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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>

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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**

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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 **5 Current codes and guidelines**

3 **5.1 German guideline**

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

$$11 \quad \varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0} \quad (1)$$

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

$$14 \quad \varepsilon_{s2} < 0.7 \frac{f_{ym}}{E_s} - \varepsilon_{s02} \quad (2)$$

15 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
16 steel caused by the permanent loads. When the stress-strain relationship of the steel is fully
17 known, Eq. (2) is replaced by:

$$18 \quad \varepsilon_{s2} < 0.9 \frac{f_{0.01m}}{E_s} - \varepsilon_{s02} \quad (3)$$

19 with $f_{0.01m}$ the average yield strength based on a strain of 0.01% (elastic zone). The third stop
20 criterion defines limits to the crack width for new cracks and increase in crack width for existing
21 cracks, as shown in Table 1. The fourth stop criterion limits the residual deflection to 10% of the
22 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

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10 load test; (c) after a load test.

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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	$w \leq 0.5 \text{ mm}$	$\leq 0.3w$

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