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State-of-the-art on load testing of concrete bridges

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Abstract

Load testing of bridges is a practice that is as old as their construction. In the past, load testing gave the traveling public a feeling that a newly opened bridge is safe. Nowadays, the bridge stock in many countries is aging, and load testing is used for the assessment of existing bridges. This paper aims at giving an overview of the current state-of-the-art with regard to load testing of concrete bridges. The work is based on an extensive literature review, dealing with diagnostic and proof load testing, and looking at the current areas of research. Additional available information about load testing of steel, timber, and masonry bridges, buildings, and collapse testing is briefly cited. For the implementation of load testing to the aging bridge stock on a large scale, efficiency in procedures is required. The areas requiring future research are identified, based on the available body of knowledge.

Keywords

concrete bridges; existing bridges; instrumentation; load testing; proof load testing; state-of-the-art

1 Introduction

Load testing of bridges is a practice as old as building bridges [1]. In the early days, when analytical methods for determining bridge response were not well-developed yet, load tests were carried out prior to opening bridges to the traveling public, as a way to show that the bridge is safe. Sometimes, the load test resulted in the collapse of the new bridge [1]. In some countries, such as Switzerland [2] and Italy [3], such load tests are still required prior to opening.

Since the early days, load testing has also been used to evaluate the performance of existing bridges. While nowadays the analytical methods for predicting bridge responses are much more refined, and the need for convincing the traveling public that a bridge is safe has diminished, the uncertainties on the bridge's behavior increase over time due to the effect of deterioration mechanisms. Moreover, the design methods prescribed in the codes aim at providing a conservative method, suitable for design. Upon assessment, the goal is to have an estimate of the bridge behavior that is as precise as possible. Therefore, additional mechanisms, which are traditionally not considered in the codes, can be counted on, such as transverse load distribution for shear in reinforced concrete slabs [4, 5]. In bridge types where the additional mechanisms are not well-known, load tests can be used to have a better understanding of the bridge behavior. This understanding can be in terms of response, in order to calibrate analytical models, as used for diagnostic load testing, or in terms of fulfilling the requirements of the code with regard to performance under the prescribed live loads, as used for proof load testing [6]. In proof load tests, stop criteria are identified. These criteria are evaluated based on the measured structural responses. If a stop criterion is exceeded, further loading can cause irreversible damage or collapse. Therefore, when a stop criterion is exceeded, the proof load test must be terminated.

To determine which type of field testing is recommended, a decision-making approach was developed [7].

This paper gives an overview of the state-of-the-art with regard to load testing, by discussing knowledge related to diagnostic load testing, proof load testing, testing of other types of structures, and current codes and guidelines. The focus of this paper is on bridges, for two reasons:

1. The live load models combine concentrated and distributed loads, which results in discussions about the representative test load and the method of load application.
2. Bridge load testing typically requires lane or bridge closures, affecting the traveling public. Therefore, a swift execution of a load test is more important for bridges than for buildings.

2 Diagnostic load testing of concrete bridges

2.1 Determination of transverse flexural distribution

Strain measurements over the width of a bridge can be used to determine the transverse distribution based on the field test results. A guideline for using diagnostic load test results for determining the transverse distribution is prescribed in ACI 342R-16 [8]. When comparing the transverse flexural distribution from the AASHTO LRFD code [9] to field measurements of the flexural distribution from diagnostic load tests, differences of over 500% in the resulting rating factor are found [10, 11]. The use of diagnostic load tests for the determination of the transverse flexural distribution has been reported in Florida [12, 13], Delaware [14] and Ohio [15] on concrete slab bridges, in Australia [16] on girder bridges, in Texas on reinforced concrete pan girder bridges [17], in Pennsylvania on concrete T-beam bridges [18], and in Poland on prestressed concrete bridges [19].

2.2 Evaluation of stiffness

Deflection measurements in diagnostic load tests are used to compare the analytical stiffness of a bridge to the actual stiffness [20], and to assess the influence of material degradation on the structural performance. On the other hand, the increased hydration of cement paste over time results in an increased concrete compressive strength, and an increased stiffness over time [21]. To evaluate if concrete girders are cracked or uncracked, strain gages can be applied over the height of the girder to determine the position of the neutral axis [22-24].

Besides the stiffness of the bridge elements that are to be rated, the stiffness of the piers and bearings can also be evaluated in a diagnostic load test [25]. Finally, a diagnostic load test can be used to evaluate how non-structural elements, such as parapets and railings, contribute to the overall stiffness of a bridge [26]. Composite action of the structural elements can also be verified [27].

2.3 Testing prior to opening, over time, and after rehabilitation

Diagnostic load testing can be used upon opening of a new bridge to quantify load bearing mechanisms that typically are not accounted for in design, such as arching action [28]. Newly proposed design methods can be verified with a diagnostic load test to show the correspondence between the proposed design method and the actual structural behavior [29]. For uncommon bridge types, such as integral bridges [30], bridges with self-consolidating concrete [31], high performance concrete [32, 33], lightweight concrete [34], and new precast systems [35, 36], diagnostic load tests can be used upon opening to verify the design assumptions. For non-standard concrete mixes, these design assumptions can be related to the time-dependent behavior of the concrete, or the assumed stiffness.

A diagnostic load test upon opening of a bridge can be used as a reference measurement. If the load test is then repeated over time, the results on the aged bridge can be compared to the reference [37].

To verify if rehabilitation measures are performing properly, diagnostic load tests can be used [38, 39]. The impact of a rehabilitation intervention can also be quantified by carrying out a load test prior to and after rehabilitation [40]. Just as bridges can be load tested at several points over time, strengthened bridges can be load tested over time to check the performance over time and possible degradation of the rehabilitation measures [41, 42].

3 Proof load testing of concrete bridges

3.1 Determination of the target proof load

The goal of a proof load test is to directly, by means of the proof load test, show that the tested bridge can carry the prescribed factored live loads without distress. As such, the determination of the target proof load, which needs to reflect the prescribed factored live loads, is of the utmost importance. In the past, the most common load combination for determination of the target proof load was [43]:

$$PL = D_d + L_d$$

with D_d the factored dead load and L_d the factored live load. A rule of thumb that was used to determine the target proof load was that the proof load should be twice the maximum allowable load [44]. Similarly, in Germany, a factor of 1.5 for the traffic loads is used [45]. More recently [46], the determination of the target proof load is determined based on equivalent sectional moments: the bending moment caused by the proof load should equal the bending moment caused by the factored live load model.

For Europe, where the prescribed live load model from NEN-EN 1991-2:2003 [47] does not directly reflect a certain vehicle type nor the specific situation of the different European countries, proof load factors were determined. These factors are used to multiply a nominal value of the traffic action to obtain the maximum load effect required in the proof load test. These factors were calibrated based on WIM data from various European countries analyzed separately [48, 49], and determined for different reliability levels, different span lengths, and different ratios R/R_n.

