



Delft University of Technology

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

Lantsoght, Eva; van der Veen, C.; de Boer, A.; Hordijk, Dick

DOI

[10.1016/j.engstruct.2017.07.050](https://doi.org/10.1016/j.engstruct.2017.07.050)

Publication date

2017

Document Version

Accepted author manuscript

Published in

Engineering Structures

Citation (APA)

Lantsoght, E., van der Veen, C., de Boer, A., & Hordijk, D. (2017). State-of-the-art on load testing of concrete bridges. *Engineering Structures*, 150, 231-241. <https://doi.org/10.1016/j.engstruct.2017.07.050>

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.

1 © 2017 Manuscript version made available under CC-BY-NC-ND 4.0 license

2 <https://creativecommons.org/licenses/by-nc-nd/4.0/>

3 Postprint of Engineering Structures

4 Volume 150, 1 November 2017, Pages 231-241

5 Link to formal publication (Elsevier): <https://doi.org/10.1016/j.engstruct.2017.07.050>

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

7

8

9 Eva O.L. Lantsoght^{a,b,c} (E.O.L.Lantsoght@tudelft.nl) Tel: +593 2 297-1700 ext. 1186

10 Corresponding Author), Cor van der Veen^b (C.vanderveen@tudelft.nl), Ane de Boer^d
11 (ane.de.boer@rws.nl), Dick A. Hordijk^b (D.A.Hordijk@tudelft.nl)

12

13 ^aUniversidad San Francisco de Quito, Politecnico, Diego de Robles y Vía Interoceánica,
14 Quito, Ecuador

15 ^bDelft University of Technology, Concrete Structures, Stevinweg 1, 2628CN Delft, The
16 Netherlands

17 ^cAdstren, Plaza del Rancho, Of. 203, Via Tanda, Cumbaya, Quito, Ecuador

18 ^dMinistry of Infrastructure and the Environment, Griffioenlaan 2, 3526 LA Utrecht, The
19 Netherlands

20

21

22

23

1 **Abstract**

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

12

13 **Keywords**

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

16

1 **1 Introduction**

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

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

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

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

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

12

13 **2 Diagnostic load testing of concrete bridges**

14 **2.1 Determination of transverse flexural distribution**

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

1 girder bridges [17], in Pennsylvania on concrete T-beam bridges [18], and in Poland on
2 prestressed concrete bridges [19].

3 **2.2 *Evaluation of stiffness***

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

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

15 **2.3 *Testing prior to opening, over time, and after rehabilitation***

16 Diagnostic load testing can be used upon opening of a new bridge to quantify load
17 bearing mechanisms that typically are not accounted for in design, such as arching action [28].
18 Newly proposed design methods can be verified with a diagnostic load test to show the
19 correspondence between the proposed design method and the actual structural behavior [29]. For
20 uncommon bridge types, such as integral bridges [30], bridges with self-consolidating concrete
21 [31], high performance concrete [32, 33], lightweight concrete [34], and new precast systems
22 [35, 36], diagnostic load tests can be used upon opening to verify the design assumptions. For

1 non-standard concrete mixes, these design assumptions can be related to the time-dependent
2 behavior of the concrete, or the assumed stiffness.

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

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

11 **3 Proof load testing of concrete bridges**

12 ***3.1 Determination of the target proof load***

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

$$18 \quad PL = D_d + L_d$$

19 with D_d the factored dead load and L_d the factored live load. A rule of thumb that was used to
20 determine the target proof load was that the proof load should be twice the maximum allowable
21 load [44]. Similarly, in Germany, a factor of 1.5 for the traffic loads is used [45]. More recently
22 [46], the determination of the target proof load is determined based on equivalent sectional

1 moments: the bending moment caused by the proof load should equal the bending moment
2 caused by the factored live load model.

3 For Europe, where the prescribed live load model from NEN-EN 1991-2:2003 [47] does
4 not directly reflect a certain vehicle type nor the specific situation of the different European
5 countries, proof load factors were determined. These factors are used to multiply a nominal value
6 of the traffic action to obtain the maximum load effect required in the proof load test. These
7 factors were calibrated based on WIM data from various European countries analyzed separately
8 [48, 49], and determined for different reliability levels, different span lengths, and different ratios
9 R/R_n .

10 **3.2 Large proof loading campaigns**

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

19 **3.3 Evaluation of bridges without plans**

20 Proof load testing is preferred over diagnostic load testing when the uncertainties on the
21 structure are large. One application is using proof load tests to evaluate bridges without structural
22 plans [56, 57]. This application combines estimates of the prestressing steel based on the Magnel
23 diagrams, using a rebar scanner to estimate the available prestressing, and the actual testing at

1 diagnostic and proof load levels. The combination of these activities then leads to an improved
2 bridge rating. Many bridges owned by the US Army do not have plans, and have the added
3 challenge that they need to be rated for and tested with a loading vehicle that is representative of
4 the military vehicles that use these bridges [52]. Again, a combination of non-destructive testing
5 and proof load testing was proposed to rate these bridges.

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

9 **3.4 Evaluation of deteriorated bridges**

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

16 **4 In-situ testing of other structures**

17 **4.1 Other bridge types**

18 The procedures for diagnostic and proof load testing are generally independent of the
19 type of bridge that is tested. The only differences in the execution are related to the response that
20 should be measured, and the stop criteria in proof load testing. For the updating of a load rating
21 based on analytical methods with the results of a diagnostic load test, clear recommendations
22 were originally developed for steel bridges [26, 62, 63]. In these recommendations, the sources
23 for differences between analytical predictions and measured responses that are considered and

1 analyzed separately are the actual impact factor, the actual section dimensions, unaccounted
2 system stiffness resulting from curbs and railings, the actual lateral live load distribution, the
3 bearing restraint effects, the actual longitudinal live load distribution, and the effect of
4 unintended composite action. Unintended composite action [64] can break down at the ultimate
5 limit state, and should be ignored in strength calculations [65].

