

Delft University of Technology

Methodology for Proof Load Testing

Lantsoght, Eva

Publication date 2019 **Document Version** Accepted author manuscript Published in Load Testing of Bridges

Citation (APA)

Lantsoght, E. (2019). Methodology for Proof Load Testing. In E. Lantsoght (Ed.), *Load Testing of Bridges: Proof Load Testing and the Future of Load Testing* (Vol. 13). CRC Press / Balkema - Taylor & Francis Group.

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

Chapter 13. Methodology for proof load testing

E.O.L. Lantsoght

Politécnico, Universidad San Francisco de Quito, Quito, Ecuador & Concrete Structures, Delft University of Technology, Delft, the Netherlands

ABSTRACT: This chapter deals with the methodology for proof load testing. All aspects of proof load testing that are shared with other load testing methods have been discussed in Part II. In this chapter, the particularities of proof load testing are discussed. These elements include the determination of the target proof load, the procedures followed during a proof load test (load-ing method, instrumentation, and stop criteria), and the post-processing of proof load test da-ta, including the assessment of a bridge after a proof load test.

1 INTRODUCTION

Proof load testing is a method of load testing in which a load representative of the factored live load is applied to the structure. If the structure can carry this load without signs of distress, the test is considered successful and the structure has been shown experimentally to fulfil the code requirements. Since for this type of load testing large loads are involved, the risk and cost involved with proof load testing is higher than for diagnostic load testing. The risk encompasses possible damage to the structure or its collapse (structural safety), as well as the risk for the executing personnel and the traveling public. To minimize the risk for the structure, the tested structure needs to be instrumented and the measurements need to followed in real-time. If a preset threshold for these measurements, a so-called "stop criterion" is exceeded, further loading is not permitted, even though the target proof load may not be achieved yet. To minimize the risk for the exist for the executing personnel and the traveling public, safety regulations need to be implemented, and a safety plan needs to be developed prior to the load test.

To guarantee the structural safety, the proof load test needs to be carefully prepared. On the other hand, however, there is a need to develop methods to quickly carry out proof load tests so that with a minimum number of sensors and simplified loading protocol, an advice about the bridge can be given. This "quick and easy" type of proof load testing can only be applied to bridges of which the structural behaviour is well-understood and for ductile failure modes. The

development of recommendations for this type of proof load testing is the subject of current research, but is a promising application of proof load testing for the future.

The preparations for a regular proof load test include extensive calculations and predictions of the behaviour of the bridge, as well as the preparation of the sensor plan and the development of the threshold values for the stop criteria. At least two qualified testing engineers should be following and evaluating the measurements during the test.

The followed safety philosophy using stop criteria (Deutscher Ausschuss für Stahlbeton 2000) is shown in Figure 1. If a stop criterion is reached, the corresponding load is F_{lim} . Loading beyond this point is not allowed. A proof load test is successful if the sum of the permanent loads G_l and the target proof load F_{target} is smaller than the limiting load F_{lim} . If the opposite is found in a proof load test, the bridge does not fulfil the requirements of the code for the considered safety level that was the target for the proof load test, but it may still fulfil the requirements at a lower safety level.



Figure 1: Use of stop criteria during proof load test.

The safety plan for the proof load test needs to be developed after a technical inspection of the bridge. This inspection should signal possible safety risks, and should consider the access to the test site. All possible dangerous situations, as well as all possible problems (technical, electrical, electronical, planning-related...) that may arise during the on-site activities need to be reported, and possible solutions and back-up plans for these events need to be presented (Koekkoek et al. 2015). During all activities on-site, the safety of the personnel and traveling public needs to be guaranteed by the presence of a safety engineer. In the Netherlands, it is re-

quired that the information of all emergency services is visible on site in case of a calamity, and that a first-aid kit and at least one person with first-aid training is always present on site. The access to the tested structure should be restricted during testing. Only the executing personnel is allowed access to the bridge during the test. During the test, nobody is allowed to go under the bridge, unless this event has been communicated with all parties and the load is removed. If the bridge cannot be closed for traffic during the proof load test, special safety considerations should be taken for the traveling public. It is strongly advised to temporarily close the bridge when the target load is applied.

For those who are not directly involved with the proof load test, but that may be affected by it, such as the traveling public and inhabitants of the houses near the bridge, information should be provided. Similarly, for the press and other interested parties, information should be available upon request. It is recommended that the communications expert of the local road authority develops this information.

2 DETERMINATION OF TARGET PROOF LOAD

2.1 Dutch practice

In Dutch practice, the target proof load should be equivalent to the factored loads from the required load combination with load factors corresponding to the governing code. This equivalence is described in terms of an equivalent sectional force or moment. For this purpose, a linear finite element model is used. In this finite element model, the applied loads correspond to the required load combination. For the assessment of bridges, this load combination typically consists of the self-weight of the structure, the superimposed dead load, and the live loads according to the live load model from the code under consideration.



Figure 2: Load Model 1 from NEN-EN 1991-2:2003 (CEN 2003): (a) side view; (b) top view. The loads needs to be multiplied with a factor α_{Qi} for the tandem and α_{qi} for the lane loads, with *i* the number of the lane. In the Netherlands, all α_{Qi} equal 1, α_{q1} = 1.15 and α_{qi} = 1.4 for *i* > 1. Conversion: 1 kN = 0.225 kip, 1 m = 3.3 ft, 1 mm = 0.04 in, 1 kN/m² = 0.021 kip/ft².

In NEN-EN 1991-2:2003 (CEN 2003), the live load model consists of the distributed lane load and a design tandem for each lane, see Figure 2. Outside of the notional lanes a distributed load of 2.5 kN/m² (0.05 kip/ft²) is applied, and on the sidewalk a load of 5 kN/m² (0.10 kip/ft²) corresponding to pedestrian loading needs to be applied. The distributed lane load can be applied in a checkerboard pattern over the different spans in a continuous bridge to find the most unfavorable loading. For the design tandem, four wheel prints with an unfactored load of 150 kN (34 kip) each on a contact surface of 400 mm × 400 mm (1.31 ft × 1.31 ft) are used. The axle distance is 1.2 m (3.9 ft) and the transverse distance is 2 m (6.6 ft). The live load model is shown in Figure 2. The tandem is centered in the notional lane of 3 m (9.8 ft). Over the height direction, the wheel print can be distributed under 45° to the slab mid-depth when shell elements are used for the finite element model.

Safety level	в	Reference period	γ perm,6.10a	$\gamma_{perm, 6.10b}$	γ II	Ywind	Yvar
RBK Design ¹	4.3	100 years	1.40	1.25	1.50	1.65	1.65
RBK Reconstruction ²	3.6	30 years	1.30	1.15	1.30	1.60	1.50
RBK Usage ³	3.3	30 years	1.25	1.15	1.25	1.50	1.30
RBK Disapproval ⁴	3.1	15 years	1.25	1.10	1.25	1.50	1.30

Table 1. Overview of different safety levels and load factors prescribed by the Dutch guidelines for the assessment of existing bridges (RBK) (Rijkswaterstaat 2013).

