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Abstract:

In this paper, the results of a research program that investigated the behavior of two-way RC flat slabs with a centered square opening are presented. Three slabs were tested to failure, consisting of a control specimen with no opening, one specimen with an opening and no strengthening, and one with an opening and three CFRP plies applied to the tension face along each side of the opening. These results revealed that externally bonded CFRP laminates significantly increased both the overall stiffness and flexural capacity of the slabs with an opening. It is shown that such positive-moment strengthening of cutout slabs is entirely viable using CFRP laminates. CFRP anchoring can further increase the performance of the strengthening scheme adopted. Experimental load-deflection curves and failure modes are reported.

Introduction

Reinforced concrete (RC) structures often require strengthening or repair at some point during their design lifetime. The requirement for strengthening can arise for a variety of reasons, including a need for upgrading the load-carrying capacity, a necessity to make changes in the structure or a need to solve problems that have occurred during construction. When dealing with RC slabs, post-construction installation of escalators, elevators or utilities such as air conditioning, heating or wiring ducts are often required. In these cases, holes in slabs become one of the most common problems encountered. 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 approach [Casadei *et al*. 2003].

To date, most research in this field has been conducted to understand the behavior of slabs containing openings placed in the positive moment region to address the design issues that may rise when cutouts are created [Zaslvasky 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, 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]. Unfortunately, this work has been mainly limited to one-way slabs. Zhang *et al.* [2001] studied the behavior and strength of two-way slabs externally strengthened with steel plates. Erki and Heffernan [1995] appear to have presented the only study on two-way slabs with two-way supports. These experiments involved square slabs, simply supported on all four sides and strengthened with FRP laminates to enhance the punching shear capacity, an issue outside the scope of this work.

The present paper thus describes, to the best of the writers' knowledge, the first study on the behavior and strength of simply-supported two-way square RC slabs with a centered opening strengthened for flexural enhancement with CFRP laminates under concentrated loads placed around the cutout.

Experimental Program

Test Matrix

Table 1 summarizes the overall dimensions of the three two-way RC slabs that were constructed for this experimental program. The specimens were cast and cured under laboratory conditions. The three specimens consisted of a control slab with no opening (SQ1), a slab with a centrally-located opening and no strengthening (SQ2), and one with a centrally-located opening and CFRP laminates applied to the tension face (SQ3).

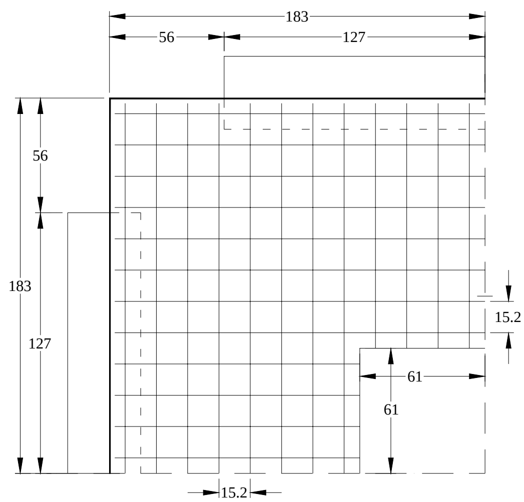
Table 1 - Test Matrix

Series	*Dimension of square slab, m (ft)*	*Thickness of slab, cm (in.)*	*Cut out dimensions, m (ft)*	*Steel ratio in each direction, %*	*Steel reinforcement lost in the cutout in each direction, %* (1)	*CFRP strengthening along each side of the opening*
SQ1	3.66 × 3.66 (12×12)	14.0 (5.5)	-	0.419	-	-
SQ2	3.66 × 3.66 (12×12)	14.0 (5.5)	1.22×1.22 (4×4)	0.419	33	-
SQ3	3.66 × 3.66 (12×12)	14.0 (5.5)	1.22×1.22 (4×4)	0.419	33	3 plies (2)

(1) Total % of bars lost in the cross section in each direction, top & bottom reinforcement.
(2) See Fig.3a for detailed geometry.

Details of the rebar arrangement and specimen geometry are given in Figure 1(a) and 1(b).

a) Layout of reinforcement



b) Detail of quarter-slab
(dimensions in SI units, 1cm = 0.394 in)

Figure 1 - Geometry

Measured material properties of the concrete and steel are given in Table 2.

