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Vertical shear interaction model between external FRP transverse plates and internal steel stirrups

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Abstract

A convenient and proven technique for increasing the vertical shear capacity of reinforced concrete beams is to externally bond fibre reinforced polymer (FRP) to the sides of the beam with the fibres orientated in the transverse or vertical direction. The FRP, which can be in the form of pultruded plates or applied in the wet lay-up procedure, acts as external FRP stirrups resisting vertical shear in the same way as the conventional internal steel stirrups. However, internal steel stirrups are ductile as they are both fully anchored and can yield, which is in contrast to external FRP stirrups that can debond in a brittle fashion and do not yield. Hence, there is no guarantee that the peak vertical shear forces that can be resisted by the steel stirrups and by the transverse FRP plates coincide. In this paper, a partial-interaction model has been developed that quantifies the vertical shear interaction between transverse FRP plates and steel stirrups.

Keywords: FRP; Retrofitting; Vertical shear; Reinforced concrete; Externally bonded; Near surface mounted; Wet lay-up; Transverse plates

1. Introduction

Increasing the vertical shear capacity of reinforced concrete (RC) beams by adhesively bonding FRP to the sides of the beam, where the fibres are in the transverse or vertical direction as in Fig. 1, is now a convenient, inexpensive and established procedure. The FRP can take the form of externally bonded pultruded plates, or near-surface mounted plates, or can be applied using the wet lay-up procedure. The early research of Triantafillou [10] clearly showed that transverse FRP can increase the vertical shear capacity, and an equivalent strain approach was developed to quantify the increase in strength due to transverse plates. This was followed by research by Teng et al. [9] and Chen and Teng [3] who related the contribution to the vertical shear capacity by the transverse FRP plates V_{frp} to the intermediate crack (IC) debonding resistance of the plates that can be derived directly from pull-tests. Also Pellegrino and Modena [8] and Deniaud and Cheng [4] showed through tests that there is not always full interaction between the vertical shear capacity of the external FRP stirrups V_{frp} and the vertical shear capacity of the internal steel stirrups V_s, that is the system is not always ductile enough to allow both V_{frp} and V_s to occur simultaneously.

There has been some very good research on quantifying the fundamental interface shear-stress/slip characteristics associated with IC debonding of externally bonded plates in pull–push tests [2,9,11]. Whenever slip occurs between two elements in a structure, a discontinuity in the strain is induced, that is a slip-strain, which is fundamental to partial-interaction analyses [5,6]. This partial-interaction theory has been further developed in an excellent generic fundamental study of IC debonding of plated pull–push shear tests [12], where a solution for a softening interface was developed. This generic research of the IC debonding resistance in pull–push tests [12] can be directly applied to the vertical shear resisted by transverse FRP plates in beams as in both cases the plate is intercepted by the equivalent of a single crack; in a pull–push test this is simply the end of the block, whereas, in a beam it is the critical diagonal crack as can be seen in Fig. 1. In this paper, the research by Yuan et al. [12] is further developed to quantify the interaction between internal steel stirrups and external FRP stirrups, that

