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Experimental investigation on rehabilitation effectiveness of locally corroded RC slabs using external CFRP strip plates

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Abstract

This work aims to investigate the rehabilitation effectiveness on the loading resistance of a locally-corroded RC slab using experimental testing. The experimental program comprised seven scaled one-way RC slabs, including one uncorroded and six corroded, and nine two-way RC slabs, including one uncorroded and eight corroded specimens. The corroded RC slabs were retrofitted using CFRP strip plates (CFRP-p), CFRP sheets (CFRP-s), and spot-welded wire mesh (WWM). Besides the retrofit work in the rehabilitation, this work adopts non-shrinkage cement mortar and lightweight epoxy mortar to do the patch repair of the corroded regions. After the patch repair and retrofit, monotonic loading tests are conducted to investigate the mechanical behavior of RC slabs, focusing on the application of CFRP-p, which offer greater convenience than CFRP-s and WWM in site construction. The slab specimens are locally-corroded using the electrical-chemical method. According to the test results, compared with CFRP-s and WWM, CFRP-p provide superior improvements in load-carrying capacity while reducing deformation and crack width. CFRP-p is also demonstrated to be an effective strengthening solution for restoring the stiffness of corrosion-damaged one-way and two-way RC slabs under serviceability conditions. Localized corrosion significantly reduces stiffness and flexural capacity while increasing ductility due to reinforcement ratio loss. A modified ACI 440.2R based design equation accounting for localized corrosion is proposed to determine CFRP-p dimensions and restore only the lost structural capacity.

Keywords: Reinforced concrete (RC) slabs; localized-corrosion; CFRP strip plate (CFRP-p); CFRP sheet (CFRP-s); spot-welded wire mesh (WWM).

1 Introduction

Reinforced concrete (RC) structures in Taiwan's coastal regions are subjected to harsh environmental conditions, where moisture, chloride ions, and carbon dioxide contribute to concrete spalling and cracking, accelerating the corrosion of steel reinforcement. This deterioration often results in a significant reduction in structural integrity, failing to meet design criteria, particularly in high-humidity environments such as basements and bathroom slabs, e.g. Chiu, and Fan (2015). Corrosion in RC structures compromises their durability and overall performance. Numerous studies have investigated the causes and mechanisms of corrosion, aiming to understand its impact on concrete properties and the structural behavior of RC elements, especially in cases of severe damage, Fernandez, Herrador, and Marí (2016). RC slabs, essential components of buildings and bridges, are particularly susceptible to corrosion over time, especially in aggressive environments with high chloride ion concentrations, (Said 2019, and Qian 2022). The corrosion of reinforcing steel bars in slabs reduces the moment resistance of RC members, weakening structural integrity and shortening service life, Fernandez, Herrador, and Bairán (2018).

Few studies have specifically investigated the effectiveness of CFRP-p in improving the flexural strength of RC slabs with localized corrosion damage in the tension reinforcement. Moreover, comparative studies on the performance of different patch repair materials, such as non-shrinkage cement mortar and epoxy mortar, in combination with CFRP-p, CFRP-s, and spot-welded wire mesh (WWM) remain limited. Most researchers have focused on analyzing how corrosion affects RC slabs' punching shear strength, (Said 2019, Qian 2022, Ikehata 2020). However, researchers have not been thoroughly investigated the CFRP strip plate effectiveness on the flexural strength of localized-corroded RC slabs. Additionally, most studies have focused on strengthening conventional, uncorroded flat RC slabs and slab-column connections, (Al-Mawed 2023, Torabian 2024). Therefore, to address this research gap, this research experimentally evaluates the rehabilitation efficiency of local-corroded RC slabs strengthened with external CFRP strip plates and proposes a modified design equation to accurately determine the required CFRP strip plate dimensions for compensating flexural strength loss caused by reinforcement corrosion.