Table 2 - Properties of Construction Materials

Material	*Cylinder compressive strength(1), MPa (ksi)*			*Yield strength MPa (ksi)*	*Modulus of elasticity GPa (ksi)*	*Cross section of rebar used, A_s mm^2 (in^2)*
	SQ1	*SQ2*	*SQ3*			
Concrete (2)	32(4.7)	33(4.8)	38(4.9)		-	-
Steel (3)		-		413 (60)	200 (29,000)	71 (0.11)

(1) Tested at 28 days, when the specimens were tested.
(2) Average of 6 specimens [15.24 cm×30.48 cm (6 in×12 in) cylinders].
(3) Average of 6 specimens [91.44 cm (36 in) long].

Slab SQ3 was strengthened using 3 plies per strip of unidirectional carbon FRP laminate, applied by manual lay-up. Each ply was 53.3 cm (21 in) wide and of varying length (335 cm (132 in.), 320 cm (126 in.) and 305 cm (120 in.)) in order to reduce the stress concentration effect at the ends of the laminate. The amount of CFRP used to strengthen slab SQ3 was computed under the premise that the loss of steel reinforcement caused by the cutout would be replaced by an equivalent amount of FRP according to the following simple relationship:

$$\frac{E_s A_s^{lost}}{E_f A_f} = 1 \tag{1.1}$$

The amount of steel reinforcement lost is equivalent to:

$$A_s^{lost} = N \times A_s = 568\text{mm}^2 (0.88\text{in}^2) \tag{1.2}$$

where N (=8) is the number of steel bars which have been cut. Substituting into eq.(1.1) we can compute the equivalent area of CFRP:

$$A_f = \frac{E_s}{E_f} \times A_s^{lost} = 500\ \text{mm}^2\ (0.773\ \text{in}^2) \tag{1.3}$$

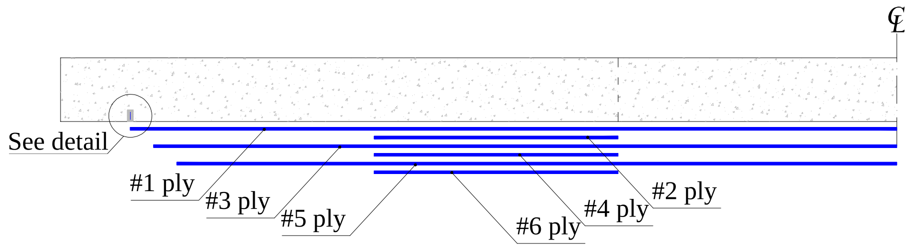
Since each ply has a nominal width b_f = 533 mm (21 in), the necessary overall thickness of CFRP laminate is given by:

$$t_{tot} = \frac{A_f}{b_f} \tag{1.4}$$

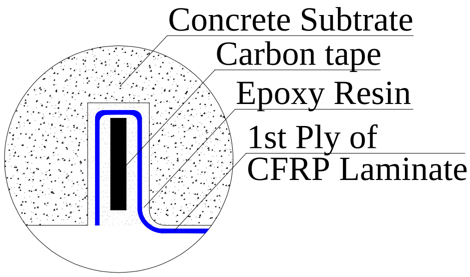
Given that thickness of one ply, t'=0.165 mm (0.0065 in), the total number of plies required is:

$$n' = \frac{t_{total}}{t'} = 5.7 \text{ plies} \tag{1.5}$$

A total of six plies were applied: three were placed on one side of the cutout and three on the other side in each direction (see Figure 2b).



a) Plies numbered as per sequence of laminate application



b) Overview of the completed strengthening

c) Detail of the anchoring device

Figure 2 - CFRP Laminates application by manual wet lay-up on tension side of specimen SQ3

The bonding processes used for the CFRP laminates were as follows. The tension face of the RC slab was abraded by sandblasting to remove all the laitance and to expose the aggregate before bonding. At this stage, four grooves were cut as shown in Figure 2(c), each 25.4 mm deep (1 in.) and 6.35 mm wide (¼ in.), to house the carbon tape used to anchor the first ply of the laminate. Once the grooves had been cut, the surface was thoroughly brushed to remove all loose particles, and vacuum-cleaned. Once the surfaces had been prepared, CFRP laminates were bonded to the tension face by epoxy resin, as per manufacturer recommendations. In order to avoid any concentrated uneveness in the location in which the plies overlapped on the four diagonals, the plies in the two perpendicular directions were applied one at a time in sequence (see Figure 2(a)). The laminates were bonded adjacent to the edge of the opening in order to resist the peaks of localized stress that occur near corners of openings. The mechanical characteristics of the CFRP laminates are shown in Table 3 and have been validated by tests [Yang, 2001].

