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Numerical simulation of the shear capacity of bolted side-plated RC beams

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ABSTRACT

A numerical model was developed using the finite element method (FEM) software OpenSees to simulate the shear behavior of bolted side-plated (BSP) reinforced concrete (RC) beams. The multi-layer shell elements, truss elements, flat shell elements, and coupled zero-length elements were employed to model the concrete, reinforcement, steel plates, and bolt connection. Good agreement between the numerical results and the testing in literature indicates that the proposed FEM model can simulate the shear behavior of BSP beams. A parametric study was then conducted to reveal the variation of the shear performance with different factors, including the depth, thickness and yield strength of the bolted steel plates, the diameter, horizontal spacing, and number of rows of the anchor bolts, as well as the shear span ratio. By incorporating the piecewise transverse slip profile and improving the hypotheses in the shear-compression failure model of BSP beams, a semi-empirical design formula was derived based on the force equilibrium of the beam segment outside the main diagonal crack, thus the shear capacity of BSP beams can be evaluated. The accuracy of this theoretical model was then validated by comparing the prediction with the experimental and numerical results.

1. Introduction

Due to design or construction faults, increased demands or damages, existing reinforced concrete (RC) structures may need retrofitting. Available strengthening techniques include steel jacketing [1–3], external bonding [4,5] and near-surface mounting [6,7] of fiber reinforced polymers (FRP), and increasing cross-section with newly cast concrete or engineered cementitious composites (ECC) [8–10]. Among them, bolted side-plating (BSP) is a new innovative steel jacketing technique for rehabilitation of RC beams, where the steel plates are bolted onto the beams' opposite side faces [11–13].

Comprehensive efforts have been made at this technique over the past two decades, most of which focused on the flexural performance of BSP beams. Oehlers et al. studied the flexural behavior of BSP beams and established analytical models for the partial interaction between the bolted steel plates and the RC beam [14]. Nguyen et al. further derived the relationship between longitudinal and transverse partial interactions by using the same curvature for both the steel plates and the RC beam [15]. Siu and Su studied the flexural performance of BSP beams and found the enhancement could be overestimated by up to 30% if the partial interaction was ignored in theoretical computation [16]. Li et al. found the relative slips were controlled by both plate–RC stiffness ratio and shear stiffness of anchor bolts, and proposed a simplified "two-factor and three-step" design method for flexural strengthening [17–19]. Smith et al. investigated the local buckling behaviour of the bolted steel plates in BSP beams, and developed formulae for buckling using the Ritz method by simplifying the boundary conditions as being simply supported, clamped and free [20,21]. Li et al. further studied the local buckling phenomenon of the bolted steel plates and proposed empirical formulae to evaluate the field capacity [22,23].

Considerable researches were also carried out to investigate the shear behavior of BSP beams. Subedi et al. conducted tests on three BSP beams and found although the specimens failed in shear, their failure mode was ductile [24]. Barnes et al. put forward an analytical method to calculate the shear capacity of RC beams strengthened with steel plates, and revealed that fixing steel plates onto the sides faces increased the shear capacity significantly [25]. Jiang et al. investigated the shear strengthening effect of BSP technique on RC beams after exposed to fire [26]. Although experimental approaches have been conducted by researchers to study the shear capacity of BSP beams, available test data are still very limited. Numerical analysis using the finite element method (FEM), which has been widely applied in different fields of basic science [27–29], maybe a practical and economic

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research approach to investigate the shear performance of BSP beams.

OpenSees [30] is an open source object-oriented software framework developed by UC Berekeley. Extensive researches have been conducted by using this software. Miao et al. proposed a multi-layer shell model in OpenSees using the shellMITC4 element [31], which was based on the principles of composite material mechanics, capable of simulating coupled in-plane or out-of-plane bending, in-plane direct shear, and coupled bending-shear of RC members. The shell element was made up of many layers with different thickness, and different material properties were assigned to various layers [32]. During the FEM calculation, the axial strain and curvature of the middle layer in an element were obtained, then the strains and curvatures of the other layers were calculated according to the plane-section hypothesis, thus the corresponding stress was calculated through the constitutive relations of the material assigned to the layer [33]. The simple and concise equations and geometric descriptions of the flat shell element made large deformation algorithm can be conveniently developed [34]. Based on the theory of generalized conforming element, a high-performance quadrilateral shell element shellDKGQ was proposed, which avoided the “stress lock” difficulty and saved CPU time [35]. Although researchers and engineers has employed OpenSees for mechanical especially seismic analyses of RC structures for decades, its implementation on BSP beams has yet been found in literature.

In addition, the existing design models that can estimate the shear capacity of BSP beams are not readily available, due to the deficiency in accounting for factors controlling shear capacity. Some models ignored the effect of transverse slip on the tensile stress distribution of steel plates [25]. The bolt arrangement is a main parameter to affect shear capacity, but it is difficult to take into account [36]. Therefore, the shear behavior of BSP beams should be refined by considering the aforementioned factors and other possible influential parameters.

