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Proof load testing of the viaduct De Beek

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Abstract

Proof load testing can be a suitable method to show that a bridge can carry the required loads from the code without distress. This paper addresses the preparation, execution, and analysis of a proof load test on a four-span reinforced concrete solid slab bridge, viaduct de Beek. The bridge has one lane in each direction, but was restricted to a single lane, since an assessment showed that the capacity is not sufficient to allow both lanes. For this proof load test, the bridge was heavily equipped with sensors, so that early signs of distress can be seen. The difficulty in this test was that, for safety reasons, only the first span could be tested, but that the lowest ratings were found in the second span. A direct approval of the viaduct by proof loading was thus not possible, and an analysis was necessary after the field test. The result of this analysis is that only by allowing 6.7% of plastic redistribution in the second span, sufficient capacity can be demonstrated.

Keywords: existing bridges; load testing; proof load testing; reinforced concrete bridges; bending moment capacity; sensors; slab bridges

1 Introduction

For existing bridges, proof load testing (1-4) can be a suitable method to show that a bridge can carry the required loads from the code without distress. Practically, a proof load test is carried out by placing a load that corresponds to the factored live loads on the bridge, and verifying if the bridge can carry this load without signs of distress. Proof load testing can be used for structures where information is lacking, such as the structural plans (1), or where the effect of material degradation on the capacity is not known, such as for bridges with alkali-silica reaction damage (5). Proof load testing is one type of load testing, in which high loads are applied. A type of load testing at lower load levels is diagnostic load testing (6-8). In a diagnostic load test, a lower load level is applied to verify the structural behavior of a bridge. This behavior could include the transverse distribution, or the participation of non-structural elements such as barriers and parapets to the stiffness. Whereas diagnostic load testing is a tool to update analytical models used for the rating of bridges, proof loading does not require rating calculations after the test, if the load can be applied at the critical position.

Since proof load testing requires large loads, the risk of structural damage is larger than in a diagnostic load test. Therefore, a proof load test needs to be executed carefully. First of all, the target proof load is not applied directly. Instead, a loading protocol is developed based on several load levels (9). This loading protocol is typically cyclic, as recommended by the German guidelines for load testing (10) and ACI 437.2M-13 (11). The advantage of a cyclic loading protocol is that the linearity and repeatability of the measurements can be verified. The second element of carefully executing a proof load test, is applying sensors to follow the structural responses closely during the proof load test. At signs of distress or nonlinearity, further loading is not permitted, and the proof load test should be terminated. Signs of distress in the structure can be evaluated based on the so-called "stop criteria". A stop criterion is a criterion based on the measurements that signals the possible onset of structural distress. If a stop criterion is exceeded, the proof load test should be terminated. Stop criteria are given in the German guidelines for load testing (10). In the ACI 437.2M-13 (11) code, acceptance criteria are given, which are criteria, based on the measurements, that need to be fulfilled to consider a proof load test as successful and not causing structural distress. The available stop and acceptance criteria have been developed based on testing buildings in flexure. Stop criteria for shear are currently not available in the existing guidelines, but are a topic of current research (12, 13).

2 Viaduct de Beek

This paper addresses the preparation, execution and analysis of a proof load test on a reinforced concrete solid slab bridge, the viaduct de Beek, see Figure 1. This viaduct is located above the highway A67 in a local road in the province of Noord Brabant. The bridge was built in 1963, and is owned and managed by the Dutch Ministry of Infrastructure and the Environment. The viaduct has four spans, with end spans of 10.81 m and central spans of 15.40 m. The width of the viaduct is 9.94 m, facilitating a carriageway of 7.44 m. The height changes parabolically between 470 mm and 870 mm, see Figure 2.

Figure 1. Viaduct de Beek

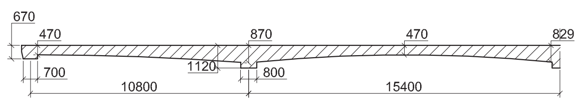

Figure 2. Longitudinal view of viaduct de Beek, showing the end and mid span.

