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Investigation of headed bar joints between precast concrete panels

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ABSTRACT

The paper addresses the design and behaviour of narrow cast in-situ joints between precast concrete elements in which continuity of reinforcement is achieved through overlapping headed bars. Using headed bars minimises the lap length required within the cast-in-situ joint region. Confining reinforcement in the form of transverse bars and vertical shear studs is also installed in the joint. The paper describes a series of tensile tests which were carried out to simulate the tensile zone of a joint loaded in pure flexure. The headed bars used in the tests were 25 mm in diameter with 70 mm square heads and yield strength of 530 MPa. The tests studied the influences of concrete strength, headed bar spacing, splice length, transverse reinforcement and confining shear studs on joint strength. A lap length of 100 mm in concrete with 28 MPa cylinder strength was found to be sufficient to develop the full strength of the headed bars. A strut-and-tie model (STM) is presented for determining joint strength. Analysis shows that the STM gives safe results even though it does not fully capture the observed joint behaviour. An upper bound plasticity model is found to give relatively good predictions of joint strength in most cases, although it also does not always capture the correct failure mechanism. The tests provide insights into joint behaviour which, in conjunction with numerical modelling, will facilitate the development of an improved design method. Widespread use of this system would lead to improvements in buildability, sustainability and health and safety in the construction of concrete structures.

1. Introduction

In precast concrete construction, satisfactory design of connections between individual elements is crucial for ensuring overall strength and robustness. Many methods can be adopted to connect precast concrete elements including, amongst others, welded connections, grouted dowels and in-situ stitches. The optimum choice of connection method is strongly influenced by the forces that need to be transferred between precast elements. The paper addresses the design and behaviour of narrow cast in-situ joints between precast concrete elements in which continuity of reinforcement is achieved through overlapping headed bars. The use of headed bars can achieve a full strength joint in tension, while significantly reducing the lap length compared to traditional straight bar laps. This type of connection has many practical applications. For example, it is used by Laing O'Rourke in their patented E6 floor system to form a continuous concrete floor by connecting precast concrete floor planks within the floor depth. The use of precast elements separated by narrow joints allows a very efficient construction process in which the planks are temporarily connected by steel brackets until the joint concrete has cured, eliminating the need for traditional propping and facilitating an extremely rapid construction programme for the structure, installation of other manufactured elements, and follow-on trades. Since the joints lie within the slab depth, storey heights can be minimised when compared to other types of precast concrete construction.

The heads used in this study are large enough to develop the full yield strength of the bar by bearing at the head, without any contribution from bond along the bar. The headed bars in adjoining precast slabs are placed out of phase by half the bar spacing as shown in Fig. 1. Transverse bars and confining vertical shear studs are installed prior to concreting the joint which is designed using a strut-and-tie model (STM) to fail by yielding of the headed bars. The paper presents the results of an experimental programme carried out at Imperial College London to obtain a better understanding of the mechanical behaviour of tension splices using headed bars. The tests investigate the influence of transverse reinforcement, confining shear studs and concrete strength on joint strength and ductility. The test results are used to assess a STM of the joint developed by Laing O'Rourke and Arup.