Table 3 - Properties of CFRP Constituent Materials

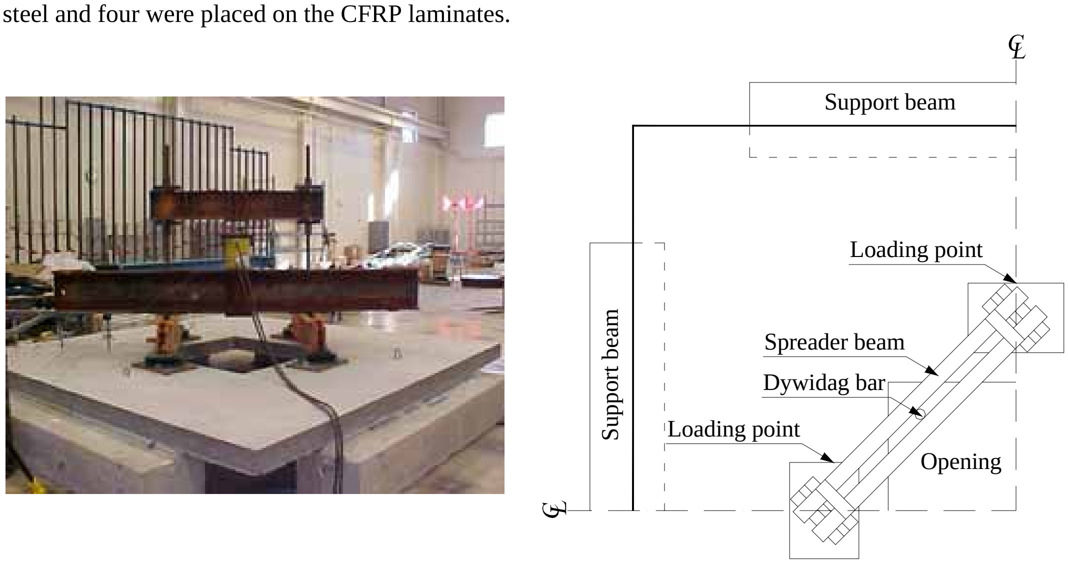
Material	*Ultimate tensile strength f_{fu} MPa (ksi)*	*Ultimate rupture strain ε_{fu} (mm/mm)*	*Tensile modulus of elasticity E_f GPa (ksi)*	*Nominal thickness t_f mm (in)*	*Poisson's ratio*
Primer (1)	17.2 (2.5)	40	0.7 (104)	-	0.48
Putty (1)	15.2 (2.2)	7.0	1.8 (260)	-	0.40
Saturant (1)	55.2 (8.0)	7.0	1.8 (260)	-	0.48
High Strength Carbon Fiber (2)	3790 (550)	0.017	228 (33,000)	0.1651 (0.0065)	-

(1) Values provided by the manufacturer

(2) Tested as laminate with properties related to fiber area

Test Setup

The experimental setup is shown in Figure 3(a) and 3(b). The slabs were tested under simply supported conditions and subject to four symmetrical concentrated loads. A 227 ton (500 kips) capacity hydraulic jack, activated by a manual pump, was used to load each specimen. The force generated by the hydraulic jack was transferred to the specimen by means of two steel spreader beams supported on rollers, which applied the load at mid side of the opening. The load was applied in cycles. An initial cycle at low load was performed in every slab to verify that both the mechanical and electronic equipment were working properly. Data from an 890 kN (200 kip) load cell, linear variable differential transducers (LVDTs), string transducers and strain gauges were collected by a data acquisition system once per second. A total of four LVDTs and two string transducers were used to register deflections. The LVDTs were placed along the diagonal on the top surface, located at 12.7 cm (4.5 in), 53.34 cm (21 in), 96.5 cm (38 in) and 140 cm (55 in) from one corner respectively. The string transducers were placed on the tension face of the slab, one at the corner of the cutout along the diagonal on which the LVDTs had been placed, in order to have a clear understanding of how the diagonal cross section behaved, and the other at mid side of the cutout (for slabs SQ2 and SQ3) or at this equivalent position in the absence of a cutout (for slab SQ1). A total of 23 strain gauges were monitored in each specimen. For slabs SQ1 and SQ2, 19 were placed on the steel reinforcement and four on the concrete bottom and top face. In slab SQ3, 19 were placed on steel and four were placed on the CFRP laminates.