Nine cores were drilled from the slab to determine the concrete compressive strength. The characteristic concrete compressive strength was determined as f_{ck} = 44.5 MPa, which gives a design compressive strength of f_{cd} = 30 MPa. The properties of the steel were also determined based on sample tests. The conclusion of the tests on the steel was that a steel quality QR 24 was used, with a design yield strength of f_{yd} = 252 MPa.

In span 1, the longitudinal reinforcement consists of 6 layers of ϕ 25 mm bars with a spacing of 560 mm, so that A_s = 5259 mm^2/m. In the second span, only 4 layers of ϕ 25 mm bars with a spacing of 560 mm are shown in the reinforcement drawing, so that A_s = 3506 mm^2/m.

The bridge has two lanes (one in each direction), but is restricted to a single lane, since an assessment (14, 15) showed that the bending moment capacity is not sufficient for keeping both lanes open. Originally, load posting was proposed, but posting would mean that local heavy agricultural trucks need to detour. Therefore, it was decided to change the lane layout with the use of barriers to a single lane with unrestricted traffic, see Figure 3.

Figure 3. Traffic restriction on viaduct de Beek

The difficulty in this test is that, for safety reasons, only the first span could be tested, but that the lowest ratings were found in the second span, which has a larger span length but a smaller amount of flexural reinforcement than the first span. Testing the second span would require closing of the highway, which was considered not feasible. A direct approval of the viaduct by proof loading was thus not possible, and an analysis was necessary after the field test.

3 Preparation of proof load test

3.1 Target proof loads

For existing bridges in the Netherlands, different safety levels, each with different safety factors and a different target reliability index are defined in the Dutch code NEN 8700:2011 (16) and the Guidelines for the Assessment of Bridges (RBK) (17). In the preparation for a proof load test, all load factors are used as prescribed by NEN 8700:2011 (16) and the RBK (17), except for the load factor for the self-weight. For self-weight, the load factor is taken as $\gamma_{sw} = 1.1$. The dimensions of the structure are not a random variable anymore, so that only the model factor remains. According to NEN-EN 1992-2+C1:2011 (18), the model factor equals 1.07, which is rounded off to 1.10.

The target proof load should be equivalent to the factored live load. The live loads are as prescribed by NEN-EN 1991-2:2003 (19) Load Model 1. This load model consists of a design tandem in each lane, combined with a distributed lane load. For the proof load test, only a single proof load tandem is applied. The equivalence is determined based on finding the same sectional moment or shear for the Eurocode live load model as for the proof load tandem. The choice for sectional moment or sectional shear is related to the goal of the test: testing for bending moment or shear.

To test at the critical loading position for bending moment, first the situation with the Eurocode live loads is studied. The design tandems are moved until the position that results in the largest bending moment. The Eurocode live loads are then removed, and replaced by a single tandem with four wheel prints of 230 mm × 300 mm, the proof load tandem, at the critical position of the Eurocode design tandem in the first lane. This position was found to be at 3.55 m from the end support. The load on the proof load tandem is then increased until the same sectional moment is found as with the Eurocode live loads. The values for the proof load for bending moment P_b at the different safety levels (with the associated reliability index β) is given in Table 1. In this table, not only the load levels for existing bridges from NEN 8700:2011 (16) and the RBK (17) are used, but also the load levels for new structures from NEN-EN 1990:2002 (20) at the ultimate limit state and the serviceability limit state.

Table 1. Required proof loads for different safety levels, and associated reliability index.

