Applying Experimental Results to the Shear Assessment Method for Solid Slab Bridges

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Abstract: The combination of increased live loads and a more conservative shear capacity in the recently implemented Eurocodes, resulted in a large number of existing solid slab bridges in the Netherlands being shear-critical upon assessment. However, an enhancement of the shear capacity can occur in slabs under concentrated wheel loads due to transverse load redistribution. To quantify this effect, a comprehensive series of experiments on slabs and slabs strips under a concentrated load near to the support and under a combination of a concentrated and a line load was carried out. The experiments show the difference in behaviour for slabs, carrying the load in a two-dimensional way, as compared to beams in shear. The results from the laboratory research are used to develop recommendations, that are easily used in combination with the codes. These recommendations are implemented in a spreadsheet-based first-level assessment tool, the Quick Scan method. The assessment with this tool of selected cases of existing solid slab bridges shows that applying the experimental results into the assessment practice leads to an improved selection ability of the Quick Scan method.

Keywords: slabs, shear, bridge assessment, effective width, experiments.

1. Introduction

A large number of the existing bridges in the Netherlands are short-span solid slab bridges without shear reinforcement that were built during the expansion of the road network in the decades after the second World War. Within the current bridge stock, 60% of the structures have been built before 1975. Upon assessment according to the governing codes, these bridges are found not fulfil the criteria for shear. There are two reasons for this observation:

1. the prescribed live loads have increased, and
2. the shear provisions have become more conservative (shear was not checked according to codes used prior to 1974).

In the recently implemented Eurocode that determines the loads on bridges, NEN-EN 1991-2:2003 (1), larger concentrated loads at smaller axle distances and with a smaller number of axles (2 instead of 3) are used in Load Model 1 for the design truck loads. The shear provisions in the Eurocode for concrete design NEN-EN 1992-1-1:2005 (2) are more conservative than the provisions of the previously used national Dutch code NEN 6720:1995 (3), especially for deep cross-sections and for lightly reinforced cross-sections. However, when shear-critical slab bridges are inspected, no signs of distress are observed (4). Experiments on decommissioned slab bridges indicated that this bridge type possesses a high residual capacity that can be a multiple of the original design capacity (5-7).

The shear provisions from NEN-EN 1992-1-1:2005 (5-7) are based on a statistical analysis of a large number of experiments on (mostly) heavily reinforced, small concrete beams in four-point bending. Slabs subjected to a concentrated load close to the support will have a larger shear capacity as a result of the action of transverse load redistribution. When the shear capacity of a one-way slab subjected to a concentrated load is to be determined, not the full element width can be used as done for beams. A certain effective width in shear carries the load at the support. The effective width in shear is determined based on local practice and rules of thumb. In Dutch practice, horizontal load spreading is assumed under a 45° angle from the center of the load towards the support (Fig. 1a). In French practice (2), load spreading is assumed under a 45° angle from the far corners of the loading plate towards the support (Fig. 1b). The *fib* Model Code 2010 (8) advises a similar load spreading method to determine the effective width, but uses a 60^o angle for simply supported elements (Fig. 1c).

