# CFRP LAMINATES TO STRENGTHEN REINFORCED CONCRETE FLAT SLABS AGAINST PROGRESSIVE COLLAPSE


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## ABSTRACT

Although progressive collapse is relatively low probability events, the catastrophic consequence leads to structural engineer and building owners had interesting to evaluate the ability of existing buildings in resisting such kind of collapse. Previous studies had found that reinforced concrete (RC) flat slabs had much higher vulnerability for progressive collapse compared with RC beam-slab structures due to without beams to redistribute the axial force initially carried by the lost column. Thus, in order to reduce the likelihood of collapse of flat slabs, necessary strengthening should be applied to the existing buildings. However, to date, limited studies had been carried out to investigate the efficiency of strengthening schemes to mitigate the progressive collapse of flat slabs. Therefore, a series of experimental and analytical analysis was carried out for this purpose. Two different strengthening schemes were proposed and evaluated. The experimental and analytical results indicated that proposed strengthening schemes could significantly improve the progressive collapse performance of flat slabs.



**Keywords:** Progressive Collapse, Fiber Reinforced Polymer, Flat Slab, Strengthening, Retrofitting


## 1. INTRODUCTION

Abnormal loading events such as explosions, vehicle collisions, and foundation failure are not considered in normal structural design. The local failure caused by such low-probability events, however, may lead to chain reaction of structural damage, even total collapse of the building. The damage of Ronan Point apartment building in London, Murrah Federal Building in Oklahoma City has gained increasing interest in the civil engineering research community. Several design guidelines (GSA 2003 and DoD 2009) had been proposed to assess the potential of progressive collapse of a building after removal of one or several load-carrying members. Moreover, several research studies had been conducted by Qian and Li (2012a,b and 2013a) to study the performance of beam-slab substructures to mitigate progressive collapse under the loss of a corner column scenario. Qian and Li (2013a) conducted several push-down tests to study the quasi-static performance of RC buildings under the loss of a corner column scenario while Qian and Li (2012a)


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conducted a series of dynamic tests with similar specimens as Qian and Li (2013a) to simulate progressive collapse behavior of RC buildings under suddenly removal of column scenario. The dynamic effects due to sudden removal of column were evaluated by comparison of their static and dynamic performances. As in ordinary cast-in-place buildings, beam, column, and slab are cast monolithically, it is necessary to evaluate the slab effects on the vulnerability of RC buildings in resisting progressive collapse. Thus, Qian and Li (2012b) conducted several beam-slab substructures to study the slab effects. Although the researchers had done relatively many studies to deal with beam-slab structures in resisting progressive collapse, limited studies were carried out regarding the performance of flat slab or flat plate structures in resisting collapse. Hawkins and Mitchell (1979) had discussed the factors influencing the initiation and propagation of progressive collapse in flat plate structures. However, in Hawkins and Mitchell (1979)'s study, more attentions were taken on the failure of flat slab due to punching failure in construction or over-load, rather than the propagation of failure after removal of one or several columns. In order to understand the vulnerability of flat slab or flat plate structures in resisting progressive collapse caused by the loss of a corner column, a study was carried out by Qian and Li (2013b). It was found that flat slab especially flat plate structures had very high vulnerability for collapse if one of the corner columns is lost. Thus, it is necessary to do some research on strengthening flat slab or flat plate structures to mitigate or eliminate the risk of progressive collapse. In this paper, three specimens were carried out to study the efficiency of proposed strengthening schemes to improve the progressive collapse performance of flat plate structures. One of the specimens is taken as control specimen while the remaining two specimens are strengthened by two different strengthening schemes.

## 2. EXPERIMENTAL PROGRAM

### 2.1. Test Specimens

Three flat slabs (C, SO, and SD) were tested in this study. C, SO, and SD represents control specimen, strengthened specimen by orthogonally bonded CFRP strips, and strengthened specimen by diagonally bonded CFRP strips, respectively.

