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Performance of severely damaged reinforced concrete flat slab-column connections strengthened with Carbon Fiber Reinforced Polymer

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A R T I C L E I N F O

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A B S T R A C T

The punching shear failure of a slab-column connection is a sudden catastrophic failure. The majority of studies have been focused on the strengthening aspects of non-cracked slab-column connections. However, the attention given to the retrofitting of heavily damaged slab-column connections is comparatively less. Therefore, it is crucial to investigate the suitable damage repairing methods as well as post-strengthening methods to enhance performance of damaged slab-column connections. In this study, a total of twenty-six heavily damaged medium-scale flat slab-column connections were repaired using an in-situ chip concrete mixture. Then the damage repaired specimens were retrofitted using alternative arrangements of Carbon Fiber Reinforced Polymer (CFRP) in such a way to investigate the effects of sensitivity of bond parameters on punching shear performance. The punching shear capacity enhancements observed from retrofitted connections were in the range between 20% and 90%.

1. Introduction

Punching shear performance of a reinforced concrete flat slab is crucial due to the nature of sudden failure with fewer prior warnings. Therefore, in recent years many studies were carried out experimentally, numerically, and theoretically to investigate the behavior of flat slab-column connections [1,2]. When considering the retrofitting methods, the use of Carbon Fiber Reinforced Polymer (CFRP) as a retrofitting material has become quite popular. There are two basic approaches to strengthen slab-column connections using CFRP; External Strengthening and Internal Strengthening. External strengthening consists of attaching CFRP on the tension side of the slab to indirectly improve the punching shear capacity by increasing the flexural reinforcement ratio [1]. The external strengthening is done using CFRP fabrics [3,4] and CFRP strips [5]. According to the previous studies, the maximum punching shear capacity gain was noticed roughly around 35% [1,23]. The internal strengthening consists of embedding of CFRP rods [6] or CFRP fan anchors [7] through the slabs near the shear critical area. The studies revealed that the punching shear capacity enhancement obtained through internal strengthening of CFRP is approximately around 95% [2]. Since the premature failure at the concrete/adhesive interface is quite commonly identified in CFRP external strengthening applications, studies related to bond behavior of CFRP/adhesive and adhesive/concrete interfaces [8], the performance of bond behavior under different temperatures [9], and provision of insulation covers to protect the CFRP bond [10] have also been carried out.

Most of the studies conducted so far had discussed the performance of retrofitted non-cracked reinforced concrete flat slab-column connections emphasizing the strengthening of strength deficient slab-column connections due to construction or design errors before failure occurs. However, if unexpected damages to slab-column connections occur due to increments in service loads, material degradation caused by external environmental factors, and design or construction faults, the investigation for possible retrofitting techniques for such degraded members become important.

In order to observe the previously damage percentage influence on punching shear capacity in CFRP retrofitted slab-column connections, Gherdaoui & Guenfoud [13] pre-loaded the specimens up to 60% and 80% of their ultimate capacity. It was found that CFRP retrofitted slab panels had 10% − 30% gain in load carrying capacity with external application of CFRP without end anchors. In the study, the preloaded damage areas were not repaired prior to retrofitting using CFRP. Robertson & Johnson [14] investigated the behavior of CFRP externally strengthened pre-cracked specimens which were initially damaged by giving 8% of lateral drift. Prior to strengthening with CFRP, the cracks on the concrete were repaired by an epoxy and 20% of load carrying capacity increment was noted. In order to investigate the crack propagation, the specimens were cast in halves. Further, the

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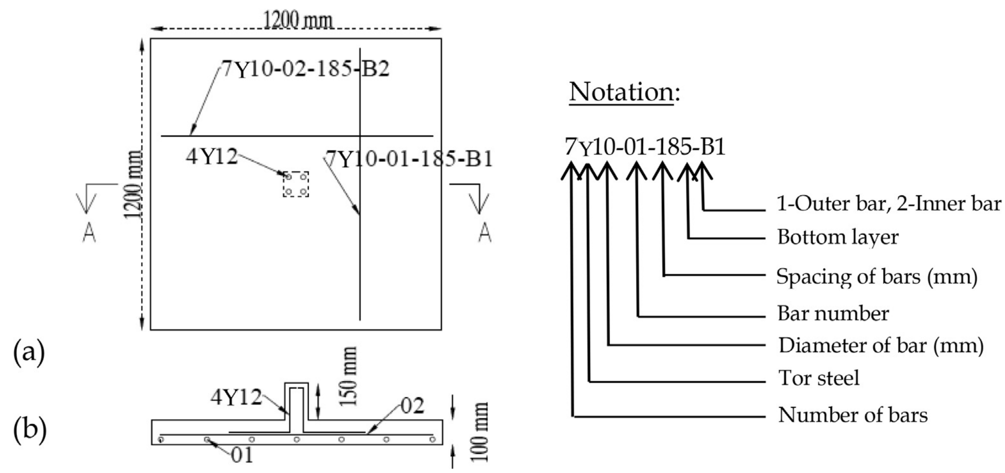


Fig. 1. Schematic diagram of steel reinforcement arrangement (a) Plan view (b) Sectional view A-A.

use of steel studs as a retrofitting material on heavily damaged concrete slab columns has also been experimentally investigated [15]. The insertion of such shear studs in heavily damaged slab structures should be carefully done, otherwise adverse collapsible situations might occur. Therefore, in order to avoid retrofitting approaches related to damaging the existing structure, the investigations for non-damaging retrofitting techniques shall be promoted.

The selection of the repairing methods and materials is based on the nature and significance of the damage, the economic requirements of construction, and the constraints in the application. The traditional means of repairing techniques have shown drawbacks such as corrosion, durability issues, the difficulty of post-installation, high weight/strength ratio, etc [11]. Therefore, the application of CFRP as a retrofitting material can be taken as a solution to overcome most of the aforementioned issues. Among different CFRP strengthening techniques, the repairing of damaged flat slabs can be done by attaching CFRP on the external surface. Internal strengthening of damaged flat slabs using CFRP can cause negative effects unless properly repaired [11,12].

