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Shear performance of bolted side-plated reinforced concrete beams

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ABSTRACT

Although the bolted side-plating (BSP) technique is feasible to upgrade the shear capacity of reinforced concrete (RC) beams, related studies on its strengthening effect have yet to be sufficient. Therefore, an experimental study of seven specimens was conducted to investigate the shear performance of BSP beams. The failure mode was found shifting from shear–tension to shear–compression after strengthening. The decrease of bolt spacing, the increase of plate breadth and thickness improved the shear capacity, stiffness and ductility effectively. Although the additional stiffeners improved the stiffness considerably, it exhibited no obvious improvement in the shear capacity and caused a serious reduction in ductility. Due to the shear deformation of bolt shaft and the tensile principal stress in the steel plates that was perpendicular to the main diagonal crack, uneven relative longitudinal and transverse slips existed on the interface between the bolted steel plates and the RC beams. An analytical model was developed according to the force equilibrium and deformation compatibility of the beam segment in the shear span. A design procedure, which can be conducted conveniently using ordinary computing software or even a calculator by structural engineers in their strengthening design practise, was also provided to estimate the shear bearing capacity of BSP beams.

1. Introduction

Reinforced concrete (RC) beams in existing buildings may need to be strengthened due to material deterioration and change in usage. Enhancing the cross section by attaching steel plates or fibre reinforced polymers (FRPs) to the beam surface has been utilized comprehensively in strengthening practise, due to its less space occupancy, ease for construction, and enhancing efficiency in both strength and ductility. The steel plates and FRPs can be attached to the bottom soffit or the opposite side faces of RC beams, either adhesively or mechanically, to improve the flexural and the shear performance [1–4]. However, the steel plates and FRPs bonded adhesively to the surface of RC beams were usually observed to suffer from the premature debonding and peeling failure on the steel–concrete or FRP–concrete interface, especially at the ends of the bonded plates or FRPs [5–8]. Thus enormous efforts have been made to suppress these kinds of premature delamination failures, such as the near surface mounting (NSM) of FRPs [9], the mechanically fastened FRP laminates [10], the additional bolt anchorage at the plate or FRP ends [11,12], and the U-strips around the bottom and side faces of RC beams for the FRPs bonded to the tensile soffit [13].

In this case, many researchers proposed using anchor bolts alone to attach the steel plates [14–18], in which way the delamination failure can be suppressed effectively. Although bolting steel plates to the beams' tensile soffits can increase the flexural strength and stiffness, it may lead to over-reinforcement and a subsequent serious reduction in ductility. On the other hand, bolting steel plates to the side faces, i.e., the bolted side-plating (BSP) technique, can increase both the compressive and tensile reinforcement of RC beams thus provide an improved flexural strength without an obvious ductility reduction [14,19]. Furthermore, because the steel plates are in the vertical plane and parallel to the shear force, their shear resistance is significant, thus the BSP technique can also be used to enhance the shear capacity of the RC beams [20,21].

As the BSP technique has been utilized worldwide in strengthening practise, studies on BSP beams, most of which were related to the flexural behaviour, have been conducted by researchers all over the world. Ahmed [22] found that there were both longitudinal and transverse slips between the bolted steel plates and the RC beams, and developed mathematical models to quantify the transverse slip and shear force. Oehlers et al. [23] established analytical

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models for the transverse partial interaction and its interaction with the longitudinal partial interaction, which were further developed to determine the number of anchor bolts required to resist the transverse force and to limit the transverse partial interaction. Smith et. al. [24,25] introduced the Rayleigh-Ritz method to analyse the local buckling of BSP beams and validated the theoretical model by an experimental study. Siu and Su [26] investigated the flexural behaviour of BSP beams experimentally, and found the enhancement in flexural capacity was reduced by up to 30% compared with the results of theoretical model with full interaction assumption. They also defined two deformation-based parameters, namely the strain and the curvature factors, to quantify the degree of partial interaction. Li et al. [14] conducted comprehensive tests and found deeper steel plates resulted in a more satisfactory enhancement in flexural strength, and the relative slips were controlled by both the plate–RC stiffness ratio and the force−slip relation of anchor bolts. They also developed a program to optimize the strain and the curvature factors, thus proposed a simplified design procedure that could account for the partial interaction in the computation of flexural capacity [27,28].