¹ These values correspond to Consequences Class 3 from NEN-EN 1990:2002.

² These values correspond to the reconstruction level for Consequences Class 3 from NEN 8700:2011, taking the values for structures built before 2012.

³ These values correspond to the disapproval level for Consequences Class 3 from NEN 8700:2011, not taking the values for structures built before 2012.

⁴ These values correspond to the disapproval level for Consequences Class 3 from NEN 8700:2011, taking the values for structures built before 2012.

To make the load combination, the respective load factors should be used. For existing bridges in the Netherlands, besides the Eurocodes, the codes for existing bridges NEN 8700:2011 (Code Committee 351001 2011a) and the guidelines for the assessment of bridges from the Dutch Ministry of Infrastructure "RBK" (Rijkswaterstaat 2013) should be consulted. All existing structures in the Netherlands should fulfill the requirements of the NEN 8700 series of codes, with NEN 8700:2011 (Code Committee 351001 2011a) outlining the general safety philosophy, which is in line with NEN-EN 1990:2002 for new structures (CEN 2002), and NEN 8701:2011 (Code Committee 351001 2011b) outlining the loads and load factors, in line with NEN-EN 1991-2:2003 (CEN 2003). The RBK guidelines define different safety levels at which an assessment of a highway bridge can be carried out, each with associated load factors, reliability index β , and the reference period, see Table 1. The defined load factors are the load factors for the permanent load γ_{perm} , which depend on whether Equation 6.10a or b from NEN-EN 1990:2002 (CEN 2002) is governing, resulting in $\gamma_{perm,6.10a}$ or $\gamma_{perm,6.10b}$. For Equation 6.10a, a factor for the combination value of a variable action is used, whereas Equation 6.10b applies a reduction factor for unfavorable permanent loads. The remaining load factors are γ_{ll} for the live loads, γ_{wind} for the wind loads, and γ_{var} for other variable loads.

In a proof load test, the applied load should correspond to these prescribed safety levels. The load combination that is considered is the combination of the self-weight, superimposed load and live load. The load factors are taken based on Table 1 at the different safety levels, with the exception that the load factor for the self-weight γ_{sw} is taken as 1.10 for al load levels. The reasoning behind this reduction is that the dimensions of an existing bridge are not a random variable anymore, but instead a deterministic value. As such, only the model factor remains, which is taken as 1.10. An overview of the resulting load factors at the different load levels is then shown in Table 2. For the proof load, no load factor is used so that $\gamma_{proof} = 1.00$ (the load factor on the proof load) for all considered safety levels.

Safety level	γ _{sw}	γsd	γıı	γproof
RBK Design	1.10	1.25	1.50	1.00
RBK Reconstruction	1.10	1.15	1.30	1.00
RBK Usage	1.10	1.15	1.25	1.00
RBK Disapproval	1.10	1.10	1.25	1.00

Table 2. Load factors for the different safety levels recommended for the use with proof load tests

In the finite element model, first the design tandems are moved in their respective lanes until the position is found for which the largest sectional moment results, see Figure 3. A transverse distribution of 3 m (9.8 ft) is used for bending moment for concrete decks. For other bridge types, no transverse distribution is used. The position that results in the largest sectional moment or force is called the critical position. For shear in concrete bridges, the critical position is taken at a face-to-face distance between the load and the support of $2.5d_l$ (Lantsoght et al. 2013b), with d_l the effective depth to the longitudinal reinforcement. A transverse distribution of $4d_l$ is used for shear (Lantsoght et al. 2013a) for concrete bridge decks. For other bridge types, no transverse distribution is used and the critical position for shear should be determined based on the finite element model. For skewed bridges, the largest stress concentrations are found in the obtuse corner (Cope 1985), so that the proof load tandem should be applied in the obtuse corner.



Figure 3: Wheel print locations for shifting the design tandem along the longitudinal axis of a viaduct that is to be proof load tested (Koekkoek et al. 2016).

Once the critical position is determined, all live loads are removed from the finite element model. Then, a single proof load tandem is applied in the first lane. This method is suitable for bridges with a small width (maximum three lanes in total). For wider bridges, more than one lane should be loaded in the field. Once the proof load tandem (or tandems for wider bridges) is applied in the model at the critical position, the load on the tandem is increased until the same sectional moment or shear is found as with the live load combination. On the proof load tandem, no load factors are used ($\gamma_{proof} = 1.00$). The load for which the same sectional moment or shear is found as the target proof load. With this load, it can be proven that the considered span can carry the prescribed loads of the code, if the structure does not show any signs of distress during the load test. In the Netherlands, this procedure is followed for the different safety levels shown in Table 1, with the highest target proof load usually corresponding to the RBK Usage level.

Since the applied loads during a proof load test can be rather large, an extensive preparation is required to guarantee the structural safety and the safety of the personnel and travelling public. For the structural safety, the preparations include the following calculations:

- if not available from previous reports, an analytical assessment of the structure needs to be prepared. In the Netherlands, this assessment is carried out based on a Unity Check UC, the ratio of the occurring load effect to the capacity of the cross-section, taking into account the prescribed load and resistance factors. In North America, the assessment is expressed in terms of the rating factor RF.
- determination of the expected bending moment capacity, based on the average and measured values of the material properties
- determination of the expected moment-curvature and load-displacement diagram for comparison to the measured results during the experiment

- determination of the expected shear capacity, based on the average and measured values of the material properties
- determination of the expected punching shear capacity, based on the average and measured values of the material properties
- verification of possible problems for the substructure
- if during the technical inspection prior to the load test, other critical situations were observed, these should be verified analytically and monitored during the test.

Depending on the structure type, it may be valuable to carry out a nonlinear finite element simulation of the structure and proof load test for the preparations. Depending on the type of structure as well, specific methods can be used for predicting the maximum load. For reinforced concrete slab bridges, the maximum expected load that causes failure can be predicted with the Extended Strip Model (Lantsoght et al. 2017b).

If the margin between the expected capacity and the target proof load is small, the risk involved with the proof load test increases. The bridge owner then should decide if more preparations are required for the proof load test, and if the risk of testing is acceptable or not. If the risk is considered acceptable, the instrumentation during the proof load test as well as the prepared loading protocol will be crucial to decide during the test if loading to the next load step can be attempted. The sensor plan should then be developed to meet this requirement.

The current approach is fully based on the requirements of the Eurocodes. Since no rating vehicles for assessment are prescribed in the Eurocodes, another possible approach, which could significantly reduce the required target proof load and involved risk, consists of the use of WIM data (Casas and Gómez 2013). With this approach, the required load factors to determine the target proof load can be calibrated to the actual traffic for the site considered.