a) Test setup

b) Loading positions

Figure 3 - Test setup

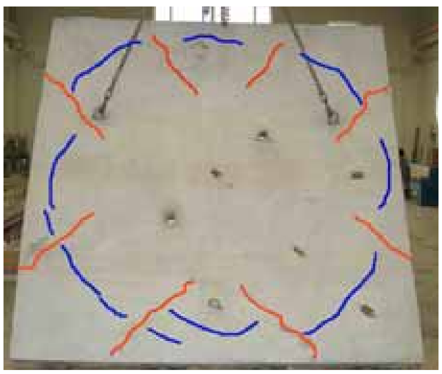
Results and Discussion

All slabs failed similarly in flexure. Following steel yield, slabs SQ1 and SQ2 exhibited moderate crushing, extensive cracks and deflection prior to flexural failure by concrete crushing. In slab SQ3, failure was caused by sudden pull-off of the anchoring system at the end of one laminate, with a considerable amount of concrete substrate. Table 4 reports the test results, while Figure 4 provides images of the failure modes.

Table 4 - Test results for SQ1-SQ3

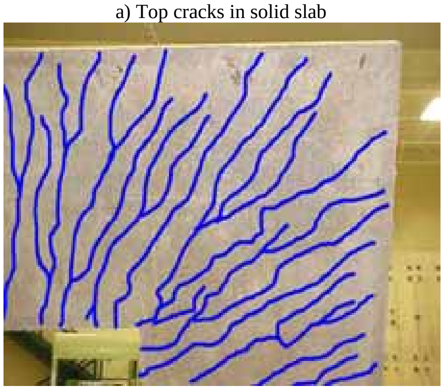
Slab	*Failure load, kN (kip)*	*Load capacity (%)*	*Load at first yield of steel reinforcement kN (kip)* (1)	*Max FRP elongation as % of ultimate*
SQ1	489 (110)	100	124 (28)	-
SQ2	336 (75.5)	69	102 (23)	-
SQ3	676 (152)	138	147 (33)	50%

(1) Strain measured on the same bar and at the same location in each specimen



a) Top cracks in solid slab

b) Shear crack along the support side



c) Typical crack pattern on bottom of the slab

d) Shear crack in the opening

e) Delamination of the CFRP plies on one corner

f) Failure of anchoring: pull off of the concrete cover

Figure 4 - Failure Modes

Flexural cracks started either at the center of the slab (SQ1) or along the edges of the cutouts (slabs SQ2 and SQ3), developing perpendicular to the adjacent line of support. Under increasing load, these cracks developed diagonally towards the four support corners, symmetrically located across the entire tension face (see Figure 4(c)). On the top surface, crushing developed in a circular pattern around the loading points, and also linearly from the application load at roughly a 45° angle towards the lines of support, illustrated in Figure 4(a). This pattern was repeated in all three slabs and occurred more evidently at high levels of load. In all slabs, flexural-shear cracks developed along the sides at a 45° angle, connecting the bottom flexural cracks with the top-surface ones (see Figure 4 (b)); in slabs SQ2 and SQ3, similar types of crack developed on the sides of the openings, starting from the corners of the hole and moving at an angle of about 45° towards the center of the cutout (see Figure 4 (d)). Post-failure inspection showed that these cracks sliced through the plane of the slab, which may be interpreted as a form of punching shear behavior. The simply supported conditions under which these tests were performed would have helped to encourage a more flexural type of behavior at the expense of such punching shear. If the four corners of the slab had been restrained from lifting up, it is possible that punching shear would have been the definitive controlling mode of failure. Slab SQ3 experienced a very similar crack pattern to that of specimen SQ2, but in this case, failure of the specimen occurred in the anchoring device of the FRP. Debonding of the laminates started from flexural cracks at the maximum bending moment region around the hole, and particularly in the area where the two perpendicular strips overlapped on the diagonal (see Figure 4 (e)), but the anchoring prevented the laminates from debonding prematurely. At failure, the entire concrete cover was pulled off suddenly (see Figure 4 (f)).

