EFFECT OF LOADING CONFIGURATIONS ON THE STRUCTURAL BEHAVIOR OF FRP STRENGTHENED CONCRETE BEAMS

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ABSTRACT

In recent years, the bonding of fiber reinforced polymer (FRP) has been accepted as an effective and efficient method for strengthening and retrofitting concrete structures. In this investigation, to study failure behavior of the FRP strengthened beams under practical conditions, two kinds of tests different to the three-point and four-point bending tests are performed. In the first test, simply supported beams are tested under quasi-distributed loading. In the second test, to simulate the condition in a continuously supported member, hogging moments are applied on the two ends of a beam and the FRP plate is terminated within the compression zone. According to the test results, for beams with thin FRP plate, load uniformity can increase the moment capacity without changing the failure mode. However, for beams with thick FRP plate, there will be a change of failure mode from crack induced debonding to concrete cover separation and a corresponding reduction in the moment capacity. With part of the FRP plate terminated within the compression zone, the longitudinal compression around the plate end can lead to a transition of failure mode from plate end failure to crack-induced debonding, with a corresponding enhancement of the moment capacity. The transition of the failure mode indicates that the loading configuration has important effects on the structural behavior of the FRP strengthened concrete beam.

KEYWORDS

FRP, RC beams, Quasi-distributed loading, Hogging moment, Failure behaviour.

INTRODUCTION

In recent years, the bonding of fiber reinforced polymer (FRP) has been accepted as an effective and efficient method for strengthening and retrofitting concrete structures. Based on a large number of research studies, the failure mode of FRP strengthened concrete beams can be categorized into six types under three failure mechanisms, i.e., flexural failure, including FRP rupture and concrete crushing in the compression zone, shear failure as well as local failure, including concrete cover separation, plate end interfacial debonding and crack-induced debonding. The first two failure modes (flexural and shear failure) can be avoided by proper strengthening design. Concrete cover separation and plate end interfacial debonding are caused by local stress concentrations due to the abrupt termination of the plate near the support (Saadatmanesh and Malek 1998). Crack-induced debonding is caused by high interfacial stresses at the vicinity of an opening flexural/shear crack in the strengthened beam (Leung, 2001).

In existing experimental investigations, the FRP strengthened concrete beams are commonly loaded in three or four-point bending. The FRP plate is hence always under tension. However, under some conditions, for example, in FRP strengthened continuous beams, FRP plates may be subject to compressive stresses. In general, the Young’s Modulus of CFRP in compression is lower than that in tension. As stated by CEB-fib (2001), external bonded FRP plates may fail by local buckling at relatively low compressive stress levels. It is hence suggested that FRP should not be used as compression reinforcement. Up to the present, experimental investigations regarding the bonded plate under longitudinal compression is very limited. One test with a FRP laminate bonded in the compression zone of a RC beam was reported by Deuring (1993). However, no buckling failure of the plate was observed. On the other hand, tests for simply supported aluminum beams bonded with CFRP laminates demonstrated that premature local buckling of the CFRP is possible (Triantafillou et al. 1991). The analysis of CFRP local buckling would involve idealizing the CFRP as an elastic thin plate supported over an elastic beam. According to CEB-fib (2001), some initial efforts have been put on the problem, but no firm results are available yet. In this investigation, hogging moments are applied at both ends of the span of strengthened members to produce compression zones within which CFRP plates are terminated. With different hogging-to-sagging
moment ratios, the influence of compression at plate ends can be investigated. Plate thickness is also investigated as it can affect the shear transfer, the ultimate capacity and the failure mode of the specimen. The loading configuration affects the variation of moment and shear along the beam and should also be an important factor affecting the structural behavior of FRP strengthened concrete beams. In practical situations, it is common to have distributed loads acting on the beam rather than loading at one or two points as in the laboratory tests. In this investigation, strengthened members are also loaded with different load distributions to see how the different moment and shear distributions may affect the failure behavior. Two important parameters, the number of loading points and the plate thickness, will be investigated.

