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Assessment of existing concrete bridges by load testing: barriers to code implementation and proposed solutions

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ABSTRACT
As the existing bridge stock is aging, the task of assessing these bridges becomes increasingly important. One of the assessment methods for existing bridges is load testing. Improvements in the field of diagnostic load testing are related to the use of numerical models. Improvements in the field of proof load testing focus on the safety of the execution of the test as well as the required load in the test. What is still lacking is a reflection of these recent advances in the codes and guidelines used for load testing of bridges. Two approaches are proposed to address this lack. The first approach attempts to answer fundamental questions with regard to bridge load testing through research. The second approach is to coordinate efforts and facilitate collaboration and exchange of ideas internationally through the IABMAS Technical Committee on Bridge Load Testing. In conclusion, it is expected that these efforts will form the basis of improved recommendations for the assessment of concrete bridges by load testing to be included in codes and guidelines and to serve the community of engineers faced with the task of assessing ageing infrastructure.

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1. Introduction

As our bridge stock is aging, the task of assessing the existing bridges becomes increasingly important. For example, in the Netherlands, the majority of the existing bridges were built during the 1960s and 1970s, in the era of reconstruction after the Second World War. In total, 60% of the bridges owned by Rijkswaterstaat (Dutch Road Directorate, part of the Ministry of Infrastructure and Water Management) are built before 1975 (Lantsoght, van der Veen, de Boer, & Walraven, 2013; Walraven, 2010). Similarly, in the United States 42% of the existing bridges are at least 50 years old, i.e. from 1971 or earlier (Infrastructure Report Card, 2021). As such, the task for assessment and load rating of the existing bridges is increasingly important for bridge engineers.

While calculation methods that are similar to those used for design may be sufficient for the assessment of bridges in some cases, in other cases other methods are necessary to assess the existing bridge. An additional concern here can be that insufficient information is available about the existing bridges, and that, for example, structural plans are missing (Harrewijn, 2019; Jauregui, Weldon, & Aguilar, 2019; Shenton, Chajes, & Huang, 2007). When the minimum required information is available and no major deterioration or degradation is observed, the engineer carrying out the assessment usually starts with a simple evaluation based on sectional capacity and sectional demand due to the load combination of live load, superimposed dead load, and self-weight. This evaluation can be done by hand, or programmed into a spreadsheet. When this approach shows that the bridge meets the requirements of the code, no further analysis is carried out.

If the simple approach shows insufficient capacity, the next step is usually to make a linear finite element model to better study the load effect. The capacity side of the equation is not altered. Again, if this approach now shows that the bridge meets the requirements of the code, the analysis is considered satisfactory. On the other hand, if the analysis shows that the capacity is insufficient, then alternative assessment methods may be suitable. Such alternative assessment methods include the use of nonlinear finite element models (de Boer, Hendriks, & Lantsoght, 2019), probabilistic studies (Monteiro, Delgado, & Pinho, 2016), and obtaining field data. Methods to obtain field data include non-destructive testing to obtain more information about the materials and bridge condition (FHWA., 2016), structural monitoring (Miceli, Moon, Paterson, & Vanderzee, 2019), and load testing (Alampalli et al., 2019), or a combination of such methods (Parvez, Rahimzadeh, Fok, & Ton, 2022).

The approach of increasing refinement of the assessment is in line with the Levels of Approximation, first introduced in the *fib* Model Code 2010 (fib, 2012). Figure 1 illustrates the concept of the Levels of Approximation. For assessment,

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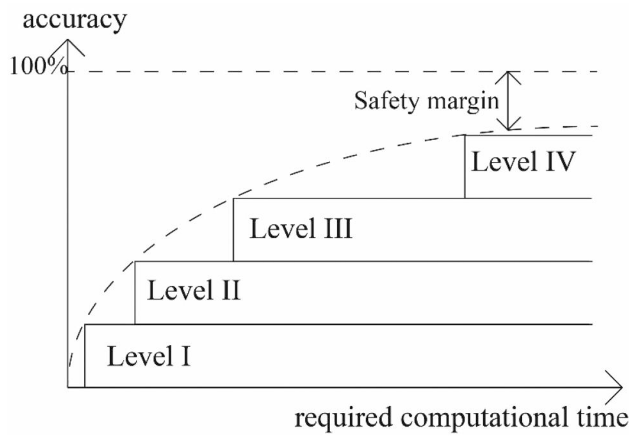


Figure 1. Principle of increasing Levels of Approximation from fib Model Code. Reproduced from Lantsoght, De Boer, et al. (2017) with permission.

this approach is called Levels of Assessment (Lantsoght, De Boer, & Van der Veen, 2017). Many of the techniques mentioned, such as the use of non-destructive testing, structural monitoring (Mandić Ivanković, Skokandić, Žnidarič, & Kreslin, 2019), and assessment using nonlinear finite element analysis currently do not form part of the structural or bridge engineering curriculum, but these techniques are becoming increasingly important tools for bridge engineers.

In this article, the method for assessment discussed is bridge load testing (Pimentel et al., 2023). In a load test, a known load is applied in a controlled manner, and the structural responses are recorded. The load can be applied by using vehicles or by using systems with hydraulic jacks. In the past, dead weight was also used during load testing, but this approach may pose safety risks. Depending on the magnitude of the applied load, the information from the test can be used to update analytical models of the bridge after a so-called diagnostic load test, or it can be used to directly demonstrate that the bridge fulfils the code requirements in terms of its ability to carry the code-prescribed live loads after a so-called proof load test.

Indeed, the objective of a diagnostic load test is to quantify bridge response under a known applied load (Bonifaz, Zaruma, Robalino, & Sanchez, 2018; Commander, 2019; Hernandez & Myers, 2018; Lantsoght, 2020; Lantsoght, Yang, van der Veen, Hordijk, & de Boer, 2019a). In particular, information that can be obtained is related to, for example, evaluating composite action (Yarnold, Golecki, & Weidner, 2018), the contribution of non-structural members (Barker, 2001), transverse load distribution (ACI Committee 342, 2016), and the efficiency of repairs (Zwicky & Brühwiler, 2015). This information can then be used to developed better analytical models for the load rating of the bridge.

