Performance of CFRP Anchors under Dynamic Loading

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Abstract. This paper presents an experimental study of reinforced concrete beams strengthened with CFRP laminates and anchored with carbon fibre anchors under monotonic static and cyclic loading. To gain full advantage of externally bonded CFRP technique, it is important to avoid premature debonding of the laminates, and CFRP anchors have the potential to prevent this happening by transferring the stress from steel reinforcement to the laminates. In this study, cyclic tests were conducted to investigate the fatigue behaviour of the strengthened beams and to identify strengthening effects of various anchoring depths. The aim of the monotonic tests was to determine strengthening efficiency of the new anchoring technique and to evaluate serviceability and ultimate states of the beams. According to the results, a damage index was proposed based on fractal analysis of cracks under cyclic loading and validated through ultrasonic inspection analysis. In addition, an empirical equation between average reduction of ultrasonic wave velocity and residual bearing capacity was established.

1. Introduction

FRP strengthening is a widely used technology for the rehabilitation and repair of various reinforced concrete (RC) structures. There are many contributions in the area of flexural strengthening of reinforced concrete members subjected to monotonic loading [1]. FRP fabrics are prone to premature debonding in a generally brittle manner; on average, the CFRP sheet is exhausted at a low ratio of its tensile strength when the specimen failed because of intermediate crack debonding [2], which is severe limitation to this strengthening method. With the aim of preventing premature debonding, novel fabric-reinforced cementitious matrix (FRCM) materials are under investigation in order to increase the bond strength of the FRP with the substrate [3]. Alternatively, anchorage system of CFRP is another method that behaves in a similar manner to traditional chemical anchors and steel mechanical fasteners, involving a great increase in capacity [4].

CFRP anchors, also referred to as CFRP dowels have been proposed as an effective means to delay or avoid the premature delamination of CFRP sheets. The main advantages of this anchorage system are high strength-to-weight ratio, non-corroding characteristics and easy to be constructed. Earlier studies in Kobayashi et al. [5], have noted the efficacy of this system in resisting premature debonding of FRP sheets. More than ten years later, the parameters affecting the performance of FRP anchors are still being studied.

To adapt an externally bonded CFRP strengthening and CFRP anchoring system for real RC structures that subjected to cyclic loading such as bridge and long piled wharf, the influence of loading cycle numbers, RC members’ own characteristics and CFRP anchor installation parameters must be investigated.

This paper focuses on CFRP anchors embedded in RC beams that strengthened with CFRP fabrics under cyclic bending conditions, in order to assess performance of the strengthened beams and the
reliability of the CFRP anchorage system. Moreover, it is aims provide fundamental understanding of the strengthening effects of anchors installation geometrical parameters on the load transferring mechanism under cyclic loading.

2. Experimental details
A total of 7 RC beam specimens with and without anchors were tested under three-point bending loading. Figure 1 shows the details of beams while Figure 2 shows the test set-up. The beams were nominally 120mm wide by 150mm deep by 400mm long and reinforced by two 12-mm diameter deformed bars and 8-mm diameter plain stirrups spaced at 80mm. A concrete cover of 20-mm thick was used around the stirrups. The CFRP anchors and plates were manufactured by the same kind of carbon fibre sheets that were nominally 0.11-mm thick per layer. CFRP plates of 100-mm width used herein were made from two layers of carbon fibre sheets in a wet lay-up manner. The supported area of beams was created by pre-bonding thick steel blocks of 30-mm length at both ends of bottoms. The specimens are divided into two series and described in detail in Table 1.

The bending test program was selected as a common working condition in wharf engineering. The loads were provided by an HTS 300 kN SANE250 electro-hydraulic servo actuator which was restrained in a steel reaction frame. Beam F-0 in control series was only tested under monotonic quasi-static loading and the remaining six specimens were initially tested under cycling loading followed by destructive monotonic quasi-static loading tests to determine their residual bending capacity. In all cases, every beam specimen was finally tested to failure under monotonic quasi-static loading.

Beams of anchored series and S-0, SH-0 were first preloaded monotonically up to the required cyclic load level (equals to half of F-0’s ultimate load capacity, corresponding to the loading of 64.8 kN) at a load rate of approximately 2 kN/s. After that, the fatigue was applied with a frequency of 1 Hz and a constant amplitude, as shown in Figure 2.

| Series          | Specimen ID | Bonded plate | Anchor Details | Loading |
|-----------------|-------------|--------------|----------------|---------|
| Control Series  | F-0         | N            | -              | S       |
|                 | S-0         | N            | -              | S&C     |
|                 | SH-0        | Y            | 0              | S&C     |
| Anchored Series | SH-15       | Y            | 15             | S&C     |
|                 | SH-25       | Y            | 25             | S&C     |
|                 | SH-35       | Y            | 35             | S&C     |
|                 | SH-45       | Y            | 45             | S&C     |

a Y/N = strengthened with CFRP/not strengthened  
b C/S = cyclic loading/monotonic static loading

Figure 1. Specimen geometry and measuring scheme (all dimensions in mm).
3. Experimental results and discussion

3.1. Time history curves of strain under cyclic loading

The incoordinate deformation between steel and concrete had developed with the accumulation of damage induced by cyclic loading, as shown in Figure 3. A typical three-stage characteristic could be described as stage I-III which indicate the cooperation between anchorage system and RC beam, partial failure of the anchorage system and total failure of the anchorage system, respectively (points c1 and c2 are the numbers of cycles at the boundary of stage I, II and II, III, respectively).

