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PROOF LOAD TESTING OF REINFORCED CONCRETE SLAB BRIDGES IN THE NETHERLANDS

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ABSTRACT

The bridges built during the development of the Dutch road network after the Second World War are reaching their originally devised service life. A large subset of the Dutch bridge stock consists of reinforced concrete slab bridges. This bridge type often rates insufficient according to the recently introduced Eurocodes. Therefore, more suitable methods are developed to assess reinforced concrete slab bridges to help transportation officials make informed decisions about the safety and remaining life of the existing bridges.

If information about a bridge is lacking, if the reduction in structural capacity caused by material degradation is unknown, or if an assessment shows insufficient capacity but additional capacity can be expected, a bridge might be suitable for a field test. A proof load test demonstrates that a given bridge can carry a certain load level. In the Netherlands, a number of existing reinforced concrete slab bridges have been proof loaded, and one bridge has been tested to collapse. Bridges with and without material damage were tested. These bridges were heavily instrumented, in order to closely monitor the behavior of the bridge. Critical positions for bending moment and shear were studied.

Based on the proof load tests that were carried out over the past years, a set of recommendations for the systematic preparation, execution, and analysis of proof load test results is compiled. These recommendations will ultimately form the basis of the guideline for proof load testing for the Netherlands, which is currently under development.

Keywords: Assessment, Bending moment capacity, Field test, Proof load test, Reinforced concrete bridge, Shear capacity, Slab bridge

INTRODUCTION

The main expansion of the Dutch road network took place during the decades following the Second World War. The bridges built in this era are reaching the end of their originally devised service life. Moreover, they were designed for the live loads of that era.

A large subset of the Dutch bridge stock consists of reinforced concrete solid slab bridges. This bridge type often rates insufficient for shear according to the recently introduced Eurocodes. The reason for these low ratings is that, on one hand, the prescribed live loads from NEN EN 1991-2:2003 (*1*) are heavier than from the old Dutch code, and that, on the other hand, the shear capacity according to NEN EN 1992-1-1:2005 (*2*) is smaller than according to the previously used Dutch code. The fact that reinforced concrete slab bridges rate insufficient for shear does not directly imply that these bridges are on the brink of collapse, and that there is a danger for the traveling public. Instead, it means that more suitable methods for assessing reinforced concrete slabs for shear need to be developed to help transportation officials make informed decisions about the safety and remaining life of the existing bridges.

An important aspect for slabs subjected to concentrated live loads is the ability of the slab to distribute stresses in the transverse direction, which increases its shear capacity (*3*). This mechanism is neglected by the code provisions, which were developed for beams. For slabs, however, better methods can be developed.

For existing bridges in the Netherlands, a guideline for the assessment is available. This guideline is called the “Richtlijnen Beoordeling Kunstwerken (Guideline Assessment Bridges)”, abbreviated as RBK (*4*). Different safety levels for assessment are prescribed, which use different load factors, related to different reliability indices β and reference periods. Depending on the safety level a structure fulfils in its rating, the owner has to take certain measures.

LITERATURE REVIEW

A bridge can be suitable for field testing for a number of reasons, such as:

- sufficient information about the bridge is lacking (e.g. structural plans) to carry out a proper assessment (*5*),
- the reduction in structural capacity caused by material degradation from processes such as corrosion or alkali-silica reaction is unknown,
- an assessment shows insufficient capacity but additional capacity can be expected, …

Two types of field tests can be carried out: diagnostic load tests, which are used to verify if the bridge’s behavior is as predicted by a model, or proof load tests, which demonstrate that a given bridge can carry a certain load level.

Diagnostic load testing (*6*-*8*) can be used on new bridges to verify the design assumptions and is particularly useful for atypical bridges. Some countries, such as Italy (*9*), Switzerland (*10*) and France (*11*) require a diagnostic load test prior to opening a bridge. In France, this information is also used to compare with diagnostic load tests carried out during the lifespan of the bridge, to see how the stiffness reduces as a result of material degradation. The results of a diagnostic load test for assessment are used to update the bridge rating.

Proof loading (*12, 13*) can be carried out on existing bridges. If a certain load can be carried, sufficient capacity is proven. Proof loading also results in an updating of the reliability index by truncating the probability density function of the resistance (*14, 15*), see FIGURE 1.

