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Recommendations for proof load testing of reinforced concrete slab bridges

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Abstract

Proof loading of existing bridges is an option to study the capacity when crucial information about the structure is lacking. To define the loading criteria for proof load testing, a review of the literature has been made, finite element models of existing viaducts have been made, and on these viaducts, proof loading tests have been carried out. These bridges were heavily instrumented, to learn as much as possible about the structural behaviour during proof loading. Additional laboratory experiments have been used to develop controlled loading protocols, and to identify which stop criteria can be used for which case. As a result of the analysis and experiments, recommendations are given for proof loading of bridges with respect to the required maximum load and the stop criteria. These recommendations have resulted in a guideline for proof loading of existing reinforced concrete slab bridges for The Netherlands.

Keywords: guidelines; proof load testing; slab bridges; reinforced concrete; field testing; stop criteria; flexure; shear.

1 Introduction

As the bridge stock in The Netherlands and Europe is ageing, various methods to analyse existing bridges are being studied. These methods can be categorized based on the Levels of Approximation from the *fib* Model Code (1), and are called Levels of Assessment (2). A common bridge type in the Netherlands from the 1960s – 1980s is the reinforced concrete solid slab bridge. This bridge type often rates too low, especially in shear. The developed methods start from the lowest Level of Assessment with a simple spreadsheet-based calculation, the Quick Scan (3, 4). At the second level, linear finite element methods are used (5), and at a higher level, reliability-based methods (6) and non-linear finite element models (7) can be used. It is only necessary to assess a structure at a higher level when it does not fulfil the criteria at the considered level. If none of the analytical methods lead to satisfactory results, but there are possible sources for additional capacity in the structure, a proof load test can be considered.

Proof loading of bridges is an option to study the capacity when crucial information about the structure is lacking. This information could be with regard to the effect of material degradation on the structural capacity (8), with regard to the reinforcement layout when structural plans are missing (9), and with regard to the load path at higher load levels (10). In a proof load test, a load that corresponds to the factored live load is placed at a critical location on the bridge. If the bridge can carry this load without signs of distress, it has passed the proof load test successfully, which means that it fulfils the requirements of the code.

When it is decided to proof load a bridge, the question arises which maximum load should be attained during the experiment to approve the capacity of the bridge, and which criteria, based on the measurements during the test, would indicate that the proof loading needs to be terminated before reaching the maximum desired load (the so-called stop criteria). Some guidance can be found in existing codes and guidelines for proof load testing, such as the German guidelines (11), ACI 437.2M-13 (12), the Manual for Bridge Rating through Load Testing (13). Other guidelines, such as the British (14), Irish (15), and French (16) guidelines focus on diagnostic load testing, which is a different type of load test. In a diagnostic load test, a low load level is used to compare the structural response to an analytical model, and to use these results to update a bridge rating (17-19).

2 Proof load testing in the Netherlands

2.1 Background

As a large number of existing bridges, and in particular reinforced concrete slab bridges, are subject to discussion in the Netherlands, research is carried out to explore the feasibility of proof load testing for the assessment of existing bridges. Most of the existing guidelines for proof load testing, such as the German guideline (11) and ACI 437.2M-13 (12) have been developed for concrete buildings. The particularities of testing bridges are of course different. Moreover, the existing guidelines only prescribe stop criteria for flexure, and do not allow load testing for shear. As a number of the existing reinforced concrete slab bridges are analytically found to be shear-critical, these bridges would not be candidates for proof load testing, which defeats the purpose of using proof load testing for the assessment of these bridges.

To define the required loading criteria, a review of the literature has been made (20), finite element models of existing viaducts have been made, and on these viaducts, proof loading tests have been carried out. These bridges were heavily instrumented, with a goal of learning as much as possible about the structural behaviour during proof loading.