The Control Specimen C was designed in accordance with ACI-08 (2008). The dead load of the prototype structure due to 210.0 mm thick slab was 5.1 kPa. The additional dead load was assumed to be 1.0 kPa. The equivalent additional dead load due to the weight of in-fill walls was 2.25 kPa. The live load was assumed to be 2.0 kPa. One-third scaled substructures were cast and tested in this study. For detail derivation, please refer to Qian and Li (2012a). Fig. 1 illustrates the dimensions and reinforcement details of the Control Specimen C. As shown in the figure, one corner column stub, three enlarged columns and a slab with 70 mm thickness were cast monolithically. The column stub in the corner represented the remnants of a removed column. The size of the corner stub was 200 mm × 200 mm. The size of the remaining columns was 250 mm× 250 mm. It was enlarged to prevent damage occurring in these columns and to ensure equivalent fixed constraints applied on these columns. The slab reinforcement in the middle strip comprised of R6 rebar at 250.0

mm in two layers at the top and bottom whereas the column strip was composed of two layers of R6 rebar spaced at 125.0 mm and 250.0 mm at the top and bottom, respectively. Moreover, reinforcements were installed in the slab-corner column connection to prevent or delay possible brittle failure of the specimen within the small deformation stage due to punching shear.

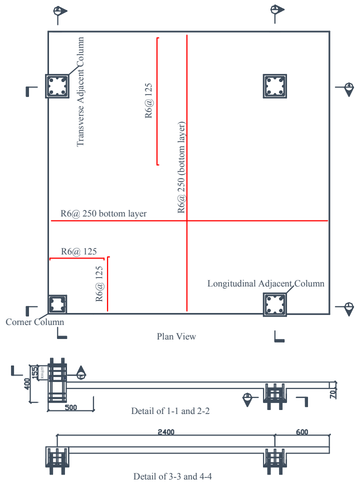



Fig. 1: Dimensions of the test specimens

As the test results from control specimens had indicated, the existing dimension and reinforcement details could not prevent progressive collapse of the flat slabs if a corner column was suddenly removed. Thus, in order to upgrade the resistant capacity of the flat slabs, another two specimens (SO and SD) were strengthened by externally bonded CFRP laminates. It should be noted that the dimension and reinforcement details of the Strengthened Specimens SO and SD were similar to the Control Specimen C. The details of the strengthening schemes are described in following sections. The average concrete compressive strengths were about 19.5 MPa, 31.7 MPa, and 29.9 MPa for Specimens C, SO, and SD, respectively. The yield strength, yield strain, and ultimate strength of the R6 reinforcement were 430 MPa, 2210 με and 516 MPa, respectively. The material properties of the CFRP are shown in Table 1.

**Table 1: Properties of Tyfo® Fibrwrap composite system**

| Parameters | Propertiesa |
|---|---|
| | CFRP with epoxy, Tyfo® SCH-41 Composite |
| Type of FRP | Unidirectional CFRP sheet |
| Ultimate tensile strength in primary fiber direction | 986 MPa |
| Elongation at break | 1.0% |
| Tensile Modulus | 95.8×103 MPa |
| Laminate thickness | 1.0 mm |

Note: a Properties values given are based on test value by supplier (FYFE Asia Pte. Ltd in Singapore)

## 2.2. Test Setup

A schematic of the experimental setup is shown in Fig. 2. A hydraulic jack was utilized to apply vertical displacement on the corner stub. It should be noted that the loading process was force-controlled before the specimens reaching their first peak capacities. After that, a displacement-controlled loading process with 10 mm interval was applied. Vierendeel action can be characterized by relatively vertical displacement between slab-column connections and double curvature deformations of column strips and columns. In order to equivalently simulate Vierendeel action applied on the test specimens or create positive bending moment (tensile at bottom) at the column strip near the corner column, a steel assembly was specially designed. For the detailing of design of the steel assembly, please refer to Qian and Li (2013b). Furthermore, three steel legs were utilized to support the specimens and to provide equivalent fixed support conditions on the adjacent and interior columns. Finally, in order to partially simulate the influence of the continuity of the slabs on the overall performance, the slab was extended beyond the fixed-support by one-fourth of the span in both directions. Five steel weight assemblies were applied on the extended part of the slab to simulate the influence of the continuity of surrounding slabs on the response of the specimens.

