Flexural Strengthening of Concrete Slabs by a Three-stage Prestressing FRP System Enhanced with the Presence of GFRP Anchor Spikes

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ABSTRACT: Some of the advantages that results from the structural strengthening of concrete slabs using prestressed fiber reinforced polymer (FRP) systems are as follows: the prestressed FRP delays the formation and propagation of cracks, and both the serviceability and the flexural capacity are increased. In this research program, the flexural performance of a concrete slab strengthened with a three-stage prestressing system using Carbon FRP (CFRP) sheets was investigated under a four-point static load test setup at the University of Missouri Rolla (UMR). Debonding of the CFRP sheets was prevented by installing three glass FRP (GFRP) anchor spikes at each end of the prestressed FRP sheets. An un-strengthened slab designated in this paper as the control unit was also tested under a separate research program and is described in this paper only as a source for comparison with the strengthened slab. As expected, test results indicate that both the serviceability and flexural capacity were significantly increased, and no debonding from the ends of the CFRP sheets was observed due to the presence of the GFRP anchor spikes.

1 INTRODUCTION

Application of reinforced concrete (RC) beams/slabs strengthened with prestressing systems generally falls into three categories that include: a cambered beam system, a system that tensions the FRP sheets against an independent external reaction frame, and a system that tensions the FRP sheet against the strengthened beam itself (El-Hacha & El-badry 2001).Each of these methods includes three phases to achieve the desired level of prestressing in the FRP sheet. First, the prestress is applied to the FRP sheets with a hydraulic jack or another device. Second, the FRP sheets are bonded to the concrete surface with an adhesive. Finally, after the adhesive has properly cured the FRP sheets are cut near the ends and the prestress device is removed. The prestress level in the FRP is critical in order to guarantee the strengthening system does not fail near the anchorage zones when the prestress is released (Quantrill & Hollaway 1998).

Debonding is a critical consideration in the strengthening of RC members since this failure mode limits the capacity of the system below the ultimate flexural capacity. In addition, this failure mode can be characterized by sudden separation of the FRP sheet from the member rather than by the ultimate flexural capacity of the cross section. Such failures are commonly referred to as debonding failure, which are characterized : (a) those that initiate at or near a plate end and then propagate from the plate end (b) those that initiate at an intermediate flexural or flexural–shear crack and then initiate the debonding (Sagawa et al. 2001, Teng et al 2001). For either failure type, debonding will occur at the ends of the FRP sheets. For RC members strengthened with prestressed FRP sheets, bonding near the ends of the FRP is more critical since high stress concentrations develop at the ends of the FRP sheets before any additional load can be applied (Hollaway & Leeming 1999). Various anchorage systems for application to FRP laminates/sheets have been investigated (Quantrill & Hollaway 1998, Tumialan et al 2001, Triantafillou et al 1992). Mechanical anchorage by means of steel angles, steel plates, or anchor bolts are some of the systems that are often used. Decreasing stress concentrations in the laminate/sheets ends by anchorage plates and/or increasing the bond strength near the ends are some of the effective solutions in preventing or delaying any debonding failure. Because of the potential for galvanic corrosion due to the contact between the CFRP composites and any steel anchorage such mechanical devices may not be effective solutions for improving the bond capacity.

In this research program the flexural performance of a concrete slab strengthened with a three-stage prestressing system using CFRP sheets was investigated under a four-point static load test setup. Prestressing of the CFRP sheets was achieved by imposing a camber profile on the concrete slab such that upon release of the prestressing system initial stresses would develop in these CFRP sheets. In addition, debonding of the CFRP sheets was prevented by installing three glass FRP (GFRP) anchor spikes at each end of the prestressed FRP sheets. These GFRP anchor spikes were made by impregnating strands of glass fibers with resin.

Strengthening of the slab by these three-stage prestressing FRP system with presence of the GFRP anchor spikes include the following steps:

Step 1. Cambering of the concrete slab by stressing external steel cables with hydraulic jacks.

Step 2. Bonding of CFRP sheets to the concrete surface with an epoxy-based paste and embedding of three GFRP anchor spikes into the concrete slab at both ends of the sheets.

Step 3. Releasing of the steel cables stressed in step 1.