2.2 Pilot proof load tests

To gain experience with the technique of proof load testing, and to see if it can be used both for flexure- and shear-critical bridges, a number of pilot tests have been carried out in the Netherlands. An overview of these tests is given in (21). In this section, a short overview of the tested bridges is given. The first pilot proof load test was on the viaduct Heidijk in 2007 (22), which is a reinforced concrete slab bridge with material damage caused by alkali-silica reaction. A loading frame with hydraulic jacks was used to apply the load, with a maximum applied load of 640 kN.

The second pilot proof load test, in 2009, was on the viaduct Medemblik, a concrete girder bridge with material damage caused by reinforcement corrosion. For this proof load test, the BELFA truck (23) from Germany was used, and the maximum applied load was 545 kN. A photograph of the BELFA is given in Figure 1.

In 2013, the first pilot proof load test with involvement of Delft University of Technology was carried out on the viaduct Vlijmen-Oost (24). The viaduct is a reinforced concrete slab bridge with damage caused by alkali-silica reaction. The test was carried out with the BELFA vehicle, see Figure 1, at different static positions with a maximum applied load of 900 kN. The difficulty in this proof load test was that only one lane could be used for the test, whereas the adjacent lanes had to remain open for traffic. This situation caused noise on the measurements, especially the acoustic emission measurements.

Figure 1. Photograph of the BELFA on the viaduct Vlijmen-Oost.

In 2014, Delft University of Technology tested the Halvemaans Bridge (25), see Figure 2, a single span reinforced concrete slab bridge from 1939 of which the analytical bending moment capacity was insufficient. In this proof load test, for the first time a system with a steel spreader beam, counterweights, and hydraulic jacks was used, see Figure 3. The maximum applied load was 900 kN, which proved that the bridge fulfills the requirements for bending moment.

Figure 2. Halvemaans Bridge in Alkmaar

The next pilot proof load test took place on the viaduct Zijlweg (8), Figure 4, a reinforced concrete slab bridge with cracking caused by alkali-silica reaction. This viaduct had an insufficient shear capacity upon an analytical assessment. The load was applied by using the system with a steel spreader beam (Figure 3). Two tests were carried out: one test on a flexure-critical position, and one test on a shear-critical position. In the first test, a maximum load of 1368 kN was applied, and in the second test 1377 kN. Both tests showed that the behavior of the viaduct is satisfactory and fulfills the requirements of the codes.

Figure 3. Load application system with steel spreader beam, counterweights, and hydraulic jacks on the Ruytenschildt Bridge.

Figure 4. Viaduct Zijlweg.

The most recent pilot proof load test was carried out on the viaduct De Beek (26, 27), Figure 5, a reinforced concrete slab bridge without material damage. This bridge did not fulfil the requirements for bending moment upon analytical assessment. As a result, the use of the viaduct was reduced from two lanes (one lane in each direction) to a single lane. The maximum applied proof load was 1751 kN on a flexure-critical position and 1560 kN on a shear-critical position, and the load was applied through the system with the load spreader beam. The difficulty for the assessment of this viaduct was that the critical span could not be tested, as this span is above the highway and would require closing of the highway during the test.

Figure 5. Viaduct de Beek.

In addition to the pilot proof load tests, two collapse tests have been carried out. In the summer of 2014, the Ruytenschildt Bridge (Figure 3), a reinforced concrete slab bridge that had to be replaced for functional reasons, was tested to collapse in two spans (28-30). In the fall of 2016, the Vecht Bridge (31), a prestressed concrete girder bridge, was tested to collapse in two spans: one span in which the original structure was not modified, and one span in which the deck was cut. As such, the difference between the composite behavior of the structure and the behavior of the individual beams could be analyzed.

2.3 Laboratory testing

To further study the required loading protocol in a proof load test and the stop criteria, experiments have been carried out in the laboratory. The first series of experiments was carried out on beams which were sawn from the Ruytenschildt Bridge (32). The existing stop criteria for bending were analysed, and first conclusions and recommendations were developed. In a second series of experiments, beams cast in the lab were tested (33) in shear and flexure, see Figure 6. In these experiments, different load speeds, number of loading cycles, and timing of the constant load were studied to develop recommendations for the loading protocol. The beams were carefully instrumented, to evaluate the existing stop criteria and to propose additional stop criteria. One of the main conclusions from these tests was that a distinction in stop criteria should be made between beams that were already cracked in bending and beams that were not. The presence of bending cracks changes the stiffness properties, which are used to study the linearity of the structural response. Moreover, a distinction between shear failure and bending failure should be made.