Reliability level	**β**	**P_b [kN]**	**P_s [kN]**
Eurocode Ultimate Limit State	4.3	1656	1525
RBK Design	4.3	1649	1516
RBK Reconstruction	3.6	1427	1311
RBK Usage	3.3	1373	1262
RBK Disapproval	3.1	1369	1257
Eurocode Serviceability Limit State	1.5	1070	976

To test a reinforced concrete slab bridge at the critical position for shear, the face-to-face distance between the first axle of the first tandem and the support is taken as 2.5d_l, with d_l the effective depth to the longitudinal reinforcement. This distance was determined as the critical distance for reinforced concrete slab bridges in shear (21). For the first span of viaduct de Beek, the critical distance is at 1.1 m from the end support. The shear stress obtained in the finite element program can be averaged over a transverse distance 4d_l (22). This average shear stress caused by the Eurocode live loads can then be compared to the average shear stress caused by the proof load tandem. The load on the proof load tandem should be increased until the same sectional shear is achieved as for the Eurocode live loads. The resulting target values for the proof load for shear P_s at the different safety levels is given in Table 1.

3.2 Sensor plan

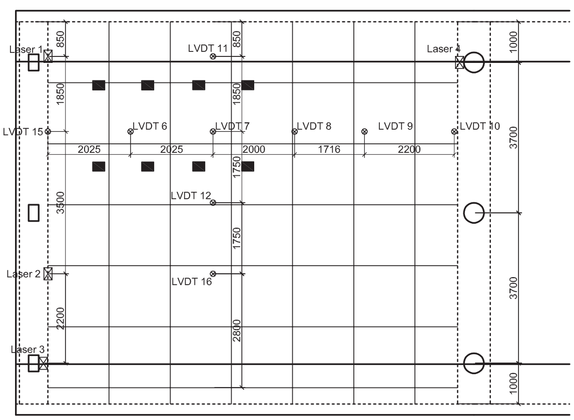

Figure 4. Measurements for vertical deflections

For this proof load test, the bridge was heavily equipped with sensors, so that early signs of distress can be seen. Laser triangulation sensors (lasers) and linear variable differential transformers (LVDTs) are used to measure the deflections on a longitudinal and transverse line (see Figure 4), the vertical deflections at the supports, strain on the bottom concrete layer (using an LVDT over 1 m length), and the opening of existing cracks. Strain gages are used to measure strains in the reinforcement steel. Acoustic emission sensors measure the cracking activity. The applied load on the four wheel prints of the proof load tandem is measured with load cells.

4 Execution of proof load test

4.1 Loading protocol

For proof load testing, a cyclic loading protocol is required to safely load to the highest load level. Whereas according to the guidelines for existing bridges in the Netherlands (17), the required safety level in an assessment is the RBK Usage Level, in the pilot proof load test the highest load level was the Eurocode Ultimate Limit State with a 5% addition to account for small local variations in the material properties. Moreover, to have a safe method for loading the bridge, a method using a load spreader beam, counterweights, and jacks is used. With this system, the load spreader beam is supported on the foundations of the tested bridge. The counterweights are applied on the steel spreader beam prior to the load test, and this load is carried off to the foundations of the tested bridge. During the load test, the jacks are activated, and the loading of the bridge takes place. The advantage of this system is that, if the bridge should suddenly deform more than expected, the bridge will not be loaded further, and a collapse can be prevented. A photograph of the loading system is shown in Figure 5.

Figure 5. Loading system, showing load spreader beam, counterweights, and hydraulic jacks.

Four load levels are used for the cyclic loading protocol in the first test for bending moment. The first load level is a low load level of 550 kN to check the functioning of all sensors. The second load level is the Serviceability Limit State, with a load of 950 kN. The third load level is the RBK Usage Level, with a load of 1350 kN. The final load level is the Eurocode Ultimate Limit State, with an applied load of 1699 kN. Adding the weight of the jacks and steel plates gives a total load of 1751 kN, or 6% above the Eurocode Ultimate Limit State load. For the shear test, the same load levels were used, and the corresponding applied loads are 250 kN, 750 kN, 1250 kN, and 1508 kN. The maximum applied load was then 1560 kN, or 2% above the Eurocode Ultimate Limit State load. The resulting loading protocol is illustrated for the shear test in Figure 6.

