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Flexural behaviour of headed bar connections between precast concrete panels

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A B S T R A C T

The use of headed bars in joints between precast concrete elements allows continuity of reinforcement to be achieved over very short splice lengths. The paper describes a series of flexural tests carried out on specimens consisting of pairs of precast elements connected by overlapping headed bars of 25 mm diameter. The headed bars overlapped by 100 mm within a 200 mm wide in situ concrete joint in which transverse bars and vertical shear studs were installed to provide confinement. This type of joint facilitates the construction of continuously reinforced slabs from precast elements thereby enabling significant reductions in overall construction time and improvements in construction quality due to off-site fabrication. The tests investigated the influence on joint strength, ductility and crack width of concrete strength, out-of-plane offset of precast planks and confining shear studs. Ductile failure with yield of 25 mm diameter high strength headed bars was achieved with joint concrete having a cylinder compressive strength of 39 MPa. A nonlinear finite element model is presented, which gives good predictions of joint strength as well as providing insight into joint behaviour.

1. Introduction

The paper investigates the performance of narrow cast in-situ joints between precast concrete elements in which continuity of reinforcement is achieved through overlapping headed bars, as shown in Fig. 1. Using headed instead of straight bars, significantly reduces tension splice lengths, thereby facilitating very efficient construction systems, like the 'E6 floor system' patented by Laing O'Rourke, in which headed bar splices provide continuity between precast elements within the floor depth. The narrow joint width adopted in the E6 system, made possible by the use of headed bars, allows adjacent precast units to be supported off each other during construction with easily handled steel brackets. This significantly reduces traditional propping, thereby enabling other follow-on trades to commence earlier. This in turn reduces overall construction time and improves on-site health and safety as well as construction quality due to trades being moved offsite into the factory. The system is ideal for regular slab layouts with standardised components, but can accommodate bespoke floor arrangements.

Similar connections using lapped headed bars, but with smaller diameter bars or longer laps, and U-bars have been studied by other researchers with the main emphasis on bridge deck applications [1–13]. A variety of design approaches have been proposed for these joints, including: models based on the ACI 318-02 [14] recommendations for side-blowout and bearing strength, strut-and-tie models [4,9–11], and an upper bound plasticity based model [12,13]. The authors have previously tested a series of tension specimens with the geometry shown in Fig. 2 which is intended to simulate a headed bar splice within the tension zone of a 300 mm thick slab loaded in flexure. The tension tests investigated the influence of variables including concrete strength, transverse reinforcement area and arrangement and presence or absence of confining shear studs [15].

This paper describes a series of five flexural tests which were carried out to investigate the influence on joint strength of concrete strength, out-of-plane offset of precast slabs and confining shear studs. The bar heads used in the tension and flexural tests were sufficiently large to develop the full tensile strength of the bars without any contribution from bond [16]. Therefore, tension is mainly transferred between overlapping headed bars through a series of diagonal compressive struts as shown in Fig. 3 in which the transverse headed bars resist out of balance forces at ends of diagonal struts. The paper compares and contrasts the behaviour

