Shear Performance of Damaged Concrete Beams Reinforced by Penetrating FRP

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Abstract: This experimental study examined the shear behavior of damaged concrete beams reinforced with fiber-reinforced polymer (FRP) using a penetration method (penetration FRP) to explore the failure modes of the reinforced beams. The load-displacement curves and load-strain curves of the samples were analyzed, and the development and distribution of the oblique cracks of the reinforced beams were discussed. The influences of the damage degree and the reinforcement angle on the shear bearing capacity were determined. The results showed that, prior to cracking, FRP reinforcement had no effect on the stiffness of the samples and the cracking load of the samples remained basically the same; however, after cracking, the samples reinforced with FRP exhibited a larger shear capacity. Moreover, the ultimate load was higher for the undamaged reinforced beam than the damaged reinforced beam. The penetration of the FRP material into the beam at an oblique angle inhibited the development of oblique cracks, resulting in a better reinforcement effect and optimal bearing capacity of the strengthened beam.

1. Introduction
In recent years, fiber-reinforced polymer (FRP) materials have been developed; these new type of composite materials included carbon fiber, glass fiber, aramid fiber, basalt fiber, and other composite glass fiber. Due to its low cost and desirable engineering characteristics, FRP has been widely used in bridge reinforcement [1,2], resulting in increased research focus on reinforcement technology in recent years. In 2011, Chaallal et al. of the University of Quebec conducted a loading test on 12 T-beams to verify the performance of the penetration-type reinforcement technique and compare the results with those of the externally bonded (EB) and near-surface mounted (NSM) method. The test results showed that the shear reinforcement effect of the penetration reinforcement method was considerably better and the influence on the stirrups was lower than that of the EB and the NSM methods, [3]. In 2015, Breveglieri et al. at the University of Ferrara conducted a loading test on four groups of 19 concrete T-beams to investigate the influence of factors such as the stirrups and penetration angles on the performance of the penetration reinforcement method [4].

The main features of FRP materials included the following: (1) High tensile strength. (2) Light weight. (3) Good corrosion resistance and durability; the reinforcement effect was especially good in corrosive environments [5,6]. However, current FRP reinforcement methods, such as EB and NSM were not without problems, especially surface treatments [7,8]. The reason was the weak and complex
tensile strength of the surface concrete, resulting in weak adhesion of the material to the concrete and vulnerability to fire and vandalism. To avoid the aforementioned problems and increase the suitability of the reinforced material for various applications, it was suggested that the embedded through-section (ETS) technology should be used to strengthen damaged concrete beams and FRP bars should be used as the reinforcement material [9,10].

2 Experimental overview

2.1 Static load test
The concrete used in this test was self-contained concrete, which was formed by on-site pouring and on-site maintenance. The design strength grade was C30. At the same time as the casting of the samples, 12 cube samples with a size of 150 mm were produced and the test block and the samples were cured under the same conditions. The axial pressure test showed that the final value of the measured strength of the concrete cube samples was $f_{cu} = 35$ MPa.

In this experiment, 7 simply supported rectangular beams with the same length, cross-sectional dimension, and reinforcement rate were used. The 7 beams in this test were divided into 2 groups and the control beam BS was not reinforced. The details of the beams used in the experiment were shown in Table 1. The calculated span was 1.8 m, and the standard span was 2.1 m. One of the beams was a control beam and the other six beams were reinforced beams. The Stirrups with different spacing were arranged on both sides of the samples; one side was the reinforced zone and the other side was the strengthened area. The concrete protective layer of the beam had a thickness of 25 mm. The dimensions of the test beam and the reinforcement area were shown in Figure 1.

Table 1 Details of the beams used in the experiment

| Group number | Sample number | Concrete marking | Degree of damage | FRP rib/hole diameter (mm) | Frp rib spacing (mm) | Angle between hole and lateral direction | Sample size (length X width X height mm) |
|--------------|---------------|-----------------|-----------------|--------------------------|---------------------|------------------------------------------|----------------------------------------|
| First Group  | BS            | C30             | 0               | -                        | -                   |                                          | 2100×200×300                           |
|              | BF1           | C30             | 0               | 10/20                    | 20                  | 45°                                      | 2100×200×300                           |
|              | BF2           | C30             | 30%→0           | 10/20                    | 20                  | 45°                                      | 2100×200×300                           |
|              | BF3           | C30             | 60%→0           | 10/20                    | 20                  | 45°                                      | 2100×200×300                           |
| Second Group | BF4           | C30             | 0               | 10/20                    | 20                  | 60°                                      | 2100×200×300                           |
|              | BF5           | C30             | 30%→0           | 10/20                    | 20                  | 60°                                      | 2100×200×300                           |
|              | BF6           | C30             | 60%→0           | 10/20                    | 20                  | 60°                                      | 2100×200×300                           |
In the test, four-point bending loading in a positive position was used. A diagram of the test setup was shown in Figure 2. The test was conducted by using the electro-hydraulic servo loading system at the Engineering Test Center at Wuhan University of Science and Technology. The loads of the 6 beams (all except for BS) were divided into direct loading and preloading. BF1 and BF4 were reinforced beams that were loaded directly, i.e., the FRP material was used for reinforcement prior to loading and the beam was then loaded to the limit state. BF2 and BF5 were reinforced beams with 30% damage that were preloaded. BF3 and BF6 had 60% damage and were preloaded reinforced beams. First, the test beam was loaded to 30%/60% of the ultimate load. After complete unloading, the reinforcement material penetrated the beam, which was then reloaded to the limit state. The main test contents of the test included: the first curved crack, the occurrence and development of oblique cracks, the width of the oblique crack, the deflection of the two supports and the mid-span, the FRP strain.