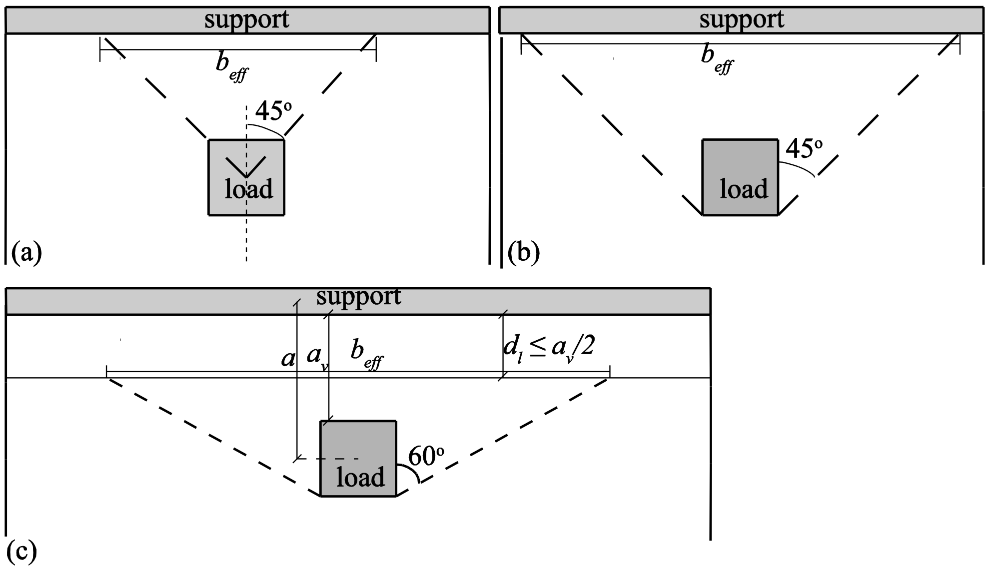


Figure 1. Effective width in shear for concentrated loads on slabs: (a) Dutch practice, (b) French practice, (c) *fib* Model Code 2010 (9).

2. Experiments

2.1 Test Setup

To quantify the beneficial effect of transverse load redistribution on the shear capacity of slabs, and to determine the effective width in shear, a comprehensive series of experiments was carried out. The tested specimens were half-scale models of reinforced concrete solid slab bridges without shear reinforcement.

In total, 26 slabs (S-series) of 5m × 2.5m × 0.3m and 12 slab strips (B-series) of 5m × 0.3m with a variable width were tested. The slabs were numbered chronologically as S1 up to S26, and the slab strips were numbered according to their width ("S" = 0.5m, "M" = 1m, "L" = 1.5m and "X" = 2m) and then chronologically as BS1 to BX3.

The first 18 slabs and the slab strips were subjected to a concentrated load close to the support. The last 8 slabs were subjected to the combination of a line load of 240kN/m at 1.2m from the support and a concentrated load close to the support. A top view of the setup as used for the slabs under a combination of loads is given in Figure 2. Slabs S1 to S14 and slab strips BS1 to BX3 were supported by line supports, slabs S15 to S18 by three elastomeric bearings per support line and S19 to S26 (Fig. 2) by seven bearings of 350mm × 280mm (steel or elastomeric) per support line.

Experiments were carried out close to the simple support (sup 1, SS in Fig. 2) and close to the continuous support (sup 2, CS in Fig. 2). At the continuous support, the rotation was partially restrained by prestressing bars that were anchored into the floor of the laboratory. Load cells at the prestressing bars were used to determine the moment over the continuous support at every point in time.

The concentrated load was placed at different distances to the support: at *a* = 600mm and at *a* = 400mm, with *a* the centre-to-centre distance between the load and the support. The concentrated load is also placed at different locations along the width: in the middle of the width ("M" in Fig. 2) and near to the edge ("E" in Fig. 2). The load-print area of the concentrated load was varied: 200mm × 200mm, as a half-scale representation of the 400mm × 400mm tyre contact area from NEN-EN 1991-2:2003 (9), and 300mm × 300mm.