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

11 **4.2 Buildings**

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

19 **4.3 Collapse tests**

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

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 $\varepsilon_{c,lim} = 0.8 \text{ ‰}$ 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

1 limits deformations in the shear span for beams without shear reinforcement. Additional stop
2 criteria are when the measurements indicate critical changes in the structure, when the stability is
3 endangered, and when critical displacements occur at the supports.

4 **5.2 Manual for Bridge Rating through Load Testing**

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

$$13 \quad L_T = X_{PA} L_R (1 + I) \quad (4)$$

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

17 **5.3 ACI 437.2M-13**

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

$$21 \quad TLM = 1.3(D_w + D_s) \quad (5)$$

$$22 \quad TLM = 1.0D_w + 1.1D_s + 1.6L + 0.5(L_r \text{ or } SL \text{ or } RL) \quad (6)$$

$$23 \quad TLM = 1.0D_w + 1.1D_s + 1.6(L_r \text{ or } SL \text{ or } RL) + 1.0L \quad (7)$$

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

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

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

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

$$11 \quad I_{pr} = \frac{I_{p^{(i+1)}}}{I_{pi}} \leq 0.5 \quad (9)$$

$$12 \quad I_{pi} = \frac{\Delta_r^i}{\Delta_{max}^i} \quad (10)$$

$$13 \quad I_{p^{(i+1)}} = \frac{\Delta_r^{(i+1)}}{\Delta_{max}^{(i+1)}} \quad (11)$$

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

$$16 \quad \Delta_r \leq \frac{\Delta_l}{4} \quad (12)$$

$$17 \quad \Delta_l \leq \frac{l_t}{180} \quad (13)$$

18

1 **5.4 Other guidelines**

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

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

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

17

18 **6 Recent research insights**

19 **6.1 Stop criteria in proof load testing**

20 Current developments in terms of stop criteria for the German guidelines look at possible
21 improvements, and perhaps the inclusion of shear [114, 115]. The best results were obtained
22 when studying the load-displacement diagram, crack widths, and plastic deformations. For shear,
23 additional measurements in the shear span, such as relative deformations and curvatures were

1 explored, rather than just the deflections between the load and the support. For shear, local
2 damage (inclined crack reaching half the depth of the beam, inclined crack growing into a
3 bending crack, or inclined crack reaching a 45° orientation) was also defined as a stop criterion,
4 based on beam tests in the laboratory. The difficulty with the implementation of this criterion is
5 that it would require visual inspection or photogrammetry to be used in the field.

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

10 **6.2 Measurement techniques**

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

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

1 Remote sensing techniques that have been tested for research purposes include digital
2 image correlation [128], radar interferometry [129, 130], and systems based on laser
3 measurements [131]. The use of a total station is part of the common load testing practice, but
4 has the disadvantage that the required time for taking the measurements can be considerable
5 [31].

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

11 **6.3 Using load testing information in probabilistic assessment**

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

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

$$20 \quad P_{fb} = \int_{-\infty}^{+\infty} (1 - F_s(r)) f_R(r) dr \quad (14)$$

21 with F_s the cumulative distribution function of the loads and f_R the probability density function of
22 the resistance. During the proof load test, only the deterministic value of the proof load s_p is

1 applied, see Figure 6b, and the probability of failure during the test P_{fd} is determined based on
2 the cumulative distribution function of the resistance F_R :

$$3 \quad P_{fd} = F_R(s_p) \quad (15)$$

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

$$7 \quad P_{fa} = \frac{1}{1 - F_R(s_p)} \int_{s_p}^{+\infty} (1 - F_s(r)) f_R(r) dr \quad (16)$$

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

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

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

1 143]. Load testing should not be considered as an isolated event during the life-cycle if a
2 structure, but should be embedded within a plan that includes inspections, load tests,
3 maintenance and repair activities, and monitoring. The optimal time in a bridge's lifespan for a
4 load test should then be determined by minimizing the total cost and maximizing the bridge
5 performance and expected service life [144, 145].

6

7 **7 Discussion and needs for future research**

8 Even though load testing has been part of the engineering practice for the last century, a
9 conclusive framework for diagnostic and proof load testing of bridges is still missing, which is
10 reflected by the large differences between the existing codes and guidelines in different
11 countries. Especially for proof load testing, different recommendations for the target proof load,
12 loading protocol, and stop criteria can be found in the literature. Further research is needed to
13 develop unified recommendations. For Europe, these recommendations should follow the safety
14 philosophy and basic principles of the Eurocodes. Additionally, none of the existing codes and
15 guidelines permit proof load testing of shear- and fracture-critical bridges, while these bridges
16 comprise a significant portion of the structures with low ratings. For example, in the Netherlands
17 600 reinforced concrete slab bridges were found to be shear-critical [146]. Some of these
18 bridges, especially those where the uncertainties caused by material degradation are large, are
19 good candidates for load testing.

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

1 approach to a systems-based approach, which requires the incorporation of systems reliability
2 methods.

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

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

12

13 **8 Summary**

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

20 Proof load testing aims at immediately giving an answer to the question if the bridge can
21 carry the prescribed factored live loads without signs of distress. A representative load is applied
22 to the bridge, and the structural responses are carefully monitored. If the structural response
23 indicates critical changes in the bridge prior to achieving the target proof load (i.e., a stop

1 criterion is exceeded), the test needs to be terminated, and the bridge will have a lower rating
2 factor. Proof load testing is particularly useful for structures with large uncertainties, such as
3 bridges without plans and deteriorated bridges.