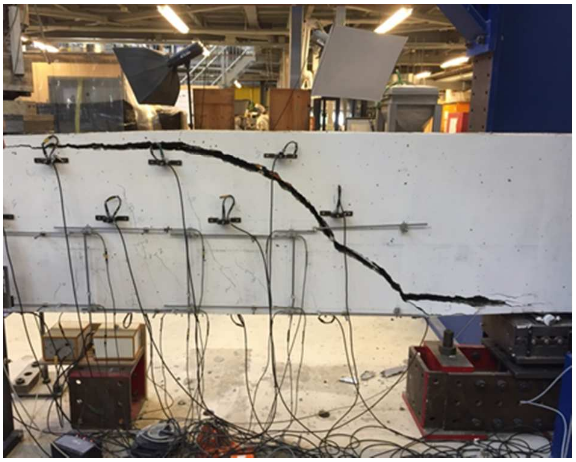

Figure 6. Shear failure of P804A2 (34).

3 Required maximum load

As a result of the analysis of the pilot proof load tests and the laboratory experiments, recommendations are given for proof loading of bridges with respect to the required maximum load. In North American practice, the live loads for evaluation (35) are based on representative vehicles. For proof load testing, a multiple of this vehicle weight (reference value is 1.4) is then applied onto the bridge. This method does not require very large loads, and dump trucks can be used for the load application. In Europe, currently no codes are available for the assessment of structures. National codes, such as the NEN 8700:2011 (36) in the Netherlands are available, but these use the same live load model as the Eurocodes for design. Therefore, guidelines need to be developed on how the prescribed factored live loads can be translated into a proof load testing setup.

From the pilot proof load tests, it was found that the method with the steel load spreader beam is most flexible and practical. A single proof load tandem is chosen when viaducts with a small width are tested, as was the case for all pilot proof load tests. The dimensions of the proof load tandem are the same as the dimensions of the tandem used in the live load model from NEN-EN 1991-2:2003 (37), with as the only difference that the wheel print is taken as 230 mm × 300 mm.

To determine the required target proof load, the load is sought that results in the same sectional shear or moment as the factored live loads from Load Model 1 from NEN-EN 1991-2:2003 (37). As the Dutch national code NEN 8700:2011 (36) and the Dutch guidelines for the assessment of bridges RBK (38) describe different safety levels for existing structures, the load combinations for these different safety levels have to be used. For bending moment, the critical position of the tandems of the live load model is determined as the position that results in the largest sectional moment. The proof load tandem is then placed at the same position, and the load on the proof load tandem is increased until the same sectional moment is found. For shear, the critical position is at 2.5d_l from the support (4), with d_l the effective depth to the longitudinal reinforcement, and the sectional shear can be equally distributed transversely over 4d_l (5).

4 Loading protocol

The laboratory experiments have been used to develop controlled loading protocols. In these experiments, the number of cycles, loading speed, duration of constant loading, and rest period between the cycles were varied to develop recommendations for the loading protocol. The recommended loading speed is between 3 kN/s and 10 kN/s, and one fixed loading speed should be selected for all loading and unloading cycles. Four load levels are recommended: 1) a low load level to check the functioning of all sensors, 2) the serviceability limit state load level, 3) an intermediate load level, and 4) the load level of the target proof load, that corresponds to the safety level the bridge needs to be assessed for. For each load level, at least three cycles are used. For load levels 3 and 4, and additional cycle is added, in which small steps are used to gradually go to the required load. This procedure is followed to check the structural response and decide if it is safe to continue loading the structure. After each cycle, unloading to 0 kN does not take place. Instead, a baseline load level of, for example, 100 kN is used, to keep all instrumentation activated. Combining these elements results in a loading protocol as shown in Figure 7.

