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Experimental Evaluation of Damaged Reinforced Concrete Slabs with Openings Strengthened Using Externally Bonded FRP Sheets

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ABSTRACT

Openings made in reinforced concrete (RC) slabs can disturb force transfer and reduce stiffness, particularly when the slab has already been damaged. This paper reports the second-stage test of six RC slab specimens that had been loaded previously under concentrated column loading. After the first-stage tests, the damaged slabs were repaired with epoxy and strengthened with one externally bonded FRP N300 sheet layer on the bottom face. The FRP sheet covered the slab soffit; for specimens with openings, the sheet was cut out at the opening region. The specimens included slabs without openings, slabs with square and circular openings, a slab with a larger square opening, a slab with an offset square opening, and one slab with a modified reinforcement arrangement inherited from the original specimens. The strengthened slabs were re-tested under incremental column loading. Vertical displacement, compressive strain, tensile strain, visible surface response, and FRP debonding were recorded. Since the tensile face was covered by FRP, crack propagation on the bottom surface was not directly observable during re-testing. The results show that FRP strengthening improved the response of several damaged slabs at higher load levels, but the improvement depended on opening geometry, opening location, inherited reinforcement layout, and bond condition. Final failure was governed mainly by FRP debonding. S6 showed the most favorable response among the tested specimens, although this result should be interpreted together with the absence of an opening and its modified reinforcement arrangement.

Keywords: Reinforced Concrete Slab; Slab Opening; Damaged Slab; FRP Sheet; Strengthening; Load–Deflection; Strain Response

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1. Introduction

Reinforced concrete (RC) slabs are essential structural members in building systems because they directly receive service loads and transfer them to beams, columns, walls, and foundations. During service life, however, RC slabs may experience cracking, excessive deflection, stiffness degradation, reinforcement corrosion, construction defects, overloading, or damage associated with changes in building function. In existing buildings, this problem becomes more critical when openings are created in slabs after construction to accommodate architectural or mechanical, electrical, and plumbing requirements. Although such openings are often necessary for building operation, they reduce the effective concrete area, interrupt the internal load-transfer path, and create stress concentration around the opening boundary. The influence is particularly unfavorable when the opening is located near column regions, supports, or zones of high bending moment and shear force. Therefore, RC slabs with openings should not be treated simply as ordinary slabs with local geometric discontinuities; rather, they represent a structural condition involving stiffness loss, crack redistribution, local stress concentration, and possible brittle failure mechanisms.

Condition assessment is an important prerequisite before selecting a repair or strengthening solution for existing RC structures. Kumar and Devi [1] emphasized that existing RCC buildings should be evaluated using visual inspection, non-destructive testing, and material assessment before intervention. This approach is highly relevant to FRP strengthening because externally bonded systems depend strongly on the condition of the concrete substrate. Existing cracks, weak concrete cover, surface contamination, moisture, and previous damage can reduce bond quality and modify the failure mechanism of the strengthened member. Therefore, the behavior of a strengthened damaged slab cannot be interpreted only from the tensile strength of the FRP material; it must also be considered together with the pre-damage condition of the concrete slab and the FRP–concrete interface.

Fiber-reinforced polymer (FRP) systems have been widely used for strengthening RC members because of their high tensile strength, low self-weight, corrosion resistance, and ease of installation. These advantages are particularly suitable for rehabilitation works where increasing dead load, reducing usable space, or interrupting building operation should be minimized. Recent studies also indicate the increasing relevance of polymer- and fiber-based materials in concrete structures. Mirzabagheri and Salem [2] investigated GFRP-reinforced concrete beams with straight and hooked-end lap splices, showing the importance of bond-related behavior in FRP-reinforced concrete systems. Kocak et al. [3] examined polymer coating for fiber-reinforced concrete beams and reported improvements in flexural strength and deflection behavior. Although these studies did not directly address damaged RC slabs with openings, they support the broader research direction that polymer-based and FRP-related materials can improve concrete member performance when deformation and bond mechanisms are properly controlled.

Despite these advantages, externally bonded FRP systems are often limited by bond failure. Buyukozturk et al. [4] identified debonding as a major challenge in RC and steel members strengthened with FRP composites, while Kang et al. [5] reviewed different debonding mechanisms of FRP laminates externally adhered to concrete. Elsayed et al. [6] specifically examined interfacial behavior and debonding failures in FRP-strengthened concrete slabs and showed that failure may be governed by interface behavior rather than FRP tensile rupture. Codina et al. [7] further evaluated fib Bulletin 90 provisions for intermediate crack debonding in flexural concrete elements strengthened with externally bonded FRP. These studies indicate that the evaluation of FRP-strengthened slabs should not be limited to ultimate load capacity; load–deflection response, strain development, crack propagation, and debonding behavior must also be examined.

A substantial number of studies have investigated FRP strengthening of slabs with openings. Tan and Zhao [8] studied one-way RC slabs with openings strengthened using CFRP systems and showed that CFRP can improve the structural capacity of slabs when openings disturb the load path. Smith and Kim [9] investigated one-way spanning RC slabs with cutouts strengthened using FRP composites and demonstrated that FRP can restore part of the lost capacity. Anil et al. [10] confirmed that the effectiveness of CFRP strengthening depends strongly on opening size, opening location, and CFRP arrangement. Afefy and Fawzy [11] compared different strengthening techniques for one-way slabs with cutouts and showed that both the strengthening layout and cutout position govern the degree of capacity recovery. Floruț et al. [12] and Shehab et al. [13] further demonstrated that FRP strengthening can improve the behavior of slabs with cut-out openings, but the level of improvement remains sensitive to the opening configuration and the strengthening scheme. These studies provide important experimental evidence, but most of them focused on one-way slabs, newly prepared specimens, or idealized cutouts rather than damaged slabs repaired before FRP strengthening.

More recent studies have expanded the investigation to different opening geometries, two-way action, and non-steel reinforcement systems. Aman et al. [14] investigated RC slabs with openings strengthened using CFRP and reported improved performance after strengthening. Golham and Al-Ahmed [15] studied GFRP-reinforced concrete slabs with openings strengthened by CFRP strips and found that CFRP improved flexural load capacity, stiffness, and service-load deflection. Hieu et al. [16] examined two-way RC slabs with openings strengthened by CFRP sheets and confirmed that CFRP can improve stiffness and load-carrying capacity. These studies collectively confirm the potential of CFRP for slab openings. However, they also reveal that strengthening effectiveness is not constant; it depends on the interaction among opening size, opening shape, opening location, reinforcement layout, FRP configuration, and bond condition.

The two studies most directly related to the present experimental configuration are the works on column-loaded slabs by Lam and co-workers. Lam and Huynh [17] experimentally investigated RC slabs subjected to column loads placed directly on the slab surface and established the relationships between load and vertical displacement, tensile strain, compressive strain, and crack development. This study provides the baseline response of RC slabs under concentrated column loading. Lam et al. [18] subsequently examined the effect of cutting openings on column-loaded slabs and showed that opening size, shape, and location strongly influence stiffness, load resistance, and failure behavior. In particular, large square openings produced a more adverse response than small or circular openings, while the position of the opening relative to the column region significantly affected slab performance. However, these studies did not investigate damaged slabs repaired and strengthened using externally bonded FRP sheets.

Another important research group concerns flat slabs and slab–column regions, where concentrated loading may interact with punching shear. Ghayeb et al. [19] reported that CFRP strengthening improved the punching shear performance of RC flat slabs. Abdul Sahib et al. [20] experimentally investigated the rehabilitation of RC flat slabs using CFRP sheets and showed that CFRP can enhance punching shear capacity. Zamani et al. [21] studied two-way RC flat slabs strengthened using CFRP sheets combined with steel dowels and grooving techniques, demonstrating that hybrid strengthening can improve punching shear resistance. Additional studies on openings and slab–column behavior, including Al Kallas et al. [22], Oukaili and Merie [23], El-Mawsly et al. [24], Abdulrahman and Aziz [25], and Abdulrahman et al. [26], also indicate that the column region is highly sensitive to opening position, local cracking, and strengthening configuration. However, most of these studies primarily focused on punching shear enhancement, while fewer studies examined the combined load–deflection and load–strain response of damaged slabs with different opening shapes, sizes, and locations after FRP strengthening.

To overcome the limitations of externally bonded FRP systems, alternative strengthening methods have also been proposed. Elsayed et al. [27] investigated mechanically fastened FRP-strengthened two-way slabs with and without cutouts, showing that mechanical fastening can reduce the dependence on adhesive bond. De Lorenzis and Teng [28] reviewed near-surface-mounted FRP reinforcement as an emerging strengthening technique, while Aljidda et al. [29] compared NSM-FRP bars and externally bonded CFRP strips for one-way slabs with cut-out openings. Other studies on anchorage, prestressed CFRP systems, long-term performance, and hybrid strengthening methods [30–33] further show that anchorage and bond reliability are essential to achieving stable strengthening performance. Nevertheless, such systems often require grooving, drilling, anchoring, or more invasive preparation. For many practical rehabilitation projects, externally bonded FRP sheets remain attractive because they are lightweight, rapid to install, and less disruptive. The key technical question is therefore not whether FRP can strengthen RC slabs, but under which opening geometry, damage condition, and reinforcement arrangement externally bonded FRP remains effective and reliable.

