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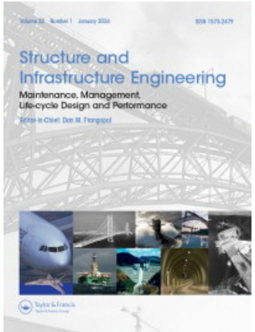

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REVIEW ARTICLE

Bridge load testing for assessment: recent advances in application, collaboration, codes, and research

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ABSTRACT

As the bridge stock in many countries is ageing, the topic of bridge assessment is gaining more importance. Bridge load testing is one of the tools that can be used to assess existing bridges. Over the past decade, assessment, and by extent, bridge load testing, have been applied, studied, and improved in various countries. This paper provides an international overview of bridge assessment practices, load testing practices, and recent research insights. Moreover, synergies in the research activities, collaboration efforts *via* technical committees, and recently published codes and guidelines are highlighted. The major topics of importance identified are linking load testing to global and element structural behaviour, improved on-site sensing techniques, incorporating load testing with structural monitoring, non-destructive evaluation, numerical modelling, probabilistic analysis, and leveraging the use of digital tools for embedding detailed load testing insights into modern bridge management systems. It can be concluded that bridge load testing is a dynamic field of application and research, for which international collaboration and comparing best practices is essential.

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1. Introduction

Globally, the average age of bridges is increasing. In Europe, the transport networks were greatly constructed during the period of reconstruction and expansion after the Second World War, making a large portion of current bridges dating back to the 1950s to 1970s (Lantsoght et al., 2013). In the case of the railway network, with around 500,000 bridges, 70% of them are more than 50 years old. In the United States, two periods of increased transportation infrastructure construction activities can be identified: the 1930s, when roads and bridges were built to reactivate the economy and mitigate the Great Depression, and in the 1960s—1980s for the construction of the Interstate highway system (Palu & Mahmoud, 2019).

Similarly, in the case of Latin America, the ageing of the road network requires an assessment of the condition of the bridges. In particular, in Chile, the bridges that have reached their useful life of 50 years have limited redundancy conditions (bridges simply supported by two beams), which makes their assessment more important (Calderón et al., 2023). In other parts of the continent, such as in Ecuador, the more recent boom in development of infrastructure has resulted in a younger bridge stock. For the case of Ecuador, a major upgrade of the road network was executed between 2007 and 2014. However, the lack of maintenance of the existing bridges has made condition assessment important (Cervantes et al., 2024b).

India has the second largest road network in the world with 6.4 million km of road with asset of approximately 12 million road bridges, with a sizeable percentage of bridges having lived more than 50 years. India also has 4[th] largest rail network in the world with more than 150,000 rail bridges, out of which about 40,000 bridges are more than 100 year old. In Japan, there are approximately 730,000 bridges, both highway and railway bridges (Ministry of Land, Infrastructure, Transport and Tourism, 2024). In 2021, 32% of them were more than 50 years old and it is estimated that this percentage will increase up to 57% in 2033. The actual condition of these bridges is that 56% need a repair in the mid-term and 4% need an urgent repair. The cost of renewal and repair is estimated around 22 billion €.

As a result of these trends globally, ageing bridges are reaching the end of the service life they were originally

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designed for. However, replacing all bridges that are at the end of their service life is not a sustainable solution: the economic and environmental costs are too large, and the indirect economic cost from rerouting traffic and goods cannot be justified. Therefore, it is important to assess the existing bridges, evaluate if and how their service life can be extended, and use strengthening and replacement only where necessary for structural safety (Yang et al., 2019).

This paper combines international insights on the assessment of existing bridges, with a focus on bridge load testing. When uncertainties regarding the global bridge performance are large (Alampalli et al., 2021), bridge load testing can provide the data on the in-situ performance of the structure and reduce the uncertainties on the assessment. Such uncertainties can result from certain mechanisms (such as increased transverse distribution when strong bands of reinforcement are used for the sidewalks) and conditions (such as the effect of the actual condition of the supports, and the stiffness contribution of the non-structural elements), and may be difficult to estimate analytically (Barker, 2001). This paper aims to give an overview of how bridge load testing is currently used internationally for the assessment of existing bridges, which new tendencies can be observed, which research is carried out and what is the synergy between these research efforts, and how these applications and research insights have resulted in code changes and new guidelines.

2. Bridge assessment internationally

2.1. General

Unlike for the design and construction of new bridges, codes for the assessment of existing bridges are not available everywhere. For example, while a full suite of Eurocodes has been available since the early 2000s to streamline design practices in Europe and beyond, a suite for the assessment of existing structures is not available yet. Therefore, the practice of bridge assessment is more fragmented, and strongly dependent on national experience and practices. The amount of field data that is used for assessment is also dependent on national practices, with some countries focusing on an assessment based on a visual inspection and estimate of the condition (Cervantes et al., 2024a; Jia et al., 2024), and others focusing on analytical calculations, such as a capacity-to-demand ratio, a unity check (of factored demand to capacity) or a rating factor.

2.2. United States

The United States relied almost exclusively on visual inspection of existing bridges as the main tool for bridge assessment. Visual inspection being a subjective tool, relied heavily on the experience and judgement of the inspectors and focused on obvious signs of deterioration like corrosion, cracks, and spalling. Visual inspections are to be carried out according to the National Bridge Inspection Standards (NBIS) (Federal Highway Administration, 2022), which were most recently updated in 2022. The aim of the updates over the years is to reduce the variability in outcomes of visual inspections (Alampalli, 2009).