2.2 AASHTO Manual for Bridge Evaluation method

The method to determine the target proof load that is presented in the AASHTO Manual for Bridge Evaluation (MBE) (AASHTO 2016) is based on the procedures described in the Manual for Bridge Rating through Load Testing (NCHRP 1998). The target proof load should be representative of the vehicles used for rating the viaduct, taking into account the dynamic load allowance, and a load factor for the required margins of safety. The approach used in the United States is thus much more closely related to a vehicle that is used for rating, whereas the approach used in the Netherlands is linked to an entire load model. The reason why in Europe entire load models need to be proven to be equivalent is that there are no Eurocodes for assessment available yet. Some countries have national codes for assessment that can prescribe a rating vehicle, which then could be linked to the target proof load.

The factor that needs to be used to account for the required margin of safety is X_{pA} , and the total load that needs to be applied is the weight of the rating vehicle multiplied with the dynamic load allowance and X_{pA} . The factor X_{pA} is determined by multiplying the factor $X_p = 1.4$ with adjustment factors that take into account properties of the bridge under study. The adjustments to X_p are as given in Table 3, so that X_{pA} can be determined as:

$$X_{pA} = X_p \left(1 + \frac{\Sigma\%}{100} \right) \tag{1}$$

with $X_p = 1.4$. The value of $\Sigma\%$ is the sum of the adjustment percentages from Table 3 for the considered bridge. In Table 3, *RF* is used for the rating factor, and ADTT is used for the average daily truck traffic.

Table 3: Adjustments to X_p, as shown in Table 8.8.3.3.1-1 from MBE (AASHTO 2016)

Consideration	Adjustment
One lane load controls	+15%
Non-redundant structure	+10%
Fracture-critical details present	+10%
Bridge in poor condition	+10%
In-depth inspection performed	-5%
Rateable, existing $RF \ge 1.0$	-5%
ADTT ≤ 1000	-10%
ADTT ≤ 100	-15%

According to the MBE, the strength based on the test is R_n :

$$R_n = X_p \left(L + I \right) + D \tag{2}$$

with L the live load, I the dynamic allowance and D the dead load. The strength based on a calculation equals:

$$R_n = \gamma_{LL} (L+I) + \gamma_D D \tag{3}$$

with γ_{LL} the load factor for the live load and γ_D the load factor for the dead load. The dead load in the test is deterministic and does not need a load factor since the load cannot change anymore over time.

The target proof load L_T can then be determined as a function of the load of the rating vehicle L_R :

$$L_T = X_{nA} L_R \left(1 + IM \right) \tag{4}$$

with *IM* the dynamic load factor. In practice, dump trucks (Saraf et al. 1996) can be used to achieve the target proof load, as well as military vehicles (Varela-Ortiz et al. 2013).

The value of $X_p = 1.4$ was based on a first-order reliability calculation, assuming all loads are normally distributed. The values assumed for the bias (mean to design value) and coefficient of variation are given in Table 4. The bias for the live load is based on measurements, and then extrapolated to 75 years to find the mean maximum load as 1.79 HS20 vehicles. The coefficient of variation on the live load is either 18% when both the uncertainties on the heavy truck occurrences and the uncertainties of the effect of these trucks on the members of the structure are considered, and 14% when only the uncertainties of the truck occurrences is considered. The target values of the reliability index β were defined as 3.5 for the inventory design levels and 2.3 for the operating rating levels. The magnitude of future live loads and possible future deterioration are the main remaining uncertainties after the proof load test. The value of X_p was derived based on an example with an 18 m (59 ft) span with D = L. The factor was found to be conservative for another example with a shorter span and one with a longer span with D/L = 3.0.

	COV – prior to test	COV – after test	BIAS
Resistance	10%	0%	1.12
			1.0 distress in test
Dead load	10%	0%	1.0
Live load	18% truck + members	18%	1.79 one lane
	14% truck only	14%	1.52 two lanes
Impact	80%	80%*	1.00

Table 4. Factors used to calibrate the first-order reliability model that was used to determine $X_p = 1.4$.

*unless a moving load test is performed to investigate the impact

Other approaches that have been used to determine the target proof load in the past include using twice the maximum allowable load of the rating vehicle (Saraf et al. 1996). If proof load testing has as its goal to approve the passing of legal loads, a factor of 1.8 can be applied to the maximum legal load.

3 PROCEDURES FOR PROOF LOAD TESTING

3.1 Loading methods

Several methods are possible for applying the required target proof load during a proof load test. The following methods have been used in the past:

- application of dead weights, where it is important to verify if no arching in the loads occurs when the structure deflects
- using a loading vehicle
- using a system with hydraulic jacks and counterweights.

For proof load testing of buildings, dead weights can be suitable to represent the distributed loads on the floor. The disadvantage of dead weights is that the positioning of these weights is time-consuming, and thus makes using a cyclic loading protocol difficult. Similarly, if dead weights are used and signs that failure is imminent are seen, it is difficult to react quickly and offload all applied loads to prevent damage or collapse. For bridges, the use of dead weights has the additional disadvantage that this type of distributed loads cannot correctly represent the concentrated wheel loads of a design truck or tandem, or rating vehicle.

When using a loading vehicle for applying a proof load, the vehicle should be able to apply the large load required for a proof load test. An option here is to use an army tank (Varela-Ortiz et al. 2013) or similar heavy weight carried by dump trucks (Saraf et al. 1996). In Germany, a special proof load testing vehicle was built, the BelFa, see Figure 4 (Bretschneider et al. 2012). The advantage of using a loading vehicle is that several positions can be tested consecutively, without needing much time for rearranging the test setup. Additionally, dynamic testing can be carried out.



Figure 4: Load application with a loading vehicle (Lantsoght et al. 2017c). Reprinted with permission. Photograph by D.A. Hordijk. Used with permission.

An example of a test setup for a proof load test with a loading frame and hydraulic jacks is shown in Figure 5. The advantage of this system is that the load application can be carried out in a controlled manner, using the jacks for applying the load in a displacement-controlled manner and following the prescribed loading protocol. The advantage of using a displacementcontrolled system is that when large deformations occur, the applied load will be reduced and irreversible damage or collapse can be avoided. The disadvantage of this system is that building up the loading frame can be time-consuming, and that the number of positions that can be tested is limited as every new position requires changing the setup.

For a loading system to be suitable for proof load testing, it has to fulfil the following requirements:

- The system should be suitable for applying the proof load in a safe manner and it must be able to be removed quickly when signs are observed that irreversible damage or failure is imminent.
- The system should be suitable for combination with a cyclic loading protocol: the load has to be applied in increments, loading and unloading must be done within a reasonable amount of time, keeping the load constant needs to be possible, and repeating the same load levels has to be possible.

 For bridge proof load testing, the system should be able to apply the wheel prints of the considered design truck, tandem, or rating vehicle.



Figure 5: Load application with a system of jacks and counterweights.

The loading protocol that is required during a proof load test depends on the code that is used, and is discussed per code in Chapter 3. Most codes prescribe a loading protocol in which different load levels are applied. The trend in the current codes and guidelines is to move towards cyclic loading protocols. Using different load levels in cycles allows for controlling the measurements after each load cycle to see if signs of distress are observed. The highest load level is typically the target proof load, and one of the intermediate load levels corresponds to the serviceability limit state.