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

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

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

13

14 **Notation List**

15 The following symbols are used in this paper:

16 $effR_u$ capacity of the structure

17 $extF_{lim}$ additional load that can be applied to reach onset of nonlinear behavior

18 $extF_{target}$ additional load to achieve the target proof load

19 f_R probability density function of the resistance

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

21 f_s probability density function of the load

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

23 $f_{0.01m}$ average yield strength based on a strain of 0.01% (elastic zone)

- 1 l_t span length
- 2 s_p magnitude of proof load
- 3 $\tan(\alpha_i)$ the secant stiffness at any point i on the increasing loading portion of the load-deflection envelope
- 4 envelope
- 5 $\tan(\alpha_{ref})$ the slope of the reference secant line for the load-deflection envelope
- 6 w crack width
- 7 D_d factored dead load
- 8 D_s superimposed dead load
- 9 D_w self-weight of concrete
- 10 E_s modulus of elasticity of reinforcement steel
- 11 F_{lim} onset of nonlinear behavior
- 12 F_R cumulative distribution function of the resistance
- 13 F_s cumulative distribution function of the load
- 14 F_{target} target proof load
- 15 G_I load caused by permanent loads
- 16 G_{di} additional permanent loads, not acting on the bridge at time of testing
- 17 I impact allowance
- 18 I_{DL} deviation from linearity index
- 19 I_{pi} permanency index for the i -th load cycle
- 20 $I_{p(i+1)}$ permanency index for the $(i+1)$ -th load cycle
- 21 I_{pr} permanency ratio
- 22 L live load
- 23 L_d factored live load

1	L_r	live load on the roof
2	L_R	comparable live load due to the rating vehicle for the lanes loaded
3	L_T	target proof load according to the Manual for Bridge Rating through Load Testing
4	P	load
5	P_{fa}	probability of failure after proof load test
6	P_{fb}	probability of failure before proof load test
7	P_{fd}	probability of failure during proof load test
8	P_i	load in i -th load cycle
9	PL	target proof load
10	P_{max}	maximum load in load test
11	P_{min}	baseline load
12	P_{ref}	load in first load cycle
13	Q_d	transient loads
14	SL	snow load
15	R	resistance
16	RL	rain load
17	R_n	load effect
18	TLM	test load magnitude
19	X_{PA}	target live load factor
20	ε_c	strain measured during proof loading
21	$\varepsilon_{c,lim}$	limit value of the concrete strain : 0.6 ‰, and for concrete with a compressive strength
22		larger than 25 MPa this can be increased up to maximum 0.8 ‰.

1	ε_{c0}	analytically determined short-term strain in the concrete caused by the permanent loads
2		that are acting on the structure before the application of the proof load
3	ε_{s2}	steel strain during experiment: directly measured or derived from other measurements
4	ε_{s02}	analytically determined strain (assuming cracked conditions) in the reinforcement steel
5		caused by the permanent loads that are acting on the structure before the application of
6		the proof load.
7	Δ_{max}^i	maximum deformation occurring in i -th cycle, measured between beginning and peak of
8		the i -th cycle
9	Δ_r^i	residual deformation occurring between i -th and $(i-1)$ -th cycle
10	Δ_l	maximum deflection
11	Δ_r	residual deflection
12	Δ_{ref}	deflection in first load cycle
13	Δ_w	increase in crack width of an existing crack

14

15 **Acknowledgement**

16 The authors wish to express their gratitude and sincere appreciation to the Dutch Ministry of
 17 Infrastructure and the Environment (Rijkswaterstaat) and for financing this research work.

18

19 **References**

- 20 [1] Bolle G, Schacht G, Marx S. Loading tests of existing concrete structures - historical
 21 development and present practise. fib symposium Prague, Czech Republic 2011. p. 14.
 22 [2] Moses F, Lebet JP, Bez R. Applications of field testing to bridge evaluation. Journal of
 23 Structural Engineering-ASCE. 1994;120:1745-62.
 24 [3] Veneziano D, Galeota D, Giammatteo MM. Analysis of bridge proof-load data I: Model and
 25 statistical procedures. Structural Safety. 1984;2:91-104.
 26 [4] Lantsoght EOL, van der Veen C, de Boer A, Walraven J. Transverse Load Redistribution and
 27 Effective Shear Width in Reinforced Concrete Slabs. Heron. 2015;60:145-80.

- 1 [5] Azizinamini A, Boothby TE, Shekar Y, Barnhill G. Old Concrete Slab Bridges. 1.
2 Experimental Investigation. Journal of Structural Engineering-ASCE. 1994;120:3284-304.
- 3 [6] Hall WB, Tsai M. Load testing, structural reliability and test evaluation. Structural Safety.
4 1989;6:285-302.
- 5 [7] Farhey DN. Bridge Instrumentation and Monitoring for Structural Diagnostics. Structural
6 Health Monitoring. 2005;4:301-18.
- 7 [8] ACI Committee 342. ACI 342R-16: Report on Flexural Live Load Distribution Methods for
8 Evaluating Existing Bridges. Farmington Hills, Michigan: American Concrete Institute; 2016. p.
9 36.
- 10 [9] AASHTO. AASHTO LRFD bridge design specifications, 7th edition with 2015 interim
11 specifications. 7th ed. Washington, DC: American Association of State Highway and
12 Transportation Officials; 2015.
- 13 [10] Ohanian E, White D, Bell ES. Benefit Analysis of In-Place Load Testing for Bridges.
14 Transportation Research Board Annual Compendium of Papers. 2017:14.
- 15 [11] Sanayei M, Reiff AJ, Brenner BR, Imbaro GR. Load Rating of a Fully Instrumented Bridge:
16 Comparison of LRFR Approaches. Journal of Performance of Constructed Facilities.
17 2016;2016:2.
- 18 [12] Amer A, Arockiasamy M, Shahawy M. Load distribution of existing solid slab bridges
19 based on field tests. Journal of Bridge Engineering. 1999;4:189-93.
- 20 [13] Arockiasamy M, Amer A. Load Distribution on Highway Bridges Based On Field Test
21 Data: Phase III. 1998. p. 170.
- 22 [14] Jones BP. Reevaluation of the AASHTO effective width equation in concrete slab bridges in
23 Delaware: University of Delaware; 2011.
- 24 [15] Saraf VK. Evaluation of Existing RC Slab Bridges. Journal of Performance of Constructed
25 Facilities. 1998;12:20-4.
- 26 [16] Al-Mahaidi R, Taplin G, Giufre A. Load Distribution and Shear Strength Evaluation of an
27 Old Concrete T-Beam Bridge. Transportation Research Record. 2000;1696:52-62.
- 28 [17] Velázquez BM, Yura JA, Frank KH, Kreger ME, Wood SL. Diagnostic load tests of a
29 reinforced concrete pan-girder bridge. Austin, TX, USA: The University of Texas at Austin;
30 2000. p. 121.
- 31 [18] Catbas FN, Ciloglu SK, Aktan AE. Strategies for load rating of infrastructure populations: a
32 case study on T-beam bridges. Structure and Infrastructure Engineering. 2004;1:221-38.
- 33 [19] Mordak AG, Manko Z. Static Load Tests of Posttensioned, Prestressed Concrete Road
34 Bridge over Reservoir Water Plant. Transportation Research Record. 2008;2050:90-7.
- 35 [20] Aktan AE, Zwick M, Miller R, Shahrooz B. Nondestructive and Destructive Testing of
36 Decommissioned Reinforced Concrete Slab Highway Bridge and Associated Analytical Studies.
37 Transportation Research Record: Journal of the Transportation Research Board. 1992;1371:142-
38 53.
- 39 [21] Hodson DJ, Barr PJ, Pockels L. Live-Load Test Comparison and Load Ratings of a
40 Posttensioned Box Girder Bridge. Journal of Performance of Constructed Facilities.
41 2013;27:585-93.
- 42 [22] Jauregui DV, Licon-Lozano A, Kulkarni K. Higher Level Evaluation of a Reinforced
43 Concrete Slab Bridge. Journal of Bridge Engineering. 2010;15:172-82.
- 44 [23] Jeffrey A, Breña SF, Civjan SA. Evaluation of Bridge Performance and Rating through
45 Nondestructive Load Testing. University of Massachusetts Amherst; 2009. p. 271.

