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Cover separation of CFRP strengthened beam-type cantilevers with steel bolt anchorage

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ABSTRACT

Concrete cover separation is one of the premature debonding failure modes commonly observed when strengthening reinforced concrete (RC) beams that use externally bonded fibre-reinforced polymer (EB-FRP) become delaminated. Anchorage systems, which postpone or prevent debonding, have proven to be an effective method to achieve higher levels of FRP utilization. Although researchers have widely acknowledged the efficiency of anchorage systems, the effect of a bottom steel bolt anchorage system on the concrete cover separation strength remains unclear. The related design formulation is still in its initial stage, which limits the practical use of this type of anchorage system for FRP strengthening. In this study, specimens of carbon fibre-reinforced polymer (CFRP) laminate strengthened beam-type cantilevers with bottom steel bolt anchors were designed and tested. The principle design parameters such as the location, the length and the number of anchors were investigated and their effects were discussed based on the test results. Furthermore, an analytical approach considering various failure modes of anchors and cantilevers was presented to predict the concrete cover separation strength of anchored specimens. The test results were then compared to the analytical approach in order to verify reliability and accuracy.

1. Introduction

Over the last decades, external bonding of fibre-reinforced polymer (EB-FRP) to reinforced concrete (RC) members has been widely used in the rehabilitation practice of deficient concrete structures. Experiments have comprehensively shown this strengthening method to be an effective and convenient way to improve static and fatigue performance of RC structures under service loads, and to increase their ultimate strength [1–3]. This rehabilitation method has attracted researchers' interest worldwide because of its superior advantage in resistance to corrosion, increased durability, flexibility and a high stiffness-to-weight ratio compared to using steel plates.

Despite promising developments in the implementation of FRP for the repair and retrofit of RC structures, previous literature has shown that the application of FRP composites can lead to brittle failure when the FRP composite debonds before reaching design strength [4,5]. The bond deterioration caused by the single or coupled impact of environment (moisture, temperature, chloride ions, etc.), load (sustained load, fatigue, etc.) and the existence of defects at the FRP/concrete interface even made the problem even more critical [6–9]. Among premature debonding failure modes, concrete cover separation failure is often observed. This failure mode initiates at the critical plate end then propagates along the level of substrate tension reinforcement toward the beam's mid-span [10–13]. Three general topics are used to explain the concrete cover separation of a strengthened beam [14]: (1) the derivation of elastic stress concentration at the FRP end, (2) the strengthened beams' shear capacity and (3) the concrete tooth model, which was firstly proposed by Raoof and Hassanen [15,16] and the concrete cover separation was regarded as the failure of a cantilever formed between two adjacent cracks.

Standards and design guidelines impose limits on the maximum strain level of the composite material that may be utilized in design in order to prevent this type of failure [17]. Sallam et al. [18] proved that concrete cover replacement technique, which replaced the concrete cover with grout layer before strengthening, can efficiently prevent the concrete cover separation. Existing studies on steel plate or FRP laminate strengthening have shown that the application of anchoring systems is also an effective way to mitigate and suppress debonding failures to enhance the efficiency of utilization of the FRP material. To date, various anchorage measures have been investigated including

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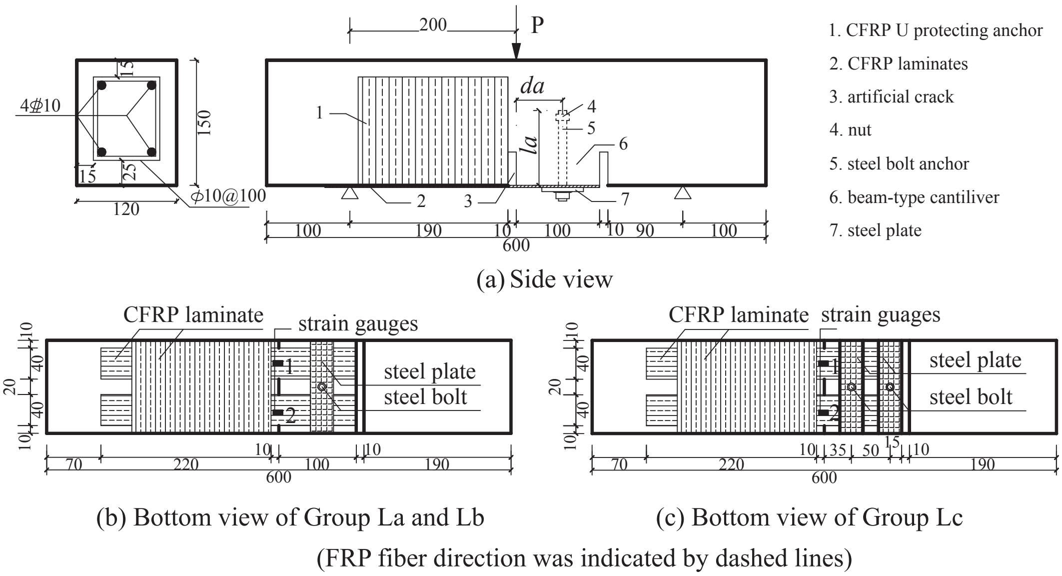

Fig. 1. Geometrical details of the specimens (unit: mm).