In this study, the implementation of CFRP external strengthening as a non-damaging strengthening method to enhance the punching shear capacity on heavily damaged slab-column connections has been explored. In order to enhance the punching shear capacity, the use of end anchorage on the external CFRP strengthening scheme, and the effect from the application of multi-layered CFRP with alternative bond arrangements at the shear critical region have been investigated.

2. Experimental program

2.1. Overview

A total of twenty-six heavily damaged flat slab-column connections were prepared for this study. In order to prepare heavily damaged specimens, initially reinforced concrete slabs of 1200 mm × 1200 mm × 100 mm were cast with 100 mm × 100 mm × 150 mm stub columns connected to it. The detailed reinforcement arrangement of each specimen is shown in Fig. 1. The compressive strength was measured using the Rebound Hammer method and the average 28th day compressive strength was 29 MPa with a standard deviation of 3.2 MPa. Then, the specimens were simply supported by four I sections and subjected to a transient point load through the stub column located at the center until the failure occurred. Afterwards, the damage evaluation of flat slab specimens was investigated and the specimens with similar flexural and punching shear cracks were identified in such a way that no yielded steel rebar existed.

Each specimen selected had failed in punching shear and several flexural cracks were also observed on the tension side (Fig. 2). Since the slab-column connections were heavily damaged, a crack sealing repair method was not selected in this study according to the ACI guidelines [16]. Therefore, the damaged area was completely removed and repaired using an in-situ concrete repair grout. Then the specimens were kept to cure for 28 days under ambient conditions. At the end of the exposure period, they were strengthened using CFRP by following the wet lay-up method.

The repairing of heavily damaged specimens was conducted in two stages;

Stage 1: Repairing the heavily damaged specimens by removing the damaged old concrete
Stage 2: Strengthening repaired specimens using CFRP external strengthening method

2.2. Repairing and strengthening of heavily damaged specimens

Initially, the commonly damaged area was identified in each specimen and the area was marked on the tension side as shown in Fig. 3. A conical area which contained the damaged old concrete was removed from each specimen by hammer drilling (Fig. 4) to represent the same level of repairing. The removal of the damaged area was done up to a depth of 70 mm from the tension face. Therefore, the flexural reinforcement bars were visible at the mid-span (Fig. 5(a)). The schematic

Fig. 2. Crack pattern on the tension face of heavily damaged specimens.

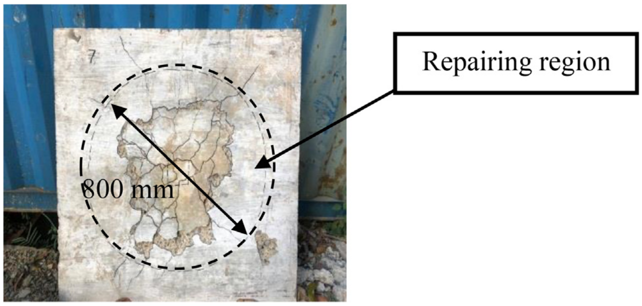


Fig. 3. The common area for repair.

Fig. 4. Drilling the damaged concrete area.

diagram of the typical cross-sectional view of a damaged area removed specimen is indicated in Fig. 6.

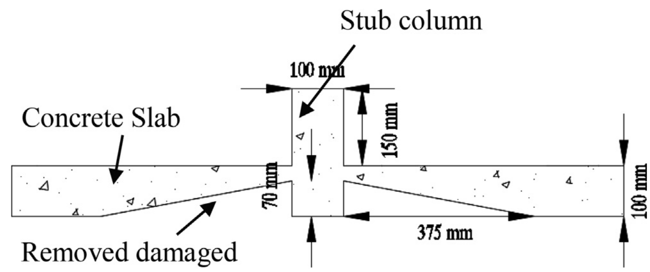


Fig. 6. The sectional view of a damaged area and the repairing area.

Table 1
Design parameters of the chip aggregate concrete.

Description	Value	Description	Value
Design strength (MPa)	40	Weight of cement (kg)	25
Slump value (mm)	100	Weight of crushed coarse aggregate (kg)	39.3
Maximum aggregate size (mm)	10	Weight of non-crushed fine aggregate (kg)	33.54
Cement strength class	OPC 42.5	Weight of water (kg)	10.9

The repairing of the old-damaged concrete was done using an in-situ chip aggregate concrete mixture. The design details of this concrete mixture are listed in Table 1. The wire brushing was done to remove loose concrete particles followed by water jetting which cleaned the old concrete surface prior to the application of the binding agent to create the bond between old-new concrete interface.

The repaired specimens were then kept for 28 days for curing before strengthening using the CFRP external strengthening technique. The strengthening schemes selected for this study are listed in Table 2.