EXPERIMENTAL PROGRAM

In this experimental study, two series of tests were conducted. The first one is FRP strengthened concrete beams under quasi-distributed loading configuration applied through a wiffle-tree system. The second series is FRP strengthened concrete beams with part of plate bonded in the compression zone arising from hogging moment at both ends of the span. To generate the hogging moments, the beams are cantilevered at both ends and loading is applied outside the supported span. For ease of result presentation, the notation of the specimens is described as follows. For example, in the name D4-P8-L2, or C10-M025-L6, the first part gives the test series to which the specimen belongs. “D” means that the beam is subjected to quasi-distributed loading. “C” refers to tests with the plate ends terminated within the compression zone. The number that follows “D” or “C” denotes the specimen number. For specimens in test series D, the second part indicates the number of loading points. For specimens in test series C, the second part specifies the hogging-to-sagging moment ratio. For instance, “M025” indicates that the specimen is loaded with a ratio of 0.25 between the maximum hogging and sagging moments. The last part gives the number of CFRP layers. A letter “s” after the number indicates that stacking is applied at the plate ends to produce tapered plates.

Specimen Preparation

In the experiments, each beam specimen is 150mm in width and 200mm in depth, and is reinforced with two ribbed bars of 10mm diameter at an effective depth of 163mm. Inside the member, 12mm diameter stirrups made of mild steel spaced at 80mm were employed to avoid shear failure. For the specimens in the series D, the CFRP plate was cut off at 75mm from the support. For the specimens in the series C, two 20mm diameter ribbed tension bars are provided to resist the hogging moment above the supports. To avoid brittle shear failure, apart from adding more shear reinforcements, the span of specimen in test series C is lengthened to 2200mm from 1800mm (for the test series D). In test series D, to perform testing under multiple-point loading, the wiffle-tree system illustrated in Fig.1(a) was adopted. For beams, the effective shear span \( \mu_E = \frac{M_{\text{max}}}{V_{\text{max}}} \) is an important parameter affecting the structural behavior. The effective shear spans for 2-point, 4-point and 8-point tests are 787.5mm, 562.5mm and 450mm respectively. In test series C, strengthened beams are loaded with part of the plate bonded in the compression zone. In order to generate longitudinal compression around the plate ends, cantilevers are left on the two sides of the supported span and loading is applied on the cantilever with the help of the wiffle-tree system in Fig.1(b). Different levels of compression can be adjusted by moving the loading points to different position of the span outside the supports. The length of the cantilever span of the specimen in test series C is 650mm, and the hogging-to-sagging moment ratio ranges from 0 to 1. The detailed information about the specimens in the two test series is shown in Table 1.

In the experiments, for the test series D, nine specimens were tested for different combinations of the following parameters: number of loading points (2-point, 4-point and 8-point) and number of CFRP layers (2-ply, 4-ply and 6-ply). Among these specimens, one specimen, D9-P8-L6s, has tapers at the plate end, made with 2 stacks of 3-ply CFRP, terminated at a distance of 150mm apart. For the test series C, the effect of two important parameters, hogging-to-sagging moment ratio and plate thickness, are investigated. In this series, a total of ten specimens were prepared and tested.