- 1 [24] Hag-Elsafi O, Kunin J. Load Testing For Bridge Rating: Dean's Mill Road Over Hannacrois
2 Creek. Albany, NY: Transportation Research and Development Bureau, New York State
3 Department of Transportation; 2006. p. 71.
- 4 [25] Jáuregui DV, Barr PJ. Nondestructive Evaluation of the I-40 Bridge over the Rio Grande
5 River. *Journal of Performance of Constructed Facilities*. 2004;18:195-204.
- 6 [26] Barker MG. Quantifying Field-Test Behavior for Rating Steel Girder Bridges. *Journal of*
7 *Bridge Engineering*. 2001;6:254-61.
- 8 [27] Nilimaa J, Blanksvärd T, Taljsten B. Assessment of concrete double-trough bridges. *Journal*
9 *of Civil Structural Health Monitoring*. 2015;2015:29-36.
- 10 [28] Taylor SE, Rankin B, Cleland DJ, Kirkpatrick J. Serviceability of bridge deck slabs with
11 arching action. *Aci Structural Journal*. 2007;104:39-48.
- 12 [29] Ferrand D, Nowak AS, Szerszen MM. Field Test and Finite Element Analysis of Isotropic
13 Bridge Deck. *Transportation Research Record*. 2005;CD 11-S:153-8.
- 14 [30] Lawver A, French C, Shield CK. Field Performance of Integral Abutment Bridge.
15 *Transportation Research Record*. 2000;1740:108-17.
- 16 [31] Hernandez ES, Myers JJ. In-situ field test and service response of Missouri Bridge A7957.
17 *European Bridge Conference*. Edinburgh, UK2015. p. 10.
- 18 [32] Yang Y, Myers JJ. Live-Load Test Results of Missouri's First High-Performance Concrete
19 Superstructure Bridge. *Transportation Research Record*. 2003;1845:96-103.
- 20 [33] Barnes RW, Stallings JM, Porter PW. Live-Load Response of Alabama's High-Performance
21 Concrete Bridge. *Transportation Research Record*. 2003;1845:115-24.
- 22 [34] Taylor P, Hosteng T, Wang X, Phares B. Evaluation and Testing of a Lightweight Fine
23 Aggregate Concrete Bridge Deck in Buchanan County, Iowa. 2016. p. 51.
- 24 [35] Konda TF, Klaiber FW, Wipf TJ, Schoellen TP. Precast Modified Beam-in-Slab Bridge
25 System - An Alternative Replacement for Low-Volume Roads. *Transportation Research Record*.
26 2007;1989:335-46.
- 27 [36] Kirkpatrick J, Long AE, Thompson A. Load distribution characteristics of spaced M-beam
28 bridge decks. *The structural engineer*. 1984;62B:86-8.
- 29 [37] McGrath TJ, Selig ET, Beach TJ. Structural Behavior of Three-Sided Arch Span Bridge.
30 *Transportation Research Record*. 1995;1541.
- 31 [38] Au A, Lam C, Au J, Tharmabala B. Eliminating Deck Joints Using Debonded Link Slabs:
32 Research and Field Tests in Ontario *Journal of Bridge Engineering*. 2013;18:768-78.
- 33 [39] Bell ES, Sipple JD. Special topics studies for baseline structural modeling for condition
34 assessment of in-service bridges. *Safety and Reliability of Bridge Structures2009*. p. 274-89.
- 35 [40] Russo FM, Wipf TJ, Klaiber FW. Diagnostic Load Tests of a Prestressed Concrete Bridge
36 Damaged by Overheight Vehicle Impact. *Transportation Research Record*. 2000;1696:103-10.
- 37 [41] Myers JJ, Holdener D, Merkle W. Load Testing and Load Distribution of Fiber Reinforced,
38 Polymer Strengthened Bridges: Multi-year, Post Construction/Post Retrofit Performance
39 Evaluation. *FRP Composites and Sustainability: Focusing on Innovation, Technology*
40 *Implementation and Sustainability*. New York, NY2012. p. 163-91.
- 41 [42] Alkhrdaji T, Nanni A, Mayo R. Upgrading Missouri Transportation Infrastructure - Solid
42 Reinforced-Concrete Decks Strengthened with Fiber-Reinforced Polymer Systems.
43 *Transportation Research Record*. 2000;1740:157-63.
- 44 [43] Fu GK, Tang JG. Risk-based Proof-load Requirements for Bridge Evaluation. *Journal of*
45 *Structural Engineering-ASCE*. 1995;121:542-56.

