width (the same as the original cube width) and 125 mm in height (cube height minus 25 mm). Thus, the contact area for each side is 18750 mm^2. The direct shear bond strength of each examined specimen can be determined by dividing the maximum load recorded by the compression machine by the total contact area between the substrate and the overlay layers, based on the number of sides used in the strengthening. Figure 5 illustrates a schematic of the strengthened cubes from two and three sides. As shown in Fig. 6, each SIFCON jacketing layer was internally reinforced with one stirrup of 10 mm bars at the center of the jacket layer. The yield and ultimate tensile strengths of the used bars were 519.4 MPa and 647.9 MPa, respectively.

Fig. 4 The molds for casting the jackets on the reinforced NSC Cube Samples

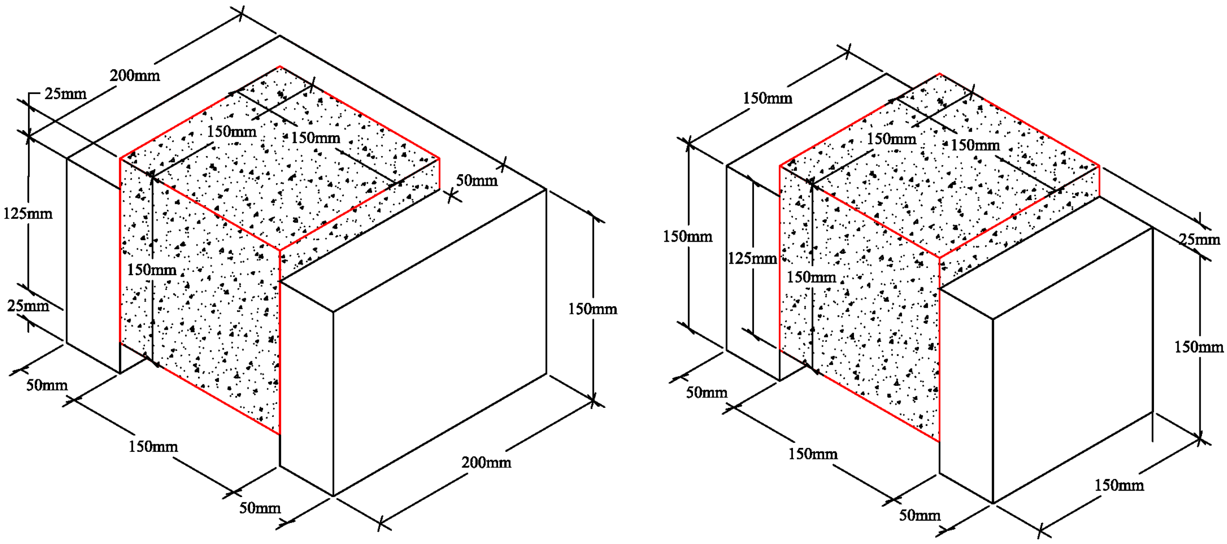

Fig. 5 Schematic of the strengthened cubes from two and three sides

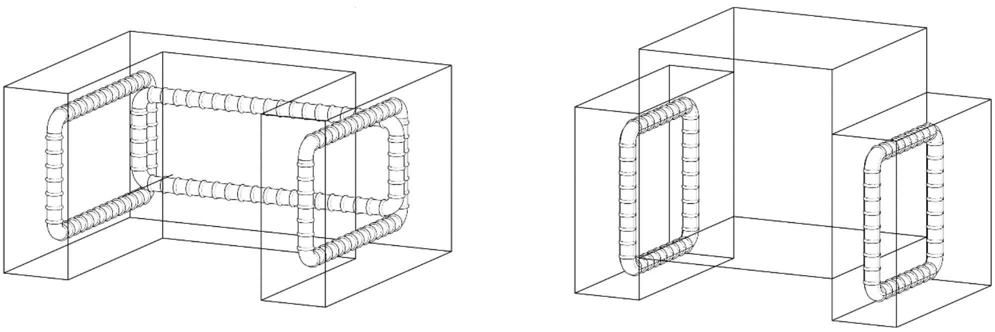

Fig. 6 Reinforcement details of the Jackets

In some of the current case studies, one dowel on each jacket side was anchored into the concrete cube by drilling a hole with an electric drill with a diameter of 14 mm and a length of 60 mm. Sika AnchorFix-2 Tropical was used to anchor the dowels in the cubes. Figure 7 displays the details of the embedded dowels . Figure 8 illustrates the direct shear test setup. A compression machine applied a static monotonic compression load to create direct shear stress at the interface between the substrate and the overlay SIFCON layers.

