Construction and Building Materials 79 (2015) 370–378

Contents lists available at ScienceDirect

Construction and Building Materials

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

Innovative hybrid bonding method for strengthening reinforced concrete beam in flexure

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HIGHLIGHTS

- The performance of hybrid bonding technique is better compared with the plate bonding method.
- With the increase of stiffness ductility was not affected in hybrid technique compared with plate bonding method.
- Bond performance between plate and concrete was increased by hybrid method.

ARTICLE INFO

Article history:
Received 27 December 2012
Received in revised form 8 November 2014
Accepted 27 December 2014
Available online 28 January 2015

Keywords:
Strengthening
Hybrid bond
Steel plate
Steel bar
Reinforced concrete

ABSTRACT

This paper presents the test results of the experimental behavior of reinforced concrete (RC) beams strengthened with the newly proposed hybrid bonding technique, which is the wise combination of plate bonding and near surface mounting (NSM) technique. Many studies have focused on the experimental behavior of RC beams strengthened with externally bonded steel plates. However, the presence of high interfacial shear stresses at the end of the plate may reduce the resistance to failure of the strengthened structure. Recently, to a certain extent, the development of the near surface mounted strengthening technique can reduce the problem of this premature end debonding failure. However, the application of this method may be limited due to the absence of sufficient width and clear cover of the existing unstrengthened deficit beam. The hybridization bonding method could eliminate the limitations of these two methods to some extent. As data on the performance of structures strengthened with the hybrid bonding method are not available, the main purpose of this paper is to investigate the experimental behavior of RC beams strengthened with the hybrid bonding method. Seven medium-sized beams (one control and six strengthened) were tested. Steel plates and bars were used for strengthening. The failure load, failure mode, deflection, strain and cracking behavior are discussed. The test results confirm that the proposed hybrid bonding is the most effective strengthening technique without significantly hampering the ductility and its performance is 32% higher than that of corresponding plate bonding method through improvement of the bond performance.

1. Introduction

Strengthening and upgrading of structures is required for several reasons including extension of design life, functional change, mechanical damage and environmental effects, updated design requirements, and errors due to design and construction [1]. It is both environmentally and economically desirable to upgrade structures rather than rebuild them, particularly if rapid, effective and simple strengthening methods are available [2]. There are many methods available for strengthening existing deficient structures, among which, external plate bonding method and NSM techniques are the most popular.

Bonding steel plates or Carbon fiber reinforced plastic (CFRP) plates to the soffit of the RC structures to increase their strength or serviceability has been utilized worldwide since the late 1960s. However, the development of high interfacial shear stresses at the plate ends could cause the premature debonding failure without utilizing the structure's full capacity. Many studies with the aim of finding solutions to reduce these stresses have been conducted [3]. One of the proposed solutions was to vary the thickness of the adhesive layer or the steel or FRP plate or the joint geometry by tapering the plate [4]. However, although the use of geometrical changes in plate ends with taper form is an effective method to reduce the stresses in adhesive joints, it is quite

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http://dx.doi.org/10.1016/j.conbuildmat.2014.12.081
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Symbols

a_g	groove spacing
a_e	edge clearance
CB	control beam
HS	hybrid strengthening
PS	plate bonding
LVDT	linear variable differential transducer

complex, time consuming and requires higher cost. Another way to prevent debonding is to limit the design strain in FRP to a certain value, however, the results of this approach are highly conservative [5].

More recently, near-surface mounted (NSM) reinforcement has attracted an increasing amount of research as well as practical application because it is less prone to premature debonding [6]. However, it has some limitations in application. Sometimes, the width of the beam may not be wide enough to provide necessary edge clearance and clear spacing between two adjacent NSM grooves. ACI 440 recommends that the minimum edge clearance (a_e) and the clear spacing of the NSM groove (a_g) should be four and two times the groove depth. However, this recommendation has also been proven to be inadequate by De Lorenz [7] where one of the beams was strengthened with NSM spirally wound round bars with $a_g = 30$ mm (i.e. about 1.8 times the groove size and 3.6 times the bar diameter) and $a_e = 69$ mm (i.e. about 4.3 times the groove size and 8.6 times the bar diameter), failed by debonding of the NSM bars involving the spalling of the concrete cover of the longitudinal steel reinforcement along the edges. In addition, the concrete cover should be higher to provide sufficient groove depth [8].

