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Proposal for the extension of the Eurocode shear formula for one-way slabs under concentrated loads

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ABSTRACT

A large number of existing reinforced concrete solid slab bridges in the Netherlands are found to be insufficient for shear when assessed for the governing live load models. However, due to transverse load redistribution, the shear capacity of reinforced concrete slabs under concentrated loads is larger than the capacity of beams, on which the code provisions for shear are based. Therefore, an extension of the Eurocode shear provisions for the case of slabs under concentrated loads in shear may be warranted. To study the increase in capacity of slabs as compared to beams, a series of experiments on concrete slabs was carried out. These experimental results are combined with Monte Carlo simulations to quantify the increase in shear capacity in slabs as a result of transverse load redistribution. From the analysis of different subsets of experiments follows a proposal to extend the Eurocode shear provisions for the case of slabs under concentrated loads. Using this new expression and allowing larger shear stresses in slabs under concentrated loads results in less shear-critical cross-sections for existing slab bridges.

1. Introduction

A large number of the existing reinforced concrete bridges in the road network of the Netherlands consist of short span solid slab bridges, 60% of which are built before 1976. It is necessary to reassess [1] the shear capacity of these bridges, as the code-prescribed traffic loads increased significantly since the implementation of the Eurocodes, and the shear provisions have become more conservative. Therefore, the Dutch Ministry of Infrastructure and the Environment initiated a project to assess the shear capacity of existing bridges under the live loads as prescribed by the recently implemented Eurocodes. An initial assessment indicated that 600 solid reinforced concrete slab bridges can be classified as shear-critical. The initial assessment is based on the unity check: the ratio between the shear stress at the support due to dead load, superimposed loads and live loads as prescribed by Load Model 1 from NEN-EN 1991-2:2003 [2] and the shear capacity from NEN-EN 1992-1-1:2005 [3]. While no signs of distress are reported on the structures, some of the controlled cross-sections are reported to have a unity check value far above the limit value of 1 [4].

Improved methods to quantify the shear capacity of slab bridges are required, so that the service life of the existing structures can be prolonged. This understanding already resulted in the development of different sets of load factors for existing structures, which can be found in NEN 8700:2011 [5]. Two sets can be observed: the level "repair" and the level "replacement". For existing bridges (Consequences Class 3 from NEN-EN 1990:2002 [6]) built before 2012, the load factors at the repair level are based on a reliability index β of 3.6 [7].

The improvements in the shear assessment method that can lead to prolonging the service life of the structure, are applicable to concentrated loads on slabs. It is shown [8] that concentrated loads contribute for 30–60% to the overall shear stress at the support. Taking into account transverse load redistribution can have a significant influence on the resulting shear rating of a structure. The semi-empirical expression for the shear capacity from NEN-EN 1992-1-1:2005 is based on a statistical analysis [9]. Therefore, the extension of the code formula that takes into account the enhancement of the shear capacity in slabs under concentrated loads close to supports as a result of transverse redistribution, should be based upon a similar statistical analysis, and should satisfy the same requirements with regard to the failure probability.

