Shear tests of reinforced concrete slabs and slab strips under concentrated loads

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Abstract

In slabs subjected to concentrated loads, the shear strength checks are conducted for two limit states: 1) shear over an effective width, and 2) punching shear on a perimeter around the point load. In current practice, the shear strength at the supports is determined with models that do not consider the transverse redistribution of load that occurs in slabs, which results in underpredictions for the actual slab shear capacity. Currently, an experimental program is being conducted at Delft University of Technology to determine the shear capacity of slabs under point loads near to the support. This paper presents the results of the tests conducted in continuous slabs and slab strips. In addition to studying the influence of the slab width, the specimens are tested with two types of reinforcement (ribbed and plain bars). The results of the experiments are compared to strength predictions from current design models. Also, recommendations for the support effective width and an enhancement factor for considering the effect of transverse load redistribution are given.

1 Introduction

Shear in reinforced concrete one-way slabs loaded with a concentrated load near the support is typically checked in two ways: by calculating the beam shear capacity over a certain effective width and by checking the punching shear capacity on a perimeter around the load. The method of horizontal load spreading, resulting in the effective width b_{eff} of the support which carries the load, depends on local practice. In most cases (eg. Dutch practice) horizontal load spreading is assumed under a 45° angle from the centre of the load towards the support, Fig. 1 (left). The lower limit for the effective width is typically $2d$ for loads in the middle of the width and d for loads at the edge and corner of the slab. In French practice [1], load spreading is assumed under a 45° angle from the far corners of the loading plate towards the support, Fig. 1 (right). The punching shear (two-way shear) capacity in code formulas is developed for two-way slabs. Most empirical methods for punching shear have been derived from tests on slab areas around a column; a loading situation which is significantly different from a slab under a concentrated load close to the support.

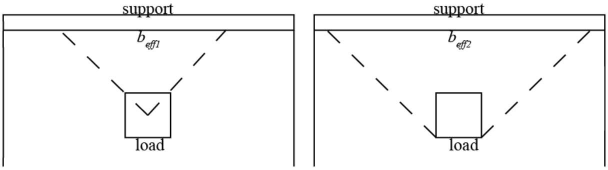

Fig. 1 Effective width (left) assuming 45º load spreading from the centre of the load: b_{eff1}; (right) assuming 45º load spreading from the far corners of the load: b_{eff2}; top view of slab.

2 Previous research

Recent research concerning shear in slabs has mainly focused on one-way slabs under line loads [2]. It was experimentally shown that one-way slabs under line loads behave like beams and that beam shear provisions lead to good estimates of their shear capacity. A database of 206 experiments on wide beams and slabs [3] shows that test data regarding the shear capacity of one-way slabs (b_{eff2} from Fig.1 (right) smaller than the total specimen width, b) under concentrated loads are scarce and only 22 experiments with a/d < 2,5 are available [4-7]. The majority of these experiments were car-

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ried out on small specimens (d < 15cm). A comparison between these results from the literature and EN 1992-1-1:2004 [8] “EC2” (combined with two different load spreading methods and $C_{Rd,c}$ = 0,15 [9]) and the French National Annex [1]) and Regan’s method [4] is shown in Table 1. The average (AVG), standard deviation (STD) and coefficient of variation (COV) of the results for the experimental value divided by the calculated value indicate that the traditional method of calculating the one-way shear strength (EC2 + b_{eff1}) underestimates the capacity. The French National Annex [1] and Regan’s method [4] lead to the best results. The French National Annex allows shear stresses in slabs 2,27 times higher (for k = 2) than in beams as a result of transverse redistribution. Regan’s method combines an enhancement factor from one-way shear with a punching perimeter from two-way shear. These results indicate that slabs can support higher concentrated loads as a result of their extra dimension. However, not enough experimental evidence is available to support this statement. Therefore, a series of experiments on slabs with d = 265mm is carried out.

Table 1 Comparison between test results from literature and design methods.

	EC2 [8] + b_{eff1}	EC2 [8] + b_{eff2}	EC2 + French NA [1]	Regan [4]
AVG	3,411	2,038	1,022	0,966
STD	1,005	0,501	0,294	0,204
COV	29,5%	24,6%	28,8%	21,1%

3 Experiments

3.1 Experimental setup

A top view of the test setup with a slab is presented in Fig. 2. The line supports (sup 1 and sup 2 in Fig. 2) are composed of a steel beam (HEM 300) of 300mm wide, a layer of plywood and a layer of felt [10] of 100mm wide. Experiments are carried out with a concentrated load close to the simple support (sup 1 in Fig. 2) and close to the continuous support (sup 2 in Fig. 2), where the rotation is partially restrained by vertical prestressing bars which are fixed to the strong floor of the laboratory. The prestressing force is applied before the start of every test, offsetting the self-weight of the slab. During the course of the experiment, some rotation could occur over support 2 due to the deformation of the felt and plywood and the elongation of the prestressing bars.