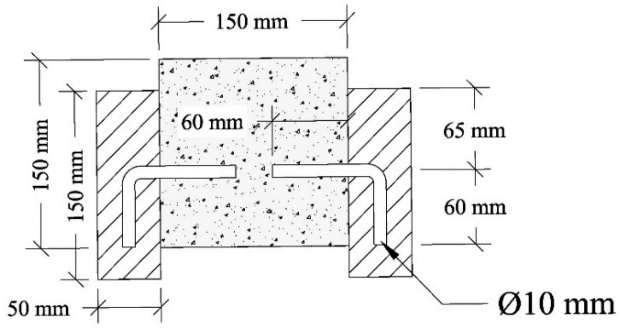

Fig. 7 Details of the embedded dowels

This study compared the diamond cutting (DC) and the chipping (CH) method. Figure 9 shows the details of the diamond cutting process. To investigate the effectiveness of using a bonding agent in enhancing the bond performance, the roughened surface was coated with either epoxy (E) or latex (L) and compared with the case of without bonding agent (NB) application. Figures 10 and 11 show the steps of preparing and applying the epoxy resin (Sikadur-32 LP) and the synthetic rubber emulsion latex (SikaLatex-IQ).

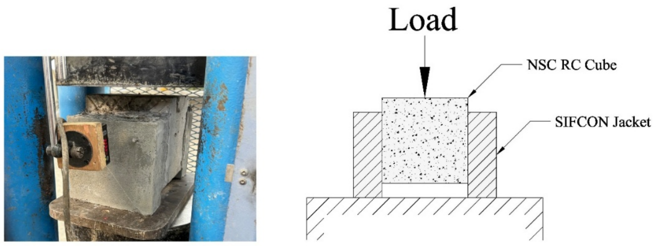

Fig. 8 Test setup of the direct shear test for the strengthened cubes

The study also included verifying the contribution of dowel placement to enhancing the bond strength between the NSC substrate and the SIFCON Jacket. The case without dowels was denoted as (ND), and the issue with added dowels was denoted as (D). The RC cubes were strengthened on two sides, denoted as 2S, or three sides, then characterized as 3S. Figure 12 shows the steps for preparing a reinforced NSC cube externally bonded with SIFCON jackets with a hardened substrate and fresh overlay layer. Figure 12-a illustrates the surface preparation process; Fig. 12-b depicts the hole drilling for dowel anchoring; Fig. 12-c demonstrates the dowel fixation process; and Fig. 12-d presents the process of coating the substrate surface with the bonding agent material. Figure 12-e shows the placement of the cube in the mold, and Fig. 12-f shows the casting of the SIFCON.

Fig. 9 Details of the diamond cutting process

Fig. 10 Steps of preparing and applying the epoxy resin (Sikadur-32 LP)

Fig. 11 Steps of preparing and applying the synthetic rubber emulsion latex (SikaLatex-IQ)

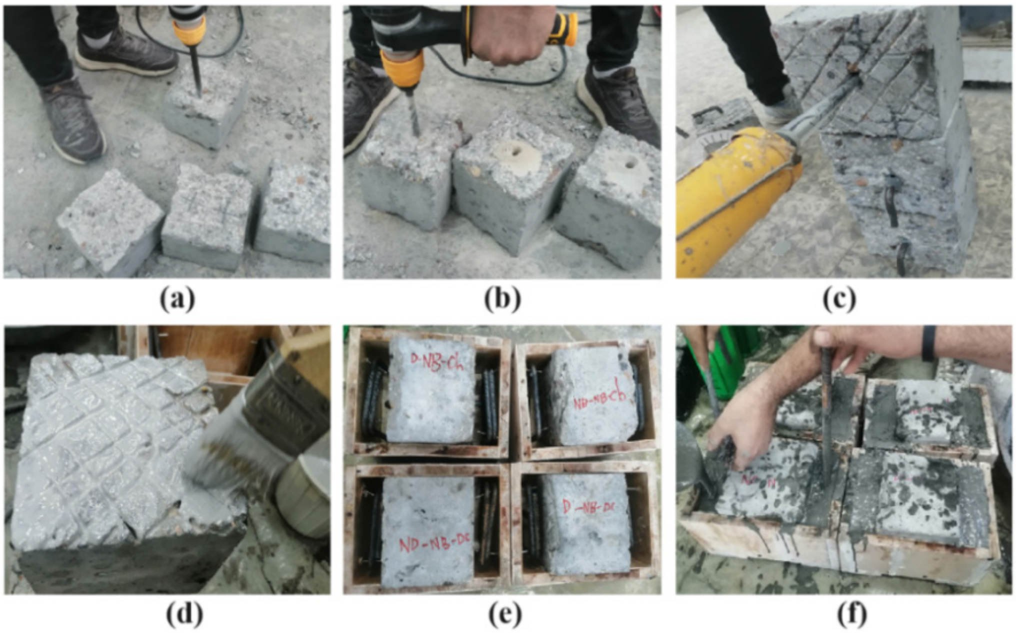

Fig. 12 Steps for preparing a reinforced NSC cube externally bonded with SIFCON jackets with a hardened substrate and fresh overlay layer

