Engineering Structures 136 (2017) 149–164

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Uniform Design Method for punching shear in flat slabs and column bases

Dominik Kueres [a,*], Carsten Siburg [b], Martin Herbrand [a], Martin Classen [a], Josef Hegger [a]

[a] RWTH Aachen University, Institute of Structural Concrete, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany
[b] H+P Ingenieure GmbH, Kackertstr 10, 52072 Aachen, Germany

ARTICLE INFO

Article history:
Received 12 September 2016
Revised 29 December 2016
Accepted 30 December 2016

Keywords:
Punching shear
Flat slabs
Column bases
Design provisions
Punching shear reinforcement
Eurocode 2

ABSTRACT

The punching shear design of flat slabs and column bases was revised with the introduction of Eurocode 2. While in many former codes the punching shear resistance was determined regardless of the type of member, in Eurocode 2 two different design equations for flat slabs and column bases were introduced. Additionally, different control sections for flat slabs and column bases were defined. The differentiation between flat slabs and column bases and especially the iterative design procedure for the determination of the punching shear resistance of column bases require great effort in daily practice.

Based on the punching shear provisions according to Eurocode 2, a new Uniform Design Method (UDM) for flat slabs and column bases is developed. The derivation of the design method is described in detail. To verify the changes in the current design provisions, the new design method is evaluated using large databanks for flat slabs and column bases without and with shear reinforcement as well as systematic test series.

1. Introduction

The punching shear behavior of reinforced concrete slabs was investigated extensively by various researchers in the past. As a result of these theoretical and experimental investigations, different approaches for the determination of the punching shear resistance of flat slabs and column bases were derived. A brief description of the various approaches can be found e.g. in [1–4].

Due to more compact dimensions and soil-structure interaction, column bases achieve significantly higher punching shear capacities than flat slabs [5–10]. Considering these differences, Eurocode 2 [11] introduced two different design equations for flat slabs and column bases. Additionally, different control sections for flat slabs and column bases were defined. While for flat slabs the control section is given in a distance 2.0*d* from the column's perimeter, for column bases this distance has to be determined iteratively minimizing the punching shear resistance. The differentiation between flat slabs and column bases and especially the iterative design procedure for the determination of the punching shear resistance of column bases increased the effort in daily engineering practice compared to former codes.

In this paper, possible improvements for the current punching shear provisions according to Eurocode 2 are identified by means of databank evaluations as well as experiences with the code provisions. Based on the results of the evaluation of the current design provisions, a new Uniform Design Method (UDM) for punching shear in flat slabs and column bases is developed and its derivation is described in detail.

2. Evaluation of design provisions according to Eurocode 2

2.1. General

In this section, the punching shear provisions for flat slabs and column bases according to Eurocode 2 [11] are evaluated by means of comparisons with test results. Based on the results of the databank evaluations and experiences with the code provisions, possible improvements are identified and presented. A brief description of the punching shear provisions for flat slabs and column bases according to Eurocode 2 is presented in Appendix A. A more detailed description of the design provisions can be taken from [12–16].

2.2. Test databanks

Critically reviewed test databanks can be considered for both, the evaluation of existing code provisions and the derivation of

* Corresponding author.
E-mail addresses: dkueres@imb.rwth-aachen.de (D. Kueres), csiburg@huping.de (C. Siburg), mherbrand@imb.rwth-aachen.de (M. Herbrand), mclassen@imb.rwth-aachen.de (M. Classen), jhegger@imb.rwth-aachen.de (J. Hegger).

http://dx.doi.org/10.1016/j.engstruct.2016.12.064
0141-0296/

Nomenclature

Latin lower-case letters

a_λ	shear span
d	effective depth
d_0	transitional size
f_c	concrete compressive strength
f_{ck}	characteristic value of concrete compressive strength
$f_{ck,cyl}$	characteristic value of concrete compressive strength (cylinder: 150 × 300 mm)
$f_{cm,cyl}$	mean value of concrete compressive strength (cylinder: 150 × 300 mm)
f_{ywd}	design value of the yield strength of the shear reinforcement
f_{ywm}	mean value of the yield strength of the shear reinforcement
k	factor accounting for the influence of size effects
k_d	factor accounting for the influence of size effects
k_λ	factor accounting for the influence of column size and shear span-depth ratio
u_0	perimeter of the loaded area
$u_{0.5d}$	control perimeter in a distance 0.5d from the face of the loaded area
$u_{control}$	control perimeter
u_{out}	control perimeter at which shear reinforcement is not required
x_p	5%-quantile
$x_{p,x}$	5%-quantile (Standard normal distribution)
$x_{p,y}$	5%-quantile (Log normal distribution)