3.2 Large proof loading campaigns

Since proof load testing involves large loads, typically special vehicles or other loading methods are required for proof load testing. In Florida, a special vehicle [50] and in Germany, the BELFA vehicle [51] were developed. A photograph of the BELFA is shown in Figure 1. In some cases, military vehicles such as tanks have been used to apply large loads [52]. Proof load testing is integrated in New York State's bridge safety assurance program [53]. In the Netherlands, a number of pilot proof load tests have been carried out [54] for the future development of guidelines for proof load testing [55]. An example of a bridge, proof load tested in the Netherlands using a system of hydraulic jacks, is shown in Figure 2.

3.3 Evaluation of bridges without plans

Proof load testing is preferred over diagnostic load testing when the uncertainties on the structure are large. One application is using proof load tests to evaluate bridges without structural plans [56, 57]. This application combines estimates of the prestressing steel based on the Magnel diagrams, using a rebar scanner to estimate the available prestressing, and the actual testing at diagnostic and proof load levels. The combination of these activities then leads to an improved bridge rating. Many bridges owned by the US Army do not have plans, and have the added challenge that they need to be rated for and tested with a loading vehicle that is representative of the military vehicles that use these bridges [52]. Again, a combination of non-destructive testing and proof load testing was proposed to rate these bridges.

In Delaware [58], analytical methods, using sectional analysis and the resulting load-displacement diagram with an unknown steel area and height of the compressive zone, are combined with proof load testing for the rating of bridges without plans.

3.4 Evaluation of deteriorated bridges

Another case where proof loading is to be preferred over diagnostic load testing is when deterioration and material degradation have resulted in large uncertainties with regard to the capacity of an existing bridge. For old bridges [59], where the amount of degradation is difficult to estimate, this method can be used. For bridges with damage caused by alkali-silica reaction, where the effect of the material degradation on the shear capacity is difficult to estimate, proof load testing is also recommended [60, 61].

4 In-situ testing of other structures

4.1 Other bridge types

The procedures for diagnostic and proof load testing are generally independent of the type of bridge that is tested. The only differences in the execution are related to the response that should be measured, and the stop criteria in proof load testing. For the updating of a load rating based on analytical methods with the results of a diagnostic load test, clear recommendations were originally developed for steel bridges [26, 62, 63]. In these recommendations, the sources for differences between analytical predictions and measured responses that are considered and analyzed separately are the actual impact factor, the actual section dimensions, unaccounted system stiffness resulting from curbs and railings, the actual lateral live load distribution, the bearing restraint effects, the actual longitudinal live load distribution, and the effect of unintended composite action. Unintended composite action [64] can break down at the ultimate limit state, and should be ignored in strength calculations [65].

When historical bridges are load tested, special care and preparation is required [66-70]. Field tests on other bridge types have also been used to evaluate the performance of new concepts [71-73], as well as the performance of retrofitting actions [74-77]. Since arch bridges (masonry arch bridges or plain concrete arches) have a large redistribution capacity, load testing can be recommended, as analytical assessment virtually never shows sufficient capacity [78].

4.2 Buildings

For buildings, proof load testing is more common than diagnostic load testing. The German guidelines [79] and ACI 437.2M-13 [80] are developed for building applications. The target proof load for buildings [81] was determined as 85% of the factored design gravity loads, minus the loads in place at the time of testing. Typical applications of proof load testing of buildings include performance testing of existing structures [82-86], checking an incomplete project [87], verifying strengthening measures [88], and verifying performance including seismic loading [89, 90].

4.3 Collapse tests

Collapse tests can be used to learn more about the onset of nonlinear behavior and the ultimate capacity of structures. This information can then be translated into stop criteria for proof load tests. Both bridges [5, 16, 91-104] and buildings [105-107] have been subjected to collapse tests in the past.

5 Current codes and guidelines

5.1 German guideline

The German guideline [79] was developed for plain and reinforced concrete buildings. The guideline does not allow for testing of shear-critical structures. Load testing is permitted in case of insufficient knowledge on the calculation methods, the composite action and load path, the effect of material damage, and the effect of repair actions. A proof load test is either finished when the target proof load is achieved, or when a stop criterion is exceeded. This safety philosophy is shown in Figure 3. Five stop criteria are identified. The concrete strain ε_c is limited to:

$$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0} \tag{1}$$

with $\varepsilon_{c,lim}$ = 0.8 ‰ when the concrete compressive strength is larger than 25 MPa, and ε_{c0} the strain in the concrete caused by the permanent loads. The steel strain ε_{s2} is limited to:

$$\varepsilon_{s2} < 0.7\frac{f_{ym}}{E_s} - \varepsilon_{s02} \tag{2}$$

with f_{ym} the yield stress of the steel, E_s the Young's modulus of the steel, and ε_{s02} the strain in the steel caused by the permanent loads. When the stress-strain relationship of the steel is fully known, Eq. (2) is replaced by:

$$\varepsilon_{s2} < 0.9\frac{f_{0.01m}}{E_s} - \varepsilon_{s02} \tag{3}$$

with $f_{0.01m}$ the average yield strength based on a strain of 0.01% (elastic zone). The third stop criterion defines limits to the crack width for new cracks and increase in crack width for existing cracks, as shown in Table 1. The fourth stop criterion limits the residual deflection to 10% of the maximum deflection, or to the point of onset of nonlinear behavior, and the fifth stop criterion limits deformations in the shear span for beams without shear reinforcement. Additional stop criteria are when the measurements indicate critical changes in the structure, when the stability is endangered, and when critical displacements occur at the supports.

5.2 Manual for Bridge Rating through Load Testing

The recommendations from the Manual for Bridge Rating through Load Testing [108] are also included in the Manual for Bridge Evaluation [109]. The Manual describes diagnostic and proof load testing. Testing of shear-critical and fracture-critical bridges is not permitted. The Manual links field testing to the determination of the rating factor of the bridge component under study. For diagnostic load testing, a method is proposed to update the rating factor based on the difference between the analytically determined and experimentally measured strains. For proof load testing, the operating rating factor is found to be one if the applied proof load is the target proof load. This target proof load is determined as:

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

The value of X_{PA} ranges between 1.3 and 2.2, with 1.4 as the standard value before adjustments are applied. These calibrations were based on a reliability index of 2.3 for the operating level, and normally distributed parameters.

5.3 ACI 437.2M-13

ACI 437.2M-13 describes loading protocols and stop criteria for the proof load testing of structural concrete buildings. The prescribed test load magnitude, *TLM*, is based on a load combination, and is the largest of:

$$TLM = 1.3\left(D_W + D_S\right) \tag{5}$$

$$TLM = 1.0D_W + 1.1D_S + 1.6L + 0.5\left(L_r \text{ or } SL \text{ or } RL\right) \tag{6}$$

$$TLM = 1.0D_W + 1.1D_S + 1.6\left(L_r \text{ or } SL \text{ or } RL\right) + 1.0L \tag{7}$$

Equations (5), (6), and (7) are valid when only part of the structure is assumed to have flaws, or when the structure is statically indeterminate. For other cases, lower load factors can be used.