[17]: (1) Mechanically fastened metallic anchors [19–22], (2) U-jacket anchors [23–26] and (3) FRP anchors [27–30]. Metallic anchorages with a steel bolt anchorage system were one of the first types of FRP end anchorage devices investigated [31]. Researchers such as Garden and Hollaway [19], Duthinh and Starnes [21] and Maaddawy and Soudki [32] have discovered that the use of metallic anchorages provides a significant increase in anchorage strength, as well as ductility enhancement. Although FRP anchor has its advantage over conventional steel anchor especially due to its high corrosion resistance, steel anchor still shows its practical importance in easy and well developed installation technique, relative lower cost and induce of compressive stress acting on the interface to enhance the bond strength of FRP/concrete interface by tightening steel nut with torque wrench [18]. Stainless steel anchor is also one of options for corrosive environment.

Steel bolt anchorage combined with EB-FRP is also called a hybrid-bonding FRP system (HB-FRP) in some literatures [32–36]. Wu and Huang [33] installed steel nails as anchorage along the bonded FRP strip's length to produce greater resistance to the separation of the FRP strip from the concrete substrate. Results showed that the interfacial bonding strength in HB-FRP strengthened members was 7.5 times of the bonding strength in EB-FRP strengthened members. Zhang et al. [35] conducted a total of 17 beam-shear experiments with mid-span pre-cutting fissures, and proposed formulas for calculating the debonding stress induced by intermediate cracks of EB-FRP and HB-FRP strengthened beams. Wu et al. [36] developed an improved hybrid bonded FRP (IHB-FRP) technique by applying a given pre-tightening force to the steel bolts, and found a more uniform strain distribution in the FRP strip in specimens with anchorage.

Despite extensive research efforts to study the effectiveness of steel bolt anchorage systems and to develop pre-stressed anchorage systems [36] and a bonding strength model [37], the study results are still far away from practical use. Parameters such as the location, the height and the spacing of steel bolts in the previous experiments were random, and didn't have a unified design code. Most of the previous studies focused on the effect of the anchorage system on the interfacial delamination of the FRP-concrete interface, through either bond shear testing with a given bond length or member testing with various anchorage arrangements [38–41]. There is still a lack of specially designed testing to clarify the mechanism of concrete cover separation and the anchorage system. In most of the available experiments in which concrete cover separation was observed, the location of cracks that formed the concrete teeth was not pre-determined. Thus the effect of the geometry of the concrete teeth and location of anchorages remained unclear, and the measurement of FRP strain exactly at the cracked section was difficult. In fact, FRP design guidelines stipulate that the practical implementation of anchorage devices should be substantiated by representative experimental testing (ACI 2008) [42]. Therefore, further efforts are necessary to reach a thorough understanding of the effect of anchorage systems, from which a reliable design could be proposed.

The authors are conducting a series of studies aiming at the development of an analytical approach for flexural strengthening of an existing structure with external FRP composites with various anchorage systems. The present work concentrates specifically on the use of a steel bolt anchorage system and its influence on the concrete cover separation of CFRP-strengthened specimens. Beam-type cantilever tests were designed with pre-determined geometry of concrete teeth (cantilever) and the location of anchorage system. Thus the measurement of FRP strain exactly at the cracked section through the read of strain gauges became possible, making the verification of the strength model easier and more reliable. The behaviors of CFRP strengthened specimens with and without bolted anchorage are experimentally and analytically investigated. An analytical model is developed to predict the response of CFRP-strengthened specimens with bolted anchorage. The reliability and accuracy of the proposed analytical procedure are then verified by comparing the analytical and experimental debonding load of the CFRP-strengthened cantilevers provided in this paper.

2. Experiment program

2.1. Testing specimens

The geometry and reinforcement arrangement of the RC members are shown in Fig. 1. The cross-section of the RC beam-type cantilever specimens is 120 mm × 150 mm, and the length is 600 mm. All specimens had a clear span of 400 mm, and employed two deformed bars of diameter 10 mm as respective compression and tension reinforcement. 10 mm diameter plain bar stirrups spaced at 100 mm were placed along the entire length of the beam. The thickness of concrete cover at bottom was 25 mm, and 15 mm for both the side and top. The beam-type cantilever sections were formed between two adjacent 10 mm wide artificial cracks up to the level of tension reinforcement. CFRP U-anchor with height of 120 mm and width of 200 mm were used in another side to guarantee the targeted failure mode.