Engineering Structures 103 (2015) 1–14

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental investigation on shear capacity of reinforced concrete slabs with plain bars and slabs on elastomeric bearings

Eva O.L. Lantsoght [a,b,*], Cor van der Veen [b], Joost Walraven [b], Ane de Boer [c]

[a] *Universidad San Francisco de Quito, Politecnico, Diego de Robles y Vía Interoceánica, Quito, Ecuador*
[b] *Delft University of Technology, Concrete Structures, Stevinweg 1, 2628 CN Delft, The Netherlands*
[c] *Ministry of Infrastructure and the Environment, Griffioenlaan 2, 3526 LA Utrecht, The Netherlands*

ARTICLE INFO

Article history:
Received 2 March 2015
Revised 5 June 2015
Accepted 21 August 2015
Available online 9 September 2015

Keywords:
Bond
Slab
Punching shear
Shear
Structural load test

ABSTRACT

One-way slabs supported by line supports and reinforced with deformed bars were shown previously to behave differently in (one-way) shear than beams. For the application to existing slab bridges, the influence on the shear capacity of using plain reinforcement bars and of supporting the slab by discrete bearings is investigated. To study these parameters and their influence on the shear capacity, a series of experiments was carried out on continuous one-way slabs ($5\ \text{m} \times 2.5\ \text{m} \times 0.3\ \text{m}$), subjected to concentrated loads close to the support line. The results from these experiments are compared to code provisions and a method developed by Regan. These experiments confirm the findings that slabs subjected to concentrated loads close to supports have larger shear capacities than beams.

1. Introduction

A large number of the existing Dutch reinforced concrete solid slab bridges were found to be shear-critical upon assessment according to the recently introduced Eurocodes NEN-EN 1992-1-1:2005 for concrete [1] and NEN-EN 1991-2:2003 for loads [2]. The shear provisions from NEN-EN 1992-1-1:2005 are based on a statistical analysis of experimental results of a large number of beams that were mostly small, heavily reinforced and tested as a simply supported beam subjected to two point loads [3]. One could doubt how extrapolations of this limited subset to all possible cases of elements loaded in shear reflect the shear behavior of the aforementioned structural elements. For the shear capacity of one-way slabs, additional sources of capacity can be identified, such as transverse load redistribution [4,5]. The effect of the additional dimension in a slab on the shear capacity as compared to a beam was studied in a preceding series of experiments [6]. All specimens in the previous series of experiments were slabs supported by line supports and reinforced with deformed bars. The existing Dutch bridges, built before 1963, were reinforced with plain bars, which led to the necessity to study slabs reinforced with plain bars and compare their capacity and behavior to the previously tested slabs reinforced with deformed bars. Some of the more recent slab bridges are supported by bearings, resulting in the necessity to compare the behavior of slabs on discrete supports to the behavior of slabs on rigid line supports. To study the influence of these parameters eight additional specimens were tested.

Recent research on the shear problem focuses on the shear capacity of more advanced concrete mixes, tested on beam specimens [7–9], improved code [10] and theoretical [11] models, which can be based on advanced programming techniques [12–14], as well as deepening the understanding of known effects in shear such as the size effect [15].

The present research studies the behavior of slabs with concentrated loads close to discrete supports and of slabs reinforced with plain bars, for which previously no experiments were carried out. This study is needed for the assessment of existing structures [16,17]. The conducted experiments are important, because shear design rules for slabs are mostly derived from shear tests on beams and lead to an underestimation of the shear resistance of one-way slabs.

2. Shear in one-way slabs

To study the one-way shear capacity and effect of transverse load redistribution for slabs subjected to concentrated loads close to supports, a preceding series of experiments was executed at

---

* Corresponding author at: Universidad San Francisco de Quito, Politecnico, Diego de Robles y Vía Interoceánica, Quito, Ecuador. Tel.: +593 2 297 1700x1186.

E-mail addresses: E.O.L.Lantsoght@tudelft.nl (E.O.L. Lantsoght), C.vanderveen@tudelft.nl (C. van der Veen), J.C.Walraven@tudelft.nl (J. Walraven), ane.de.boer@rws.nl (A. de Boer).