On the other hand, a proof load test directly evaluates if a bridge fulfils the code requirements by checking if the bridge can carry the code-prescribed live loads (Alampalli et al., 2021; Halicka, Hordijk, & Lantsoght, 2018; Lantsoght et al., 2019b). This approach requires applying high loads, so that a sectional moment or shear corresponding to the factored load combination from the code can be reached in the cross-section. However, applying high loads on bridges involves high risks as well. Therefore, it is important to properly instrument bridges during proof load testing and to carefully increment the load in a predetermined loading protocol. The responses should be evaluated at each load level.

If the responses reach or exceed pre-set thresholds, the so-called stop criteria, further loading may result in permanent damage or even collapse. As such, further loading after reaching a stop criterion is not permitted. If such a situation occurs during a proof load test, then the target proof load cannot be reached during the load test. Depending on the maximum achieved load level, the bridge may still be able to carry lower levels of loading and may require posting, or the responsible bridge engineer may need to propose other measures. In addition, the responsible engineer should evaluate after a proof load test if no mechanisms that are not reliable in the long term contribute during the load test. If such mechanisms can be identified, the contribution of these mechanisms should be removed, and for this purpose, a numerical model is typically used.

Engineers have used bridge load testing as a method to assess existing bridges for over a century. Initially, proof load tests were used during the opening ceremony of a bridge to show the traveling public that the bridge is safe (Bolle, Schacht, & Marx, 2011). In addition, as early as the nineteenth century, proof load testing was used as a method to assess existing railway bridges in Switzerland, and to check the condition of the existing bridges. Load testing has been a tool used by engineers to better understand bridges and their behaviour. In this paper, the focus is on current developments in load testing, so that this tool, which engineers have used for centuries, can be used in the context of bridge engineering in the twenty first century.

2. Literature review

2.1. Recent developments in diagnostic load testing

As engineers face an increasing assessment task, the interest in bridge load testing has increased over the past decade. Recent improvements in the field of diagnostic load testing are related to the use of numerical models for the analytical models that are used together with the procedures (Commander, 2019), improvements related to sensing techniques (Sanayei, Reiff, Brenner, & Imbaro, 2016; Zarate Garnica, Lantsoght, & Yang, 2022), and the application of the method to new materials (Hernandez & Myers, 2018) and repair applications (Olaszek, Łagoda, & Casas, 2014; Russo, Wipf, & Klaiber, 2000). Figure 2 shows an example of a diagnostic load test on a planless prestressed concrete bridge (Borges, Lantsoght, Castellanos-Toro, & Casas, 2021; Castellanos-Toro et al., 2022), carried out at night to minimize disturbance of the traffic flow. This bridge had visible cracking in some of the girders and the diaphragms did not follow the intended straight line. The load test was used to estimate the transverse distribution and update the load rating of the bridge assisted by finite element analysis, as has been proposed by other authors as well (Hutchinson, Peiris, & Harik, 2022).

As the use of finite element models becomes more standard practice, the combination of diagnostic load testing with

Figure 2. Diagnostic load test over the lili bridge, cali, Colombia. For details of load test, see (Castellanos-Toro et al., 2022).

finite element models becomes a powerful tool for the assessment of existing bridges. The procedure that is recommended (Alampalli et al., 2019; Alampalli et al., 2021) for the combination of these methods is to first develop a finite element model of the bridge that needs to be assessed, to study the behaviour of the bridge and load distribution under linear elastic conditions. The finite element model also serves to prepare the load test, as an estimate of the expected structural responses will inform the choices for the sensor plan, and the most critical load positions and paths can be determined with this model. Various parameters that are subject of discussion can be explored with the model by comparing the structural responses as a function of changes in the parameters under discussion (Borges et al., 2021).

The information is then compared to the measured structural responses during the field test. Various parameters, such as the stiffness of the bearings and overall stiffness of the structure can be modified to develop a field-validated finite element model of the bridge. Optimization techniques can be used to find the parameter values for which the error between the output of the finite element model and the measured responses is minimized. However, it is always necessary for the engineer to check if the parameters that result from the optimization are physically possible, and in particular, if the combination of various parameters are not contradictory (Bridge Diagnostics Inc., 2012; Castellanos-Toro et al., 2022). For the bridge illustrated in Figure 2, the effect of cracking in the deteriorated girders was taken into account by reducing the stiffness of the damaged girders and by comparing the measured and numerically determined strain responses.

If the finite element model and the results from the load test are to be used for rating, then the field-validated model needs to be adjusted (Abedin, De Caso y Basalo, Kiani, Mehrabi, & Nanni, 2022). First of all, the occurring mechanisms should be evaluated, and the engineer should analyse if over time or under higher loading these mechanisms could break down. Examples are: the restraint caused by frozen bearings, which may be scheduled for replacement, or unintended composite action which may break down under higher loads. The influence of such mechanisms should be removed from the finite element model. In addition, where the field-validated model is based on average values of material properties to mimic the structural responses during the load test as closely as possible, the model that is used for load rating and assessment should use the design values of the material properties.

For concrete bridges in particular, there is an increased interest in the use of diagnostic load testing for assessment (Olaszek et al., 2014). For reinforced concrete bridges, diagnostic load testing may be sufficient to answer the open questions about the bridge. In these cases, the more expensive proof load testing can be avoided. For this purpose, defining the objectives of the load test, and selecting the appropriate load testing method is always of crucial importance.

For prestressed concrete bridges, diagnostic load testing is often the load testing method of preference. In prestressed bridges, loads that could cause cracking should be avoided. As such, the lower load levels of diagnostic load testing are recommended. These lower load levels also correspond better to the serviceability limit state for which prestressed bridges are typically designed (whereas these bridges are checked for the ultimate limit state). Similarly, for bridges using new concrete mixes (Hernandez, 2018), concrete-like materials such as alkali-activated concrete (Ahmed, Jaf, & Yaseen, 2020), or new reinforcing materials (Hung, Sung, Chang, Yin, & Yeh, 2016), a diagnostic load test can be used to check if the behaviour of the bridge is as expected.

When it comes to modelling, the user has a number of options in a linear finite element model that represent better the condition of the bridge. For example, for a reinforced concrete slab bridge with visible cracking, the slab can be modelled with orthotropic properties (Lantsoght, De Boer, Van der Veen, & Hordijk, 2018). Similarly, the flexural stiffness EI (with E the modulus of elasticity of the concrete and I the moment of inertia of the cross-section) of concrete girders with cracking can be modelled by reducing the properties to represent the smaller moment of inertia of the cracked cross-section, in which the contribution of the concrete under tension is neglected (Castellanos-Toro et al., 2022). With the right adjustments based on engineering judgment, linear finite element models of concrete bridges can be a powerful tool in combination with diagnostic load tests.