Two major practical bonding strategies exist for attaching concrete jackets to structural members. Both methods are commonly used in practice and research. The concrete jacket is poured either in situ (fresh overlay on hardened substrate) [35-37] or as a precast jacketing layer bonded to the substrate (hardened precast layer on hardened substrate) [38,39]. The precast layer is usually bonded to the substrate using a special epoxy paste or bolts to achieve a mechanical bond, or by combining bonding material with mechanical bonding. In the present study, four samples were prepared and tested to investigate the bond performance between the hardened substrate and the hardened jacket. The surfaces of two of the four samples were prepared by diamond cutting (DC), while the other two samples were prepared by chipping. For each surface preparation method, two samples were examined. In the first sample, the SIFCON jacket was bonded using a 3 mm-thick epoxy paste material (Sikadur-31 CF Slow) without bolts, denoted as (NB). In the second sample, a combination of a mechanical bond utilizing anchored bolts and a 3 mm-thick epoxy paste material (Sikadur-31 CF Slow) was employed and characterized as (B). To eliminate the need for drilling the SIFCON layer, a plastic tube with a 14 mm outer diameter was installed in the mold before pouring the SIFCON, and it was removed when the mold was demolded. As shown in Fig. 13, a bolt with a 10 mm diameter was embedded 60 mm into the cube and anchored using Sika AnchorFix-2 Tropical. The precast SIFCON layer was then placed, and pressure was applied with clamps to ensure proper bonding. Before testing, the SIFCON layer was fixed to the bolt with a 2 mm-thick washer and a nut, and any excess bolt length was trimmed. The yield and ultimate tensile strengths of the bolts used were 305 MPa and 515 MPa, respectively. Table 1 shows the details of the samples studied. Figure 14 illustrates the terminology used to describe one tested specimen.

Fig. 13 Steps for preparing a reinforced NSC cube externally bonded with SIFCON jackets with a hardened substrate and hardened overlay layer

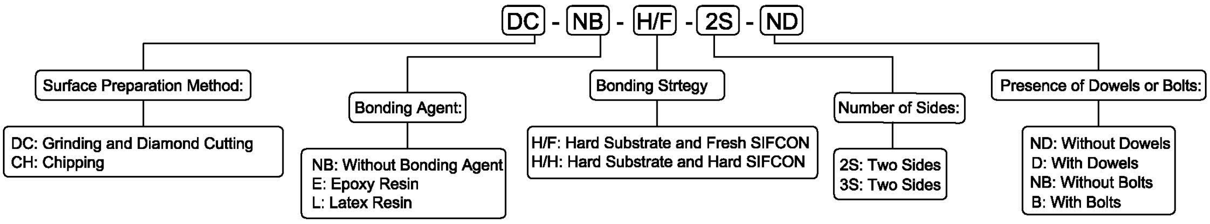

Fig. 14 The terminology used to describe one specimen of the second group

Table 1. Details of the samples

Specimen designation	Surface Preparation method	Bonding agent	Bond Strategy	Number of sides	Presence of dowels or bolts
DC-NB-H/F-2S-ND	Diamond cutting	Without a Binder	Hard substrate & fresh overlay	2	Without dowels
DC-E- H/F -2S-ND	Diamond cutting	Epoxy /Sikadur-32	Hard substrate & fresh overlay	2	Without dowels
DC-L- H/F -2S-ND	Diamond cutting	Latex	Hard substrate & fresh overlay	2	Without dowels
DC-NB- H/F -2S-D	Diamond cutting	Without a Binder	Hard substrate & fresh overlay	2	With dowels
DC-E- H/F -2S-D	Diamond cutting	Epoxy /Sikadur-32	Hard substrate & fresh overlay	2	With dowels
DC-L- H/F -2S-D	Diamond cutting	Latex	Hard substrate & fresh overlay	2	With dowels
CH-NB- H/F -2S-ND	Chipping	Without a Binder	Hard substrate & fresh overlay	2	Without dowels
CH -E- H/F -2S-ND	Chipping	Epoxy /Sikadur-32	Hard substrate & fresh overlay	2	Without dowels
CH -L- H/F -2S-ND	Chipping	Latex	Hard substrate & fresh overlay	2	Without dowels
CH -NB- H/F -2S-D	Chipping	Without a Binder	Hard substrate & fresh overlay	2	With dowels
CH -E- H/F -2S-D	Chipping	Epoxy /Sikadur-32	Hard substrate & fresh overlay	2	With dowels
CH -L- H/F -2S-D	Chipping	Latex	Hard substrate & fresh overlay	2	With dowels
CH-E-H/F -3S-ND	Chipping	Epoxy /Sikadur-32	Hard substrate & fresh overlay	3	Without dowels
CH-E-H/F -3S-D	Chipping	Epoxy /Sikadur-32	Hard substrate & fresh overlay	3	With dowels
DC-E-H/H-2S-NB	Diamond cutting	Epoxy /Sikadur-31	Hard substrate & hard overlay	2	Without bolts
DC-E-H/H-2S-B	Diamond cutting	Epoxy /Sikadur-31	Hard substrate & hard overlay	2	With bolts
CH-E- H/H-2S-NB	Chipping	Epoxy /Sikadur-31	Hard substrate & hard overlay	2	Without bolts
CH-E-H/H -2S-B	Chipping	Epoxy /Sikadur-31	Hard substrate & hard overlay	2	With bolts