The reviewed literature shows a clear progression of knowledge. Earlier studies established that FRP can restore part of the capacity lost due to slab openings. Later studies confirmed that opening size, opening location, FRP arrangement, and bond behavior govern strengthening efficiency. Recent studies extended the problem to GFRP-reinforced slabs, two-way slabs, flat slabs, punching shear, mechanical fastening, NSM systems, and hybrid strengthening. However, an important limitation remains: most experimental programs were conducted on newly cast or intentionally prepared slabs, whereas actual strengthening works are commonly performed on slabs that have already cracked, deflected, and lost stiffness during service. In damaged slabs, existing cracks and local concrete deterioration may change the FRP–concrete bond, accelerate debonding, and alter both load–deflection and load–strain responses. Therefore, additional experimental evidence is needed for damaged column-loaded RC slabs with openings that are repaired and strengthened using externally bonded FRP sheets.

The present study addresses this gap by experimentally evaluating damaged RC slabs with different opening configurations strengthened using externally bonded FRP sheets. The test program used six previously loaded slab specimens with dimensions of 1.2 × 1.6 × 0.12 m. The configurations included square openings of 200 × 200 mm and 400 × 400 mm, a circular opening with a diameter of 200 mm, an opening located 200 mm from the column face, and one specimen without an opening but with a modified reinforcement arrangement. Compared with earlier work, the contribution of this paper is not the casting of a new specimen series, but the re-testing of damaged slabs after epoxy repair and FRP strengthening. The paper therefore focuses on the load–vertical displacement and load–strain response of repaired slabs and on the debonding behavior of the externally bonded FRP layer under repeated column-type loading.

2. Materials and Methods

2.1. Experimental Program

The experimental program was planned as a second-stage rehabilitation test. The six RC slab specimens used here were the same specimens previously tested under concentrated column loading in Lam and Huynh [17] and Lam et al. [18]. In the first stage, those studies established the baseline response of column-loaded slabs and the effect of cutting openings. After that stage, the damaged slabs were retained, repaired, strengthened with externally bonded FRP sheets, and re-tested in the present work. All specimens had the same nominal dimensions, 1.2 m × 1.6 m × 0.12 m, while the opening geometry and inherited reinforcement layout varied from one specimen to another.

The specimen set comprised one slab without an opening, slabs with square and circular openings, one slab with a larger square opening, one slab with a square opening located away from the column region, and one slab without an opening but with a modified reinforcement arrangement. All specimens were repaired and strengthened using the same FRP procedure before being re-tested under concentrated loading. The details of the specimens are summarized in **Table 1**.

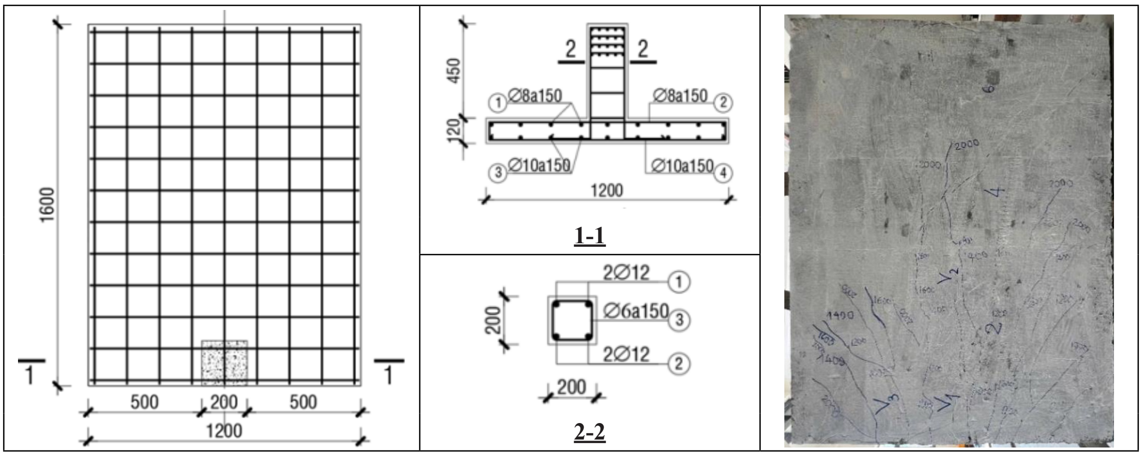
Table 1. Details of tested slab specimens.

Specimen	Opening Configuration	Compression Reinforcement	Tension Reinforcement	Strengthening Condition
S1	No opening	Ø8a150	Ø10a150	Epoxy repair + FRP sheet
S2	Square opening, 200 × 200 mm	Ø8a150	Ø10a150	Epoxy repair + FRP sheet
S3	Circular opening, D200 mm	Ø8a150	Ø10a150	Epoxy repair + FRP sheet
S4	Square opening, 400 × 400 mm	Ø8a150	Ø10a150	Epoxy repair + FRP sheet
S5	Square opening, 200 × 200 mm, located 200 mm from the column face	Ø8a150	Ø10a150	Epoxy repair + FRP sheet
S6	No opening, modified reinforcement direction	Ø10a150	Ø8a150	Epoxy repair + FRP sheet

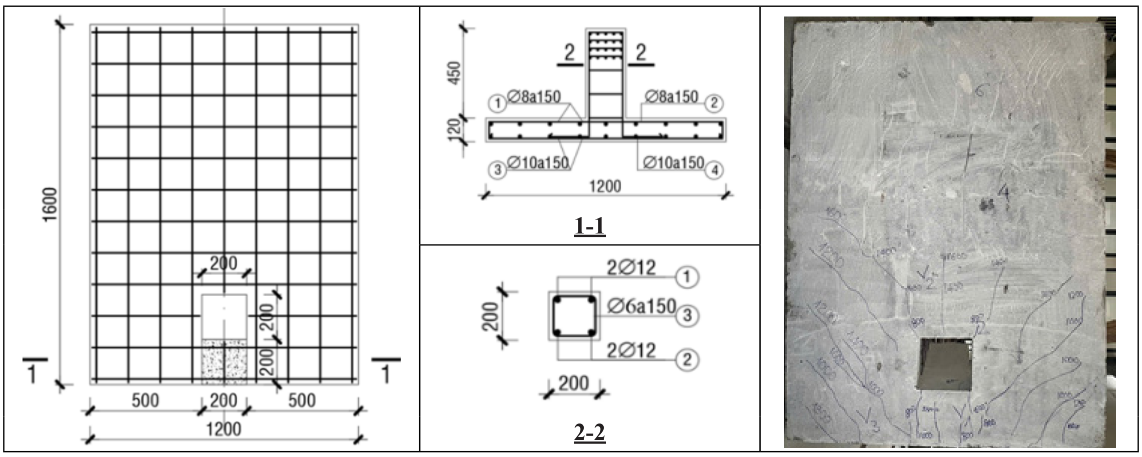
Source: Authors, based on the first-stage specimens reported in Lam and Huynh [17] and Lam et al. [18].

The variables considered in the comparison were opening shape, opening size, opening position relative to the column region, and the inherited reinforcement arrangement. These variables were used to examine how geometric discontinuity and the original reinforcement configuration affected the response of damaged slabs after FRP strengthening.

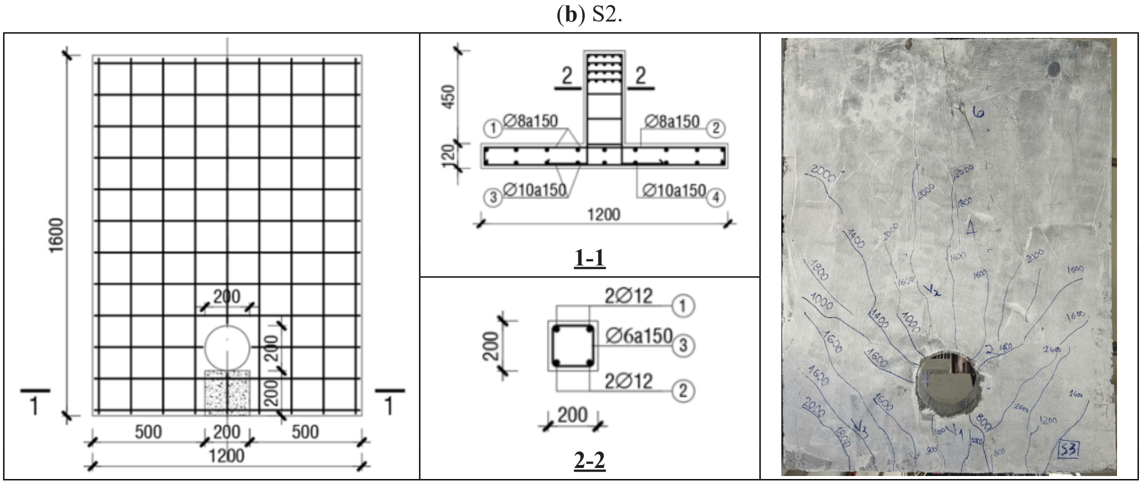
Figure 1 presents the specimen configurations and the corresponding pre-strengthening damage conditions of specimens S1–S6. The figure is included to make clear that the present tests were performed on previously damaged slabs rather than on newly cast undamaged specimens.



