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Debonding of steel plates adhesively bonded to the compression faces of RC beams

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Abstract

Reinforced concrete beams in buildings and bridges are increasingly being retrofitted by adhesively bonding steel or FRP plates to their tension faces. However, tests have shown that tension face plates are prone to premature debonding. One way of preventing or inhibiting debonding of tension face plates in continuous beams is to extend the plate-ends past the points of contraflexure into the compression faces. In this paper: it is shown that compression face plates are less likely to debond than tension face plates; results of thirteen tests on debonding due to vertical shear forces (critical diagonal crack debonding) and curvature (flexural end plate debonding) are described; and critical diagonal crack and flexural end plate debonding models are developed for compression face plates that can be used to ensure that beams with tension face plates that are extended into the compression faces do not debond prematurely.

Keywords: Reinforced concrete beams; Steel plates; Retrofitting

1. Introduction

A major growth area in civil engineering throughout the world is the rehabilitation and retrofitting of existing infrastructure, hence there is an urgent need to develop inexpensive and unobtrusive rehabilitation techniques such as the adhesive bonding of steel plates to the tension faces of reinforced concrete (RC) structures. However tension face plates are prone to premature debonding that can be prevented or inhibited by extending the plates into the compression face regions such as plate E–H in Fig. 1; in fact, it is common practice in fibre reinforced polymer (FRP) plating to extend the plate to the supports in continuous beams. Rules are developed in this paper which will enable the engineer to design against debonding of compression face plated beams and slabs.

An example of a plated continuous reinforced concrete beam or slab is shown in Fig. 1. The most common form of retrofit by plating [1–5] is to bond steel or fibre reinforced polymer (FRP) plates to the tension faces, such as plates A–B and C–D in Fig. 1; as the plate is at its furthest extremity from the compression region and, hence, the composite flexural action is at its maximum. However, research has shown that these plates are prone to the three major forms of debonding illustrated in Fig. 2 that are named after the overall beam deformations that induce the debonding mechanism.

Axial intermediate crack debonding (AIC) is caused by a flexural or flexural/shear crack intercepting the plate as in Fig. 2(a) and is probably the most widely researched form of debonding [6]. To accommodate the

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Nomenclature

tfp	tension face plate
cfp	compression face plate
AIC	Axial Intermediate Crack
CDC	Critical Diagonal Crack
FEP	Flexural End Plate
a	shear span
A_s	area of internal longitudinal reinforcement
b	width of the beam
b_{cfp}	width of the compression face plate
b_{tfp}	width of the tension face plate
E_c	Young's modulus of concrete
$(EI)_{cp}$	flexural rigidity of the cracked plated section
E_p	Young's modulus for plate steel
E_s	Young's modulus of steel
$(f_a)_t$	maximum tensile stresses
$(f_a)_c$	maximum compressive stresses
f_b	Brazilian or splitting tensile strength of concrete
f_c	the cylinder compressive strength of concrete
$(f_c)_c$	maximum compressive stresses
$(f_c)_t$	maximum tensile stresses
$f(\rho_{tfp})$	tensile reinforcement ratio and tension face plate area parameters
f_{yp}	yield strength of the plate
h	depth of the beam
k_{cfp}	compression face plated beam coefficient
k_{tfp}	tension face plated beam coefficient
L_b	length of plate
M_p	FEP debonding moment resistances
$P_{b,tfp}$	maximum axial force that can be applied over the plate of length L_b
m	modular ratio (E_s/E_c)
P	applied load
t_{cfp}	thickness of the compression face plate
t_{tfp}	thickness of the tension face plate
V	shear
V_I, V_{II}	shear load to cause Stage I and Stage II cracks
V_{peel}	CDC debonding resistances
V_u	total shear strength; shear load to cause failure by sliding
V_{uc}	concrete component of the shear strength of the unplated RC beam
V_{us}	contribution of the shear stirrups to the shear strength of the beam
V_{cr}	shear load to cause the diagonal shear crack
x	projection of the critical diagonal crack

intersection of the flexural crack adjacent to the plate, interface debonding cracks are induced, as shown, that emanate from the intercept of the plate with the flexural crack and propagate outwards towards the plate ends. Crack propagation is at first gradual then rapid and often starts in regions of high flexure as shown in Fig. 1. Critical diagonal crack debonding (CDC) is caused by the sliding action across a critical diagonal crack that is formed by vertical shear forces in the beam as illustrated in Fig. 2(b). In this case, the debonding crack emanates from the intercept of the critical diagonal shear crack with the plate and propagates very rapidly [7,8], a similar form of debonding that is induced by the formation of critical diagonal cracks occurs with side plated beams [4]. Flexural end plate debonding (FEP) is induced by the curvature in the beam as shown in Fig. 2(c) where the plate resists the increase in curvature by trying to stay straight. Unlike AIC and CDC debonding, in this case the debonding cracks emanate from the plate ends and move inwards at first gradually and then very rapidly [9].

One way of inhibiting premature debonding of tension face plates is to extend the plate-ends past the points of contraflexure and into the compression face regions, such as plate E–H in Fig. 1, which is the subject of this paper. In these compression face plated regions E–F and G–H, AIC debonding will not induce premature debonding as a flexural crack will not intercept the compression face plate. However, it will be shown that CDC and FEP debonding can occur. Models for CDC and FEP debonding of compression face plates will be developed for steel plates, however, it may be worth noting that tests have shown that FRP plates exhibit similar debonding mechanisms as steel plates [10].

2. Critical diagonal crack debonding

2.1. Critical diagonal crack debonding tests

The CDC debonding specimens are shown in Fig. 3 where each span of the beam provides an individual test; the loads P were applied individually to each beam in order to test each short shear span by itself which provides five tests in all from three beams. Test SP-C12 on the left shear span in Fig. 3(a) had a 12 mm thick steel plate that was adhesively bonded to the compression face of the beam and Test SP-C6 on the right hand side of the beam had a 6 mm thick compression face plate. The beam in Fig. 3(b) was the same as that in Fig. 3(a) except that the plates were now bonded to the tension faces which provided two tension face plated tests SP-T12 and SP-