3.2. Fractal analysis of cracking pattern

Geometric morphology of the cracks marked during the cyclic tests were mapped, using different colors to distinguish the recorded time, as shown in Figure 4.
Fractal dimension (D) was used as a geometric parameter to characterize the irregularity of cracking maps [6]. The box-counting method that counted the number of boxes containing cracks N(r) as a function of box size r (m) was applied to estimate the fractal dimension of cracks on the surface of specimens.

Figure 5 illustrates the evolution of the fractal dimension with cycle times that contains two stages (the growth stage and the plateau stage). The fractal dimension (D) increases linearly in growth stage and then reaches a plateau. The comparison among the specimens shows that the values of D decrease firstly and then rise with the increase of embedment depths and the minimum is achieved by SH-35.

3.3. Proposed damage index (FD)
The fractal dimension (D) would vary between 1 and 2 if an appropriate box size was selected. To estimate the extent of strengthening efficiency of CFRP anchorage system, a “damage index” (FD) was defined as described by Eq. (1):

\[
FD = (D_i - 1)/(2 - D_F)
\]

Where \(D_i\) is the fractal dimension computed at \(i\) times load cycle, and \(D_F\) is the fractal dimension at the moment that cracks first become visible. Thus, FD varies between 0 and 1 and represents the difference between the current status of crack patterns and the baseline status \(D_F\).

3.4. Strength loss correlated with “damage index” (FD)
Damage condition could be classified as “weak”, “moderate” or “severe”, and the damage degree was correspondingly divided into three levels: I, II, III, according to values of loss rates of ultimate load (\(\alpha_{P_{max}}\)). Table 6 summarizes \(\alpha_{P_{max}}\), D and FD for different specimens.
Table 2. damage degree defined by the values of the damage index and fractal dimension.

| Specimen | $p_{max}$ (KN) | $\alpha_{p_{max}}$ (%) | Damage degree | Strengthening efficiency | D  | FD  |
|-----------|----------------|------------------------|---------------|--------------------------|----|-----|
| S-0       | 82.7           | 36.2                   | III severe    | 1.461                    | 0.47|
| SH-0      | 97.6           | 24.7                   | II moderate   | 1.448                    | 0.45|
| SH-15     | 107.7          | 16.9                   | II moderate   | 1.427                    | 0.43|
| SH-25     | 132.6          | -2.3                   | I weak        | 1.39                     | 0.39|
| SH-35     | 139.7          | -7.8                   | I weak        | 1.133                    | 0.13|
| SH-45     | 77.0           | 40.6                   | III severe    | 1.462                    | 0.73|

The loss rates of ultimate load ($\alpha_{p_{max}}$) could assess the strength loss with an accepted error. Therefore, FD can be exploited to judge the damage condition of beams strengthened with CFRP system (which could also indicate the strengthening and protection effects of different depths anchors) through visual inspection of crack pattern in case where damage condition and mechanical testing are not available.

4. Conclusions
In this study, the crack patterns of beams strengthened with CFRP fabrics and anchors under monotonic static and cyclic loading were studied by analysing the fractal dimension and supersonic non-destructive detection. The following conclusions can be drawn.

CFRP anchors can remarkably prevent the premature debonding of CFRP sheets. Fractal analysis together with the supersonic non-destructive detection can be exploited to assess the damage to RC beams when a mechanical test is not available.

The fractal dimension (D) whose values increase with the cyclic loading can be a parameter to identify the crack pattern. A damage index (FD) based on fractal dimension (D) of cracks can be used to estimate the damage degree due to cyclic loading. The average reduction of supersonic wave velocity increasing with damage degree is consistent with bearing capacity and damage index (FD), according to which, the accuracy of damage index (FD) is verified.

The performance of beams under both monotonic and cyclic loading is improved firstly and then deteriorates with the increase of anchoring depth. (In this study, the bearing capacity of 35mm anchored beam was approximately 43.1%, 29.7%, 5.4% and 81% higher than those in unanchored, 15, 25 and 45mm depth anchored specimens, respectively). Therefore, the anchoring depth of 1.75 times of cover is recommended for beams under cyclic loading.

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