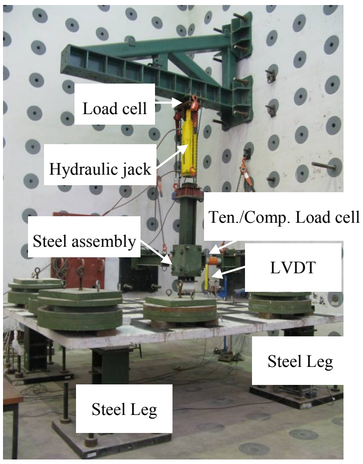



**Fig. 2: A CFRP strengthened specimen ready for test**

## 2.3. Instrumentation

A load cell was utilized to measure the vertical load applied on the corner stub. One linear variable differential transformer (LVDT) with 300.0 mm travel was installed vertically to measure the vertical movement of the corner column stub during the test. In order to monitor the horizontal movement of the corner joint during the test, a line displacement transducer with 1200.0 mm travel was installed horizontally. For control specimen, a total of 23 strain gauges were mounted on the reinforcements at strategic locations in order to monitor the strain variation along the corner column and slab during the test. For strengthened specimens, strain gauges were not only installed in the corner column and slab, but were also placed on the CFRP laminates.

## 3. TEST RESULTS AND OBSERVATIONS

### 3.1. Behavior and failure modes of control specimens

The failure mode of Control Specimen C is shown in Fig. 3. As shown in the figure, severe diagonal cracks passed through the center of the slab. Flexural cracks were not only observed in the top face of the slab near the adjacent column, but also in the bottom face near the corner column due to Vierendeel action. No damage was observed at the corner column. For detailed description of the failure modes and crack pattern development, please refer to Qian and Li (2013b).

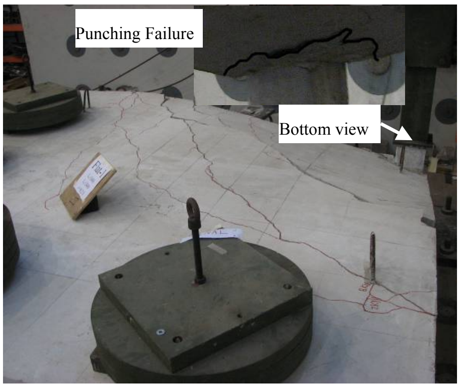



**Fig. 3. Failure modes of Control Specimens C**

The vertical load-displacement curves of test specimens are shown in Fig. 4. As seen from the figures, significantly tensile membrane action was observed in the load-displacement curve at large displacement stage. It should be noted that punching failure was observed in the slab-corner column connection. However, the punching failure did not prevent the development of tensile membrane action may be due to ‘Hanging Effects’ by bottom integrity reinforcement.

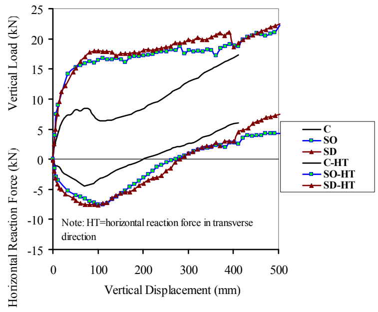



**Fig. 4: The vertical load versus the vertical displacement of the test specimens**

### 3.2. Strengthening schemes

Through analytical analysis of the test results of the control specimens, the dynamic ultimate strength of Control Specimen C was predicted as 10.0 kN. However, the design axial force of this specimen was 15.9 kN. Thus, this specimen would collapse if the corner column was suddenly removed and without any strengthening. Detailed explanation of the dynamic ultimate strength was shown in the discussion sections. Therefore, two strengthening schemes were proposed to upgrade the resistant capacity of Specimen C. Before the application of CFRP laminates, the specimens were carefully prepared by grinding the regions which will be bonded to the CFRP laminates, to achieve a fully smooth surface. The slab-column interfaces were rounded at a radius of about 20 mm to avoid CFRP cracks due to local stress concentration. The wet lay-up CFRP application method was employed on the specimens. It involves the use of epoxy resin for bonding and impregnation of the CFRP laminates. Putty was applied to prevent debonding due to unevenness. The following describes the procedures for the CFRP strengthening schemes proposed.