Two loading protocols are described, a monotonic and a cyclic loading protocol, see Figure 4. The monotonic loading protocol requires that the maximum load be applied for 24 hours, and is similar to technologies used since the 1920s [46]. For the cyclic loading protocol, from which similar conclusions can be drawn [110], acceptance criteria are defined. The first acceptance criterion (see Figure 5a) is the deviation from linearity index, I_{DL}:

$$I_{DL} = 1 - \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} \leq 0.25 \quad (8)$$

The second acceptance criterion (see Figure 5b) is the permanency ratio I_{pr}, which requires the comparison between pairs of load cycles at the same load level:

$$I_{pr} = \frac{I_{p(i+1)}}{I_{pi}} \leq 0.5 \quad (9)$$

$$I_{pi} = \frac{\Delta_r^i}{\Delta_{\max}^i} \quad (10)$$

$$I_{p(i+1)} = \frac{\Delta_r^{(i+1)}}{\Delta_{\max}^{(i+1)}} \quad (11)$$

The last acceptance criterion prescribes that the residual deflection should fulfil the following requirement:

$$\Delta_r \leq \frac{\Delta_l}{4} \quad (12)$$

$$\Delta_l \leq \frac{l_t}{180} \quad (13)$$

5.4 Other guidelines

In France [111], every bridge has to be subjected to a diagnostic load test prior to opening, including pedestrian bridges. Testing is carried out with vehicles or with ballast blocks. The required load level should correspond to the traffic with a return period between one week and one year. The measured and analytically determined responses need to be compared, and the measured responses may not be 1.5 times larger than the analytically determined responses. For standard bridge types, simplified guidelines are given. For example, for concrete slab bridges, two trucks of 26 metric ton should be used per lane.

In Ireland [112], diagnostic load tests can be used to support the assessment of existing bridges. Testing of shear-critical bridges is not permitted. The measurements of strains and deflections can be analyzed to assess the hidden reserve capacity of the bridge, which can then be implemented into the assessment calculations.

The guideline for load testing from the UK [113] prescribes diagnostic load tests on existing bridges, which became important as a result of changes to the live load model, and is also suitable for testing new bridges. Load testing is not recommended when a brittle failure mode can occur, or for a structure in a poor condition.

6 Recent research insights

6.1 Stop criteria in proof load testing

Current developments in terms of stop criteria for the German guidelines look at possible improvements, and perhaps the inclusion of shear [114, 115]. The best results were obtained when studying the load-displacement diagram, crack widths, and plastic deformations. For shear, additional measurements in the shear span, such as relative deformations and curvatures were explored, rather than just the deflections between the load and the support. For shear, local damage (inclined crack reaching half the depth of the beam, inclined crack growing into a bending crack, or inclined crack reaching a 45^o orientation) was also defined as a stop criterion, based on beam tests in the laboratory. The difficulty with the implementation of this criterion is that it would require visual inspection or photogrammetry to be used in the field.

In the Netherlands, research on beams tested in the laboratory is used to formulate recommendations for the stop criteria, for both bending and shear [116-118]. Further research is required to determine the critical crack width and the limiting strain for proof load testing for shear.

6.2 Measurement techniques

Besides the traditional measurements of deflections, support deformations, and strains, other measurement techniques are being explored. Research on the use of acoustic emission signals during load testing [48, 57, 119, 120], and the development of stop criteria based on these measurements [121], is close to reaching recommendations. For the application of acoustic emission signals during load tests, it is important to distinguish between laboratory and field conditions.

A second option that is under research is the use of fiber optic measurements [122]. For concrete bridges [123, 124], the difficulty is that when cracks form, the fiber can break. For prestressed concrete, currently good results are obtained [125]. The added benefit of fiber optic measurements is that these can be installed for long-term monitoring of the bridge. For new bridges, the embedment of sensors can be interesting [126, 127], creating the opportunity to combine structural health monitoring and periodic load tests.

Remote sensing techniques that have been tested for research purposes include digital image correlation [128], radar interferometry [129, 130], and systems based on laser measurements [131]. The use of a total station is part of the common load testing practice, but has the disadvantage that the required time for taking the measurements can be considerable [31].

Whereas the possibilities for measurements and the different types of sensors keep increasing, it is important as well to think about simplifying the sensor plan. For load testing to be an economically viable method to assess bridges, it is required to keep the sensor plan as simple as possible. Reducing the sensor plan to its minimum will also reduce the on-site preparation time. Recommendations in this regard need to be developed.

6.3 Using load testing information in probabilistic assessment

When a structure can carry a certain load during a proof load test, it is known that the capacity is larger than this load [132], and the probability distribution function of the capacity can be truncated. To have an effect on the resulting reliability index, the load has to be sufficiently high [133]. The effect of proof loading is larger for structures with a larger uncertainty on the capacity [134]. The probability of failure during the proof load test also needs to be determined [135].

The probability of failure before the proof load test P_{fb} is determined with the regular convolution integral, see Figure 6a:

$$P_{fb} = \int_{-\infty}^{+\infty} \left(1 - F_s\left(r\right)\right) f_R\left(r\right) dr \qquad (14)$$

with F_s the cumulative distribution function of the loads and f_R the probability density function of the resistance. During the proof load test, only the deterministic value of the proof load s_p is applied, see Figure 6b, and the probability of failure during the test P_{fd} is determined based on the cumulative distribution function of the resistance F_R:

$$P_{fd} = F_R\left(s_p\right) \quad (15)$$

After the proof load test, the probability density function of the capacity is updated with the knowledge that the capacity is larger than the applied load s_p, so that the convolution integral of the probability of failure after the test P_{fa} becomes, see Figure 6c:

$$P_{fa} = \frac{1}{1-F_R\left(s_p\right)}\int_{s_p}^{+\infty}\left(1-F_s\left(r\right)\right) f_R\left(r\right) dr \quad (16)$$

When using a probabilistic assessment, the coefficient of variation that needs to be assumed for the distribution functions of the load and the resistance has a major influence on the resulting probability of failure and reliability index [136]. Currently, no guidelines are available with recommendations for the values of the coefficient of variation. Therefore, it is important for the international load testing community and the reliability community to cooperate in this regard and formulate recommendations. Whereas the current approaches mostly focus on the probability of failure of a component, further research is needed to link the results of load testing to the probability of failure of the entire structural system.

The live loads for assessment of existing bridges may be lower than for new bridges, as the reference period is different [137]. Additionally, for existing bridges, the load history (which can increase the reliability index) and the effect of deterioration (which can decrease the reliability index) should be taken into account [138, 139].

As the bridge maintenance community is moving towards life-cycle cost optimization techniques, this philosophy should also be adopted for load testing. For monitoring, methods are available to determine the optimum age of the structure and time frame for monitoring [140-

143]. Load testing should not be considered as an isolated event during the life-cycle if a structure, but should be embedded within a plan that includes inspections, load tests, maintenance and repair activities, and monitoring. The optimal time in a bridge's lifespan for a load test should then be determined by minimizing the total cost and maximizing the bridge performance and expected service life [144, 145].