When vehicles are used for the loading protocol, the different load levels can correspond to different levels of loading of the vehicles, or a different total number of vehicles. Typically, different load paths are tested to study the critical structural response in different members. When hydraulic jacks are used, the load levels correspond to the load applied on the wheel prints, which should be equal for each wheel print, or which should correspond to the distribution of load over different axles if the loading represent a certain truck. When hydraulic jacks are used, complete unloading after the cycles is not recommended. Instead, loading to a low load level is recommended to make sure that all sensors and the jacks remain activated during the entire load test. An example of a cyclic loading protocol can be seen in Figure 6.



Figure 6: Example of loading protocol, used for bending moment position of proof load test of viaduct De Beek (Koekkoek et al. 2016). Modified from (Lantsoght et al. 2017a), reprinted with permission from ASCE.

Based on field tests on reinforced concrete slab bridges (Lantsoght et al. 2017c) and laboratory testing (Lantsoght et al. 2017d), a recommended loading protocol for proof load testing of reinforced concrete (slab) bridges was developed. The loading speed during the test should be a constant value, which can be chosen between 3 kN/s and 10 kN/s (0.7 kip/s – 2.2 kip/s). A cyclic loading protocol is prescribed, with at least four load levels:

- 1. Level 1: a low load level (20% 30% of Level 4) to check if all sensors and the data acquisition and visualization system function properly
- 2. Level 2: the load level corresponding to the serviceability limit state
- 3. Level 3: an intermediate level between Levels 2 and 4
- 4. Level 4: the highest load level that has to be demonstrated by the proof load test. In the Netherlands, this load level for existing highway bridges is typically RBK Usage, plus 5% to cover the uncertainties of proof load testing.

Per load level, at least three load cycles should be carried out. Each level is kept for 2 minutes and the time of application of the baseline load is also 2 minutes. For load levels 3 and 4, an extra cycle is carried out prior to the three load cycles. In this cycle, the load is increased in small steps, and at each intermediate load level during this cycle, the load is kept constant during three minutes to verify all measurements. Between the load cycles, a low load level should be maintained to make sure all sensors and loading equipment remains activated. A sketch of the resulting loading protocol is shown in Figure 7.



Figure 7: Cyclic loading protocol recommended by the Dutch guidelines. From (Lantsoght et al. 2017d), reprinted with permission from ACI.

3.2 Monitoring bridge behavior during the test

Since proof load testing requires large loads, monitoring the bridge behavior during the test is important to avoid irreversible damage to the structure or collapse. This monitoring should be carried out in real-time during the proof load test, see for example Figure 8. As mentioned before, it is good practice to load to a low load level at the beginning of the proof load test, to verify if all sensors are functioning properly. The effect of temperature and humidity on the sensors should be known prior to the load test. A compensation sensor which is only subjected to the effect of temperature and humidity, and which is applied outside of the loaded area, should be used to find the net effect of the applied loading for the sensors that are subjected to both the structural response and the environmental influences.

According to the MBE (AASHTO 2016), different load levels should be used during a proof load test to verify the response of the bridge under each load increment. This verification should include checking if no non-linear behavior occurs, and to limit distress due to cracking or other physical damage. A visual verification is required as well, and when visible signs of distress are observed, such as buckle patterns in compressive zones in steel elements, or cracking in the concrete, the proof load test should be stopped. For this purpose, the following measurements are recommended:

- strains (stresses) in bridge components,
- relative or absolute displacements of bridge components,

- relative or absolute rotation of bridge components, and
- dynamic characteristics of the bridge.



Figure 8: Monitoring measurement output during a proof load test. Photograph by S. Ensink. Printed with permission.

In the Netherlands, the structural response during a proof load test is followed in real time to verify if no irreversible damage occurs. It is recommended to monitor and evaluate the following structural response during a bridge load test:

- The load-displacement diagram.
- The strains in the members, to verify if strain limits are not exceeded. For girders, strains
 can be monitored at different locations over the height of the member, and the strain profile can be followed during the test.
- In concrete bridges, the width of existing cracks can be monitored to see if cracks are activated. Crack widths smaller than 0.05 mm (0.002 in) can be considered to be equal to 0 mm.
- The output of all displacement sensors should be followed to see if the results are in line with the analytical predictions. If there are significant differences between the predictions and the measurements, the results should be analyzed further, and a reason for the differ-

ence should be sought. Deflection profiles should be plotted to see if no nonlinearity occurs.

For shear-critical concrete bridges, and fracture- and fatigue-critical steel bridges, and other bridges that can fail in a brittle manner, the instrumentation becomes important to avoid a brittle failure during the test. For these cases, special considerations are required.

To develop a sensor plan, the following guidelines can be used. At least the following parameters should be measured:

- Deflection or deformation for at least five positions in the longitudinal direction.
- Deflection or deformation for at least three positions in the transverse direction.
- Deformations at the supports on both sides of the tested span if elastomeric bearings are used.
- Strains at the bottom for at least one position for slab bridges. For girder bridges, one girder should be instrumented over the height to follow the change in positon of the neutral axis.
- Reference strain measurement to assess the influence of temperature and humidity.
- For concrete bridges, the crack width for at least one existing bending crack should be monitored, if the bridge is already cracked in bending.
- The applied load, for each wheel print separately if jacks are used, or the position of the load if loading vehicles are used.
- Other parameters can be measured, for example critical elements identified during the technical inspection.

During the proof load test, the engineers analyzing the measurements have to be in direct communication with the load operator. The responsible measurement engineer will tell the load operator when to apply or remove the load. After each load cycle, all structural responses are checked, and the measurement engineer will give permission to continue the test if no signs of distress are observed.

3.3 Stop criteria

The stop criteria are criteria based on the measurements obtained during the proof load test that are used to evaluate if irreversible damage is imminent. The stop criteria are an integral part of the safety philosophy for proof load testing, see Figure 1, but not all codes and guidelines define the stop criteria with the same level of detail. Some codes that encompass numerous structure types give only general guidance. Other codes with a more limited scope give a quantitative description of the stop criteria. A proof load test can have two outcomes:

- 1. The target proof load is achieved without exceedance of a stop criterion, $F_{target} \leq F_{lim}$, and it has been shown experimentally that the structure fulfills the requirements of the code.
- 2. A stop criterion is exceeded before the target proof load is achieved, $F_{lim} > F_{target}$, and the test is terminated at a lower load level. The structure can then be shown to fulfil a lower load level of the code, or lower demands, if a load corresponding to this lower load level or these lower demands was achieved during the proof load test.

The stop criteria that are defined in the MBE (AASHTO 2016) and the Manual for Bridge Rating through Load Testing (NCHRP 1998) are the onset of non-linear behavior, or the occurrence of damage such as cracking in concrete or compressive distress in steel. Some codes use acceptance criteria, which are verified after a proof load test to see if the behavior of the structure is acceptable. Acceptance criteria cannot be used to warn for the onset of nonlinear behavior.