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Notation

α	Angle between the diagonal strut and the transverse bar axis
γ_c	Partial safety factor for concrete
γ_s	Partial safety factor for steel reinforcement
θ	Angle of line drawn between centrelines of opposite heads to line normal to headed bars
ν	Effectiveness factor for concrete
σ_2	Confinement pressure
$\sigma_{tr,\ measured}$	Measured transverse bar axial stress at failure
$\sigma_{tr,\ pred\ test}$	Predicted transverse bar axial stress at the measured joint failure load
Φ_T	Transverse reinforcement mechanical ratio
$\varnothing_b$	Bar diameter
$\varnothing_{hb}$	Headed bar diameter
$\varnothing_{stud}$	Shear stud diameter
$\varnothing_{sh}$	Shear stud head diameter
$\varnothing_{tr}$	Transverse bar diameter
$A_{confinement}$	Confined concrete area
A_{hb}	Headed bar cross-sectional area
$A_{s,tr}$	Total transverse bar cross-sectional area
A_{tr}	Transverse bar cross-sectional area
D_{hb}	Diagonal length between adjacent headed bars
E_s	Reinforcement elastic modulus
L_{hb}	Headed bar lap length between bearing faces of heads
N_{hb}	Force applied to central headed bar
N_{tr}	Force in transverse bar
N_{strut}	Force in diagonal concrete compressive strut
$N_{u,\ joint}$	Joint capacity
$N_{u,\ strut}$	Concrete strut capacity
$N_{y,hb}$	Headed bar yield load
$N_{y,tr}$	Transverse bar yield load
P_{STM}	Predicted STM failure load
P_{test}	Maximum load achieved in test
P_{UB}	Predicted upper bound failure load
S_{hb}	Spacing of headed bars with same orientation
a	Projected length of diagonal failure plane in transverse direction
b_{hb}	Head size of headed bar
b_{strut}	Diagonal concrete strut width
c_{hb}	Cover to headed bar
c_{stud}	Cover to stud head
$f_{c,cyl}$	Measured concrete cylinder compressive strength
f_{ck}	Characteristic concrete cylinder compressive strength
$f_{ck,c}$	Characteristic confined concrete cylinder compressive strength
f_{ct}	Measured concrete tensile strength
f_u	Measured reinforcement ultimate stress
f_y	Measured reinforcement yield stress
$f_{yk,\ hb}$	Headed bar characteristic yield stress
$f_{yk,\ tr}$	Transverse bar characteristic yield stress
h_{conf}	Perpendicular distance from headed bar centreline to the underside of shear stud
$h_{strut,c}$	Confined strut depth
h_{stud}	Depth of confined concrete strut
n_{tr}	Number of transverse bars contributing to the tie in the STM
r	Coefficient in upper bound model
t_{stud}	Thickness of stud head
x_t	Transverse bar offset from the centreline of the joint

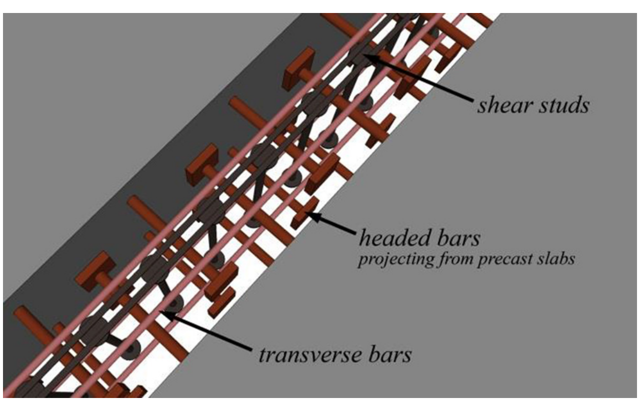

Fig. 1. Typical headed bar joint.

2. Previous studies

Headed bars are anchored through a combination of bond and bearing at the head with tests showing that the full bar strength can be developed at the head when it has a net bearing area of nine times the bar diameter [1]. According to the Canadian Code CSA A23.3-14 [2] bars with a head area equal to ten times the bar area are "deemed capable of developing the tensile strength of the bar without crushing of the concrete under the head provided that the specified concrete compressive strength is equal to or greater than 25 MPa and the yield strength of the bar used in the design does not exceed 500 MPa". There have been several previous studies into headed bar joints [3–7] mainly focussed on bridge deck applications. Thompson et al. [3,4] developed a model for the resistance provided by head bearing based on recommendations given in ACI 318-02 [8] for side-blowout and bearing strength. Due to small head sizes, most of the bars used in their studies required a contribution from the bonded length to develop the full bar strength. The model [3] is applicable for anchorage lengths of at least six times the bar diameter which is greater than the anchorage of four times bar diameter provided in the majority of tests reported in this paper. Although Thompson et al. tested some specimens with additional transverse reinforcement, the beneficial effect of this is not considered by their model. The effect of transverse reinforcement was later investigated by Chun [5], who conducted tests on beams with headed bar lap splices under four-point bending. Most of Chun's tests were done using 29 mm diameter bars with a head bearing area of four times the bar area, and lap lengths varying from 435 mm to 870 mm. He concluded that providing transverse reinforcement in the form of stirrups increased anchorage strengths by up to 67% and restrained prying action of the headed bars resulting from curvature of the beam.

Li et al. [6] conducted bending tests on slabs with overlapping 16 mm bars with 13 mm thick, 51 mm diameter circular friction welded heads capable of developing the full bar strength. The headed bar spacing in the precast units was either 102 mm or 152 mm and the lap was varied between 64 mm and 152 mm. Concrete strengths varied from 53 MPa to 72 MPa. Two 16 mm bars with 35 mm circular heads at each end were placed transversely across the specimen at the centre of the joint, one above and one below the overlapping headed bars. In order to develop a full strength joint in which reinforcement yielded before concrete crushing, the authors recommend a minimum lap length of 152 mm. Li et al. [7] also investigated the influence of fatigue