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Bridge load testing: Recent advances in research, collaboration, and codes

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ABSTRACT: Bridge load testing is one of the tools engineers are using for the assessment of existing bridges, which is becoming increasingly important to manage the existing bridge stock in a sustainable manner. Over the past years, various research groups have worked on theoretical and practical research regarding load testing. Moreover, various international committee work on load testing recommendations. This paper provides an overview of recent research efforts in Denmark, the Netherlands, and Sweden. The way in which recent research efforts are implemented in new committee reports and guidelines is highlighted. Overall, the efforts have focused on combining load testing with insights in structural behavior, applying improved instrumentation techniques, combining with numerical analyses, and providing a probabilistic substantiation. In conclusion: bridge load testing is a dynamic field of research that benefits from international collaboration. Further improvements to existing codes and guidelines will be forthcoming in the next years.

1 INTRODUCTION

In Europe, the decades after the end of the Second World War marked a time of economic expansion and growth, which is reflected, among other aspects, by the expansion of the transportation network. As a result, many of the existing bridges in Europe are from the 1950s to 1970s (Lantsoght *et al.* 2013). These bridges are reaching the end of their originally devised service life. Replacing bridges at the end of their service life is however not a wise decision: the economic cost and CO_2 emissions are high, the impact on traffic flows creates a high indirect economic cost, and natural resources are dwindling. In short, to manage the existing bridge stock sustainably, it is important to assess existing bridges and decide how and in which way the service life of the existing bridges can be extended (Yang *et al.* 2019).

Load testing of bridges can be a valuable method for assessment when uncertainties regarding the overall behavior of the bridge are large (Alampalli *et al.* 2021). Often these uncertainties are dedicated to the contributions from certain mechanisms (such as the effect of support boundary conditions, transverse distribution when strong bands of reinforcement are used for the sidewalks, or to quantify the contribution of the non-structural elements), which are difficult to quantify analytically. Typically, two types of load tests can be distinguished: diagnostic load tests and proof load tests. In a diagnostic load test, a known live load is applied and the resulting structural responses are compared to analytically determined responses to better

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understand the overall bridge behavior. Ultimately, a field-validated model can be developed and used for assessment. In a proof load test, a load representative of the factored live load is applied directly to the bridge to demonstrate in the field that the bridge fulfills the code requirements. As high loads are involved, the load needs to be applied incrementally, and at each load level, the structural responses need to be compared to pre-determined thresholds, the so-called stop criteria (Lantsoght *et al.* 2019; Christensen *et al.* 2022). When a stop criterion is reached, further increasing of the load is not permitted. A final type of field test is a collapse test, in which a bridge is loaded to failure, which can give a full insight into the structural behavior of the bridge and all its load-carrying mechanisms.

2 PROOF LOADING ASSESMENT

2.1 *General*

Proof loading methods used as a means to capacity-upgrade existing concrete structures are, at present state, highly country dependent. However, proof load testing assessments seem to be limited by procedure uncertainty, lack of consistent methodologies, guidelines and codes. Often reluctance towards proof loading is present since safety measures and traffic disturbances occur during testing. Short testing time and environmental conditions could influence the result acquisition. This challenge, combined with a possibility of structural collapse, provides an important bridge owner caution that has to be addressed to ensure confidence in proof loading methods.

2.2 *Denmark*

A comprehensive concrete bridge-proof loading research project in Denmark has been ongoing for approximately half a decade. The project collaborators are the Danish Road Directorate, the Technical University of Denmark (DTU), Aalborg University (AAU), and COWI A/S.

The proof loading concept has its basis in the Danish classification system, where specified axle loads are given for each classification vehicle (Vejdirektoratet - The Danish Road Directorate 2017; Schmidt *et al.* 2020). The heavy vehicles' positioning is described, where a classification vehicle A is placed in the desired position on the bridge. Adjacent to the vehicle A, a stable vehicle B load is applied. A bridge has sufficient resistance if the bridge class is higher than the class of the passing vehicle. The research includes a multidisciplinary approach that combines experimental testing, theoretical response evaluations, and probabilistic assessments. Bridges on a road stretch between Herning and Holstebro in Denmark were initially tested in the Danish bridge testing project. Some of the weakest bridges were seen to have significantly larger resistance than predicted theoretically (Schmidt *et al.* 2018). Several pilot-proof loadings were performed during the research project to verify the developed methods and to get unique experience with the in-situ response- and handling of sensitive equipment. It was experienced that in-situ proof load can be very challenging compared to laboratory testing due to the environmental and practical conditions which may affect result acquisition. This aspect is combined with a short testing time demand to reduce related costs and traffic disturbances. Advanced testing equipment should thus be efficiently optimized and reduced to an extent that meets these challenges and generates the desired output. The outcome aims to accommodate a satisfactory evaluation of deformations, stop criteria, target loads, etc., to ensure a sufficient proof load decision basis.

