

# SHEAR CAPACITY OF SLABS UNDER A COMBINATION OF LOADS

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## Abstract

Existing solid slab bridges under a combination of wheel loads and distributed traffic loads sometimes do not fulfil the code requirements for shear. However, reinforced concrete slabs loaded close to the support are subjected to shear stresses which might result in a failure mode of combined punching and shear. This behaviour is studied in a first series of experiments on slabs under a concentrated load close to the support, and these experiments resulted in a set of recommendations. To verify if these recommendations can be used when assessing solid slab bridges under distributed and concentrated loads, slabs under a combination of a line load, representing the dead weight, and a concentrated load, representing a wheel load, are tested up to failure. The experimental results are used to assess the ultimate shear which can be carried at the support and the influence of the varied parameters is discussed. The results demonstrate how different types of loading such as dead loads and live loads can be superposed and how a stress check at the support can be carried out.

**Keywords:** Bridge Engineering, Design, Effective width, Experiments, Punching, Shear, Slabs

## 1 Introduction

The current first level assessment practice in the Netherlands for shear is based on comparing the shear stress at the support due to dead load, superimposed loads and live loads to the design shear capacity. If this first level approach indicates that the capacity is sufficient, no further analysis is carried out. Otherwise, the complexity of the approach can be increased to achieve more precise results. The initial, first level approach is developed for the shear assessment of a large number of slab bridges. This spreadsheet-based method as developed by the Dutch Ministry of Infrastructure and the Environment originally used the shear capacity from the former Dutch code NEN 6720:1995.

The shear capacity according to the recently implemented EN 1992-1-1:2005 is smaller for a typical cross-section in a slab bridge than when using NEN 6720:1995. On the other hand, due to the increased traffic loads and volumes, the prescribed live load models in the current codes (EN 1991-2:2003) result in higher shear stresses at the support. The combination of higher prescribed loads and smaller capacities has raised concerns with regard to the shear capacity of reinforced concrete solid slab bridges, as the majority of these bridges are designed and constructed before 1976. In total, 600 slab bridges need to be assessed for shear: in a first round, the first level method is applied to sieve the database; then, the bridges which need a higher level approach for assessment are studied in more detail.

The live load model from EN 1991-2:2003 that is used for assessment is Load Model 1. This load model consists of wheel loads and a design lane load. The design truck, consisting of two axles at 1,2m spacing, has a tyre contact area of 400mm × 400mm and an axle load of  $\alpha_{Q1} \times 300\text{kN}$  in the first lane,  $\alpha_{Q2} \times 200\text{kN}$  in the second lane and  $\alpha_{Q3} \times 100\text{kN}$  in the third lane, with all  $\alpha_{Qi} = 1$  according to the Dutch National Annex. The largest shear stress at the support is found when the first design truck is placed close to the support.

When placing concentrated loads (such as the wheel loads) on a slab, an enhancement of the shear capacity as a result from transverse load redistribution might occur. The beam shear provisions and design methods do not take into account the transverse load redistribution, while the punching shear provisions and design methods do not take direct load transfer into account. To investigate the

enhancement from transverse load redistribution on the beam shear capacity and the behaviour of slab bridges under concentrated loads close to the support, research was carried out.

## 2 Previous research

### 2.1 Slabs under concentrated loads in the literature

The provisions for shear from NEN 6720 and EN 1992-1-1:2005 are semi-empirical formulas, as a function of the parameters which experimentally are found to be governing for shear. Most of the considered experiments are four-point bending tests on small, heavily reinforced, concrete beams. Recent research on slabs in shear has mostly focused on slabs under distributed loads. It is experimentally proven that a slab under a line load perpendicular to the span direction behaves as a wide beam in shear (Sherwood et al., 2006; Lubell et al. 2009).

For slabs under concentrated loads close to the support, not many results can be found in the literature. The most comprehensive series of experiments is carried out by Regan (1982). He used the results of experiments on 7 small-scale slabs ( $d_l = 84\text{mm}$  for the effective depth to the longitudinal reinforcement) to enhance the punching provisions for concentrated loads close to the support. For direct load transfer near the support, an enhancement factor on the part of the punching perimeter at the support is applied. To take into account the moment distribution at the continuous support, an enhancement factor is applied to the punching capacity. Regan's method combines elements of one-way shear (direct load transfer as used in beam shear close to the support) and two-way shear (punching perimeter). The disadvantage of Regan's method is that it is aimed at quantifying the maximum force on the concentrated load. For slab bridges under a combination of distributed loads and concentrated loads, this method cannot be easily implemented.

To overview the experimental work that has been done on slabs and wide beams in shear, a database is compiled (Lantsoght, 2012a). In this database, all relevant results are gathered: experiments on slabs or wide beams under distributed loads and concentrated loads, experiments on simply supported, continuously supported or cantilevering specimens in the laboratory as well as experiments on decommissioned bridges, punching failures as well as (wide) beam shear failures. All information with regard to the load and support conditions as well as the failure mode observed from pictures or sketches in the original test reports are included in the database.

### 2.2 First series of experiments from Delft University of Technology

A first series of experiments at Delft University of Technology is carried out to study the enhancement due to transverse load redistribution for slabs under a concentrated load close to the support and to determine the effective width in shear (Lantsoght et al., 2012a; 2013). In total, 18 continuous slabs and 12 continuous slab strips were tested under a concentrated load near the support. Overall, 133 experiments were carried out in the first series. The experiments carried out on uncracked specimens are reported (Lantsoght, 2012b) separately from the experiments carried out in the vicinity of a local failure (Lantsoght, 2012c), which reduced the capacity to an average of 81% of the shear capacity of an undamaged specimen. It was initially not expected that a damaged and locally failed specimen would be able to carry large loads when tested in the vicinity of a local failure. This surprising observation indicates the large capacity for load redistribution in slabs.