Material properties

The concrete mixes used in the tests were ordered from a commercial concrete supplier to ensure consistent properties for all specimens in the same series. After casting, specimens were wet cured under outdoor condition up to 28 days. After curing, the concrete strengths for test series D and C were found to be 59MPa and 39.8MPa respectively. The tension steel reinforcement used in all test series was high yield steel with a yielding strength of 550MPa and Young Modulus of 202GPa. For compression steel reinforcement, two mild steel bars with diameter of 8mm were placed at a depth of 36mm. In the current experimental program, uni-directional carbon fiber composite formed with a wet lay-up process was used for flexural strengthening. For a ply of FRP sheet,
the nominal thickness is 0.11 mm. The tensile strength of FRP is 4200MPa and the Young’s modulus is 235GPa. In all of the tests, the width of the bonded plate is the same as that of the concrete beams, i.e. 150 mm. Two types of epoxy resins, i.e. epoxy primer and epoxy resin, were used to bond FRP sheets on the concrete substrates. To perform the bonding, the resin was mixed thoroughly with hardener in ratio of 3:1 by weight. The tensile modulus, shear modulus and Poisson’s ratio of these epoxy resins can be taken as 3.5GPa, 1.28GPa and 0.37, respectively. The thickness of the adhesive is about 2 mm.

Table 1 Specimen information for test series D and C

<table>
<thead>
<tr>
<th>Test series D</th>
<th>Loading Points</th>
<th>Layers</th>
<th>Effective Shear Span (mm)</th>
<th>Max. Moment (kNm)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1-P2-l2</td>
<td>2</td>
<td>2</td>
<td>787.5</td>
<td>24.5</td>
<td>FR</td>
</tr>
<tr>
<td>D2-P2-l2</td>
<td>2</td>
<td>2</td>
<td>787.5</td>
<td>26.3</td>
<td>IC</td>
</tr>
<tr>
<td>D3-P4-l2</td>
<td>4</td>
<td>2</td>
<td>562.5</td>
<td>29.7</td>
<td>IC</td>
</tr>
<tr>
<td>D4-P8-l2</td>
<td>8</td>
<td>2</td>
<td>450</td>
<td>31.0</td>
<td>IC</td>
</tr>
<tr>
<td>D5-P8-l4</td>
<td>8</td>
<td>4</td>
<td>450</td>
<td>40.4</td>
<td>IC</td>
</tr>
<tr>
<td>D6-P2-l6</td>
<td>2</td>
<td>6</td>
<td>787.5</td>
<td>37.2</td>
<td>IC</td>
</tr>
<tr>
<td>D7-P4-l6</td>
<td>4</td>
<td>6</td>
<td>562.5</td>
<td>33.6</td>
<td>PE</td>
</tr>
<tr>
<td>D8-P8-l6</td>
<td>8</td>
<td>6</td>
<td>450</td>
<td>32.9</td>
<td>PE</td>
</tr>
<tr>
<td>D9-P8-l6s</td>
<td>8</td>
<td>6 (stacking)</td>
<td>450</td>
<td>34.7</td>
<td>PE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test series C</th>
<th>FRP Layers</th>
<th>M2,M4</th>
<th>M2R,M4</th>
<th>Shear Span (mm)</th>
<th>Max. moment (kNm)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-M0-l2</td>
<td>2</td>
<td>0</td>
<td>-0.1</td>
<td>1000</td>
<td>29.6</td>
<td>IC</td>
</tr>
<tr>
<td>C2-M03-12</td>
<td>2</td>
<td>0.33</td>
<td>0.2</td>
<td>1000</td>
<td>28.4</td>
<td>IC</td>
</tr>
<tr>
<td>C3-M1-l2</td>
<td>2</td>
<td>1</td>
<td>0.8</td>
<td>1000</td>
<td>33.4</td>
<td>IC</td>
</tr>
<tr>
<td>C4-M0-l6</td>
<td>6</td>
<td>0</td>
<td>-0.2</td>
<td>1000</td>
<td>40.8</td>
<td>IC</td>
</tr>
<tr>
<td>C5-M0-l6</td>
<td>6</td>
<td>0</td>
<td>-0.2</td>
<td>1000</td>
<td>40.8</td>
<td>IC</td>
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<tr>
<td>C6-M0-l6</td>
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<td>-0.2</td>
<td>1000</td>
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<tr>
<td>C7-M043-l6</td>
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<td>C8-M067-l6</td>
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<td>43.1</td>
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<tr>
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<td>1</td>
<td>0.6</td>
<td>1000</td>
<td>NA</td>
<td>AF</td>
</tr>
<tr>
<td>C10-M1-6</td>
<td>6</td>
<td>1</td>
<td>0.6</td>
<td>1000</td>
<td>39.1</td>
<td>IC</td>
</tr>
</tbody>
</table>

Note: FR means fibre rupture failure, IC indicates intermediate crack induced debonding, PE refers to plate end failure, and AF means adhesive failure.