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Notation

a	length of the microcracking region of the interface
a_u	effective bond length; bond length required to achieve $P_{\max}$
A_s	cross sectional area of internal stirrup
b_c	width of concrete block
b_p	plate width
D	distance between end anchorage of internal steel stirrup
E_c	Young's modulus of concrete
E_p	Young's modulus of plate
E_s	Young's modulus of the steel
f_{ys}	yield strength of the stirrup
k	interaction factors
k_e	initial elastic component of stiffness
L	length of bonded region of the plate; anchorage length of plate
L_{lw}	anchorage length of plate below the critical diagonal crack
L_{up}	anchorage length of plate above the critical diagonal crack
P	axial force in plate
P_{deb}	maximum axial force in plate when $L < a_u$
P_L	axial force in plate at crack face
$P_{\max}$	maximum axial force in plate when $L > a_u$
$(P_{\max})_L$	maximum value of P_L
s_{pl}	longitudinal spacing of external plates
s_s	longitudinal spacing of internal steel stirrup
t_c	block thickness
t_p	plate thickness
V_c	concrete component of vertical shear capacity
V_e	vertical shear resisted by the external plate
$(V_e)_{\max}$	IC debonding resistance of external plate; sum of all IC debonding capacities
V_i	vertical shear resisted by internal steel stirrup
$(V_i)_{\max}$	yield capacity of internal steel stirrups crossing diagonal crack
V_{frp}	vertical shear capacity of transverse FRP plates
V_s	vertical shear capacity of internal steel stirrup
V_t	total vertical shear resisted by external plates and internal steel stirrups
$(V_t)_{\max}$	maximum vertical shear assuming full interaction; $(V_i)_{\max} + (V_e)_{\max}$
w	crack width
w_y	crack width required to yield the stirrups
δ	interface slip
δ_f	slip at zero shear strength
δ_L	crack face slip
δ_{lw}	slip at crack face of lower plate
δ_{up}	slip at crack face of upper plate
$\varepsilon_{\max}$	maximum strain in plate
ε_s	strain in the steel stirrup
ε_y	yield strain of the stirrup
σ_p	axial stress in plate
$(\sigma_p)_L$	axial stress in plate at crack face
τ	interface shear stress across the bonded length
τ_i	interface bond between the stirrup surface and concrete
τ_e	interface bond between plate and concrete
τ_f	peak shear capacity
τ_L	interface shear stress adjacent to crack face

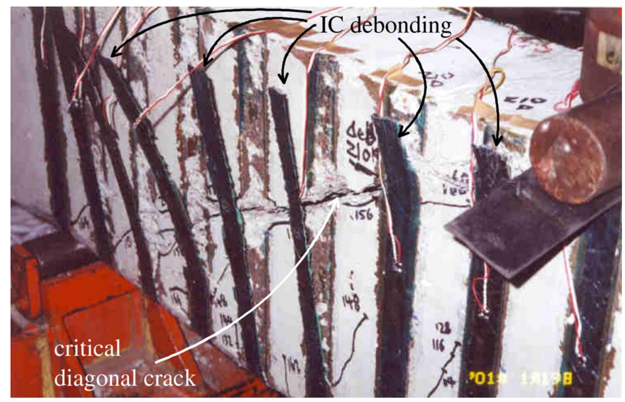

Fig. 1. IC debonding of transverse FRP plates [9].

is transverse plates. The results are then used to illustrate the vertical shear interaction in reinforced concrete beams with externally bonded side plates, near-surface mounted side strips and wrapped wet lay-up sheets.

2. Local vertical shear interaction mechanism

Internal steel stirrups may consist of smooth high yield bars that are fully anchored at their ends by bending the stirrups around longitudinal bars as in Fig. 2(a). Hence the force in an internal steel stirrup V_i, which directly resists the vertical shear, does not rely on interface bond τ_i between the stirrup surface and the concrete but is induced by separation of the end anchorage that is shown as D apart after the formation of a shear crack. Furthermore, the force in the internal steel stirrup is not induced until a critical diagonal shear crack is formed that intercepts the stirrup as in Fig. 2(b). It is this vertical opening w of the diagonal shear crack that causes the anchor zones of the stirrup to separate and gradually induce strains ε_s of w/D in the internal steel stirrups. Hence a finite crack width w_y is required to yield the stirrups after which the force in the stirrups remain constant at their yield capacity V_s and the system is ductile.

Transverse FRP plates, which will be referred to as external FRP stirrups, can also be fully anchored by wrapping the FRP around the whole beam as may occur in the wet lay-up procedure. However in most cases, external FRP stirrups are not anchored at both their ends as in the side plates in Fig. 2, in which case the force in the plate V_e is induced by the IC bond shear strength τ_e. The plates can be partially anchored by U-jacketing around the soffit as in the left plate in Fig. 2(a), in which case the plate below the critical diagonal crack is fully anchored by the edge of the beam and the plate above the critical diagonal crack relies on the IC interface bond τ_e. The