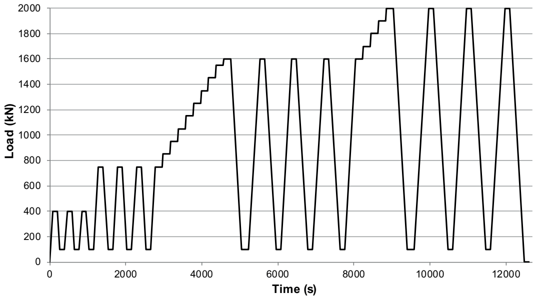

Figure 7. Example of loading protocol.

5 Stop Criteria

The laboratory experiments are also used to identify which stop criteria can be used for which case. The stop and acceptance criteria from the German guidelines (11) and ACI 437.2M-13 (12) were evaluated, and additional possible stop criteria were evaluated. In the experiments, both shear and flexural failures were studied. The considered cases for the selection of stop criteria depend on the failure mode (ductile – flexure, or brittle – shear), and whether the element is cracked in bending or not.

An overview of the proposed stop criteria is given in Table 1. The proposed stop criteria for shear need to be evaluated with further experiments, and may need to be extended with stop criteria based on the mechanics of shear failure (39). In Table 1, the following symbols are used: ε_c is the measured strain in the concrete, ε_{c0} is the strain in the concrete caused by the permanent loads, w_{max} is the crack width at maximum load, and w_{res} is the residual crack width at unloading. Crack widths of smaller than 0.05 mm can be neglected. The deformation profiles can be plotted at the different load levels, to see if the behavior is as expected and remains linear.

Table 1. Overview of proposed stop criteria

	Existing flexural cracks?	
Failure mechanism	*Uncracked*	*Cracked*
Flexural failure	$\varepsilon_c < 0.8$ ‰ $- \varepsilon_{c0}$ $w_{max} \leq 0.5$ mm $w_{res} \leq 0.1$ mm $w_{res} < 0.3w_{max}$ Stiffness reduction ≤ 25 % Deformation profiles Load-displacement graph	$\varepsilon_c < 0.8$ ‰ $- \varepsilon_{c0}$ $w_{max} \leq 0.5$ mm $w_{res} \leq 0.1$ mm $w_{res} < 0.2w_{max}$ Stiffness reduction ≤ 5 % Deformation profiles Load-displacement graph
Shear failure	$\varepsilon_c < 0.8$ ‰ $- \varepsilon_{c0}$ $w_{max} \leq 0.3$ mm Stiffness reduction ≤ 5 % Deformation profiles Load-displacement graph	$\varepsilon_c < 0.8$ ‰ $- \varepsilon_{c0}$ Stiffness reduction ≤ 5 % Deformation profiles Load-displacement graph

These recommendations have resulted in a proposal for a guideline for proof loading of existing reinforced concrete slab bridges for the Netherlands.

6 Conclusions

To assess existing reinforced concrete slab bridges that do not fulfil the requirements based on an analytical assessment, proof load testing can be used. The feasibility of using proof load testing for the assessment of concrete bridges, and in particular reinforced concrete slab bridges, is studied in the Netherlands through a series of pilot proof load tests. These tests showed that proof load testing can be used to show that a given bridge can carry the prescribed factored live loads without distress. Proof load testing is particularly interesting when large uncertainties affect the analytical assessment, such as the effect of material degradation. The pilot proof load tests served as a background to develop recommendations for the determination of the required maximum load in a proof load test.

In addition to the pilot proof load tests, controlled laboratory experiments were carried out to fine-tune the details of the execution of proof load testing, with the goal of standardization. The first element that was studied in detail is the loading protocol. The loading speed, number of cycles, required load levels, and duration of the constant load are prescribed based on varying these parameters in the laboratory experiments. The second element is the stop criteria. Currently, stop criteria for bending moment are recommended, depending on whether there are flexural cracks in the cross-section or not. For shear, further research is necessary to finalize the recommendations for the stop criteria.

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