The first series of experiments was designed such that specimens are cast in pairs of two slabs, one on which loading is carried out in the middle of the width and then, on a damaged specimen, near the edge. For the second slab the loading sequence is altered such that the experiments near the edge are executed first, and then, on a damaged specimen, the experiments in the middle of the width. The parameters that are varied in the first series of experiments are:

- the size of the loading plate to study the influence of the size of the tyre contact area,
- the loading sequence as discussed previously,
- location of the load: loading in the middle of the width or near the edge as is the case for the design truck in the first lane,
- the amount of transverse flexural reinforcement, to study the influence of the properties for two-way shear,

- loading near the simple or continuous support to study the influence of the moment distribution at the continuous support,
- the distance between the load and the support to study direct load transfer,
- the concrete compressive strength which is traditionally considered (one of) the most important parameter(s) determining the shear capacity,
- the overall width to study the effective width,
- the difference between deformed and plains bars as used in existing bridges built before 1962, and
- the difference between line supports and elastomeric bearings.

The results from the first series of experiments led to the conclusion that reinforced concrete slabs under a concentrated load behave in an essentially three-dimensional way, which is distinctly different from the two-dimensional shear carrying behaviour in beams (Lantsoght, 2012b). The test results have indicated that the important parameter for the shear capacity of slabs under concentrated loads close to the support are: the size of the loading plate, the distance between the load and the support and the overall width of the member. This observation indicates that the shear capacity of slabs under concentrated loads close to the support mainly depends on the geometrical properties. The influence of the concrete compressive strength is found to be insignificant for the studied mixtures.

### 2.3 Recommendations

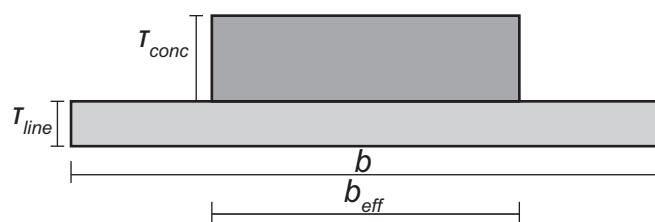
The results from the first series of experiments resulted in a set of recommendations that are used to improve the first level assessment practice. The recommendations are the following (Lantsoght et al, 2012b):

- Use the effective width resulting from the French load spreading method. This method assumes load spreading under  $45^\circ$  from the far side of the concentrated load to the face of the support.
- Use a minimum effective width of  $4d_l$ , provided that this value is a lower bound for  $1,3(1,5b_{load} + d_l + b_r)$  with  $b_{load}$  the width of the tyre contact area in the span-direction and  $b_r$  the distance between the edge of the slab and the centre of the tyre contact area.
- For concentrated loads close to the support on slabs, the reduction factor from EN 1992-1-1:2005  $\beta = a_v/2d_l$  for  $0,5d_l \leq a_v \leq 2d_l$  can be replaced by  $\beta_{new} = a_v/2,5d_l$  for  $0,5d_l \leq a_v \leq 2,5d_l$  with  $a_v$  the clear shear span, i.e. the face-to-face distance between the load and the support.
- The minimum shear capacity is expressed as a function of the yield strength of the steel  $f_{yk}$ , such that the higher shear stress up to which a flexural failure can be expected for a slab reinforced with low strength steel can be taken into account.

## 3 Experiments

### 3.1 Goal: Study the hypothesis of superposition

The first series of experiments are the basis for the recommendations from §2.3. However, in reality the loads on a slab bridge consist of distributed loads and concentrated loads. It needs to be verified now if the larger capacity for a concentrated load on a slab can be counted for when a combination of loads acts on a slab. It also needs to be verified if the contribution of the concentrated load can be distributed over the chosen effective width when the slab is loaded under a combination of loads. In short: the hypothesis of superposition for concentrated loads according to the recommendations with distributed loads needs to be verified for the resulting shear stress at the support.