Diagnostic load tests can be static (i.e. with the loading truck placed at a given position) as well as dynamic (i.e. with the loading truck passing at several speeds). Dynamic load testing can be used for the assessment of railway bridges (Olaszek et al., 2014; Olaszek, Świercz, & Boscagli, 2021). With dynamic load testing and the use of a speed bump, the impact factor (also called: dynamic amplification factor) of a bridge can be quantified as well (Paultre, Chaallal, & Proulx, 1992). Other types of dynamic testing, which are in the realm of vibration-based measurements and which aim at finding the model frequencies of the bridge, are outside the scope of this article.

2.2. Recent developments in proof load testing

In the field of proof load testing, various recent research projects have focused on making proof load testing safer as well as extending the application of proof load testing to shear-critical structures. In the history of proof load testing, collapses during proof load testing often resulted in injured workers, or even death (ElBatanouny, Schacht, & Bolle, 2019). To make the execution of proof load tests safer, closer attention is paid to the structural responses during the load test. Various thresholds of structural performance, the so-called stop criteria, are studied. Different stop criteria for different failure modes are identified. In addition, more attention is being paid to the preparation of proof load tests, so that the engineers involved in load test have a better prior understanding of the risks involved and the expected behaviour during the test. In particular, the chance of a brittle failure mode in concrete bridges (Cheung & Li, 2003) requires careful preparation and consideration.

Secondly, several existing reinforced concrete bridges were designed with codes that may have assigned a larger shear capacity than when using the current codes. Traditionally, proof load testing for shear was not permitted, as it was feared that a brittle failure could take place during the test (NCHRP, 1998). Recent pilot proof load tests focused on demonstrating that shear-critical bridges can carry the code-prescribed load for the failure mode of shear (de Boer, Ha, & Quansah, 2022; Lantsoght, Van der Veen, De Boer, & Hordijk, 2017). This concept was also applied recently in North America (Saroufim, Issa, Mahdi, & Issa, 2023). These pilot proof load tests showed that for reinforced concrete slab bridges, with and without material deterioration, proof load testing for shear is possible and can be done in a safe and controlled manner.

Another aspect of recent research is the determination of the target proof load. Guidance on the choice of target proof load is available in the Manual for Bridge Evaluation (AASHTO, 2016), the German Guidelines for Load Testing (Deutscher Ausschuss für Stahlbeton, 2020), and in Denmark (Christensen, 2023). In the past, the required factor between the rating vehicle and the proof load vehicle was taken equal to two (Shahawy, 1995). With calculations based on concepts of structural reliability, this factor was reduced to 1.4 in the 1990s (NCHRP, 1998).

Practical aspects that are an improvement in the practice of proof load testing are related to the method of load application and the instrumentation. While the use of dead load for proof load testing of bridges was commonly used in the past (ElBatanouny et al., 2019), there are serious drawbacks related to the use of dead load. For example, arching action in the loads can occur when the bridge deck deflects, so that the load is not properly distributed over the deck. Sand bags can absorb water when it rains, which can lead to undesired increases in the applied load. If there is a (sudden) risk of irreversible damage or even collapse, fast unloading of the weights is not possible when using dead load. Therefore, in recent years, various approaches based on the use of hydraulic jacks and an auxiliary steel frame have been developed. In the Netherlands, the focus has been on applying four wheel prints that represent the tandem used in the Eurocode NEN-EN 1991-2:2003 (CEN, 2003) live load model (Lantsoght, Van der Veen, et al., 2017), as shown in Figure 3. In Denmark, a method to apply loading in two lanes is used, to represent the vehicles from the Danish national classification system (Schmidt, Halding, Jensen, & Engelund, 2018). In Germany, a special vehicle (BELFA—Belastungsfahrzeug) was developed, which can be used to apply large loads necessary for proof load testing (Bretschneider, Fiedler, Kapphahn, & Slowik, 2012; Hochschule Bremen - City University of Applied Sciences, 2018; Steffens, Opitz, Quade, & Schwesinger, 2001).

Figure 3. Proof load test on viaduct De beek, showing counterweights, steel distribution structure, and hydraulic jacks.

In terms of instrumentation, the recent developments are also applicable to diagnostic load testing. Recent developments include the application of non-contact and distributed sensing techniques (Zarate Garnica et al., 2022). For example, digital image correlation can be used during a proof load test to follow the development of cracks, which can be a qualitative way to evaluate the structural response (Christensen, Schmidt, Halding, Kapoor, & Goltermann, 2021; Halding, Schmidt, & Christensen, 2018). Interferometric radar is a promising non-contact technique for measuring the deflections of a few points within the line of sight of the radar (Beben & Anigacz, 2014; Dei, Mecatti, & Pieraccini, 2013). Recent advances in terms of understanding acoustic emission signals in shear-critical structures in the light of the structural behaviour also show a promising path forward (Zhang, 2022).

The focus in the load testing community is shifting from measuring deflections to measuring strains, which give better insight in the structural response. Deflections were often measured in the past using a total station or a simple yardstick, which is a cheap method, but the information that can be obtained with these methods is rather limited. Therefore, the consensus is to move towards the use of strain measurements, which can require more time and budget to apply to the structure, but which result in more information and thus more value for the load test and subsequent assessment.

2.3. Current challenges

While major steps forward have been made in terms of research related to load testing for the assessment of existing bridges, recommendations for practice are not yet always available. There is a strong need to translate research insights into practical guidelines. In addition, there is a need to discuss these topics during the civil engineering curriculum, so that graduating engineers have a basic understanding of (bridge) assessment and the tools they can use for this task. In addition, experimental justification of new proposals, such as shear stop criteria for reinforced concrete members, is not available yet. As a result, there is a gap between the theoretically derived insights and the current codes and guidelines used for load testing of bridges. Researchers, educators, practicing engineers, and bridge owners need to come together to address these challenges and update the codes and guidelines on bridge load testing so that the practice of bridge load testing can be modernized for the twenty first century.