3. Results and discussion

In this research, eighteen reinforced cubes were strengthened using various bonding systems and tested with the direct shear test (DST). The parameters investigated included the surface preparation method, binder type, bonding strategy, jacket configuration, and mechanical bonding. Table 2 presents the ultimate recorded failure load, the overall direct shear stress (ultimate failure load divided by the surface bond area), and the failure mode of the samples. Figure 15 illustrates the ultimate recorded failure load of all studied DST samples. Table 2 shows two failure modes: failure at the bond interface (BI) and a combination of weaker concrete and the bond interface (WC-BI). All samples with hardened SIFCON overlays on hardened NSC substrates failed at the bond interface. Most samples prepared through diamond cutting (DC) also failed at the bond interface. In the case of a fresh overlay layer on the hardened substrate, only two samples from the diamond cutting (DC) surface preparation method, which were fixed with dowels and binder applications (epoxy or latex), failed in WC-BI. In contrast, only two samples prepared using the chipping (CH) surface method exhibited bond interface failure. These two samples did not include dowels; one lacked a binder application, while the second utilized latex as a bonding agent. In the samples that failed at the bond interface (BI), shear failure occurred at the interface between the NSC substrate layer and the added SIFCON overlay layer, with no observable deterioration in the reinforced concrete cube and no cracks appearing in the substrate. However, cracks appeared at the contact surface between the substrate and the jacket layer. In some samples that were not secured with dowels, the SIFCON jacket detached from the cube. In contrast, in the samples that failed in the WC-BI failure mode, cracks were found in both the reinforced concrete cube and the interface bond surface. Figures 16 and 17 show samples strengthened with two opposing fresh SIFCON overlay layers cast on a hardened substrate which failed in BI and WC-BI, respectively. Figure 18 shows the tested specimens, which were strengthened from three sides. Figure 19 shows the tested samples strengthened with precast SIFCON layers.

Table 3 and Fig. 20 present a comparative study of samples strengthened with two opposing fresh SIFCON overlay layers cast on a hardened substrate, with the surface prepared through diamond cutting (DC) versus chipping (CH). The results indicate that the chipping (CH) surface preparation specimens exhibit better bonding performance compared to their corresponding samples prepared through diamond cutting (DC). Using chipping instead of diamond cutting improved the bonding strength by 8.91% to 13.84%. Table 4 and Fig. 21 show the results of the subset samples previously presented in Table 2 and Fig. 15. It was chosen to illustrate the contributions of dowels to the enhancement of bond strength in samples strengthened with two opposing fresh SIFCON overlay layers cast on a hardened substrate. The results show that using dowels in the bond systems significantly enhanced the bond performance of the DST samples. When comparing the samples without dowels in their connection system to the corresponding samples with dowels, the improvement in the ultimate load-carrying capacity ranges from 10.89% to 16.97%.

This study investigated the bond performance of two different jacketing configurations. The RC cubes were strengthened by applying 50 mm SIFCON jackets on either two opposite sides (2S) or three sides (3S) in a U-shape. Table 5 and Fig. 22 show the difference in bond performance when in situ strengthening jackets were cast on two or three sides, with (D) or without (ND) dowels as a shear connector, for specimens whose surfaces were prepared with chipping, and the epoxy was applied on the surface as a binder. The results show that adding jackets on three sides instead of two significantly improves the overall load-carrying capacity. Although the contact area increased by 50%, using a jacket on three sides instead of two sides improved the ultimate failure load by 31.76% when dowels were used in both the two-sided and three-sided strengthened samples, and by 35.45% in the absence of dowels in both types of strengthened specimens.