(**a**) S1.

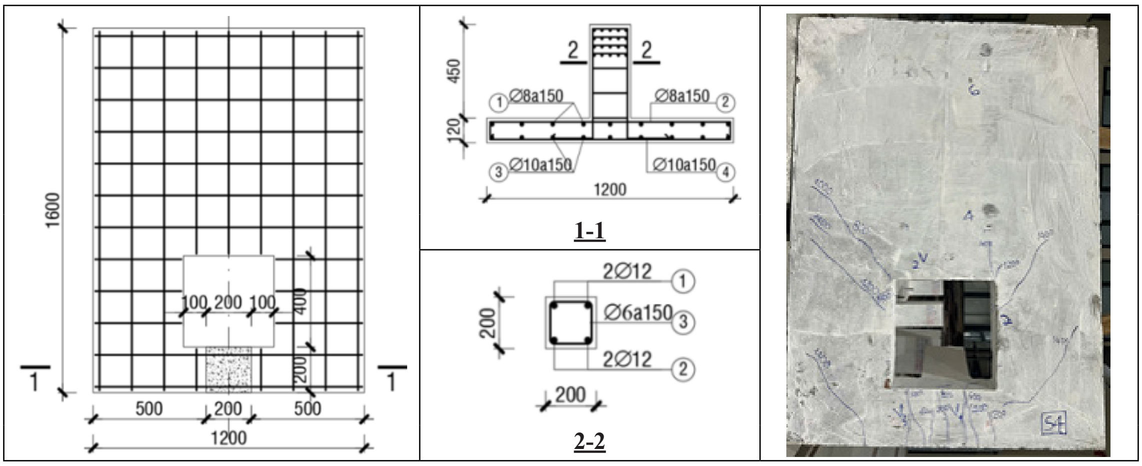


(**b**) S2.

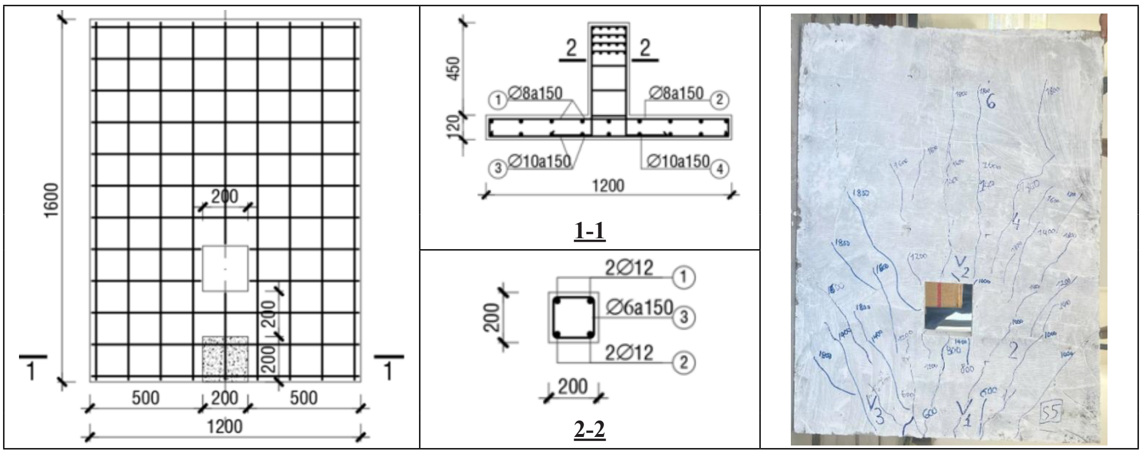


(**c**) S3.

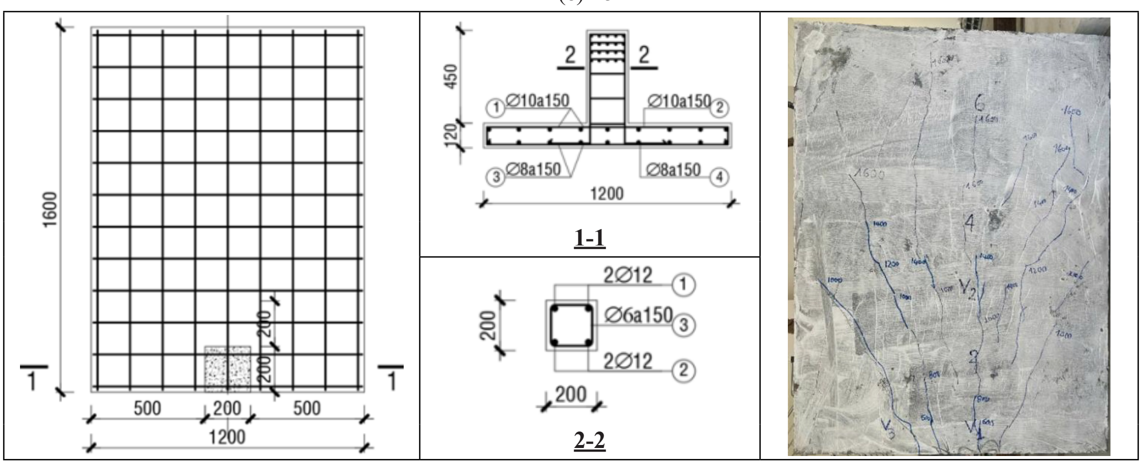
Figure 1. *Cont.*



(**d**) S4.



(**e**) S5.



(**f**) S6.

Figure 1. Specimen configurations and pre-strengthening damage condition: (**a**) S1; (**b**) S2; (**c**) S3; (**d**) S4; (**e**) S5; (**f**) S6.
Source: Authors, based on the first-stage experimental specimens reported in Lam and Huynh [17] and Lam et al. [18].

2.2. Materials

The slab specimens were made of normal-weight reinforced concrete with a design grade of B25. In the original casting program, 150 mm cube specimens were tested at 28 days, giving measured compressive strengths of 32.5, 33.6, 34.8, 30.6, 35.3, and 32.6 MPa, with an average value of approximately 33.23 MPa. The internal reinforcement layout is reported only to define the inherited configuration of the original RC slabs. For specimens S1–S5, Ø8 bars at 150 mm spacing were placed in the compression zone, and Ø10 bars at 150 mm spacing were placed in the tension zone. For specimen S6, this arrangement was reversed. No additional steel reinforcement was installed during the present FRP strengthening stage.

The strengthening material used in the present rehabilitation stage was an externally bonded FRP sheet, commercially identified as FRP N300. According to the manufacturer's technical data, the sheet had an areal weight of 300 g/m^2, a nominal thickness of 0.167 mm, a tensile strength of 3,400 N/mm^2, and a tensile elastic modulus of 245,000 N/mm^2. The supplied roll size was 50 m × 0.5 m. The main properties of the FRP sheet are presented in **Table 2**.

A two-component epoxy system was used for crack treatment and surface preparation before FRP installation. Epoxy E500 had a working time of 60 ± 10 min, a surface drying time of 14 ± 5 h, and a full curing time of 24–36 h. The mixing ratio of component A to component B was 1.0:0.5 by weight. Its reported bond strength, tensile strength, and compressive strength were 8 N/mm^2, 35 N/mm^2, and 65 N/mm^2, respectively. The main properties of the epoxy are summarized in **Table 3**.

Table 2. Main properties of the FRP sheet used for strengthening.

Property	Value
Product name	FRP N300
Origin	Korea
Areal weight	300 g/m^2
Nominal thickness	0.167 mm
Tensile strength	3,400 N/mm^2
Elastic modulus	24,5000 N/mm^2
Roll size	50 m × 0.5 m

Source: Manufacturer's technical data used in the experimental program.

Table 3. Main properties of epoxy E500 used for crack repair.

Property	Value
Chemical base	Two-component epoxy
Working time	60 ± 10 min
Surface drying time	14 ± 5 h
Full curing time	24 –36 h
Mixing ratio	A:B = 1.0:0.5 by weight
Bond strength	8 N/mm^2
Tensile strength	35 N/mm^2
Compressive strength	65 N/mm^2

Source: Manufacturer's technical data used in the experimental program.

2.3. Initial Damage Condition and Crack Repair

Before FRP strengthening, all slab specimens had already been damaged during the first-stage column-loading tests [17,18]. The pre-strengthening damage condition was documented by visual crack mapping and photographs. The main visible damage consisted of flexural cracking that had developed from the column-loaded region, together with additional local damage around the openings in the specimens with cut-outs.