With respect to a number of drawbacks in the above two methods, this paper presents an idea to strengthen RC beams by combining the plate bonding method with the NSM strengthening technique and defines it as the hybrid bonding method. Through hybridization, both methods will complement each other and thereby possibly mutually overcome their limitations. It is known that the reduction in plate thickness decreases the magnitude of stress concentration at the plate extremities. Instead of tapering the plate, hybridization could make it possible to reduce the plate thickness by transferring a portion of the plate material from plate bonding to the NSM technique. Consequently, the size or number of NSM bars can also be reduced through shearing with plate bonding method, and, thus provide sufficient space for edge clearance and clear spacing of the groove.

In order to realize the above advantages of the hybrid bonding technique, the structural behavior of RC elements strengthened with the hybrid bonding method need to be fully characterized. Seven RC beams (one control six strengthened) were tested in this study. The examined variables were bonding technique, geometrical dimensions of the plate and NSM bar, number of grooves or NSM bars, performance of the tested beams and modes of failure are presented and discussed in this paper. Subsequently, the results of the experimental tests of the hybrid bonding method are compared with the corresponding plate bonding method. The test results show that the hybrid bonding method is better than the plate bonding method with respect to both strength and ductility performance, and, therefore it is a more effective and efficient strengthening technique.

2. Theoretical advantages of the hybrid strengthening technique

The main purpose of the hybrid strengthening technique is to improve the bond performance against premature failure between the existing concrete substrate and the applied strengthening plate and bar. Plate end debonding can probably be prevented through reduction of the interfacial stress. The reduction of interfacial shear and normal stress can be achieved in two ways - through hybridization of the plate bonding and NSM technique. One way is to reduce plate thickness by transferring some of the strengthening material from the plate to the NSM system. After transferring, the amount of strengthening material would be the same and produce similar flexure capacity of the beam. However, the magnitude of interfacial stress will be reduced due to the reduced plate thickness, because, the plate thickness is one of the most important parameters in reducing the interfacial stress. Fig. 1 shows the effect of the plate end thickness on the interfacial shear stresses in the CRFP strengthened beam [9].

Besides the experimental investigation, most of the codes of practice [10,11] also recommended limiting the design strain on the plate to eliminate debonding. Other studies [12–15] have confirmed similar limits. However, in most cases, the design debonding strains are inversely proportional to plate thickness. For a fixed FRP ratio, debonding potential was shown to increase significantly with increasing FRP thickness [16]. Although the above study was based on the FRP strengthening system, it will be similarly applicable to the steel plate strengthening system.

A number of studies have focused on steel plate end debonding. Swamy et al. [17] showed that premature debonding of steel plates can effectively be avoided by ensuring that the width-thickness ratio of the plate is not less than 50. Swamy and Mukopadhyaya [18] have shown that this recommendation holds true for FRP plates when glass, glass-carbon, and aramid fibers are used. Oehlers [19] proposed a model based on interaction between the flexural and shear capacity of the beam where the ultimate debonding moment is also inversely proportional to plate thickness. Zibra's [20] model is a shear capacity based model where the debonding shear force decreases with steel plate thickness. To avoid debonding, Hassanen and Raoof [21] proposed design plate strain which is inversely proportional to the plate thickness. Therefore, reduction of the plate thickness is an effective way of preventing plate debonding.

Another way to reduce the interfacial stress is to increase the surface area. Since the hybrid strengthening technique is a combination of external plate bonding and the NSM technique, cutting a

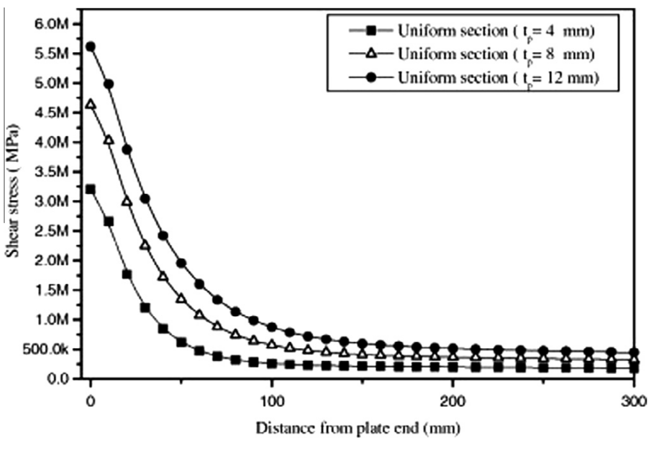

Fig. 1. The effect of the plate end thickness on the interfacial shear stresses [9].