Table 2. The ultimate recorded failure load, the overall direct shear stress, and the failure mode of the DST samples

Specimen designation	Surface Bond Area (mm2)	Failure Load (kN)	Overall Direct Shear Bond Strength (MPa)	Failure Mode
DC-NB-H/F-2S-ND	37500	165	4.40	BI
DC-E- H/F -2S-ND	37500	202	5.39	BI
DC-L- H/F -2S-ND	37500	183	4.88	BI
DC-NB- H/F -2S-D	37500	193	5.15	BI
DC-E- H/F -2S-D	37500	224	5.97	WC-BI
DC-L- H/F -2S-D	37500	206	5.49	WC-BI
CH-NB- H/F -2S-ND	37500	184	4.91	BI
CH -E- H/F -2S-ND	37500	220	5.87	WC-BI
CH -L- H/F -2S-ND	37500	202	5.39	BI
CH -NB- H/F -2S-D	37500	215	5.73	WC-BI
CH -E- H/F -2S-D	37500	255	6.80	WC-BI
CH -L- H/F -2S-D	37500	227	6.05	WC-BI
CH-E-H/F -3S-ND	56250	298	5.30	WC-BI
CH-E-H/F -3S-D	56250	336	5.97	WC-BI
DC-E-H/H-2S-NB	37500	142	3.79	BI
DC-E-H/H-2S-B	37500	153	4.08	BI
CH-E- H/H-2S-NB	37500	148	3.95	BI
CH-E-H/H -2S-B	37500	162	4.32	BI