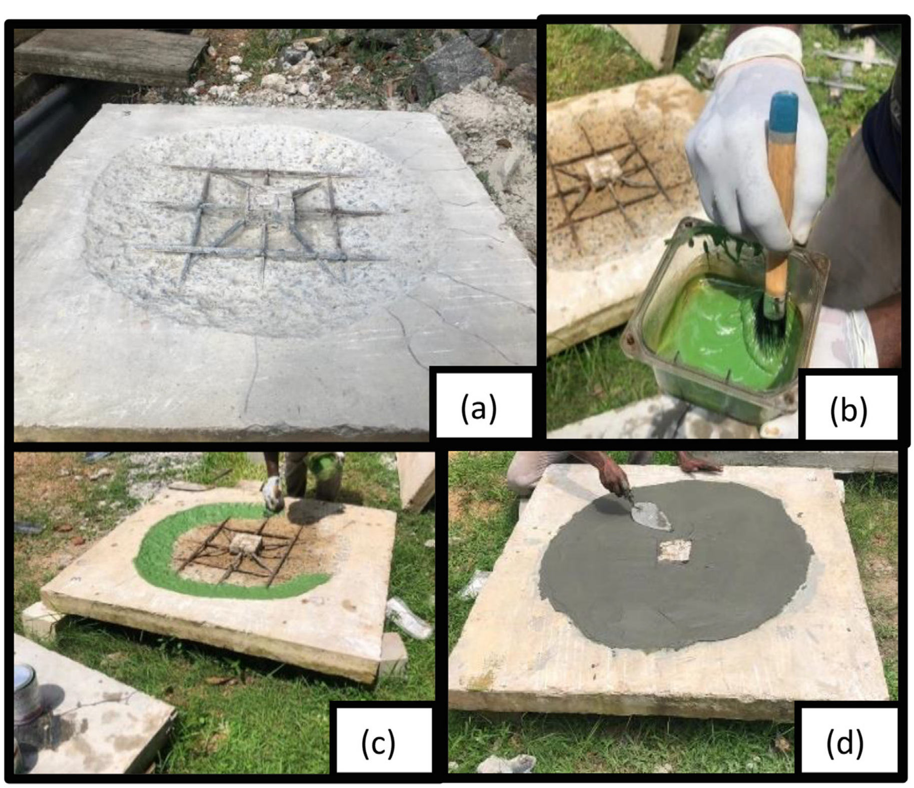


Fig. 5. Repairing of damaged samples (a) Prepared surface for repairing (b) Mixing the adhesive (c) Application of adhesive (d) Finishing of a repaired concrete flat slab-column specimen.

Table 2
Retrofitting of heavily cracked specimens using CFRP external strengthening technique.

Strengthening category	Specimen notation	Description	Number of specimens
Control sample	C-R	Repaired, non-strengthened control specimen (Fig. 7(a))	2
(1) Arrangement of CFRP at the shear critical area – Constant area of CFRP	O-R	Repaired specimen strengthened externally in orthogonal directions using 2 num: of 100 mm wide CFRPs (Fig. 7(d))	2
	S-R	Repaired specimen strengthened externally in skewed directions using 2 num: of 100 mm wide CFRPs (Fig. 7(e))	2
(2) Number of CFRP layers for the strengthening system	F-R	Repaired specimen strengthened externally in radial direction using a single layer of 4 num: of 50 mm wide CFRPs (Fig. 7(f))	2
	2F-R	Repaired specimen strengthened externally using two layers of 4 num: of 50 mm wide CFRPs (Fig. 7(f))	2
	3F-R	Repaired specimen strengthened externally using three layers of 4 num: of 50 mm wide CFRPs (Fig. 7(f))	2
(3) CFRP end anchoring on the strengthening system	S-E-R	Repaired specimen strengthened externally using 2 num: of 100 mm wide CFRPs in skewed direction and end anchored using one layer of externally attached CFRP patches (Fig. 7(j))	2
	OS-E-R	Repaired specimen strengthened externally using 50 mm wide CFRPs (100 mm strips split in two) in orthogonal direction and end anchored using one layer of externally attached CFRP patches (Fig. 7(h))	2
	SS-E-R	Repaired specimen strengthened externally using 50 mm wide CFRPs (100 mm strips split in two) in skewed direction and end anchored using one layer of externally attached CFRP patches (Fig. 7(g))	2
(4) Number of CFRP layers used for the end anchor system	F-E-R	Repaired specimen strengthened externally using four 50 mm wide CFRPs and end anchored using a single layer of externally attached CFRP patches (Fig. 7(i))	2
	F-2E-R	Repaired specimen strengthened externally using four 50 mm wide CFRPs and end anchored using two layers of externally attached CFRP patches (Fig. 7(i))	2
(5) Application of discontinuous CFRP strips for the strengthening	FC-R	Repaired specimen strengthened externally using four 100 mm wide CFRPs and in radial direction (Fig. 7(c))	2
	FD-R	Repaired specimen strengthened externally using four 100 mm wide discontinuous CFRPs and in radial direction (Fig. 7(b))	2

Table 3
Material properties of CFRP and adhesive.

Properties of CFRP fabrics [18]	Value	Properties of CFRP fabric Adhesive [19]	Value
Thickness (mm)	0.166	Tensile strength (MPa)	25
Modulus of Elasticity (GPa)	175.62	Compressive strength (MPa)	94
Yield Strength (MPa)	1575	Shear strength (MPa)	18
Elongation at Break	1%	Flexural Strength (MPa)	45
		Young's Modulus (GPa)	0.58

The measured material properties of the CFEP and adhesive are listed in Table 3. The schematic diagram of the CFRP strengthening scheme is shown in Fig. 7. The strengthening scheme was developed to compare the effects from five different bond sensitivity parameters as indicated in Table 2.

2.3. Test set up and instrumentation

Each slab specimen was placed on four steel I sections as shown in Fig. 8. A point load was applied through the stub column at a rate of 0.5 kN/mm using a hydraulic jack with a 500 kN capacity. The column was protected with a 20 mm thick steel cover to avoid the stress concentration at a loading point on the column face during loading. The downward deflection in the middle of the slab was monitored using three-dial gauges as shown in Fig. 8 until failure.

3. Test results and discussion

The failure load, failure mode, crack initiation, propagation and corresponding central deflection were monitored during and after testing. The effects from the arrangement of CFRP, the number of CFRP layers attached as flexural reinforcements, the number of CFRP layers attached as end anchors, and the effect from multiple CFRP strip attachments were determined.

3.1. Load versus deflection behavior

In general, the load–deflection relationship of structural elements yields the behavior of members in their service life. Table 4 shows the average ultimate punching shear capacity of repaired CFRP strengthened specimen with respect to repaired non-strengthened specimens (C-R). In addition to that, the maximum average deflection at the Centre of the slab is also presented.

3.1.1. The effects from the arrangement of CFRP at shear critical region

The study conducted by Malalanayaka et al. [4] demonstrated that the skewed placement of CFRP is recommended for non-cracked specimens compared to the orthogonal arrangement of CFRP. As indicated in Table 4, the punching shear capacity gain of the repaired and retrofitted flat slab column connections with radially applied CFRP specimens (F-R) was 26% higher than the skewed placement (S-R). This may be due to the distributed arrangement of CFRP at the shear critical area (Fig. 9).