Testing equipment

All tests were conducted on a hydraulic loading machine DARTEC 2500 with a maximum capacity of 2500kN. In the experiments, the specimens were loaded under stroke control with a loading rate of 0.0085 mm/s. The force exerted by the machine is measured using a calibrated load cell and the stroke is measured using an internal Linear Variable Differential Transformer (LVDT). Data measured during the tests included the force applied by DARTEC, the displacement of the ram, and mid-span deflection of the beam measured by a LVDT and strains measured by six electrical resistance strain gauges. Simultaneous data collection during testing was carried out with an automatic data logger.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Failure Characterization

In the test series D, the beams with two FRP layers failed by intermediate crack induced debonding except one of the 2-point beams which failed by unexpected fiber rupture. For all of these specimens, the first set of flexural cracks developed simultaneously at a moment of 6kNm in the constant moment zone. With the decrease of the stiffness of the strengthened beam, these flexural cracks grew into the concrete compression zone. The second stage can be visualized graphically from the second sharp slope change at a moment of about 18kNm in Fig.2. In this stage, the tension steel bars has already yielded and loading on the FRP increased at a higher rate. It was observed that, for the 2-point and 4-point specimens, there was a major flexural-shear crack just next to or near the constant moment zone. For the 8-point beam, however, mainly vertical cracks could be found around the middle span. Since these cracks are not inclined, they are flexural cracks rather than flexural-shear cracks. Fig.2 depicts the moment responses of all the 2-ply beams in test series D. As shown in the figure, the structural behaviors are nearly identical before the yielding of tension steel bars. However, when there are more loading points, the ultimate debonding moment and the final deflection of the specimen are higher.

In test series D, only one beam with 4 CFRP layers was tested. It was loaded with 8 loading points and failed by FRP debonding from an intermediate crack. The crack pattern as well as the moment-deflection diagram is
similar to those of the 2-ply specimens. The cracking moment, yielding moment and debonding moment of this specimen are 6kNm, 22.7kNm and 40.4kNm respectively. Four 6-ply specimens were tested under 2-point, 4-point and 8-point loading configurations, and their moment-deflection responses are shown in Fig.3. Among these specimens, one of them was strengthened with stacked CFRP and tested under 8-point loading. For the 2-point test (D6-P2-L6), the beam failed by FRP debonding from an intermediate crack. For the other 6-ply specimens (D7-P4-L6, D8-P8-L6 and D9-P8-L6), they failed by concrete cover separation. With the same failure mode, the debonding moments of D7-P4-L6, D8-P8-L6 and D9-P8-L6, are 33.3kNm, 32.8kNm and 34.5kNm, respectively.

In test series C, the beams with two plies of FRP failed by intermediate crack induced debonding. Fig.4 depicts the moment responses of all the 2-ply beams. For these specimens, the initial cracking moment is about 6kNm, and the moment corresponding to steel yielding is about 20kNm. With increasing load, initial debonding of the FRP plate from an intermediate crack occurred. This brittle failure was accompanied by a sharp moment drop, and the residual moment was very close to the yielding moment of the beam before strengthening. For C2-M033-L2, instead of a sudden debonding, the interfacial crack stopped near the point where the sectional moment was zero, resulting in a partial drop of the moment (as shown in Fig.4). From the figure, the behaviors of C1-M0-L2 and C2-M033-L2 are similar before debonding. The latter specimen has a slightly higher stiffness after the first cracking. For the specimen with the largest compression region (C3-M1-L2), its stiffness and debonding moment are the highest compared to the other two cases. However, in this case, the lowest deflection at debonding is obtained.

