Engineering Structures 168 (2018) 44–57

Contents lists available at ScienceDirect

Engineering Structures

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

Flexural capacity model for RC beams strengthened with bolted side-plates incorporating both partial longitudinal and transverse interactions

Z.W. Shan, R.K.L. Su*

Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

ARTICLE INFO

Keywords:
Reinforced concrete beams
Bolted side-plate
Partial transverse interaction
Longitudinal interaction
Strain factor
Curvature factor
Design method

ABSTRACT

Existing reinforced concrete (RC) beams with inadequate flexural capacity can be strengthened by bolting steel plates onto both sides of the face of beam. However, the effectiveness of these bolted side-plated (BSP) beams is affected by the mechanical slipping of bolts which is known as the partial interaction of the steel plates and the RC beam. To avoid overestimating the flexural capacity of the strengthened beam, the effects of partial interaction should be properly quantified in the structural design. Therefore, a new design model to determine the flexural capacity of BSP beams that takes into consideration both partial longitudinal and transverse interactions has been developed in this study. Strain and curvature factors are introduced to quantify the partial interaction. Based on these two factors, modified moment capacity equations are presented. The proposed model is then validated by comparing the analytical results with the test results from another study. Finally, a simplified design method is proposed based on the results of a parametric study.

1. Introduction

Structural deterioration, usage changes or amended design specifications and safety requirements may require the enhancement of the load-carrying capacity of structural elements. It is well recognized that lightly reinforced concrete (RC) beams can be effectively strengthened by bolting bottom plate. However, for moderately reinforced beams, this method can lead to over-reinforcement problem and significant reduction in ductility capacity. On the other hand, using bolted side plate method to strengthen RC beams, the side plate can be extended from tensile to compression zone and can act as both tension and compression reinforcement. Thus the over-reinforcement problem can be avoided and the flexural capacity of beam can be greatly enhanced without losing ductility capacity [1,2]. During the past few years, many researchers have conducted comprehensive studies of this strengthening method due to its convenience in construction and cost effectiveness [3–15].

However, partial interaction caused by bolt slipping remains a key issue that needs to be resolved when designing bolted side-plated (BSP) beams. The strain profile of a BSP beam with full interaction (or in other words, without any bolt slipping) is shown in Fig. 1(b). The strain profiles of the longitudinal and partial transverse interactions are presented in Fig. 1(c) and (d). It can be seen that the longitudinal and transverse slips lead to the reduction of longitudinal deformation and curvature of the steel plate compared to those of full interaction.

Oehlers et al. [8] developed fundamental mathematical models for partial transverse interaction and further determined the number of connectors required to resist transverse forces and limit the amount of partial transverse interaction in BSP RC beams. Nguyen et al. [7] obtained the longitudinal slip strain induced by both longitudinal and partial transverse interactions and examined the neutral axis separation between the steel plate and RC beams. A realistic model was developed to describe the longitudinal slip and neutral axis separation by Nguyen et al. [16]. Zhu and Su [14] evaluated the strength of BSP coupling beams with a mixed analysis method and rigid plastic analysis (RPA). Their results showed that partial interaction has considerable effects on the flexural capacity of the strengthened coupling beams. Although the aforementioned studies have provided the basis for further investigation of partial interaction, they have not quantified the effects of partial interaction on the flexural capacity of strengthened BSP beams.

Su et al. [17] investigated the longitudinal interaction in BSP RC beams under different load conditions. Li et al. [18] and Su et al. [19] studied the transverse interaction in BSP RC beams by using a piecewise linear transverse shear transfer model. Siu and Su [10] introduced strain and curvature factors to represent longitudinal and partial transverse interactions. Based on these two factors, Lo et al. [20] assumed that longitudinal and partial transverse interactions are independent and proposed optimum strain and curvature factors for calculating the flexural capacity of BSP beams. However, the longitudinal and partial transverse interactions are not independent because

* Corresponding author.
E-mail address: klsu@hku.hk (R.K.L. Su).

https://doi.org/10.1016/j.engstruct.2018.04.069
Received 12 December 2017; Received in revised form 18 April 2018; Accepted 18 April 2018