2 Materials and Methods

The experimental program consisted of seven scaled one-way RC slabs, including one uncorroded and six corroded, and nine two-way RC slabs, including one uncorroded and eight corroded specimens. For the one-way RC slab

specimens, the control specimen was designated as CG. For the two-way RC slab specimens, the control specimen was RCS-0, along with specimens artificially corroded to 10% (RCS-10) and 20% (RCS-20). The remaining specimens were repaired and retrofitted using various selected materials, including non-shrink cement mortar (N), lightweight epoxy mortar (E), welded wire mesh (WWM), CFRP sheets (CFRP-s), and CFRP strip plates (CFRP-p), respectively. Material tests were performed for each RC slab specimen, including concrete compressive strength, tensile strength of reinforcing steel bars, and tensile strength of CFRP strip plates. An accelerated corrosion technique was applied by maintaining a constant current to achieve the targeted reinforcement mass loss (Figure 1), with all bar intersections insulated using tape and ties to prevent electrical conduction, and theoretical mass loss calculated using the Faraday equation (Ikehata 2020, Said 2019, Qian 2022) (see Eq. (1)).

$$Mass\ loss = \frac{tIM}{ZF} \tag{1}$$

Where M is the atomic weight (for iron, M = 56 g/mol); Z is the ion charge (two moles of electrons); t is the time elapsed in seconds; I is the current elapsed in amperes; and F is the Faraday's constant (F = 96,500 coulombs per mole (C/mol).

For the selected patch repair materials, flexural, compressive, and bond strength tests were conducted in accordance with relevant standards. Seven scaled RC slabs with identical geometry were constructed and tested under monotonic loading. The one-way slabs were simply supported at both ends, while the two-way slabs were supported along all four edges with allowance for corner uplift and subjected to monotonic loading. In addition to the experimental investigation, the moment strength of CFRP-p retrofitted specimens was analytically evaluated using the ACI 440.2R code, showing strong agreement with test results. This study introduces a modified design approach that considers localized corrosion to determine the optimal CFRP-p dimensions, developed and validated through experimental findings. Furthermore, the work revises existing design formulas to optimize the application of CFRP strip plates for retrofitting locally-corroded slabs, aiming to restore reduced initial stiffness while ensuring adequate flexural strength and improved ductility.

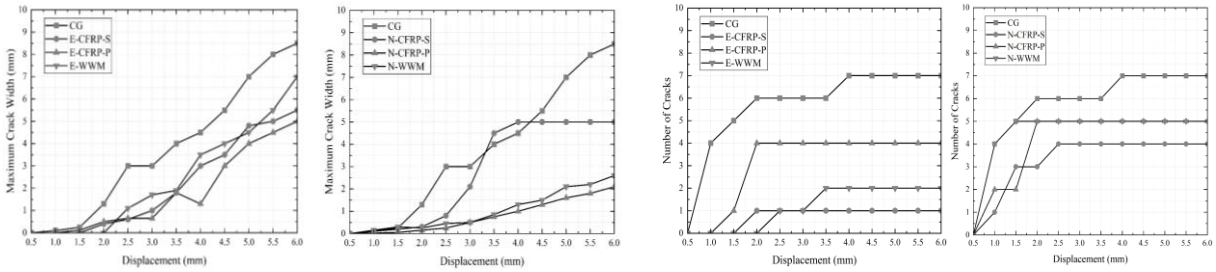
(a) (b)

Figure 1. Constant current accelerated corrosion setup; (a) one-way RC slab specimen; (b) two-way RC slab specimens.

