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**CIES
03-38**

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EXPERIMENTAL RESULTS OF ONE-WAY SLABS WITH OPENINGS STRENGTHENED WITH CFRP LAMINATES

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One-way RC slabs are very common as a floor system in US structures. It often happens that structures need to be renovated due to many factors, such as placing new staircases, elevators, additional skylights or (more often) wiring and ducts through the existing floor slabs. In these instances, openings usually need to be created, weakening the existing floor system. Fiber-reinforced polymer (FRP) matrix composites can provide an efficient method for strengthening slabs after installation of cut-outs, but it is important to define guidelines for the designer, particularly when the openings are created in the negative moment region. This paper presents the results of an experimental program that investigated the behavior of RC one-way continuous flat slabs with openings in both the positive and negative moment regions, strengthened with externally-bonded CFRP laminates following two different schemes of strengthening. The significance of this work is that instead of testing specimens manufactured in the laboratory, the authors had the possibility of using as a research test bed, an old parking garage scheduled for demolition. Experimental results revealed that externally-bonded CFRP sheets can significantly increase the flexural capacity of the system for those specimens containing an opening in the positive moment region. For specimens with an opening in the negative moment region and strengthened using top-surface CFRP laminates, shear failure occurred at a lower load capacity than the original unstrengthened specimen. This has considerable implications for the design of such negative-moment strengthening schemes, and reasons for this behavior are discussed.

INTRODUCTION

Strengthening of existing reinforced concrete (RC) structures can arise for many different reasons: upgrading the load-carrying capacity, the necessity to make changes in the structure or the need to solve problems that have occurred during construction. Holes in slabs are one of the most common problems encountered. In these cases, installation of escalators, elevators or utilities such as air conditioning, heating or wiring ducts is often required.

Depending on the type of upgrade, the position of the opening could be either in the positive or negative moment region of the slab, creating differing problems that cannot be addressed using the same philosophy.

To date, most research in this field has been conducted to understand behavior of slabs containing openings placed in the *positive* moment region to address the design issues that may arise when cutouts are created (Zaslavsky 1967, Lash and Banerjee 1967, Islam and Park 1971). Over the past ten years, the problem of strengthening slabs using FRP has been addressed by researchers by substituting the previously commonly-used steel plates, thereby overcoming many problems encountered using this technique, such as weight and difficulty in handling (especially in areas where access is limited), potential corrosion, length limitations and difficulties associated with joints (Ichimasu et al. 1993, Arockiasamy et al. 1995, Karbhari et al. 1999, Takahashi and Sato 2001, Teng et al. 2002). Another important aspect that seems to have been neglected in such research is the role that boundary conditions play in a continuous flat RC slab. Enhancement in flexural strength of RC slabs due to horizontal restraint at the boundaries has been amply demonstrated through both theoretical and experimental work, showing that increase in strength due to compressive membrane forces induced at the boundary restraints can be substantial (Andreasen and Nielsen 1986, Lahlouh and Waldron 1992).

The research described in this paper is part of an ongoing effort to investigate the use of FRP as a means of strengthening and repairing concrete slabs containing cutouts. The uniqueness of this work is related to the use as a test bed of an existing parking garage, which had been scheduled for demolition. The results of tests on this structure are described.

EXPERIMENTAL PROGRAM

Building characteristics

The parking garage used for the tests was located in St. Louis, Missouri, and was scheduled for demolition in July 2002. The structure was constructed in the 1950s, consisting of a concrete-encased steel frame, supporting a one-way RC floor system (see Figure 1a and 1b). Due to the old age of the structure, no construction or maintenance records were available from the owner. For this reason, a field investigation to evaluate geometry and material properties of the structure was carried out.