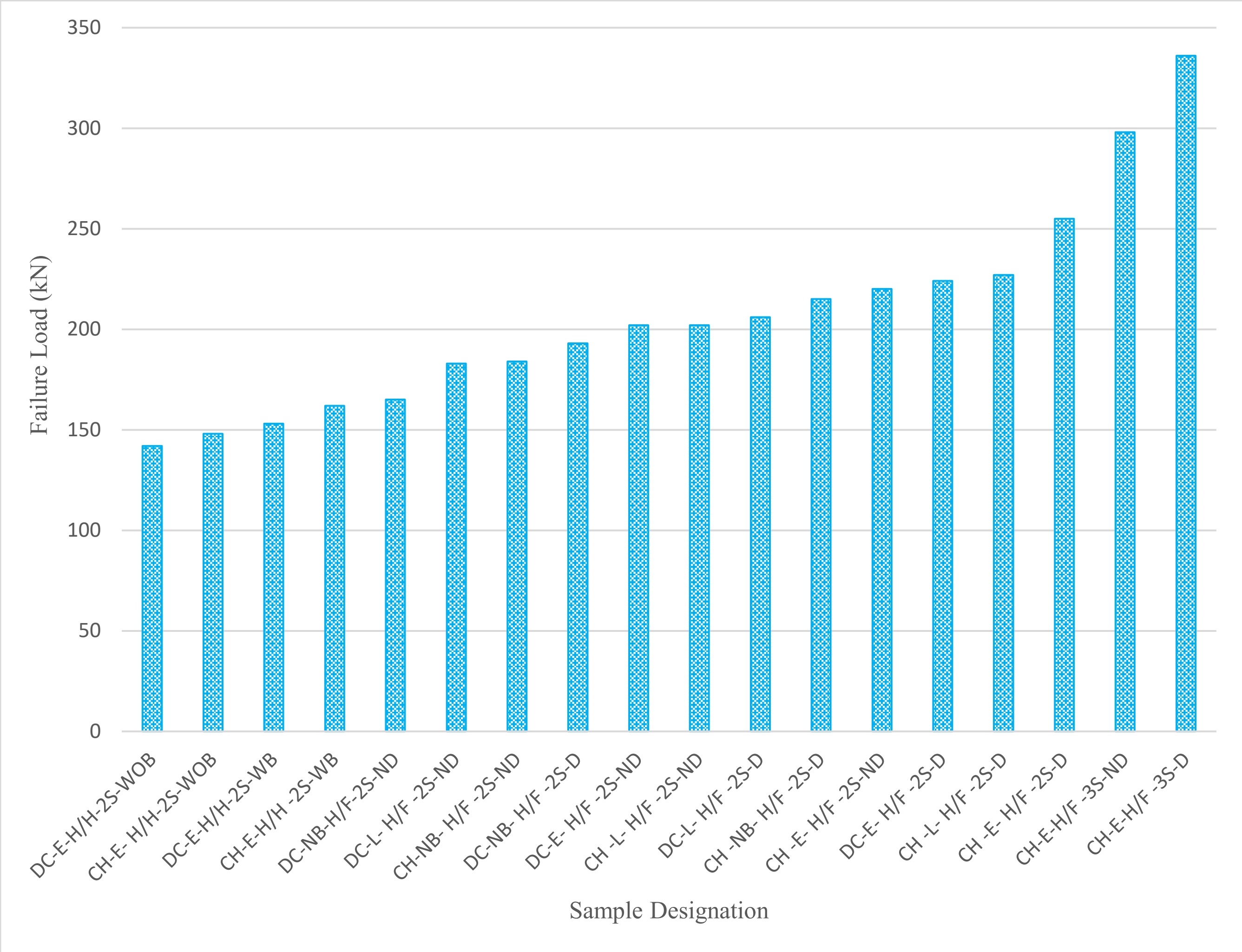

Fig. 15 The ultimate recorded failure load of all the studied direct shear test (DST) samples

Fig. 16 Cases of specimens that failed in the Bond Interface (BI) failure mode

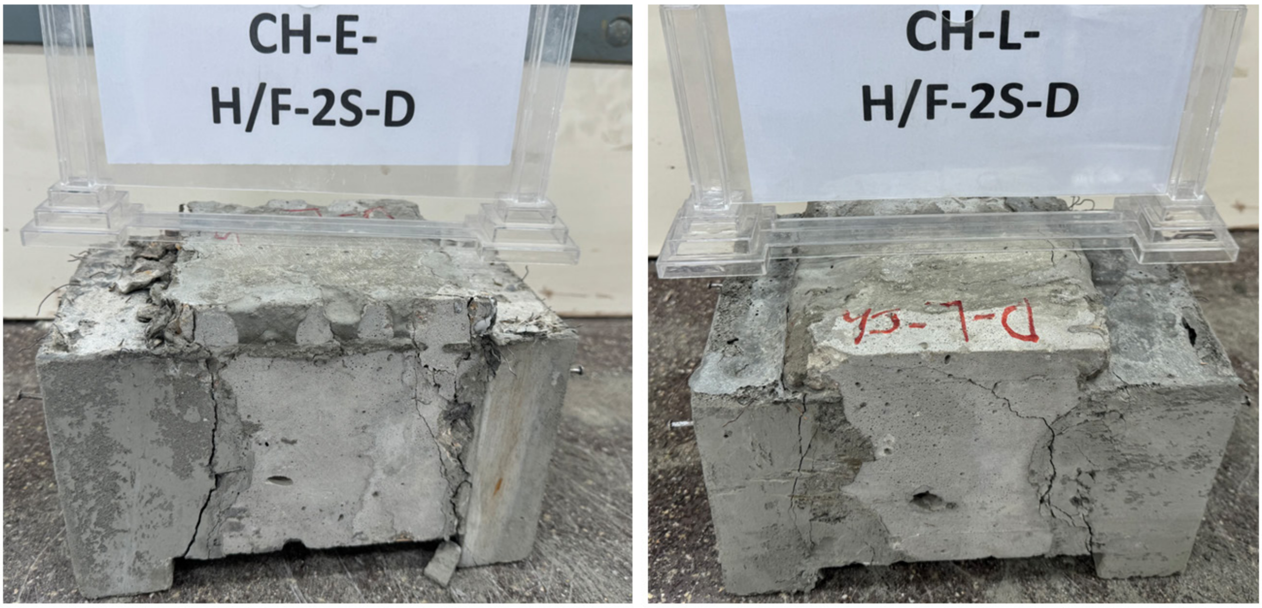

Fig. 17 Cases of specimens that failed in the Weaker Concrete and Bond Interface (WC-BI) failure mode