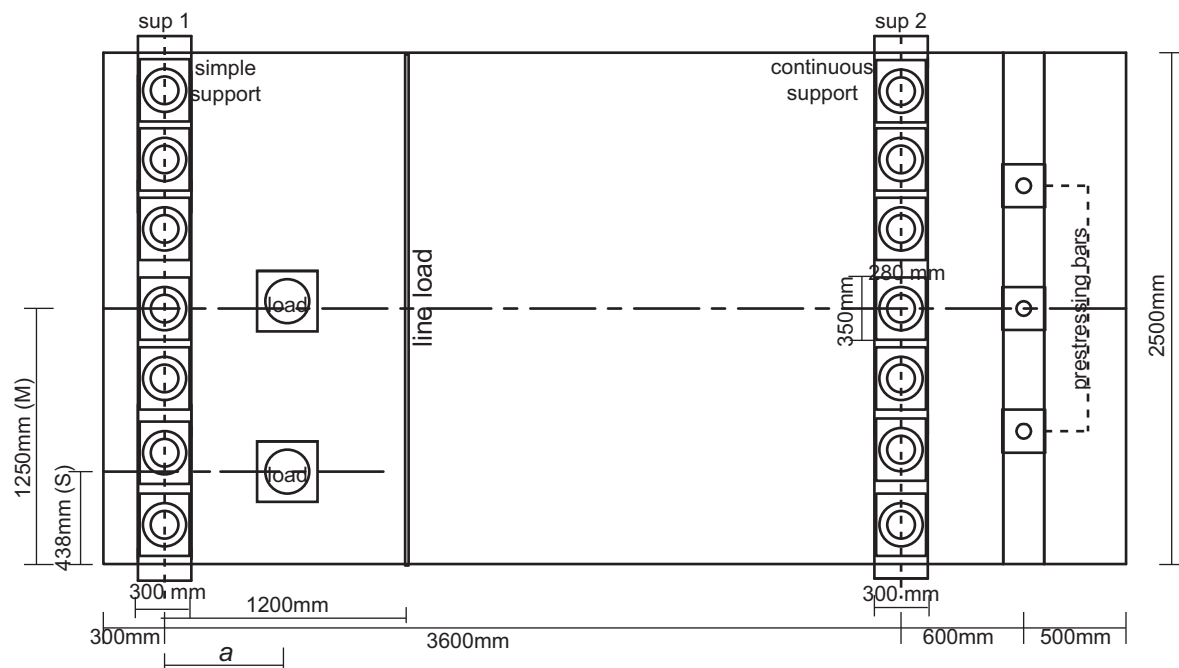
**Fig. 1** Principle of the hypothesis of superposition applied to a combination of a concentrated load over the associated effective width and a distributed load over the full slab width.

The concept of the hypothesis is sketched in Fig. 1. If the hypothesis of superposition is valid, then the sum of the shear stress due to the concentrated load over the effective width  $\tau_{conc}$  and the shear stress due to the distributed load at failure over the full width  $\tau_{line}$  should be larger than or equal to the ultimate shear stress in an experiment with a concentrated load only,  $\tau_{tot,cl}$ . For the assessment practice for existing bridges, this principle can then be applied to the distributed and concentrated loads.

In the literature and resulting slab shear database (Lantsoght, 2012a), no report is made of experiments on slabs under a combination of concentrated and distributed loads, except for experiments in which a small line load representing an edge load is applied at the tip of a cantilevering deck (Reißen and Hegger, 2012; Rombach and Latte, 2009). Therefore, it is decided to start a second series of experiments on slabs under a combination of loads.

### 3.2 Test setup

The experiments on slabs in shear under a combination of loads were designed such that the shear stress at the support due to the line load corresponds to 50% of the shear stress at failure observed in previously tested slab strips of 0,5 m wide. The failure shear stress in the specimens with a small width is considered to be representative for the failure shear stress in a slab under a line load, as Sherwood et al. (2006) showed that the behaviour of a slab under a line load in shear is essentially the same as the behaviour of a very wide beam. As a result, a line load of 240 kN/m is applied at 1,2 m from the centre of the support at which the experiment is carried out (Fig. 2). The resulting ratio of the contribution of the concentrated load and the distributed load to the shear stress at the support more closely resembles the ratio of concentrated loads to distributed loads for the case of a slab bridge under composite dead load and live loads.



**Fig. 2** Top view of the test setup for the experiments on slabs under a concentrated load and a line load.

The concentrated load, applied in a displacement-controlled way by a hydraulic jack, can be moved along the width and span of the slab. The line load was applied through an HEM 1000 beam loaded by a force-controlled hydraulic jack. In every experiment, the line load was applied as preloading, after which the concentrated load was increased until failure of the slab. The experiments are carried out both close to support 1 (SS, sup 1 in Fig. 2) and support 2 (CS, sup 2 in Fig. 2). The supports consist of a steel beam (HEM 300) of 300mm wide, on which 7 bearings of 350 mm × 280 mm × 45 mm equipped with load cells and hinges were placed. The bearings were either steel (S19 – S22, S25, S26) or elastomeric (S23, S24) bearings. The elastomeric bearings contained 3 layers of 8 mm natural

rubber, 4 layers of 4 mm steel S235 and 2 layers of 2,5 mm chloroprene, resulting in a compression stiffness of 2361 kN/mm. On top of the steel bearings, there was a steel strip of 100 mm × 15 mm × 2500 mm and 7 strips of felt type N100 of 100 mm × 5 mm × 280 mm (for the properties of the felt, see Prochazkova and Lantsoght, 2011).

Support 1 represents a simple support. Vertical prestressing bars coupled the cantilevering end of the slab past support 2 to the laboratory floor (Fig. 2). The force in the prestressing bars creates a moment over support 2 and thus simulates a continuous support (CS). The prestressing was applied at the beginning of every experiment to offset the self-weight. As a result of the deformation of the felt or the elastomeric bearings and the elongation of the steel prestressing bars, some rotation occurred over support 2. Load cells measured the magnitude of the force in the prestressing bars such that the moment over support 2 is known at all time during the experiment. Lasers on auxiliary frames over the supports and close to the loads were used to measure the displacements. A complete description of the experiments and instrumentation can be found in the full test report (Lantsoght, 2012c).

