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Development of recommendations for proof load testing of reinforced concrete slab bridges

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ABSTRACT

As the bridge stock in the Netherlands and Europe is ageing, various methods to analyze existing bridges are being studied. Proof load testing of bridges is an option to experimentally demonstrate that a given bridge can carry the prescribed live loads. Based on extensive research on proof load testing of reinforced concrete slab bridges carried out in the Netherlands, recommendations for proof load testing of reinforced concrete slab bridges were developed. The recommendations for the preparation, execution, and post-processing of a proof load test are summarized in this paper. The novelty of the recommendations is that proof load testing for shear is studied, and that a proposal for stop criteria for shear and bending moment has been formulated. Further research on the shear behavior is necessary, after which the recommendations will be converted in guidelines for the industry.

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1. Introduction

Many of the existing bridges in the Netherlands were built in the decades following the Second World War. As these bridges are approaching the end of their originally devised service life, methods are developed to identify which bridges need replacement, or strengthening, and which bridges are still safe for the traveling public [1]. A large subset of the Dutch bridge stock consists of reinforced concrete slab bridges, and these bridges typically have low ratings for shear as a result of the higher live load models and the lower shear capacities in the recently introduced Eurocodes [2,3]. These bridges are typically short span bridges, with span lengths of around 10 m.

For the assessment of reinforced concrete slab bridges, a method with different levels of approximation was developed [4]. The first level is a spreadsheet-based method [5,6] that takes recommendations developed based on experiments [7–10] into account. The second level includes linear finite element models [11], and the third level nonlinear finite element models [12] and probabilistic methods [13]. The highest level, which is used when regular analysis methods are insufficient (for example, due to a lack of information, or because the effect of material degradation on the structural behavior is unknown), includes load testing.

Two types of load testing exist: diagnostic load testing and proof load testing. Diagnostic load testing [14–19] can be used to update the analytical model of the bridge, so that the load rating can be refined. Proof load testing [20–25] is used to demonstrate that a bridge can carry its prescribed factored live loads without permanent structural damage. Therefore, higher load levels are required in a proof load test than in a diagnostic load test. The inherent danger of proof load testing is that, since large loads are used, permanent damage or collapse of the structure can be caused. To avoid this risk, the structural responses have to be monitored carefully during proof load testing with an extensive sensor plan. If the measurements indicate distress in the structure, the proof load test has to be terminated and further loading will not be permitted. Determining whether the measurements indicate distress is done based on the so-called "stop criteria", which are criteria based on the measurements that indicate if further loading

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Nomenclature

$d_{asphalt}$	thickness of asphalt layer
d_l	effective depth to the longitudinal reinforcement
eff_{Ru}	capacity of the bridge
$f_{c,m}$	mean concrete compressive strength
$f_{y,m}$	mean steel yield strength
h	thickness of slab
k	size effect factor
k_{slab}	factor that takes into account the increased redistribution capacity of slabs around weak spots
v_{min}	lower bound to shear capacity
$v_{R,c}$	mean predicted shear capacity
w_{max}	maximum crack width during load cycle
w_{res}	residual crack width at the end of the load cycle
F_{target}	target load
F_{lim}	limit after which further loading can cause permanent damage
G_1	effect of permanent loads
G_k	characteristic value of a permanent action
$G_{k,j}$	characteristic value of permanent action j
P	relevant representative value of a prestressing action
Q_k	characteristic value of a single variable action
$Q_{k,1}$	characteristic value of the leading variable action 1
$Q_{k,i}$	characteristic value of the accompanying variable action i
γ_G	partial factor for permanent actions, also accounting for model uncertainties and dimensional variations
$\gamma_{G,j}$	partial factor for permanent action j, also accounting for model uncertainties and dimensional variations
γ_{ll}	load factor for the live load
γ_P	partial factor for prestressing actions
$\gamma_{perm6.10a}$	load factors for permanent load when Expression 6.10 a from NEN-EN 1990:2002 is governing
$\gamma_{perm6.10b}$	load factors for permanent load when Expression 6.10 b from NEN-EN 1990:2002 is governing
γ_Q	partial factor for variable actions, also accounting for model uncertainties and dimensional variations
$\gamma_{Q,i}$	partial factor for variable action i
γ_{sd}	load factor for the superimposed dead load
γ_{sw}	load factor for the self-weight
ε_c	strain measured during proof loading
$\varepsilon_{c,lim}$	limit value of the concrete strain: 0.8‰ if the concrete compressive strength $\geq$25 MPa
ε_{c0}	analytically determined short-term strain in the concrete caused by the permanent loads that are acting on the structure before the application of the proof load
ξ	a reduction factor for unfavourable permanent actions G
ρ_l	ratio of longitudinal reinforcement
ψ_0	factor for combination value of a variable action
Σ	implies "the combined effect of"
"+"	implies "to be combined with"