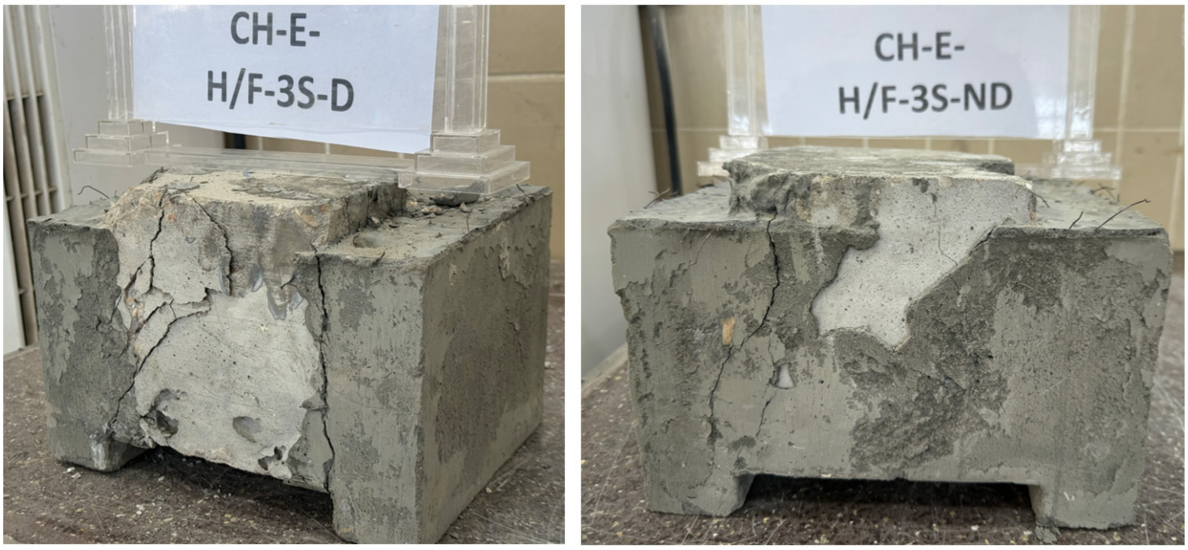

Fig. 18 The tested specimens were strengthened on three sides

Fig. 19 The tested samples were strengthened with precast SIFCON layers:
(a) DC-E-H/H-2S-NB, (b) DC-E-H/H-2S-B, (c) CH-E- H/H-2S-NB, (d) CH-E-H/H -2S-B

Table 3. The ultimate recorded failure load, the overall direct shear stress, and the failure mode of the DST samples

code	Binder	Presence of Dowels	Failure Load (kN)		Gain (%) CH over DC
			(DC)	(CH)	
NB-ND	No binder	Without dowels	165	184	11.52
L-ND	Latex	Without dowels	183	202	10.38
E-ND	Epoxy	Without dowels	202	220	8.91
NB-D	No binder	With dowels	193	215	11.40
L-D	Latex	With dowels	206	227	10.19
E-D	Epoxy	With dowels	224	255	13.84

Four samples of reinforced concrete cubes strengthened with precast SIFCON layers were created and subjected to direct shear tests to compare the bond performance between reinforced cube substrates strengthened with SIFCON jackets cast in situ and those with precast jackets. Additionally, the study conducted a comparative investigation of diamond cutting (DC) versus chipping (CH) surface preparation methods, as well as the presence (B) and absence (NB) of a mechanical bond through embedded bolts. The results demonstrate a clear superiority of the cast-in-situ specimens. All precast-strengthened specimens failed due to brittle failure at the interface bond plane, without any cracks appearing in the reinforced concrete cubes. Furthermore, the recorded failure load values for the precast specimens were lower than those of the corresponding cast-in-situ specimens. Employing a mechanical bond through embedded bolts slightly enhanced the bond performance of the samples, which was strengthened with precast SIFCON layers. Using bolts as shear connectors and securing the jacket layers increased the ultimate failure loads in the DST by 7.7% and 9.4% for the DC and CH surface preparation methods, respectively. The specimens with surfaces prepared by chipping showed slightly better bond performance than those prepared with the diamond cutting method. Using the chipping surface preparation method instead of the diamond cutting method resulted in a 5.9% increase in ultimate failure loads for the specimens strengthened with bolts (B) and a 4.2% increase for those without bolts (NB) in the DST.

Table 4. The ultimate recorded failure load, the overall direct shear stress, and the failure mode of the DST samples

Code	Surface Preparation Method	Bonding agent	Failure Load (kN)		Gain (%) D over ND
			Without dowels (ND)	With dowel s (D)	
DC-NB	DC	No binder	165	193	16.97
DC-L	DC	Latex	183	206	12.57
DC-E	DC	Epoxy	202	224	10.89
CH-NB	CH	No binder	184	215	16.85
CH-L	CH	Latex	202	227	12.38
CH-E	CH	Epoxy	220	255	15.91

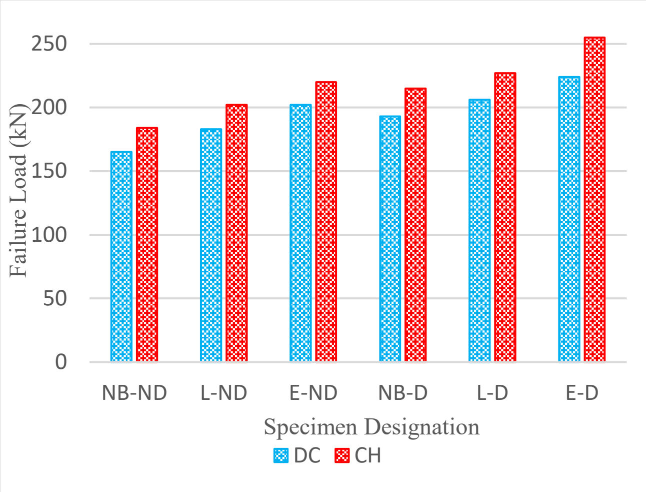

Fig. 20 Comparison of the failure load between samples prepared by the DC vs. CH method in the DST