A number of national guidelines for load testing exist. In North America, currently the Manual for Bridge Rating through Load Testing (*16*) and ACI 437.2M-13 (*17*) for buildings are available. Germany (*18*), Ireland (*19*), Great Britain (*20*) and France (*11*) have national guidelines for load testing. Only the German guideline and ACI 437.2M-13 prescribe “stop criteria” (or: acceptance criteria in ACI 437.2M-13). These criteria, based on the measurements, indicate when a threshold for damage is exceeded. Increasing the load past a stop criterion could cause irreversible damage in the structure, which is not acceptable for nondestructive load testing.

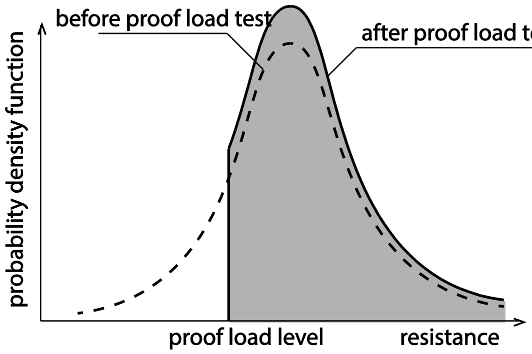

FIGURE 1 Truncation of probability density function of resistance after proof load test, based on (*14*).

OVERVIEW OF PROOF LOAD TESTS IN THE NETHERLANDS

Introduction to proof load tests

In the Netherlands, a number of existing reinforced concrete slab bridges have been proof loaded, and one bridge has been tested to collapse. Bridges with and without material damage were tested. Three bridges had damage caused by alkali-silica reaction (ASR), which results in very small values for the uniaxial tensile strength of the concrete (*21*), which resulted in discussion about the effect of ASR-damage on the shear capacity of existing bridges. Experiments from the literature sometimes indicated a reduction in the shear capacity (*22*), whereas other experiments indicated an increase in the shear capacity (*23*). The increase in capacity can be explained by the fact that the restraint of the ASR-induced expansion of the member creates a compressive force, like prestressing, on the cross-section. Given the uncertainties on the behavior, and how to model the behavior, proof load testing was used and not diagnostic load testing. Moreover, to calibrate models together with a diagnostic load test, it is useful to measure strain distributions over the height. For reinforced concrete slab bridges, which are solid structures, this type of measurements is not possible without drilling a hole for applying the sensors, thus damaging the structure.

The pilot bridges were heavily instrumented. More sensors were applied than strictly necessary to study the stop criteria from the German guideline (*18*) and from ACI 437.2M-13 (*17*), so that these criteria can be validated, refined, replaced by new requirements, and extended to brittle failure modes. Acoustic emissions measurements were added to the experiments (*24*).

FIGURE 2 Overview of the studied bridges: (a) Halvemaans Bridge, (b) viaduct Zijlweg, (c) viaduct Vlijmen-Oost, (d) viaduct De Beek, (e) Ruytenschildt Bridge.

Medemblik and Heidijk

The proof load tests on the viaducts Medemblik and Heidijk were carried out with limited participation of Delft University of Technology. The viaduct Heidijk (*25*), tested in 2007, has material damage caused by ASR, so that the calculated shear capacity of the structure was insufficient. The critical position for shear was estimated at $3.5d_l$ from the support (with d_l the effective depth to the longitudinal reinforcement). In the proof load test, the load was applied with hydraulic jacks in a loading frame anchored to the substructure of the bridge, and the load was applied with a hand pump, so that the loading speed could not be controlled. Three load cycles were applied per load level, and load levels in increments of 50 kN (11 kip) were used. The maximum applied load was 640 kN (144 kip). The final conclusion of the test was that the viaduct can be qualified as a “Class 30” (for vehicles of 30 tonnes (metric tons) = 33 US standard tons).