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Nomenclature

ε_2	NLFEA reinforcement strain at σ_2
ε_3	NLFEA reinforcement strain at σ_3
ε_c	Strain in the compression zone concrete
ε_{c1}	Strain at peak compressive stress
ε_s	Shear stud measured strain
η	Concrete strain ratio
σ_2	NLFEA reinforcement stress at ε_2
σ_3	NLFEA reinforcement stress at ε_3
σ_c	Concrete compressive stress
σ_y	NLFEA steel yield stress
υ	NLFEA steel Poisson's ratio
$\varnothing_b$	Reinforcement diameter
$\varnothing_{tr}$	Transverse bar diameter
E_{cm}	Concrete elastic modulus
E_s	Reinforcement elastic modulus
H	NLFEA steel hardening modulus
L_{hb}	Headed bar lap length between bearing faces of heads
M	Maximum moment at joint-precast interface
M_{hb}	Bending moment in headed bar at bar head
M_{fl}	Maximum applied bending moment at joint-precast interface
$M_{p,hb}$	Longitudinal headed bar plastic moment of resistance
$M_{p,tr}$	Transverse bar plastic moment of resistance
M_{test}	Maximum measured or equivalent calculated bending moment achieved in test
M_{tr}	Bending moment in transverse bar
N_{hb}	Measured longitudinal headed bar force
N_{2hb}	Longitudinal headed bar force on the two bar side
$N_{3hb,centre}$	Central longitudinal headed bar force on the three bar side
$N_{3hb,edge}$	Edge longitudinal headed bar force on the three bar side
$N_{y,hb}$	Longitudinal headed bar yield load
$N_{y,tr}$	Transverse bar yield load
N_{tr}	Force in transverse bar
N_s	Force in shear stud
P	Maximum flexural test load
P_{tens}	Maximum tensile test measured load
P_{fl}	Maximum flexural test measured load
S_{hb}	Spacing of headed bars with same orientation
S_F	Shear factor in NLFEA
d_g	Maximum aggregate size in NLFEA
f'_c	NLFEA concrete cylinder compressive strength
f'_{c0}	Onset of concrete compressive nonlinear behaviour in NLFEA
f'_t	NLFEA concrete tensile strength
$f_{c,cyl,j}$	Measured joint concrete cylinder compressive strength
$f_{c,cyl,p}$	Measured precast concrete cylinder compressive strength
f_{cm}	Mean concrete cylinder compressive strength
$f_{ct,j}$	Measured joint concrete tensile strength
f_u	Reinforcement ultimate strength
f_y	Reinforcement yield strength
r_c	Compressive strength of cracked concrete factor in NLFEA
w_d	Plastic displacement in concrete softening law in NLFEA
x_2	Precast slab out-of-plane offset
x_t	Transverse bar offset from the centreline of the joint

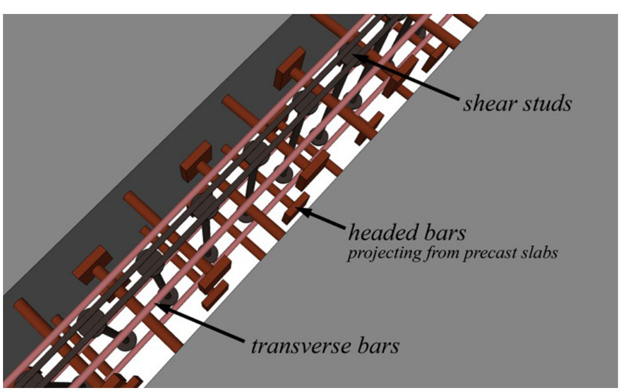

Fig. 1. Typical headed bar joint.

of the headed bar splice joints in the authors' tension and flexural tests.

2. Laboratory testing

2.1. Tension test specimen details

A full description of the direct tension tests is given elsewhere [15] so only pertinent points are summarised here. In total 27 tension specimens were tested to investigate the influence on joint strength of variables including concrete strength, transverse reinforcement and presence or absence of confining shear studs. The headed bars used in the tests were 25 mm in diameter with 70 mm square heads and yield strength of 530 MPa. Only specimens G1-26-2H20:TT′-S-100-200, G1-40-2H20:TT′-S-100-200 and G2-26-2H20:TT′-100-200 are discussed in this paper since they are directly comparable with flexural tests B2-26-2H20-S-0, B2-39-2H20-S-0 and B2-24-2H20-/-0 respectively. The geometrical dimensions and longitudinal reinforcement arrangement of these specimens (see Fig. 2) are the same as for the uncracked tension zone of the tested slabs. Where present, two 10 mm diameter 125 mm long shear studs with 30 mm diameter heads were placed in the positions shown in Fig. 2. The minimum and maximum covers to the stud head were zero and 25 mm. The 36 mm spacing of the transverse bars shown in Fig. 2 was chosen to allow sufficient space for concrete to be placed in contact with the bar heads and to allow clearance for the friction weld flash. The tests focussed on concrete controlled failures with a view to determining the critical concrete strength at which bar yield precedes concrete failure. Table 1 provides details of the three tension specimens most pertinent to this study. The test ID describes the specimens as follows:

For example, G1-26-2H20:TT′-S-100-200:

"G1 " – Test group
"26" – Measured concrete cylinder strength at time of testing
"2H20" – Number and diameter of transverse bars
"TT′" – Position of transverse bars as indicated in Fig. 2
"S" – Shear studs included
"100" – Lap length of headed bars
"200" – Spacing of headed bars

In Table 1, $f_{c,cyl,j}$ and $f_{ct,j}$ are the measured joint concrete cylinder compressive strength and tensile splitting strength respectively. $\varnothing_{tr}$ is the transverse bar size, S_{hb} is the spacing of the headed bars in the same orientation, L_{hb} is the lap length between