3. Experimental results

3.1 Bearing capacity
The control beam BS was not damaged and had not been reinforced. When it was loaded to 90 kN, small curved cracks appeared in the span. As the load was sustained, the length of the crack continues upwardly along the beam. When the load increased to 150 kN, a new oblique crack appeared in the curved shear zone. Finally, when the load rose to 300 kN, the deflection of the control beam increased sharply. When the load was removed, the beam broke. At this time, the longitudinal steel in the beam had not yielded and there were obvious displacements on both sides of the oblique cracks, which was a typical shear failure. The bearing capacity of the six samples was shown in Table 2.

| Sample number | Degree of damage | Damage load (KN) | Ultimate load(KN) | Ultimate load increase |
|---------------|------------------|------------------|-------------------|-----------------------|
| 1             |                  |                  |                   |                       |
The results indicated that the ultimate loads of the FRP-reinforced beam were higher than that of the control beam and the ultimate loads of the non-damaged reinforced beams were higher than those of the damaged reinforced beams. However, under the same condition, the differences in the load between the three damaged reinforced beams and the control beam were rather small. The beams that were reinforced at angles of 45° had greater ultimate bearing capacity than those reinforced at angles of 60° because the main crack of the beam had a certain angle of inclination. When the FRP penetrated the beam at an oblique angle with the beam axis (preferably perpendicular to the main oblique cracks that may occur), the development of oblique cracks was prevented or the oblique cracks developed slowly and the reinforcement effect was better.

3.2 Load deflection

Figure 3 showed the Load-deflection analysis of reinforced beams.

For the reinforced beams strengthened with the FRP bars, the cracking load of the strengthened beams was not higher but the FRP bars prevented oblique cracks. However, after cracks appeared in the strengthened beams, the FRP bars played a major role in improving the ultimate bearing capacity of the beams. The degree of damage had little effect on the stiffness of the reinforced beam. The FRP reinforcement of the beam effectively inhibited the development of oblique cracks and improved the aggregate interlock of the concrete at the oblique cracks; this effect was similar to that of the stirrup. To some extent, the stiffness of the concrete beam increased.

3.3 FRP strain

The magnitude and changes of the measured strain values of the FRP bars that penetrated into the test beam reflect the stress state of the reinforced beams. The strain gauge locations on the FRP bars were
shown in Figure 4. Taking the test beam BF3 as an example, the relationship between the load and the strain of the FRP was demonstrated in Figure 5.

Taking the test beam BF3 as an example, the relationship between the load and the strain of the FRP was demonstrated in Figure 5. In the initial loading stage, the strain of the FRP bars was small for all reinforced beams. With the increase in the load, oblique cracks occurred in the bending and shearing zone of the samples and the increase in the strain of the FRP bars was large, which affected the shear performance. The strain of the FRP bars was larger in the middle of the curved shear zone than near the support. The FRP bars near the support exhibited almost no reinforcement effect, indicating that the effect of the FRP bars was related to the position of the bars. There were also differences in the strain value between the FRP bars in the middle of the curved shear zone. The FRP bars near the crack exhibited large strain and carried more of the load. In general, the FRP bars near the crack exhibited the largest strain and the strain values decreased toward both sides. Since the samples were showed shear failure, the FRP had a strong reinforcement effect. Therefore, the FRP bars had large strain values at last.

4. Conclusion
In this study, the shear behavior of damaged concrete beams reinforced with FRP was determined and the failure modes of the beams were determined. The following conclusions were drawn:

(1) The reinforced beams exhibited significant higher ultimate bearing capacity than the non-reinforced beam. Especially for the damaged beam, the average increase was 10% to 15%.

(2) Epoxy resin was used in this experiment; it had higher solid resistance, better temperature resistance, and was more environmentally friendly than ordinary plant-based rubber. Moreover, the ETS method has better adhesion than the EB and NSM methods and peeling does not occur when the reinforced samples experience failure.

(3) The ultimate reinforcement capacity was greater for the beam strengthened at a 45° angle than that at a 60° angle. The reason was that the main crack of the beam had a certain angle of inclination; the oblique cracks generally approached 45°, and the FRP rib angle of 45° was perpendicular to it. The oblique penetration of the FRP material successfully inhibited the development of oblique cracks, resulting in a better reinforcement effect.

(4) In the damage beams, there were already cracks in the samples prior to reinforcement and the different sized cracks meant that different FRP bars shared the load. The greater the degree of the damage, the wider the crack was, and the sooner the FRP had to bear the load.
The results of this study indicate that the ETS method represents provided a good reinforcement effect.
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