### 3.3 Specimens

An overview of the properties of the eight tested slabs (5 m × 2,5 m × 0,3 m) is given in Table 1. All slabs were C28/35 concrete with glacial river aggregates (maximum aggregate size = 16mm) and were reinforced with bars S500 ( $f_y = 541$  MPa;  $f_u = 658$  MPa) (Prochazkova and Lantsoght, 2011). The reinforcement layout was identical to the layout in the first series of experiments for comparison. The concrete cover was 25 mm, resulting in an effective depth to the longitudinal reinforcement  $d_l$  of 265 mm. In Table 1, the following symbols are used:

$f_c'$	the average cube compressive strength measured at the age of the first test on the slab specimen
$f_{ct}$	the average tensile splitting strength measured at the age of the first test on the slab specimen
$\rho_l$	the percentage of longitudinal reinforcement of the specimen
$\rho_t$	the percentage of transverse reinforcement of the specimen
$a$	the centre-to-centre distance between the load and the support
$d_l$	the effective depth to the longitudinal reinforcement
$a_v$	the face-to-face distance between the load and the support
$z_{load}$	the size of the side of the square loading plate; equals $b_{load} = l_{load}$
M/S	loading with the concentrated load in the middle (M) or near the edge (S) of the width (Fig. 2)
age	the age of the concrete slab specimen at testing.

**Table 1** Properties of slabs S19 – S26.

Slab nr.	$f_c'$ (MPa)	$f_{ct}$ (MPa)	$\rho_l$ (%)	$\rho_t$ (%)	$a/d_l$	$a_v/d_l$	$z_{load}$ (mm)	M/S	age (days)
S19	56,92	4,67	0,996	0,258	2,26	1,17	300	M	89
S20	60,51	4,67	0,996	0,258	2,26	1,17/1,36	200/300	M	176
S21	56,76	4,48	0,996	0,258	2,26	1,51	300	M	187
S22	57,97	4,48	0,996	0,258	2,26	1,51	300	S	188
S23	58,87	4,65	0,996	0,258	2,26	1,51	300	M	197
S24	58,87	4,65	0,996	0,258	2,26	1,51	300	S	183
S25	58,57	4,47	0,996	0,258	2,26/1,51	1,51/0,76	300	M	170
S26	58,57	4,47	0,996	0,258	1,51	0,76	300	M&S	174

## 4 Results and Discussion

### 4.1 Test results

The results of the experiments on specimens that are not influenced by the failure due to a previous experiment are given in Table 2, in which the following symbols are used:

$b_r$	distance between the edge and the centre of the concentrate load
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SS/CS	loading near the simple or continuous support. In the cases of the additional experiments in which the prestressing was removed, and the slab was rotated by 180°, the support side is denoted as SS'
$P_u$	the force on the concentrated load at failure
$P_{line}$	the force on the line load, this force is then distributed over 2,5m.
Mode	the observed failure mode: failure as a wide beam in shear with inclined cracks on the bottom of the specimen (WB); failure as a beam in shear with a noticeable shear crack at the side (B); beam shear failure away from the support, typically between the concentrated load and the line load (B') or development of a partial punching surface on the bottom face (P)
$F_{pres}$	the sum of the forces on the three prestressing bars
$V_{max}$	the resulting maximum shear force at the support, taking into account the concentrated load, line load, self-weight of the slab, self-weight of the line load (HEM 1000 profile) and the force due to the prestressing bars.

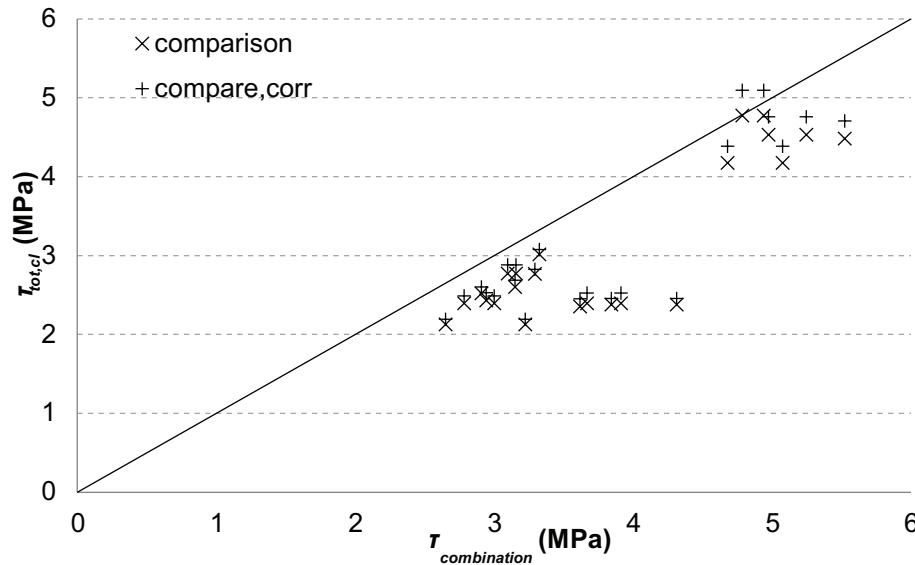
**Table 2** Overview of experimental results on undamaged specimens