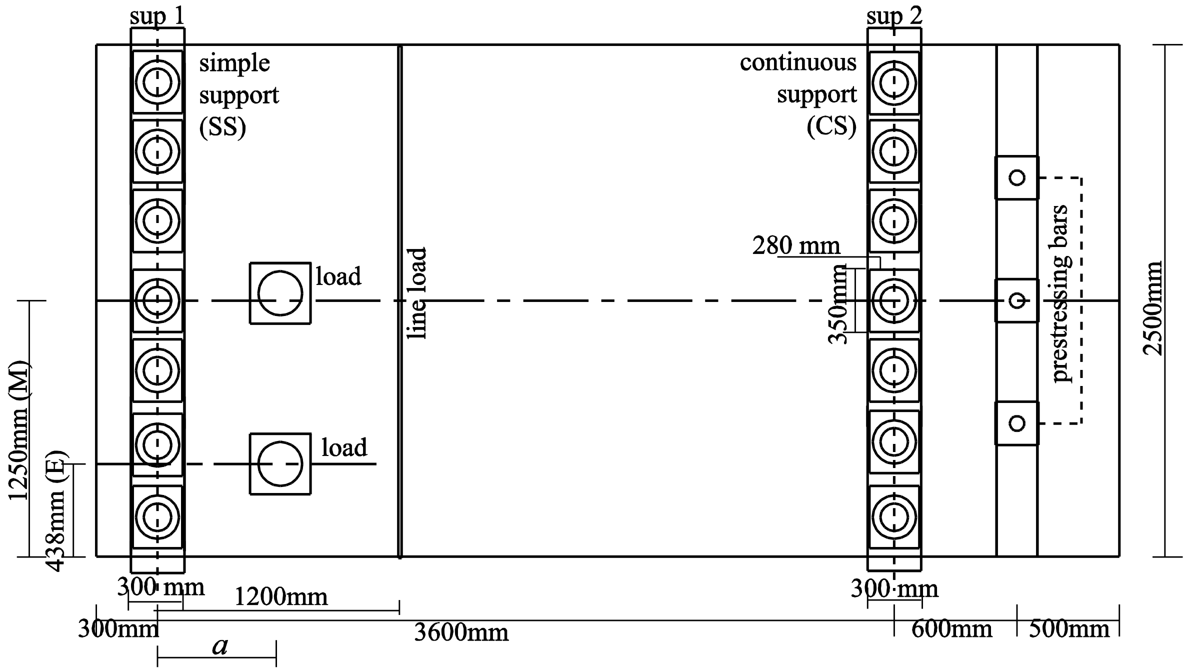


Figure 2. Top view of test setup as used for S19 – S26, slabs subjected to a combination of loads.

2.2 *Specimens*

The tested specimens were cast at Delft University of Technology, with reinforcement cages delivered from an external company and concrete delivered by mixer truck. During each cast, two slab specimens with identical properties were made. The slab strips were cast at the same time as the high strength concrete slabs. The following parameters were varied in the specimens:

- the amount of transverse flexural reinforcement to study the influence of the reinforcement layout on the transverse load redistribution,
- the concrete compressive strength to study the difference between normal strength and high strength concrete,
- the type of reinforcement to study the difference between deformed bars and plain bars, and
- the overall width of the specimen.

All specimens had a cross-sectional depth h of 300mm. The effective depth to the longitudinal reinforcement was d_l = 265mm for S1 to S14, S19 to S26 and all slab strips. For the slabs supported by elastomeric bearings, a virtual beam of reinforcement was used over the support to guarantee one-way load-carrying action. The increased cover to the larger reinforcement bars used in the virtual beam resulted in an effective depth d_l of 255mm for S15 to S18.

The properties of the tested specimens are given in Table 1. On each specimen, multiple experiments were carried out. For the slabs in which the load is placed close to the free edge ("E" in Fig. 2 and Table 1) 4 experiments were carried out per specimen and for the slabs with the load in the middle ("M" in Fig. 2 and Table 1) 2 experiments were carried out per specimen. The concrete cube compressive strength and tensile strength are given as measured at the age of carrying out the first experiment on the specimen. This age is given in the last column of Table 1.

Further details of the individual experiments and their failure loads and sectional forces at failure are described elsewhere (1).

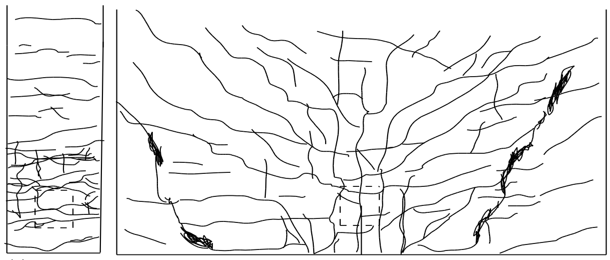
3. Comparison between beams and slabs

The main findings of the parameter analysis are given here, in order to highlight the differences in the behaviour between beams and slabs in shear and to explore the effects of transverse load redistribution.

Table 1. Specimen details.