Compared with the numerous researches on the flexural performance of BSP beams, studies on the shear behaviour is still far less than sufficiency. Limit reports on the shear retrofitting of coupling beams were found: Su and Zhu [29] investigated the shear performance of coupling beams strengthened by BSP technique, and found that even small slips on the plate–RC interface would cause serious loss in shear capacity. Su and Cheng [21] conducted experiments on four half-scale deep RC coupling beams retrofitted by bolted steel plates with or without adding a buckling restraining device, which revealed that the deformation and energy dissipation were improved while the flexural stiffness did not increase. Moreover, the specimens with buckling restraining had better post-peak behaviours, more ductile failure modes, and enhanced rotation deformability. Analogous to the coupling beams, studies on the shear retrofitting of floor beams are even barely found in literature: Aykac et al. [30] investigated the behaviour of shear deficient RC T-beams strengthened with perforated steel plates, and the failure mode was found to shift from shear to flexure. The bolted steel plates increased the ductility, energy dissipation capacities and permanent deformations of the specimens. Barnes et al. [3] observed a significant increase in the shear capacity of RC beams when plates were fixed to the sides faces by two methods of plate attachment, adhesive bonding and bolting. A method of shear capacity analysis was also developed based on the equilibrium of forces along the critical diagonal section. However, the full section yield assumption for the bolted steel plates may lead to overestimating the shear bearing capacity of the strengthened beams.

Although the BSP technique has been proven to be an effective retrofitting method, its positive impact on the shear strength of RC beams, especially on RC floor beams, still has not been validated satisfactorily by comprehensive experimental studies. Furthermore, although it is of great importance to predict the shear capacity of BSP beams, corresponding theoretical models have yet to be developed.

Therefore, an experimental study including seven RC floor beams was designed in this paper to investigate the shear strengthening effect of the BSP technique, especially the contribution of the breadth and thickness of the bolted steel plates, the horizontal bolt spacing and the stiffeners of steel angles. The failure modes, shear capacity, stiffness, and ductility were summarized and analysed in detail. The strains of stirrups, longitudinal reinforcements, and steel plates were also compared. After that, the longitudinal and transverse slips were analysed to explain their crucial effect on the interaction of the RC beams and the bolted steel plates. Finally, based on the shear failure assumptions of conventional RC beams and the experimental evidences, an analytical model was proposed according to the force equilibrium and deformation compatibility of the beam segment in the shear span. A design procedure, which can be conducted conveniently, was also provided to estimate the shear capacity of BSP beams for engineers in their strengthening design practise.

2. Experimental program

2.1. Specimen details

A total of seven specimens were designed, as shown in Table 1. The length of the RC beams was 2600 mm, the cross-sectional size was 200 mm × 400 mm, and the concrete cover was 30 mm. Fig. 1(a) presents the dimensions and the reinforcement details of the RC beams. In order to guarantee that the shear failure would occur for all specimens, compressive and tensile reinforcements were chosen as 2H12 and 3H25, and the shear stirrups was set to be M6-200, therefore the tensile and shear reinforcement ratio was 2.1% and 1.0% respectively, thus the flexural capacity was much greater than the shear capacity. The notations 'H' and 'M' denote the high-yield deformed steel bars and the mild steel round bars, their geometries and mechanical properties are listed in Table 2.

To demonstrate the shear performance of RC beam without strengthening, a reference specimen CTRL was designed. The other six specimens were retrofitted by the BSP technique and named in accordance with the strengthening parameters as shown in Table 1. Fig. 1(b)-(g) shows the strengthening arrangement of all the BSP beams. For instance, the specimen P2B2 represents an RC beam retrofitted by two steel plates with a thickness of 4 mm and a depth of 200 mm installed by 2 rows of anchor bolts with a uniform horizontal spacing of 200 mm in the shear span. To demonstrate the variation in the shear behaviour of BSP beams as the breadth of the bolted steel plates, another specimen, i.e., P3B2, which was the same as P2B2 except that the plate depth is 300 mm, was designed. P3B2-stiff was the same as P3B2 except that the bolted steel plates in the shear span were stiffened by steel angles of L63 × 5 to investigate the buckling restraining effect of stiffeners. P2B1 was the same as P2B2 but the horizontal bolt spacing was 100 mm, in the aim of investigating the influence of bolt spacing. And P2B1-t6 was the same as P2B1 but the plate thickness was 6 mm, thus the effect of increasing the cross-sectional area of the bolted steel plates could be investigated.

It is noteworthy that in the lower area of the pure bending zone, the horizontal bolt spacing was increased. This was because in this area both the longitudinal and the shear stresses were relatively low, thus the number of anchor bolts could be decreased.

2.2. Strengthening procedure

First of all, drilled holes with a diameter of 14 mm were formed in the steel plates. The RC beam was placed on its side and the steel plate was fixed on its top side face. The central axes of the steel plates and the RC beam should coincide with each other. Then holes with a diameter of 14 mm and a depth of 92 mm were drilled in the RC beam and cleaned thoroughly. Afterwards HIT-RE 500 adhesive mortar was injected into the holes, and M12 anchor bolts of Grade 8.8 were turned into the mortar until they reached the required depth of 92 mm. The steel plates were fixed to the side faces after the adhesive mortar was cured.

For the specimen P3B1-stiff, steel angles of L63 × 5 were anchored onto the steel plates by bolt connection in the shear span to restrain the possible occurrence of local buckling.