For concrete bridges, detailed stop criteria are the subject of current research (Lantsoght et al. 2018c). A proposal for stop criteria, based on pilot proof load tests, a collapse test in the field, additional testing in the laboratory, and analytical research, encompasses bridges that are flexure- and shear-critical, both for the case of a structure that has been previously cracked in bending, as well as for the case of a structure that has no significant flexural cracking. Further experimental work is required for the verification of the proposed stop criteria for shear. Two types of stop criteria should be distinguished:

- 1. Stop criteria that indicate that further loading can cause irreversible damage.
- 2. Stop criteria that indicate that further loading can cause collapse.

For the first type, in exceptional cases the bridge owner can give permission to continue loading and will take responsibility for repairing the damage after the proof load test. For the second type, further loading can never be permitted. Further research is necessary to develop these two categories of stop criteria. Analyzing the results of the experiments in the field and in the laboratory in the light of the existing stop and acceptance criteria resulted in a first proposal for stop criteria (Lantsoght et al. 2017d). This proposal was then refined based on theoretical considerations. The stop criteria for flexure are adequately supported by field and laboratory testing. For shear, stop criteria are proposed but further experimental validation is necessary. For flexure, flexural beam theory was used to derive a stop criterion for the limiting concrete strain and crack width (Lantsoght et al. 2018b). For shear, a limiting crack width was derived based on aggregate interlock theory (Lantsoght 2017, Yang et al. 2017). The analysis of experiments on beams with plain bars cast in the laboratory showed that the stop criteria should be different for the failure modes of shear and flexure, and for members previously cracked in bending or not. The resulting four possible situations and their governing stop criteria are given in Table 5. The stop criterion for the limiting concrete strain ε_{stop} is for flexure:

$$\mathcal{E}_c < \mathcal{E}_{stop}$$
 (5)

with ε_c the measured strain, and:

$$\varepsilon_{stop} = 0.65\varepsilon_{bot,\max} - \varepsilon_{c0} \tag{6}$$

$$\varepsilon_{bot,\max} = \frac{h-c}{d-c} 0.9 \frac{f_y}{E_s}$$
(7)

with ε_{c0} the strain caused by permanent loads, *h* the height of the member, *d* the effective depth of the member, *c* the height of the compression zone when the strain in the steel is 90% of the yield strain, f_y the yield stress of the steel, and E_s the Young's modulus of the steel. For shear, the strain is limited as

$$\mathcal{E}_{DAfStB} < \mathcal{E}_{c,lim} - \mathcal{E}_{c0} \tag{8}$$

with ε_c = the measured strain; ε_{c0} = the strain caused by the permanent loads, and $\varepsilon_{c,lim}$ = 800 $\mu\varepsilon$ for concrete with a compressive strength larger than 25 MPa (3.6 ksi). A proposal for the limiting strain based on the Critical Shear Displacement Theory (Yang et al. 2016) is also available, but needs further simplification to come to a closed-form solution (Benitez et al. 2018).

All crack widths smaller than 0.05 mm (0.002 in) are neglected. For flexure, the maximum crack width w_{max} is limited to w_{stop} :

$$w_{stop} = 2 \frac{0.9 f_{y} - 0.6 \sigma_{sr}}{E_{s}} \left(c_{cover} + 0.139 \frac{\phi_{s}}{\rho_{s,eff}} \right)$$
(9)

with c_{cover} the concrete cover, ϕ_s the diameter of the reinforcement bar, and $\rho_{s,eff}$ the reinforcement ratio in the effective height h_{eff} :

$$h_{eff} = 2.5(h-d) \le \frac{h-c}{3} \tag{10}$$

The steel stress at cracking is given as:

$$\sigma_{sr} = \frac{f_{ctm}}{\rho_{s,eff}} \left(1 + \alpha_e \rho_{s,eff} \right) \tag{11}$$

with f_{ctm} the tensile strength of the concrete, and $\alpha_e = E_s/E_c$ with E_c the Young's modulus of the concrete. For shear, the maximum crack width is a fraction of the crack width w_{ai} at which the aggregate interlock capacity becomes smaller than the inclined cracking load:

$$w_{ai} = w_d + 0.01mm \tag{12}$$

$$w_{d} = \frac{0.03 f_{c}^{0.56} \frac{S_{cr}}{d} \left(978\Delta_{cr}^{2} + 85\Delta_{cr} - 0.27\right) R_{ai}}{v_{RBK}}$$
(13)

with f_c the concrete compressive strength, and s_{cr} the crack spacing:

$$s_{cr} = \left(1 + \rho_s \alpha_e - \sqrt{2\rho_s \alpha_e + (\rho_s \alpha_e)^2}\right)d\tag{14}$$

and ρ_s is the reinforcement ratio. For high strength concrete, a correction factor R_{ai} is used:

$$R_{ai} = 0.85 \sqrt{\left(\frac{7.2}{f_c - 40MPa} + 1\right)^2 - 1} + 0.34 \text{ for } f_c > 65MPa$$
(15)

The critical shear displacement (Yang et al. 2017) is determined as:

$$\Delta_{cr} = \frac{25d}{30610\phi_s} + 0.0022mm \le 0.025mm \tag{16}$$

The shear stress at inclined cracking is:

$$v_{RBK} = \max(1.13k_{slab}k\sqrt{\frac{f_c}{f_{ym}}}; 0.15k_{slab}k(100\rho_s f_c)^{1/3})$$
(17)

with $k_{slab} = 1.2$ for slabs and 1.0 for other elements, and k the size effect factor:

$$k = 1 + \sqrt{\frac{200mm}{d}} \le 2 \tag{18}$$

For flexure, the limits to the residual crack width w_{res} after a cycle from the German guideline can be used, see Table 5.

	Cracked in bending or not?			
Failure mode	Not cracked in bending	Cracked in bending		
Bending moment	Concrete strain ε_{stop}	Concrete strain ε_{stop}		
	$W_{max} \leq W_{stop}$	$W_{max} \leq W_{stop}$		
	<i>w</i> < 0.05 mm => <i>w</i> ≈ 0 mm	<i>w</i> < 0.05 mm => <i>w</i> ≈ 0 mm		
	$w_{res} \leq 0.3 w_{max}$	$w_{res} \leq 0.2 w_{max}$		
	25% reduction of stiffness	25% reduction of stiffness		
	Deformation profiles	Deformation profiles		
	Load-deflection diagram	Load-deflection diagram		
Shear	Concrete strain ε_{DAfstB}	Concrete strain ε_{DAfstB}		
	$w_{max} \leq 0.4 w_{ai}$	$w_{max} \leq 0.75 w_{ai}$		
	<i>w</i> < 0.05 mm => <i>w</i> ≈ 0 mm	<i>w</i> < 0.05 mm => <i>w</i> ≈ 0 mm		
	25% reduction of stiffness	25% reduction of stiffness		
	Deformation profiles	Deformation profiles		
	Load-deflection diagram	Load-deflection diagram		

The stiffness is determined as the tangent to the load-displacement diagram in the loading branch. For all cases, the reduction of the stiffness calculated on the load-deflection diagram is limited to 25%. The deformation profiles are the plots of the measured deformations (typically deflections) in the longitudinal and transverse direction. For all cases, the deformation profiles need to be qualitatively followed during the proof load test, to signal changes to the structural

behavior. The load-displacement graph should be plotted and observed during the load test, to check for signs of nonlinear behavior.