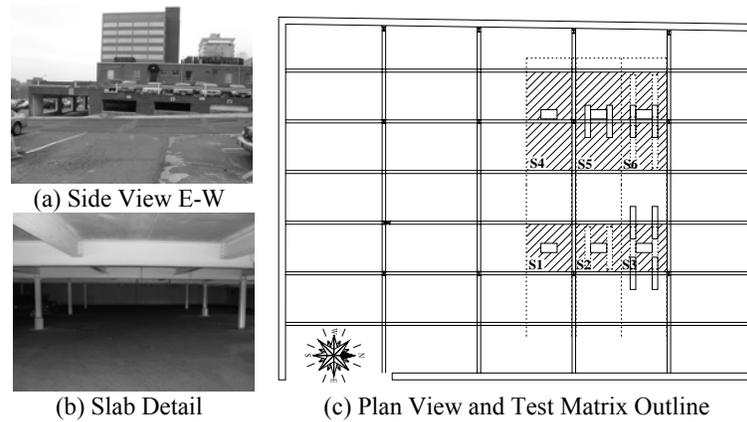


Figure 1–Parking Garage

Based on the survey, it was determined that the typical RC slab was 5.5 in (14 cm) thick, 16.8 ft (512 cm) long and 8.38 ft (255 cm) wide. The main reinforcement consisted of one layer of #4 (12 mm) steel bars spaced 12 in (30 cm) center-to-center at mid span, and #4 steel bars spaced 12 in (30 cm) center-to-center at the support in the E-W direction. In the N-S direction, #4 steel bars, spaced 18 in (45.7 cm) center-to-center were used as temperature and shrinkage reinforcement. All steel bars tested showed an average yield strength of $f_y = 60$ ksi ($f_y = 415$ N/mm²). Concrete properties were evaluated using six cores taken from different locations in the slab prior to testing and an average concrete cylinder strength of $f'_c = 4500$ psi ($f'_c = 31$ N/mm²) was found.

Test matrix

A total of six one-way square slab specimens were available to be tested within the deck of the garage (see Figure 1c), by saw-cutting the deck (full depth) along carefully defined lines. Two different series of tests are described in this paper.

In the first, three slabs (S1 to S3, see Figure 2a) were tested to failure to investigate the effectiveness of CFRP-strengthening schemes for slabs with cutouts centered at mid span. All test slabs were of the same dimensions of 102 in \times 97 in \times 5.5 in (259 cm \times 246 cm \times 14 cm). Each slab had approximately eight #4 bars as bottom reinforcement at mid span and the same amount as top reinforcement at the support, spanning one third of the span in each direction. Specimen S1 served as the control specimen with opening of dimensions 35 in \times 20 in (89 cm \times 51 cm) but with no

strengthening, while the other two slabs (S2 – S3) were both strengthened using CFRP laminates in a wet lay-up application. The sheets had ultimate strength of 550 ksi (3790 MPa), tensile elastic modulus of 33,000 ksi (228,000 MPa), and each had a nominal thickness of 0.0065 in (0.16 mm). The concrete surface was first sandblasted to assure good bond. The external reinforcement was applied in two ways, namely strengthening only on the bottom side (slab S2) and on both top and bottom sides (slab S3). Slab S2 contained two strips of two plies, each 12 in (30 cm) wide and 91 in (231 cm) long. Slab S3 had the same quantity of fiber on the bottom face but also contained four strips on the top surface.

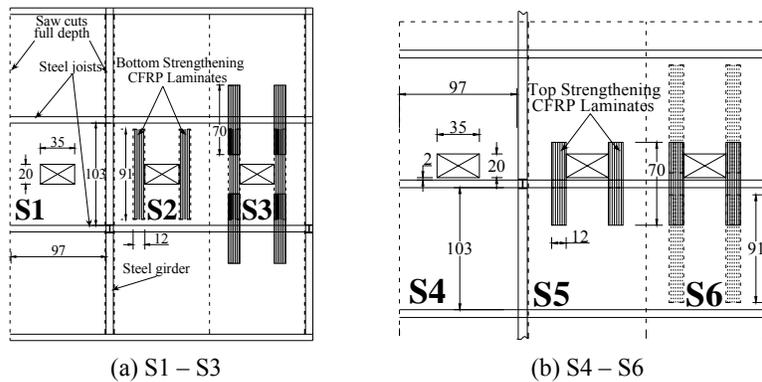


Figure 2– Geometry and Detail of Strengthening of Slabs

In the second series of tests, three slabs (S4 to S6, see Figure 2b) with openings cut in the negative moment region were tested to failure. Isolation cuts were performed as in the first series of slabs. Slab S4 served as control specimen and slabs S5 and S6 were prepared using the same philosophy followed for the first series of specimens. The dimensions of the openings were the same as for slabs S1-S3 with the only difference being that for this series, the opening was cut very close to the support (≈ 2 in (5 cm) from the edge of the steel joist). The external reinforcement was applied in a similar fashion to slabs S2 and S3: slab S5 was strengthened only on the top surface, centered over the support, by applying a total of two strips with two plies each, each of them 12 in (30 cm) wide and 70 in (178 cm) long; slab S6 had the same amount of strengthening on the top face as slab S5, but also had four strips on the underside, positioned as for specimen S2.

Test setup

Two different, but conceptually identical, setups were used to test the two series of specimens. A closed loop scheme was chosen for both test series, as shown in Figure 3.

