Engineering Structures 148 (2017) 571–583

Contents lists available at ScienceDirect

Engineering Structures

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

Distribution of peak shear stress in finite element models of reinforced concrete slabs

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

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

ARTICLE INFO

Article history:
Received 11 May 2015
Revised 29 June 2017
Accepted 3 July 2017

Keywords:
Experiment
Finite element models
Punching shear
Slab
Shear
Shear stress
Structural load test

ABSTRACT

Existing reinforced concrete solid slab bridges in the Netherlands are re-assessed for shear based on a Unity Check: the ratio of the shear stress caused by the applied loads to the shear capacity of the concrete cross-section. The governing shear stress resulting from the self-weight, weight of the wearing surface, distributed and concentrated live loads, can be determined with a simplified spreadsheet-based method, the Quick Scan (Level of Assessment I) as well as with a linear finite element model (Level of Assessment II). When a finite element model is used, a distribution of shear stresses over the width of the slab bridge is automatically found. To compare the governing shear stress caused by the loads to the shear capacity, it is necessary to determine over which width the peak shear stress from the finite element model can be distributed. To answer this question, a finite element model is compared to an experiment. The experiment consists of a continuous, reinforced concrete slab subjected to a single concentrated load close to the support. Seven bearings equipped with load cells that measure the reaction force profile along the width of the slab are used to compare to the stress profile obtained from the finite element model. From this analysis, it is found that the peak shear stress in a linear finite element model can be distributed over $4d_l$ with d_l the effective depth to the longitudinal reinforcement of the slab. The comparison of measured reaction force profiles over the support to the stress profile from a finite element model results in a research-based distribution width that replaces the rules of thumb that were used until now.

1. Introduction

The Dutch road network underwent a large expansion during the decades following the Second World War. Fifty percent of the bridges and viaducts in the Netherlands were built before 1976. The bridges that were constructed at that time are now reaching the end of their originally devised service life. Since the original design and construction of these bridges, the traffic loads and volumes have increased significantly, resulting in heavier live load models in NEN-EN 1991-2:2003 [1]. At the same time, the shear provisions of the recently introduced Eurocode NEN-EN 1992-1-1:2005 [2] allow for smaller shear capacities of concrete cross-sections than the former national Dutch code NEN 3880:1974 [3] and NEN 1009:1962 [4] (or earlier).

One bridge type that, upon assessment, is particularly vulnerable to these code changes is the subset of the reinforced concrete solid slab bridges. This bridge type is common in the older part of the Dutch road network, and is typically used for covering short spans. The number of slab bridges that need further study in the Netherlands is 600. While the calculated cross-sectional shear capacity might be insufficient, these bridges did not show signs of distress upon inspection [5]. This observation indicates that reinforced concrete slabs possess additional sources of capacity that are traditionally not taken into account in the concrete design codes. In slabs, one of the major sources of additional capacity is the slab's ability for transverse load redistribution [6] and the influence of the width of the member [7]. A full literature survey on the shear strength of reinforced concrete slabs [8] and review of experiments available in the literature [9] confirm the increased shear capacity of reinforced concrete slabs as compared to beams [10–13].

This paper deals with the assessment of reinforced concrete slab bridges based on linear finite element models, as part of an approach based on Levels of Approximation. For the first time,

---

* Corresponding author at: Universidad San Francisco de Quito, Politecnico, Diego de Robles y Vía Interoceánica, Quito, Ecuador.

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

http://dx.doi.org/10.1016/j.engstruct.2017.07.005
0141-0296/

Nomenclature

a	center-to-center distance between the load and the support
a_v	face-to-face distance between the load and the support
d_l	effective depth to the longitudinal reinforcement
$f_{c,cube}$	cube compressive strength of the concrete
f_{ck}	characteristic concrete cylinder compressive strength
f_{ct}	cube splitting strength of concrete
f_{ym}	yield strength of steel
f_{um}	ultimate tensile strength of steel
h	height
k	size effect factor
s	displacement
t	time
v_{Ed}	governing shear stress in cross-section from the applied loads
v_{min}	lower bound for shear capacity
$v_{Rd,c}$	shear capacity of cross-section as prescribed by NEN-EN 1992-1-1:2005 [2]
x	position along the width of the slab
F	applied load
F_i	measured force on the prestressing bars, with i the number of the bar (1, 2 or 3)
F_{max}	maximum concentrated load in the experiment
$F_{tot,2d}$	total applied reaction force over $2d_l$
$F_{tot,4d}$	total applied reaction force over $4d_l$
P_u	maximum applied load in experiment
UC	Unity Check value
V_{min}	minimum shear capacity
ρ_l	longitudinal reinforcement ratio
ρ_t	transverse reinforcement ratio
τ_{2d}	resulting shear stress over $2d_l$
τ_{4d}	resulting shear stress over $4d_l$

the distribution width of the peak shear stress is studied experimentally, whereas in the past, rules of thumb were used.