Moreover, if the inspection identified other critical structural elements, their response should be followed during the load test and stop criteria should be agreed upon prior to the proof load test. Additional measurements, such as acoustic emission signals, may be required to capture changes prior to brittle failure modes. In certain cases, for shear-critical bridges, the development of cracks can be followed, and the stop criterion could be the development of a bending crack in the shear span, as such a crack could become the critical crack for a shear-flexural failure.

The stop criteria from the German guideline (Deutscher Ausschuss für Stahlbeton 2000), the acceptance criteria from ACI 437.1-07 (ACI Committee 437 2007) and ACI 437.2M-13 (ACI Committee 437 2013), and the acceptance criteria from the Czech and Slovak (Frýba and Pirner 2001), Polish (Research Institute of Roads and Bridges 2008), and French (Cochet et al. 2004) guidelines for load testing are all discussed in Chapter 3.

For steel bridges, a stop criterion can be to limit the total steel strain to 90% of the yield strain and to pay attention to compressive distress in elements that are critical for buckling. Fractureand fatigue-critical bridges need special considerations. For timber, masonry and plastic composite bridges, the test engineer needs to determine the stop criteria prior to the load test. A limiting strain based on the known stress-strain diagram of the material can be suggested.

4 PROCESSING OF PROOF LOAD TESTING RESULTS

4.1 On-site data validation of sensor output

The first step in reviewing the load test data is to verify all measurements after each load cycle. This step is required to check if none of the stop criteria are exceeded, but also to see if the output of the sensors is reasonable (i.e. repeatable across cycles, symmetric where applicable, and linear). For this purpose, a cyclic loading protocol is required. As mentioned before, such a loading protocol can be achieved by using hydraulic jacks, or by repeating the same driving path of one or more loading vehicles. During the first load level, the response of all sensors must be checked in detail to make sure that all sensors are working properly. If sensor malfunctioning is detected, the proof load test should not be attempted, and the sensor should be replaced first. Then, this low load level should be applied again to confirm that all sensors are working properly.

When a cyclic loading protocol is used, the reproducibility of the sensor output for identical load cases needs to be confirmed. In addition, the linearity and symmetry of measurements should be verified after each load cycle. If the measurements do not align with the expected response, it is necessary to analyze in more detail what is happening within the structure or with the sensors, the data acquisition system, or the data visualization system.

4.2 Final verification of stop criteria

The stop criteria are verified in real-time during a proof load test. The main conclusion of a proof load test is made at the end of the on-site test:

- 1. the bridge has been shown to fulfil the requirements of the code if the proof load test was successful (the target proof load is applied without observing signs of distress), or
- 2. the bridge should be used for a lower load level, if a stop criterion was exceeded prior to achieving the target load level, but if a load that corresponds to a lower load level was achieved.

However, the last step of a load test, as discussed in Chapter 7, is to post-process all data, report the results of the proof load test to the owner, and formulate recommendations.

For a proof load test, the results of the measurements that are reported are the output of all sensors, in a graphical manner, as well as the verification of the measurements against the stop criteria. In this stage, the measurements should be corrected for the support displacements for bridges on elastomeric bearings and for the effect of temperature and humidity. From the corrected data, the following output should be developed for the report:

- The load-displacement diagram of the test as executed, with all load cycles, and the envelope of the load-displacement diagram.
- The measured loading protocol. The protocol is shown as the load versus time diagram (see for example Figure 6) if hydraulic jacks were used, or loading paths and load versus time at a fixed position for testing with loading vehicles. If hydraulic jacks were used, the measured forces in the wheelprints separately should be plotted as well to show that the load was distributed as intended (equally or to fulfil a certain ratio of values between axles).

- Deformation profiles: for each load level, the deformation profiles in the longitudinal and transverse direction should be shown based on the net displacement of the superstructure. An example is shown in Figure 9.
- Crack width for reinforced concrete bridges: the opening of the measured crack(s) should be presented as a function of time and as a function of applied load.
- Strains: the results of the measured strains as a function of time and as a function of the applied load should be plotted. For girders, the strain distribution over the girder height and position of neutral axis should be shown.
- Other measurements: if a structural element was found to require additional attention during the technical inspection prior to the proof load test, this element should be monitored during the proof load test, and the measured results should be reported and discussed.

Based on the corrected data, the final verification of the stop criteria should be reported. It is good practice to compare the strains and deflections that were measured in the experiment should be compared to the predictions made with the linear finite element model used to determine the target proof load and to prepare the proof load test.



Figure 9: Plot of deflections in the longitudinal direction, taken from the shear-critical loading position on viaduct De Beek (Koekkoek et al. 2016). From this plot, it can be seen that the behavior over the different load levels is linear.

Another element that needs to be reported is the total applied load. When dead weights are used, the number of dead weights and their individual weight should be reported. When loaded vehicles are reported, the results of weighing each vehicle without and with its cargo should be reported. When intermediate load levels are achieved by applying increments of cargo, the vehicle with its cargo should be weighed prior to each load application. When jacks are used, the weight of the additional elements that are used for the test setup should be added to the load that is applied with hydraulic pressure. For this case, for example, the weight of the jacks themselves should also be considered, see Figure 10. If load cells are used to measure the applied load, the results of the calibration should be given. If the calibration has an effect on the applied load, this correction should be part of the post-processing stage. Photographs of the execution of the load test should be added to the report for future reference.



Figure 10: Weight of a single jack as used during a proof load test.

5 BRIDGE ASSESSMENT BASED ON PROOF LOAD TESTS

If a proof load test has been carried out, and the test was successful (the structure could carry the target proof load), then it has been demonstrated experimentally that the structure can carry the studied load combination. A further assessment is not necessary. This idea is followed as well by the rating procedure after a proof load test from the MBE (AASHTO 2016). The rating factor will be at least RF = 1 after a proof load test when the load calculated to be equivalent to the live loads from the code is applied during the proof load test. The rating factor will be larger than 1 if loading to higher levels was carried out. The target proof load from the MBE is determined such that the rating factor becomes RF = 1. After the proof load test, the rating factor RF_0 is determined as:

$$RF_0 = \frac{OP}{L_R \left(1 + IM\right)} \tag{19}$$

with

$$OP = \frac{k_0 L_p}{X_{pA}} \tag{20}$$

with L_R the load rating vehicle, *IM* the dynamic impact factor, L_p the applied maximum load in the proof load test, and X_{pA} as defined in Equation (1). When a proof load test is successful, the applied maximum load L_p is the target proof load L_T . The factor k_0 takes into account if the proof load test was successful or not: $k_0 = 1$ if the target proof load was reached and $k_0 = 0.88$ if signs of distress were observed prior to reaching the target proof load. The 12 percent reduction is consistent with observations that show that nominal material properties used in calculations are typically 12 percent below observed material properties from tests. It can be seen from Equations (19), (20), and (4) that if $L_p = L_T$, and thus $k_0 = 1$, the value of RF_0 becomes $RF_0 = 1$.