Prior to FRP installation, the damaged concrete surface was prepared by grinding and cleaning to remove weak concrete, laitance, dust, and loose particles. Existing visible cracks were treated using Epoxy E500. The epoxy was brushed onto the cracked surface and allowed to penetrate into visible crack lines; excess epoxy appearing on the surface was taken as a practical indication that the cracks had been filled at the surface level.

After the epoxy had cured, the repaired surface was cleaned again, and local irregularities were ground to obtain a reasonably smooth bonding surface for the FRP sheet. This step was important because the effectiveness of an externally bonded FRP layer depends not only on the FRP material itself but also on the condition of the concrete substrate and the adhesive interface.

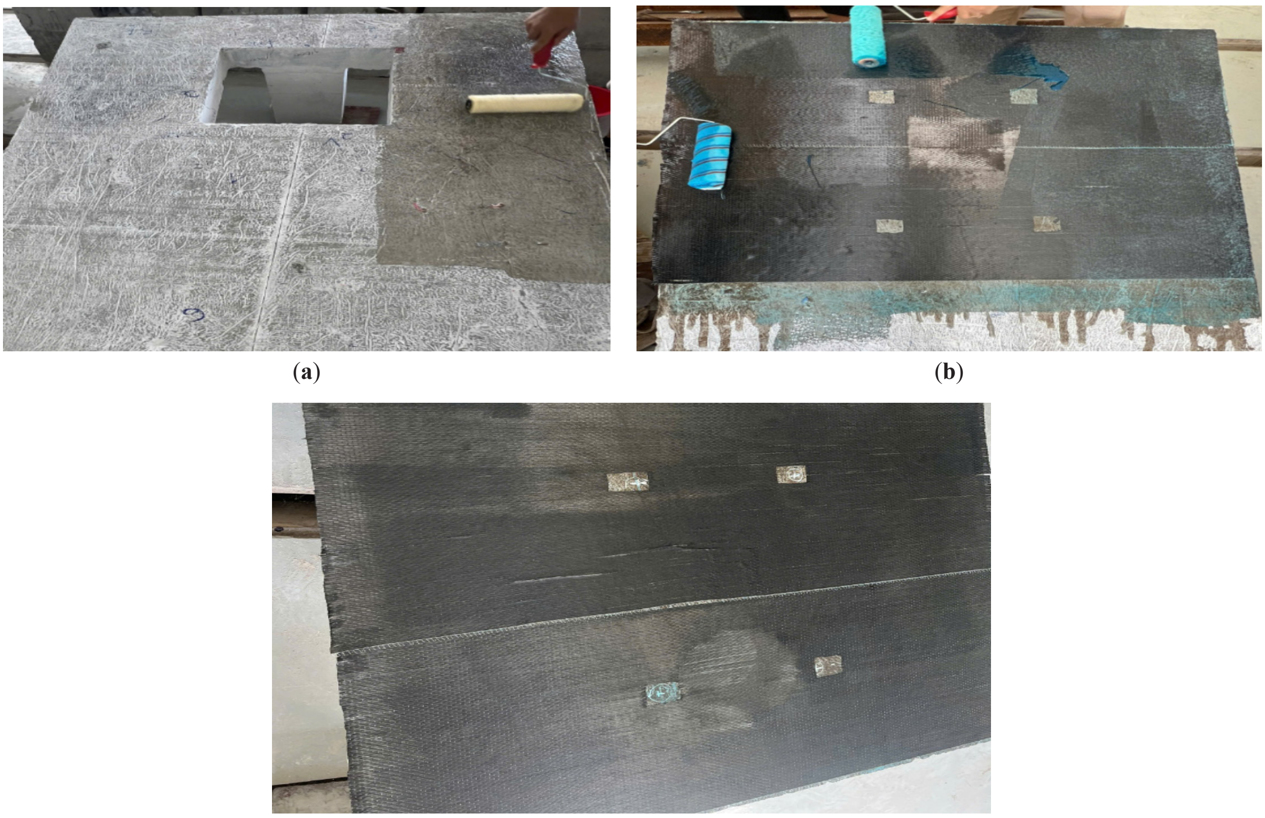
2.4. FRP Strengthening Procedure

After crack repair, one layer of FRP N300 sheet was externally bonded to the bottom surface of each damaged slab specimen. The FRP sheet was applied over the full soffit area of the slab. For specimens with openings, the FRP was cut out at the opening location so that the opening remained unobstructed. The sheet length followed the longitudinal direction of the slab, and adjacent sheet segments were placed edge-to-edge where required. No mechanical anchors or additional FRP anchorage devices were used.

The strengthening work followed a simple wet lay-up procedure. First, the bonding surface was ground and cleaned. Second, epoxy resin was applied to the prepared concrete surface. Third, the FRP sheet was laid on the epoxy-coated soffit and pressed carefully to remove trapped air. Finally, an additional epoxy coating was applied to impregnate and protect the FRP layer.

The same repair and strengthening procedure was applied to all specimens, allowing the influence of opening configuration and inherited reinforcement layout to be compared under a consistent strengthening scheme. After installation, the strengthened specimens were kept under laboratory conditions before testing. Where the project record did not specify a longer curing period, a minimum curing period of 3 days was adopted according to the manufacturer's recommendation.

The repair and strengthening sequence used for the damaged RC slab specimens is illustrated in **Figure 2**. The sequence included surface cleaning, epoxy treatment of visible cracks, installation of one FRP layer on the bottom surface, and final epoxy coating.



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

Figure 2. Preparation and externally bonded FRP strengthening procedure: (**a**) Surface cleaning, crack preparation, and epoxy treatment of visible cracks; (**b**) Installation of one FRP layer on the slab bottom surface; (**c**) Final epoxy coating and completed strengthened specimen.

Source: Authors' experimental program.

2.5. Test Setup and Instrumentation

The strengthened slabs were tested under concentrated loading applied through the column region. Each slab was placed on a steel support frame. The support condition consisted of three supported edges and one free edge, representing a column-loaded slab panel with one free boundary. A hydraulic jack was used to apply the load to the column region. To reduce local crushing and distribute the load more uniformly, a steel bearing plate of 200 mm × 200 mm × 6 mm was placed at the loading area.

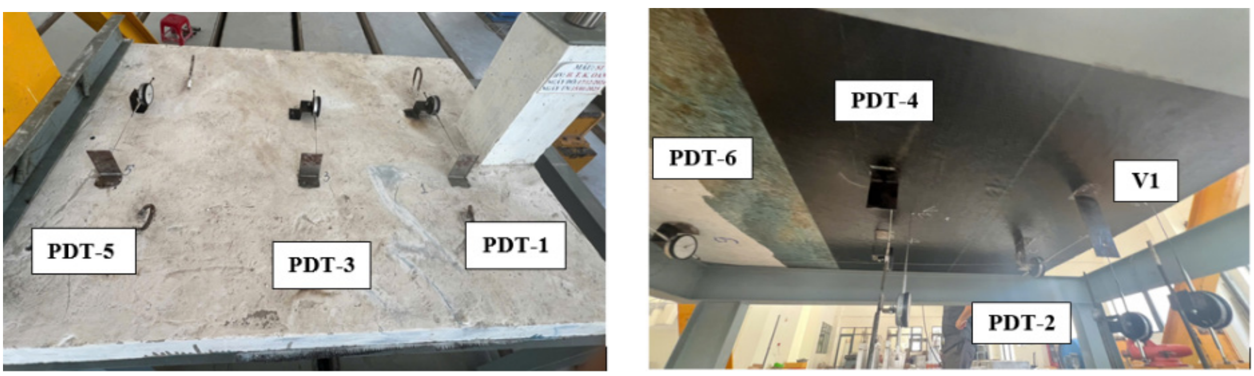
The three-supported-edge and one-free-edge boundary condition was adopted to represent a slab panel with one free or less restrained side and to maintain consistency with the first-stage reference tests. This boundary condition is a simplified laboratory configuration and is not intended to represent all slab-support conditions in buildings.

The test setup was arranged to measure vertical displacement, compressive strain, tensile strain, and FRP debonding behavior. Vertical displacement was measured at the bottom surface of the slab using a dial gauge denoted as V1. Strain measurements were obtained using displacement/strain measuring devices installed on the top and bottom surfaces of the slab. PDT-1 was used to record compressive strain at the top surface, while PDT-2 was used to record tensile strain at the bottom surface (**Figure 3**). The gauge length used for strain measurement was 300 mm. Because the bottom tensile face was covered by the FRP sheet after strengthening, crack propagation on that surface could not be directly observed during the re-test; therefore, the post-strengthening damage assessment relied mainly on displacement, strain trends, visible surface response, and FRP debonding.

The strain was calculated as (Equation (1)):

$$\varepsilon = \Delta l / l_0, \tag{1}$$

where ε is the measured strain, Δl is the measured change in gauge length, and l_0 is the initial gauge length, equal to 300 mm. In this study, compressive strain was taken as negative, tensile strain was taken as positive, and vertical displacement was taken as positive in the downward direction.