The next proof load test was on the viaduct Medemblik in 2009 (*26*), where the BelFa (“Belastungsfahrzeug” = Loading vehicle) from Germany was used, see FIGURE 3a. This viaduct was a girder bridge, with material damage (concrete spalling) caused by corrosion of the reinforcement. With the proof loading truck, five positions to study shear, punching, and bending moment were tested in two spans. The maximum applied load was 545 kN (123 kip). The result of the load test and analysis was a proposal to reduce the use of the bridge to one lane, and post it for maximum 30 tonnes (33 tons).

Viaduct Vlijmen-Oost

For the proof load test on the viaduct Vlijmen-Oost (*27*) in 2013, see FIGURE 2c, Delft University of Technology was involved with the measurements, but not with the load application and determination of the maximum required load and critical loading positions. The load was applied by the BelFa truck from Germany, see FIGURE 3a. The viaduct Vlijmen-Oost, a reinforced concrete solid slab bridge with a skew angle of 40^o, has material damage caused by ASR, causing concerns with regard to the shear capacity. Sensors to monitor expansion caused by ASR were installed in 1997. The sensors showed that the threshold for critical expansion was exceeded in 2012. A difficulty in load testing the viaduct Vlijmen-Oost was that only one lane could be closed for traffic during the test.

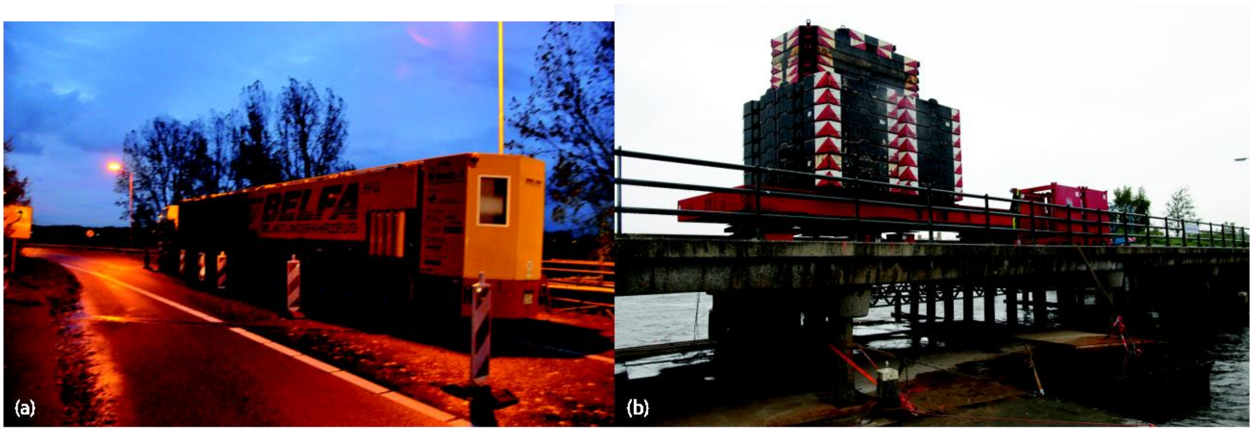

FIGURE 3 Methods of load application: (a) BelFa loading truck on viaduct Vlijmen-Oost; (b) System with steel load spreader structure, hydraulic jacks, and counter weights, on Ruytenschildt Bridge.

Three different static positions of the BelFa truck were used. The first position was used for studying the bending moment capacity, with a maximum applied total load of 900 kN (202 kip). The second position was a critical shear position, loaded up to 800 kN (180 kip). The third position was used for the assessment of the bearings and the joint between the deck and the abutment, with a maximum axle load of 400 kN (90 kip).

An analysis with a linear finite element model indicated that the chosen position for the bending test was not the most critical. The results of the shear test and the finite element model show that the viaduct has sufficient shear capacity to fulfil the requirements of the reconstruction safety level of the RBK (β = 3.6 in a reference period of 30 years).

Halvemaans Bridge

The Halvemaans Bridge (*28*), see FIGURE 2a , was tested in Spring 2014. For this test, Delft University of Technology was responsible for the measurements and the analysis after the test. This bridge is a single span reinforced concrete slab bridge from 1939 with a span of 8.2 m (26.9 ft) and a skew angle of 22^o. Calculations had shown that the bending moment capacity is not sufficient for Eurocode live load model 1.