When a Unity Check is used instead of a Rating Factor, similar procedures are followed. Whereas the Unity Check was larger than 1 prior to the proof load test or could not be determined due to the large uncertainties, it will be found to be equal to or smaller than 1 based on the results of the proof load test. A Unity Check UC = 1 is found when exactly the target proof load is applied during the test, and UC < 1 is found when a larger load is applied. When different safety levels and their corresponding load factors are considered as in the Netherlands, the assessment has to be carried out at the highest safety level required by the governing codes.

For other load combinations and/or spans that were not tested, it may be necessary to carry out an assessment by taking into account the benefit obtained from the proof load test (Lantsoght et al. 2018a). To take into account the information obtained from the proof load test, the finite element model that was used for the determination of the critical position and target proof load can be updated with the measurements from the proof load test. The principles for updating the finite element model are similar as for a diagnostic load test, and have been discussed in Part III. The possible sources for differences (Barker 2001) between the calculated and measured deformations and strains need to be identified, and the differences between the tested structure and the finite element model should be made as small as possible. Once the finite element model is updated, it can also be used to rate the entire structure when only one span is proof load tested, or it can be used to apply other load combinations in the finite element model. Updating the finite element model also results in a better understanding of the structure's behavior and can facilitate future ratings. It is not allowed to take the ratio of the rating factor after and before the proof load test, and multiply the rating factors of other spans and/or for other load combinations with this ratio. This method is too crude, and does not take into account the uncertainties on the results of the proof load test, as well as the differences between the structural elements or spans that must be assessed. For buildings, NEN 8700:2011 (Code Committee 351001 2011a) gives a method to cover all floors of a building when only a limited number of floors are tested. This approach can only be extended to bridges when all spans are equal in geometry and material properties.

The decisions about the tested structure that are taken after a proof load test remain the full responsibility of the bridge owner. The report about the proof load test includes the measurements, the assessment of the structure, and possible advice. This advice can include the removal or application of posting to the considered bridge, or it can be a recommendation for further research and (material) testing of the considered bridge to better evaluate the material properties and state of degradation. The application of this advice is the decision and responsibility of the bridge owner.

6 SUMMARY AND CONCLUSIONS

This chapter discussed the methodology for proof load testing. All general recommendations that apply to all types of load tests were discussed in detail in Part II. Here, topics that are of specific interest for proof load tests are highlighted.

The first important topic for proof load testing is the determination of the target proof load. Regardless of the considered code, the main idea for the target proof load is that this load has a magnitude that will result in a sufficient rating or assessment of the tested structure. As such, the procedures for determining the target proof load are inherently linked to the assessment practices. Where assessment codes and guidelines prescribe certain vehicles that need to be rated for, the determination of the target proof load is more straightforward, which can be seen in the provisions from the AASHTO Manual for Bridge Evaluation for the determination of the target proof load. When more general live load models are used, more choices need to be made to determine the target proof load, as can be seen when looking at the method used in Dutch practice.

The second topic that was discussed is related to the execution of proof load tests. For the execution, the loading method becomes important, since a relatively large load needs to be applied. Dead weights, special vehicles, and a loading frame with hydraulic jacks are options, which each have their advantages and disadvantages. Nowadays, most proof load tests on bridges are carried out either by using special vehicles or by using a setup with a loading frame and hydraulic jacks. Another important element of the execution of proof load tests is the sensor plan. The applied sensors are used to monitor the structural response in real-time during the bridge load test, and to verify if no signs of irreversible damage occur. To verify the linearity, reproducibility, and symmetry of the measurements, a cyclic loading protocol is recommended. Moreover, a cyclic loading protocol allows for the verification of all measurements after each load step, to analyze if further loading can be allowed. This analysis is carried out based on the so-called "stop criteria". The stop criteria are based on the measured parameters. If a stop criterion is exceeded, further loading could result in irreversible damage to the structure or even collapse, and further loading is not permitted. After a proof load test, acceptance criteria may need to be checked, depending on the governing code.

The third topic that was discussed in this chapter is the processing of the results of the proof load test. The result of a proof load test is pass/fail: either the structure can carry the target proof load, and the test is successful for the considered load combination, or a stop criterion is exceeded prior to achieving the target proof load. For the latter case, it must be analyzed if the structure was able to resist a load that corresponds to lower demands during the proof load test. In that case, the conclusion of the proof load test may be that the structure is suitable for the use at a reduced demand level. In some cases, more load than the target proof load can be applied, as long as none of the stop criteria is exceeded, to learn more about the lower bound of the structural capacity. This latter method is generally not allowed by codes and only carried out for special cases.

As can be seen from the discussion about the outcome of a proof load test, the main answer is given at the end of the proof load test itself. The result of the assessment of the structure for the considered load combination is found by the outcome of the proof load test. For other load combinations, or when other structural elements or spans that were not subjected to the proof load test must be assessed, the results of the proof load test can be taken into account. For this purpose, the finite element model that was used to determine the target proof load can be updated with the results of the experiment, as done for a diagnostic load test. The updated model can then be used for an improved assessment of elements or spans that were not subjected to a proof load test or to facilitate future assessments for special vehicles and other load combinations.

For the post-processing and reporting of the test, it is important to give a visual overview of the observations made during the experiment, and to write down the conclusions that were drawn at the end of the test. The post-processing also allows for the correction of the data for the effect of temperature and humidity, and to find the net deflection of the superstructure by correcting for the measured deflections at the supports. In the report, the total applied load must be mentioned, and the verification of the stop criteria must be included. Photographs of the execution of the load test should illustrate the report for future reference.