2. Levels of assessment

In the 2010 *fib* Model Code [14], a new concept is introduced for structural engineers: the use of Levels of Approximation, as shown in Fig. 1. Increasing the Level of Approximation means using a computational technique that requires more time but that gives results that are expected to be more accurate.

The concept of using Levels of Approximation is used for the analysis of the 600 shear-critical reinforced concrete slab bridges in the Netherlands. The Levels of Approximation for the assessment of bridges are renamed as “Levels of Assessment”. All bridges that are under discussion need to be analyzed with Level of Assessment I. The bridges that fulfil the criteria of Level of Assessment I, or, in other words, when the shear capacity of the cross-section is larger than the shear stress resulting from the applied loads, are not analyzed further. The bridges with one or more cross-sections that do not fulfill the requirements of Level of Assessment I are reanalyzed with Level of Assessment II. As before, the bridges with cross-sections that are found to be sufficient with Level of Assessment II, are not studied further. The bridges with one or more cross-sections that do not fulfill the Level of Assessment II criteria are taken into Level of Assessment III. This procedure is repeated throughout the higher Levels of Assessment.

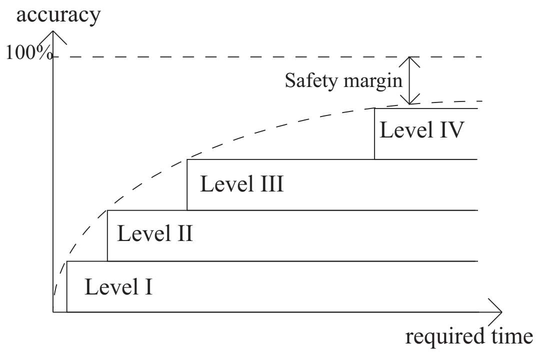

Fig. 1. Principle of Levels of Approximation as introduced in the *fib* Model Code 2010 [14].

For assessment of the existing reinforced concrete slab bridges, Level of Assessment I consists of a spreadsheet-based calculation, which is similar to a hand calculation. This approach is called the “Quick Scan” [15,16]. The shear stress resulting from the acting forces is determined by using superposition of the individual contributions. The shear stress from the distributed loads is determined based on static equilibrium and the shear stress from concentrated loads is based on a 45° load distribution in the plane of the slab so that the effective width in shear over which this load is acting can be determined. The shear capacity is determined by NEN-EN 1992-1-1:2005 [2] with a lower bound v_{min} as derived by Walraven [17]. The spreadsheet can read in all information from the database of the bridges under study, and as output it gives the maximum Unity Check (the ratio between the design value of the applied shear stress resulting from the loads (composite dead load and live load) and the shear resistance as prescribed by the Eurocode [2]), of the critical cross-section, per bridge section span. This method allows for a fast identification of which bridges can be considered sufficient and which bridges need further study. A number of conservative assumptions have been made in the Quick Scan: the effective width of the concentrated loads is determined per axle of the design truck, and the same effective width is used for both axles of the design truck (giving a smaller effective width to the second axle than when 45° load spreading would be applied) [18]. A smaller effective width will result in a larger shear stress for the same applied live load model. Moreover, the larger distributed live load in the first lane with slow truck traffic is distributed over only a small portion of the width, which is a more conservative approach than using a distribution based on Guyon-Massonet [19]. The thickness of the asphalt layer is conservatively assumed to be 12 mm, which leads to larger shear stresses than a smaller layer [18].

For Level of Assessment II a linear finite element model is used to find the governing shear stress caused by the applied loads. A linear elastic finite element model is used in Level of Assessment II instead of a non-linear analysis (Level of Assessment III), which can take cracking and transverse load redistribution into account and provides a more rigorous analysis, because it is less time-consuming and can be sufficient for a number of structures under study. The shear stress caused by the applied loads is compared to the shear capacity of the cross-section, as defined by NEN-EN 1992-1-1:2005 [2] with a lower bound v_{min} as described by Walraven [17]. The design tandems have to be moved in such a way that the most unfavorable position is found, resulting in the largest