In our tests, six 6-ply beams were also loaded with different moment ratios. All the beams failed by intermediate crack induced debonding. For these specimens, the first set of cracks was formed at the middle span at about 7kNm. After a sharp change of stiffness, the deflection of these beams increased linearly with increasing moment until the yielding point of the tension reinforcement was reached. With increasing moment, the CFRP plates eventually debonded from an intermediate crack in the span. For two specimens which were loaded as simply-supported beams (C5-M0-L6 and C6-M0-L6), their debonding moments are 40.8 kNm and 40.6 kNm respectively (Fig.5). When hogging moments were applied with the hogging-to-sagging moment ratio of 0.43, 0.67 and 1, the debonding moments are 43.2kNm, 43.1kNm and 39.1kNm respectively. The stiffness of most 6-ply specimens after first cracking generally increases with hogging-to-sagging moment ratio.
Influence of the load uniformity

From the above test results of test series D, for 2-ply beams, ignoring the one which failed by unexpected fiber rupture, they all failed by FRP debonding from the intermediate crack. The load and deflection at failure increase with the load uniformity. There are two main reasons which may lead to the enhancement. For crack induced debonding, Niedermeier (2000) proposed that the increase in tensile stress within the FRP plate is transferred by means of bond stresses between two subsequent flexural cracks. When this increase exceeds the critical value that can be transferred, debonding will initiate at flexural cracks. When the loading becomes more uniform, the moment difference between the locations of two adjacent cracks is smaller. Hence, the increase in tensile stress $\Delta \sigma$ becomes more gentle. In order for failure to occur, higher load has to be applied onto the beam, and, consequently, larger deformation is also attained. In current tests, when the load uniformity increases, there are less flexural-shear cracks in the specimen as shear force is comparatively lower along the shear span. Debonding is therefore triggered mainly by the longitudinal tensile stresses acting on the plate at each flexural crack. However, FRP debonding may occur easier with flexural-shear cracks. Sebastian (2001) stated that the opening of these inclined cracks induces local bending, or, in other words, dowel action of the plate. This causes the plate to exert a vertical pull on the concrete-to-adhesive layer adjacent the crack. The presence of the peeling force will make it easier for debonding to occur (Pan and Leung, 2007).

For beams strengthened with 6 plies of CFRP, load uniformity affects both the failure load and failure mode. Specifically, as load uniformity increases, the failure mode of CFRP-strengthened beams changes from intermediate crack induced debonding mode to concrete cover separation. It is generally considered that plate end failure is initiated by the interfacial shear and normal stresses at the plate end (Saadatmanesh and Malek 1998). Considering two specimens under different load uniformity but the same maximum moment, the moment and shear force acting on the section at the plate end are much higher in the case with more loading points. Hence, the specimen under more uniform load has a higher tendency to fail at the plate end.

Influence of the plate thickness

It is commonly considered that plate thickness is a crucial factor that affects the structural behavior of FRP strengthened RC beams. According to the experimental observations with 8 loading points, the failure mode changes from the intermediate crack induced debonding for 2-ply and 4-ply specimens to concrete cover separation for the 6-ply specimens. The 4-point tests have shown a similar trend with the 2-ply and 6-ply tests. Sebastian (2001) pointed out that boundary conditions at the cut-off point should result in zero curvature in the plate. However, at the same location, nonzero moments and nonzero curvatures exist in the beams. The plate ends therefore tend to bend away from the soffit. Thicker plate will generate larger peeling stresses because of its higher bending stiffness. Therefore, when thicker plate is used, concrete cover separation is more likely to occur. While considering intermediate crack induced debonding alone, the increase in plate thickness enhances the load and deflection at debonding. This trend is consistent with the prediction from fracture-mechanics based models (e.g. Täljsten 1996, Teng et al. 2002) which shows that the plate thickness and the maximum tensile load acting on the plate should be proportional to the square root of the plate thickness. These claims are also true regardless of the load uniformity according to current test results (D2-P2-L2 vs. D6-P2-L6 and D4-P8-L2 vs. D5-P8-L4).