The failure modes of control specimens (refer to Fig. 3) had indicated that severe flexural cracks were observed in the top slab-adjacent column interfaces and bottom slab-corner column interfaces. Thus, in order to upgrade the resistant capacity of the flat slabs, the flexural strength of the column strips should be strengthened. As shown in Fig. 5, one layer of CFRP L-wrap (Step 1 in Fig. 5a) was applied at each slab-column interface. The CFRP sheet was bent at 90 degrees and thereafter extended 50 mm along the column and 540 mm along the slab. Although the theoretical width of the flange of the slab is four times of the slab depth (Park and Paulay 1975), the width of 225 mm and 200 mm was selected for CFRP L-wrap near the adjacent column and corner column respectively for easy connection with the columns. The length of the CFRP L-wrap (540 mm) along the slab was designed to coincide with the cut-off point of the slab top reinforcement. 0.3 times of the clear span, as recommended in ACI-08 (2008). Then, a CFRP strip with 50 mm width (Step 2 in Fig. 5a) was wrapped around the column to better bond the CFRP L-wrap along the slab and delay the debonding of CFRP L-wrap at the slab-column interfaces. It should be emphasized that both top and bottom faces of the column strips were flexurally strengthened as the flat slabs not only had possibility of losing corner columns, but also had possibility of losing exterior or interior columns.

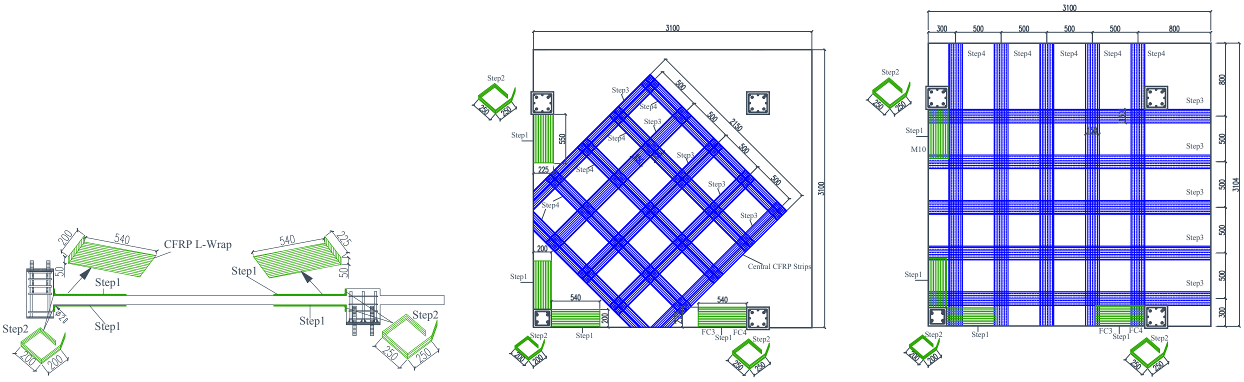
It should be noted that severe diagonal cracks were observed in the center slab as no top reinforcements were installed in the center of the slab. Thus, flexural strength of the center slab also had to be strengthened for reducing the crack width and increase the resistant capacity. For strengthening Scheme 1 (SO), the flexural strength of the center slab was strengthened via externally bonded orthogonal (0-90 degrees) CFRP strips with 150 mm width on the top face of the slab (refer to Fig. 5b). For strengthening Scheme 2 (SD), as shown in Fig. 5c, CFRP strips with 150 mm width were diagonally (45-135 degrees) bonded on the top face of the slab. It was understandable that Scheme 1 (0-90 degrees) was an easier application compared to the Scheme 2 (45-135 degrees).