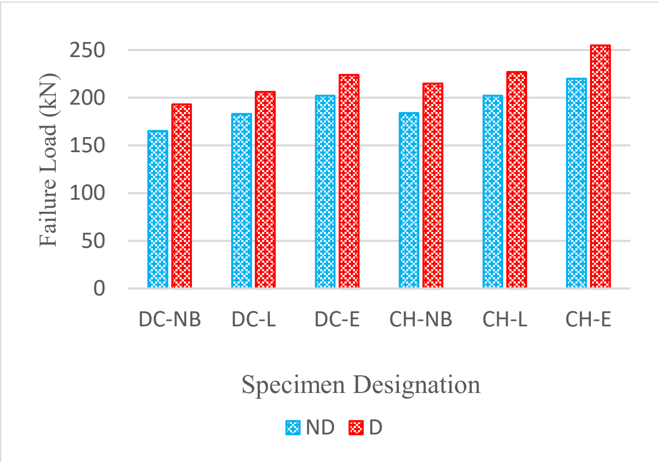

Fig. 21 Comparison of the failure load between samples with dowels versus without dowels in the DST

Table 5. The ultimate recorded failure load, the overall direct shear stress, and the failure mode of the DST samples

Specimen Designation	Failure Load (kN)		Gain (%)
	2S	3S	3S over 2S
ND (without dowels)	220	298	35.45
D (with dowels)	255	336	31.76

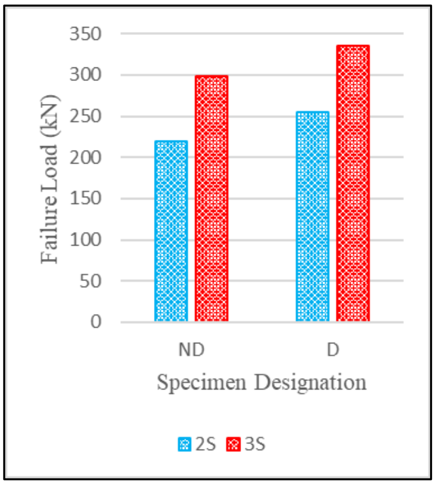

Fig. 22 Comparison of bond performance for in situ strengthening jackets cast on two or three sides

4. Conclusions

The conclusions of this study can be summarized as follows:

- The chipping (CH) surface preparation specimens show superior bonding performance compared to their corresponding samples prepared through diamond cutting (DC). Using chipping instead of diamond cutting increased the bonding strength by 8.91% to 13.84%.
- Using bonding agents significantly improved the bond strength. Epoxy proved to be more effective than latex.
- Using dowels in the bonding systems significantly improved the bond performance of the direct shear test (DST) samples. When comparing samples without dowels in their connection system to those with dowels, the improvement ranges from 10.89% to 16.97%.
- Applying jackets to three sides instead of two significantly enhanced the ultimate load-carrying capacity. Although the contact area increased by 50%, using a jacket on three sides instead of two sides improved the ultimate failure load by 31.76% when dowels were used in both the two-sided and three-sided strengthened samples, and by 35.45% in the absence of dowels in both types of strengthened specimens.
- In comparison to the samples strengthened with precast jacket layers, the cast-in-situ specimens demonstrate superiority. All precast-strengthened specimens failed due to brittle failure at the interface bond plane, with no cracks appearing in the reinforced concrete cubes. Furthermore, the recorded failure load values for the precast specimens were lower than those for the corresponding cast-in-situ specimens.
- Employing a mechanical bond through embedded bolts slightly enhanced the bond performance of the samples, which was strengthened with precast SIFCON layers. Using the bolts increased the ultimate failure loads in the DST by 7.7% and 9.4% for the DC and CH surface preparation methods, respectively.
- The specimens strengthened with precast SIFCON layers and prepared by chipping exhibited slightly better bond performance than those prepared using the diamond cutting method. Using the chipping surface preparation method instead of the diamond cutting method resulted in a 5.9% increase in ultimate failure loads for specimens strengthened with bolts and a 4.2% increase for those without bolts in the DST.

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