3.1.2. The effects from the number of layers of CFRP for the strengthening system

The effect of applying CFRP in multiple plies was compared from the specimens F-R, 2F-R, and 3F-R. The CFRP plies were attached by epoxy adhesive using the wet lay-up method. Each ply consisted of four 50 mm × 1000 mm CFRP strips and the plan view of the retrofitting application is shown in Fig. 7(f). Further, in order to observe the effect of CFRP application in multiple plies, the CFRP strengthening scheme of F-R, 2F-R, and 3F-R specimens were prepared using one ply, two plies and three plies of CFRP respectively, as described in Table 2. The load-carrying capacity increases with the number of CFRP layers (Fig. 10). According to the test results, the provision of CFRP layers from one to three, enhanced the punching shear capacity from 60% to 82% with respect to the control specimens, C-R (Table 4). However, the decrease in the gradient of the punching shear strength versus the number of CFRP plies curve in Fig. 11 shows that the punching shear capacity enhancement is not linearly proportionate to the number of CFRP layers in the strengthening scheme.

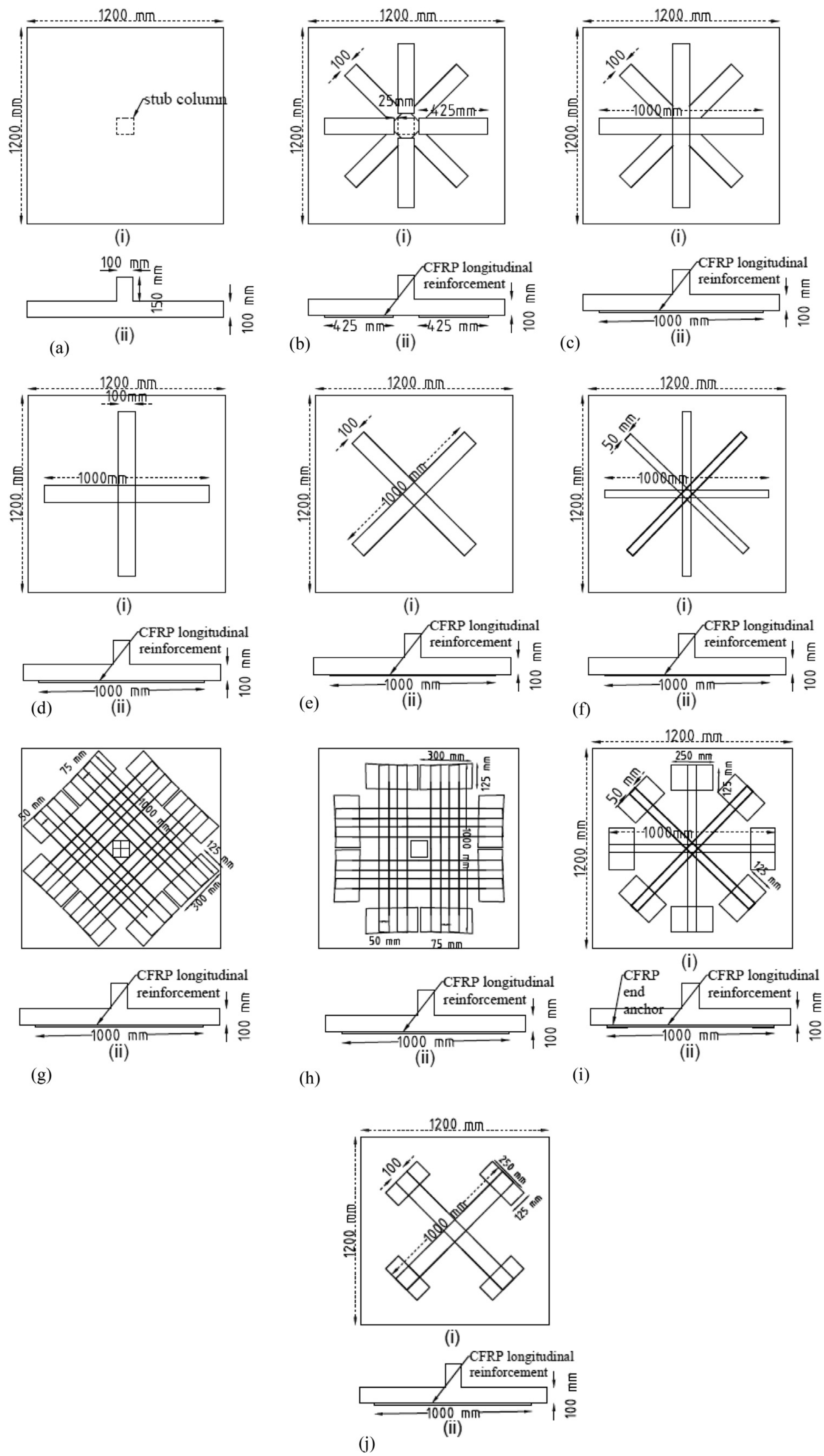


Fig. 7. Strengthening scheme of heavily cracked specimens (a) C-R (b) FD-R (c) FC-R (d) O-R (e) S-R (f) F-R, 2F-R & 3F-R (g) SS-E-R (h) OS-E-R (i) F-E-R & F-2E-R (j) S-E-R.

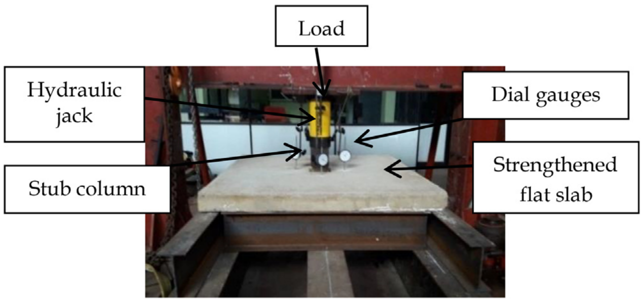


Fig. 8. Test setup and instrumentation.