3 Result and discussion

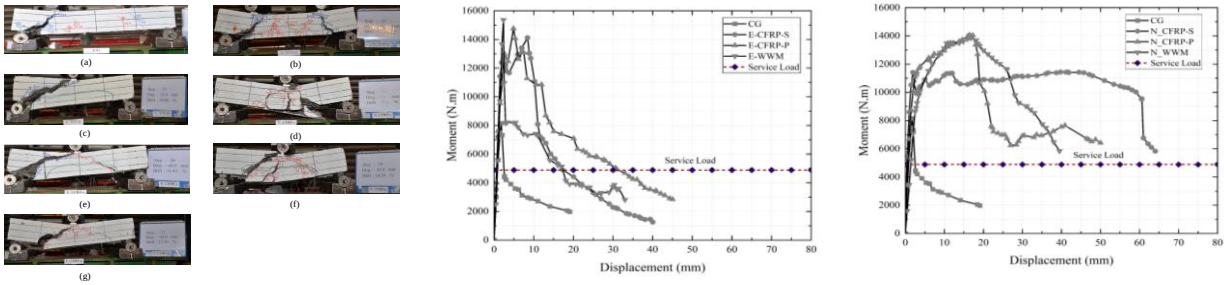
Artificial corrosion tests showed severe damage near specimen centers. Weight loss and minimum bar diameter were measured digital weight measurement machine. Before patch repair, concrete cover was grouted, remove corrosion products, and repair areas defined based on concrete cover damage extent for effective rehabilitation. Failure modes for one-way RC slabs were identified through response curve analysis. Shear failure exhibited a steep initial slope followed by a sudden load drop, indicating brittle behavior with minimal deformation. Flexural-shear failure showed gradual load increase, a yield plateau, and moderate decline after peak, reflecting ductile behavior. Based on these criteria, two modes were observed: shear failure (CG, E-WWM) and flexural-shear failure (N-WWM, N-CFRP-s, N-CFRP-p, E-CFRP-s, E-CFRP-p). Specimens E-CFRP-p and N-CFRP-p achieved moment resistance improvements of 81.3% and 72.8% over the control (CG). Except for E-WWM, CFRP-p retrofitted slabs showed the highest recovery rates. Patch repair materials significantly influenced deformation capacity, with non-shrink cement mortar providing better deformation performance than epoxy mortar. Service load performance was evaluated at 60% of CG's tested moment strength (4885.04 kN-mm) to define flexural stiffness, Said and Hussein (2019). Results indicate CFRP-p effectively controls deformation under service loads, while N-CFRP-s offers the best deformation control. Regardless of the patch repair materials, CFRP-p provides a similar flexural stiffness when the applied moment is lower than the specified moment strength, as shown in Figure 3.

Specimens repaired with lightweight epoxy mortar exhibited fewer cracks but larger widths, mainly at the concrete epoxy interface, with no cracks inside the repaired zone. In contrast, non-shrinkage cement mortar resulted in more cracks of smaller width, occurring at both the interface and within the repair material. CFRP-p retrofitting significantly reduced crack width due to its high tensile strength and stiffness, effectively limiting deformation and crack propagation. Additionally, the CFRP-p repaired specimens exhibited fewer cracks than those retrofitted with WWM or CFRP-s, as shown in Figure 2.



(a) (b)

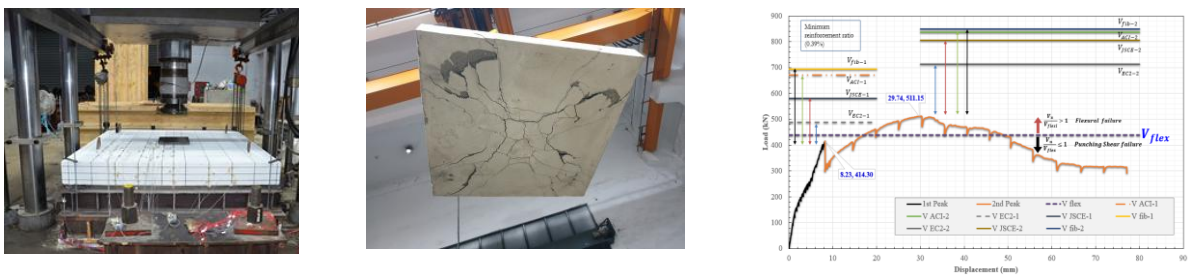
Figure 2. (a) Crack width of each specimen; (b) Number of cracks of each specimen.