- 1 [44] Saraf VK, Nowak AS, Till R. Proof load testing of bridges. In: Frangopol DM, Grigoriu
2 MD, editors. Probabilistic Mechanics & Structural Reliability: Proceedings of the Seventh
3 Specialty Conference 1996. p. 526-9.
- 4 [45] Schwesinger P, Bolle G. EXTRA - a new experiment supported condition assessment
5 method for concrete bridges. In: Aktan AE, Gosselin SR, editors. Proc SPIE 3995,
6 Nondestructive Evaluation of Highways, Utilities, and Pipelines IV 2000. p. 11.
- 7 [46] Galati N, Nanni A, Tumialan JG, Ziehl PH. In-situ evaluation of two concrete slab systems.
8 I: Load determination and loading procedure. Journal of Performance of Constructed Facilities.
9 2008;22:207-16.
- 10 [47] CEN. Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges, NEN-EN 1991-
11 2:2003. Brussels, Belgium: Comité Européen de Normalisation; 2003. p. 168.
- 12 [48] Olaszek P, Świt G, Casas JR. Proof load testing supported by acoustic emission. An
13 example of application. IABMAS 2012 2012.
- 14 [49] Casas JR, Gómez JD. Load Rating of Highway Bridges by Proof-loading. KSCE Journal of
15 Civil Engineering. 2013;17:556-67.
- 16 [50] Shahawy MA. Non Destructive Strength Evaluation Of Florida Bridges. SPIE. Oakland,
17 CA 1995. p. 23.
- 18 [51] Bretschneider N, Fiedler L, Kappahn G, Slowik V. Technical possibilities for load tests of
19 concrete and masonry bridges. Bautechnik. 2012;89:102-10 (in German).
- 20 [52] Varela-Ortiz W, Cintrón CYL, Velázquez GI, Stanton TR. Load testing and GPR
21 assessment for concrete bridges on military installations. Construction and Building Materials.
22 2010;38:1255-69.
- 23 [53] O'Connor JS. Bridge Safety Assurance Measures Taken in New York State. Transportation
24 Research Record. 2000;1696:187-92.
- 25 [54] Lantsoght EOL, Van der Veen C, De Boer A, Hordijk DA. Proof load testing of reinforced
26 concrete slab bridges in the Netherlands. Structural Concrete. in press:29.
- 27 [55] Koekkoek R, Lantsoght E, Yang Y, Boer Ad, Hordijk D. Defining loading criteria for proof
28 loading of existing reinforced concrete bridges. fib symposium 2016: Performance-based
29 approaches for concrete structures. Cape Town, South Africa 2016. p. 10.
- 30 [56] Aguilar CV, Jáuregui DV, Newtonson CM, Weldon BD, Cortez TM. Load Rating a
31 Prestressed Concrete Double-Tee Beam Bridge without Plans by Proof Testing. Transportation
32 Research Board Annual Compendium of Papers. Washington DC 2015. p. 19.
- 33 [57] Anay R, Cortez TM, Jáuregui DV, ElBatanouny MK, Ziehl P. On-Site Acoustic-Emission
34 Monitoring for Assessment of a Prestressed Concrete Double-Tee-Beam Bridge without Plans.
35 Journal of Performance of Constructed Facilities. 2016;30.
- 36 [58] Shenton HW, Chajes MJ, Huang J. Load Rating of Bridges Without Plans. Newark,
37 Delaware: Department of Civil and Environmental Engineering, University of Delaware;
38 Department of Civil Engineering, Widener University; 2007. p. 66.
- 39 [59] Juntunen DA, Isola MC. Proof load test of R01 of 61131 M-37 over CSX Railroad, South of
40 Bailey, Michigan. Michigan Department of Transportation; 1995. p. 58.
- 41 [60] Koekkoek RT, Lantsoght EOL, Hordijk DA. Proof loading of the ASR-affected viaduct
42 Zijlweg over highway A59. Delft, The Netherlands: Delft University of Technology; 2015. p.
43 180.
- 44 [61] Lantsoght EOL, Koekkoek RT, Hordijk DA, De Boer A. Towards standardization of proof
45 load testing: pilot test on viaduct Zijlweg. Structure and Infrastructure Engineering. in press.