3. Methods

3.1. Fundamental research

In order to come up with recommendations for codes and guidelines for bridge load testing in the twenty first century, two necessary approaches are identified. The first approach is to carry out research to answer fundamental questions regarding bridge load testing, and in particular proof load testing of concrete bridges. This fundamental research is necessary to align the load testing codes and guidelines with modern design codes. For this reason, the focus in the fundamental research is on proof load testing: the execution and applied target proof load of a proof load test need to be aligned with the safety philosophy of the modern design codes. In other words, it is necessary to develop a probabilistic substantiation of the practice of proof load testing (de Vries, Lantsoght, & Steenbergen, 2021; de Vries, Lantsoght, Steenbergen, & Fennis, 2022; Owerko & Winkelmann, 2020; Owerko, Winkelmann, & Górski, 2020; B. Zheng, Zheng, Cao, & Zhang, 2023; X. Zheng, Yi, Yang, & Li, 2023).

Moreover, existing codes and guidelines restrict the use of proof load tests to flexure-critical structures only, whereas many existing bridges are found to be shear-critical upon assessment. As such, carrying out fundamental research to extend proof load testing to shear-critical bridges is necessary, and this research needs to provide the input to develop methods for the safe execution of a proof load test on a shear-critical bridge. The methods applied to achieve a more fundamental understanding of proof load testing are: experimental work on reinforced concrete slabs to better understand the behaviour prior to failure, theoretical work to derive sound stop criteria for shear in reinforced concrete members, theoretical work to align proof load testing procedures with the safety philosophies of existing codes, and theoretical work to quantify the uncertainty on the stop criteria.

3.2. International collaboration

The second method to improve the codes and guidelines for bridge load testing is developing international collaborations. The goal of this method is to coordinate efforts and facilitate collaboration and exchange of ideas internationally. To make such collaboration and exchange possible, the IABMAS Technical Committee on Bridge Load Testing was formed. The mission of this committee is published on the IABMAS website (IABMAS., 2021). In summary, the committee's mission is related to defining aspects of load testing, identifying uses of bridge load testing, disseminating new technologies for load testing and successful applications, and becoming the leading international forum for exchanging ideas related to bridge load testing. For this purpose, the committee aims to bring together academics, practitioners, and bridge owners, distributed geographically.

The goals of the committee are also outlined on the IABMAS website (IABMAS, 2021). In summary, the committee members lead and participate in activities for the dissemination of research and case studies related to load testing, exchange information on research advances, successful case studies, standards and guidelines, establish (research) collaborations, and liaise with other relevant committees and organizations.

4. Results and analysis

4.1. Stop criteria for shear for proof load testing

In concrete bridges, recent research has focused on the development of stop criteria that are based on theoretical considerations. In current codes and guidelines, stop criteria are often based on simple thresholds, such as a single limiting value of crack width or concrete strain. Recent work has resulted in theoretically-based stop criteria for reinforced concrete members expected to fail in flexure (Lantsoght et al., 2019). These stop criteria have been verified with laboratory experiments and with pilot proof load tests. For shear, theoretically-based stop criteria that allow for the safe application of proof load testing of reinforced concrete bridges still need to be developed. This section addresses the current advances in this research.

The first step towards developing stop criteria for shear for the proof load testing of reinforced concrete slab bridges is to gather information on the behaviour of slabs under concentrated loads under cycles of loading as used during a proof load test (Zarate Garnica & Lantsoght, 2021). For this purpose, six reinforced concrete slabs were tested: four slabs with ribbed reinforcement bars and two slabs with plain bars (as many of the existing reinforced concrete slab bridges in the Netherlands are built using plain bars). The experiments consisted of applying a concentrated load of $0.2\,\text{m} \times 0.2\,\text{m}$ on a reinforced concrete slab of $2.5\,\text{m} \times 5\,\text{m} \times 0.3\,\text{m}$. This load was applied in cycles that represent a proof load test. The slabs were made continuous by anchoring prestressing bars to the strong floor, so that a bending moment over one of the supports developed.

The slabs were heavily instrumented, because one of the goals of the experiments was to study the behaviour of slabs under cycles of loading by following the structural responses as closely as possible. A second goal was to develop recommendations for practice in terms of instrumentation during (proof) load testing. For this purpose, different sensor types were used to quantify the same structural response (for example, strain). The following sensors and sensing techniques were applied in all or some of the experiments: load cells, LVDTs (linear variable differential transducers), laser triangulation displacement sensors, strain transducers, 2D DIC (digital image correlation), 3D DIC, acoustic emission sensors, smart aggregates, and fiber optic sensors of the fiber Bragg grating type. Figure 4 shows an overview of the test setup, with the loading frame, instrumentation, and slab specimen.

In total, 24 experiments were carried out. Eight experiments failed in flexure and 16 in shear. The slabs were designed in such a way that both flexural and shear failures could be achieved, depending on the position in the span of the concentrated load. As such, the experiments served to study stop criteria in reinforced concrete slab bridges for shear and flexure. Within flexural failures, the observed indicator of the failure could be (the onset) of the yielding plateau in the structural response, as well as a flexure-induced punching shear failure (Ghali, Gayed, & Dilger, 2015). Within the shear failures, the observed failure mode was either a failure in which the shear crack appeared at the side face of the slab (beam shear failure) and/or a shear failure in which the shear crack developed inside the mass of the slab (wide beam shear failure), detected by a pair of lasers placed on top and bottom of the slab. If the lasers indicated an increase in thickness of the slab, the opening of an internal shear crack was registered. For all types of shear failure, the failure mode was brittle and resulted in a drop of the load.

While the development of theoretically-based stop criteria for shear is work in progress, a few remarks based on experimental observations can be made. First of all, in terms of structural responses, there is no difference between the behaviour of slabs previously cracked in bending and slabs not tested previously, except in terms of stiffness and maximum load. This observation is in contrast to previous observations from testing reinforced concrete beams without shear reinforcement (i.e. slab strips), for which distinct differences in structural responses and behaviour between beams previously cracked in bending and those not tested before could be observed (Lantsoght, Yang, van der Veen, de Boer, & Hordijk, 2017), and which resulted in the recommendation to develop separate stop criteria for members previously cracked in bending and members not previously cracked in bending.

A second result from these experiments is that the use of 2D and 3D DIC during the experiments as well as for the analysis of the experiments is very promising. During the experiments, the processing of images is rather quick nowadays thanks to the current computing power. After the experiment, processing the images also gives an excellent overview of the development of cracks under various cycles of loading and at various load levels.

