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The influence of reinforcement on load carrying capacity and cracking of the reinforced concrete deep beam joint

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ABSTRACT

The paper presents the results of experimental research of the spatial reinforced concrete deep beam systems orthogonally reinforced and with additional inclined bars. Joint of the deep beams in this research was composed of the longitudinal deep beam with a cantilever suspended at the transversal deep beam. The cantilever deep beam was loaded throughout the depth and the transversal deep beam was loaded at the mid-span by longitudinal deep beam attached to it. Morphology of cracking and stresses in the reinforcing steel, as well as the load distribution in the cantilever deep beams using Strut-and-Tie model taking into account an effort of concrete compression strut and efficiency of softening coefficient are presented and discussed. In the paper, the effectiveness of the mixed reinforcement in both tested deep beam systems, as referred to the design recommendation proposed in the published papers is also verified. It is also demonstrated that the inclined reinforcement favorably influences the width of cracks in cantilever and transversal deep beams and ensures the increase of the load carrying capacity.

1. Introduction

In recent years, we can observed a major increase in the number of high-rise buildings especially in the large cities, where the demand is often associated with a lack of available land. Therefore importance of design reinforced concrete deep beams significantly increased as main structural elements in this type of structures (Fig. 1). Seeking the more attractive architectural forms of buildings, the unusual special shape of the building's body, as well as diversified facades are looked for. In such cases, the deep beams are the essential structural elements. They are applied in order to break the monotony of smooth walls with the help of jutties (bays) thus creating special deep beam joints with the elements of cantilever deep beams.

The loading applied on particular deep beams, cantilever ones included, produce stress state and cracks different from flat deep beams that are tested most frequently. The standard regulations, both EC 2 [1], and ACI 318 [2], or MC 2010 [3], do not consider cantilever and transversal deep beams loaded along their depth.

The extensive experimental research of concrete reinforced deep beams conducted so far, in a large majority concerned the load carrying capacity of flat deep beams, single or twin span loaded with forces concentrated on the upper edge with unbounded edges [4–6], or suspended to the columns [7]. The variable parameters were diversified in those tests and concerned, i.a., reinforcement [8–10], various deep beams geometry [11,12], and the influence of the concrete strength [13].

The tests of the spatial system of deep beams where the cantilever deep beam was an element of system loaded along the upper edge, were conducted in the 60th of the XX century by Leonhardt [14] and Walther [15]. On the basis of obtained results, Leonhardt formulated the design recommendations, concerning i.a. the cantilever elements loaded indirectly along the depth, that are applied till today.

2. The state of knowledge regarding the actual design recommendations

The Leonhard's [14] recommendations regarding the cantilever deep beams uniformly loaded along depth are based on the assumption that vertical bars in the form of stirrups, concentrated near the edge of the cantilever are to be dimensioned for the force of $0.6F$, while the bent up bars should be dimensioned for the force of $0.4F_1/\sin\alpha$ as in Fig. 2.

$$A_{sw1} = 0.6 \cdot \frac{F_1}{f_{ywd}} \qquad (1)$$

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Nomenclature

a_F	dimension the force from the edge of the cantilever deep beam
A_{sw1}	area of the vertical bars
A_{sw2}	area of the bent up bars
d	effective height of the cantilever deep beam
E_c	Young modulus of concrete
f_c	compressive strength
$f_{cm,cyl}$	cylinder compressive strength of concrete
f_y	yield strength of the reinforcement
F	total applied force acting on the deep beam system
F_1	force distributed throughout the depth of the cantilever deep beam
F_3	force transmitted to the transversal deep beam along its depth
$F_{c1,cal}$, $F_{c2,cal}$	compressive force of concrete in the strut from the analysis S–T
$F_{s1,cal}$, $F_{s2,cal}$	tensile force of reinforcement from the analysis S–T
$F_{s1,exp}$, $F_{s2,exp}$	tensile force of reinforcement from the exp. tests
F_{cr}	cracking force
F_t	force in diagonal reinforcement
F_u	failure load
$F_{u,design}$	designed failure load
F_v	force in vertical reinforcement
H	height of the deep beam
l_k	overhang length of the cantilever deep beam
t	thickness of the deep beam
u	vertical displacement of the bottom horizontal edge at the end of the cantilever deep beam
w_i	width of the cracks
α	angle between the bent up bars and the horizontal axis
α_2	angle between the force F_{s2} and the vertical axis
β	softening coefficient
ε_c	compressive strain in the concrete
ε_{ct}	tensile strain in the concrete
θ	angle between the force F_{c1} and F_{s1}
$\sigma_{c1,cal}$, $\sigma_{c2,cal}$	compressive stresses of concrete in the strut from the analysis
$\sigma_{s,exp}$	stresses of the main reinforcement from the exp. tests

Fig. 1. High-rise buildings and building due to architectural reasons.

$$A_{sw2} = 0.4 \cdot \frac{F_1}{\sin\alpha \cdot f_{ywd}} \tag{2}$$

The vertical bars shaped as a stirrup closed at the whole depth of the deep beam, transmitting the force 0.6F, are to be disposed in the transversal beam on the 2t section from its edge.

The suggestions recommended by Schröeder's [16] are different. He proposes that the bent up bars take over the entire force acting on the cantilever F_1, and that the additional vertical stirrups dimensioned for the force of 0.4F are placed. These recommendations do not take into account angle of inclined bars according to span–depth ratio (see Fig. 3).

$$A_{sw1} = 0.4 \cdot \frac{F_1}{f_{ywd}} \tag{3}$$

$$A_{sw2} = \frac{F_1}{f_{ywd}} \tag{4}$$

In the case of the reinforcement of a simple-supported deep beam, on which another deep beam is attached along its whole height, Leonhardt [14] recommends to introduce the additional reinforcement in the form of stirrups, or the reinforcement in the form of vertical stirrups and bent up bars of bending diameter equal to 20ϕ. While the vertical reinforcement is applied at the deep beams joint, the stirrups transmitting the entire force F should be situated along the width of 3t nearly the joint [16] (Fig. 4).

3. The importance of the research

In order to experimentally determine the effectiveness of diagonal reinforcement according to Leonhardt's [14] recommendations of, as well as to check up of application of the orthogonal reinforcement only, in the case of a joint with the cantilever deep beam loaded at its depth, the original research of two spatial deep beam systems was carried on. For the analysis of the flow of forces