3.2 Specimens and Results

All slabs (“S”) and slab strips (“B”) have a thickness h of 300mm and an effective depth d of 265mm. The slabs are either loaded at the middle of the slab width (position M) at the simple and continuous support (two tests per slab), or consecutively at the east and west side (position S) at the simple and continuous support (four tests per slab).

Ribbed reinforcing bars with a diameter of 10mm (measured mean yield strength f_{sy} = 537MPa and measured mean ultimate strength f_{su} = 628MPa) and 20mm (f_{sy} = 541MPa and f_{su} = 658MPa) are used [10]. For S11 to S14, plain reinforcing bars with a diameter of 10mm (f_{sy} = 635MPa and f_{su} = 700MPa) and 20mm (f_{sy} = 601MPa and f_{su} = 647MPa) are used [10]. The flexural reinforcement is designed to resist a bending moment caused by a load of 2MN (maximum capacity of the jack) at position M (Fig. 2) along the width and 600mm along the span (a/d = 2,26). In practice, the amount of transverse flexural reinforcement for slabs is taken as 20% of the longitudinal flexural reinforcement. In the tested slabs, 13,3% of the longitudinal flexural reinforcement is used in S1 and S2; 25,9% in S3, S5 to S14 and 27,2% in the slab strips. In S4 the amount of transverse flexural reinforcement is only doubled as compared to S1 and S2 in the vicinity of the supports.

The properties and results of S1 to S9 and the slab strips can be found in [11]. The properties of S11 to S14 are given in Table 2, in which the following symbols are used:

f_c' the cube compressive strength of the concrete at the age of testing the slab,
f_{ct} the splitting tensile strength of the concrete at the age of testing the slab,
ρ_l, ρ_t the longitudinal (ρ_l) and transverse (ρ_t) reinforcement ratios of the slab,
a the centre-to-centre distance between the load and the support,
M/S loading at the middle (M) or side (S) of the slab width, Fig. 2,
$b_{load} \times l_{load}$ the size of the loading plate.

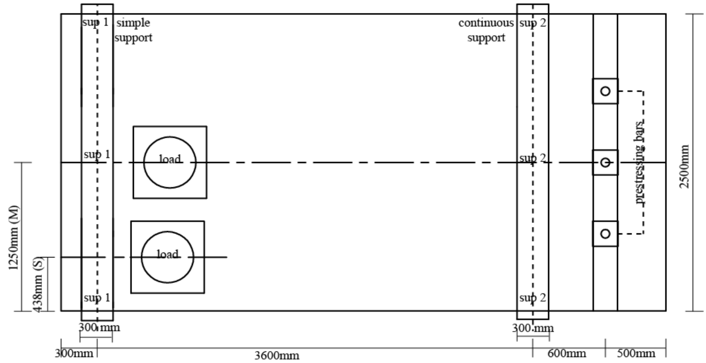

Fig. 2 Sketch of test setup, top view.

Table 2 Properties of slabs S11 to S14.

Slab nr.	b (m)	f_c' (MPa)	f_{ct} (MPa)	ρ_l (%)	ρ_t (%)	a/d	M/S	$b_{load} \times l_{load}$ (mm × mm)	test age (days)
S11	2,5	54,9	4,2	1,375	0,358	2,26	M	200 × 200	90
S12	2,5	54,8	4,2	1,375	0,358	2,26	S	200 × 200	97
S13	2,5	51,9	4,2	1,375	0,358	1,51	M	200 × 200	91
S14	2,5	51,3	4,2	1,375	0,358	1,51	S	200 × 200	110

The results of S11 to S14 are given in Table 3, in which the following symbols are used:

SS/CS experiment at the simple (SS, sup 1) or continuous support (CS, sup 2), Fig. 2,
P_u the measured ultimate load,
WB/P/B failure mode: wide beam shear (shear crack at the inside), punching shear or beam shear,
F_{pres} the force in the prestressing bars at failure,
V_{max} the resulting maximum shear force,
$V_{max,EC}$ the maximum shear force including reduction of the loads within 2d of the support [8].