An un-strengthened slab designated as the control unit was also tested under a separate research program and is described in this paper as a source for comparison with the strengthened slab. The strengthened and the un-strengthened slabs were subjected to a simply supported 4-point concentrated static load test setup. As expected, test results indicate that both the serviceability and flexural capacity were significantly increased due to the presence of the prestressed CFRP sheets. The strengthened slab failed due to rupture of the CFRP sheets at mid-span and no debonding at ends of the CFRP sheets was observed. Furthermore, bond stress profiles along the length of the CFRP sheets were computed from strain gage data and suggest that the GFRP anchor spikes were effective in preventing debonding of the CRFP sheets. This conclusion is evident as a result of an increase in the computed bond stress near the first anchor spikes. However, further researches will have to be conducted to further prove these results.

2 RESEARCH SIGNIFICANCE

This study provides the experimental results on the flexural behavior of one full-scale slab strengthened with a three-stage prestressing FRP system by combining traditional steel cables with CFRP strips. Development of GFRP anchor spikes and their application in bonding CFRP strips to this slab were also investigated in this program.

3 EXPERIMENTAL PROGRAM

3.1 *Test matrix*

3.1.1 *Phase one: development of anchor spikes*

In order to improve the bond capacity of the FRP sheet/laminate, GFRP anchor spikes were developed with plain fibers (Eshwar, N., 2002). The procedure to manufacture these spikes is as follows: first, bundle dry glass fibers together. Then, impregnate the bundled fibers with saturant thoroughly. Next, pass the impregnated fibers through a circular hole on a steel plate to obtain the desired diameter of the anchor spikes. Only part length of the fibers can be impregnated with the saturant as the leftover length is used for bonding purposes. After this stage, the spikes cured in ambient temperature, and can be trimmed to different lengths according to specific requirements.

Standard pullout tests were conducted for these spikes. Fibers were fully impregnated with saturant along the whole length to make GFRP bars for these tests. For anchors with # 3 diameter embedment lengths of 25.4 mm, 50.8 mm, 76.2 mm and 101.6 mm were studied in the pullout tests. A 533.8 kN Tinus-Olsen machine was used for these pullout tests to evaluate the mechanical properties of the precured GFRP anchor spikes. The recorded average full-out failure loads were 21.4 kN, 28.9 kN, 35.6 kN and 31.1 kN respectively.

3.1.2 *Phase two: prestressing steel cables and CFRP strips*

These procedures include the following steps:

Step 1: Prestress two steel cables and the slab with two hydraulic jacks (Fig. 1).

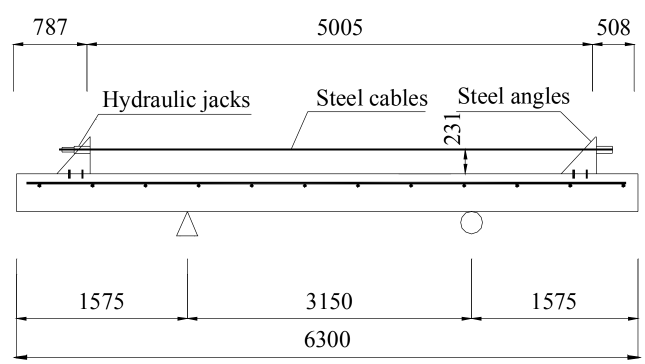

Figure 1. Test setup for prestressing

Using a single pump, the load was simultaneously applied to the two steel cables. The system was temporarily fixed to the slab by twenty-four high strength anchor bolts and four steel angles (Fig. 2). All the data was recorded by a data acquisition system (DAS) at a frequency rate of 1 HZ. The approximate maximum load applied on each steel cable was 44 kN.

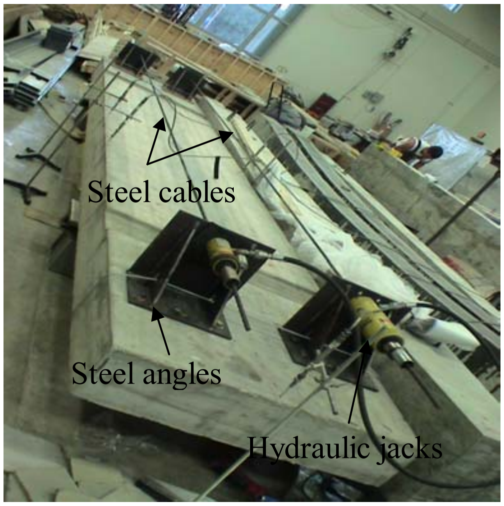

Figure 2. Concrete slab under prestressing

Step 2: By manually lay-up, two 229-mm-wide CFRP strips were installed to the concrete surface. These slab surfaces were sandblasted and cleaned before operation. Twelve holes with 90 mm depth and 12.7 mm diameter were drilled and cleaned by an air vacuum for installation of the GFRP anchor spikes.