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Nomenclature

a	shear span: the centre-to-centre distance between the load and the support
a_{Beta}	defines interval on which general beta distribution is defined
a_v	clear shear span: face-to-face distance between the load and the support
Age	age at which the specimen is tested for the first time
b	member width
b_{Beta}	defines interval on which general beta distribution is defined
b_{eff}	effective width in shear
$b_{eff,1}$	effective width as used in Dutch practice
$b_{eff,2}$	effective width as used in French practice
b_w	web width, or for slabs the effective width in shear, b_{eff2}, Fig. 1b
d_l	effective depth to the longitudinal reinforcement
$f_{c,cube}$	measured cube compressive strength of the concrete at the age of testing
$f_{ct,cube}$	measured cube splitting strength of the concrete at the age of testing
$f_{ck,calc}$	characteristic concrete cylinder compressive strength
$f_{c,meas,28}$	mean cylinder concrete compressive strength
g	limit state function
i	running index
k	size factor
$k_{Frechet}$	constant determining Frechet distribution
$l_{bearing,i}$	length of the i-th bearing along the support
l_{sup}	supported length
m_e	median value
n	number of experiments on the considered specimen
$n_{bearings}$	number of bearings on support line
q_{Beta}	determines shape of general beta distribution
r_{Beta}	determines shape of general beta distribution
$u_{Frechet}$	constant determining Frechet distribution
u_{Gumbel}	mode of distribution in Gumbel distribution
z_{load}	size of side of the square loaded area
A_s	amount of tension steel in the considered cross-section
$C_{Rd,c}$	0.18 as default value for NEN-EN 1992-1-1:2005 [3]
$C_{Rd,c,test}$	0.15 for the comparison with test data
E	concentrated load is placed near the edge
M	concentrated load is placed in the middle of the width
P	chance of function
P_f	probability of failure
R	resistance function
R_d	design resistance function
S	load function
Test/Prediction	ratio of experimental shear capacity to predicted shear capacity
$V_{Rd,c,prop}$	proposed formula for shear capacity of slabs under concentrated loads close to supports
α	covers the sensitivity factors according to a first order reliability method
α_{Gumbel}	measure of dispersion in Gumbel distribution
β	reliability index
β_{EC}	reduction factor for loads close to the support
γ_1	skewness of distribution
γ_2	kurtosis of distribution
γ_c	1.5 for concrete
ε	standard deviation of lognormal distribution
Φ	standard Gaussian function
λ	mean value of the natural logarithm in lognormal distribution
λ_r	reduction factor for reduced support length
μ	mean value
μ_L	average of load
μ_R	average of resistance
ρ_l	ratio of longitudinal steel
ρ_t	ratio of transverse flexural reinforcement
σ_s	standard deviation
σ_L	standard deviation of load
σ_R	standard deviation of resistance
ξ_{prop}	enhancement factor

2. Background to the shear problem in slabs

2.1. Transverse load redistribution and effective width

The shear capacity of slab bridges is calculated as the shear capacity of a beam with a large width. Theoretically, the effective slab width is determined so that the shear force resulting from integrating the total shear stress over the support width equals the shear force resulting from the maximum shear stress over the effective width [10]. For design purposes a method of horizontal load spreading is chosen, resulting in the effective width b_{eff} at the support. The method of horizontal load spreading depends on local practice. 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 [11] under 45° from the far corners of the load (Fig. 1b). It was shown that the effective width as used in French practice leads to the best shear predictions [12,13]. This conclusion is based on:

- experimental results from a series of elements with increasing widths, where the threshold width was sought for which an increase in width does not lead to a further increase in capacity [13],
- analysis of the stress distribution over the support in non-linear finite element models [14,15],
- statistical analysis of tested-to-predicted values based on the Eurocode, taking into account different load spreading methods. This approach showed that the average value of tested-to-predicted was closest to unity and had the lowest coefficient of variation when the French load spreading method was used.

For slab bridges under concentrated loads, transverse load redistribution is of particular interest. Transverse load redistribution, fanning out in the direction perpendicular to the span direction, can be taken into account by using an enhancement factor for slabs under concentrated loads in shear [16].

2.2. Limit state function

In a reliability analysis, the variability of the loads and elements of the resistance is studied [17,18]. When analysing experimental results to extend a codified approach, a different technique is required, as the load is not variable. The limit state that is studied in this case is based on a probabilistic comparison between the test results and the design shear capacity. To compare the experimental results to the design shear capacity from NEN-EN 1992-1-1:2005 [3], the approach used to determine the factor for the bending moment resistance of steel beams [19,20] is used as an inspiration. The quantity of the ratio between the experimental result and its prediction is treated as a random variable, which is added as a