3.1.3. The effects from the CFRP end anchoring on the strengthening system

The ultimate punching shear capacity of the end anchored skewed attached CFRP system (SS-E-R) was 56% higher than the non-end anchored skewed attached specimens (S-R) as given in Table 4. According to Fig. 12, when end anchors were provided, a considerable stiffness enhancement was induced to the structure.

3.1.4. Number of CFRP layers used for the end anchoring system

End anchoring on CFRP can delay the premature debonding failure of CFRP strengthening schemes. There are two types of end anchorage systems based on the application of anchor to the hosting body; end anchorage by damaging [1] and end anchorage by non-damaging [17]. In this study, as far as the damage repaired flat slab specimens are concerned, the non-damaging end anchoring method was selected to observe the end anchorage effect on enhancing the punching shear capacity. The types F-E-R and F-2E-R contain a similar arrangement of strengthening applications as indicated in Fig. 7(i). Two layers of size 250 mm × 125 mm CFRP strips were provided as the end anchors for F-2E-R and a single layer CFRP with the same size was provided as the end anchor for F-E-R. The load versus deflection behavior is indicated in Fig. 13. The application of two layers of CFRP for end anchors (F-2E-R) was noticed as 34% more effective in enhancing punching shear capacity than that of a single-layered end anchoring system (F-E-R) according to Table 4 average load capacities.

3.1.5. Application of discontinuous CFRP strips versus continuous CFRP strips for strengthening

When considering the radial arrangement of CFRP at the shear critical area, the application of continuous CFRP strips (FC-R) was found 41% less effective than discontinuous application of CFRP (FD-R) as shown in Table 4. The load versus deflection performance is indicated in Fig. 14. Further, the CFRP strip part of FC-R at the shear critical region was subjected to a higher tension compared to FD-R. Further, the comparatively high deflection at the stub column area induces a higher rotation angle at the tension face of the slab and that increases the tensile stresses [20]. In the case of FD-R specimens, each CFRP strip was not subjected to a high rotation as in FC-R and it only provides anchorage to the CFRP at the localized tensile stress area where the shear critical perimeter lies. Since the stress distribution in CFRP in the experiment cannot explain the exact scenario at interface levels, a finite element model was created to observe the behavior of FD-R and FC-R specimens.

3.2. Mode of failure and crack patterns

Since these specimens were prepared by removing the damaged old concrete area, the punching shear failure occurred at the old and new concrete interface, which is the weakest part of the system. The flexural cracks started appearing at the tension face when the load level reached 15% of punching shear capacity. Once the crack widths approximately reached 0.5 mm, the punching shear failure occurred and the crack patterns at the failure are shown in Fig. 15.

4. Finite element modeling to understand the behavior of the application of discontinuous CFRP strips for strengthening

A numerical model was developed using the commercially available software ABAQUS [21]. Initially, the geometrical modeling was done for concrete, steel rebars, CFRP, and adhesive layers. The concrete and steel elements were discretized using six-node linear triangular prism elements (C3D6R) in the ABAQUS solid element library [22]. CFRP was modeled using 6-node triangular in-plane shell elements (SC6R) and adhesive modeling was done using 6-node three-dimensional cohesive element (COH3D6) [21].

When assigning material properties, the Concrete Damage Plasticity Model (CDPM) was used as it is capable of defining the damage characteristics both in tension and compression and also the complete inelastic behavior. Since the maximum aggregate size used in the experimental program was 20 mm, the mesh size of concrete was selected as 20 mm × 20 mm. However, a mesh sensitivity analysis was also conducted. It indicated the selected model with that mesh density yields optimum solutions.

The damage properties of steel were not presented in the model because in the experimental program flexural reinforcement yielding was not noticed. Therefore, only elastic properties were introduced [22] for steel. The damage modeling of CFRP was done using the

Table 4
Test results of the damaged CFRP retrofitted specimens.

Specimen	Ultimate load (kN)	Max. deflection (mm)	Specimen	Ultimate load (kN)	Max. deflection (mm)	Average Load Carrying Capacity (kN)	Average deflection at failure (mm)	*Percentage Capacity gain (with respect to control specimen)
C-R-a	27.05	4.97	C-R-b	30.5	5.00	28.78	4.99	–
O-R-a	38.5	3.52	O-R-a	38.2	7.86	38.35	5.69	33.28%
S-R-a	39.58	1.43	S-R-b	37.74	3.87	38.66	2.65	34.35%
F-R-a	45.2	5.03	F-R-b	46.85	4.52	46.03	4.78	59.92%
2F-R-a	47.58	3.85	2F-R-b	47.2	3.3	47.39	3.58	64.66%
3F-R-a	51.95	4.1	3F-R-b	52.8	2.15	52.38	3.13	81.98%
S-E-R-a	35.91	2.26	S-E-R-b	37.41	2.20	36.66	2.23	27.40%
OS-E-R-a	44.26	6.82	OS-E-R-b	45.30	6.54	44.78	6.68	55.62%
SS-E-R-a	52.78	6.30	SS-E-R-b	56.50	5.78	54.64	6.04	89.89%
F-E-R-a	36.41	4.93	F-E-R-b	44.42	3.51	40.42	4.22	40.45%
F-2E-R-a	55.11	8.44	F-2E-R-b	45.1	3.44	50.11	5.94	74.13%
FC-R-a	33.74	6.24	FC-R-b	35.6	6.00	34.67	6.12	20.49%
FD-R-a	46.76	6.53	FD-R-b	45.9	6.25	46.33	6.39	61.01%

1. Here, '-a' and '-b' at the end of each specimen type indicate the existence of twin specimens in each specimen type.
2. * capacity gain (%) = [Average capacity of considered sample – Average capacity of control sample (C-R)] × 100 /[Average capacity of control sample (C-R)].