(a) (b)

Figure 3. (a) Crack patterns at the final stage of each specimen; (b) Moment-displacement curve of repaired specimens for lightweight epoxy mortar and non-shrinkage cement mortar.

For two-way RC slab specimens, the post-test analysis of the control specimen (RCS-0), particularly after cutting at the edge of the loading plate revealed a failure mode classified as flexural-triggered punching shear failure. The load displacement diagram indicates that a 10% mass loss significantly reduces initial stiffness and peak load capacity. This degradation alters the failure mechanism: instead of a flexural-triggered punching failure, the slab failure transitions to a pure flexural failure mode. Verification using various design codes confirms that shear reinforcement significantly contributes to the second peak strength by enabling load redistribution following the initial punching failure, as shown in Figure 4. The control specimen (RCS-0) exhibited an initial stiffness of 101.84 kN/mm, whereas the corroded specimen (RCS-10) with 10% mass loss showed a reduced stiffness of 82.20 kN/mm, representing a 19.28% decrease. Specimen RCS-10 exhibited a 33.4% increase in energy dissipation capacity compared to RCS-0, primarily due to the reduction in reinforcement ratio caused by rebar corrosion. This reduction promotes a more ductile failure mode, enabling greater deformation and energy absorption. By modifying the existing formula Soudki, El-Sayed, and Vanzwol (2012), and determining the optimal size of CFRP-p, the goal is to enhance only the damaged or reduced capacity of the two-way RC slab. After evaluating the change in capacity, repairs are applied only to the areas where a reduction is observed, as illustrated in Figures 4 and 5.



(a) (b) (c)

Figure 4. (a) RCS-0 specimen during monotonic loading; (b) Crack pattern at the final stage; (c) load-displacement diagram.

(a) (b) (c)

Figure 5. (a) RCS-10 specimen during monotonic loading; (b) Crack pattern at the final stage; (c) load-displacement diagram.

4 Conclusions

This work aimed to investigate the retrofit effectiveness on the moment resistance in locally corroded RC slabs using CFRP-p. All experimental tests were conducted under monotonic loading. Additionally, based on the test results, the following conclusions can be addressed:

a) For one-way RC slabs, lightweight epoxy mortar improved flexural strength, achieving higher moment capacity, while non-shrink cement mortar offered better ductility and superior bonding under thermal cycles, ensuring durability. CFRP-p retrofitting provided the highest recovery of moment strength and effectively controlled deformation under service loads. Analytical predictions using ACI 440.2R closely matched experimental results, enabling optimize sizing of CFRP-p for strength restoration. Overall, CFRP plates (CFRP-p) demonstrate strong potential for rehabilitating locally corroded RC slabs by extending service life, reducing maintenance costs, and supporting practical retrofit applications. The experimental results confirm the effectiveness of CFRP-p in enhancing structural durability and provide valuable guidance for rehabilitation practice.

b) In the experimental and analytical investigation of two-way RC slabs, post-test analysis particularly after cutting at the edge of the loading plate revealed a failure mode classified as flexural-triggered punching shear failure. Shear reinforcement enhanced secondary peak strength by enabling load redistribution after initial punching failure. Punching cone angles ranged from 9° to 26°, with asymmetry likely due to concrete quality variations. The load–displacement response shows that a 10% mass loss markedly reduces initial stiffness and peak load capacity, causing a shift in failure mode from flexural-triggered punching to pure flexural failure. Corrosion reduced stiffness by 19.3% (RCS-10 vs. RCS-0) but increased energy dissipation by 33.4%, promoting ductile behavior. Both experimental and analytical results confirmed that CFRP-p retrofitting effectively restores flexural capacity and stiffness, with ACI 440.2R predictions closely matching test outcomes. A modified design approach optimizes CFRP-p dimensions for targeted repair, ensuring strength recovery, improved ductility, and long-term durability.

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