Composite Structures 200 (2018) 36–46

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Inclined FRP U-jackets for enhancing structural performance of FRP-plated RC beams suffering from IC debonding

B. Fu[a], X.T. Tang[a], L.J. Li[a,*], F. Liu[a], G. Lin[b]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou, Guangdong Province, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China

ARTICLE INFO

Keywords:
FRP
Flexural strengthening
RC beam
Debonding
U-jacket

ABSTRACT

Intermediate crack debonding (i.e., IC debonding) commonly controls the failure of FRP-plated RC beams. Such IC debonding often occurs with the maximum strain of the FRP soffit plate being far lower than its rupture strain, thus leading to a low utilization of the high strength of expensive FRP material. It is of increasing interest of the research and engineering community to explore an effective anchorage for enhancing the structural performance of FRP-plated RC beams suffering from IC debonding. Inclined FRP U-jacketing is among the easiest and most effective options for this purpose. This paper presents an experimental study to systematically investigate the effect of inclined FRP U-jacketing on the structural performance of FRP-plated RC beams suffering from IC debonding. Eight full-scale RC beams were tested with the width, height and inclination of the U-jacket as the experimental variables. Findings from the present tests show that inclined FRP U-jacketing could successfully lead to concrete crushing failure from IC debonding in the control specimen without anchorage, and significant increase in the load and mid-span deflection of up to 55.8% and 229% over these of the control specimen.

1. Introduction

External bonding of a fiber-reinforced polymer (FRP) plate onto the soffit of a reinforced concrete (RC) beam, leading to what is commonly referred to as an FRP-plated RC beam, has been widely used for upgrading the flexural strength of the original RC beam [1,2]. Its popularity is mainly due to the superior properties of the FRP composites, such as excellent corrosion resistance and high strength-to-weight ratio. Simply-supported beams are assumed in all discussions in the present paper, and conclusions reached herein can be directly applicable to other beams by treating a segment between two points of inflection as an isolated member [1]. The FRP plate bonded onto the tension face of a RC beam can be a pultrude plate or formed using a standard wet layup procedure, and is referred to as "soffit plate". In order to avoid ambiguity in description, the number of U-jackets and soffit plate ends is counted in the half span of the beam under investigation, unless otherwise indicated.

Such an FRP-plated RC beam commonly fails by a debonding failure in the form of either concrete cover separation or intermediate crack debonding (i.e., IC debonding). Concrete cover separation typically initiates with the formation of a flexural-shear crack at the end of the FRP soffit plate, and the subsequent formation of a major horizontal crack at the height of the steel tension bars. The horizontal crack then propagates along the steel tension bars and from the soffit plate end toward the high moment region, and the propagation of the horizontal crack finally leads the concrete cover separate from the beam [3,4]. Concrete cover separation involves a complex mechanism, and its likelihood to occur depends on various factors, such as the combination of moment and shear force at the section, where the soffit plate terminates, concrete cover thickness and soffit plate stiffness [3,4]. IC debonding initiates at the toe of a major flexural crack in the high moment region of the beam, and then propagates toward the direction of decreasing moment. IC debonding occurs in concrete several millimetres beneath the soffit plate, and therefore its strength (i.e., the resisted load of the FRP-plated beam when IC debonding occurs) significantly depends on the strength of concrete, which the FRP soffit plate is bonded onto [5–7].

Both debonding failures occur with the maximum strain of the FRP soffit plate (i.e., FRP debonding strain) being much lower than the tensile rupture strain of the FRP plate (e.g., 30–50% of the tensile rupture strain of the FRP plate), lead to a low utilization of the tensile strength of the expensive FRP material [8]. More importantly, the larger the beam size is, the lower the load enhancement ratio (i.e., the load enhancement/the strength of the original RC beam) that the external bonding of an FRP plate can be optimally achieved. The load carrying capacity can sometimes be increased by even less than 10% as

* Corresponding author.
E-mail address: lilj@gdut.edu.cn (L.J. Li).

https://doi.org/10.1016/j.compstruct.2018.05.074
Received 1 June 2017; Received in revised form 28 March 2018; Accepted 17 May 2018
Available online 18 May 2018
0263-8223/

a result of debonding failures, when external bonding of an FRP plate is used for upgrading flexural strength of large bridge girders [9]. Debonding failures of FRP-plated RC beam therefore become an important impediment to fully utilize the high tensile strength of the expensive FRP material and effectively upgrade the flexural strength of RC members of a large size.

Enhancing the structural performance of FRP-plated RC beams suffering from debonding failures has been attracting an increasing attention of researchers from around the world [8–11]. Concrete cover separation is closely related to the formation of the flexural-shear crack near the soffit plate end and the horizontal crack at the level of tension steel bars, and therefore use of various anchorages measures to restraint the development of these critical cracks could effectively suppress concrete cover separation. A recent study shows that an FRP U-jacket near the end of the FRP soffit plate can effectively suppress the concrete cover separation [4], and prevent the concrete cover separation from being the control failure mode of FRP-plated RC beams. IC debonding fails in the concrete beneath the FRP soffit plate several millimetres, which results in more difficulty to enhance the structural performance of FRP-plated RC beams suffering from IC debonding than that failed by concrete cover separation [12].