### 3.3. Behavior and Failure Modes of the Strengthened Specimens

The failure modes of Strengthened Specimens SO and SD are shown in Figs. 6a and 6b, respectively. The failure of strengthened specimen is controlled by de-bonding of CFRP strips. As shown in Fig. 4, the Strengthened Specimen SO had its first peak capacity, initial stiffness, peak tensile membrane action, and dynamic ultimate strength increased by 97.7 %, 77.6 %, 28.9 %, and

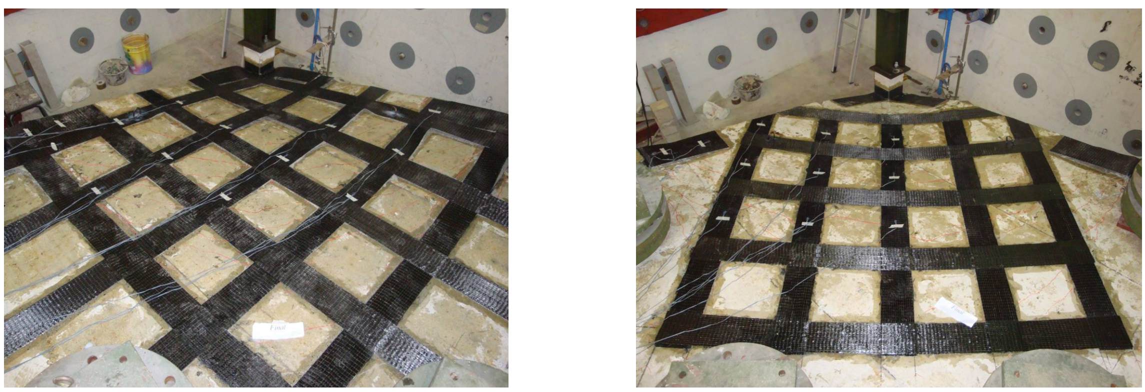
74.0 % respectively compared with the Control Specimen C. However, for Strengthened Specimen SD, the first peak capacity, initial stiffness, peak tensile membrane action, and dynamic ultimate strength were increased by 111.8 %, 90.3 %, 30.1 %, and 82.0 % respectively. It should be noted that the initial stiffness was defined as the secant stiffness at the first yield strength in this study.

Comparing the performance of SD with that of SO, it can be seen that SD generally performed slightly better than SO. This was possibly due to the central CFRP strips were placed directly perpendicular with the diagonal crack (along the principal tensile stress) in Scheme 2 (45-135 degrees). As explained in above, theoretically, Scheme 1 (0-90 degrees) could increase the bending moment capacity similar as Scheme 2 (45-135 degrees). In reality, the interaction of the orthogonal strips could possibly jeopardize the effectiveness.




(a) (b) (c)

**Fig. 5: Proposed strengthening schemes: (a) elevation view of strengthening of column strips, (b) plan view of strengthening scheme 1 (SO), (c) plan view of strengthening scheme 2 (SD)**



(a) (b)

**Fig. 6: Failure mode of strengthened specimens: (a) SO, (b) SD**

## 4. CONCLUSIONS

1. The Control Specimen C has a high likelihood of developing progressive collapse following the sudden removal of a corner column. Thus more attention should be paid to flat slabs during the evaluation of the RC structures to mitigate progressive collapse.

2. Strengthened Specimens SO and SD could increase the dynamic ultimate strength of Control Specimen C by 74.0 % and 82.0 %, respectively. Thus, Scheme 2 (45-135 degrees) performed slightly better as compared to Scheme 1 (0-90 degrees) with respect to resistance capacity. This can be attributed to the fact that the CFRP strips were directly perpendicular with the main slab diagonal cracks in Scheme 2. However, for Scheme 1 (0-90 degrees), the CFRP strips in two directions worked together to resist the tensile principal stress of the slab diagonal cracks. The interaction of the perpendicular CFRP strips might jeopardize the effectiveness. However, it should be noted that the difference in load resistant capacity between the SO and SD was small. Considering the ease of the application, deformation behavior and ductility, the authors suggest using the Scheme 1 (0-90 degrees) in practice.

3. The failure of the strengthened specimens was mainly due to debonding of the CFRP laminates and severe cracks concentrated in the cutoff point of the CFRP sheets and strips. To increase the effectiveness of strengthening, it is suggested that fiber anchors or other mechanical anchors be applied to CFRP laminates and to apply continual CFRP sheets (Step 1 in Fig. 5a) for column strip retrofitting and continual central CFRP strips (Step 3 in Fig. 5c) for central slab retrofitting in real practice.

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