(**a**) (**b**)

Figure 3. Experimental test setup and instrumentation: (**a**) Top surface arrangement; (**b**) Bottom surface arrangement.
Source: Authors' experimental program.

2.6. Loading Procedure

Before the main test, a preliminary loading step was carried out to check the stability of the loading system, support frame, and measuring devices. The load was then released, and all measuring devices were reset to zero.

The main loading process was conducted incrementally. The load was increased by 10 kN at each loading step. At every load level, the readings of vertical displacement, compressive strain, and tensile strain were recorded. Since the bottom surface was covered by FRP, crack mapping on the strengthened tensile face was not possible during re-testing. Instead, the visible response of the specimen, changes in measured strain and displacement, and signs of FRP debonding were monitored.

The 10 kN load increment was selected for consistency with the first-stage tests and was adequate for recording the global load-displacement and load-strain trends.

However, sudden local events such as first cracking, local bond degradation, or the onset of FRP debonding may have occurred between two adjacent load levels. Smaller load increments or continuous data acquisition should be used in future work to identify such events more precisely.

The test was continued until the specimen reached failure or could no longer sustain additional loading. Failure was identified by excessive vertical displacement, abrupt strain change, concrete distress visible on accessible surfaces, FRP debonding, or loss of load-carrying capacity.

2.7. Data Analysis

The experimental results were analyzed through three main relationships: load–vertical displacement, load–compressive strain, and load–tensile strain. The load–vertical displacement relationship was used to evaluate stiffness recovery and displacement control after FRP strengthening. The load–compressive strain relationship was used to assess the response of the compression zone. The load–tensile strain relationship was used to evaluate tensile deformation, and the contribution of the bonded FRP layer before debonding became dominant.

The strengthened specimens S1–S6 were compared with the corresponding first-stage reference specimens reported in Lam and Huynh [17] and Lam et al. [18]. In the figures, curves labelled [17,18] refer to the first-stage tests, whereas curves without this label refer to the repaired and FRP-strengthened specimens tested in the present study. The comparison was used to interpret the influence of FRP strengthening together with opening size, opening shape, opening position, inherited reinforcement configuration, and FRP–concrete bond behavior.

3. Results

3.1. General Experimental Response and FRP Debonding

The strengthened specimens were evaluated mainly through vertical displacement, compressive strain, tensile strain, visible surface response, and FRP debonding. During re-testing, the slabs showed a nonlinear response typical of previously damaged members repaired with an externally bonded composite layer. Because the FRP sheet covered the bottom tensile surface, new crack propagation on that face could not be directly followed during loading. The final response of all strengthened specimens was governed by debonding of the FRP sheet from the concrete substrate.

The influence of opening geometry was therefore interpreted from the pre-strengthening damage maps, the load–displacement and load–strain curves, and the location and severity of FRP debonding observed after testing. Specimens with square openings showed less stable response trends than the circular-opening specimen, which is consistent with stress concentration expected at square opening corners. The large square opening in S4 remained the most unfavorable configuration, while S5 showed a milder global response because its opening was located farther from the column-loaded region. S6 showed the most favorable response among the tested specimens, but it should be interpreted together with the absence of an opening and its modified inherited reinforcement arrangement.

The main response parameters of the strengthened specimens are summarized in **Table 4**. The values should be read as specimen-specific comparisons rather than statistical averages because each configuration was represented by one specimen.

3.2. Load–Vertical Displacement Response

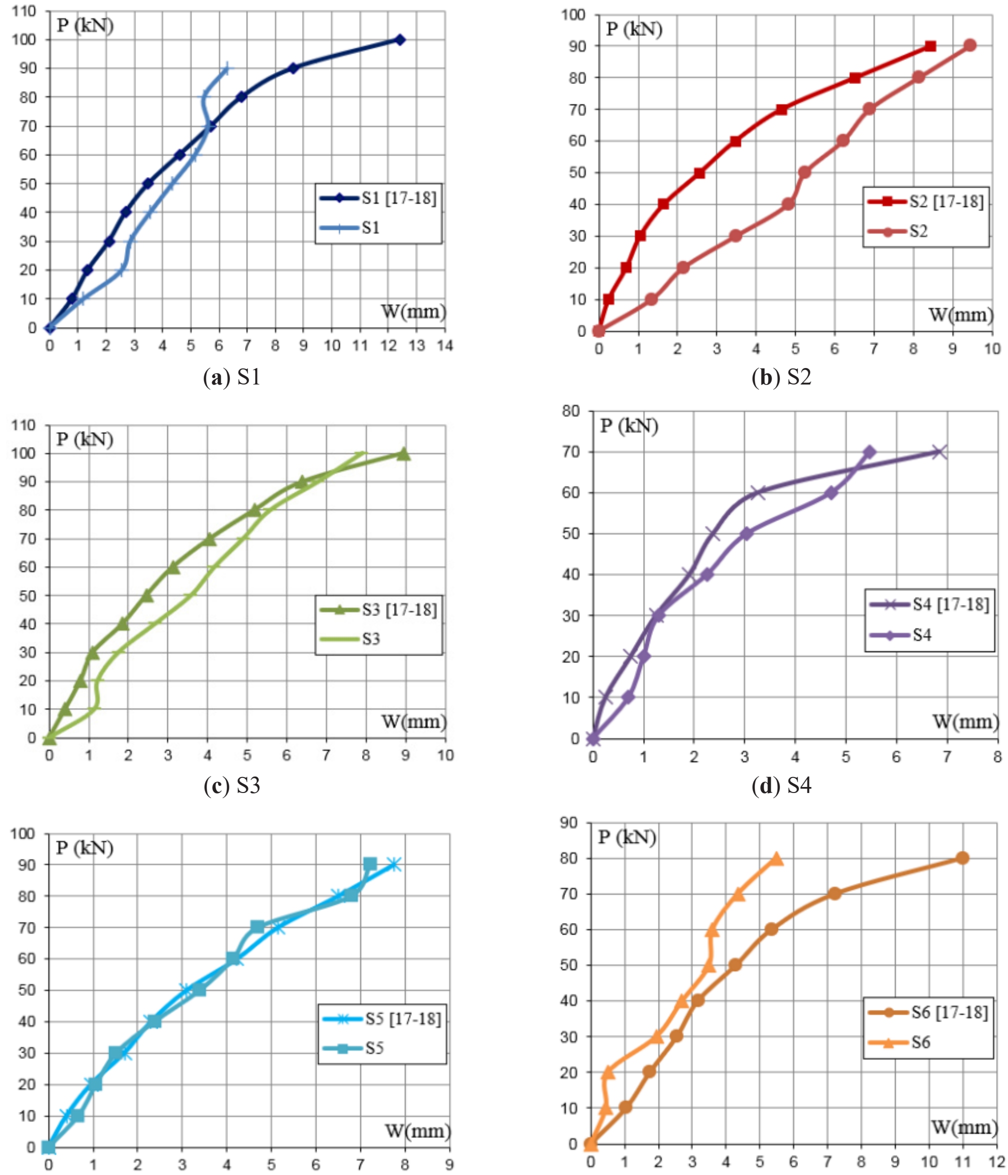
The load–vertical displacement responses measured at point V1 are presented in **Figure 4**. The curves labelled [17,18] represent the first-stage reference tests, while the curves without this label represent the repaired and FRP-strengthened slabs tested in the present study. These curves were used to assess how much displacement control was recovered after repair and strengthening.

For S1, the strengthened slab still showed larger displacement than the first-stage reference slab up to about 70 kN, which indicates that the previous damage continued to affect the early stiffness after repair. At higher loads, the trend changed. At 90 kN, S1 reached a displacement of 6.28 mm, compared with 8.63 mm for S1 [17], corresponding to a reduction of approximately 27.2%. This suggests that the bonded FRP layer became more effective after the slab entered the higher-load range.

Table 4. Summary of main experimental observations of strengthened specimens.

Specimen	Opening Configuration	Main Observed Response After FRP Strengthening
S1	No opening	Lower displacement than the reference specimen at high load; at 90 kN, displacement was reduced by approximately 27.2%.
S2	Square opening, 200 × 200 mm	Larger displacement than the reference specimen in most load stages; the difference is reduced at high loads, reaching about 11.8% at 90 kN.
S3	Circular opening, D200 mm	Larger displacement at low and medium loads, but lower displacement than the reference specimen by about 11.6% at 100 kN.
S4	Square opening, 400 × 400 mm	Overall unfavorable response due to the large square opening; although a lower displacement was recorded at 70 kN than in S4 [18], this single comparison was interpreted cautiously because of severe opening geometry and previous damage history.
S5	Square opening, 200 × 200 mm, 200 mm from the column face	Displacement close to the reference specimen; at 90 kN, displacement was about 6.7% lower.
S6	No opening, modified reinforcement direction	Most favorable displacement response among the tested specimens; at 80 kN, displacement was approximately 50.2% lower than the reference specimen.

Source: Authors' experimental results.