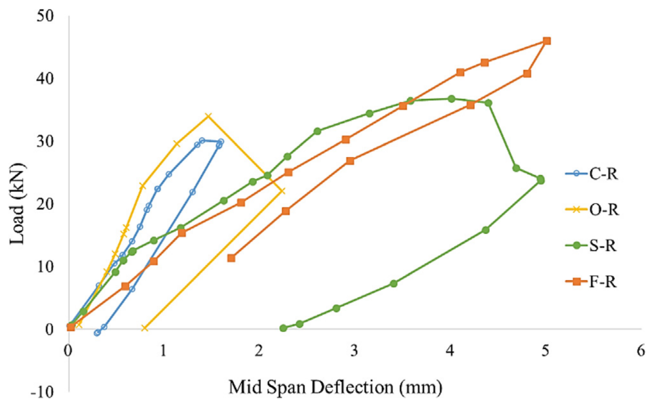


Fig. 9. Load versus deflection behavior of arrangement of CFRP at the shear critical area.

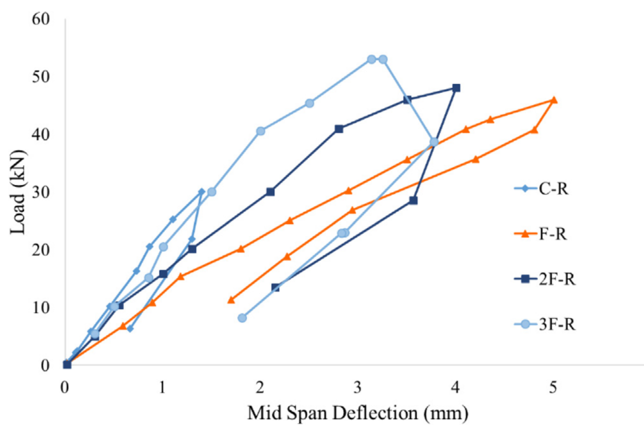


Fig. 10. Load versus deflection behavior of radially attached CFRP strips in multiple layers.

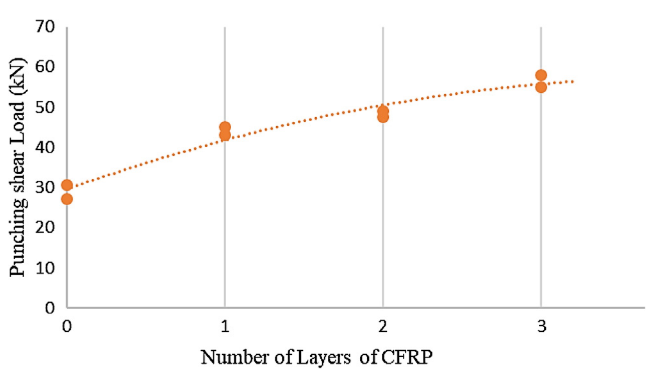


Fig. 11. Punching shear capacity variation with respect to multi-layered CFRP systems.

Hashin's damage model considering the failure modes of fiber in compression and tension [21].

The adhesive layer was defined using the cohesive element with the continuum approach. A finite thickness of 0.1 mm was used for the cohesive element. The adhesive layer damage modeling is important for the onset and propagation of delamination. The definition of failure was input using stress–strain criteria. The interface between CFRP and adhesive was modeled assuming perfect tie constraint bond conditions and the adhesive/concrete interface was defined using tangential slip behavior.

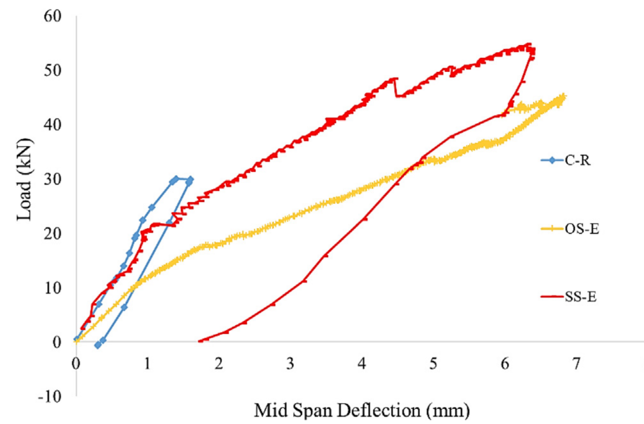


Fig. 12. Load versus deflection behavior of CFRP strengthened specimens with end anchors.

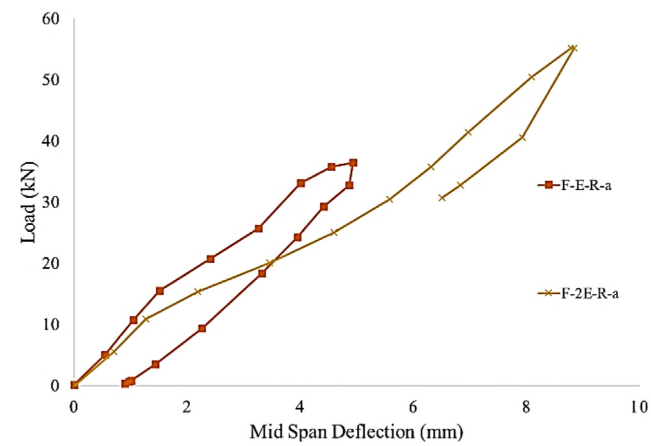


Fig. 13. Load versus deflection of when applying end anchors in multiple layers.

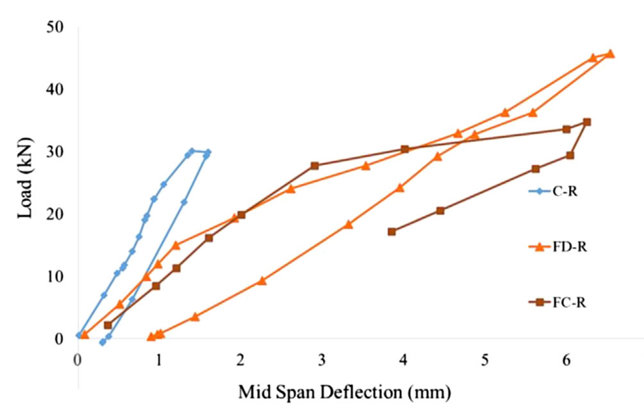


Fig. 14. Load versus deflection of radially attached CFRP strips.