- 1 [62] Barker MG, Imhoff CM, McDaniel WT, Frederick TL. Field testing and load rating
2 procedures for steel girder bridges. MoDOT; 1999. p. 194.
- 3 [63] Barker MG. Steel girder bridge field test procedures. *Construction and Building Materials*.
4 1999;13:229-39.
- 5 [64] Chajes MJ, Mertz DR, Commander B. Experimental load rating of a posted bridge. *Journal*
6 *of Bridge Engineering*. 1997;2:1-10.
- 7 [65] Bakht B, Jaeger LG. Ultimate Load Test of Slab-on-Girder Bridge. *Journal of Structural*
8 *Engineering*. 1992;118:1608-24.
- 9 [66] Coletti DA. Analytical and Field Investigation of Roma Suspension Bridge. *Journal of*
10 *Bridge Engineering*. 2002;7:156-65.
- 11 [67] Moen CD, Shapiro EE, Hart J. Structural Analysis and Load Test of a Nineteenth-Century
12 Iron Bowstring Arch-Truss Bridge. *Journal of Bridge Engineering*. 2013;18:261-71.
- 13 [68] Schenck TS, Laman JA, Boothby TE. Comparison of Experimental and Analytical Load-
14 Rating Methodologies for a Pony-Truss Bridge. *Transportation Research Record*. 1999;1688:68-
15 75.
- 16 [69] Marefat MS, Ghahremani-Gargary E, Ataei S. Load test of a plain concrete arch railway
17 bridge of 20-m span. *Construction and Building Materials*. 2004;18:661-7.
- 18 [70] Wipf TJ, Ritter MA, Wood DL. Evaluation and Field Load Testing of Timber Railroad
19 Bridge. *Transportation Research Record*. 2000;1696:323-33.
- 20 [71] Ji HS, Son BJ, Chang SY. Field Testing and Capacity-Ratings of a Short-Span Bridge
21 Superstructures Made of Advanced Composite Materials. *KSCE Journal of Civil Engineering*.
22 2006;10:113-21.
- 23 [72] Harris DK, Gheitasi A, Civitillo JM. Field testing and numerical modeling of a hybrid
24 composite beam bridge in Virginia. *European Bridge Conference*. Edinburgh, UK2015. p. 12.
- 25 [73] Shekar V, Aluri S, GangaRao HVS. Performance Evaluation of Fiber-Reinforced Polymer
26 Composite Deck Bridges. *Transportation Research Record*. 2005;CD 11-S:465-72.
- 27 [74] Shifferaw Y, Fanous FS. Field testing and finite element analysis of steel bridge retrofits for
28 distortion-induced fatigue. *Engineering Structures*. 2013;49:385-95.
- 29 [75] Zhou YE, Beecher JB, Guzda MR, Cunningham II DR. Investigation and Retrofit of
30 Distortion-Induced Fatigue Cracks in a Double-Deck Cantilever-Suspended Steel Truss Bridge.
31 *Journal of Structural Engineering*. 2015;141:D4014011:1-12.
- 32 [76] Wipf TJ, Phares BM, Klaiber FW, Al-Saidy AH, Lee Y-S. Strengthening Steel Girder
33 Bridges with Carbon Fiber-Reinforced Polymer Plates. *Transportation Research Record*.
34 2005;CD 11-S:435-47.
- 35 [77] Gutkowski RM, Shigidi AMT, Tran AV, Peterson ML. Field Studies of Strengthened
36 Timber Railroad Bridge. *Transportation Research Record*. 2001;1770:139-48.
- 37 [78] Orban Z, Gutermann M. Assessment of masonry arch railway bridges using non-destructive
38 in-situ testing methods. *Engineering Structures*. 2009;31:2287-98.
- 39 [79] Deutscher Ausschuss für Stahlbeton. DAFStb-Guideline: Load tests on concrete structures.
40 *Deutscher Ausschuss für Stahlbeton*; 2000. p. 7 (in German).
- 41 [80] ACI Committee 437. Code Requirements for Load Testing of Existing Concrete Structures
42 (ACI 437.2M-13) and Commentary Farmington Hills, MA2013. p. 24.
- 43 [81] Mettemeyer M, Nanni A. Guidelines for rapid load testing of concrete structural members.
44 *University of Missouri-Rolla*; 1999. p. 97.
- 45 [82] De Luca A, Zadeh HJ, Nanni A. In Situ Load Testing of a One-Way Reinforced Concrete
46 Slab per the ACI 437 Standard. *Journal of Performance of Constructed Facilities*. 2014:1-10.

- 1 [83] Luca AD, Galati N, Nanni A, Alkhrdaji T. In-Situ Load Testing: A Theoretical Procedure to
2 Design a Diagnostic Cyclic Load Test on a Reinforced Concrete Two-Way Slab Floor System.
3 2007.
- 4 [84] Dilek U, Reis EM. Evaluation and Load Testing of Posttensioned Concrete Structure
5 Exhibiting Distress. *Journal of Performance of Constructed Facilities*. 2016;30:1-10.
- 6 [85] Tumialan G, Galati N, Nanni A. Structural Testing: Issues and advances related to structural
7 testing: Part 1: Rationale, Objectives, and Execution. *Structure Magazine*. 2014:10-2.
- 8 [86] Tumialan G, Galati N, Nanni A. Structural Testing: Issues and advances related to structural
9 testing: Part 2: Test Protocols and Case Studies. *Structure Magazine*. 2014:16-8.
- 10 [87] Saleem MA, Siddiqi ZA, Javed MA, Aziz M. Nondestructive Evaluation of an Existing
11 Concrete Structure using Load Test and Core Test. *Pak J Engg & Appl Sci*. 2012;11:66-72.
- 12 [88] Galati N, Alkhrdaji T. Load Test Evaluation of FRP-strengthened Structures. the 7th
13 International Conference on FRP Composites in Civil Engineering. Vancouver, Canada 2014. p.
14 6.
- 15 [89] Corte GD, D'Aniello M, Landolfo R. Field Testing of All-Steel Buckling-Restrained Braces
16 Applied to a Damaged Reinforced Concrete Building. *Journal of Structural Engineering*.
17 2015;141:D4014004.
- 18 [90] Shih CT, Chu SY, Liou YW, Hsiao FP, Huang CC, Chiou TC et al. In Situ Test of School
19 Buildings Retrofitted with External Steel-Framing Systems. *Journal of Structural Engineering*.
20 2015;141:D4014002.
- 21 [91] Azizinamini A, Shekar Y, Boothby TE, Barnhill G. Old concrete slab bridges. 2: Analysis.
22 *Journal of Structural Engineering-ASCE*. 1994;120:3305-19.
- 23 [92] Haritos N, Hira A, Mendis P, Heywood R, Giufre A. Load testing to collapse limit state of
24 Barr Creek Bridge. *Fifth International Bridge Engineering Conference, Vols 1 and 2: Bridges,*
25 *Other Structures, and Hydraulics and Hydrology 2000*. p. A92-A102.
- 26 [93] Jorgenson JL, Larson W. Field Testing of a Reinforced Concrete Highway Bridge to
27 Collapse. *Transportation Research Record: Journal of the Transportation Research Board*.
28 1976;607:66-71.
- 29 [94] Miller RA, Aktan AE, Shahrooz BM. Destructive testing of decommissioned concrete slab
30 bridge. *Journal of Structural Engineering-Asce*. 1994;120:2176-98.
- 31 [95] Wang FM, Kang SZ, Cai YC, Li XL. Destructive Test Study of A Prestressed Concrete
32 Hollow Slab Beam Bridge. *Geotechnical Special Publication No 214 - American Society of Civil*
33 *Engineers*. 2011:57-64.
- 34 [96] Zhang J, Peng H, Cai CS. Destructive Testing of a Decommissioned Reinforced Concrete
35 Bridge. *Journal of Bridge Engineering*. 2013;18:564-9.
- 36 [97] Zhang J, Peng H, Cai CS. Field Study of Overload Behavior of an Existing Reinforced
37 Concrete Bridge under Simulated Vehicle Loads. *Journal of Bridge Engineering*. 2011;16:226-
38 37.
- 39 [98] Zhang J-r, Peng H, Zhang K-b, Hao H-x. Test Study on Overload and Ultimate Behavior of
40 Old Reinforced Concrete Bridge Through Destructive Test of Corroded Bridge. *Engineering*
41 *Mechanics*. 2009;26:213-24.
- 42 [99] Bergström M, Täljsten B, Carolin A. Failure Load Test of a CFRP Strengthened Railway
43 Bridge in Örnköldsvik, Sweden. *Journal of Bridge Engineering*. 2009;14:300-8.
- 44 [100] Ferreira D, Bairan J, Mari A. Efficient 1D model for blind assessment of existing bridges:
45 simulation of a full-scale loading test and comparison with higher order continuum models.
46 *Structure and Infrastructure Engineering*. 2014;11:1383-97.