(**a**) S1 (**b**) S2 (**c**) S3 (**d**) S4 (**e**) S5 (**f**) S6

Figure 4. Load–vertical displacement responses measured at V1: (**a**) S1; (**b**) S2; (**c**) S3; (**d**) S4; (**e**) S5; (**f**) S6.

Source: Authors' experimental results.

For S2, which contained a 200 × 200 mm square opening, the strengthened specimen generally displaced more than S2 [18]. The difference was more noticeable at the early load levels and became smaller as the load increased. At 90 kN, the displacement of S2 was only about 11.8% higher than that of S2 [18]. The response suggests that the square opening continued to disturb the local stiffness, but the FRP layer helped limit further displacement growth near the final loading stage.

For S3, with a circular opening of 200 mm diameter, the strengthened slab also showed larger displacement than S3 [18] at low and intermediate loads. Near the upper load range, however, the two curves became close, and at 100 kN the displacement of S3 was approximately 11.6% lower than that of S3 [18]. This response is consistent with the more gradual stress redistribution expected around a circular opening.

For S4, with the 400 × 400 mm square opening, the displacement response remained unfavorable over most of the loading range. The large cut-out reduced the effective load-transfer area and increased local disturbance around the opening. At 70 kN, the measured displacement was 5.47 mm, about 20% lower than S4 [18], but this single value should be interpreted cautiously because S4 had the most severe opening configuration and was also affected by its previous damage history.

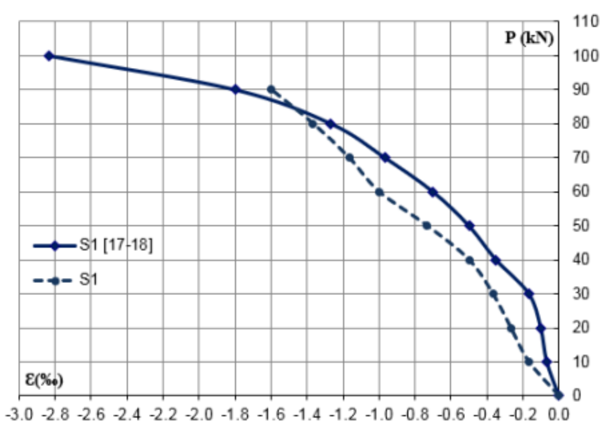
For S5, the displacement response stayed close to that of S5 [18]. At 90 kN, S5 had a displacement of 7.23 mm, approximately 6.7% lower than S5 [18]. Moving the 200 × 200 mm square opening 200 mm away from the column face therefore reduced its influence on the global displacement response when compared with an opening placed closer to the column region.

S6 showed the most favorable displacement response among the tested specimens. At 80 kN, its displacement was about 50.2% lower than that of S6 [17]. This result should not be attributed to the reinforcement arrangement alone because S6 had no opening and also had a modified inherited reinforcement layout. Within the tested set, however, this configuration provided the clearest displacement control after FRP strengthening.

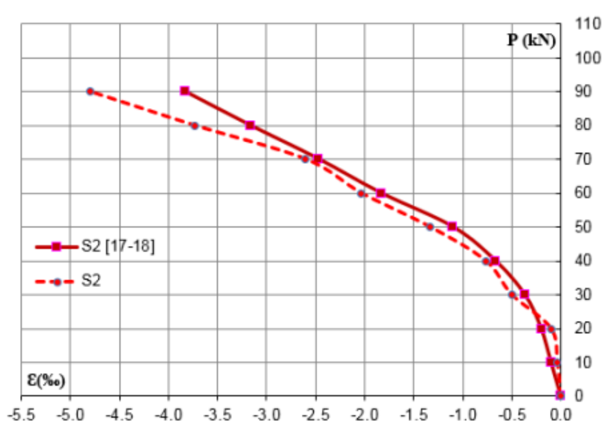
Overall, the displacement results indicate that FRP strengthening improved the high-load response of several damaged specimens, but the degree of improvement depended on the specimen configuration. The large square opening in S4 remained critical; the circular opening in S3 behaved more favorably than a square opening of similar nominal size, and the offset opening in S5 produced a less severe displacement response than an opening close to the column region.

3.3. Load–Compressive Strain Response

The load–compressive strain responses measured at PDT-1 are presented in **Figure 5**. Compressive strain was taken as negative. These results were used to follow the response of the compression zone and to identify abrupt changes associated with stiffness loss or FRP debonding.

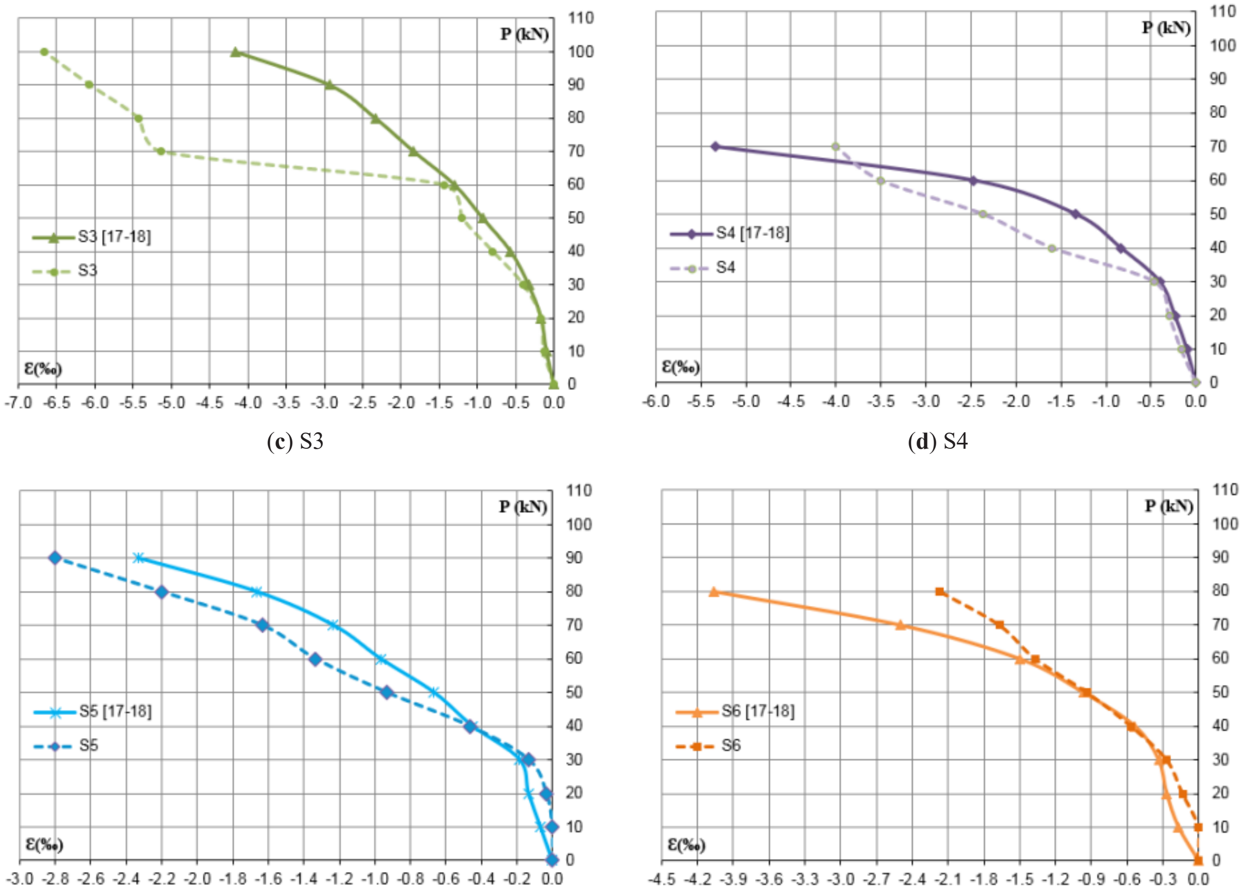


(**a**) S1



(**b**) S2

Figure 5. *Cont.*



(**c**) S3 (**d**) S4

(**e**) S5 (**f**) S6

Figure 5. Load–compressive strain responses measured at PDT-1: (**a**) S1; (**b**) S2; (**c**) S3; (**d**) S4; (**e**) S5; (**f**) S6.

Source: Authors' experimental results.

For S1, the compressive strain of the strengthened slab was generally higher than that of S1 [17] before the high-load range. This indicates that the repaired slab did not recover its original stiffness completely. Close to failure, the strain response changed rapidly and was accompanied by FRP debonding, showing that the interface condition governed the final stage of behavior.

For S2, S3, S4, and S5, the compressive strain curves show that the opening configuration and FRP bond condition both influenced the response. In S3, the strengthened and reference curves were close below about 60 kN, but the strengthened curve increased more rapidly at higher loads. This change is consistent with a reduction in bond effectiveness as deformation concentrates near the opening and loading region.