7 Discussion and needs for future research

Even though load testing has been part of the engineering practice for the last century, a conclusive framework for diagnostic and proof load testing of bridges is still missing, which is reflected by the large differences between the existing codes and guidelines in different countries. Especially for proof load testing, different recommendations for the target proof load, loading protocol, and stop criteria can be found in the literature. Further research is needed to develop unified recommendations. For Europe, these recommendations should follow the safety philosophy and basic principles of the Eurocodes. Additionally, none of the existing codes and guidelines permit proof load testing of shear- and fracture-critical bridges, while these bridges comprise a significant portion of the structures with low ratings. For example, in the Netherlands 600 reinforced concrete slab bridges were found to be shear-critical [146]. Some of these bridges, especially those where the uncertainties caused by material degradation are large, are good candidates for load testing.

The current methods for load testing are mostly rooted in deterministic approaches. To make the step to a reliability-based approach, further research is needed. The influence of previous traffic, and the coefficients of variation that should be assumed for the load and resistance need to be determined. Moreover, there is a need to move from a member-based approach to a systems-based approach, which requires the incorporation of systems reliability methods.

The advantages of load testing are that field test data can be used to have a better understanding of the response of a bridge. Uncertainties with regard to the load distribution, the structural performance, the influence of material degradation, etc. can be reduced, which leads to a better assessment of the tested structure.

While load testing of bridges has clear advantages for assessment, its limitations should also be discussed. Load tests, especially proof load tests, can be time-consuming and expensive. Lane closures and/or full bridge closures may be necessary, which affects the traveling public. Extrapolation of data measured on one span to another span may not be permitted, which can raise doubts for the assessment of a bridge when its critical span cannot be tested.

8 Summary

Two types of in-situ tests on concrete bridges are typically carried out: diagnostic load tests and proof load tests. Diagnostic load tests aim at using measured structural responses for the updating of an analytical model. Information results with regard to the transverse flexural distribution, overall stiffness or member stiffness, and the behavior of the structure over time (if several diagnostic load tests are carried out). The updated analytical model is then used to recalculate the rating factor of the bridge.

Proof load testing aims at immediately giving an answer to the question if the bridge can carry the prescribed factored live loads without signs of distress. A representative load is applied to the bridge, and the structural responses are carefully monitored. If the structural response indicates critical changes in the bridge prior to achieving the target proof load (i.e., a stop criterion is exceeded), the test needs to be terminated, and the bridge will have a lower rating factor. Proof load testing is particularly useful for structures with large uncertainties, such as bridges without plans and deteriorated bridges.

The most interesting existing codes and guidelines for load testing are the German guideline, the Manual for Bridge Rating through Load Testing, and ACI 437.2M-13. The German guideline and ACI 437.2M-13 give advice on stop and acceptance criteria.

Current research related to load testing mostly focuses on the following topics:

- the definition of stop criteria, especially for brittle failure modes that currently are not permitted for proof load testing,
- new measurement techniques, and
- moving from a deterministic approach to a reliability-based approach for load testing, especially for proof load testing.

Notation List

The following symbols are used in this paper:

effR_u capacity of the structure

extF_{lim} additional load that can be applied to reach onset of nonlinear behavior

extF_{target} additional load to achieve the target proof load

f_R probability density function of the resistance

f_R* probability density function of resistance, updated with information of proof load test

f_s probability density function of the load

f_{ym} average yield strength of steel on the tension side of the cross-section

$f_{0.01m}$ average yield strength based on a strain of 0.01% (elastic zone)

l_t span length

s_p magnitude of proof load

$\tan(\alpha_i)$ the secant stiffness at any point *i* on the increasing loading portion of the load-deflection envelope

$\tan(\alpha_{ref})$ the slope of the reference secant line for the load-deflection envelope

w crack width

D_d factored dead load

D_s superimposed dead load

D_w self-weight of concrete

E_s modulus of elasticity of reinforcement steel

F_{lim} onset of nonlinear behavior

F_R cumulative distribution function of the resistance

F_s cumulative distribution function of the load

F_{target} target proof load

G_1 load caused by permanent loads

G_{di} additional permanent loads, not acting on the bridge at time of testing

I impact allowance

I_{DL} deviation from linearity index

I_{pi} permanency index for the *i*-th load cycle

$I_{p(i+1)}$ permanency index for the (*i*+1)-th load cycle

I_{pr} permanency ratio

L live load

L_d factored live load

L_r live load on the roof

L_R comparable live load due to the rating vehicle for the lanes loaded

L_T target proof load according to the Manual for Bridge Rating through Load Testing

P load

P_{fa} probability of failure after proof load test

P_{fb} probability of failure before proof load test

P_{fd} probability of failure during proof load test

P_i load in *i*-th load cycle

PL target proof load

P_{max} maximum load in load test

P_{min} baseline load

P_{ref} load in first load cycle

Q_d transient loads

SL snow load

R resistance

RL rain load

R_n load effect

TLM test load magnitude

X_{PA} target live load factor

ε_c strain measured during proof loading

$\varepsilon_{c,lim}$ limit value of the concrete strain : 0.6 ‰, and for concrete with a compressive strength larger than 25 MPa this can be increased up to maximum 0.8 ‰.

ε_{c0} analytically determined short-term strain in the concrete caused by the permanent loads that are acting on the structure before the application of the proof load

ε_{s2} steel strain during experiment: directly measured or derived from other measurements

ε_{s02} analytically determined strain (assuming cracked conditions) in the reinforcement steel caused by the permanent loads that are acting on the structure before the application of the proof load.

Δ^i_{max} maximum deformation occurring in *i*-th cycle, measured between beginning and peak of the *i*-th cycle

Δ^i_r residual deformation occurring between *i*-th and (*i*-1)-th cycle

Δ_l maximum deflection

Δ_r residual deflection

Δ_{ref} deflection in first load cycle

Δw increase in crack width of an existing crack

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References

[1] Bolle G, Schacht G, Marx S. Loading tests of existing concrete structures - historical development and present practise. fib symposium Prague, Czech Republic2011. p. 14.
[2] Moses F, Lebet JP, Bez R. Applications of field testing to bridge evaluation. Journal of Structural Engineering-ASCE. 1994;120:1745-62.
[3] Veneziano D, Galeota D, Giammatteo MM. Analysis of bridge proof-load data I: Model and statistical procedures. Structural Safety. 1984;2:91-104.
[4] Lantsoght EOL, van der Veen C, de Boer A, Walraven J. Transverse Load Redistribution and Effective Shear Width in Reinforced Concrete Slabs. Heron. 2015;60:145-80.