With the same resin used for the pre-cured portion, the spikes were inserted into holes predrilled in the slab at both ends. The dry fibers portions were attached to the outer surface of the strips (Fig. 3). Embedment length was 8 times the diameter of the anchor spikes. Location of the spikes is shown in Figure 4.

Figure 3. Splitting GFRP fi-

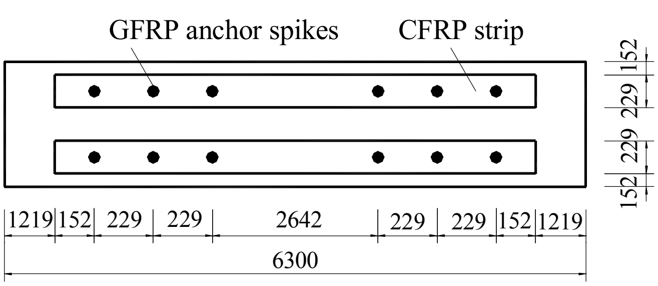

Figure 4. Location of GFRP anchor spikes

Step 3. This step is accomplished after the epoxy has cured and consists of release and removal of the prestressing device and steel cables. In this manner prestressing of the CFRP sheets can be achieved by imposing the camber profile and release of the action that forces this camber on the slab

3.1.3 *Phase three: testing of the slabs*

The strengthened slab was installed in support blocks and tested to failure. Load was applied by means of two 50 ton hydraulic jacks equally and recorded with a 222.4 kN and an 88.96 kN load cell. Strains on the CFRP strips and internal steel bars and deflections of the slab were recorded according to the instrumentation layout depicted in Figure 5. One control slab with the same reinforcement and dimensions without strengthening was tested under the same load condition. All the data was recorded by a data acquisition system at a sampling frequency of 1 HZ.

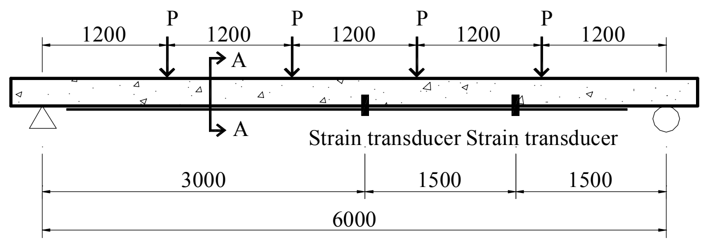

Figure 5. Test setup and location of strain transducers

Slab details

Slabs with the same dimensions of 1000 x

220 x 6300 mm were fabricated with ready-mix concrete and cured under normal laboratory conditions. Detail of the slab reinforcement is given in Figure 6.

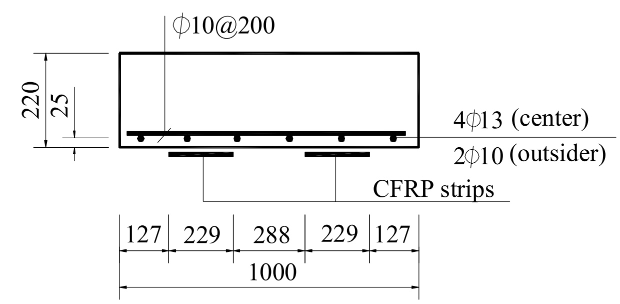

Figure 6. Slab cross-section A-A

3.2 *Material properties*

The average concrete strength, determined according to ASTM C 39-99 for 152.4 mm diameter by 304.8 mm concrete cylinders, was 41.37 MPa.

The average tensile strength of internal flexural reinforcement was obtained from three tensile tests and was 413.7 MPa with an elastic modulus of 199.9 GPa. The amount of steel reinforcement was designed for an under-reinforced section. Steel strands, with a nominal diameter of 12.7 mm, were used in this program for prestressing of the slabs.