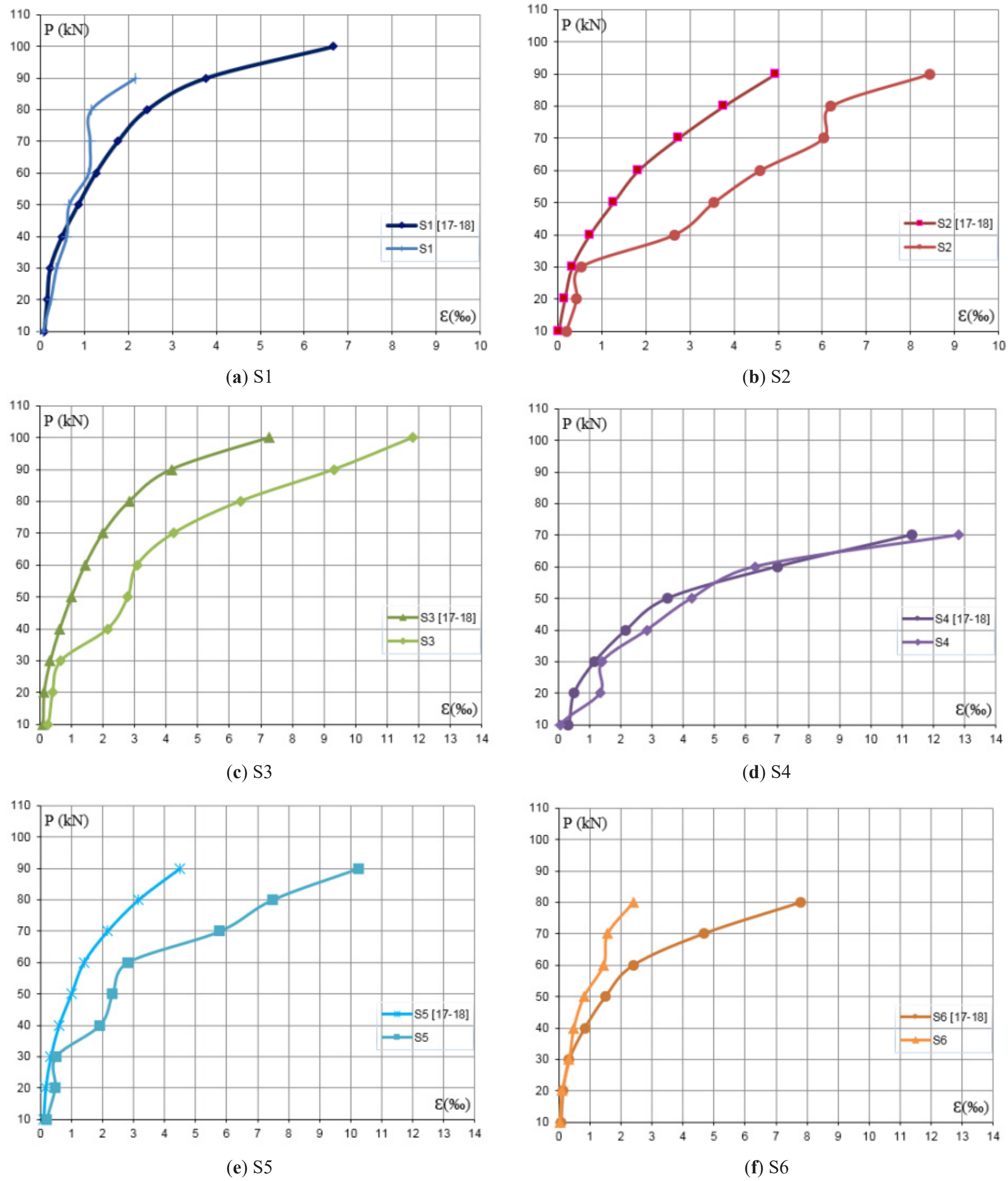
For S4, the strengthened and reference slabs were similar at the early load levels, but the strain of the strengthened specimen increased more sharply after the response became nonlinear. The 400 × 400 mm square opening created a severe discontinuity in the slab, and the FRP layer could not fully compensate for this disturbance. At 70 kN, S4 still showed lower compressive strain than S4 [18], but the overall response remained less stable than that of the smaller-opening specimens.

S6 again showed a stable compressive strain response within the tested range. At 80 kN, the compressive strain of S6 [17] was about 87.7% higher than that of the strengthened S6. As noted for the displacement response, this comparison reflects the combined influence of no opening, the inherited reinforcement arrangement, epoxy repair, and FRP strengthening.

In general, the compressive strain results indicate that the repaired and strengthened slabs did not respond uniformly. The specimens with openings were more sensitive to local disturbance and bond deterioration, while S6 had the most stable compressive-strain trend among the tested configurations.

3.4. Load–Tensile Strain Response

The load–tensile strain responses measured at PDT-2 are shown in **Figure 6**. Tensile strain was taken as positive. These data are important because the FRP sheet was bonded to the tensile face of the slab. Since the FRP covered this face, tensile-face crack development during re-testing was inferred from strain response and debonding observations rather than from direct crack mapping.



(**a**) S1 (**b**) S2 (**c**) S3 (**d**) S4 (**e**) S5 (**f**) S6

Figure 6. Load–tensile strain responses measured at PDT-2: (**a**) S1; (**b**) S2; (**c**) S3; (**d**) S4; (**e**) S5; (**f**) S6.

Source: Authors' experimental results.

For S1, the tensile strain response indicates that the FRP layer helped restrain tensile deformation at the higher load levels. The response was not fully linear, and debonding developed near the final loading stage. This confirms that the contribution of the FRP layer was eventually limited by loss of bond rather than by rupture of the sheet.

For S2, S3, S4, and S5, the tensile strain of the strengthened slabs was generally higher than that of the corresponding first-stage reference specimens over much of the loading range. This behavior is consistent with the combined effects of previous damage, local discontinuity caused by openings, and progressive bond deterioration. For S5, the tensile strain remained higher than that of S5 [18] at most load levels, even though the displacement response was relatively close to the reference curve.

In contrast, S6 showed a marked reduction in tensile strain at the high-load stage. At 70–80 kN, the tensile strain of the strengthened S6 was approximately 66–69% lower than that of S6 [17]. This result shows that the FRP layer was effective in this configuration, but it should be read together with the absence of an opening and the modified inherited reinforcement arrangement.

Overall, the tensile strain results show that the FRP layer was most effective when the load path was not interrupted by an opening. In specimens with openings, especially square openings, tensile deformation was more difficult to control, and debonding limited the strengthening effect before the FRP sheet could be fully mobilized.

3.5. Effect of Opening Configuration and Reinforcement Arrangement

The combined displacement and strain results show that the response of the strengthened specimens was controlled by the opening configuration, inherited reinforcement layout, and FRP–concrete bond. The large square opening in S4 remained the most unfavorable case because it reduced the effective slab area and created a strong geometric discontinuity. S3 behaved more favorably than S2, which is consistent with the absence of sharp corners around the circular opening.

The location of the opening also affected the response. S5, with the square opening located 200 mm from the column face, showed a displacement curve close to the reference specimen and a smaller displacement difference at high load. This indicates that moving the opening away from the main column-loaded region reduced its influence on global displacement.

Among all specimens, S6 showed the most favorable response. This specimen had no opening and had a modified inherited reinforcement arrangement, so its behavior should not be interpreted as the effect of reinforcement arrangement alone. At high load levels, its tensile strain reduction reached approximately 66–69%, and its displacement reduction reached approximately 50.2% at 80 kN compared with the corresponding first-stage reference specimen.

The experimental results therefore indicate that externally bonded FRP sheets can improve the response of damaged RC slabs, but their efficiency is not uniform. The observed response was governed by the combined effects of opening size, opening shape, opening location, inherited reinforcement layout, previous damage, and FRP–concrete bond behavior.

4. Discussion

The results show that externally bonded FRP sheets can be useful for rehabilitating damaged RC slabs with openings, but the benefit depends on the existing damage state, the opening geometry, the opening location, the inherited reinforcement layout, and the FRP–concrete interface. In this program, the slabs were not new members; they had already been loaded and damaged in the first-stage tests before repair. The response reported here is therefore the response of repaired slabs under a second loading stage, not the response of undamaged slabs strengthened from the beginning.

4.1. Influence of Initial Damage and Crack Repair

The strengthened slabs did not always show lower displacement or strain than their corresponding first-stage reference specimens at early load levels. This is reasonable because the previous loading had already produced damage and stiffness loss. Epoxy repair helped prepare the substrate for FRP bonding, but it could not make the slabs equivalent to newly cast specimens.

This distinction is important. Many FRP-strengthening studies use newly cast specimens or intentionally prepared openings, where the concrete substrate is sound before strengthening. The present specimens had a different starting condition. Their early response was influenced by prior cracking and local damage, while their final response was governed mainly by FRP debonding.

At higher load levels, several strengthened specimens showed better displacement control than their corresponding first-stage reference specimens. This suggests that the bonded FRP layer became more active after the slabs entered the nonlinear range. The benefit, however, was limited when debonding developed or when the opening caused a severe local disturbance.