[5] Azizinamini A, Boothby TE, Shekar Y, Barnhill G. Old Concrete Slab Bridges. 1. Experimental Investigation. Journal of Structural Engineering-ASCE. 1994;120:3284-304.
[6] Hall WB, Tsai M. Load testing, structural reliability and test evaluation. Structural Safety. 1989;6:285-302.
[7] Farhey DN. Bridge Instrumentation and Monitoring for Structural Diagnostics. Structural Health Monitoring. 2005;4:301-18.
[8] ACI Committee 342. ACI 342R-16: Report on Flexural Live Load Distribution Methods for Evaluating Exisiting Bridges. Farmington Hills, Michigan: American Concrete Institute; 2016. p. 36.
[9] AASHTO. AASHTO LRFD bridge design specifications, 7th edition with 2015 interim specifications. 7th ed. Washington, DC: American Association of State Highway and Transportation Officials; 2015.
[10] Ohanian E, White D, Bell ES. Benefit Analysis of In-Place Load Testing for Bridges. Transportation Research Board Annual Compendium of Papers. 2017:14.
[11] Sanayei M, Reiff AJ, Brenner BR, Imbaro GR. Load Rating of a Fully Instrumented Bridge: Comparison of LRFR Approaches. Journal of Performance of Constructed Facilities. 2016;2016:2.
[12] Amer A, Arockiasamy M, Shahawy M. Load distribution of existing solid slab bridges based on field tests. Journal of Bridge Engineering. 1999;4:189-93.
[13] Arockiasamy M, Amer A. Load Distribution on Highway Bridges Based On Field Test Data: Phase III. 1998. p. 170.
[14] Jones BP. Reevaluation of the AASHTO effective width equation in concrete slab bridges in Delaware: University of Delaware; 2011.
[15] Saraf VK. Evaluation of Existing RC Slab Bridges. Journal of Performance of Constructed Facilities. 1998;12:20-4.
[16] Al-Mahaidi R, Taplin G, Giufre A. Load Distribution and Shear Strength Evaluation of an Old Concrete T-Beam Bridge. Transportation Research Record. 2000;1696:52-62.
[17] Velázquez BM, Yura JA, Frank KH, Kreger ME, Wood SL. Diagnostic load tests of a reinforced concrete pan-girder bridge. Austin, TX, USA: The University of Texas at Austin; 2000. p. 121.
[18] Catbas FN, Ciloglu SK, Aktan AE. Strategies for load rating of infrastructure populations: a case study on T-beam bridges. Structure and Infrastructure Engineering. 2004;1:221-38.
[19] Mordak AG, Manko Z. Static Load Tests of Posttensioned, Prestressed Concrete Road Bridge over Reservoir Water Plant. Transportation Research Record. 2008;2050:90-7.
[20] Aktan AE, Zwick M, Miller R, Shahrooz B. Nondestructive and Destructive Testing of Decommissioned Reinforced Concrete Slab Highway Bridge and Associated Analytical Studies. Transportation Research Record: Journal of the Transportation Research Board. 1992;1371:142-53.
[21] Hodson DJ, Barr PJ, Pockels L. Live-Load Test Comparison and Load Ratings of a Posttensioned Box Girder Bridge. Journal of Performance of Constructed Facilities. 2013;27:585-93.
[22] Jauregui DV, Licon-Lozano A, Kulkarni K. Higher Level Evaluation of a Reinforced Concrete Slab Bridge. Journal of Bridge Engineering. 2010;15:172-82.
[23] Jeffrey A, Breña SF, Civjan SA. Evaluation of Bridge Performance and Rating through Nondestructive Load Testing. University of Massachusetts Amherst; 2009. p. 271.

[24] Hag-Elsafi O, Kunin J. Load Testing For Bridge Rating: Dean's Mill Road Over Hannacrois Creek. Albany, NY: Transportation Research and Development Bureau, New York State Department of Transportation; 2006. p. 71.
[25] Jáuregui DV, Barr PJ. Nondestructive Evaluation of the I-40 Bridge over the Rio Grande River. Journal of Performance of Constructed Facilities. 2004;18:195-204.
[26] Barker MG. Quantifying Field-Test Behavior for Rating Steel Girder Bridges. Journal of Bridge Engineering. 2001;6:254-61.
[27] Nilimaa J, Blanksvärd T, Taljsten B. Assessment of concrete double-trough bridges. Journal of Civil Structural Health Monitoring. 2015;2015:29-36.
[28] Taylor SE, Rankin B, Cleland DJ, Kirkpatrick J. Serviceability of bridge deck slabs with arching action. Aci Structural Journal. 2007;104:39-48.
[29] Ferrand D, Nowak AS, Szerszen MM. Field Test and Finite Element Analysis of Isotropic Bridge Deck. Transportation Research Record. 2005;CD 11-S:153-8.
[30] Lawver A, French C, Shield CK. Field Performance of Integral Abutment Bridge. Transportation Research Record. 2000;1740:108-17.
[31] Hernandez ES, Myers JJ. In-situ field test and service response of Missouri Bridge A7957. European Bridge Conference. Edinburgh, UK2015. p. 10.
[32] Yang Y, Myers JJ. Live-Load Test Results of Missouri's First High-Performance Concrete Superstructure Bridge. Transportation Research Record. 2003;1845:96-103.
[33] Barnes RW, Stallings JM, Porter PW. Live-Load Response of Alabama's High-Performance Concrete Bridge. Transportation Research Record. 2003;1845:115-24.
[34] Taylor P, Hosteng T, Wang X, Phares B. Evaluation and Testing of a Lightweight Fine Aggregate Concrete Bridge Deck in Buchanan County, Iowa. 2016. p. 51.
[35] Konda TF, Klaiber FW, Wipf TJ, Schoellen TP. Precast Modified Beam-in-Slab Bridge System - An Alternative Replacement for Low-Volume Roads. Transportation Research Record. 2007;1989:335-46.
[36] Kirkpatrick J, Long AE, Thompson A. Load distribution characteristics of spaced M-beam bridge decks. The structural engineer. 1984;62B:86-8.
[37] McGrath TJ, Selig ET, Beach TJ. Structural Behavior of Three-Sided Arch Span Bridge. Transportation Research Record. 1995;1541.
[38] Au A, Lam C, Au J, Tharmabala B. Eliminating Deck Joints Using Debonded Link Slabs: Research and Field Tests in Ontario Journal of Bridge Engineering. 2013;18:768-78.
[39] Bell ES, Sipple JD. Special topics studies for baseline structural modeling for condition assessment of in-service bridges. Safety and Reliability of Bridge Structures2009. p. 274-89.
[40] Russo FM, Wipf TJ, Klaiber FW. Diagnostic Load Tests of a Prestressed Concrete Bridge Damaged by Overheight Vehicle Impact. Transportation Research Record. 2000;1696:103-10.
[41] Myers JJ, Holdener D, Merkle W. Load Testing and Load Distribution of Fiber Reinforced, Polymer Strengthened Bridges: Multi-year, Post Construction/Post Retrofit Performance Evaluation. FRP Composites and Sustainability: Focusing on Innovation, Technology Implementation and Sustainability. New York, NY2012. p. 163-91.
[42] Alkhrdaji T, Nanni A, Mayo R. Upgrading Missouri Transportation Infrastructure - Solid Reinforced-Concrete Decks Strengthened with Fiber-Reinforced Polymer Systems. Transportation Research Record. 2000;1740:157-63.
[43] Fu GK, Tang JG. Risk-based Proof-load Requirements for Bridge Evaluation. Journal of Structural Engineering-ASCE. 1995;121:542-56.

