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Ultimate shear behaviour of hybrid reinforced concrete beam-to-steel column assemblages

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ABSTRACT

This paper examines the shear transfer mechanisms and ultimate behaviour of hybrid systems consisting of reinforced concrete beams connected to structural steel columns. A series of five large scale tests on structural assemblages, in which steel shear-arms are welded directly to the steel columns and embedded in the reinforced concrete beams, is presented. After describing the experimental arrangement and specimen details, the main results and observations obtained from the tests are provided and discussed. The test results offer a direct evaluation of the ultimate shear behaviour of such hybrid systems. The experimental findings also enable a comparison with the strength predictions obtained from analytical models which are commonly used in the design of conventional reinforced concrete members. The discussions and comparative assessments presented in this paper provide an insight into the influence of various shear transfer mechanisms including transverse reinforcement, compressive zones, residual tensile stresses, aggregate interlock, and dowel action, in addition to the interfacial bond between the steel profile and concrete. The activation and contribution of the key shear transfer mechanisms are assessed in light of the experimentally-monitored crack growth, path and pattern, as well as in comparison with widely-adopted analytical approaches. The results show that the contribution of each transfer mechanism is a function of the crack kinematics and corresponding level of applied load. Finally, modifications to existing analytical approaches for conventional reinforced concrete elements are proposed in order to provide a reliable evaluation of the ultimate shear capacity of such hybrid systems. The suggested expressions account for the influence of the shear-arms' characteristics on the ultimate shear strength, and offer a more realistic prediction of the behaviour in comparison with conventional reinforced concrete design provisions.

1. Introduction

Situations in which reinforced concrete floor elements need to be combined with vertical steel members often arise in multi-storey buildings, either due to loading and performance constraints or as a result of practical and constructional considerations. However, the design of such 'hybrid reinforced concrete/steel members' often poses various uncertainties related to the direct applicability of codified rules which are typically developed and validated for conventional reinforced concrete or structural steel configurations.

Many previous studies have examined the performance of various forms of hybrid steel/concrete elements. For example, various investigations have been carried out on the performance of composite steel coupling beams connected to reinforced concrete wall elements [1–4], and on the behaviour of connections between steel beams and reinforced concrete columns [5–7]. Several recent studies have also examined the performance of flat slab-to-tubular steel or composite column connections [8–11] by means of embedded shear-arms. Nevertheless, there is a dearth of fundamental assessments on the shear transfer mechanisms and ultimate behaviour of hybrid reinforced concrete beam-to-steel column systems.

The presence of an embedded steel element within a reinforced concrete member creates a discontinuity within two distinct regions (i.e. composite and non-composite), and results in more complex behavioural characteristics than those occurring in conventional reinforced concrete members. A number of failure modes can occur within the two regions of the hybrid member, either in flexure or shear, with the latter involving more intricate inter-dependent behavioural mechanisms. In a recent numerical study by the authors [12], typical shear failure mechanisms involving diagonal tension or shear crushing that can occur in hybrid beams, were explored. As expected, early stages of behaviour are described by flexural cracking. When flexural failure is not

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Nomenclature

Greek letters

θ, θ_{cr}	crack inclination
Δ	deflection
Δ_{dow}	dowel displacement
Δ_s	crack slip
ε_i	strain
η	stiffness ratio (E_cI_c/E_vI_v)
λ	shape of the compression block factor, load proportionality factor
λ_K	proportionality constant
λ_v	embedded length factor
μ	friction coefficient
ρ_k	ratio between volume of aggregates to concrete
ρ_l	flexural reinforcement ratio
ρ_v	composite reinforcement ratio
ρ_w	shear reinforcement ratio
σ_i	normal stress
σ_{pu}	compressive strength of cement matrix
$\tau_{b,i}$	bond stress
τ_i	tangential stress
ψ	rotation
v_i	shear stress

Lowercase latin letters

a	shear span
a_v	composite shear span
a_i	lever arm
a_w, a_s	contact areas (for aggregate interlock action)
b	concrete section width
c	depth of the compression zone
c_{nom}	concrete cover
d	effective depth
d_b	bar diameter
$d_{g,i}$	aggregate dimension
e'	eccentricity
f_c	concrete cylinder strength
f_{ct}	concrete tensile strength
$f_{y,i}$	yield strength of steel
$f_{t,i}$	ultimate strength steel
h	concrete section depth
$h_{c,v}$	column depth
h_v	depth of the shear-key
l_{dow}	dowel span
l_v	embedded length
$l_{x,cr}$	horizontal projection of the shear crack
r_s	clear half span (from column face)
s_w	spacing of transverse reinforcement
z_i	lever arm
w_i	crack width
$w_{\max}$	maximum crack width
x,y,z	coordinates

Uppercase latin letters

$A_{s,i}$	reinforcement sectional area
A_w, A_s	contact areas (aggregate interlock action)
A_v	shearkey cross sectional area
E_i	modulus of elasticity
I_i	moment of inertia
L_s	moment span
L	length
N_i	axial force
M_i	bending moment
P_i	applied load
V_i	shear force

Subscripts

agg	aggregate interlock
ch	concrete compressive zone
b	bond
c	concrete
cr	crack
s	longitudinal steel
dow	dowel action
max	maximum
res	concrete residual stresses
sw,i; *sw*; *w*	transverse reinforcement
STM	values from detailed assessment
test	test values
u	ultimate
v	composite slip, shearkey

governing and high shear forces are mobilised in the section, diagonal cracking occurs. Shear failure takes place when stresses cannot be transferred through the crack interfaces and the member divides into two rigid bodies rotating along a fixed point located at the crack tip in the compression zone. Shear transfer can include contributions from several mechanisms including the concrete compressive zone, aggregate interlock, dowel action and transverse reinforcement [13–26], as well as the interfacial bond between the steel member and surrounding concrete [27–29]. The activation of each mechanism depends on the material strength, reinforcement details and member size.

Taylor [14,15] carried out investigations focusing on the distribution of shear stresses in the compression zone of reinforced concrete beams by monitoring the strains using a detailed arrangement of electrical strain gauges. The results showed that, before cracking, the shear stress distribution is nearly parabolic and the force carried by the compression zone increases slowly up to 20–40% of the total shear force until the beam approaches failure. It was reported that the tension zone of the beam can carry up to 75% of the total shear force, with the transfer through aggregate interlock contributing up to 33–50% of the total shear and the dowel action in the range of 15–25%; the latter two mechanisms decrease significantly when stirrups are present. The results presented by Swamy and Andriopoulos [22] are also in agreement with the above, and showed that shear transferred through aggregate interlock decreases with the increase in load.

Several models have been proposed to estimate the contribution of aggregate interlock to the ultimate shear strength [e.g. 16,17,19,22,30]. The model proposed by Walraven and Reinhard [16] and Walraven [17] accounts for the physical behaviour of the interlocking crack faces and is based on a cumulative distribution function of the aggregates in the crack plane. Modified approaches incorporating other width-to-slip relationships have also been proposed by Ulaga [31] and Guidotti [32]. On the other hand, Dei Poli et al. [19] adopted an idealised crack model where the aggregate interlock contribution was assessed by assuming that the reinforced concrete beam behaves as a plane truss with shear and confinement stresses along the diagonal cracks. In