4.2. Effect of Opening Geometry

Opening geometry clearly affected the response. Square openings were more unfavorable than the circular opening of similar nominal size, mainly because square corners promote local stress concentration. This interpretation is supported by the first-stage damage maps and by the post-strengthening displacement and strain curves.

S4, with a 400 × 400 mm square opening, was the most critical opening specimen. The large opening reduced the effective load-transfer area and increased local deformation around the cutout. FRP strengthening helped control displacement at a high load level, but the large square opening still produced an unstable response and a high risk of debonding.

S3, with a circular opening, showed a more favorable response than the square-opening specimen of similar nominal size. This agrees with the expected smoother stress redistribution around a circular boundary and with the first-stage findings reported by Lam et al. [18].

4.3. Effect of Opening Location Relative to the Column Region

The location of the opening relative to the column-loaded region significantly influenced the structural response. Specimen S5, which had a 200 × 200 mm square opening located 200 mm from the column face, showed displacement behavior close to that of the reference specimen. At high load, the displacement of S5 was slightly lower than that of S5 [18]. This indicates that moving the opening away from the critical column region reduced its negative influence on global stiffness and deformation.

This result has practical significance because openings in existing slabs are often created for building services without sufficient consideration of structural stress fields. When an opening is located near a column region, it may interfere with concentrated load transfer, punching-related stress distribution, and flexural force flow. Previous studies on flat slabs and slab–column connections also showed that the column region is highly sensitive to local discontinuities, cracking, and strengthening configurations [22–26]. The present results confirm that the same principle applies to damaged RC slabs strengthened with FRP sheets: openings located farther from the column region are less detrimental than openings placed within the main load-transfer path.

However, the tensile strain response of S5 was still higher than that of the reference specimen over most loading stages. This means that a favorable displacement curve alone is not sufficient to judge strengthening efficiency. Strain response and debonding behavior must also be considered.

4.4. Role of Reinforcement Arrangement

Among all tested specimens, S6 showed the most favorable response. This result should be interpreted carefully because S6 had no opening and also had a modified inherited reinforcement arrangement. The lower displacement and tensile strain therefore reflect the combined effect of specimen configuration, prior damage state, epoxy repair, and FRP strengthening.

This result also shows that FRP strengthening should not be considered separately from the existing slab configuration. The externally bonded sheet can contribute to tensile-force transfer, but its effectiveness depends on whether the existing geometry allows a continuous load path. When an opening interrupts this path, the FRP contribution may be reduced even if the same material and bonding procedure are used.

For practical design, the existing reinforcement layout and opening position should be reviewed before selecting a strengthening scheme. In existing slabs, the reinforcement cannot usually be changed. The FRP layout should therefore be arranged to support the expected tensile-force path and to reduce the risk of premature debonding near openings.

4.5. FRP–Concrete Bond and Debonding Behavior

The tests confirm that FRP–concrete bond behavior controlled the final stage of the strengthened specimens. Because the FRP layer was bonded to the bottom face, crack growth on that face could not be directly observed during re-testing. The main visible evidence of failure was separation of the FRP sheet from the concrete substrate, together with abrupt changes in strain and displacement response.

Debonding is a well-known limitation of externally bonded FRP systems. Buyukozturk et al. [4] and Kang et al. [5] emphasized that debonding may prevent the FRP material from reaching its tensile capacity. Elsayed et al. [6] also showed that FRP-strengthened slabs may fail due to interface behavior rather than FRP rupture. The present results are consistent with these findings. In damaged slabs, the risk of debonding may be even higher because existing cracks and repaired zones create a non-uniform substrate for FRP bonding.

The observed behavior suggests that surface preparation and epoxy treatment are necessary, but they do not remove the possibility of debonding. For slabs with large or sharp-cornered openings, additional anchorage or a modified FRP layout may be needed to improve bond reliability. Such measures would add construction work, so their benefit should be balanced against the simplicity of externally bonded sheets.

4.6. Comparison with Previous Studies

The present results are generally consistent with previous studies [8–12] showing that FRP can improve the behavior of RC slabs with openings [12–16]. However, this study provides a more specific contribution by focusing on damaged slabs that were repaired before FRP strengthening. Previous studies mainly examined newly cast slabs, slabs with pre-planned openings, or strengthening applied under relatively ideal substrate conditions. The current results show that the residual damage condition can influence the early stiffness, strain response, and debonding behavior of strengthened slabs.

The results also extend the findings of Lam and Huynh [17] and Lam et al. [18]. These previous studies clarified the baseline response of column-loaded RC slabs and the effect of cutting openings on column-loaded slabs. The present study builds on those findings by examining the next rehabilitation stage, in which the damaged slabs were repaired and strengthened using externally bonded FRP sheets. This connection is important because it transforms the problem from "how openings affect column-loaded slabs" to "how damaged column-loaded slabs with openings behave after FRP strengthening."

Compared with studies on punching shear strengthening of flat slabs [22–26], the present study focuses more on load–deflection and load–strain behavior under column loading. Although punching-related mechanisms may influence the response near the column region, the main contribution of this study lies in evaluating deformation recovery, strain redistribution, and strengthening efficiency after damage. This distinction is useful because serviceability behavior and strain control are often critical in existing slabs, even before complete punching failure occurs.

4.7. Practical Implications

The findings of this study provide several practical implications for the rehabilitation of damaged RC slabs with openings. First, externally bonded FRP sheets can be used to improve the behavior of damaged slabs, but their effectiveness should not be assumed to be uniform for all opening configurations. Large square openings are more critical than small or circular openings because they produce stronger stress concentration and greater interruption of load transfer.

Second, the location of an opening relative to the column region should be carefully considered. Openings located closer to the column-loaded area are more likely to affect stiffness, damage progression, strain distribution, and debonding risk. When possible, service openings should be placed away from the main load-transfer region to reduce structural disturbance.

Third, the existing reinforcement arrangement and the opening position should be reviewed before strengthening. The response of S6 was favorable, but it should not be used as evidence for reinforcement layout alone because the specimen also had no opening.

Finally, bond reliability must be treated as a key design issue. Proper surface preparation, epoxy application, FRP installation, and curing are required. Where large openings or severe local deformation are expected, additional anchorage may be needed to reduce the likelihood of premature FRP debonding.

Future work may combine the present test results with refined numerical modelling to examine stress redistribution around openings and FRP–concrete debonding in greater detail.

5. Conclusions

This study experimentally investigated the behavior of previously damaged reinforced concrete slabs with openings repaired with epoxy and strengthened using externally bonded FRP sheets. Six damaged slab specimens from the first-stage tests [17,18] were strengthened with one FRP layer bonded to the bottom surface and then re-tested under concentrated column loading. Based on the experimental results, the following conclusions can be drawn:

1. Externally bonded FRP sheets improved the response of several damaged RC slabs, especially at higher load levels. The improvement was not uniform and depended on opening size, opening shape, opening location, inherited reinforcement layout, previous damage, and FRP–concrete bond condition.
2. Opening geometry influenced the strengthened response. The circular opening produced a more favorable load–displacement trend than the square opening of similar nominal size, while the large square opening remained the most unfavorable opening configuration.
3. The 400 × 400 mm square opening caused a severe discontinuity in the slab. Although FRP strengthening helped reduce displacement at one high-load comparison point, the specimen remained sensitive to local deformation and FRP debonding.
4. The location of the opening was important. When the 200 × 200 mm square opening was placed 200 mm away from the column face, its influence on global displacement was reduced. At 90 kN, the strengthened S5 specimen showed approximately 6.7% lower vertical displacement than the corresponding first-stage reference specimen.
5. S6 showed the most favorable response among the tested specimens. At 80 kN, its vertical displacement was approximately 50.2% lower than that of the corresponding reference specimen, and its tensile strain was approximately 66–69% lower at high load levels. This result should be interpreted together with the absence of an opening and the modified inherited reinforcement arrangement.
6. The load–strain results indicate that the FRP layer was most effective when the load path was not interrupted by an opening. In specimens with square openings, tensile deformation was harder to control, and debonding limited the strengthening effect.
7. FRP–concrete bond behavior governed the final stage of all strengthened specimens. Since the FRP sheet covered the bottom tensile face, crack propagation on that face could not be directly observed during re-testing; the main observable failure feature was FRP debonding. Careful surface preparation, epoxy treatment, curing, and, where necessary, additional anchorage should be considered for practical applications.

Author Contributions

C.B.T. and H.K.L. contributed to conceptualization and methodology. H.K.L. and H.D.N. conducted the investigation, data analysis, and visualization. C.B.T. supervised the study, provided resources, and managed the project. C.B.T. and H.K.L. prepared the original draft, and all authors reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study did not involve human participants, animal subjects, clinical samples, pathology reports, or personal data. The experimental program was conducted on reinforced concrete slab specimens under laboratory conditions.

Informed Consent Statement

Not applicable. This study did not involve human participants, animal subjects, clinical samples, pathology reports, or personal data. The experimental program was conducted on reinforced concrete slab specimens under laboratory conditions.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

No AI tools were used for experimental design, data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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