[44] Saraf VK, Nowak AS, Till R. Proof load testing of bridges. In: Frangopol DM, Grigoriu MD, editors. Probabilistic Mechanics & Structural Reliability: Proceedings of the Seventh Specialty Conference1996. p. 526-9.
[45] Schwesinger P, Bolle G. EXTRA - a new experiment supported condition assessment method for concrete bridges. In: Aktan AE, Gosselin SR, editors. Proc SPIE 3995, Nondestructive Evaluation of Highways, Utilities, and Pipelines IV2000. p. 11.
[46] Galati N, Nanni A, Tumialan JG, Ziehl PH. In-situ evaluation of two concrete slab systems. I: Load determination and loading procedure. Journal of Performance of Constructed Facilities. 2008;22:207-16.
[47] CEN. Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges, NEN-EN 1991-2:2003. Brussels, Belgium: Comité Européen de Normalisation; 2003. p. 168.
[48] Olaszek P, Świt G, Casas JR. Proof load testing supported by acoustic emission. An example of application. IABMAS 20122012.
[49] Casas JR, Gómez JD. Load Rating of Highway Bridges by Proof-loading. KSCE Journal of Civil Engineering. 2013;17:556-67.
[50] Shahawy MA. Non Destructive Strength Evaluation Of Florida Bridges. SPIE. Oakland, CA1995. p. 23.
[51] Bretschneider N, Fiedler L, Kapphahn G, Slowik V. Technical possibilities for load tests of concrete and masonry bridges. Bautechnik. 2012;89:102-10 (in German).
[52] Varela-Ortiz W, Cintrón CYL, Velázquez GI, Stanton TR. Load testing and GPR assessment for concrete bridges on military installations. Construction and Building Materials. 2010;38:1255-69.
[53] O'Connor JS. Bridge Safety Assurance Measures Taken in New York State. Transportation Research Record. 2000;1696:187-92.
[54] Lantsoght EOL, Van der Veen C, De Boer A, Hordijk DA. Proof load testing of reinforced concrete slab bridges in the Netherlands. Structural Concrete. in press:29.
[55] Koekkoek R, Lantsoght E, Yang Y, Boer Ad, Hordijk D. Defining loading criteria for proof loading of existing reinforced concrete bridges. fib symposium 2016: Performance-based approaches for concrete structures. Cape Town, South Africa2016. p. 10.
[56] Aguilar CV, Jáuregui DV, Newtson CM, Weldon BD, Cortez TM. Load Rating a Prestressed Concrete Double-Tee Beam Bridge without Plans by Proof Testing. Transportation Research Board Annual Compendium of Papers. Washington DC2015. p. 19.
[57] Anay R, Cortez TM, Jáuregui DV, ElBatanouny MK, Ziehl P. On-Site Acoustic-Emission Monitoring for Assessment of a Prestressed Concrete Double-Tee-Beam Bridge without Plans. Journal of Performance of Constructed Facilities. 2016;30.
[58] Shenton HW, Chajes MJ, Huang J. Load Rating of Bridges Without Plans. Newark, Delaware: Department of Civil and Environmental Engineering, University of Delaware; Department of Civil Engineering, Widener University; 2007. p. 66.
[59] Juntunen DA, Isola MC. Proof load test of R01 of 61131 M-37 over CSX Railroad, South of Bailey, Michigan. Michigan Department of Transportation; 1995. p. 58.
[60] Koekkoek RT, Lantsoght EOL, Hordijk DA. Proof loading of the ASR-affected viaduct Zijlweg over highway A59. Delft, The Netherlands: Delft University of Technology; 2015. p. 180.
[61] Lantsoght EOL, Koekkoek RT, Hordijk DA, De Boer A. Towards standardization of proof load testing: pilot test on viaduct Zijlweg. Structure and Infrastructure Engineering. in press.

[62] Barker MG, Imhoff CM, McDaniel WT, Frederick TL. Field testing and load rating procedures for steel girder bridges. MoDOT; 1999. p. 194.
[63] Barker MG. Steel girder bridge field test procedures. Construction and Building Materials. 1999;13:229-39.
[64] Chajes MJ, Mertz DR, Commander B. Experimental load rating of a posted bridge. Journal of Bridge Engineering. 1997;2:1-10.
[65] Bakht B, Jaeger LG. Ultimate Load Test of Slab-on-Girder Bridge. Journal of Structural Engineering. 1992;118:1608-24.
[66] Coletti DA. Analytical and Field Investigation of Roma Suspension Bridge. Journal of Bridge Engineering. 2002;7:156-65.
[67] Moen CD, Shapiro EE, Hart J. Structural Analysis and Load Test of a Nineteenth-Century Iron Bowstring Arch-Truss Bridge. Journal of Bridge Engineering. 2013;18:261-71.
[68] Schenck TS, Laman JA, Boothby TE. Comparison of Experimental and Analytical Load-Rating Methodologies for a Pony-Truss Bridge. Transportation Research Record. 1999;1688:68-75.
[69] Marefat MS, Ghahremani-Gargary E, Ataei S. Load test of a plain concrete arch railway bridge of 20-m span. Construction and Building Materials. 2004;18:661-7.
[70] Wipf TJ, Ritter MA, Wood DL. Evaluation and Field Load Testing of Timber Railroad Bridge. Transportation Research Record. 2000;1696:323-33.
[71] Ji HS, Son BJ, Chang SY. Field Testing and Capacity-Ratings of a Short-Span Bridge Superstructures Made of Advanced Composite Materials. KSCE Journal of Civil Engineering. 2006;10:113-21.
[72] Harris DK, Gheitasi A, Civitillo JM. Field testing and numerical modeling of a hybrid composite beam bridge in Virginia. European Bridge Conference. Edinburgh, UK2015. p. 12.
[73] Shekar V, Aluri S, GangaRao HVS. Performance Evaluation of Fiber-Reinforced Polymer Composite Deck Bridges. Transportation Research Record. 2005;CD 11-S:465-72.
[74] Shifferaw Y, Fanous FS. Field testing and finite element analysis of steel bridge retrofits for distortion-induced fatigue. Engineering Structures. 2013;49:385-95.
[75] Zhou YE, Beecher JB, Guzda MR, Cunningham II DR. Investigation and Retrofit of Distortion-Induced Fatigue Cracks in a Double-Deck Cantilever-Suspended Steel Truss Bridge. Journal of Structural Engineering. 2015;141:D4014011:1-12.
[76] Wipf TJ, Phares BM, Klaiber FW, Al-Saidy AH, Lee Y-S. Strengthening Steel Girder Bridges with Carbon Fiber–Reinforced Polymer Plates. Transportation Research Record. 2005;CD 11-S:435-47.
[77] Gutkowski RM, Shigidi AMT, Tran AV, Peterson ML. Field Studies of Strengthened Timber Railroad Bridge. Transportation Research Record. 2001;1770:139-48.
[78] Orban Z, Gutermann M. Assessment of masonry arch railway bridges using non-destructive in-situ testing methods. Engineering Structures. 2009;31:2287-98.
[79] Deutscher Ausschuss für Stahlbeton. DAfStb-Guideline: Load tests on concrete structures. Deutscher Ausschuss fur Stahlbeton,; 2000. p. 7 (in German).
[80] ACI Committee 437. Code Requirements for Load Testing of Existing Concrete Structures (ACI 437.2M-13) and Commentary Farmington Hills, MA2013. p. 24.
[81] Mettemeyer M, Nanni A. Guidelines for rapid load testing of concrete structural members. University of Missouri-Rolla; 1999. p. 97.
[82] De Luca A, Zadeh HJ, Nanni A. In Situ Load Testing of a One-Way Reinforced Concrete Slab per the ACI 437 Standard. Journal of Performance of Constructed Facilities. 2014:1-10.