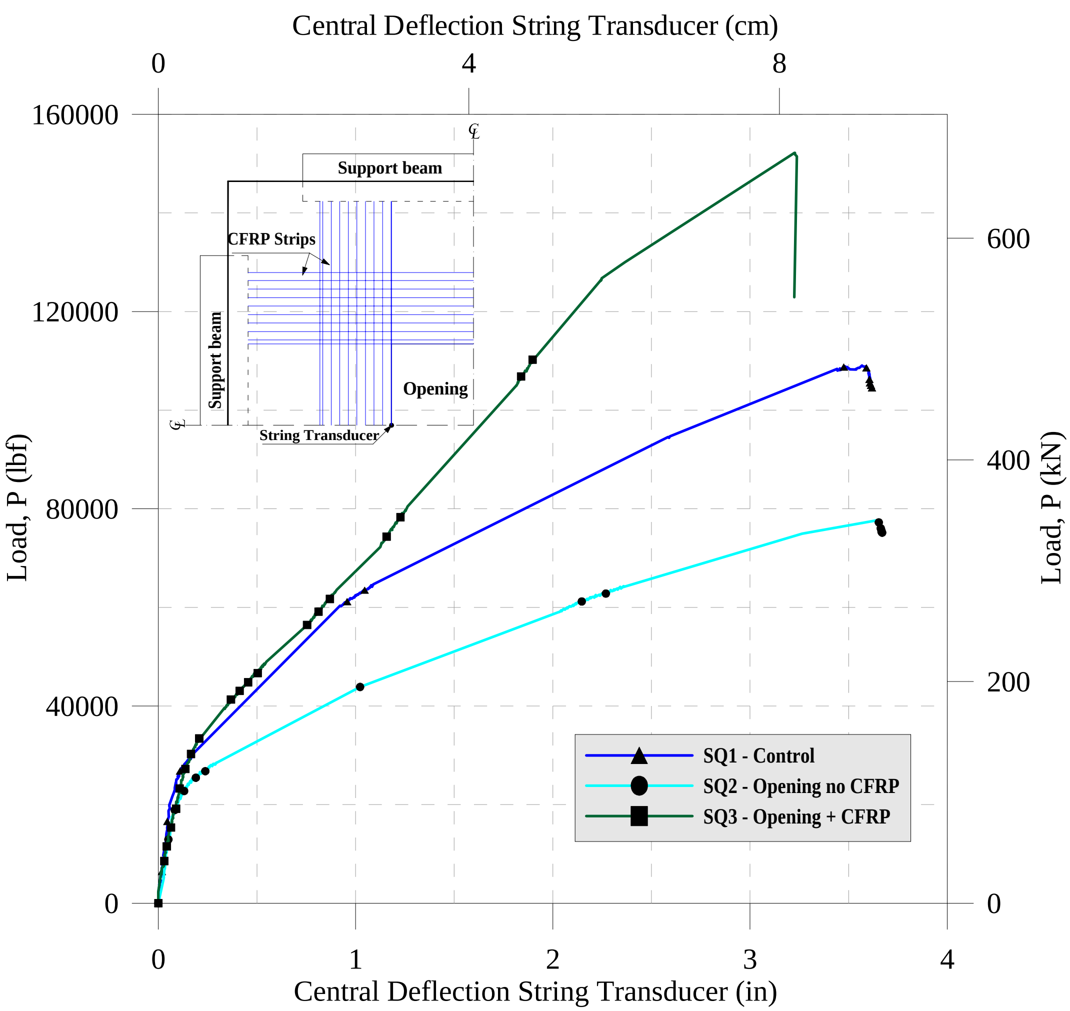


Figure 5 - Load vs Deflection curves

Figure 5 shows the Load vs Deflection curves for the three specimens, with the deflection measured at mid side of the opening in slabs SQ2 and SQ3 and at the same location in slab SQ1. It may be observed that the capacity of the strengthened slab SQ3 was increased by approximately 40% with respect to the control specimen SQ1 and 50% with respect to SQ2. There are three distinct phases in the behavior of slab SQ1. Up to a load of 147 kN (32 kip), the reinforcement in the central part of the slab (covering the area that was cut out in specimen SQ2) remained elastic. From 147 kN (32 kip) to 285 kN (64 kip), the central reinforcement yielded and the remaining reinforcement approached yielding. From 285 kN to failure, all reinforcement yielded. This sequence of events is borne out by consideration of slab SQ2, in which, due to the absence of centrally-located reinforcement, the stiffness dropped significantly initially. Thereafter, this stiffness was held right through to failure, approaching which, the stiffness ended up being not significantly less than that of slab SQ1, as might be expected following substantial areas of steel yielding in both specimens. The maximum displacement was approximately the same in both SQ1 and SQ2, but it was reached at a lower load in SQ2. Slab SQ3 behaved in a similar bi-linear fashion to SQ2, with a substantially higher stiffness being maintained after the initial stages of loading. Once yielding of the steel bars started, the presence of the CFRP reinforcement dominated stiffness, as confirmed by the strain profiles reported in

Figure 6. Note that strains reported in these plots were measured at the same location (on the steel bars for specimens SQ1 and SQ2, and on the CFRP for specimen SQ3). At failure, the strain in the CFRP was about 50% of its ultimate strain. The sudden drop in the Load vs Displacement plot for slab SQ3 demonstrates sudden failure of the anchoring system.