Experiences and findings from the Danish proof loading research project have generated input for a Danish bridge proof loading guideline, which is expected to be published soon. The guideline describes how to perform proof loading on one-span bridges with a background in the Danish classification system. A pilot project was initiated to verify whether the guideline procedure was possible. Four class 80 bridges were identified on a chosen road stretch, which was aimed to be upgraded to class 100 using the developed proof loading method. The bridges were tested successfully in three days, (including a manageable traffic disturbance (Christensen *et al.* 2023)). Consequently, the road stretch was upgraded to class 100, and the results could be integrated into the Danish strategic road network.

2.3 *The Netherlands*

In the Netherlands, research related to assessment of existing concrete bridges originally focused mostly on reinforced concrete slab bridges, as a large number of these bridges form the 1960s and 1970s were found to be insufficient for shear upon assessment according to the newly introduced Eurocodes (Lantsoght *et al.* 2013; Lantsoght *et al.* 2017a). These efforts were in line with the development of the Dutch Guidelines for the Assessment of Existing Bridges (RBK) (Rijkswaterstaat 2013).

Assessment of existing bridges in the Netherlands is carried out at four different Levels of Approximation (LoA). The first LoA is usually a spreadsheet-based hand calculation, which compares the factored load effect in a simplified way with the factored capacity from the code. If the Unity Check, i.e. the ratio of demand to capacity, is more than one, the assessment is taken to the next level. If not, it is found with a simplified approach that the critical cross-section, and by extent, the bridge, fulfills the requirements. At the next LoA, a linear finite element analysis is used for finding the factored load effect, and the factored capacity is again determined using the code expressions. Then, if a next level is necessary, a nonlinear finite element analysis may be considered, following the Dutch Guidelines for Nonlinear finite element analysis of concrete structures (Rijkswaterstaat 2012). Finally, if none of the analytical approaches can demonstrate that the bridge fulfills the code requirements, and it is expected that additional sources of capacity can be activated, a proof load test may be considered.

Proof load testing in the Netherlands is not a common method of assessment. At this moment, a series of pilot proof load tests have been carried out (Lantsoght *et al.* 2017b). These pilot proof load tests showed the feasibility of proof load testing for the assessment of existing reinforced concrete bridges in the Netherlands, both for flexure and shear. However, it was decided to first carry out fundamental research to determine stop criteria for shear and to develop a probabilistic substantiation of proof load testing in line with the current code requirements before proof load testing can be carried out by market parties.

2.4 *Sweden*

Sweden owns approximately 30,000 bridges, of which about 4,000 are railway bridges and the remaining are road bridges BaTMan (Trafikverket 2023). Some 70% of these bridges are owned by the Swedish Transport Administration (Trafikverket), while the rest, exclusively road bridges, are owned by regional counties. Very few railway bridges are also owned by private companies. The bridge population is relatively young, with many built after the Second World War, and their design lifetimes vary. As codes have evolved and the quality of materials and workmanship has improved, many bridges have been designed with longer lifetime expectations. It is also acknowledged that the quality of the bridges is high. To the authors' best knowledge, failures or service impairments have been seldom encountered. Currently, capacity assessment is conducted using a national code issued by the Swedish Transport Administration (TRVINFRA-00331 2023), based on the European Norms (Eurocodes), incorporating adjustments from the previous Swedish national codes.

The assessment of the bridges is largely undertaken by consulting companies, supervised by 10 bridge specialists from Trafikverket. The initial assessment step involves automated worksheets or simple linear elastic calculations based on design values, complemented by verification through inspection reports in BaTMan. If the capacity conditions are met, no further steps are taken. If not, Trafikverket may contract more detailed analysis, which can include non-linear finite element simulations, in-depth inspections, and structural health monitoring. Sweden has a relatively short history of proof load testing of bridges.

According to (Elfgren *et al.* 2018), thirteen full-scale bridges have undergone testing in the past three decades, with five tested to the point of failure. The objectives of these proof load tests varied, including monitoring the bridge under controlled loads, validating advanced calculations, verifying strengthening methods, or checking for settlements. The tests conducted to the point of failure aimed to collect data for verifying and comparing capacities in shear of concrete and prestressed concrete bridges under concentrated loads, using methods like finite element modeling (FEM). The results consistently showed discrepancies between code estimates, test results, and numerical simulations, thus prompting further developments.