[83] Luca AD, Galati N, Nanni A, Alkhrdaji T. In-Situ Load Testing: A Theoretical Procedure to Design a Diagnostic Cyclic Load Test on a Reinforced Concrete Two-Way Slab Floor System. 2007.
[84] Dilek U, Reis EM. Evaluation and Load Testing of Posttensioned Concrete Structure Exhibiting Distress. Journal of Performance of Constructed Facilities. 2016;30:1-10.
[85] Tumialan G, Galati N, Nanni A. Structural Testing: Issues and advances related to structural testing: Part 1: Rationale, Objectives, and Execution. Structure Magazine. 2014:10-2.
[86] Tumialan G, Galati N, Nanni A. Structural Testing: Issues and advances related to structural testing: Part 2: Test Protocols and Case Studies. Structure Magazine. 2014:16-8.
[87] Saleem MA, Siddiqi ZA, Javed MA, Aziz M. Nondestructive Evaluation of an Existing Concrete Structure using Load Test and Core Test. Pak J Engg & Appl Sci. 2012;11:66-72.
[88] Galati N, Alkhrdaji T. Load Test Evaluation of FRP-strengthened Structures. the 7th International Conference on FRP Composites in Civil Engineering. Vancouver, Canada2014. p. 6.
[89] Corte GD, D'Aniello M, Landolfo R. Field Testing of All-Steel Buckling-Restrained Braces Applied to a Damaged Reinforced Concrete Building. Journal of Structural Engineering. 2015;141:D4014004.
[90] Shih CT, Chu SY, Liou YW, Hsiao FP, Huang CC, Chiou TC et al. In Situ Test of School Buildings Retrofitted with External Steel-Framing Systems. Journal of Structural Engineering. 2015;141:D4014002.
[91] Azizinamini A, Shekar Y, Boothby TE, Barnhill G. Old concrete slab bridges. 2: Analysis. Journal of Structural Engineering-ASCE. 1994;120:3305-19.
[92] Haritos N, Hira A, Mendis P, Heywood R, Giufre A. Load testing to collapse limit state of Barr Creek Bridge. Fifth International Bridge Engineering Conference, Vols 1 and 2: Bridges, Other Structures, and Hydraulics and Hydrology2000. p. A92-A102.
[93] Jorgenson JL, Larson W. Field Testing of a Reinforced Concrete Highway Bridge to Collapse. Transportation Research Record: Journal of the Transportation Research Board. 1976;607:66-71.
[94] Miller RA, Aktan AE, Shahrooz BM. Destructive testing of decommisisioned concrete slab bridge. Journal of Structural Engineering-Asce. 1994;120:2176-98.
[95] Wang FM, Kang SZ, Cai YC, Li XL. Destructive Test Study of A Prestressed Concrete Hollow Slab Beam Bridge. Geotechnical Special Publication No 214 - American Society of Civil Engineers. 2011:57-64.
[96] Zhang J, Peng H, Cai CS. Destructive Testing of a Decommissioned Reinforced Concrete Bridge. Journal of Bridge Engineering. 2013;18:564-9.
[97] Zhang J, Peng H, Cai CS. Field Study of Overload Behavior of an Existing Reinforced Concrete Bridge under Simulated Vehicle Loads. Journal of Bridge Engineering. 2011;16:226-37.
[98] Zhang J-r, Peng H, Zhang K-b, Hao H-x. Test Study on Overload and Ultimate Behavior of Old Reinforced Concrete Bridge Through Destructive Test of Corroded Bridge. Engineering Mechanics. 2009;26:213-24.
[99] Bergström M, Täljsten B, Carolin A. Failure Load Test of a CFRP Strengthened Railway Bridge in Örnsköldsvik, Sweden. Journal of Bridge Engineering. 2009;14:300-8.
[100] Ferreira D, Bairan J, Mari A. Efficient 1D model for blind assessment of existing bridges: simulation of a full-scale loading test and comparison with higher order continuum models. Structure and Infrastructure Engineering. 2014;11:1383-97.

[101] Nilimaa J, Bagge N, Blanksvärd T, Täljsten B. NSM CFRP Strengthening and Failure Loading of a Posttensioned Concrete Bridge. Journal of Composites for Construction. 2015:04015076:1-7.
[102] Puurula AM, Enochsson O, Sas G, Blanksvärd T, Ohlsson U, Bernspång L et al. Assessment of the Strengthening of an RC Railway Bridge with CFRP Utilizing a Full-Scale Failure Test and Finite-Element Analysis. Journal of Structural Engineering. 2015;141:D4014008:1-11.
[103] Zou ZQ, Enochsson O, He GJ, Elfgren L. Finite Element Analysis of Small Span Reinforced Concrete Trough Railway Bridge. Advances in Concrete and Structures. 2009;400-402:645-50
978.
[104] Lantsoght EOL, Van der Veen C, De Boer A, Hordijk DA. Collapse test and moment capacity of the Ruytenschildt Reinforced Concrete Slab Bridge Structure and Infrastructure Engineering. available online ahead of print.
[105] Schacht G, Bolle G, Marx S. Experimental in-situ investigation of the shear bearing capacity of pre-stressed hollow core slabs. In: F.Dehn, Beushausen H-D, Alexander MG, Moyo P, editors. Concrete Repair, Rehabilitation and Retrofitting IV Leipzig, Germany2015. p. 851 - 9.
[106] Ekeberg PK, Sjursen A, Thorenfeldt E. Load-carrying capacity of continuous concrete slabs with concentrated loads (in Norwegian). Nordisk betong. 1982;4:153-6.
[107] Egger G. Static load tests on buidling floors: seminar Unterstrass and school building Riedtli, Zürich (in German). Schweizer Ingenieur und Architekt. 1998;116:644-7.
[108] NCHRP. Manual for Bridge Rating through Load Testing. Washington, DC1998. p. 152.
[109] AASHTO. The manual for bridge evaluation. 2nd ed. Washington, D.C.: American Association of State Highway and Transportation Officials; 2011.
[110] Casadei P, Parretti R, Nanni A, Heinze T. In Situ Load Testing of Parking Garage Reinforced Concrete Slabs: Comparison between 24 h and Cyclic Load Testing. Practice Periodical on Structural Design and Construction. 2005;10:40-8.
[111] Cochet D, Corfdir P, Delfosse G, Jaffre Y, Kretz T, Lacoste G et al. Load tests on highway bridges and pedestrian bridges (in French). Bagneux-Cedex, France: Setra - Service d'Etudes techniques des routes et autoroutes; 2004.
[112] NRA. Load Testing for Bridge Assessment. Dublin, Ireland: National Roads Authority; 2014. p. 11.
[113] The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges. Guidelines for the Supplementary Load Testing of Bridges. London, UK1998. p. 44.
[114] Schacht G, Bolle G, Marx S. Load testing - international state of the art (in German). Bautechnik. 2016;93:85-97.
[115] Schacht G, Bolle G, Curbach M, Marx S. Experimental Evaluation of the shear bearing safety (in German). Beton- und Stahlbetonbau. 2016;111:343-54.
[116] Lantsoght EOL, Yang Y, van der Veen C, de Boer A, Hordijk DA. Beam experiments on acceptance criteria for bridge load tests. ACI Structural Journal. (in press).
[117] Lantsoght EOL. Beams from Ruytenschildt Bridge: Analysis of stop criteria. Delft University of Technology; 2017. p. 77.
[118] Lantsoght EOL, Yang Y, Tersteeg RHD, van der Veen C, de Boer A. Development of Stop Criteria for Proof Loading. IALCCE 2016. Delft, The Netherlands2016. p. 8 pp.
[119] Rücker W, Hille F, Rohrmann R. Guideline for the Assessment of Existing Structures. Berlin, Germany: Federal Institute of Materials Research and Testing (BAM); 2006. p. 48.