Slab nr.	Width b (m)	Compressive Strength f_c' (MPa)	Tensile Strength f_{ct} (MPa)	Long. reinf. ρ_l (%)	Transv. reinf. ρ_t (%)	shear span to depth ratio *a/d*	location along width M/E	size of load z_{load} (mm)	age at testing (days)
S1	2.5	35.8	3.1	0.996	0.132	2.26	M	200	28
S2	2.5	34.5	2.9	0.996	0.132	2.26	M	300	56
S3	2.5	51.6	4.1	0.996	0.258	2.26	M	300	63
S4	2.5	51.7	4.2	0.996	0.182	2.26	E	300	76
S5	2.5	48.2	3.8	0.996	0.258	1.51	M	300	31
S6	2.5	50.6	3.9	0.996	0.258	1.51	E	300	41
S7	2.5	82.1	6.2	0.996	0.258	2.26	E	300	83
S8	2.5	77.0	6.0	0.996	0.258	2.26	M	300	48
S9	2.5	81.7	5.8	0.996	0.258	1.51	M	200	77
S10	2.5	82.4	5.8	0.996	0.258	1.51	E	200	90
S11	2.5	54.9	4.2	1.375	0.358	2.26	M	200	90
S12	2.5	54.8	4.2	1.375	0.358	2.26	E	200	97
S13	2.5	51.9	4.2	1.375	0.358	1.51	M	200	91
S14	2.5	51.3	4.2	1.375	0.358	1.51	E	200	110
S15	2.5	52.2	4.2	1.035	1.078	2.35	M	200	71
S16	2.5	53.5	4.4	1.035	1.078	2.35	E	200	85
S17	2.5	52.5	3.7	1.035	1.078	1.57	M	200	69
S18	2.5	52.1	4.5	1.035	1.078	1.57	E	200	118
S19	2.5	56.9	4.7	0.996	0.258	2.26	M	300	89
S20	2.5	60.5	4.7	0.996	0.258	2.26	M	var	176
S21	2.5	56.8	4.5	0.996	0.258	2.26	M	300	187
S22	2.5	58.0	4.5	0.996	0.258	2.26	E	300	188
S23	2.5	58.9	4.7	0.996	0.258	2.26	M	300	197
S24	2.5	58.9	4.7	0.996	0.258	2.26	E	300	183
S25	2.5	58.6	4.5	0.996	0.258	2.26 & 1.51	M	300	170
S26	2.5	58.6	4.5	0.996	0.258	1.51	M&E	300	174
BS1	0.5	81.5	6.1	0.996	0.258	2.26	M	300	55
BM1	1	81.5	6.1	0.996	0.258	2.26	M	300	62
BL1	1.5	81.5	6.1	0.996	0.258	2.26	M	300	189
BS2	0.5	88.6	5.9	0.996	0.258	1.51	M	200	188
BM2	1	88.6	5.9	0.996	0.258	1.51	M	200	188
BL2	1.5	94.8	5.9	0.996	0.258	1.51	M	200	180
BS3	0.5	91.0	6.2	0.996	0.258	2.26	M	300	182
BM3	1	91.0	6.2	0.996	0.258	2.26	M	300	182
BL3	1.5	81.4	6.2	0.996	0.258	2.26	M	300	171
BX1	2	81.4	6.0	0.996	0.258	2.26	M	300	47
BX2	2	70.4	5.8	0.996	0.258	1.51	M	200	39
BX3	2	78.8	6.0	0.996	0.258	2.26	M	200	40

The crack patterns of a slab and a beam under a concentrated load are compared in Figure 3. While the beam (Fig. 3a) only shows cracking in the transverse direction, the slab (Fig. 3b) shows transversal and longitudinal cracking, as well as inclined cracks on the bottom face. As can be seen from the crack patterns in Figure 3, the one-way load-carrying behaviour of a beam in shear is different from the two-directional load-carrying behaviour in a one-way slab. The additional dimension of the width in a slab enables transverse load redistribution, so that more concrete material is activated and larger shear capacities are obtained.