The third result from these experiments is a full description of slabs under concentrated load prior to failure. The flexural behaviour can be illustrated using experiment SP1M2, which was the second experiment on the first slab reinforced with plain bars with a yield strength of 304 MPa. The reinforcement ratio was 2.02% for the longitudinal reinforcement and 0.423% for the transverse flexural reinforcement and the average cube concrete compressive strength at the age of testing was 61.77 MPa. The load was placed in the middle of the slab width and at 1200 mm from the simple support. Figure 5 shows the loading protocol used in SP1M2, which used the following load levels:

- A low load level of 50 kN to check the performance of all sensors.
- The SLS (serviceability limit state) load level of 300 kN, which is also repeated four more times to check the behaviour at the SLS level after higher loads have been applied.
- The ULS (ultimate limit state) load level as would be used in a proof load test of 400 kN (resulting in the same shear stress in the section as the ULS load combination from the code)
- Three load levels (500, 600, and 900 kN) to achieve the theoretically-derived strain stop criterion for flexure, which was calculated as 1260 $\mu\varepsilon$.
- The final loading steps until 1150 kN, when the beginning of the yield plateau was observed in the experiment.

Figure 6 shows part of the instrumentation used on SP1M2, and Figure 7 shows the load-displacement diagram on which the important observations during the loading are identified. In particular, the following changes in responses are observed and catalogized:

- Development of cracking,
- Marked increases in horizontal deformations as measured with the LVDTs,

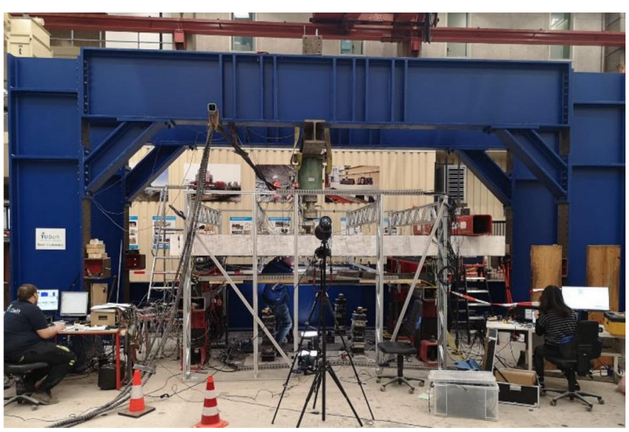


Figure 4. Test setup of slab experiments, showing all instrumentation.

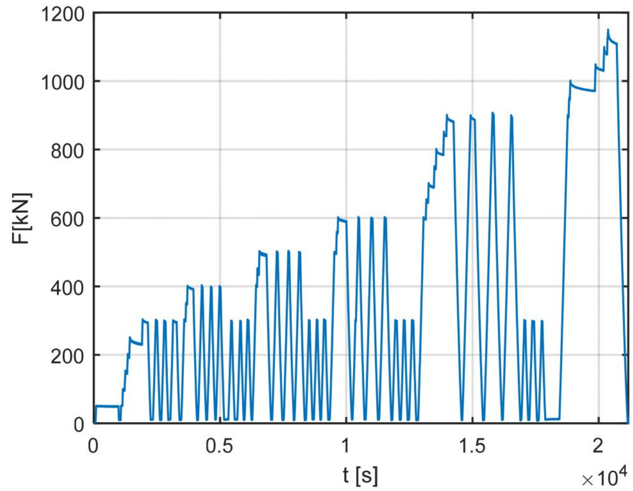


Figure 5. Loading protocol for SP1M2 (Zarate Garnica & Lantsoght, 2021).

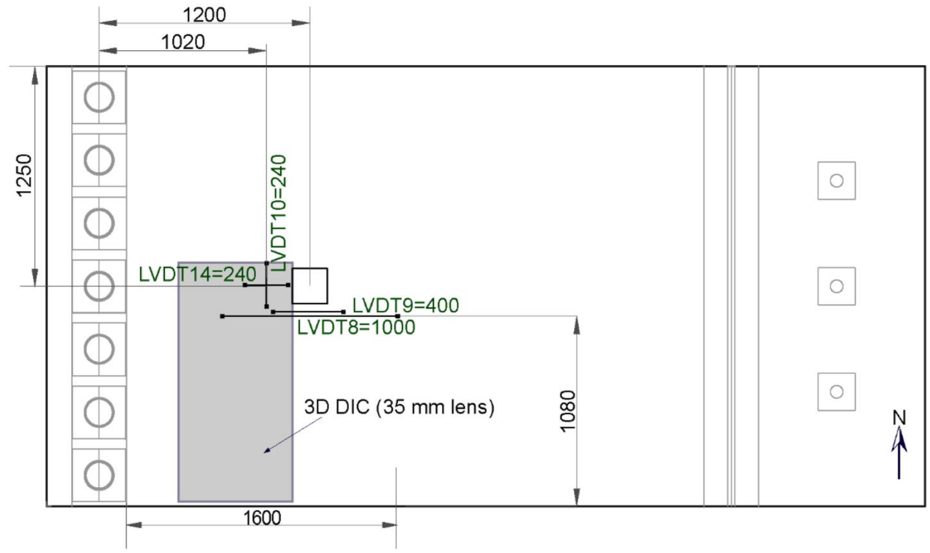


Figure 6. LVDTs applied on the bottom of SP1M2, indicating also the Region monitored with 3D DIC (Zarate Garnica & Lantsoght, 2021).

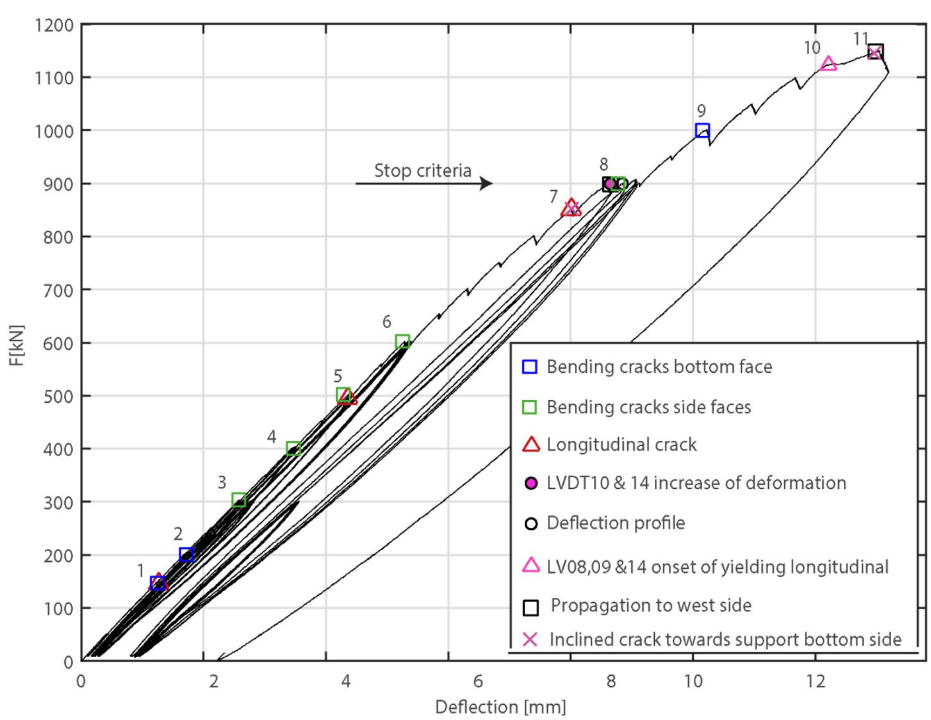


Figure 7. Load-deflection diagram of SP1M2, showing observations during the test (Zarate Garnica & Lantsoght, 2021).