Despite the fact that various anchorage measures such as steel bolts, steel clamps, and fiber anchors has been explored [13–18], FRP U-jacketing with fibers being perpendicular to the beam axis (i.e., vertical FRP U-jacketing) is among the most attractive options for enhancing the structural performance of FRP-plated RC beams suffering from IC debonding due to ease of its application, and excellent corrosion resistance [19–23]. It seems that somewhat contradictory conclusions have been drawn from existing studies on the effect of vertical FRP U-jackets on the structural behaviour of FRP-plated RC beams suffering from IC debonding. Brena et al. [19] achieved a significant increase of 18% in the load-carrying capacity over the FRP-plated RC beams without any anchorages by uniformly distributing 6 vertical FRP U-jackets along each half of the beam. Results of tests conducted by Yalim et al. (2008) [20] showed that U-jackets of a large amount (e.g., U-jackets fully placed throughout the span, or 11 U-jackets uniformly distributed along the span) could significantly enhance the load carrying capacity and ductility of the FRP-plated RC beams, even led to a failure mode of rupture of the tension plate. By contrast, other studies showed that use of vertical FRP U-jackets, especially near the end of the FRP soffit plate, led to small increases in the load-carrying capacity, compared to that of their control counterparts without vertical U-jackets [21–23]. For instance, Kotynia et al. [21] used an FRP U-jacket of 3100 mm in width that covered the high moment region to mitigate IC debonding, and achieved an increase of only 6%-9% in the load-carrying capacity compared to its control specimen without FRP U-jacketing. Despite use of 10 vertical U-jackets uniformly installed along the entire length of Girder EB1S, it still failed by IC debonding with only a 9% increase in the load carrying capacity over that of the control specimen without any anchorages. Matthys [22] investigated one specimen with both the FRP soffit plate and one vertical FRP U-jacket at each end of the soffit plate, and observed the load carrying capacity even 1% decrease than the control specimens strengthened with the FRP soffit plate only. A number of studies indicated that vertical FRP U-jackets performed much better in mitigating concrete cover separation than IC debonding [4,24], as they can well constrain the development of the horizontal crack at the height of tension steel bars, which is critical to the presence of concrete cover separation. However, if a narrow FRP U-jacket is used, concrete cover separation may still occur and initiate near the inner side of the U-jacket (i.e., the side closer to the mid span), as the development of the flexural-shear crack near the soffit plate end leads to the part of the soffit plate near its end under compression, and the propagation of the “real end” of the soffit plate, where the FRP strain is close to zero, toward the inner side of the U-jacket [4].

FRP U-jacketing with fibers inclined to the beam axis by a certain angel other than 90° (refer to as inclined FRP U-jackets hereafter) has been recently investigated by a limited number of researchers [4,23,25–27]. A series of single shear tests, in which a group of three identical specimens with inclined U-jacketing was contained, was conducted by Lee and Lopez [24]. It was found that these three specimens with inclined FRP U-jackets performed best among all the specimens with different vertical FRP U-jackets, and had the bond strengths higher than their control specimen that are without any end anchorage by up to 118%. Tajaddini et al. [25] installed two or three inclined U-jackets near the end of the FRP soffit plate end to enhance the ability of moment redistribution of FRP-strengthened continuous RC beams. They found that inclined FRP U-jackets significantly enhanced the ductility of FRP-strengthened beams, and therefore improved the moment redistribution ability, with leading to the maximum failure strain of the FRP soffit plate being 12,000 με from 3500 με in their counterparts strengthened with an FRP soffit plate only. Fu et al. [23] explored different FRP anchorages to mitigate IC debonding failure, and had three specimens with inclined FRP U-jackets. Their study revealed that use of an inclined U-jacket led to the beam failed by the rupture of the FRP soffit plate and a significant increase of up to 43% in the mid-span deflection at beam failure. They concluded that after IC debonding the soffit plate could be held and the specimens could resist further increase in the applied load. Findings from existing studies have indicated that an inclined U-jacket in the low-moment region of the beam is a promising option to enhance the structural performance of FRP-plated RC beams suffering from IC debonding. However, all these studies investigated the effect of inclined U-jacketing as one side effect, and included only one or two specimens with inclined U-jacketing in the low-moment region. Inclined FRP U-jacketing near the soffit plate end showed be effective in constraining the development of both flexural-shear crack near the soffit plate end and the horizontal crack at the height of tension steel bars, thus successfully suppressing concrete cover separation, even a narrow one was used [4,25–27].

This paper presents an experimental study to systematically investigate the effect of inclined FRP U-jacket in the low-moment region on the structural behaviour of FRP-plated RC beams suffering from IC debonding. Eight full-scale RC beams were tested with the width, height and inclination of U-jacketing as the experimental variables. Structural performance of specimens with various inclined FRP U-jackets has been compared and interaction between the FRP soffit plate and the inclined U-jacket has been clarified for future use in establishing a rational design approach.

2. Experimental programme

2.1. Specimen design

The present experimental programme consisted of eight full-scale rectangular RC beams, which had the same geometry: a width of 200 mm, a depth of 450 mm and a clear span of 3800 mm (Fig. 1). The reinforcements of the specimens were carefully designed to ensure that the gap in strengths governed by IC debonding and other failure modes (e.g., concrete crushing failure, rupture of the FRP soffit plate and shear failure) was significant enough to distinguish the effects of different inclined FRP U-jackets. Specifically, all the beams were under-reinforced using three 12 mm deformed steel bars as the internal tension reinforcement, two 12 mm deformed steel bars as the internal compression reinforcement, and 10 mm deformed steel bars with a centre-to-centre spacing of 100 mm as the stirrups. An FRP plate was externally bonded onto the soffit of each RC beam. The soffit plate was formed from three layers of unidirectional carbon fibre sheets with each layer being 0.333 mm in thickness by following a standard wet lay-up procedure, and had a geometry of 100 mm in width, 3800 mm in length and 0.999 mm in nominal thickness.

Specimens differed from each other by the test variable (i.e., the FRP U-jacket as the end anchorage) (Fig. 2). The control specimen was strengthened with an FRP soffit plate and without any end anchorage.