could result in permanent damage or collapse. Current codes and guidelines for proof load testing [26–31] do not permit proof load testing of shear-critical structures, and at most describe stop criteria for flexure.

The research that lies at the basis of the presented recommendations for proof load testing of reinforced concrete slab bridges involves field testing, laboratory testing, and desk research. In terms of field testing, six pilot proof load tests were carried out [32], and one collapse test was carried out [13,33,34]. The laboratory testing involved testing of beams sawn from the bridge used for the collapse test [20,33], and additional testing of beams cast in the laboratory to further analyze the measurements and propose stop criteria [35,36]. The desk research included an extensive literature review on the application of diagnostic and proof load testing and on the currently available codes and guidelines [37,38] and an analysis of the pilot proof load tests [39] to formulate recommendations with regard to load application, target proof load, and stop criteria. As a result of this research, recommendations for proof load testing of flexure- and shear-critical structures can be formulated, and a proposal for stop criteria for both shear and flexure has been formulated. The inclusion of proof load testing for shear forms a significant advancement with regard to the current practice described in the available codes and guidelines for proof load testing, which do not permit testing of shear-critical structures. However, further experimental research and theoretical analyses are required before proof load testing of shear-critical bridges can be transferred to the industry, as the interpretation of the measurements in real-time still remains in the realm of research. For long span bridges and bridge types other than reinforced concrete slab bridges, the insights from this research are not directly applicable.

For diagnostic load testing, strain distributions over the height at different locations of the slab are necessary to calibrate the finite element model, which is not practical for field testing of slab bridges, so that proof load testing can be considered as more suitable. For girder bridges, on the other hand, applying the strain sensors on the individual girders, is straight-forward. Additionally, the transverse distribution in reinforced concrete slabs changes as the load is increased [40], although a diagnostic load test can give insight in the transverse load distribution at the linear elastic load levels. For flexure-critical bridges, the goals for a proof load test need to be clearly defined prior to the test, as often the available calculation methods combined with material research can suffice to improve the assessment.

In the Netherlands, proof load testing of reinforced concrete slab bridges [41] should be carried out within the framework of the guidelines for the assessment of bridges ("RBK") [42], which apply to all bridges owned by the Dutch Ministry of Infrastructure and the Environment. In these guidelines, the safety levels at which an assessment should be carried out are prescribed. The same safety levels should be obtained by proof load testing. International guidelines and codes that were consulted in developing the presented recommendations are the German guideline [28], ACI 437.2M-13 [26], the Manual for Bridge Rating through Load Testing [29], which lies at the basis of the Manual for Bridge Evaluation [27] for the section about load testing, the Irish guidelines [30], and the British guidelines [31]. Note that none of these existing guidelines allow proof load testing of shear-critical structures, nor describe stop criteria for shear-critical structures. As such, the current research marks an advancement of the state-of-the-art for proof load testing of reinforced concrete slab bridges.

For the measurements, deformations, displacements, and deflections can be used. The terms deformations is used in a general sense, and deformations that cause a translation in any direction are defined as displacements. The displacements in the direction of gravity are defined as deflections.

2. Considerations prior to a proof load test

2.1. Goals of proof load test

The main goal of a proof load test is to directly demonstrate that a structure can carry the factored live loads. It also should be

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