- 1 [101] Nilimaa J, Bagge N, Blanksvärd T, Täljsten B. NSM CFRP Strengthening and Failure
2 Loading of a Posttensioned Concrete Bridge. *Journal of Composites for Construction*.
3 2015;04015076:1-7.
- 4 [102] Puurula AM, Enochsson O, Sas G, Blanksvärd T, Ohlsson U, Bernspång L et al.
5 Assessment of the Strengthening of an RC Railway Bridge with CFRP Utilizing a Full-Scale
6 Failure Test and Finite-Element Analysis. *Journal of Structural Engineering*.
7 2015;141:D4014008:1-11.
- 8 [103] Zou ZQ, Enochsson O, He GJ, Elfgren L. Finite Element Analysis of Small Span
9 Reinforced Concrete Trough Railway Bridge. *Advances in Concrete and Structures*. 2009;400-
10 402:645-50
11 978.
- 12 [104] Lantsoght EOL, Van der Veen C, De Boer A, Hordijk DA. Collapse test and moment
13 capacity of the Ruytenschildt Reinforced Concrete Slab Bridge Structure and Infrastructure
14 Engineering. available online ahead of print.
- 15 [105] Schacht G, Bolle G, Marx S. Experimental in-situ investigation of the shear bearing
16 capacity of pre-stressed hollow core slabs. In: F.Dehn, Beushausen H-D, Alexander MG, Moyo
17 P, editors. *Concrete Repair, Rehabilitation and Retrofitting IV Leipzig, Germany 2015*. p. 851 - 9.
- 18 [106] Ekeberg PK, Sjursen A, Thorenfeldt E. Load-carrying capacity of continuous concrete
19 slabs with concentrated loads (in Norwegian). *Nordisk betong*. 1982;4:153-6.
- 20 [107] Egger G. Static load tests on building floors: seminar Unterstrass and school building
21 Riedtli, Zürich (in German). *Schweizer Ingenieur und Architekt*. 1998;116:644-7.
- 22 [108] NCHRP. *Manual for Bridge Rating through Load Testing*. Washington, DC 1998. p. 152.
- 23 [109] AASHTO. *The manual for bridge evaluation*. 2nd ed. Washington, D.C.: American
24 Association of State Highway and Transportation Officials; 2011.
- 25 [110] Casadei P, Parretti R, Nanni A, Heinze T. In Situ Load Testing of Parking Garage
26 Reinforced Concrete Slabs: Comparison between 24 h and Cyclic Load Testing. *Practice
27 Periodical on Structural Design and Construction*. 2005;10:40-8.
- 28 [111] Cochet D, Corfdir P, Delfosse G, Jaffre Y, Kretz T, Lacoste G et al. Load tests on highway
29 bridges and pedestrian bridges (in French). Bagnex-Cedex, France: Setra - Service d'Etudes
30 techniques des routes et autoroutes; 2004.
- 31 [112] NRA. *Load Testing for Bridge Assessment*. Dublin, Ireland: National Roads Authority;
32 2014. p. 11.
- 33 [113] The Institution of Civil Engineers - National Steering Committee for the Load Testing of
34 Bridges. *Guidelines for the Supplementary Load Testing of Bridges*. London, UK 1998. p. 44.
- 35 [114] Schacht G, Bolle G, Marx S. Load testing - international state of the art (in German).
36 *Bautechnik*. 2016;93:85-97.
- 37 [115] Schacht G, Bolle G, Curbach M, Marx S. Experimental Evaluation of the shear bearing
38 safety (in German). *Beton- und Stahlbetonbau*. 2016;111:343-54.
- 39 [116] Lantsoght EOL, Yang Y, van der Veen C, de Boer A, Hordijk DA. Beam experiments on
40 acceptance criteria for bridge load tests. *ACI Structural Journal*. (in press).
- 41 [117] Lantsoght EOL. Beams from Ruytenschildt Bridge: Analysis of stop criteria. Delft
42 University of Technology; 2017. p. 77.
- 43 [118] Lantsoght EOL, Yang Y, Tersteeg RHD, van der Veen C, de Boer A. Development of Stop
44 Criteria for Proof Loading. IALCCE 2016. Delft, The Netherlands 2016. p. 8 pp.
- 45 [119] Rücker W, Hille F, Rohrman R. *Guideline for the Assessment of Existing Structures*.
46 Berlin, Germany: Federal Institute of Materials Research and Testing (BAM); 2006. p. 48.