(a) (b)

Figure 3. Cracks at the bottom face of tested specimens showing the difference in cracking behaviour between beams and slabs: (a) cracks after failure of specimen of 0.5m wide; (b) cracks after failure of specimen of 2.5m wide. The dashed lines show the location of the loading plate, and thicker lines in (b) denote areas of punching damage.

The influence of transverse load redistribution can be seen from the influence of the parameters that are studied for the specimens with a variable width. The two-way shear-carrying behaviour for specimens with a large width is observed for the following parameters: the size of the loading plate, the moment distribution in the shear span and the distance between the load and the support.

The influence of the distance between the load and the support, expressed by the shear span to depth ratio becomes smaller as the specimen size increases. In all cases, the influence of the shear span to depth ratio remains an important factor determining the shear capacity. However, due to transverse load redistribution, the increase in capacity is smaller for slabs than beams when a concentrated load is placed closer to the support. This experimental observation can be explained by the formation of compressive struts that carry the load from its point of application towards the support. In beams, only one direct compressive strut will form between the load and the support. In a slab subjected to a concentrated load, a fan of struts can develop between the load and the support. The struts will carry the load at a certain angle in the horizontal plane. As a result, the load-carrying path of these struts will be longer, and the average shear span becomes larger. Note that in all cases the capacity of the slabs is larger than the capacity of the strips with a finer width when compared to the calculated capacity according to, for example, EN 1992-1-1:2005.

As the slab width increases, the influence of the size of the loading plate becomes larger. For the beam specimens with a small width, the influence of the size of the loading plate is very small. For the elements of 2.5m wide, a clear influence of the size of the loading plate is observed. In these wider elements, the larger loading plate forms a larger basis from which the compressive struts can fan out, thus resulting in a higher shear capacity.

For slabs, the influence of the moment distribution in the span is smaller than for beams. Using the measured reaction forces to determine the effective width over which the forces are distributed at the support also shows a smaller effective width at the continuous support. This result is confirmed by linear finite element models. The smaller influence of the moment distribution can thus be attributed to the influence of the transverse moment at the continuous support.

4. Recommendations

4.1. Effective width

The choice for the recommended load spreading method is based on three different methods:

- an analysis of the results of the specimens with a varying width, aiming at determining the threshold width at which not the full specimen width carries the shear load,
- a statistical analysis of the comparison between the experimental results and the shear capacities according to NEN-EN 1992-1-1:2005 (10-13) for the Dutch (Fig. 1a) and French (Fig. 1b) load spreading methods, and

- non-linear finite element calculations.

It was expected that increasing the specimen width from 0.5m to 2.5m would give an indication of the effective width in shear. For specimens with a small width, the full width carries the shear force. As the width increases, it is expected that for a certain width the specimen width will be larger than the width that can carry the load. This width is identified as the “threshold effective width”. For a larger specimen width than the threshold effective width, it is expected that the shear capacity becomes independent of the width. This threshold is indeed observed (2), and analysed for every set of parameters that were tested for the series of specimens with different widths. The threshold effective width from the experiments is compared to the effective widths as calculated based on the load spreading methods (Fig. 1), showing that the French load spreading method (Fig. 1b) gives the best estimate of the threshold effective width.

A statistical analysis of the ratio between the experimental shear capacity and the capacity calculated according to NEN-EN 1992-1-1:2005 (10) leads to average ratios closer to unity and smaller coefficients of variation when the French load spreading method is used.

The shear stress distribution from non-linear finite element models (2) also leads to good results when compared to the French load spreading method. However, the French load spreading method only takes into account the size of the loading plate and the distance between the load and the support. The experiments and finite element models have shown that other parameters, such as the moment distribution at the support, also influence the effective width.

The French load spreading method is chosen for the assessment for existing solid slab bridges subjected to the live loads from Load Model 1 from NEN-EN 1991-2:2003 (14, 15). Two wheel loads are used per axle, and therefore the effective width is taken for the entire axle. For the design truck in the first lane, an asymmetric effective width is used to the edge of the viaduct. The lower bound of the effective width is taken as $4d_l$ with d_l the effective depth to the longitudinal reinforcement.