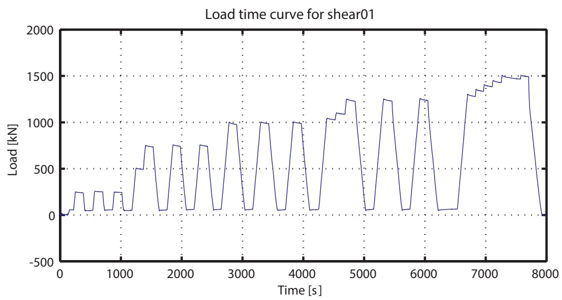

Figure 6. Loading protocol of shear test.

4.2 Measurements during test

The load-displacement diagram is used to evaluate if non-linear behavior takes place. The envelope of the load-displacement diagram, based on the LVDT closest to the center of the proof load tandem, is given in Figure 7a for the bending moment test and in Figure 7b for the shear test. Some reduction in stiffness can be observed in the bending moment test. The stiffness reduction is about 16%, which is significantly less than the maximum of 25% for bending moment that was recommended based on experiments (9, 13). In the shear test, the stiffness reduction is limited to 10%.

The ratio of the residual deflection to the maximum deflection is used as a stop criterion in the German guideline (10) and as an acceptance criterion in ACI 437.2M-13 (11). The German guideline limits this ratio to 10%, whereas ACI 437.2M-13 limits it to 25%. In the bending moment test, this ratio is 15%, and in the shear test 8%. As no signs of distress were observed, the limiting ratio of the residual to maximum deflection from the German guideline (10) can be considered as too conservative.

An analysis of the deflection plots showed no signs of non-linearity in the bending moment test and shear test. A comparison between the measured deflections and the finite element model showed that the uncracked concrete stiffness of 32.9 GPa can be used.

Additionally, the strain measurements and crack opening measurements are used to compare to the stop criteria from the German guidelines (10). The stop criterion for the concrete strain was exceeded, indicating that this criterion may be too conservative. The other stop criteria were not exceeded. The criterion for the crack opening is extended with the requirement that crack widths smaller than 0.05 mm can be neglected.

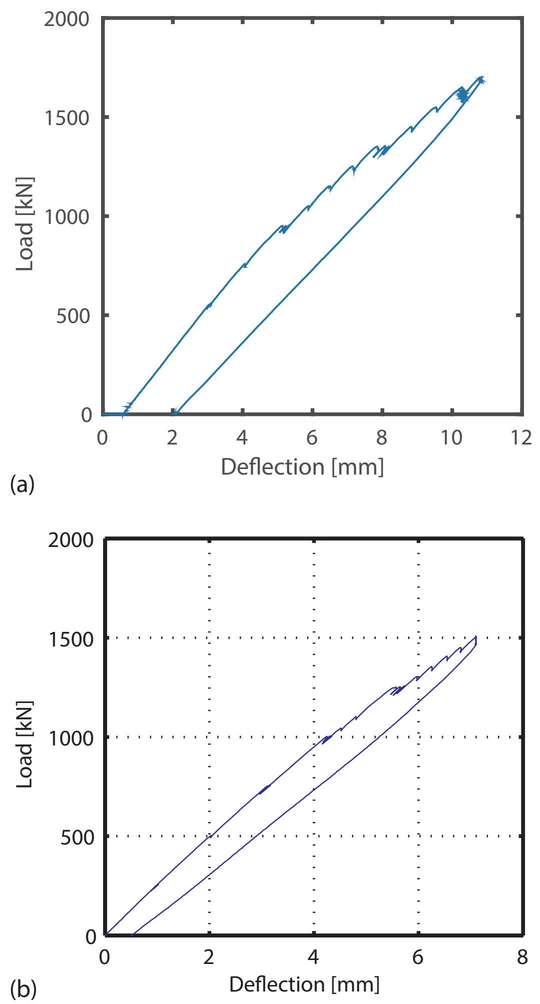

Figure 7. Envelope of the load-displacement diagram: (a) Bending moment test; (b) Shear test.