Table 3 Results of slabs S11 to S14.

Test	SS/CS	P_u (kN)	Failure mode	F_{pres} (kN)	V_{max} (kN)	$V_{max,EC}$ (kN)
S11T1	SS	1194	WB + P	165	998	848
S11T4	CS	958	WB + P	307	886	766
S12T1	SS	931	WB + B + P	162	780	663
S12T2	SS	1004	P	173	839	712
S12T4	CS	773	WB + P + B	147	705	608
S12T5	CS	806	WB + B	158	735	633
S13T1	SS	1404	WB + P	157	1253	593
S13T4	CS	1501	WB + P	240	1411	706
S14T1	SS	1214	WB + P + B	133	1088	518
S14T2	SS	1093	WB + P + B	162	975	462
S14T4	CS	1282	WB + P + B	187	1207	605
S14T5	CS	1234	WB + P + B	142	1157	578

4 Results

4.1 Influence of the width

If the concept of an effective width can be applied to concrete slabs loaded in shear, then the shear capacity ceases to increase proportionally to the width after reaching a threshold value, the effective width. Increasing widths will lead to the same capacity, as only the effective width can carry the shear force from the load to the support [12]. For loads close to the support (a/d < 2,5) the results of S8 and S9 are compared to the results of the series of slab strips with different widths (BS1/0,5m – BX3/2m). The size of the loading plate, distance between the load and support and location of testing are variable. As shown in Fig. 3, the previously described threshold is achieved after an almost linear increase in capacity for an increase in width.

Table 4 gives the results for the effective width (b_{meas}) based on the experimental results, compared to the calculated widths based on the load spreading methods from Fig. 1 and from the ModelCode 2010 (b_{MC}) [13]. Remarkably, lower effective widths are found at the continuous support. The load spreading mechanism is thus influenced by the moment distribution in the shear span. The observed relation between the effective width and the size of the loading plate as well as the distance between the load and the support, are best reflected by b_{eff2}. The effective width from ModelCode 2010 gives too conservative results and does not correctly take the influence of the size of the loading plate into account.

Table 4 Effective width as calculated from the experimental results.

Test: $b_{load} \times l_{load}$, SS/CS, a/d	b_{meas} (m)	b_{eff1} (m)	b_{eff2} (m)	b_{MC} (m)
300mm × 300mm, SS, a/d = 2,26	2,12	1,10	1,70	0,99
300mm × 300mm, CS, a/d = 2,26	1,81	1,10	1,70	0,99
200mm × 200mm, SS, a/d = 1,51	1,25	0,70	1,10	0,63
200mm × 200mm, CS, a/d = 1,51	1,11	0,70	1,10	0,63
200mm × 200mm, SS, a/d = 2,26	1,63	1,10	1,50	0,98
200mm × 200mm, CS, a/d = 2,26	1,33	1,10	1,50	0,98

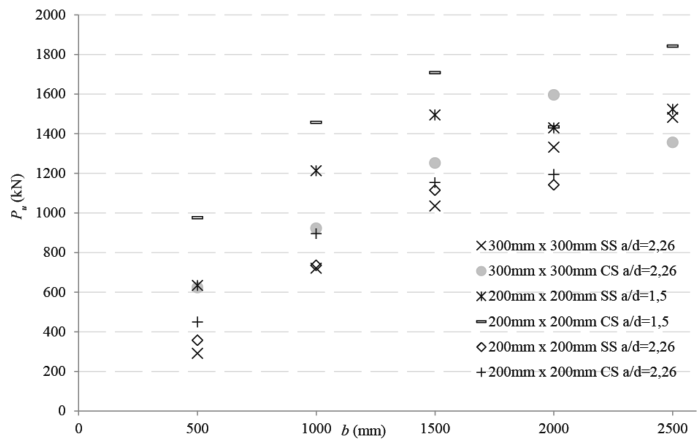

Fig. 3 Influence of overall width on shear capacity for the series discussed in Table 4.

4.2 Comparison to design models

All test results are compared to the following code methods: EN 1992-1-1:2004 [8] with $C_{Rd,c}$ = 0,15 [9] with b_{eff1} and b_{eff2}, EN 1992-1-1:2004 [8] with the French National Annex for slabs [1] and Regan's formula [4]. The comparisons are based on the measured mean material properties. Safety and material factors equal 1. Punching shear was not the governing failure mode according to EN 1992-1-

1:2004 [8]. The critical perimeter as used in Regan's method is taken with 4 sides for loading in the middle of the width for the slabs, with 3 sides for loading near to the edge of the width for slabs and with 2 sides for the smallest slab strips.