4.2. Transverse load redistribution

To take direct load transfer into account for loads close to the support, NEN-EN 1992-1-1:2005 (1) prescribes the use of the factor $\beta = a_v/2d_l$ for $0.5d_l \leq a_v \leq 2d_l$ with a_v the clear shear span (face-to-face distance between the load and the support). The factor β is used to reduce the contribution of loads close to the support to the resulting shear stress at the support.

As a result of transverse load redistribution, slabs subjected to a concentrated load close to the support have a larger shear capacity than beams. Using conservative assumptions with regard to the interpretation of the code and assuming that the ratio of the test result to the predicted value follows a normal distribution, the characteristic value (5% lower bound) of the ratio of the test result to the predicted value was found to be 1.25. A 25% larger shear capacity can thus be attributed to slabs subjected to a concentrated load close to the support as compared to beams. To align this observation with the way direct load transfer is implemented into NEN-EN 1992-1-1:2005 (2), the factor β is replaced by $\beta_{new} = a_v/2.5d_l$ for the case of concentrated loads on slabs, with $0.5d_l \leq a_v \leq 2.5d_l$.

4.3. Combining concentrated and distributed loads

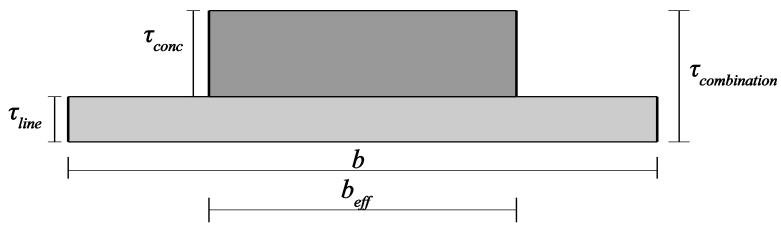


Figure 4. Principle of superposition of a concentrated load over its effective width to the distributed loads over the full width.

The experiments on S1 to S18 and the slab strips were carried out with a concentrated load only. Questions arose as to whether the resulting recommendations are still valid when a combination of loads is used. For assessment, the composite dead load (self-weight and wearing surface) and live loads from Load Model 1 (distributed lane load, heavier in the first lane and design truck loads) need to be considered. To implement the recommendations from the slabs subjected to a concentrated load, it needs to be verified if the hypothesis of superposition of loads is a valid and conservative assumption. If the hypothesis of superposition holds true, the contribution of the concentrated loads τ_{conc} distributed over their respective effective widths to the total shear stress can be superposed to the contribution of the distributed loads τ_{line} over the full viaduct width (Fig. 4). The shear stresses at failure of the slabs subjected to a concentrated load only are compared to the shear stresses at failure of the slabs subjected to a line load and a concentrated load, $\tau_{combination}$. The latter should always be at least equal to the former. The experimental results clearly show that the hypothesis of superposition is a safe assumption (2).

5. Quick Scan method

5.1. Partial factors for assessment

The current Eurocodes provide only load factors for design in NEN-EN 1990:2002 (16). The Eurocodes suitable for assessment are still in development. To facilitate assessment according to the safety philosophy and basic assumptions of the Eurocodes, a set of national codes is developed in the Netherlands (NEN 8700:2011 (17) for the basic rules, NEN 8701:2011 (18) for the actions, NEN 8702 (expected) for concrete structures, etc.). In NEN 8700:2011 (19), three safety levels are defined: “new”, identical to the design load level from NEN-EN 1990:2002 (18), “repair” and “unfit for use”.

The existing solid slab bridges are rated at the “repair” level, as decided by the Dutch Ministry of Infrastructure and the Environment. Structures are also categorized according to their Consequences Class (NEN-EN 1990:2002 (17)), numbered from “1” (small consequences) to “3” (high consequences for the loss of human life or very great economic, social or environmental consequences). The bridges owned by the Dutch Ministry of Infrastructure and the Environment are categorized as structures of Consequences Class 3. For Consequences Class 3, and the safety level of “repair”, the required reliability index of the structure is β_{rel} = 3.6 (for structures built before 2012) (17). The load factors for the “repair” level are given in NEN 8700:2011 Table A.2.2(B) as γ_{DL} = 1.15 for the dead loads and γ_{LL} = 1.3 for live loads. The material factors are the same for all safety levels.