For this experiment, the load was applied on a steel spreader beam, resting on the supports of the bridge. The bridge deck is loaded with hydraulic jacks in a gradual manner. When the jacks are not in extended, no load is applied on the bridge, and the load of the counterweights is carried directly into the substructure. When the jacks are extended, the slab is loaded, and the testing can take place. The loading system can be seen in FIGURE 3b.

Based on previous assessment calculations of the bridge, it was determined that a load of 850 kN (191 kip) would be necessary to prove sufficient safety at the RBK reconstruction level. The maximum applied load was 900 kN (202 kip), successfully proving sufficient capacity.

Ruytenschildt Bridge

The load testing and testing to failure of the Ruytenschildt Bridge, see FIGURE 2e, in Summer 2014 was fully organized by Delft University of Technology. The Ruytenschildt Bridge (*29, 30*) was a five-span reinforced concrete solid slab integral bridge with a skew angle of 18^o. Because the bridge was scheduled for demolition and replacement for functional reasons (providing a larger clearance height for the boats passing underneath), it was selected for research purposes.

For this experiment, the load was again applied with the system of a steel spreader beam, as shown in FIGURE 3b. Since the Ruytenschildt Bridge could be tested until collapse, a number of topics could be studied and used to improve the proof load testing methods: the failure mechanism was studied, the collapse load was studied in relation to the maximum load that would be necessary in a proof loading test, the measurements were carefully analyzed, and the results at the ultimate were used to confirm a plastic assessment method (Extended Strip Model (*31*)) developed based on slab shear tests (*3*).

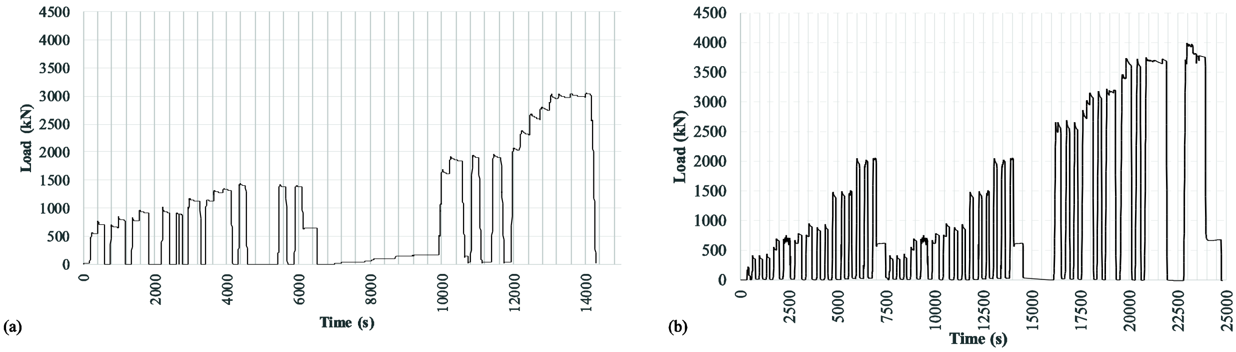

FIGURE 4 Loading scheme of tests on Ruytenschildt Bridge: (a) Span 1; (b) Span 2.

Two spans were tested. For both spans, the face of the first axle was placed at $2.5d_l$ from the face of the support (with d_l the effective depth to the longitudinal reinforcement), as this position was found to be the critical position for shear in the slab shear tests. A shear-critical position was chosen, because of the concerns with regard to the shear capacity of reinforced concrete slab bridges in the Netherlands. In the first span, the maximum load applied on the design tandem was 3049 kN (685 kip) and failure could not be achieved for a lack of counterweights. For the test in the second span, more ballast blocks were ordered, and the maximum load was 3991 kN (897 kip). The failure mode was a combination of excessive settlement of the pier and yielding of the reinforcement resulting in large flexural cracking. The loading scheme of both experiments is shown in FIGURE 4.