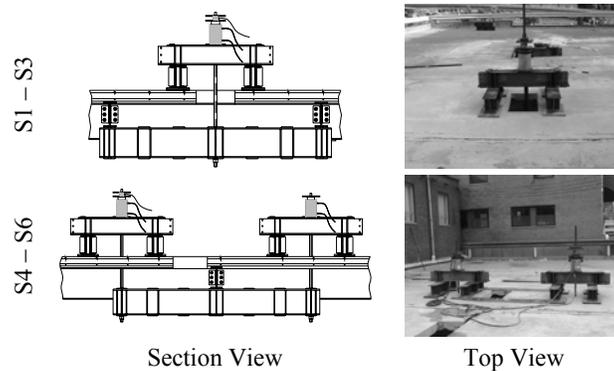


Figure 3– Test Set Up

The slabs S1-S3 were loaded at four concentrated points in order to engage the entire cross section and to simulate a distributed load around the opening. Slabs S4-S6 were loaded over eight points to achieve maximum moment over the support where the opening had been cut. The load was applied in cycles in both cases through hydraulic jacks connected to the same pump, and measured using a 200-kip (900 kN) load cell. Displacements were measured at eleven significant points using linear variable differential transformers (LVDTs). The strains in the external reinforcement were measured using strain gages (see Figure 4).

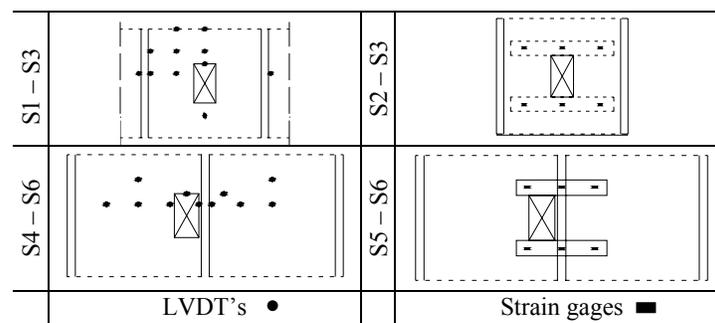


Figure 4– LVDTs and Strain Gage Positions

TEST RESULTS AND DISCUSSION

Specimens S1-S3

The slabs tested with an opening at midspan experienced flexural failure. Table 1 reports the test results.

Table 1. Test Results for S1-S3

| <i>Slab</i> | <i>Failure load, kip (kN)</i> | <i>Max FRP elongation as % of ultimate</i> | <i>Load capacity (%)</i> | <i>Failure mode</i> |
|-------------|-------------------------------|--|--------------------------|---------------------|
| <i>S1</i> | 69 (307) | N/A | 100 | Flexure (crush) |
| <i>S2</i> | 90 (400) | 20.6% | 130 | Flexure (delam.) |
| <i>S3</i> | 76 (337) | 17.6% | 110 | Flexure (delam.) |



(a) Debonding of Laminates (b) Laminate-Concrete Bond

Figure 5– Failure Modes for S1-S3

Flexural cracks started first at midspan, then developed diagonally from the corners of the opening. The slab failed by crushing of the concrete on the top surface with extensive cracking on the bottom face and, where strengthening was present, by FRP debonding (see Figure 5a) immediately afterwards. The debonding was caused by flexural cracks developed diagonally from the corners and crossing the strips of laminates. Parts of the concrete cover remained attached to the laminate, showing good bond between laminate and concrete substrate (see Figure 5b).

Figure 6 shows the Load vs Deflection curves for series S1-S3. It may be observed that the capacity of the strengthened slab S2 was increased by approximately 30% with respect to the unstrengthened S1. Unexpectedly, slab S3 failed at a lower load than slab S2, achieving only a 10% increase with respect to S1. Reasons for this behavior are discussed when specimens S5 and S6 are considered, next.

FRP debonding was experienced in both strengthened specimens. In slab S3, only 21% of the ultimate strain capacity of the CFRP was reached

due to premature debonding caused by extensive cracking. All three slabs exhibited wide cracks, propagating radially from the corners of the opening towards the supports. This crack pattern confirms the high stress concentration near the corners of openings. On the top face, cracks developed circularly around the opening.