The application of boundary conditions was done considering the symmetry of the model in such a way that the horizontal restraints were introduced at the symmetric planes to imply the experimental continuity of the specimen. Since the four edges of the slab were supported by four steel I sections, the vertical restraints were provided to the bottom of the slab at support locations (Fig. 16). The load that was applied on the stub column by the hydraulic jack during testing was

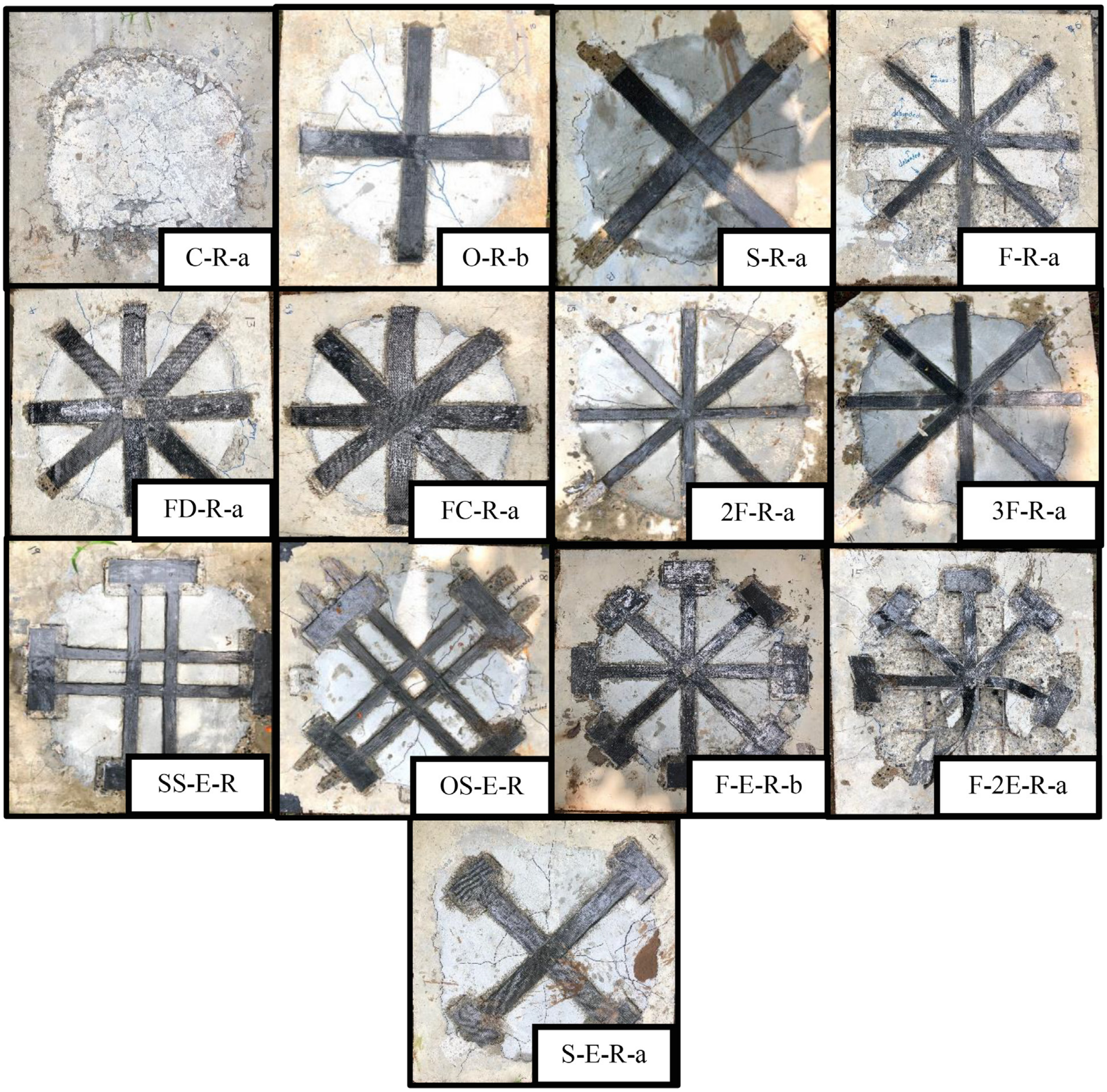


Fig. 15. Failure mechanism of repaired strengthened slab-column connections.

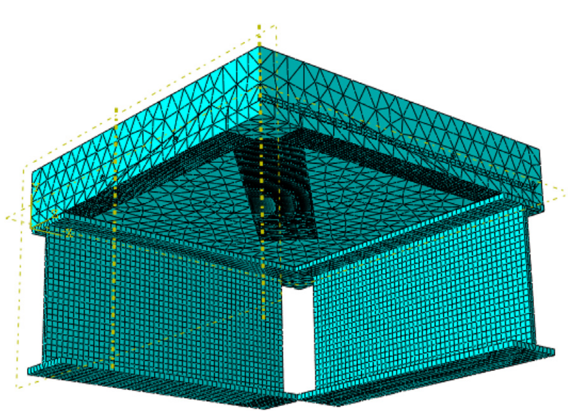


Fig. 16. Meshed model.