To approve the Ruytenschildt Bridge for sufficient bending moment capacity or sufficient shear capacity according to the live load model 1 from NEN-EN 1991-2:2003 (*1*), the maximum loads on the proof loading tandem as given in TABLE 1 are necessary. These values are determined with a linear finite element model, to see which load is necessary on the proof load tandem to create the same sectional moment or sectional shear as the Eurocode live loads. The calculated values for the proof load are indicated with subscript "*m*" for bending moment and subscript "*v*" for shear. Additionally, the values for the proof load are determined at different safety levels: subscript "*rec*" for the reconstruction level (β = 3.6 for 30 years reference period), subscript "*usg*" for the usage level (β = 3.3 for 30 years reference period), and subscript "*dis*" for the disapproval level (β = 3.1 for 15 years reference period). Since signs of distress were only noticed for loads larger than 2000 kN (450 kip), it can be concluded from the results in TABLE 1 that the Ruytenschildt Bridge would have passed the proof load test.

TABLE 1 Overview of test results and required proof load for Ruytenschildt Bridge. Conversion: 1 kN = 0.225 kip.

		Bending moment			**Shear**		
	P_{test} **(kN)**	$P_{rec,m}$ **(kN)**	$P_{usg,m}$ **(kN)**	$P_{dis,m}$ **(kN)**	$P_{rec,v}$ **(kN)**	$P_{usg,v}$ **(kN)**	$P_{dis,v}$ **(kN)**
Span 1	3049	1240	1195	1178	1086	1047	1034
Span 2	3991	1088	1040	1040	901	868	862

Viaduct Zijlweg

The proof load test on the viaduct Zijlweg, see FIGURE 2b, was carried out in Summer 2015 (*32*), led by Delft University of Technology. The viaduct Zijlweg is a four-span reinforced concrete slab bridge with a skew angle of 14.4^{o} carrying a single traffic lane. Material damage caused by ASR is present in the viaduct. Since 2003, sensors are measuring temperature, moisture, and variations in length and thickness (to study the expansion caused by ASR).

Two positions were loaded in the first span of the viaduct. One position was a critical position for bending moment and the other for shear. Both failure mechanisms were studied, since calculations at the design level of the RBK (β = 4.3 for a reference period of 100 years) indicated that the viaduct did not have enough capacity in shear and bending moment. The shear rating was too low, because the presence of ASR-damage raised concerns with regard to the tensile and shear strength of the concrete.

The most unfavorable position for bending moment was determined in a linear finite element model of the bridge subjected to its self-weight, superimposed dead loads, and distributed and concentrated loads from live load model 1 from NEN-EN 1991-2:2003 (*1*). The concentrated live loads were moved in the lane to find the most unfavorable position, and then the required proof load to create the same bending moment was sought.

For shear, the critical position of the loading tandem was taken as a face-to-face distance of $2.5d_l$ (with d_l the effective depth to the longitudinal reinforcement) between the support and the first axle. The peak shear stress was distributed over $4d_l$ (*33*) to find the governing shear stress. The required load on the proof load tandem to have the same governing shear stress as caused by the live loads from the code was then determined. The determination of the required proof loads for shear and bending moment was carried out for the different RBK safety levels.

The maximum load in the bending moment test was 1368 kN (308 kip) (safety level RBK Design + 8.7%) and the maximum load in the shear test was 1377 kN (310 kip) (safety level RBK Design + 12%). The RBK Design level corresponds with the safety level of the Eurocode for the design of new structures at the ultimate limit state, using the load factors (partial factors) for new structures. The associated reliability index is $\beta = 4.3$, for a reference period of 100 years. It can thus be concluded that the viaduct has sufficient capacity and can remain open to all traffic (one lane), provided that it is inspected frequently and the data of the ASR-monitoring are reviewed, to identify possible changes to the concrete material.

Viaduct De Beek

The proof load test on the viaduct De Beek, see FIGURE 2d, was carried out in the Fall of 2015 (*34*), led by Delft University of Technology. This viaduct did not have material damage, but rated very low, and the original two lanes (one lane each way) were reduced to a single lane by using barriers and a traffic light. Again, the position and magnitude for the proof load tandem were determined in a finite element model by finding equivalent sectional moments and shears as caused by the live load model from NEN-EN 1991-2:2003 (*1*). Two positions were proof loaded: a critical position for shear and a critical position for bending moment. In this experiment, additional measurements were performed by applying strain gages on the bottom steel reinforcement, to study the transverse distribution of stresses.