- Changes in the overall behaviour as identified by looking at the deflection profile of the slab, and
- Onset of yielding of the longitudinal steel, observed by reaching a corresponding limit on the bottom face of the cross-section.

For shear failure, experiment SR3M1 is used to explain the various steps that are observed between the application of the load to failure. The slab was reinforcement with ribbed bars with a yield strength of 585 MPa. The longitudinal reinforcement ratio was 0.996% and the transverse flexural reinforcement ratio as 0.258%. The cube concrete compressive strength was measured as 65.02 MPa on average at the age of testing. The load was placed in the middle of the width and at a distance of 800 mm from the simple support. Figure 8 displays the loading protocol used during SR3M1, which used the following load levels:

- A low load level of 50 kN to check the performance of all sensors.
- The SLS load level of 250 kN, which is also repeated three more times to check the behaviour at the SLS level after higher loads have been applied.
- The ULS load level as would be used in a proof load test of 400 kN (resulting in the same shear stress in the section as the ULS load combination from the code)

- Two load levels (500 kN and 700 kN) to approach the theoretically-derived strain stop criterion for shear based on the Critical Shear Displacement Theory (Yang, Den Uijl, & Walraven, 2016), which was calculated as 1320 $\mu\varepsilon$.
- A load level of 850 kN to test the slab under cycles of a high load.
- The final loading steps until 1143 kN, when a shear failure occurred.

Figure 9 shows the load-displacement diagram on which the important observations during the loading are identified. In particular, the following changes in responses are observed and catalogized:

- Development of cracking.
- Changes in the overall behaviour as identified by looking at the deflection profile of the slab.
- Opening of the internal shear crack, identified by looking at the increase in thickness as measured by a pair of lasers on the top and bottom of the specimen, see also Figure 10.

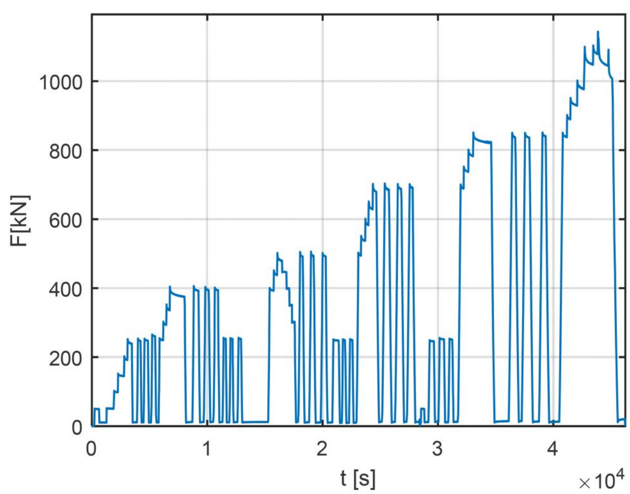


Figure 8. Loading protocol for SR3M1 (Zarate Garnica & Lantsoght, 2021).

4.2. Probabilistic approach for proof load testing

For the research on the probabilistic aspects of proof load testing, the result of the first step of this project is a case study evaluating the influence of proof load testing on the annual reliability index (de Vries et al., 2021). The case study represents a reinforced concrete slab bridge, assumed to be built in 1960 and thus designed according to the codes of the 1950s. The bridge is considered to be critical in flexure and the analysis is based on the sectional moment and bending moment capacity.

Figure 11 depicts the results of the case study for various assumptions. First of all, the 'base case' scenario does not consider changes in load and resistance over time. The 'traffic trend' case considers that the traffic data based on WIM (weigh-in-motion) measurements from 2015 change over time. A correction trend as function of the year is used, which is less than one before 2015, equal to one in 2015, and increasingly larger than one after 2015. The