Test	$a/d$	$b_r$ (mm)	SS/CS	$P_u$ (kN)	$P_{line}$ (kN)	Mode	$F_{pres}$ (kN)	$V_{max}$ (kN)
S19T2	2,26	1250	SS	1484	0	WB	112	1249
S19T1	2,26	1250	CS	1568	0	WB	217	1379
S20T1	2,26	1250	SS	1542	603	B	870	1579
S20T2b	2,26	1250	CS	1552	601	WB	678	1657
S20T3	2,26	438	CS	1337	601	WB + B	643	1487
S20T4	2,26	438	CS	1449	601	WB + B	637	1569
S21T1	2,26	1250	CS	1165	602	WB + B + B'	343	1472
S21T2	2,26	1250	SS	1386	603	WB + B'	297	1544
S21T5	3,28	438	SS'	853	0	WB + B + B'	0	678
S22T1	2,26	438	CS	984	602	WB + B	335	1320
S22T2	2,26	438	CS	961	602	WB + B	323	1298
S22T3	2,26	438	SS	978	603	WB + B	195	1221
S22T4	2,26	438	SS	895	604	WB + B	252	1143
S23T1	2,26	1250	CS	1386	601	WB + B + B'	332	1653
S23T2	2,26	1250	SS	1132	602	WB + B	230	1343
S24T1	2,26	438	CS	1358	601	WB + B'	327	1629
S24T2	2,26	438	CS	1182	601	WB + B	295	1477
S24T3	2,26	438	SS	995	602	WB + B'	190	1235
S24T4	2,26	438	SS	784	602	WB + B	262	1048
S25T1	2,26	1250	SS	1461	0	WB + P	203	1214
S25T2	1,51	1250	CS	1620	601	WB + B	372	1945
S25T4	3,28	438	SS'	854	0	WB + B	0	678
S25T5	4,26	438	SS'	968	0	WB + B	0	695
S26T1	1,51	438	SS	1448	602	WB + B'	187	1686
S26T2	1,51	438	SS	1324	602	B	238	1568
S26T3	1,51	1250	CS	1555	602	WB + B	418	1896

#### 4.2 Hypothesis of superposition

To verify the hypothesis of superposition, the failure shear stress at the support from the seconds series of tests is compared to the failure shear stress in an experiment from the first series with the concentrated load in the same position. If the principle of superposition holds true, then the shear stress of the experiment with a concentrated load only,  $\tau_{tot,cl}$ , calculated over  $b_{eff}$ , should be not greater than the sum of the shear stress due to the loads acting over the full width  $b$  (line load, dead load and vertical prestressing load),  $\tau_{line}$ , with the shear stress due to the concentrated load acting over  $b_{eff}$ ,  $\tau_{conc}$ .

In Fig. 3, the results of the experiments with a combination of loads are compared to the results of a similar experiment with a concentrated load only. There is a difference in the compressive strengths of the concrete used in the experiments with multiple loads and the experiments with a concentrated load only. Although all specimens were concrete C28/35, the age of testing was not the same, resulting in higher measured compressive strengths in the second series of experiments. Therefore, a correction has been made by multiplying  $\tau_{tot,cl}$  with the cube root (as used in the expression for the shear capacity from EN 1992-1-1:2005) of the ratio between the compressive strength of the specimen loaded with a concentrated load only  $f_{c',conc}$  and the specimen loaded with a concentrated load and a line load  $f_{c',combi}$ :  $(f_{c',combi}/f_{c',conc})^{1/3}$ , leading to the results denoted “compare, corr” in Fig. 3.



**Fig. 3** Results for the verification of the hypothesis of superposition, with  $\tau_{conc}$  = the failure stress in an experiment with a concentrated load only and  $\tau_{combination}$  = the failure stress in an experiment with multiple loads.

The results in Fig. 3 confirm the hypothesis of superposition of a reduced concentrated load distributed over an effective width with a line load. Typically, higher shear stresses can be attained when combining different loads.

When considering 36 cubes tested in compression at an age of 28 days for C28/35 concrete, a standard deviation of 3,68 MPa and a coefficient of variation of 8,5% was found. The scatter on the experimental results, with 2 cases of slabs under a combination of loads resulting in a lower shear capacity than for a slab under a concentrated load only, corrected for the difference in compressive strength due to the different age at testing, lies within the bandwidth resulting from the scatter on the material properties.

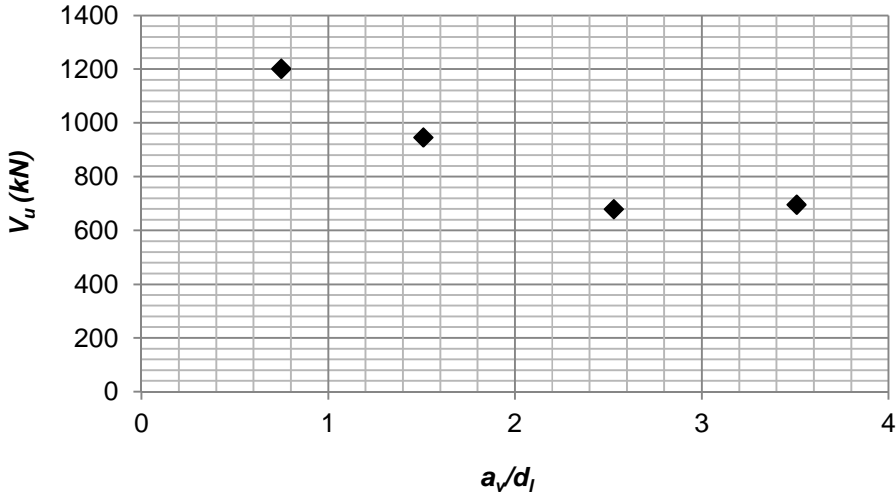
These experiments show that the wheel loads (for example, from Load Model 1) can be distributed per axle over the effective width of the axle and combined with the contribution of the composite dead load and lane load over the full width of the considered bridge.