The maximum applied proof load in the bending moment test was 1751 kN (394 kip) and 1560 kN (351 kip) in the shear test. These load levels correspond, for the first span, to a level of RBK Design ($\beta = 4.3$ for a reference period of 100 years) + 6% for the bending moment and RBK Design + 2% for shear.

The difficulty in the assessment of viaduct De Beek was that only the first span was proof loaded, because this span is not directly above the highway, whereas the second span had the lowest ratings. To extrapolate these results to the second span, which had only 2/3rd of the bending moment reinforcement of the first span, an analysis using plastic redistribution was used. Moreover, the distributed live loads were reduced to correspond to the actual lane widths and the RBK Usage level was used ($\beta = 3.3$ for a reference period of 30 years). Allowing plastic redistribution, in line with the large crack widths observed in the second span of the viaduct De Beek, does not guarantee the durability of the structure. Regular inspections, particularly to check for signs of corrosion, are recommended.

RECOMMENDATIONS FOR PROOF LOAD TESTS

Recommendations for the preparation

Preliminary inspection and rating

The first step in the preparation of a proof load test is an inspection of the bridge. In a visual inspection, changes to the structure from the original plans can be determined, such as widening of the original structure, changes to the lane layout, or increases in the thickness of the wearing surface. Signs of deterioration at the bearings and joints need to be studied, and cracking needs to be analyzed.

Typically, a structure that has been identified for proof loading has already been rated. If a rating report is not available, these calculations have to be performed. To make sure the proof load test can be executed safely, the capacity at the ultimate limit state in shear, punching, and bending moment need to be determined as well.

Determination of position and magnitude of proof load

Once it is determined that the original plans of the structure are still valid, or once the significant changes have been noted, a linear finite element model of the bridge can be made. First, the governing load combination is applied to this model. In the Netherlands, the combination consists of self-weight, superimposed dead load, and distributed and concentrated live loads from Eurocode live load model 1. The load factors depend on the considered safety level from the RBK (*4*).

To find the critical position for bending moment, the design tandems (concentrated live loads) are moved in their respective lanes until the maximum average sectional moment over a width of 3 m (9.8 ft) is found. The live loads are then removed and replaced with the four wheel prints of the proof load tandem, which is placed at the critical position in the outermost lane. On the proof load tandem no load factor is used. The magnitude of the proof load is increased until the same sectional moment over 3 m (9.8 ft) is found as for the live load model from the code. The proof load is determined for the different prescribed safety levels.

For a proof load test for shear, the critical position is taken at $2.5d_l$ between the face of the first axle and the support. First, the loads according to the code are applied, with the design tandem at $2.5d_l$ from the face of the support. The sectional shear for this configuration over $4d_l$ is determined. Then, the factored live loads (distributed and concentrated loads) from the code are removed, and the unfactored proof load tandem is applied. The magnitude of the proof load to create the same sectional shear over $4d_l$ as the loads prescribed by the code is then determined for the different prescribed safety levels.

Sensor plan

Before developing a sensor plan, it is necessary to determine which measurements are necessary. For a full analysis of a reinforced concrete slab bridge, the following load effects should be measured:

- deflection profiles in the longitudinal and transverse direction;
- deflections at the supports;
- strain on the bottom of the cross-section;
- reference strain measurement to correct for the effect of temperature;

- opening of existing cracks;
- opening of new cracks, provided that sensors can be applied during the test.

Load cells need to be used to measure the applied load, and to link the measurements of the load and the bridge's response. To select the necessary sensors for each of the selected load effects, it is important to estimate the required measurement range prior to the test.

Recommendations for the execution

Loading protocol

As a proof load test involves high loads, it is necessary to have a controlled loading protocol, so that the test can be stopped if signs of distress are observed on the structure. To study nonlinear behaviour of the structure, a cyclic loading protocol is recommended. At least four load levels are recommended (based on the safety levels prescribed for existing structures in the Netherlands):

- low load level to check the correct operation of all instrumentation;
- safety level of the serviceability limit state;
- intermediate safety level, for example the RBK usage level;
- +-5% above the maximum load level RBK design.