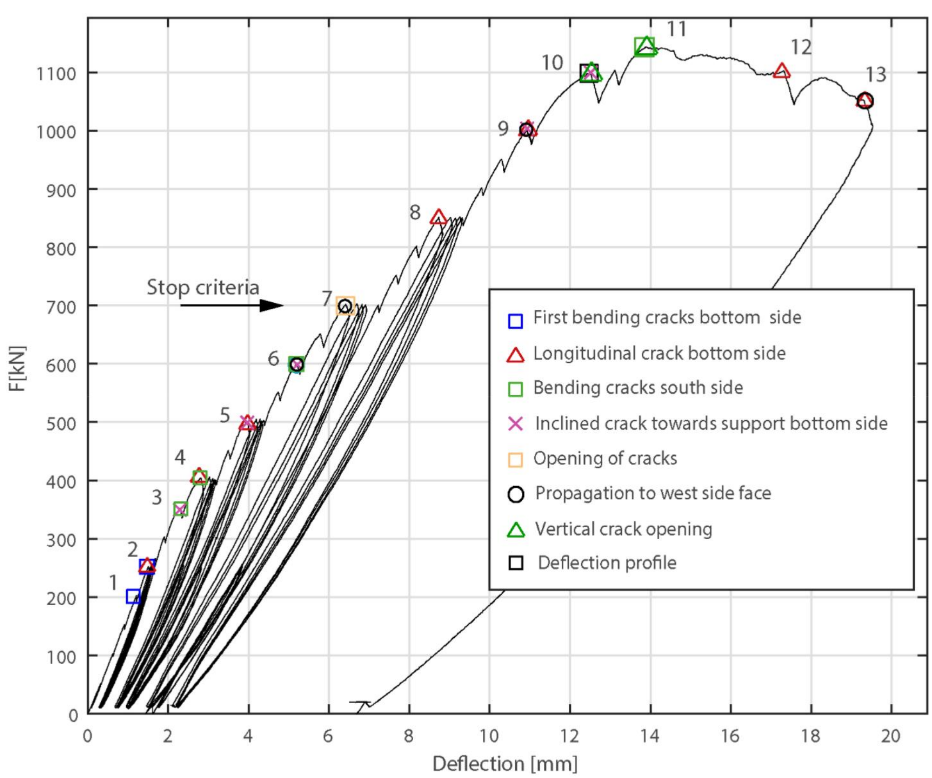
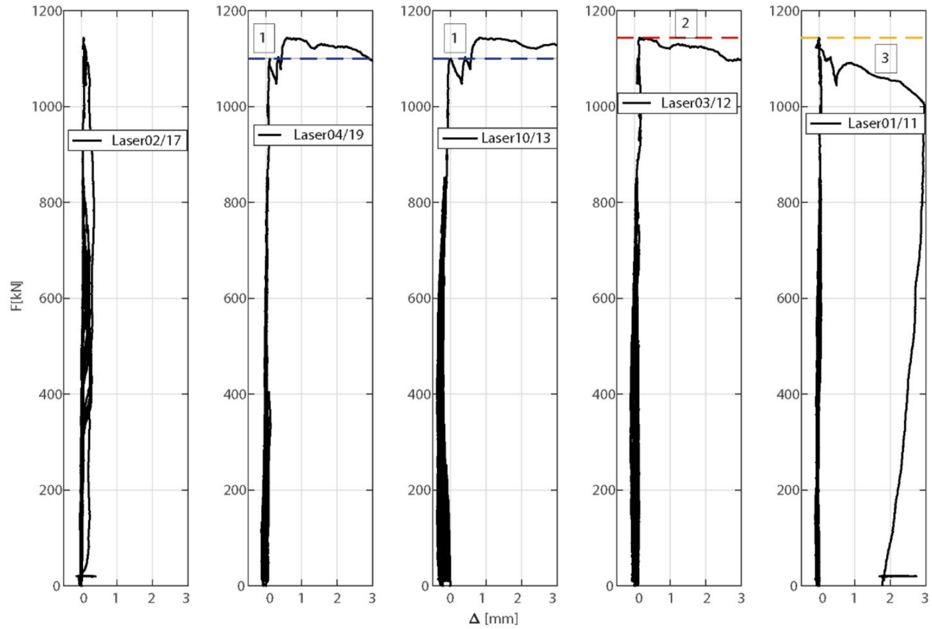
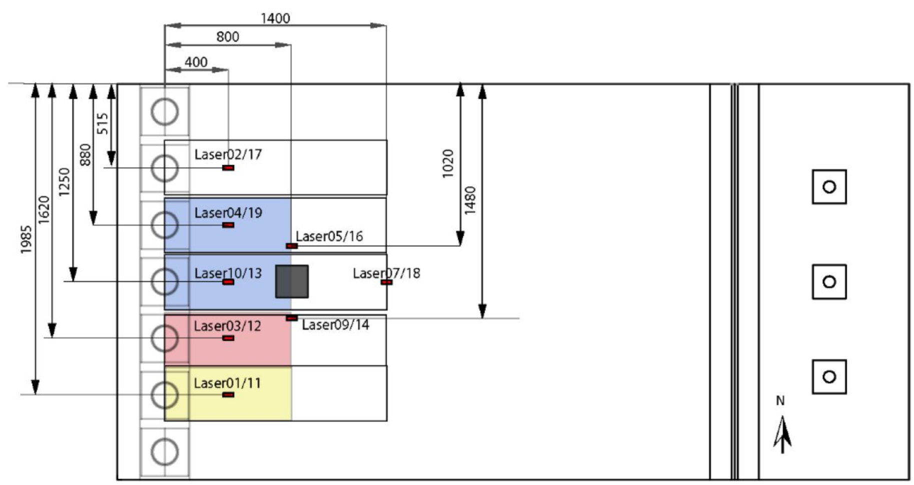


Figure 9. Load-deflection diagram of SR3M1, showing observations during the test (Zarate Garnica & Lantsoght, 2021).



(a)



(b)

Figure 10. Load – vertical displacement relationship from pair of lasers at top and bottom of SR3M1: (a) measurements, indicating when the opening of the shear crack is measured and (b) position of measurements.

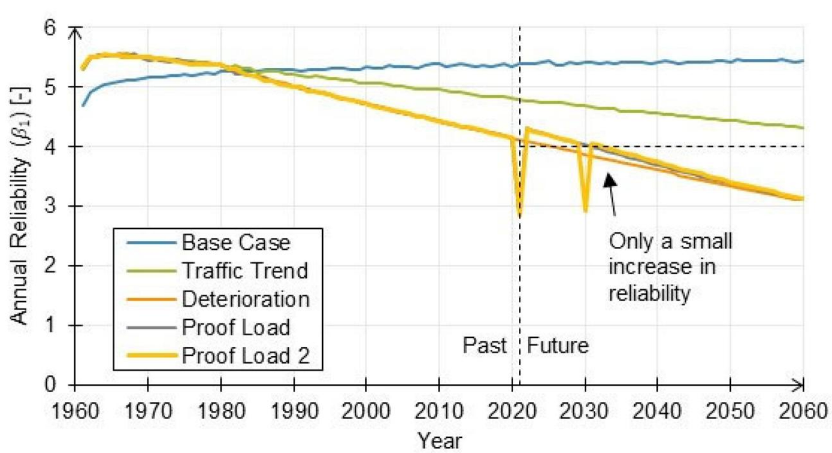


Figure 11. Results of case study of annual reliability index over time for reinforced concrete slab bridge (de Vries et al., 2021, 2022).

'deterioration' case considers the influence of time on both the load and resistance side. On the load side, the traffic trend is applied. On the resistance side, a reduction in time of the capacity is modelled which represents the effect of material degradation and deterioration (de Vries et al., 2022).

For the base case scenario, an increase in annual reliability index over time can be observed, since this reliability is conditional. The condition is that the bridge survived the previous year, and the effect of this condition is an increase over time of the annual reliability. For the cases where the load and/or resistance are time-dependent, the annual reliability index decreases over time. The results also show the influence of carrying out a proof load test. First, a proof load test which causes a sectional moment of 1750 kNm is carried out in 2021, and this scenario is named 'proof load' in Figure 11. This scenario is a modification of the deterioration scenario, in which a proof load test is carried out. The annual reliability index temporarily drops during the proof load test, because of the large load that is applied. This result is expected based on theoretical considerations (Spaethe, 1994). The benefit of the proof load test is also clear, as the reliability index after the proof load test is larger than before, assuming that the bridge passed the proof load test successfully. The benefit of the proof load test for this case lasts to the year 2030, when the annual reliability index decreases again to the minimum threshold value.