REFERENCES

- AASHTO 2016. *The manual for bridge evaluation with 2016 interim revisions,* Washington, D.C., American Association of State Highway and Transportation Officials.
- ACI COMMITTEE 437 2007. Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria (ACI 437.1R-07). Farmington Hills, MA.
- ACI COMMITTEE 437 2013. Code Requirements for Load Testing of Existing Concrete Structures (ACI 437.2M-13) and Commentary Farmington Hills, MA.
- BARKER, M. G. 2001. Quantifying Field-Test Behavior for Rating Steel Girder Bridges. Journal of Bridge Engineering, 6, 254-261.
- BENITEZ, K., LANTSOGHT, E. O. L. & YANG, Y. 2018. Development of a Stop Criterion for Load Tests based on the Critical Shear Displacement Theory. *IALCCE 2018*. Ghent, Belgium.
- BRETSCHNEIDER, N., FIEDLER, L., KAPPHAHN, G. & SLOWIK, V. 2012. Technical possibilities for load tests of concrete and masonry bridges. *Bautechnik*, 89, 102-110 (in German).
- CASAS, J. R. & GÓMEZ, J. D. 2013. Load Rating of Highway Bridges by Proof-loading. *KSCE Journal of Civil Engineering*, 17, 556-567.
- CEN 2002. Eurocode Basis of structural design, NEN-EN 1990:2002 Brussels, Belgium: Comité Européen de Normalisation.
- CEN 2003. Eurocode 1: Actions on structures Part 2: Traffic loads on bridges, NEN-EN 1991-2:2003. Brussels, Belgium: Comité Européen de Normalisation.
- COCHET, D., CORFDIR, P., DELFOSSE, G., JAFFRE, Y., KRETZ, T., LACOSTE, G., LEFAUCHEUR, D., KHAC, V. L. & PRAT, M. 2004. Load tests on highway bridges and pedestrian bridges (in French). Bagneux-Cedex, France: Setra Service d'Etudes techniques des routes et autoroutes.
- CODE COMMITTEE 351001 2011a. Assessement of structural safety of an existing structure at repair or unfit for use Basic Requirements, NEN 8700:2011 (in Dutch), Delft, The Netherlands, Civil center for the execution of research and standard, Dutch Normalisation Institute.
- CODE COMMITTEE 351001 2011b. Assessement of structural safety of an existing structure at repair or unfit for use Loads, NEN 8701:2011 (in Dutch), Delft, The Netherlands, Civil center for the execution of research and standard, Dutch Normalisation Institute.
- COPE, R. J. 1985. Flexural Shear Failure of Reinforced-Concrete Slab Bridges. *Proceedings of the Institution of Civil Engineers Part 2-Research and Theory*, 79, 559-583.
- DEUTSCHER AUSSCHUSS FÜR STAHLBETON 2000. DAfStb-Guideline: Load tests on concrete structures (in German). Deutscher Ausschuss fur Stahlbeton,.
- FRÝBA, L. & PIRNER, M. 2001. Load tests and modal analysis of bridges. *Engineering Structures*, 23, 102-109.
- KOEKKOEK, R. T., LANTSOGHT, E. O. L., BOSMAN, A., YANG, Y., VAN DER VEEN, C. & HORDIJK, D. A. 2015. Proof loading of the viaduct in the Zijlweg Risk Analysis

and Planning. Stevin Report nr. 25.5-15-07. he Netherlands: Delft University of Technology.

- KOEKKOEK, R. T., LANTSOGHT, E. O. L., YANG, Y. & HORDIJK, D. A. 2016. Analysis report for the assessment of Viaduct De Beek by Proof Loading. Stevin Report 25.5-16-01. Delft, The Netherlands: Delft University of Technology.
- LANTSOGHT, E. 2017. Development of a stop criterion for shear based on aggergate interlock. Stevin Report nr. 25.5-17-09. Delft, the Netherlands: Delft University of Technology.
- LANTSOGHT, E. O. L., DE BOER, A., VAN DER VEEN, C. & HORDIJK, D. A. 2018a. Modelling of the proof load test on viaduct De Beek. *Euro-C*. Austria.
- LANTSOGHT, E. O. L., DE BOER, A., VAN DER VEEN, C. & WALRAVEN, J. C. 2013a.
 Peak shear stress distribution in finite element models of concrete slabs. *In:* ZINGONI,
 A. (ed.) *Research and Applications in Structural Engineering, Mechanics and Computation.* Cape Town, South Africa: Taylor and Francis.
- LANTSOGHT, E. O. L., KOEKKOEK, R. T., VAN DER VEEN, C., HORDIJK, D. A. & DE BOER, A. 2017a. Pilot Proof-Load Test on Viaduct De Beek: Case Study. *Journal of Bridge Engineering*, 22, 05017014.
- LANTSOGHT, E. O. L., VAN DER VEEN, C., DE BOER, A. & ALEXANDER, S. D. B. 2017b. Extended Strip Model for Slabs under Concentrated Loads. *ACI Structural Journal*, 114, 565-574.
- LANTSOGHT, E. O. L., VAN DER VEEN, C., DE BOER, A. & HORDIJK, D. A. 2017c. Proof load testing of reinforced concrete slab bridges in the Netherlands. *Structural Concrete*, 18, 597-606.
- LANTSOGHT, E. O. L., VAN DER VEEN, C., DE BOER, A. & WALRAVEN, J. C. 2013b. Recommendations for the Shear Assessment of Reinforced Concrete Slab Bridges from Experiments *Structural Engineering International*, 23, 418-426.
- LANTSOGHT, E. O. L., VAN DER VEEN, C. & HORDIJK, D. A. 2018b. Monitoring crack width and strain during proof load testing. *IABMAS 2018*.
- LANTSOGHT, E. O. L., VAN DER VEEN, C. & HORDIJK, D. A. 2018c. Proposed stop criteria for proof load testing of concrete bridges and verification. *IALCCE 2018*. Ghent, Belgium.
- LANTSOGHT, E. O. L., YANG, Y., VAN DER VEEN, C., DE BOER, A. & HORDIJK, D. A. 2017d. Beam experiments on acceptance criteria for bridge load tests. *ACI Structural Journal*, 114, 1031-1041.
- NCHRP 1998. Manual for Bridge Rating through Load Testing. Washington, DC.
- RESEARCH INSTITUTE OF ROADS AND BRIDGES 2008. The rules for road bridges proof loadings (in Polish). Warsaw, Poland.
- RIJKSWATERSTAAT 2013. Guidelines Assessment Bridges assessment of structural safety of an existing bridge at reconstruction, usage and disapproval (in Dutch), RTD 1006:2013 1.1.
- SARAF, V. K., NOWAK, A. S. & TILL, R. 1996. Proof load testing of bridges. In: FRANGOPOL, D. M. & GRIGORIU, M. D. (eds.) Probabilistic Mechanics & Structural Reliability: Proceedings of the Seventh Specialty Conference. Worcester, MA, USA.
- VARELA-ORTIZ, W., CINTRÓN, C. Y. L., VELÁZQUEZ, G. I. & STANTON, T. R. 2013. Load testing and GPR assessment for concrete bridges on military installations. *Construction and Building Materials*, 38, 1255-1269.

- YANG, Y., DEN UIJL, J. A. & WALRAVEN, J. 2016. The Critical Shear Displacement theory: on the way to extending the scope of shear design and assessment for members without shear reinforcement. *Structural Concrete*, 17, 790-798.
- YANG, Y., WALRAVEN, J. & DEN UIJL, J. A. 2017. Shear Behavior of Reinforced Concrete Beams without Transverse Reinforcement Based on Critical Shear Displacement. *Journal of Structural Engineering*, 143, 04016146-1-13.