3 RECENT RESEARCH

3.1 *Denmark*

The bridge proof loading project's first version (V1) succeeded with significant in-situ test experience and descriptions of a test setup and related design. The optimized multidisciplinary approach seemed to work well where advanced monitoring could be optimized and reduced to an extent that enabled several pilot-proof loading tests. In addition, testing and theoretical evaluations also revealed sufficient interaction between OT elements under in situ and laboratory conditions. Thus, desirable slab behavior was obtained, enabling more optimized calculation methods and capacity upgrading of several bridges, see Figure 1.

Findings and results from the V1 project provided a good basis for continuing the Danish proof loading project based on the classification system. A good foundation for classification-based proof loading, which is economically competitive, seemed to be provided. The V1 project dealt with one-span bridges and seems to provide an excellent background for an extension to the second version 2 (V2), which will research methods to proof-load multi-span bridges. In addition, further evaluation and optimization of stop criteria is ongoing in the V2 project. This evaluation will be one of the main scopes since an open question remains concerning stop criteria related to the potentially brittle behavior of non-shear reinforced (shear-critical) slabs and prestressed concrete bridges. The extension to V2 was deemed to work in excellent synergy with upcoming international activities, ensuring an even more significant gain. One of the main aims is to extend the Danish guideline with the findings of the V2 project.

a) b)

Figure 1. a) Laboratory OT-slab point loading testing (behind glass screen) with acoustic emission, digital image correlation, LVDTs, etc. b) In-situ pilot testing using representative classification vehicles.

3.2 *The Netherlands*

Recent and current research in the Netherlands on proof load testing has mostly focused on fundamental research to support the proof load testing practice. This research has focused on developing stop criteria for shear for use during proof load testing of reinforced concrete members without shear reinforcement, and on deriving a probabilistic substantiation of proof load testing.

The research on stop criteria encompasses two series of experiments. A first series consists of 25 experiments in flexure and shear on 6 reinforced concrete slabs of 5m × 2.5 m × 0.3 m subjected by a proof load testing protocol first, and then tested stepwise to failure. A second series, ongoing at the time of writing this paper, consists of 8 skewed reinforced concrete slab specimens, see Figure 2. To develop these stop criteria, first shear stop criteria for slab strips have been developed, and then these stop criteria are extended to reinforced concrete slabs. The shear stop criteria for beams can be found in (Zarate Garnica *et al.* 2024), whereas the shear stop criteria for slabs are under development. The second series of experiments has the following goals: 1) validate the developed shear stop criteria for straight slabs for the situation of skewed slabs, and 2) validate current assessment procedures for skewed slab bridges, and in particular the way in which the load effect is determined in the obtuse corner.

Figure 2. Skewed slab testing at TU delft.

The research on the probabilistic substantiation of proof load testing is addressing the following aspects: 1) time-dependent probabilities of failure (de Vries *et al.* 2022), 2) state of information and the effect of the type of prior selected (de Vries *et al.* 2023), 3) using stop criteria and measurements during proof load testing for the probabilistic analysis (de Vries *et al.* 2024), and 4) spatial variability.

3.3 *Sweden*

During the last 30 years about fifteen tests on bridges have been conducted in Sweden, primary led by Luleå University of Technology (LTU) (Elfgren *et al.* 2018). The most recent work on proof loading of bridges in Sweden aims at contributing to the sustainability challenge by identifying the True Capacity of the existing bridges. This is done by developing tools

Figure 3. Concept used at Luleå University of Technology (LTU) for life extension of existing structures.

and methods for life cycle assessment in areas of SHM, prediction simulations and tests, see Figure 3.

A 65-year-old prestressed box-girder concrete bridge in Kalix, northern Sweden, was demolished in 2022. Prior to this, an experimental campaign was conducted to enhance our understanding of the behavior of such bridges. The work focused on three aspects: (1) condition assessment of the bridge using non-destructive testing (NDT), (2) development of a proof loading method for assessing service limit conditions with standard convoys and Structural Health Monitoring (SHM) sensors, (3) formulation of controlled demolition methods for prestressed concrete bridges. The results have shown that NDT tools are promising for identifying defects, though they require further field validation and a comprehensive understanding of the bridge's design and construction principles. The proof loading method incorporated tests with new technologies, including Fiber Optic Sensors (FOS), acoustic emission testing, and various techniques for measuring prestressing forces. The developed demolition process was successfully executed, ensuring safety and environmental cleanliness.

Figure 4. View of the midspan of the Kalix bridge under proof loading.