In this case study, the benefit of retesting is explored as well. Retesting with the same load as in 2021 (which causes a sectional moment of 1750 kNm) does not lead to a considerable gain in terms of annual reliability index. The load from 2021 is barely sufficient to offset the reduction in reliability due to the further deterioration of the capacity and the further increase in loading reflecting the traffic trend. The result of retesting with the 2021 load is that the bridge would only fulfil the reliability requirements for one year after the retest. Therefore, for retesting in 2030 a higher load is necessary. The scenario 'proof load 2' in Figure 11 represents a modification of the proof load scenario, in which a second proof load test is carried out in 2030 with a load that causes a sectional moment of 2000 kNm. For this larger load, the drop in the annual reliability is larger than when testing in 2021 with a smaller load, as also indicated in Figure 11. After the retest, the annual reliability index is larger than before (provided that the bridge survives the test), and this retest would result in the bridge fulfilling the reliability requirements until 2040.

4.3. IABMAS Bridge Load Testing committee

The IABMAS Bridge Load Testing committee held its (online) inaugural meeting on 4th June 2021. Since then, the committee has had three more virtual meetings and one hybrid meeting during IABMAS 2022 in Barcelona, Spain. The minutes of these meetings are available on the IABMAS website (IABMAS., 2021). At the moment, the committee has 38 members from 17 countries, with 24 members from academia, nine members from the industry, and five members from the government. The first meetings were dedicated to the members getting to know each other and their experience with the topic of bridge load testing. In addition, the first meeting focused on determining the mission and goals of the committee in more detail. The members gave various technical presentations during the subsequent meetings, which helps the aim of familiarizing ourselves with the work that is currently being done in the field of load testing internationally.

Finally, members have paid attention to potential liaisons with national and international committees which (partially) share the committee's mission and goals, and liaisons with TRB AKB40 'Testing and Evaluation of Transportation Structures' from the Transportation Research Board and fib TG 3.2 'Modelling of Structural Performance of Existing Concrete Structures' of the International Concrete Federation have been established.

4.4. Analysis of efforts

The outcome of these efforts is a renewed research interest in the use of bridge load testing for assessment of concrete bridges, which balances both the fundamental aspects of concrete mechanics and structural reliability as well as an ongoing conversation with industry and government members internationally to develop practical recommendations. These renewed discussions can then feed into recommendations for education as well, so that the new generation of bridge engineers graduate with a toolbox for addressing existing bridges, which contains bridge load testing as one of the available tools.

In conclusion, it is expected that the research and collaboration efforts will result in improved recommendations for the assessment of concrete bridges by load testing. These recommendations for practice can then be included in codes and guidelines that are in line with modern design codes. The broader goal of these efforts is to serve the community of engineers faced with the increased task of assessing ageing infrastructure by modernizing the procedures for load testing of bridges.

5. Discussion

Bridge load testing has a long history, and the technique has been used by engineers for centuries to understand bridges better. Nowadays, engineers are at a crossroads in the history of load testing, where the choice could be to either leave behind this old practice, or to acknowledge its value and modernize the practice. From my perspective, the latter option is to be recommended. It is necessary to spend time and effort into modernizing codes and guidelines that deal with bridge load testing, so that this engineering tool can be used for the challenging task of assessment of the aging infrastructure. Indeed, for such a challenging task, the modern engineer needs a large toolbox of potential methods for assessment.

While research in the past years has helped the engineering community to better understand how load testing can fit into the task for the assessment of existing bridges, many open research questions still exist. The open research questions deal with:

1. the application of proof load testing and the definition of stop criteria for the case of prestressed bridges, where perhaps only diagnostic load testing may be recommended,
2. moving towards fully non-contact and distributed sensing techniques during load testing, which reduces the need to build scaffolding and spend time applying sensors individually,
3. finding synergy between the research on bridge load testing, non-destructive testing techniques, and long-term structural monitoring, and
4. embedding load testing within the framework of bridge management systems.

These topics need to be addressed to remove the barriers to implementation in codes and guidelines. In addition, educators will need to develop methods to teach topics related to (bridge) assessment to their students, which will allow students to gather their toolbox of techniques to address this complex problem, and of which load testing is one of many tools.

6. Conclusions

As infrastructure is ageing, the assessment of existing bridges becomes increasingly important. Bridge load testing can be one method for the assessment of existing bridges, as it provides a unique opportunity to measure directly the structural response of the bridge (in a diagnostic load test), or even directly evaluate if the bridge fulfils the code requirements (in a proof load test). This paper focuses on two main aspects that are necessary to modernize load testing, so that codes and guidelines for load testing can be developed that are in line with the philosophy of our modern design guidelines.

Firstly, there is a need for fundamental research to address open questions related to behaviour of bridges under increased loading and the derivation of safe stop criteria for shear in reinforced concrete bridges, as well as open questions on the relation between the structural reliability concepts on which current design codes are based and the practice of bridge load testing. Secondly, there is a need for international collaboration to better exchange research insights and practical experience on the topic of bridge load testing.

The first topic is addressed (in part) by ongoing fundamental research on the definition of shear stop criteria for reinforced concrete slab bridges and the probabilistic aspects of proof load testing. In particular, experiments have resulted in a full and detailed description of the behaviour of reinforced concrete slabs failing in shear and flexure under increasing levels of loading applied in a cyclic manner. The extensive instrumentation of the slabs allowed for this detailed description of the behaviour. The second topic is addressed by the founding of an IABMAS Technical Committee on Bridge Load Testing and the development of liaisons with relevant national and international committees.

Until now, these efforts have shown that load testing can indeed be a valuable tool for the assessment of existing bridges. Further efforts will focus on the development of recommendations for practice, which in turn can be translated into codes and guidelines for bridge load testing in the twenty first century. At the same time, it is important to include topics related to bridge assessment to the curriculum, so that recently graduated engineers have a toolbox with various methods for the assessment of existing bridges, of which load testing is one of many potential tools.

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No potential conflict of interest was reported by the author(s).

Data availability statement

No new data was generated for this research.

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