#### 4.3 Distance between load and support

The distance between the centre of the concentrated load and the centre of the support is taken as 600 mm ( $a/d_l = 2,26$ ) and 400 mm ( $a/d_l = 1,51$ ) (Table 2). The shear force at the support at failure increases by 35% when the concentrated load is placed at 400 mm from the support as compared to when the concentrated load is at 600 mm from the support. The shear stress at the support, with the concentrated load distributed over the effective width  $b_{eff}$  increases by 67% when the concentrated load is placed at 400 mm from the support instead of at 600 mm. The increase in the shear stress is larger as the effective width influences the results, and the effective width depends on the distance between the load and the support as well (Lantsoght, 2012d).

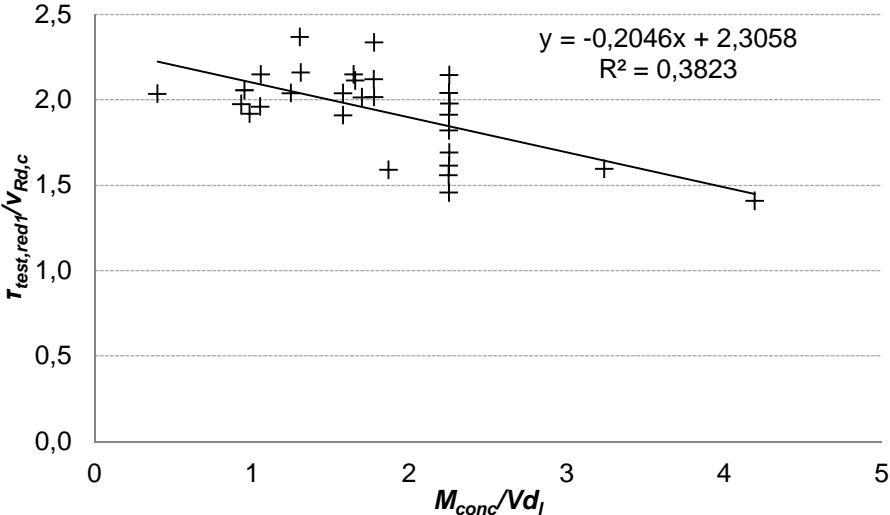
As can be seen in Table 2, S21T5, S25T4 and S25T5 are carried out at a larger  $a/d_l$  distance for the concentrated load. The line load is not applied in these experiments. The results of the shear force at the support at failure are shown as a function of  $a_v/d_l$  with  $a_v$  the face-to-face distance between the

load and the support in Fig. 4. The results from S4T1, S4T2, S6T4 and S6T5 from the first series of experiments are used in Fig. 4. The first 3 datapoints ( $a_v/d_l$  between 0,75 and 2,53) show a linear decrease in the shear capacity as a function of  $a_v/d_l$ :  $V_u = -314a_v/d_l + 1434$  ( $R^2 = 0,9982$ ). In beam shear experiments, a decrease in capacity with an increase in distance between the load and the support is observed as well (Clark, 1951; Richart, 1927; Talbot, 1909).



**Fig. 4** Results of the shear capacity at the support as a function of  $a_v/d_l$  of the concentrated load

Another reason to carry out additional experiments at a larger distance of the concentrated load to the support, is to study the failure mechanism. When the load is placed farther away from the support, it is expected that at some point the failure mode will transition from beam shear to punching shear. The results in Table 2 however show that no punching failure is observed as the load is placed farther from the support. There are two explanations for this observation: 1) these experiments were carried out near the edge, and 2) these experiments were executed on slabs that were damaged by earlier experiments. The capacity is lower, on average 81% of the capacity of an undamaged specimen, and the influence of existing cracks can alter the cracking pattern and failure mode.



**Fig. 5** Comparison between failure shear stress at the support  $\tau_{test,red1}$  and shear capacity according to EN 1992-1-1:2005  $v_{Rd,c}$  as a function of  $M_{conc}/Vd_l$ , expressing the increasing distance between the concentrated load and the support.

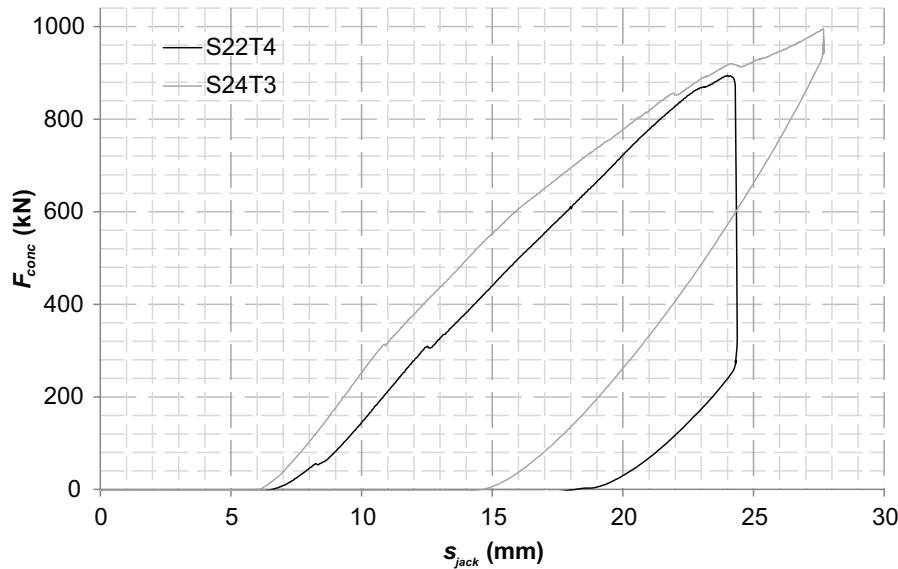
The shear stress  $\tau_{test,red1}$  at the support for comparison with the provisions from EN 1992-1-1:2005 is based on the concentrated load, line load, force due to prestressing, self-weight of the line load and self-weight of the slab, reduced with the factor  $\beta$  for the loads close to the support. When the