Table 5 shows the comparison between the test results P_u or resulting shear forces $V_{max,EC}$ and the calculated values according to the considered methods. These results show that Regan's method and EN 1992-1-1:2004 with b_{eff2}, estimate best the shear capacity of slabs under concentrated loads close to the support. The French National Annex overestimates the shear capacity as 2,27 times higher stresses are allowed for slabs (for k = 2).

Table 5 Statistical properties from comparison between experimental data and calculated values.

Test data	$V_{max,EC}/V_{EC2,beff1}$			$V_{max,EC}/V_{EC2,beff2}$			$V_{max,EC}/V_{FR}$			P_u/P_{Regan}		
	AVG	STD	COV	AVG	STD	COV	AVG	STD	COV	AVG	STD	COV
All	2,71	0,58	21%	1,97	0,32	16%	0,85	0,15	18%	1,01	0,14	14%
Slabs	2,86	0,49	17%	1,98	0,25	12%	0,89	0,12	14%	1,03	0,15	14%
Ribbed	2,98	0,49	16%	2,01	0,27	13%	0,87	0,13	15%	1,08	0,13	12%
Plain	2,60	0,41	16%	1,91	0,18	9%	0,93	0,09	9%	0,92	0,14	15%
Slab strips	2,46	0,64	26%	1,95	0,42	21%	0,78	0,17	21%	0,97	0,13	13%

The influence of the considered effective width is reflected by the results of $V_{max,EC}/V_{EC2,beff1}$ and $V_{max,EC}/V_{EC2,beff2}$; using b_{eff2} agrees better with the experimental results. The average value (AVG) becomes smaller and more uniform: compare the range of 2,4 - 3,0 for b_{eff1} to the range of 1,9 - 2,0 for b_{eff2}. The standard deviation becomes smaller, as well as the coefficient of variation. These statistical parameters confirm that the French load spreading method (Fig. 1 (right)) is to be preferred for determining the effective width.

Comparing the row with the results of the slabs and the row with the results of the slab strips, shows a larger average capacity for slabs, which can be attributed to transverse load distribution. Therefore, in combination with [8] and b_{eff2}, an enhancement factor of at least 1,25 can be applied for slabs benefitting from transverse load redistribution and loaded close to the support. Also, the minimum effective width can be taken as 4d [14].

Kani [15] showed that plain bars result in higher shear capacities than deformed bars. As the concrete compressive strength and amount of transverse reinforcement of S1 and S11 were different, a direct comparison for the test results could not be made. The experiments mainly showed a difference in the cracking pattern, and a possibility for anchorage failure in the slabs with plain reinforcement. The influence of bond on the shear capacity of slabs under concentrated loads is thus studied based on the comparison to the code methods, Table 5. These results show that the average ratio of tested to predicted value is smaller for the plain bars as compared to the ribbed bars. Regan's method [4] slightly overestimates the capacity of slabs with plain bars. The higher calculated predictions according to [4], however, are the result of the increased amounts of transverse and longitudinal reinforcement.

Comparisons to non-linear finite element models [16, 17] show that predicting the experimental values strongly depends on the choice of the input parameters. A posteriori modelling leads to good results, but it is shown [16] that choosing a certain set of input parameters from modelling one experiment does not necessarily lead to an equally close modelling of another experiment. The recommended effective width b_{eff2} also most closely corresponds to the effective width based on the stresses at the support [16].

5 Conclusions and Recommendations

Transverse load redistribution leads to higher shear capacities in slabs as compared to beams. This conclusion is reflected in tests from the literature, as well as in the results from the discussed test series.

The French load spreading method is to be preferred. This conclusion is supported by data from the literature, the series of specimens with varying width, the comparison to code methods and results from non-linear finite element analysis.

The test data indicate that slabs reinforced with plain bars have a slightly smaller shear capacity. This conclusion does not correspond to the observations for beams with plain bars failing in shear.

It is recommended to assess the one-way shear capacity of reinforced concrete slabs by using EN 1992-1-1:2004 taking into account direct load transfer between the load and the support. This code method is to be combined with the effective width b_{eff2} (resulting from the French load spreading method) with a minimum effective width of $4d$, and an enhancement factor on the capacity of at least 1,25 for loads close to the support ($a/d < 2,5$) .

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