http://dx.doi.org/10.1016/j.engstruct.2015.08.028
0141-0296/

Nomenclature

a	distance between the center of the support and the center of the load
a_v	clear shear span: distance between face of support and face of load
$a_{v,EC2}$	distance as defined in NEN-EN 1992-1-1:2005: face-to-face distance between load and support for rigid support materials and distance between the face of the load and the center of the support for flexible support materials
$a_{v,alt}$	alternative for $a_{v,EC2}$: face-to-face distance between load and support for all support materials
b_o	length of perimeter at distance $d/2$ from loaded area
b_{eff}	effective width at the support in shear, taken from the far side of the loading plate to the face of the support assuming 45° horizontal load spreading
b_{load}	width of the concentrated load
b_w	web width
b_r	distance between the center of the load and the free edge taken along the width
c	heavily cracked and locally failed specimen
d	effective depth, for punching the average of d_l and d_t is used
d_g	aggregate diameter
d_l	effective depth towards longitudinal steel
d_t	effective depth towards transverse steel
d_v	effective shear depth
$f_{c,cyl}$	mean cylinder compressive strength of concrete
$f_{c,cube}$	design cube compressive strength
$f_{c,cube,meas}$	measured cube compressive strength of the concrete at the age of testing the slab
f_{ck}	characteristic cylinder compressive strength of concrete
$f_{ct,meas}$	splitting tensile strength of the concrete at the age of testing the slab
f_R	specific rib area, ratio of average rib height to rib distance
f_{ym}	yield strength of reinforcement
f_{um}	ultimate strength of reinforcement
k	factor taking into account the size effect in shear
k_v	factor determining the shear capacity in the *fib* Model Code
k_ψ	factor determining the punching shear capacity in the *fib* Model Code
l_{load}	length of the concentrated load
q_{self}	distributed load due to the self weight of the slab
s	measured displacement
u_1	critical perimeter without the part parallel to the support in Regan's method
u_2	part of the perimeter parallel to the support in Regan's method
uc	virgin specimen
x	distance from the simple support
z	internal lever arm
A_s	area of longitudinal tension steel
B	the failure mode is beam shear failure with a noticeable shear crack at the side
CS	load is placed close to the continuous support
$C_{Rd,c}$	$0.18/\gamma_c$ with $\gamma_c = 1.5$; empirical factor for characteristic shear capacity
$C_{R,c,test}$	empirical factor for mean shear capacity found by calibrating experiments
$C_{R,c,Regan}$	0.15, empirical factor used to determine the mean shear capacity
D	deformed bars were used
E	the load is positioned near the free edge, at 438 mm from the edge
E_s	Young's modulus of reinforcement steel
F_{pu}	the sum of the forces at failure in the three prestressing bars close to the continuous support
M	load is positioned in the middle of the width of the slab
M_{Ed}	design sectional moment
M_{exp}	measured maximum moment over the continuous support
$M_{u,span}$	bending moment at ultimate at the location of the concentrated load
$M_{u,sup}$	bending moment at ultimate at the location of the continuous support
M_u	factored bending moment at section
N_{Ed}	design sectional axial load
R_{CS}	reaction force at continuous support
R_{SS}	reaction force at simple support
SF	the observed failure mode is punching of the support
SS	load is positioned close to the simple support
P	observed failure mode is punching shear
PL	plain bars were used
P	measured force at the concentrated load
P_{R1}	resistance of part of perimeter away from support
P_{R2}	resistance of part of perimeter close to the support and parallel to the support
P_{Regan}	calculated value of the ultimate load according to Regan's formula
P_u	measured peak load in an experiment
WB	observed failure mode is wide beam shear failure
V_{ACI}	shear capacity calculated according to ACI 318-14
$V_{ACI,f}$	shear capacity calculated according to ACI 318-14 multiplied by $1.5d_l/a_v \geqslant 1$
$V_{ACI,p}$	punching capacity calculated according to ACI 318-14
V_{Ed}	design shear force
V_{exp}	the shear force at the support at failure
$V_{exp,EC2}$	shear force at failure in the experiment obtained after reducing the loads close to the support with β as prescribed by NEN-EN 1992-1-1:2005
$V_{exp,EC2,\mathrm{alt}}$	shear force at failure in the experiment obtained after reducing the loads close to the support with $\beta = a_{v,alt}/2d_l$
$V_{exp,MC}$	sectional shear force in the governing cross-section (the analysis with the *fib* Model Code is done for each cross-section)
V_{MC}	shear capacity according to the *fib* Model Code
$V_{R,c}$	calculated value of the shear capacity according to NEN-EN 1992-1-1:2005
$V_{Rd,c}$	design value of the shear capacity according to NEN-EN 1992-1-1:2005
V_u	factored shear force at section
α_{Regan}	enhancement factor for loads close to the continuous support
α_s	factor for punching capacity, =40 for interior columns, 30 for edge columns, 20 for corner columns
β	reduction factor for the contribution of loads close to the support to the shear force at the support
β_p	ratio of long side to short side of a column, concentrated load or reaction area
γ_c	1.5; partial safety factor for concrete
γ_m	partial safety factor for materials
Δe	distance between neutral axis and center of internal lever arm z
ε_x	the longitudinal strain at mid-depth of the effective shear depth