resulting shear stress at the support  $\tau_{test,red1}$  is compared to the shear capacity from EN 1992-1-1:2005,  $v_{Rd,c}$ , the results can be studied as a function of  $a/d_l$ ,  $a_v/d_l$ ,  $M_{conc}/Vd_l$  and  $M_{max}/Vd_l$  with  $M_{conc}$  the moment at the concentrated load and  $M_{max}$  the maximum moment either at the location of the concentrated load or at the location of the line load. All comparisons indicate that the ratio of  $\tau_{test,red1}/v_{Rd,c}$  becomes smaller as the concentrated load is placed farther away from the support. The underprediction of the capacity by EN 1992-1-1:2005 thus becomes smaller as the concentrated load is placed at a larger distance to the support. The best correlation between the decrease in  $\tau_{test,red1}/v_{Rd,c}$  is found when the distance is expressed by  $M_{conc}/Vd_l$ , Fig. 5. However, for the studied experiments, not much difference is found in the  $R^2$  value when  $\tau_{test,red1}/v_{Rd,c}$  is expressed as a function of  $a/d_l$ ,  $a_v/d_l$ ,  $M_{conc}/Vd_l$  or  $M_{max}/Vd_l$ .

It is assumed that the effective width  $b_{eff}$  associated with the concentrated load can be determined until the effective width  $b_{eff}$  equals the full width  $b$ . The ratio between the experimental shear stress and the shear capacity according to EN 1992-1-1:2005  $\tau_{test,red1}/v_{Rd,c}$  decreases as the distance between the load and the support increases. Therefore, the question arises if there should be a limit shear span at which the effective width cannot continue to increase. The additional experiments S21T5, S24T4, S24T5 are carried out near the edge of the specimen. It is found from the decreasing trend of the results that the effective width can be used until  $a_v = 5,4d_l$ . For this case, the associated effective width is  $b_{eff} = 2,32m$ , which almost equals the upper bound for the effective width, the full width  $b = 2,5m$ . Nonetheless the effective width for loads near the edge is limited to  $5,4d_l$  for the application to the assessment of slab bridges.

#### 4.4 Flexible and rigid supports



**Fig. 6** Force-displacement (concentrated load  $F_{conc}$  versus jack displacement  $s_{jack}$ ) diagrams showing the more ductile failure for the case of a slab on elastomeric bearings (S24T3) than for a slab on steel bearings (S22T4).

Slabs S24 and S25 were supported on flexible supports. It should be noted that the same centre-to-centre distance  $a$  between the load and the support is used for these experiments, but that the support width is different, leading to a different face-to-face distance  $a_v$  (Table 1). When comparing the failure shear stress at the support, similar shear capacities were found for the slabs on flexible supports as for the slabs on rigid supports. The observed difference in the experiments is that slabs on elastomeric supports show a more ductile failure mode than slabs on steel bearings. This observation is reflected in the load-displacement diagrams (Fig. 6). The results from the measurements of the reaction forces in the load cells at the support can be used to determine an effective width. These measurements show that the effective width is larger in the case of a support line of steel bearings than for elastomeric bearings. This observation corresponds to the expectations: a line of elastomeric bearings provides a less uniform surface than a line of steel bearings. Therefore, in a line of elastomeric bearings, more load is distributed towards the stiffer parts of the support line. The result is a higher peak value and thus a smaller effective width.

EN 1992-1-1:2005 allows for a reduction in the contribution of loads close to the support due to direct load transfer with the factor  $\beta = a_v/2d_l$  for  $0,5d_l \leq a_v \leq 2,5d_l$ . For flexible supports, the distance  $a_v$  is not the clear shear span, but needs to be taken to the centre of the support according to EN 1992-1-1:2005. However, the results of the experiments do not support this code requirement, and more uniform results are obtained when for the slabs on flexible supports, the distance  $a_v$  is taken to the face of the support. Therefore, it is advised to use the clear shear span  $a_v$  to determine the factor  $\beta$  for all support conditions.

#### 4.5 Comparison to proposed method

The recommendations from section 2.3 in combination with EN 1992-1-1:2005 are now compared to experimental results. The shear stress at the support  $\tau_{rest,red2}$  results from the concentrated load, the line load, the self-weight of the slab and self-weight of the line load and the force in the prestressing bars. The reduction factor  $\beta = a_v/2d_l$  is applied on the distributed loads near to the support and  $\beta = a_v/2,5d_l$  on the concentrated loads near to the support. The results are compared for the shear capacity  $v_{Rd,c}$  from EN 1992-1-1:2005 based on measured mean average properties and  $C_{Rd} = 0,15$ . This comparison is shown in Fig. 7. The average value of  $\tau_{rest,red2}/v_{Rd,c}$  equals 1,906 with a standard deviation of 0,26 and a coefficient of variation of 14%. These results indicate the large margin of safety obtained by using the recommendations.