A commercially available saturant was used for making GFRP anchor spikes and bonding of CFRP strips to the slab. Its mechanical properties, as specified by the manufacturer, were: 54 MPa tensile strength, 3.5% elongation at break, and 3.0 GPa elastic modulus.

The CFRP strips had a nominal thickness of 0.165 mm according to specifications. Testing indicated that the ultimate strength was 3792.1 MPa and the elastic modulus was 227.5GPa. The material properties are summarized in Table 1.

Table 1. Material properties

	Tensile strength (Mpa)	Elastic modulus (GPa)	Failure elongation (%)
Steel bar	413.7	199.9	--
CFRP	3792.1	227.5	1.6
Saturant	54	3.0	3.5

Twelve GFRP anchor spikes with a 9.5 mm diameter were developed and then applied for end fixing of the strips. The dry fibers of the spikes were 101.6 mm long, and the pre-cured fibers were 76.2 mm long (Fig. 7).

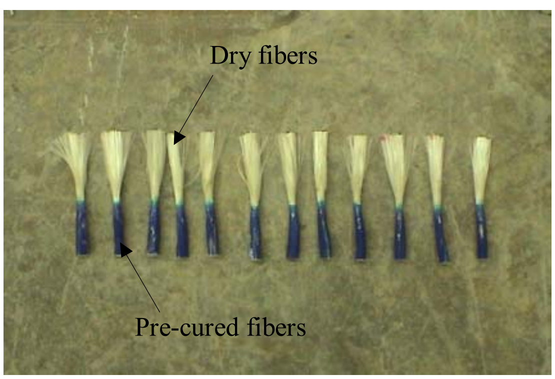

Figure 7. GFRP anchor spikes

3.3 *Instrumentation*

Twelve strain gages were attached to the internal steel bars at different locations (Fig. 8). Locations of twelve gages on the strips, as well as one gage of different type attached to the center of the slab surface to measure strains developed during prestressing, are shown in Figure 9.

Two strain transducers with 229 mm range were set at mid-span and quarter span to measure deflections during the slabs testing to failure (Fig. 5). Six linear variable differential transformers (LVDT) with 12.7 mm capacity were used in Phases two and three.

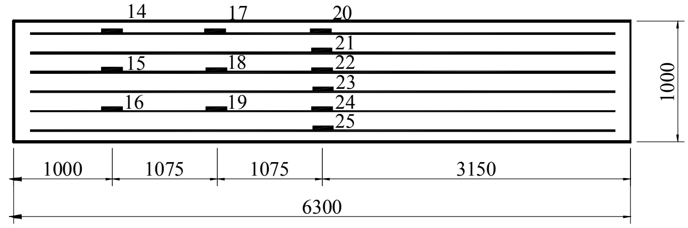

Figure 8. Location of strain gages on steel bars

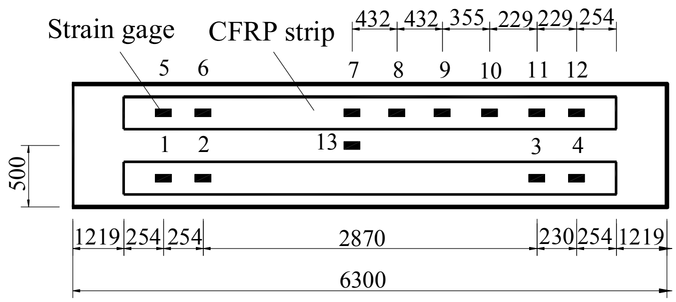

Figure 9. Location of strain gages on CFRP strips and concrete surface

4 EXPERIMENTAL RESULTS

4.1 *Control slab without strengthening*

Testing of the control unit was accomplished under a different research program (Tan et al 2003), as previously described. Test of the control unit was concluded when excessively wide-open cracks were observed at mid-span. The maximum-recorded load level was 5.60 kN, and at this load level strain gage readings of the internal steel bars were beyond the yield level.

4.2 *Strengthened slab*

This slab was tested to ultimate conditions according to the test setup shown in Figure 5.

Mode of failure: Failure originated by simultaneous rupture of the two strips observed at mid-span (Fig. 10).