5.2. Geometric assumptions

Within the scope of the existing Dutch slab bridges, not all geometric and material properties are known. Therefore, general assumptions have been developed for the application into the Quick Scan sheet for rectangular bridge decks.

For the slab bridges (built before 1976), research was carried out to study the material properties. Due to continuous hydration of the concrete over time, drilled cores resulted in high concrete compressive strengths for this bridge type. A statistical analysis of a large number of core samples showed that the characteristic cube compressive strength of the concrete $f_{ck,cube}$ can safely be taken as 45MPa (20).

The wearing surface ranges from 20mm to 120mm in existing bridges. It is therefore a conservative assumption to take a wearing surface of 120mm for the permanent load into account for all viaducts that need to be assessed. Vertical load spreading under an angle of 45^o is assumed through the wearing surface for the concentrated wheel loads of 400mm × 400mm. As a result, a fictitious tyre contact area of 640mm × 640mm is assumed at the level of the concrete surface.

In Load Model 1 from NEN-EN 1991-2:2003 (21), a design truck is assumed in every lane. To determine the most unfavourable case that should be considered in the Quick Scan approach, the truck configuration that results in the highest shear stress at the edge needs to be sought. The peak shear stress at the edge was determined as the most severe case (1), as shear cracking can initiate at the edge after which the crack can open up over the full viaduct width. Following the recommendations based on the research, the most unfavourable position for the wheel loads is found by placing the first design truck so that the face-to-face distance between the support and the first fictitious tyre contact area equals 2.5d_l. This distance is governing as the combination of transverse load redistribution and direct load transfer can be taken into account with β_{new} for loads placed up to a_v = 2.5d_l. For the design truck in the second and third lane, the largest shear stress at the edge results when these trucks are placed so that the effective width associated with the first axle reaches up to the edge of the viaduct. This situation is sketched in Figure 5. In Figure 5, the following symbols are used:

$a_{vi,j}$ the face to face distance between the support and the tyre contact area for the i^{th} truck and j^{th} axle;

b_r the edge distance to the side of the first tyre contact area, minimum 60cm;

$a_{i,j}$ the centre-to-centre distance between the support and the tyre contact area for the i^{th} truck and j^{th} axle;

b_{load} the width of the tyre contact area;

l_{load} the length of the tyre contact area;

$w_{th,i}$ the width of the ith notional lane = 3m;

$b_{effi,j}$ the effective width resulting from the French load spreading method for the i^{th} truck and j^{th} axle;
i 1.. 3, corresponding to the design truck under consideration;
j 1.. 2, corresponding to the axle of the design truck under consideration.