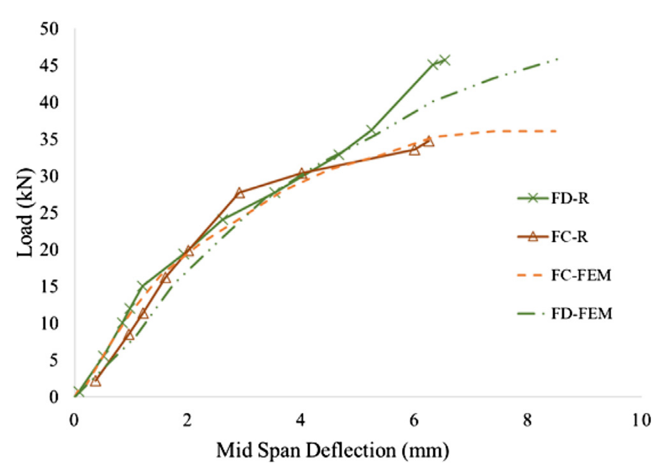
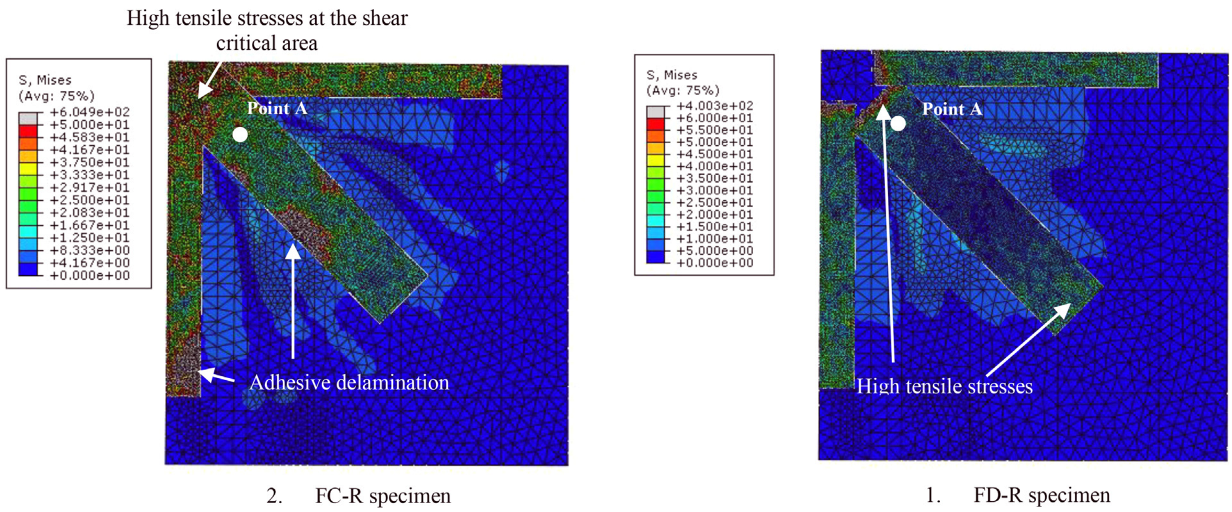


Fig. 17. Validation of the numerical models comparing the results with the experimental results.



2. FC-R specimen

1. FD-R specimen

Fig. 18. Stress distribution at the adhesive layer when the load was constant.

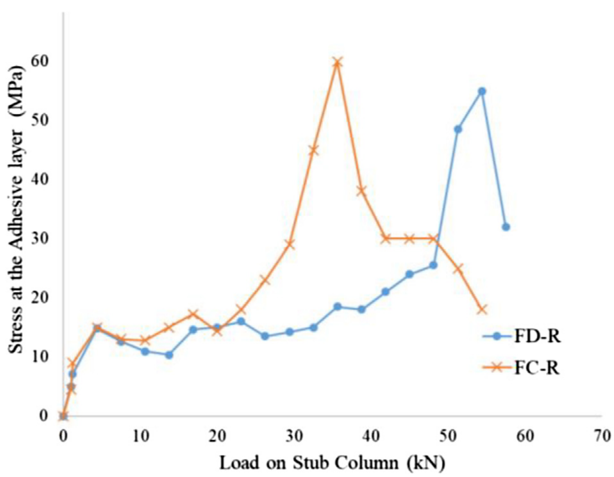


Fig. 19. The stress variation at point A.

assumed as an evenly distributed pressure on the slab area, equivalent to the stub column area.

The numerical modeling was done for both FC-R and FD-R specimens. The validation of the models was carried out by comparing the load versus deflection of the experiment with the numerical behavior (Fig. 17). Fig. 18 shows the stress behavior of specimens at 30 kN load level. Though both slabs were subjected to the same loading, the FC-R specimen shows a higher stress distribution at the adhesive layer, and due to the higher stress, delamination started. To compare the interfacial stress level variation, Point A, which is located an effective depth away from the column face on the adhesive/concrete interface was selected. The stress variation in Fig. 19 clearly shows that the stress near the column at the tension face of the slab in FC-R specimens reached higher stress levels and delaminated prior to FC-R causing the failure at a low punching shear capacity.

5. Conclusions

The behavior of CFRP strengthened heavily damaged slab-column connections was investigated. The following conclusions were made;

- An increase in the flexural reinforcement ratio using unidirectional externally bonded CFRP was found to be an effective way to enhance the punching shear capacity while improving the flexural capacity of flat slabs. The maximum punching shear capacity enhancement with external CFRP reinforcements was on average about 90% in this study. The ductility of retrofitted slab specimens was also improved with increased flexural CFRP ratio.
- The radial arrangement of CFRP on the tension face of the shear critical area of a slab could increase the punching shear capacity of flat slabs more than that of orthogonally or skewed attached CFRP.
- The provision of CFRP in layers is more effective than providing the same area of CFRP in a single layer on the tension surface to enhance the punching shear capacity of damaged slab-column connections.
- The provision of end anchors increases stress distribution and reduces stress localization. This eventually delays the failure load of the flat slab specimen. Further, the application of two layers of CFRP end anchorage increases the stress distribution at the bond line more than a single-layered CFRP anchor.
- Properties of repairing material are important to enhance the performance of retrofitted slab-column connections. The most important aspect of the damaged-repaired CFRP strengthened joint is the cold joint preparing technique because the cold joint separation can occur prior to the failure of the CFRP bond.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

CRediT authorship contribution statement

M.A.L. Silva: Methodology, Software, Validation, Formal analysis, Writing - original draft, Visualization. **K.V. Dedigamuwa:** Formal analysis, Investigation, Methodology, Software, Writing - review & editing. **J.C.P.H. Gamage:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision. **:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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