Figure 10. Rupture of CFRP strips at mid-span

Fracture of the CFRP sheets did not occur through the entire section of the sheets. For one strip, a 76.2 mm wide section fractured, while a 101.6 mm wide section was observed in the other strip. Prior to rupture of these strips, well-distributed and equally spaced cracks were observed at the mid-span of the slab. Compared to the control unit a significant decrease in the cracks width was observed, which can be attributed to the presence of the CFRP sheets and the initial stresses present in the strips. After rupture, debonding propagated from mid-span towards the end of the strips. However, no end debonding was observed and the strips were fixed to the slab firmly. Therefore, it can be concluded that the spikes significantly improved the bond performance of the strips. A thin layer of concrete remained attached to the strips after separation.

The ultimate load P and moment were 16.90 kN and 84.4 kN-m respectively, compared with the theoretical value of 24.12 kN and 110.4 kN-m based on the assumption that each strip breaks completely.

Strain in CFRP strips: Figure 11 shows the strains profiles registered in the CFRP sheets as a function of the applied load and strain gage location. These profiles increased significantly towards midspan, and this increase was nonlinear. Similar results were registered in the other ends. The computed bond stress varied from mid-span to the ends of CFRP strips, and with the increase in the applied load the bond stress near the CFRP anchor spikes also increased (Fig. 12).

When compared with other research results without these GFRP anchor spikes (ACI 440, 2001) the stress concentration decreases near the ends of these strips. This indicates that the GFRP anchor spikes were effective in preventing debonding of the CRFP sheets.

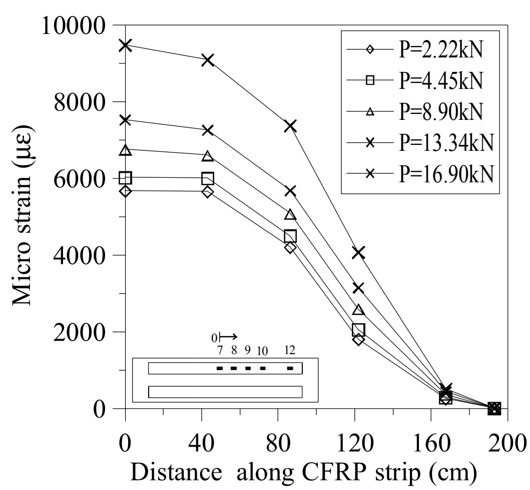

Figure 11. Strains of CFRP strip during testing to fail-

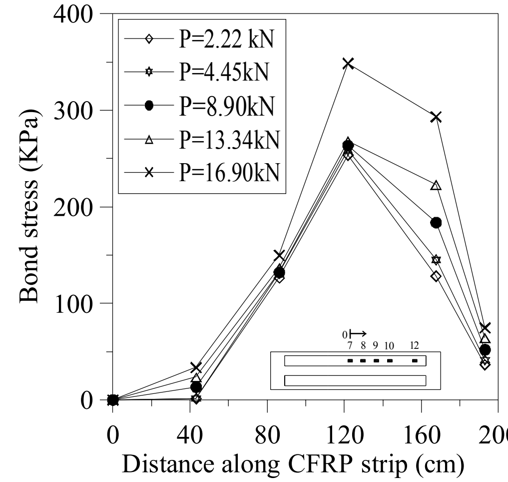

Figure 12. Bond stress along CFRP strip

Strain on steel bars: The steel bars yielded at mid-span before the strips fracture and yielding of these bars occurred when the registered load was 13.34 kN (Figs 8, 13). This is in agreement with the theoretical analysis performed using a moment curvature relation.

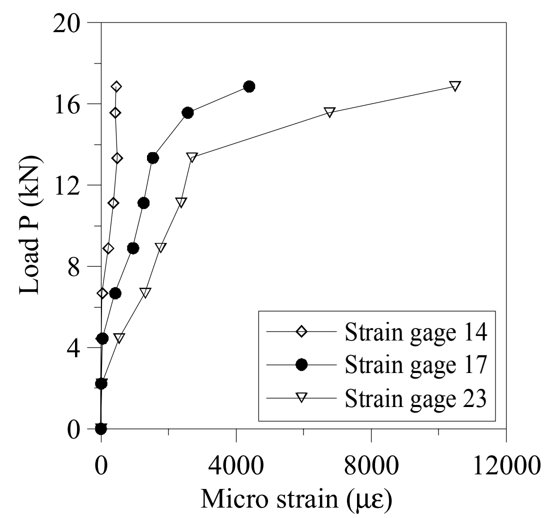

Figure 13. Strain of steel bars when testing to

Deflection of strengthened slab: The recorded maximum deflection at mid-span was 140 mm, compared with 100 mm for the control slab. The theoretical deflection profile for the strengthened slab was based on a moment-curvature analysis and computed according to the conjugate beam approach. The calculated ultimate deflection was 133 mm. Figure 14 shows the comparison of test results and theoretical deflection at mid-span.

