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Effects of bolt–plate arrangements on steel plate strengthened reinforced concrete beams

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ABSTRACT

A structure that can behave in a ductile fashion under extreme events is of paramount importance due to safety considerations. Because of such importance, ductility performance of bolted side-plated (BSP) concrete beams under different bolt–plate arrangements is investigated experimentally through four large-scale tests on BSP beams. It is observed that bolt–plate arrangements have a dominant effect on the ductility performance of beams in terms of both the post-elastic strength enhancement (defined as the ratio between the peak strength and the yield strength of the beam), and the displacement ductility (defined as the ratio between displacements at the ultimate and notional yield stages). In order to ensure ductile beam behaviour, the concept of maximum allowable plate–force demand is introduced, of which the strength of additional plates should be kept below the 'balanced' failure point, while sufficient shear strength of the bolt connections should be provided so that the strengthened beam will possess both sufficient strength enhancement and ductility.

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1. Introduction

Due to deterioration of materials and demand for additional strength, retrofitting of existing beam structures is often needed. There are basically two methods for strengthening or stiffening existed reinforced concrete (RC) beams. The first method is to attach advanced composites, such as carbon fibre reinforced polymers or glass fibre reinforced polymers [1], onto the tension surface or the side faces of the members. These composites are generally capable of increasing the ultimate load resistance but are prone to peeling and edge debonding failure [2]. The second method for strengthening or stiffening existed RC beams is to attach steel plates to the external surfaces of the structural components by means of bolting. This method can enhance both the flexural and shear performances of RC beams. A number of studies were carried out to investigate the flexural and shear behaviour of bolted side-plated (BSP) beams [3–8] and coupling beams [9] as well as the behaviour of the connecting bolt groups [10,11]. However, as the allowable plate–force demand in the bolt–plate system has not been specified in these studies, the designed BSP beams may be over-reinforced when thick plates and strong bolts are used. It is well recognized that ductility is an important structural property which provides noticeable warning at the beginning of failure of the structure to users for evacuation. Although substantial research has shown that BSP beams are effective in providing additional strength, over-reinforced BSP beams could lead to undesirable non-ductile failure [4]. It is therefore imperative to develop retrofitting techniques that can enhance flexural strength and maintain sufficient ductility. With this consideration, four-point bending tests of five simply-supported RC and BSP specimens were conducted. All these specimens have the same RC geometries, but are strengthened with different bolt–plate arrangements. The bolt–plate arrangements of specimens were properly selected so that the present experimental study would cover both over-reinforced and under-reinforced BSP beams. The experimental data obtained was analyzed and the most appropriate strengthening system that can enhance flexural strength and maintain sufficient ductility has been identified. The proposed bolt–plate arrangement can help designers to establish a ductile retrofitting scheme quickly and conveniently. It is noted that the investigation of the effect of bolt–plate arrangements on the partial interaction behaviour of BSP beams is beyond the scope of this paper. The related experimental study can be found in the companion paper [12].

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Table 1
Summary of bolt–plate arrangements of BSP specimens.

	Specimen SBSP	Specimen WBSP	Specimen WBWP	Specimen SBWP
No. of bolts on shear span	8	3	3	5
Strength of bolts on shear span P_b (kN)	608	228	228	380
Plate size[a] (mm × mm)	6 × 150 dp.	6 × 150 dp.	6 × 75 dp.	6 × 75 dp.
Plate force at ultimate state in full interaction analysis $F_{p,fi}$ (kN)	605	605	302	302
Degree of shear connection ($P_b/F_{p,fi}$)	1.00	0.38	0.75	1.26

[a] Value refers to the plate on each face of the beam, dp. = deep.

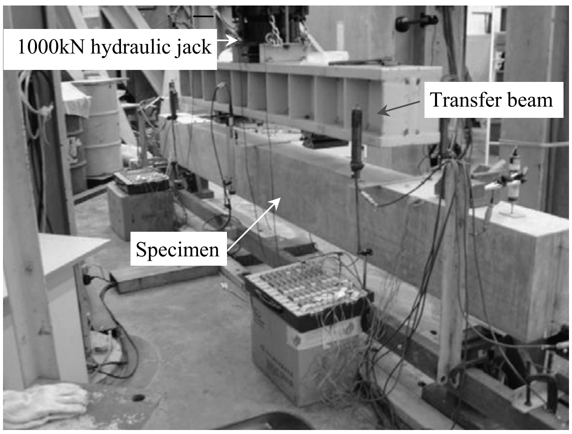

Fig. 1. Test setup.