5 Assessment of viaduct de Beek

5.1 Assessment of tested span

The measurements taken during the proof load test were analyzed to develop recommendations for the assessment of the viaduct. The assessment of the tested span is straightforward: the bridge could carry more than the Eurocode Ultimate Limit State live loads without signs of distress, so that it has been proven to fulfill the requirements.

5.2 Assessment of critical span

In the second span, the span over the highway that could not be tested, less flexural reinforcement is present while the span is larger. For this span, the load combination at the RBK Usage level results in a sectional moment of m_{Ed} = 422 kNm/m (assuming two loaded lanes), and the nominal bending moment capacity is m_{Rd} = 335 kNm/m. The resulting Unity Check is 1.26 for the RBK Usage load level, which means that this span does not fulfil the requirements for bending moment.

In a refinement, the analysis is carried out with plastic redistribution. A plastic hinge is assumed to form in the critical span when the sectional moment equals 335 kNm/m. The Unity Check for bending moment over the support then needs to be studied. The span moment of 335 kNm/m is achieved at 78% of the RBK Usage load level. A support moment of 900 kNm/m occurs for that loading. After applying the plastic hinge and increasing the load to 100% of the RBK Usage load level, the support moment becomes 960 kNm/m. The bending moment capacity over the support is 1022 kNm/m, so that the unity check over the support becomes UC = 0.94 whereas the UC = 1 at mid-span.

The result of this analysis is that only by allowing 6.7% of plastic redistribution in the second span, sufficient capacity for the RBK Usage level can be demonstrated.

5.3 Recommendations

The presented analyses are based on the available reinforcement drawings. It is rather odd that in the longer span, only 67% of the longitudinal reinforcement of the shorter span is available. This anomaly in the drawing could simply be an error of the drafter, which was not applied in the field. For this reason, it is recommended to check the reinforcement in the mid-span with a scanner, or by removing the concrete cover locally to measure the spacing between the bottom bars. An additional check of the cracks in the mid span is also necessary, to check for signs of corrosion. As corrosion of the flexural reinforcement progresses, the area of reinforcement is reduced, and thus the flexural capacity. If the condition of the mid span is satisfactory, the barriers that changed the lane layout from one lane in each direction to a single lane can be removed.

6 Conclusions

The viaduct de Beek was chosen for a pilot proof load test. The first goal of the test was to gain experience with the technique of proof load testing, for the future development of a guideline for proof load testing for the Netherlands. The second goal of the test was to evaluate if the original lane layout of the viaduct could be restored. Two proof load tests were carried out on the first span of viaduct de Beek: one proof load test for bending moment and one proof load test for shear. The structural responses were closely monitored during the proof load test, for two reasons. The first reason is to make sure that no irreversible damage occurs during the proof load test. The second reason is to evaluate the existing stop and acceptance criteria from the available guidelines.

Both proof load tests were successful. In the bending moment test, a total load of 1751 kN was applied, which equals the Eurocode Ultimate Limit State loading + 6%. In the shear test, a total load of 1560 kN was applied, which equals the Eurocode Ultimate Limit State loading + 2%. No signs of distress in the structure was observed during the analysis of the measurements. Some existing stop criteria were exceeded, which indicates that these criteria may be too conservative.

The critical span of the bridge could not be proof load tested, as this span is above the highway, and would require closing of the highway for the test.

Therefore, a more refined analysis using plastic redistribution was used. If 6.7% of plastic redistribution is allowed to take place, the viaduct can be considered as to fulfil the requirements for the RBK Usage level for the original lane layout of the bridge. Before the decision can be made to reopen the bridge to all traffic in two lanes, it is necessary to verify if there are durability or corrosion problems. Such problems would further decrease the flexural capacity of the mid span.

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