[120] Ziehl PH, Galati N, Nanni A, Tumialan JG. In-situ evaluation of two concrete slab systems. II: Evaluation criteria and outcomes. Journal of Performance of Constructed Facilities. 2008;22:217-27.

[121] Yang Y, Hordijk D, De Boer A. Acoustic emission study on 50 years old reinforced concrete beams under bending and shear tests. IAES-23, IIIAE 2016 KYOTO & ICAE-8 Kyoto, Japan2016.

[122] Matta F, Bastianini F, Galati N, Casadei P, Nanni A. Distributed Strain Measurement in Steel Bridge with Fiber Optic Sensors: Validation through Diagnostic Load Test. Journal of Performance of Constructed Facilities. 2008;22:264-73.

[123] Regier R, Hoult NA. Distributed Strain Behavior of a Reinforced Concrete Bridge: Case Study Journal of Bridge Engineering. 2014;19:1-9.

[124] Bentz EC, Hoult NA. Bridge model updating using distributed sensor data. Institute of Civil Engineers – Bridge Engineering. 2016;170:74-86.

[125] Idriss RL, Liang Z. In-Service Shear and Moment Girder Distribution Factors in Simple-Span Prestressed Concrete Girder Bridge - Measured with Built-in Optical Fiber Sensor System. Transportation Research Record. 2010;2172:142-50.

[126] Cai H, Abudayyeh O, Abdel-Qader I, Attanayake U, Barbera J, Almaita E. Bridge Deck Load Testing Using Sensors and Optical Survey Equipment. Advances in Civil Engineering. 2012:11.

[127] Sanayei M, Phelps JE, Sipple JD, Bell ES, Brenner BR. Instrumentation, Nondestructive Testing, and Finite-Element Model Updating for Bridge Evaluation Using Strain Measurements. Journal of Bridge Engineering. 2012;17:130-8.

[128] McCormick N, Lloyd J. Digital image correlation for the monitoring and investigation of bridges. Structural Faults and Repair, 13th international conference and exhibition. Edinburgh, UK2010. p. 10 pp.

[129] Gentile C, Bulgarelli S, Gallino N, Oldini A. An interferometric radar for remote sensing of deflections on large structures. Structural Studies, Repairs and Maintenance of Heritage Architecture XI2009. p. 359-71.

[130] Gentile C, Gallino N. Condition assessment and dynamic system identification of a historic suspension footbridge. Structural Control and Health Monitoring. 2008;15:369-88.

[131] Fuchs PA, Washer GA, Chase SB, Moore M. Laser-Based Instrumentation for Bridge Load Testing. Journal of Performance of Constructed Facilities. 2004;18:213-9.

[132] Lin TS, Nowak AS. Proof Loading and Structural Reliability. Reliability Engineering. 1984;8:85-100.

[133] Rackwitz R, Schrupp K. Quality-control, proof testing and structural reliability. Structural Safety. 1985;2:239-44.

[134] Val DV, Stewart MG. Safety Factors for Assessment of Existing Structures. Journal of Structural Engineering. 2002;128:258-65.

[135] Spaethe G. The effect of proof load testing on the safety of a structure (in German). Bauingenieur. 1994;69:459-68.

[136] Lantsoght EOL, Veen Cvd, Hordijk DA, Boer Ad. Reliability index after proof load testing: viaduct De Beek. ESREL 2017. Protoroz, Slovenia2017. p. 8.

[137] Nowak AS, Szerszen MM. Bridge load and resistance models. Engineering Structures. 1998;20:985-90.

[138] Stewart MG, Val DV. Role of load history in reliability-based decision analysis of aging bridges. Journal of Structural Engineering-Asce. 1999;125:776-83.

[139] Wang N, O'Malley C, Ellingwood BR, Zureick A-H. Bridge rating using system reliability assessment Part I: Assessment and verification by load testing. Journal of Bridge Engineering. 2010;in press:31pp.
[140] Frangopol DM, Kim S. Chapter 18: Life-cycle analysis and optimization. In: Chen WF, Duan L, editors. Bridge Engineering Handbook, Vol 5 Construction and Maintenance. Boca Raton, FL: CRC Press / Taylor & Francis Group; 2014. p. 537-66.
[141] Strauss A, Frangopol DM, Kim S. Use of monitoring extreme data for the performance prediction of structures: Bayesian updating. Engineering Structures. 2008;30:3654-66.
[142] Frangopol DM, Strauss A, Kim S. Use of monitoring extreme data for the performance prediction of structures: General approach. Engineering Structures. 2008;30:3644-53.
[143] Okasha NM, Frangopol DM. Integration of structural health monitoring in a system performance based life-cycle bridge management framework. Structure and Infrastructure Engineering. 2012;8:999-1016.
[144] Kong JS, Frangopol DM. Probabilistic optimization of aging structures considering maintenance and failure costs. Journal of Structural Engineering-Asce. 2005;131:600-16.
[145] Ang A-S, De Leon D. Modeling and analysis of uncertainties for risk-informed decisions in infrastructures engineering. Structure and Infrastructure Engineering. 2005;1:19-31.
[146] Lantsoght EOL, van der Veen C, de Boer A, Walraven JC. Recommendations for the Shear Assessment of Reinforced Concrete Slab Bridges from Experiments Structural Engineering International. 2013;23:418-26.
[147] Fennis S, van Hemert P, Hordijk D, de Boer A. Proof loading Vlijmen-Oost; Research on assessment method for existing structures. Cement. 2014;5:40-5.
[148] Vos W. Stop criteria for proof loading - The use of stop criteria for a safe use of ‘Smart Proof loading’. Delft, The Netherlands: Delft University of Technology; 2016.

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Table 1. Maximum crack width *w* and increase in crack *Δw* width from the German guidelines [79].

	During proof loading	After proof loading
Existing cracks	$\Delta w \leq 0.3$ mm	$\leq 0.2\Delta w$
New cracks	$w \leq 0.5$ mm	$\leq 0.3w$