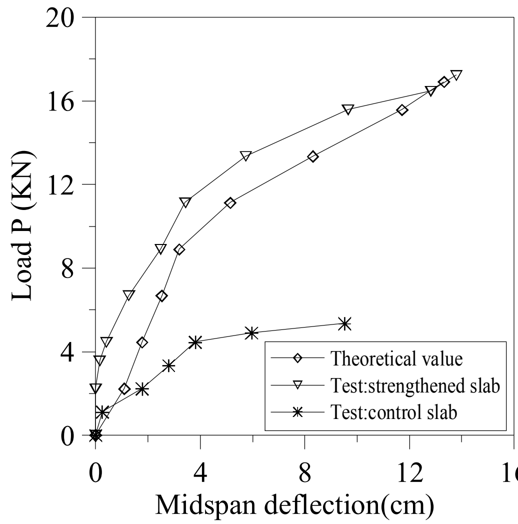

Figure 14. Comparison of mid-span deflection

5 CONCLUSIONS

The following conclusions may be drawn from this research program:

1. Flexural capacity of the slab strengthened with the three-stage prestressing system increased by about 80%.
2. Debonding did not occur due to the presence of the GFRP anchor spikes. This is an effective method to prevent debonding at the ends of FRP strips.
3. Combining the three-stage prestressing system with the GFRP anchor spikes is an effective solution to increase the serviceability and capacity of concrete slabs.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

ACI 440,2001. *Guide for the Design and Construction of externally bonded FRP System for strengthening Concrete Structure*: 69

El-Hacha, R., & Elbadry, M., 2001. Strengthening concrete beams with externally pre-stressed carbon fiber composites cable, *Fiber-reinforced plastic for reinforced concrete structures (FRPRCS-5)*, Cambridge, UK: 699-708

Eshwar, N. 2003. Carbon fiber reinforced polymer (CFRP) strengthening of concrete bridges with curved soffits, MS. Thesis, UMR, Rolla, USA (in print)

Hollaway, L. C. & Leeming, M.B. 1999. *Strengthening of reinforced concrete structure*, Woodhead Publishing Limited, Cambridge England.

Quantrill, R.J. & Hollaway, L.C. 1998. The flexural rehabilitation of reinforced concrete beams by the use of prestressed advanced composite plates. *Composites Science and Technology* (58): 1259-1275

Sagawa, Y., Matsushita, H. & Tsuruta, H. 2001. Anchoring method of carbon fiber sheet for strengthening of reinforced concrete beams. *Fiber-reinforced plastic for reinforced concrete structures (FRPRCS-5),* Cambridge, UK.

Tan, K.Y, Tumialan, G. & Nanni, A. 2003. Evaluation of externally bonded CFRP systems for the strengthening of RC slabs. *Fiber-reinforced plastic for reinforced concrete structures (FRPRCS-6),* (Inprint). Singapore

Teng, J.G., Smith, S.T., Yao, J. & Chen, J.G. 2001. Strength model for intermediate flexural crack induced debonding in RC beams and slabs. *FRP composites in civil engineering (proceeding of the international conference on FRP composites in civil engineering)*, Hong Kong, China: 579-587

Triantafillou, T.C., Deskovic, N. & Deuring, M. 1992. Strengthening of concrete structures with prestressed Fiber Reinforced Plastic Sheets *ACI Structural Journal*, May-June,1992: 235-244.

Tumialan, G., Nakano, K., Fukuyama, H. & Nanni, A. 2001. Japanese and North American guidelines for strengthening concrete structures with FRP: a comparative review of shear provisions *Fiber-reinforced plastic for reinforced concrete structures (FRPRCS-5),* Cambridge, UK: 457-466