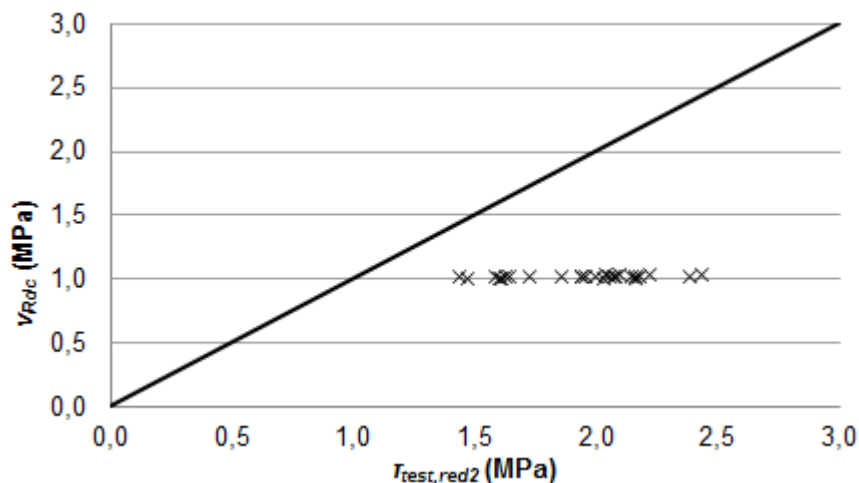
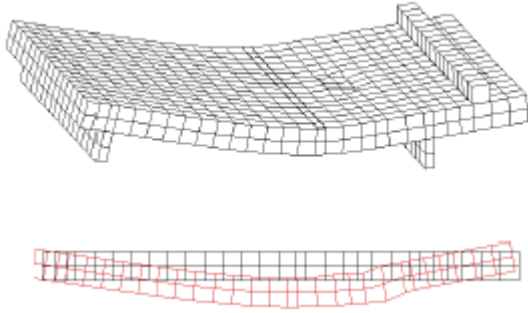


Fig. 7 Comparison between test results and shear capacity according to EN 1992-1-1:2005.

#### 4.6 Results from finite element analysis

A nonlinear finite element analysis of S21T1 and S21T2 in TNO Diana is available (Van Hemert, 2012). An analysis with two phases to represent the line load and then a phase with loading at the concentrated load until failure resulted in considerable modelling difficulties. Especially when tension softening was assumed, several convergence issues arose and resulted in a poor representation of the experiment. When tension stiffening was used, better results were obtained. However, similarity between the crack width in the experiment and the model was hard to obtain. The shape of S21T1 at failure, giving an overview of the elements and model used, is shown in Fig. 8.

Modelling the stiffness of the support is a challenge as well: using a fully fixed support resulted in large cracking over the continuous support during the application of the line load and significantly mitigated the results of the second loading step with the concentrated load. The shear retention factor was found to have a large impact on the results as well as on the failure load. A nonlinear finite elements model can be used to provide additional insight in the experimental results, but is not able yet to predict the outcome of the experiment beforehand, as too many input parameters need to be functioned to simulate the experiment.



**Fig. 8** Finite element model of S21T1 at failure: side view and 3D view showing supports, line load and concentrated load (Van Hemert, 2012).

## 5 Summary and Conclusions

To improve the shear assessment practice for slab bridges under composite dead load and live loads (from EN 1991-2:2003 Load Model 1), the following recommendations are formulated based on experiments on slabs under a concentrated load:

- Use the effective width resulting from the French load spreading method, assuming load spreading under  $45^\circ$  from the far side of the loading plate to the face of the support.
- Use a minimum effective width of  $4d_l$ .
- For concentrated loads close to the support on slabs, the reduction factor from EN 1992-1-1:2005  $\beta = a_v/2d_l$  for  $0,5d_l \leq a_v \leq 2d_l$  can be replaced by  $\beta_{new} = a_v/2,5d_l$  for  $0,5d_l \leq a_v \leq 2,5d_l$  with  $a_v$  the clear shear span, i.e. the face-to-face distance between the load and the support.
- The minimum shear capacity is expressed as a function of the steel yield stress  $f_{yk}$ , such that the higher shear stress up to which a flexural failure can be expected for a slab reinforced with low strength steel can be taken into account.

The studied slab bridges are loaded with a combination of concentrated and distributed loads. To verify if the hypothesis of superposition is valid when the concentrated load is distributed over its associated effective width a second series of experiments was carried out. In total, 26 experiments on 8 specimens are reported. The experiments show that the hypothesis of superposition leads to safe results.

Experiments are carried out on slabs supported on steel bearings and on elastomeric bearings. The slabs on flexible bearings show a more ductile failure behaviour. The results do not support the Eurocode requirement that for slabs on flexible bearings in  $\beta = a_v/2d_l$  the value for  $a_v$  should be based on the distance to the centre of the support. Instead, it is recommended for all cases to use the clear shear span for  $a_v$ .

Additional experiments with the concentrated load at a larger distance from the support have shown that a linear decrease in the shear capacity at failure is found as the distance between the load and the support is increased until  $a_v \approx 2,5d_l$ . The effective width of a concentrated load near the edge of the slab can be based on the French load spreading method up to  $a_v = 5,4d_l$ .

Comparing the experimental failure stress to the shear capacity at the support based on the recommendations gives safe results. A phased nonlinear finite element analysis provides additional insight in the experiments.

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