Latin upper-case letters

A_{sw}	area of shear reinforcement
$C_{Rk,c}$	constant factor (characteristic value)
$C_{Rm,c}$	constant factor (mean value)
V_c	contribution of concrete
V_{Ed}	applied shear force
V_{Test}	ultimate failure load in the test
$V_{Rd,c}$	design value of punching shear capacity without shear reinforcement
$V_{Rd,c+s}$	design value of punching shear capacity with shear reinforcement
$V_{Rd,s}$	design value of capacity of shear reinforcement
$V_{Rd,\max}$	design value of maximum punching shear capacity
$V_{Rk,c}$	characteristic value of punching shear capacity without shear reinforcement
$V_{Rk,c+s}$	characteristic value of punching shear capacity with shear reinforcement
$V_{Rm,gov}$	governing punching shear capacity
$V_{Rm,s}$	characteristic value of capacity of shear reinforcement
$V_{Rk,\max}$	characteristic value of maximum punching shear capacity
$V_{Rm,c}$	mean value of punching shear capacity without shear reinforcement
$V_{Rm,c+s}$	mean value of punching shear capacity with shear reinforcement
$V_{Rm,s}$	mean value of capacity of shear reinforcement
$V_{Rm,\max}$	mean value of maximum punching shear capacity
V_s	contribution of shear reinforcement
V_x	coefficient of variation (Standard normal distribution)
V_y	coefficient of variation (Log normal distribution)

Greek letters

α	angle between the shear reinforcement and the plane of the slab
α_c	factor accounting for contribution of concrete
α_{max}	increase factor
α_s	factor accounting for contribution of shear reinforcement
γ_C	partial safety factor for concrete
μ_x	mean value
ρ_l	flexural reinforcement ratio

improved design methods. Based on systematically checked test data, the accuracy and reliability of design provisions can be evaluated. It can also be examined if the included parameters are taken into account appropriately or if further parameters have to be considered.

In [17] the collected databanks for flat slabs and column bases without and with shear reinforcement of the Institute of Structural Concrete, RWTH Aachen University [18–20] were checked and extended by recent test results. In a second step, selection criteria were formulated and the collected databanks were filtered accordingly. The selection criteria are described in [17] in detail.

The evaluation of the punching shear provisions according to Eurocode 2 in this section is performed mainly on the basis of the selected test databanks for flat slabs and column bases without and with shear reinforcement (interior columns) by [17] (Appendix B). By means of the comparison of failure load and punching shear capacity according to Eurocode 2, it is investigated if the main influences on the punching shear capacity (e.g. concrete compressive strength f_c, flexural reinforcement ratio ρ_l, effective depth d, specific column perimeter u_0/d (u_0 is the perimeter of the loaded area), and shear span-depth ratio a_λ/d (a_λ is the distance between the face of the loaded area and the line of contraflexure)) are considered in a consistent manner. Also, the level of safety of the design provisions is determined and compared to the requirements according to Eurocode 0 [21] (5%-quantile $x_p \geqslant 1{,}0$). In this context, the 5%-quantile is determined based on a "Standard normal distribution" (indicated by index "x") and a "Log normal distribution" (indicated by index "y").

2.3. Punching shear resistance without shear reinforcement

For the evaluation of the punching shear provisions for flat slabs without shear reinforcement according to Eurocode 2 (Appendix A), a total of 328 tests can be considered according to [17]. Fig. 1 depicts the comparison of failure load and punching shear capacity of flat slabs without shear reinforcement according to Eurocode 2. While the influences of concrete compressive strength f_c, flexural reinforcement ratio ρ_l, specific column perimeter u_0/d, and shear span-depth ratio a_λ/d are taken into account reasonably well by the code equations, a strong trend for the influence of the effective depth d can be observed. In this context, the ratio $V_{Test}/V_{Rk,c,EC2}$ decreases with increasing effective depth d which indicates that the influence of size effect is underestimated in the current provisions. The evaluation of the ratio $V_{Test}/V_{Rk,c,EC2}$ for the 328 tests yields a mean value $\mu_x = 1.251$ with COVs (coefficients of variation) of $V_x = 0.219$ and $V_y = 0.211$, respectively. The 5%-quantile is $x_{p,x} = 0.799$ (Standard normal distribution) and $x_{p,y} = 0.866$ (Log normal distribution). Thus, the 5%-quantile is lower than required by Eurocode 0 (5%-quantile $x_p \geqslant 1.0$).

For the evaluation of the punching shear provisions for column bases without shear reinforcement according to Eurocode 2, a total of 44 tests can be considered according to [17]. Fig. 2 shows the comparison of failure load and punching shear capacity of column