- 1 [120] Ziehl PH, Galati N, Nanni A, Tumialan JG. In-situ evaluation of two concrete slab
2 systems. II: Evaluation criteria and outcomes. *Journal of Performance of Constructed Facilities*.
3 2008;22:217-27.
- 4 [121] Yang Y, Hordijk D, De Boer A. Acoustic emission study on 50 years old reinforced
5 concrete beams under bending and shear tests. IAES-23, IIIAE 2016 KYOTO & ICAE-8
6 Kyoto, Japan2016.
- 7 [122] Matta F, Bastianini F, Galati N, Casadei P, Nanni A. Distributed Strain Measurement in
8 Steel Bridge with Fiber Optic Sensors: Validation through Diagnostic Load Test. *Journal of*
9 *Performance of Constructed Facilities*. 2008;22:264-73.
- 10 [123] Regier R, Hoult NA. Distributed Strain Behavior of a Reinforced Concrete Bridge: Case
11 Study *Journal of Bridge Engineering*. 2014;19:1-9.
- 12 [124] Bentz EC, Hoult NA. Bridge model updating using distributed sensor data. *Institute of*
13 *Civil Engineers – Bridge Engineering*. 2016;170:74-86.
- 14 [125] Idriss RL, Liang Z. In-Service Shear and Moment Girder Distribution Factors in Simple-
15 Span Prestressed Concrete Girder Bridge - Measured with Built-in Optical Fiber Sensor System.
16 *Transportation Research Record*. 2010;2172:142-50.
- 17 [126] Cai H, Abudayyeh O, Abdel-Qader I, Attanayake U, Barbera J, Almaita E. Bridge Deck
18 Load Testing Using Sensors and Optical Survey Equipment. *Advances in Civil Engineering*.
19 2012;11.
- 20 [127] Sanayei M, Phelps JE, Sipple JD, Bell ES, Brenner BR. Instrumentation, Nondestructive
21 Testing, and Finite-Element Model Updating for Bridge Evaluation Using Strain Measurements.
22 *Journal of Bridge Engineering*. 2012;17:130-8.
- 23 [128] McCormick N, Lloyd J. Digital image correlation for the monitoring and investigation of
24 bridges. *Structural Faults and Repair, 13th international conference and exhibition*. Edinburgh,
25 UK2010. p. 10 pp.
- 26 [129] Gentile C, Bulgarelli S, Gallino N, Oldini A. An interferometric radar for remote sensing
27 of deflections on large structures. *Structural Studies, Repairs and Maintenance of Heritage*
28 *Architecture XI2009*. p. 359-71.
- 29 [130] Gentile C, Gallino N. Condition assessment and dynamic system identification of a historic
30 suspension footbridge. *Structural Control and Health Monitoring*. 2008;15:369-88.
- 31 [131] Fuchs PA, Washer GA, Chase SB, Moore M. Laser-Based Instrumentation for Bridge
32 Load Testing. *Journal of Performance of Constructed Facilities*. 2004;18:213-9.
- 33 [132] Lin TS, Nowak AS. Proof Loading and Structural Reliability. *Reliability Engineering*.
34 1984;8:85-100.
- 35 [133] Rackwitz R, Schrupp K. Quality-control, proof testing and structural reliability. *Structural*
36 *Safety*. 1985;2:239-44.
- 37 [134] Val DV, Stewart MG. Safety Factors for Assessment of Existing Structures. *Journal of*
38 *Structural Engineering*. 2002;128:258-65.
- 39 [135] Spaethe G. The effect of proof load testing on the safety of a structure (in German).
40 *Bauingenieur*. 1994;69:459-68.
- 41 [136] Lantsoght EOL, Veen Cvd, Hordijk DA, Boer Ad. Reliability index after proof load
42 testing: viaduct De Beek. *ESREL 2017*. Protoroz, Slovenia2017. p. 8.
- 43 [137] Nowak AS, Szerszen MM. Bridge load and resistance models. *Engineering Structures*.
44 1998;20:985-90.
- 45 [138] Stewart MG, Val DV. Role of load history in reliability-based decision analysis of aging
46 bridges. *Journal of Structural Engineering-Asce*. 1999;125:776-83.

- 1 [139] Wang N, O'Malley C, Ellingwood BR, Zureick A-H. Bridge rating using system reliability
2 assessment Part I: Assessment and verification by load testing. Journal of Bridge Engineering.
3 2010;in press:31pp.
- 4 [140] Frangopol DM, Kim S. Chapter 18: Life-cycle analysis and optimization. In: Chen WF,
5 Duan L, editors. Bridge Engineering Handbook, Vol 5 Construction and Maintenance. Boca
6 Raton, FL: CRC Press / Taylor & Francis Group; 2014. p. 537-66.
- 7 [141] Strauss A, Frangopol DM, Kim S. Use of monitoring extreme data for the performance
8 prediction of structures: Bayesian updating. Engineering Structures. 2008;30:3654-66.
- 9 [142] Frangopol DM, Strauss A, Kim S. Use of monitoring extreme data for the performance
10 prediction of structures: General approach. Engineering Structures. 2008;30:3644-53.
- 11 [143] Okasha NM, Frangopol DM. Integration of structural health monitoring in a system
12 performance based life-cycle bridge management framework. Structure and Infrastructure
13 Engineering. 2012;8:999-1016.
- 14 [144] Kong JS, Frangopol DM. Probabilistic optimization of aging structures considering
15 maintenance and failure costs. Journal of Structural Engineering-Asce. 2005;131:600-16.
- 16 [145] Ang A-S, De Leon D. Modeling and analysis of uncertainties for risk-informed decisions
17 in infrastructures engineering. Structure and Infrastructure Engineering. 2005;1:19-31.
- 18 [146] Lantsoght EOL, van der Veen C, de Boer A, Walraven JC. Recommendations for the
19 Shear Assessment of Reinforced Concrete Slab Bridges from Experiments Structural
20 Engineering International. 2013;23:418-26.
- 21 [147] Fennis S, van Hemert P, Hordijk D, de Boer A. Proof loading Vlijmen-Oost; Research on
22 assessment method for existing structures. Cement. 2014;5:40-5.
- 23 [148] Vos W. Stop criteria for proof loading - The use of stop criteria for a safe use of 'Smart
24 Proof loading'. Delft, The Netherlands: Delft University of Technology; 2016.
- 25

26

27

1 **List of Figures**

2 **Figure 1.** BELFA load testing vehicle on viaduct Vlijmen-Oost [147].

3 **Figure 2.** Proof load testing of the viaduct Zijlweg [61].

4 **Figure 3.** Safety philosophy of German guideline [148].

5 **Figure 4.** Prescribed loading protocol from ACI 437.2M-13 [80]: (a) monotonic loading
6 protocol; (b) cyclic loading protocol.

7 **Figure 5.** Stop criteria of ACI 437.2M-13: (a) Deviation from linearity index; (b) Permanency
8 ratio.

9 **Figure 6.** Probability density functions of load and resistance: (a) before a load test; (b) during a
10 load test; (c) after a load test.

11

1 **List of Tables**

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

3 [79].

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

4

5

6

7

8