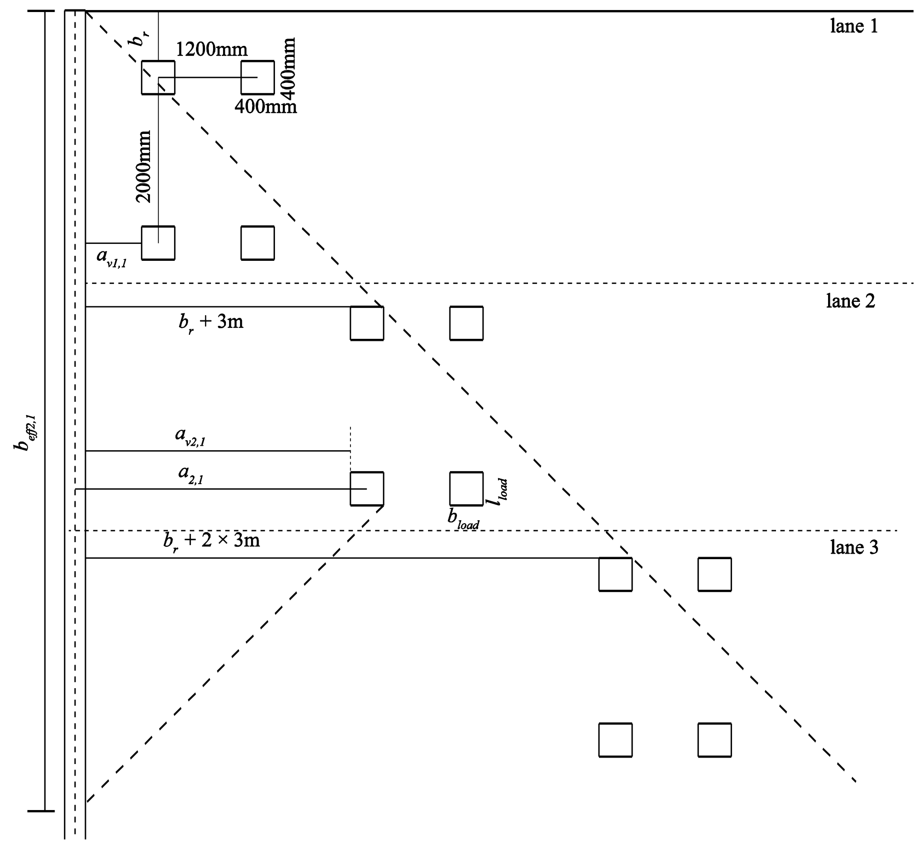


Figure 5. Most unfavourable position of the wheel loads for the shear stress at the edge of the support.

5.3. Benefit of Quick Scan

The Quick Scan method is applied as the first tool to check a large number of cross-sections for shear. The selection criterion of the Quick Scan method is the Unity Check value: the ratio of the shear stress due to the composite dead load and live load to the shear capacity. If the Unity Check of a considered cross-section is larger than 1, a more refined analysis of the bridge under study is necessary, for example by using a finite element model.

The Quick Scan method was originally developed by Dutch engineering firms in the mid-2000s for assessment according to the Dutch code NEN 6720:1995 (3), QS-VBC. With the results of the slab shear experiments, an improvement of the Quick Scan method could be made. The current Quick Scan, QS-EC2 is based on the provisions from the Eurocodes, and takes into account the recommendations that result from the experimental research.

A series of case studies on 9 existing continuous solid slab bridges and 14 North-American rigid frame bridges (22) was carried out in which the Unity Check was determined for at least three cross-sections (end support, mid support at end span and mid support at mid span). Comparing the resulting Unity Checks of QS-EC2 to the Unity Checks of QS-VBC shows the benefit of using the results from the experimental research into the assessment practice for slab bridges. This comparison shows that the shear stress as a result of the loading becomes on average 20% smaller for QS-EC2 because the beneficial effects of transverse load redistribution and direct load transfer are taken into account. The shear capacity, however, is smaller when using NEN-EN 1992-1-1:2005 (10) than for NEN 6720:1995 (2). The resulting Unity Check becomes on average 4% smaller with QS-EC2 than with QS-VBC. As QS-EC2 determines fewer cross-sections as shear-critical, less viaducts will require to be studied in further detail. The QS-EC2 has thus a better selection ability than the QS-VBC.

6. Conclusions

For the shear assessment of existing solid slab bridges, the beneficial effect of transverse load redistribution can be taken into account. To quantify this effect, and to determine the effective width in shear, a large testing program was carried out on slabs and slab strips. Comparing the results of the slabs and slab strips with respect to the varied parameters indicated that the shear-carrying behaviour in slabs is indeed enhanced by the dimension of the width and thus the transverse load redistribution capacity.

Recommendations for the shear assessment are formulated based on the experiments:

1. the effective width in shear can be based on the French load spreading method from the far side of the loading plate to the face of the support, with a minimum value of $4d_l$,
2. the contribution of concentrated loads on slabs to the shear stress at the support can be reduced by $\beta_{new} = a_v/2.5d_l$ for $0.5d_l \leq a_v \leq 2.5d_l$,
3. superposition is valid for the combination of the shear stress due to a concentrated load over its effective width and the shear stress due to a distributed load over the full slab width.

These recommendations are implemented in a first-order spreadsheet-based method, the Quick Scan, which has a refined ability to select cross-sections that need further study.

7. Acknowledgement

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