It is recommended to use at least three cycles per load level. For the higher load levels, the load can be increased with a small load step in the first cycle. The measurements are checked for signs of distress, and then a next small step is applied, to reach the required load level in a safe way. Then, the regular two or three cycles of loading and unloading can be applied. An example of such a loading scheme, as used on viaduct De Beek, is shown in FIGURE 5. A low baseline load level of, for example, 50 kN (11 kip) is recommended to keep the jacks activated and avoid irregularities in the measurements.

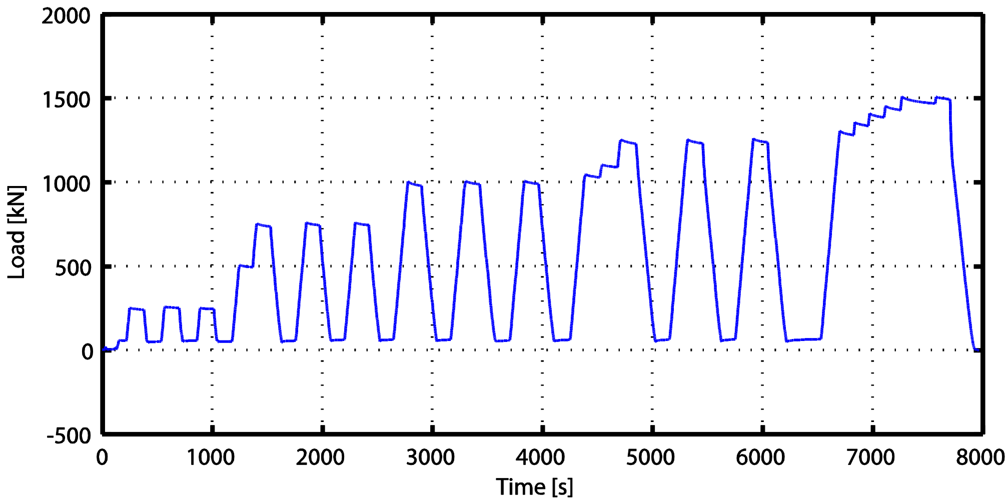

FIGURE 5 Example of cyclic loading protocol as used for viaduct De Beek, shear test.

Monitoring of measurements

To make sure the load test does not cause permanent damage in the structure, the measurements have to be monitored closely during the proof load test. Real-time data analysis has to be provided, and constant communication between the operators of the loading and the data analysts is necessary.

Recommendations for the analysis

Data analysis

After the proof load test, the measurement data need to be analysed. Corrections to the measured displacement profiles for the displacements at the supports, and to the strains for the effect of temperature need to be made. The data need to be evaluated to see if the performance of the structure was within the previously prescribed limits. These limits were already evaluated during the load test as part of monitoring of the measurements, but need to be properly calculated and reported after the proof load test.

Evaluation of finite element model

Prior to the proof load test, a linear finite element model is made to determine the required position and magnitude. This finite element model is also used for the rating of the bridge prior to the load test.

The role of the finite element model is not as large in a proof load test as in a diagnostic load test. In a diagnostic load test (*7*), the difference between the finite element model and the measurements can be used to update the rating of the structure. In a proof load test, the rating is complete and sufficient when the structure can withstand the required proof load. Nonetheless, it is recommended to revisit and evaluate the finite element model, and update the model with the measurements.

Analysis for practice

The simplest way of carrying out a proof load test, is by keeping the sensor plan as simple as possible, by limiting the numbers of load cycles, and by standardizing the post-processing. In The Netherlands, research is carried out to see if such a “quick and easy” method can be developed for proof load tests on existing solid slab bridges, so that these tests can be carried out by contractors following a standard protocol. This task is not easy, because the risks associated with the high loads are significant, and sufficient measurements need to be available to make sure no permanent damage is caused. The real-time interpretation of the measurements during the test needs to be done by experts.