2. Experimental program

2.1. Test setup

A four-point bending test setup was adopted, as shown in Fig. 1. The beam specimens were simply-supported with a clear span of 3600 mm. Load was applied by a 1000 kN hydraulic jack in the vertical direction, and divided into two equal point loads and exerted symmetrically onto the specimen through a transfer beam. With this arrangement, a pure bending zone with constant moment was created so that the flexural behaviour under pure bending could be studied.

2.2. Specimen details

Five specimens were fabricated and tested. The RC details of all specimens are identical. As shown in Fig. 2, the size of the RC sections were 225 mm × 350 mm deep. The specimens were under-reinforced by 3T16 tension bars, contributing to a steel percentage of 0.76%. Transverse reinforcement of T10-150 was applied throughout the span of the beam. This amount of longitudinal and transverse reinforcement would be sufficient to ensure that the specimens would fail in flexure in both un-strengthened and strengthened cases. This is desirable since the objective of this experimental study is to investigate the flexural responses of beams.

Specimen NBNP is the control specimen without any strengthening measure. It serves as a control specimen and is used to demonstrate the structural performance of a RC beam prior to strengthening.

Four strengthened specimens were fabricated. Being identified as the major parameters affecting the performance of beams, the bolt–plate arrangements of these specimens were properly selected so that the behaviour of beams under partial shear interaction in all cases could be captured in this study. Four different bolt–plate combinations including 'Strong Bolt Strong Plate' (SBSP), 'Weak Bolt Strong Plate' (WBSP), 'Weak Bolt Weak Plate' (WBWP) and 'Strong Bolt Weak Plate' (SBWP) are adopted and the detail arrangements of these specimens are summarized in Table 1 and illustrated in Fig. 2.

Two different plate sizes, 6 mm × 150 mm deep and 6 mm × 75 mm deep mild steel plates on both side faces of specimens were chosen to be the 'Strong' and 'Weak' plate arrangements respectively. This is equivalent to 2.3% and 1.1% of the gross sectional area of concrete. The centroidal axis of the plates was set at 250 mm from the top of the beam and in the tension region of the beam. This arrangement can prevent buckling of steel plates which is out of the scope of the present study. Buckling of steel plates occurs when relatively deep plates are used of which the top parts would be subjected to compression [13,14]. Adopting the current plate arrangement, the entire steel plate was below the mid-depth of the section and therefore the plate compression can be minimized and hence plate buckling can be avoided.

In this study, the degree of shear connection is used to consider if a bolt arrangement is 'Strong' or 'Weak'. The degree of shear connection is defined mathematically as

$$P_b/F_{p,fi}, \tag{1}$$

where P_b and $F_{p,fi}$ are the total strength of bolts on a shear span and the plate force at ultimate state under the case of full interaction respectively.

To determine the degree of shear connection of all strengthened specimens, a non-linear full interaction section analysis was carried out. A non-linear stress–strain relationship was adopted for concrete and an elastic–plastic relationship was used to model the stress–strain relationship of steel plates and reinforcement. Incremental curvatures were applied to the section until the peak moment was solved. The plate force at ultimate state and the degree of shear connection of the strengthened specimens are listed in Table 1. The degree of shear connection of Specimens SBSP and SBWP are 1.00 and 1.26 respectively, implying that sufficient bolt forces have been provided. Thus the bolt arrangement is 'Strong'. Conversely, the degree of shear connection of Specimens WBSP and WBWP are, respectively, 0.38 and 0.75, meaning that these specimens have 'Weak' bolt arrangements.

Specimens SBSP and WBSP were strengthened by the same size of plates, i.e. 6 mm × 150 mm deep steel plate strengthened on each side face of the beams, but with 'Strong' and 'Weak' bolt arrangements respectively. Specimens SBWP and WBWP have the same plate arrangement but with different degree of shear connections. By comparing these two pairs of specimens, the effect of strong and weak bolt arrangements on the behaviour of specimens could be studied. Meanwhile, the bolt arrangements of Specimens WBSP and WBWP are identical but with different plate arrangements. By comparing the results of these two specimens, the effect of plate geometry on the performance of the beams could be investigated.

The concrete beams without plate strengthening were first fabricated. Holes for allowing future installation of a bolt–plate system were reserved in the concrete core using aluminium tubes with an internal diameter of 14 mm. The aluminium tube was permanently cast in the concrete core as it is expected that the change in stiffness due to the tube is very small compared with the shear stiffness of the bolt and would not significantly affect the experimental results. The bolt–plate system was installed at least 14 days after curing of concrete. By using this arrangement, the concrete core and the steel plate are interacted purely through the bolt anchors.

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