Notations

ε_{RC}	strain in RC beam
ε_p	strain in steel plate
ϕ_p	curvature of steel plate in partial transverse interaction
ϕ_c	curvature of RC beam in partial transverse interaction
S_l	longitudinal slip
S_t	transverse slip
M	total moment in one section
M_p	moment in steel plate
M_c	moment in RC beam
V	total shear in one section
V_c	shear in RC beam
V_p	shear in steel plate
t_m	longitudinal shear flow
v_m	transverse shear flow
i_{cp}	distance between centroids of RC beam and steel plate
$\varepsilon_{cc,c}$	RC beam strain in centroid of RC beam
$\varepsilon_{pc,c}$	RC beam strain in centroid of steel plate
$\varepsilon_{pc,p}$	steel plate strain in centroid of steel plate
K_b	bolt stiffness
R_{by}	yield shear force of bolt
S_{by}	yield deformation of bolt
S_b	bolt spacing
k_m	distribution stiffness, defined by $\frac{K_b}{S_b}$
E_c	elastic modulus of RC beam
E_p	elastic modulus of steel plate
A_c	cross-section area of RC beam
A_P	cross-section area of steel plate
H	depth of RC beam
B	width of RC beam
h_p	depth of steel plate
d_p	depth of centroid of steel plate to extreme compressive fiber
d_c	center of the tensile longitudinal steel bar to extreme tensile fiber
β	factor relating depth of equivalent rectangular stress block to neutral axis
α	factor relating average stress of equivalent rectangular stress block
x_c	depth of neutral axis of RC beam
f_c	cylinder compressive strength
x_p	compressive depth of steel plate
f_{ys}	yield stress of steel bar
f_{yp}	yield stress of steel plate
A_{sc}	compressive area of steel bar
A_{st}	tensile area of steel bar
ε_{cu}	ultimate strain in RC beam
ε_{bp}	steel plate strain at the bottom of the steel plate
ε_{py}	yield strain of steel plate
α_ε	strain factor
α_ϕ	curvature factor
t_p	thickness of steel plate
$M_{partial}$	moment capacity derived by partial interaction analysis
M_{Rigid}	moment capacity derived by plastic rigid analysis
L	length of RC beam
F	force exerted by hydraulic jack
x	distance to left support
$\Delta\phi$	difference in curvature in BSP beam
$\Delta\phi_{\max}$	maximum curvature difference in BSP beam
T_m	shear force in bolt along longitudinal direction
V_m	shear force in bolt along transverse direction
T_{m1}	shear force in bolt in shear span
T_{m2}	shear force in bolt in pure bending moment region or in shear span (single point load case)
T'_{m1}	first derivation of T_{m1}
T'_{m2}	first derivation of T_{m2}
S_{t1}	transverse slip in shear span
S_{t2}	transverse slip in pure bending moment region or in shear span (single point load case)
v_{m1}	uniform shear distribution in shear span
v_{m2}	uniform shear distribution in pure bending moment region or in shear span (single point load case)
V_{p1}	shear force of steel plate in shear span
V_{p2}	shear force of steel plate in pure bending moment region or in shear span (single point load case)
M_{p1}	steel plate moment in shear span
M_{p2}	steel plate moment in pure bending moment region or in shear span (single point load case)
M'_{p1}	equal to $M_{p1}/\Delta\phi_{\max}$
M'_{p2}	equal to $M_{p2}/\Delta\phi_{\max}$
$\delta_{pc,p}$	longitudinal displacement in steel plate at centroid of steel plate
$\delta_{pc,c}$	longitudinal displacement in RC beam at centroid of steel plate
ϕ	curvature of full transverse interaction
ε_{et}	extreme tensile fiber of steel plate
F_{test}	tested results
F_{mod}	results derived from modified moment capacity analysis with two proposed factors
F_{PRA}	results derived from plastic rigid analysis
ξ	ratio of distance from loading point to left support to overall length
m	distribution load per unit length
η	ratio of flexural stiffness of steel plate to flexural stiffness of RC beam
F_{Su}	results derived from modified moment capacity analysis with two factors proposed in Su et al. (2014)
γ_{bolt}	normalized bolt stiffness
γ_M	normalized strength enhancement
M_0	moment capacity with strain factor or curvature factor equal to 0
M_1	moment capacity with strain factor or curvature factor equal to 1
M'	moment capacity with strain factor or curvature factor value in 0–1
γ_d	ratio of depth of steel plate to depth of RC beam section
γ_m	enhanced moment capacity ratio
ρ_s	longitudinal tensile reinforcement ratio
γ_t	ratio of steel plate thickness to depth of beam
$\gamma_{m,\text{model}}$	enhanced flexural capacity ratio derived from fitting function
M_{BSP}	flexural capacity of BSP beam at ultimate limit stage
M_{RC}	flexural capacity of RC beam at ultimate limit stage
n	number of bolts

the latter can cause more longitudinal slippage between the steel plates and RC beams. Hence, the effects of partial transverse interaction on partial longitudinal interaction should not be ignored.

In this study, a theoretical study is conducted which takes into account the effects of partial transverse interaction on partial longitudinal interaction. Strain and curvature factors are derived to quantify the effects of partial interaction. Furthermore, moment capacity equations (MCEs) are modified to incorporate these two factors. To validate their effectiveness, the flexural capacities obtained from various strain factors and those from the RPA are compared with test results from a