DISCUSSION AND FUTURE RESEARCH

The magnitude of the required proof load is determined based on an equivalent sectional shear or moment from the factored live load model. The resulting required loads are thus higher than the prescribed axle loads in the live load model. For example, live load model 1 from NEN-EN 1992-1-1:2005 prescribes the heaviest design tandem with two axles of 300 kN (67 kip) in the first lane, or a total load of 600 kN (135 kip). Adding the load factors, the distributed lane load, and, if necessary, the effect of the concentrated loads in the other lanes onto the proof load tandem makes that the required loads are much higher (e.g. 1751 kN = 394 kip for viaduct De

Beek). This approach is thus different from considering a rating vehicle, multiplying the standard weight of the vehicle with a factor (e.g. 1.4) and using this heavy vehicle for proof load testing, which ensures that the rating vehicle can safely pass the bridge.

Since the required axle loads are much higher with the presented approach, the load application methods are limited as well. The available axle loads with loading vehicles (for example as shown in FIGURE 3a) are limited, and typically the high required loads for a proof load test cannot be attained with a loading vehicle. Other methods, such as the application of a load spreader beam and counterweights then need to be used (see FIGURE 3b). This approach, however, is slower than driving a loading vehicle onto the structure. For other positions of the proof load tandem, more time is needed to move the setup, whereas driving a loading vehicle to another position takes less time.

From the perspective of proving a certain reliability level and associated reference period, the approach from the Netherlands based on equivalent sectional shears or moments is recommended. Moreover, if a full probabilistic analysis is made, a higher proof load will give more information. Consider FIGURE 1: reaching a certain sectional shear or moment during a load test means that the capacity is equal to or larger than the achieved capacity. The smaller capacities can thus be left out from the probability density function. To determine the probability of failure and the reliability index, the region where the load effects are larger than the capacities is studied. When the probability density function of the capacity is changed after a load test as shown in FIGURE 1, the probability of failure decreases and the reliability index increases. This effect becomes larger as larger proof loads are used, which gives another argument for applying larger loads during proof load tests.

The ultimate goal of the research is to develop a guideline for use by the industry to carry out proof load tests on reinforced concrete slab bridges, equipped with only the minimum necessary sensors. For this purpose, further research is needed to determine which measurements need to be used. Moreover, since the loading speed and number of used cycles have an effect on the stiffness of the bridge because of the time-dependent behavior of concrete, more research is needed to find out which loading speed and protocol needs to be prescribed, and what the limit values for the measurements should be. Additionally, the presented work can fit within the framework for structural identification of constructed systems (St-ID) *(35)*.

At this moment, sufficient knowledge about ductile failure modes is available to develop guidelines. However, more research is needed for brittle failure modes. For the shear tests, the option of using the results of acoustic emission measurements is explored.

SUMMARY AND CONCLUSIONS

Two methods to experimentally investigate the adequacy of existing bridges are diagnostic load tests and proof load tests. This paper focused on proof load tests, applied to reinforced concrete slab bridges. This bridge type is under discussion in the Netherlands because of its low ratings. For bridges with material damage, or when sources of additional capacity cannot directly be determined analytically, proof load testing can be used to demonstrate that the bridge can carry a certain load.

Over the past decade, a number of proof load tests have been carried out in the Netherlands. Bridges with and without material damage were studied. Material damage caused by alkali-silica reaction and reinforcement corrosion was present. For the bridges with alkali-silica reaction damage, the expected shear capacity was very low, since the tested uniaxial tensile strength was very limited in heavily cracked material samples. Different load application methods were explored. One bridge was tested to failure.

Now that a number of pilot projects have been carried out, the insights and experience gained with these experiments can be evaluated. The preparation, execution, and analysis methods can be standardized, and will be the basis for a guideline for proof load tests on reinforced concrete slab bridges for the Netherlands, so that the industry can carry out these tests. The current recommendations are summarized in this paper.

For the preparation, a visual inspection, rating, collection of documents, and development of a finite element model and sensor plan are necessary. The position and magnitude of the proof load need to be determined. It is recommended to determine the magnitude so that the same sectional shear or moment is caused as by the considered live load model. During the test, the measurements need to be carefully monitored to avoid permanent damage to the bridge. The final step is post-processing and reporting of the test: the data need to be analyzed, and the finite element model can be updated based on the measurements.

To ensure uniformity, standard load protocols and loading speeds will have to be used. Proof load testing for brittle failure modes will remain the task of experts, until the necessary measurements and criteria to show imminent failure in a brittle mode have been agreed upon.

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