Influence of stacking

While comparing the debonding moments of D8-P8-L6 (32.9kNm) and D9-P8-L6s (34.7kNm), it can be seen that the specimen with stacking gives a higher value. Theoretically speaking, regardless of the load uniformity, as long as the failure mode of concrete cover separation is observed, the beam with tapered plate ends, should give a higher debonding load. The main reason is that the stiffness of the plate ends is reduced by stacking. The peeling force which triggers plate end failure is therefore smaller. However, since there is only one test with stacked FRP, the effect of stacking should be clarified with further tests.

Influence of hogging moment

When the CFRP plate is terminated in the compression zone, the concrete element adjacent to the plate end is subjected to compressive stresses and shear stresses, as shown in Fig.6. With the compressive and shear stresses, the concrete element shows compressive principal stress. As the element is under compression, neither flexural crack nor flexural-shear crack can be formed at the plate end. Hence, the plate end failure is avoided and failure shifts to another mode, i.e. intermediate crack induced debonding.
In test series C, the purpose of applying hogging moment at both ends of the span is to generate compression at the anchor region of CFRP plates. Instead of focusing on the hogging-to-sagging moment ratio, the ratio between the moment at plate ends and the maximum sagging moment, i.e. $M_{PE}/M_S$, will be considered. The variations of the debonding moment with the moment ratio for the test series C are plotted in Fig.7. Although all the specimens in series C failed in intermediate crack induced debonding, 2-ply and 6-ply specimens do not give the same trend. For 2-ply beams, the maximum debonding moment is obtained for $M_{PE}/M_S = 0.8$ (C3-M1-L2) which is the highest ratio among the tests. However, for 6-ply beams, the ultimate moment is higher for intermediate values of moment ratio. Indeed, if one looks at all the test results, the debonding moment does not appear to be too sensitive to the moment ratio. This may be reasonable as the failure mode is the same for all cases.

In terms of the stiffness, it generally increases with the moment ratio, indicating that for given moment, the deflection decreases with the moment ratio. A typical moment diagram for the beam is shown in Fig.5.10. The deflection relative to the supports can be obtained from the moment area method. When hogging moment is applied, with the same sagging moment, the deflection will be smaller as the net moment area is smaller compared to the case of simply-supported beams. In addition, as the debonding moment is similar in the various cases, the deflection at failure is smaller when the moment ratio is increased.

CONCLUSIONS

In this paper, experimental investigations have been conducted to study the structural behavior of FRP strengthened RC beams under quasi-distributed loading configurations. Based on the test results, with higher load uniformity, beams strengthened by thin plates still fail through intermediate crack induced debonding and the debonding moment is increased. For beams strengthened with thick plates, increasing the load uniformity may lead to a transition of failure mode from intermediate crack induced debonding to concrete cover separation, with a corresponding reduction in moment capacity. For the same loading uniformity, a transition of failure mode from intermediate crack induced debonding to plate end failure may appear when the plate thickness is increased. If the failure mode remains intermediate crack induced debonding, increase in thickness can enhance the moment and deflection at debonding. Stacking of CFRP plates may increase the debonding moment when failure occurs at the plate end. The effect of the hogging-to-sagging moment ratio has also been experimentally investigated. The hogging moment can effectively produce compression zone near the supports, which converts the principal stresses near the plate ends to compression. Plate end failure is therefore avoided. Based on the test results, the debonding moment seems not to be too sensitive to the hogging-to-sagging moment ratio. However, with increasing moment ratio, the flexural deflection of the FRP strengthened RC beams is significantly increased.

REFERENCES