New research related to railway bridges began in 2021 with an investigation into potentially increasing axle loads from 30 tons to 32.5 and 35 tons on one of the most heavily utilized railway lines, the Iron Ore Line in Northern Sweden. Approximately 50% of the bridges on this line are trough-type, comprising two side beams and a slab that form a U-shaped structure filled with ballast. The study (1) verifies the existing standard load distribution model by monitoring pressure distribution between the ballast and the concrete deck and beams, and (2) assesses the impact of increased axle loads on the lifespan of these bridges. Of high interest is the development of criteria for the fatigue assessment. Experiments are conducted on a full-scale model bridge (7 m × 4 m) in the LTU laboratory, Figure 5. A suite of sensors, including standard strain gauges, Linear Variable Differential Transformers (LVDTs), Fiber Optic Sensors (FOS) on the internal reinforcement and concrete surface, and photogrammetry for crack detection and mapping, has been deployed. The data collected will be utilized for benchmarking numerical analyses and subsequent parametric stochastic validation.

Figure 5. View of the full-scale trough bridge tested at the LTU lab.

Research into developing proof loading methods for railway bridges has included analysis, condition assessment based on autonomous crack detection, and instrumentation of four bridges of various designs: trough, composite steel girder - concrete slab, concrete arch, and portal frame bridges. Sensors have been strategically placed in areas deemed critical for assessing bridge performance. Controlled train loads have been applied in both dynamic and static tests under varying seasonal conditions. These tests aim to understand how temperature fluctuations and humidity levels over a year affect the interaction between the bridges and their support structures.

3.4 *State of collaboration*

Current research in Denmark, the Netherlands, and Sweden focuses in broad lines on the following common themes: modeling of existing concrete structures, automated condition assessment, improved instrumentation methods for field measurements, and probabilistic aspects, see Figure 6. Moreover, field testing occurs under constraints of time and budget. As such, sharing experiences is to the benefit of all. In particular, a synergy of activities can be found between the three countries for the following topics: solving practical challenges related to application of loading and sensors when multiple spans need to be tested, determination of the required number of positions and proof load for the test, extrapolation of results from one span to another span for an assessment, evaluation of the choice of testing a lower number of positions under a higher load, versus a higher number of positions under a lower load, and the practical repercussions of such a choice, and developing considerations for different types of bridges, and those that are multiply statically determinate versus statically indeterminate bridges.

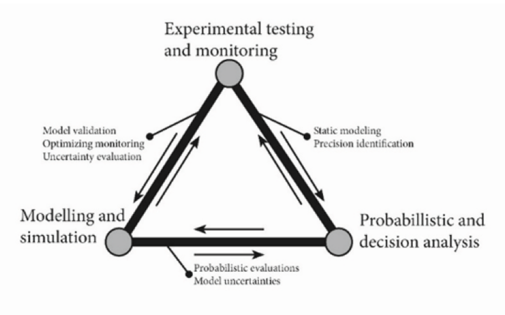

Figure 6. Synergy between research topics.

4 RECENT GUIDELINE AND ADVANCED IN INTERNATIONAL COLLABORATION

Recent research efforts related to proof load testing as illustrated above, as well as carried out by colleagues internationally, have resulted in the publication of a number of technical documents, codes and guidelines that may be of relevance to the reader. The first relevant document is a recent *fib* Bulletin of TG 3.2 (fib TG 3.2 2024), which includes a section related to proof load testing of existing structures, and in particular existing concrete bridges. For existing reinforced concrete buildings, the new ACI 437.2M-22 (ACI Committee 437 2022) code is a major development as compared to ACI 437.2M-13 (ACI Committee 437 2013), as the current version of the code includes the option to proof load test buildings for shear. For bridges, the upcoming version of the AASHTO Manual for Bridge Evaluation includes a new Chapter 8 on Load Testing, which is aligned with the contents of the TRB e-circular 257 (Alampalli *et al.* 2019).

Besides the recently published documents mentioned in the previous section, various international committees have included or are including load testing recommendations in their reports and guidelines. In particular, within IABMAS, the IABMAS Bridge Load Testing committee is working together with *fib* COM 3 on the development of a guidance document related to proof load testing of existing concrete bridges. Moreover, the members of the IABMAS Bridge Load Testing committee meet twice a year virtually, as well as in hybrid mode at the IABMAS symposia. Interested readers can find the minutes of the activities of the technical committee on the IABMAS website (IABMAS 2021), as well as find the mission, goals and membership of the committee reported.

5 CONCLUSION

This paper shows how assessment of existing concrete bridges is carried out in Denmark, the Netherlands, and Sweden, and how proof load testing is used in these countries as part of the assessment. The paper also gives a summary of recent research insights from the three countries. A summary of the research efforts show that these efforts have been focused on combining load testing with better insights in structural behavior, applying improved instrumentation techniques in the field, combining measurements with numerical analyses, and providing a probabilistic substantiation of the practice. Synergy in the research efforts is identified by looking at the broad categories of practices applied in the three countries, even though assessment and proof load testing practices are driven by national differences. In conclusion: bridge load testing is a dynamic field of research that benefits from international collaboration. It is expected that further improvements to existing codes and guidelines will be forthcoming in the next years.

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