Due to the limited experimental studies on the shear behavior of BSP beams, the shear failure mechanism remains unknown. In this paper, an FEM model based on OpenSees was developed and validated by a previous experimental study [36]. Then it was employed to conduct a parametric study to investigate the influence of different strengthening parameters on the shear performance of BSP beams. A simplified transverse slip model was thus regressed and used to estimate the tensile force of steel plates. By incorporating it into the shear-compression failure mode of BSP beams in literature [36], a design formula was derived for the evaluation of shear capacity.

2. FEM modelling

Comprehensive numerical studies based on FEM software ATENA and Abaqus were conducted by the authors to investigate the flexural behavior of BSP beams [22,37]. A numerical study will be further conducted herein to investigate the shear response, based on the general FEM software OpenSees. The results of several specimens in a previous testing [36] will be introduced to serve as benchmarks.

2.1. A brief introduction to the testing

The testing [36] was conducted by the authors in Tongji University. A control beam and four BSP beams with different steel plates and bolt configuration were extracted for benchmark as shown in Table 1. The geometry and strengthening details of the specimens, as well as the strain gauges are shown in Fig. 1, where the letters “D” and “R” indicate the high strength deformed steel bar and the mild steel round bars, respectively; and “*P*” indicates the external load. Steel plates with a thickness of 4 mm and a length of 2600 mm were bolted on both sides of RC beams for shear strengthening.

The average compressive strength at 28 days of curing, the tensile strength, and the out-of-plane shear modulus of concrete were 61.5 MPa, 3.2 MPa, and 12.5 GPa, respectively. The tested mean values of yield strengths were 471 MPa and 474 MPa for shear stirrups and longitudinal reinforcement, respectively. Steel plates was Grade Q235, whose nominal values of Young’s modulus, tensile strength, and Poisson’s ratio were tested as 209 GPa, 324 MPa, and 0.3, respectively.

Table 1
Strengthening parameters of specimens [36].

Specimen	Plate width (mm)	Bolt spacing (mm)	Number of bolt rows
Control	–	–	–
P3B1	300	100	3
P3B2	300	200	2
P2B1	200	100	2
P2B2	200	200	2

Four-point shear tests were conducted for all the beams, the distance between the two supports was 2300 mm, and the shear span was 540 mm. Monotonic loading was imposed on the beams at a loading rate of 10 kN/min to investigate the shear bearing capacity and deformability of the specimens.

2.2. Numerical modelling

2.2.1. Modelling of concrete beams

As shown in Fig. 2, the concrete beam is simulated in OpenSees with a multi-layer shell element ShellMITC4 with a mesh size of 50 mm, which is a four-node shell element based on the theory of mixed interpolated of tensorial components (MITC) [38]. Concrete is assumed to be under planar stress state, and a 2-dimensional concrete constitutive model PlaneStressUserMaterial [39] based on the damage mechanics and the smeared crack model is introduced to simulate the mechanical behaviors of concrete, whose constitutive relation can be expressed as following:

$$\sigma_c' = \begin{bmatrix} 1-D_1 & \\ & 1-D_2 \end{bmatrix} D_e \varepsilon_c'$$

where σ_c' and ε_c' are the principal stress and strain, respectively. D_e is the elastic stiffness; D_1 and D_2 are the damage parameters for tension and compression, respectively. The damage evolution curve under tension and compression recommended by Løland [40] and Mazars [41] were implemented to calculate the damage parameters.

In the FEM modelling of the BSP specimens, the compressive, tensile, and crushing strengths of concrete were defined as $f_c = 49.8$ MPa, $f_t = 3.2$ MPa, and $f_{cu} = 10.0$ MPa, respectively; the concrete strains at f_c, f_t, and f_{cu} were set as $\varepsilon_{c0} = 0.002$, $\varepsilon_{tu} = 0.001$, and $\varepsilon_{cu} = 0.0033$, respectively; and the shear retention factor was set as 0.08.

2.2.2. Modelling of reinforcing bars

The reinforcing bars are simulated by truss elements assigned with the material model Steel02 and embedded in the multi-layer shell model for the concrete beam at the corresponding nodal locations. The material Steel02 is based on a Giuffre-Menegotto-Pinto constitutive model [42] with isotropic strain hardening and uniaxial bi-linear behavior, which is defined by the following equation:

$$\sigma^* = b\varepsilon^* + \frac{(1-b)\varepsilon^*}{(1+\varepsilon^{*R})^{1/R}}$$

where σ^* and ε^* are the normalized stress and strain, the constant b defines the slope of hardening branch, the exponent R affects the curvatures of the unloading branches thus represents the Bauschinger effect.

In the FEM modelling of the BSP specimens, the yield strength of longitudinal and shear reinforcements was defined as $f_y = 480$ MPa; the initial elastic tangent, and the strain-hardening ratio were set as $E_0 = 2.0 \times 10^4$ MPa and 0.01, respectively; the parameter used for R was set as $R_0 = 18.5$.