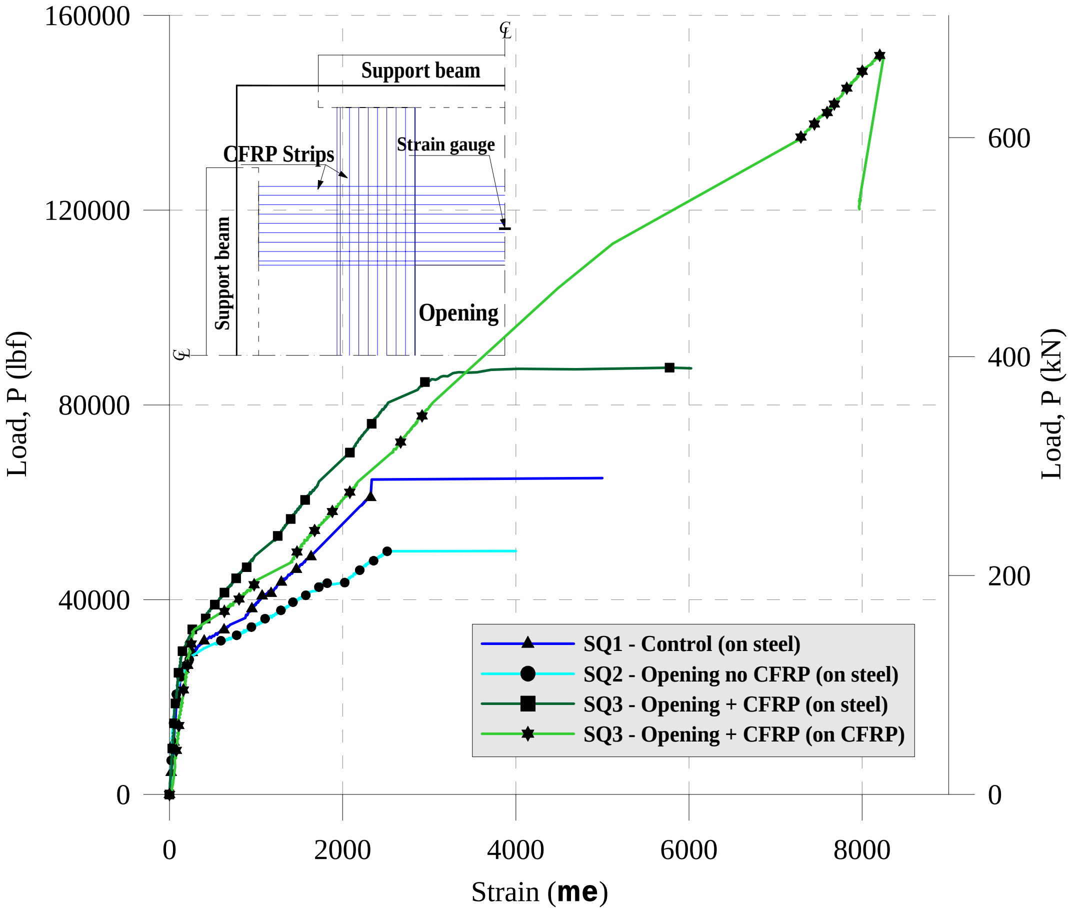


Figure 6- Load vs Strain curves

Summary and Conclusions

The following conclusions may be drawn from this experimental program:

- CFRP laminates, applied by manual lay up, have been shown to be effective in increasing both the overall capacity and stiffness of the structure in this type of loading configuration, and in establishing in the slab (with cutout) an enhanced behavior with respect to the equivalent unstrengthened system.
- Anchoring the CFRP has resulted in a high capacity without premature debonding of the laminate, which would otherwise have occurred due to the extensive flexural cracks that developed on the tension face of the specimen [Casadei *et al*. 2003].
- There appears to have been a component of punching shear behavior within the failure mode. Therefore, although this strengthening methodology has been shown to be particularly beneficial for predominantly flexural behavior, it is recognized that the possibility of punching shear (under different loading and boundary conditions) could, in fact, control the failure mode and that such an eventuality must be considered during design.

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