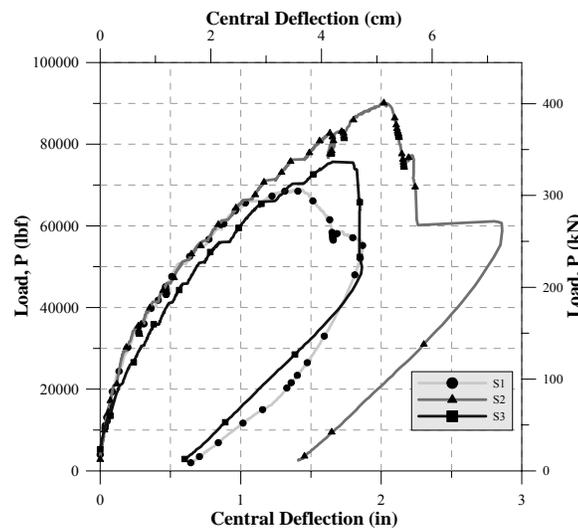


Figure 6– Load vs Deflection Curves for S1-S3

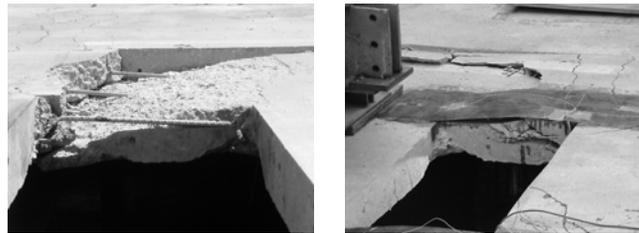
Specimens S4-S6

The slabs tested with an opening near to the support line all experienced shear failure in the concrete near the support, with no positive contribution from the FRP. Table 2 shows the test results.

Table 2. Test Results for S4-S6

| Slab | Failure load, kip (kN) | Max FRP elongation as % of ultimate | Load capacity (%) | Failure mode |
|------|---------------------------|---|----------------------|--------------|
| S4 | 52 (231) | N/A | 100 | Shear |
| S5 | 41 (182) | 19.8% | 79 | Shear |
| S6 | 48 (214) | 20.6% | 92 | Shear |

On the side of the opening, a shear plane was initiated, developing diagonally from the upper face of the slab towards the steel joist (Figure 7a and 7b). Failure was sudden.



(a) Shear Plane Failure

(b) Shear Failure

Figure 7– Failure Modes for S4-S6

Figure 8 shows the Load vs Deflection curves for series S4-S6. All slabs failed in shear. Clearly, the strengthening scheme adopted here could not return the slab to its original strength prior to the hole having been cut. In fact, the ‘strengthening’ seems to have precipitated premature failure at a load well below the unstrengthened specimen S4. Specimen S5, with only top-surface laminates, seems to have been particularly weakened by the presence of the FRP.

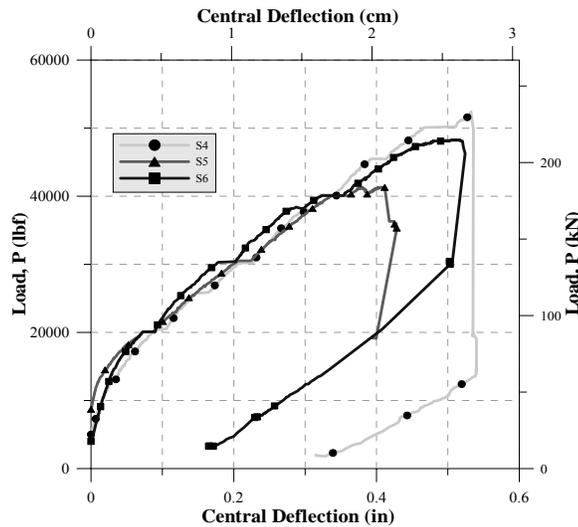


Figure 8– Load vs Deflection Curves for S4-S6

In specimen S5, the presence of the top-surface laminates would have extended the elastic range of the section at maximum negative (hogging) moment. This would have ‘attracted’ bending moment from the more

compliant positive (sagging) moment region, increasing the shear at the internal support. Given the reduction in available shear contribution from the concrete (due to the cutout), premature shear failure occurred. The presence of the soffit laminates in specimen S6 increased the capacity over that of specimen S5, presumably by restricting the wholesale concentration of bending moment at the internal support through increasing the elastic range of the positive moment region.

Specimen S3, previously, failed at a lower capacity than S2. Specimen S3 contained top-surface laminates and it is likely that this reduction in strength occurred for similar reasons to those outlined above for specimens S5 and S6. Note that specimen S3 did not fail in shear, but flexure, as the ability of specimen S3 to resist shear was rather good all round the support lines. It is the additional elastic bending moment demand at the internal supports that caused flexural failure in specimen S3.

CONCLUSIONS

The following conclusions can be drawn from this experimental program:

- a) Application of strips of CFRP laminates to strengthen slabs with cutouts in the positive moment region shows that the method is effective, with an increase in load of approximately 30% being achieved.
- b) Shear failure was found to be the controlling mechanism when cutouts were placed in the negative moment region of one-way slabs. It has been shown that externally-applied CFRP laminates are not effective under such conditions, as they tend to increase the shear demand on the concrete, possibly leading to catastrophic premature failure if the shear strength is insufficient.

ACKNOWLEDGMENTS

The authors would like to acknowledge financial support from the National Science Foundation Industry/University Cooperative Research Center at the University of Missouri–Rolla. Thanks are due to the Western Group for the cutting of the deck and sandblasting, and to Master Contractors for the installation of the FRP laminates. St Louis County provided the opportunity for testing of the structure.

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