Although inspections have undergone significant refinement over time, it was not until the 1990s that more sophisticated tools, such as Non-Destructive Testing (NDT) for material assessment and Diagnostic Load Testing (Schulz et al., 1995) for performance evaluation, gained prominence. Although proof load testing has a longer history, the diagnostic load testing approach gained greater prominence in the United States and evolved (Commander, 2019) as bridge assessment guidelines (Manual for Bridge Evaluation) were published and revised. The Manual for Bridge Evaluation (MBE), 3rd Edition, contains a method for evaluating a bridge using load testing; however, the method is based on a technical report (Lichtenstein, 1993) and uses a comparison based on a pointwise measurement, which is now widely regarded as less accurate than a diagnostic load test where the comparison is based on an analytical (often numerical) model. Analytical assessments are carried out to determine a Rating Factor, as described in the MBE, which quantifies the bridge's ability to carry live load. Chapter 8 of the MBE describes methods to update the Rating Factor using the outcome of both diagnostic and proof load tests.

2.3. Chile

In Chile, the Highway Manual is used for design, construction and maintenance at the regulatory level (MOP, 2019). It is based on the AASHTO code (AASHTO, 2018) from the United States, and uses the Rating Factor as the outcome of the assessment. In general terms, for the evaluation of the condition of a bridge, the requirements are established in the bidding processes for the maintenance of the routes, where the Ministry of Public Works establishes the standard by which testing must be regulated (Marquez et al., 2021; Márquez et al., 2021). These criteria are applied to those structures called traditional, that is, simply supported bridges, with one or several spans. However, for complex bridges such as suspension bridges, mobile structures or those defined by the Ministry, specific procedures are proposed. An example of a bridge that required an assessment is the Pedro de Valdivia Bridge, a reinforced concrete Gerber girder bridge from 1954. The assessment included a detailed evaluation and diagnosis, as well as non-destructive testing to characterise the concrete and reinforcement. This information was essential for rating the bridge, and served as input for the subsequente retrofitting.

The highway Manual does not include requirements or instructions on the load testing process. Since the 1970s, the normative use has been oriented towards the Spanish code, which is the reference framework. Notwithstanding this, the different projects have contributed to establishing base protocols for load testing to date. Documented load tests in Chile are predominantly conducted for specific diagnostic purposes, typically as part of a thesis or research project. The cases of bridge evaluation by load test in Chile include:

- End of the construction process. These tests are submitted only for complex bridges and there is no general requirement.

- End of the construction process with damage or incident. The application of a load test is requested in cases where some main element of the bridge during its construction stage has suffered some damage, for example the impact on the installation of the main trusses.
- Evaluation in operation: In cases where the maintenance programs have indicated damages that compromise the structure, load tests are requested. Load test are also used to field-validate analytical models. This is also considered for the case of passage of overweight loads, typically in mining and the wood industry.
- Dynamic tests—particularly through micro-vibrations—are used for long-term monitoring of dynamic properties, especially in structures with seismic isolation.

2.4. Ecuador

As Ecuador has a relatively young bridge stock, assessment of existing bridges has not received much attention (Cervantes et al., 2024b). The NEVI-12 road standard contains general requirements for bridges, and the aspects of maintenance are limited to the standard specifications for maintenance, including bridge restoration and conservation techniques in section 6.108 (Ministerio de Transporte y Obras Públicas del Ecuador, 2013). This section of the standard focuses on activities such as bridge pavement repair, painting, superficial repair of concrete, repair of corroded reinforcement, and repair of cracks. Assessment strategies and calculation methods are not discussed, and are not yet established. Even though the bridge stock is relatively young, the lack of maintenance and environmental conditions have resulted in a large number of bridges in fair and poor condition: 53% in the capital province Pichincha, and up to 85% in the Carchi province. Bridge load testing is mostly used as acceptance tests prior to the opening of a new bridge (Bonifaz et al., 2018).

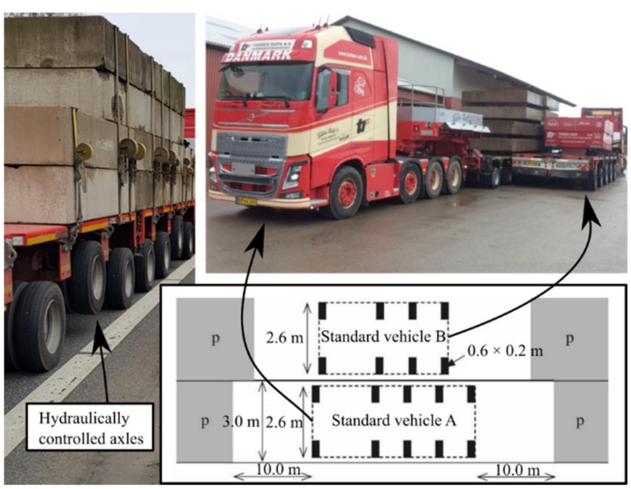

Figure 1. Layout of standard vehicles A and B, and conversion to trucks during load testing (Schmidt et al., 2025).

2.5. Denmark

One particularity of the assessment in Denmark, is that the national approach centres around special load models (Vejdirektoratet, 2017). Roadway bridges are assessed for the load configurations listed in the system. Permissions to pass bridges are associated with the loading class the specific bridge rates for. The load model consists of a standard vehicle B, a uniformly distributed load, and a standard vehicle A, see Figure 1. The total weight of the standard vehicle A provides the basis for the classification approach. The standard vehicles have classes up to 500, indicating their gross weight in tons, see example on Table 1. Different from most countries, the outcome of the assessment in Denmark is a direct load-based classification assessment according to the Danish vehicle classification system and associated bridge class.

Typically, assessment calculations start from a hand calculation and can be followed by a linear finite element analysis. For ultimate capacity evaluations, limit analysis (both lower-bound and upper-bound approaches) can be used, as well as nonlinear finite element analysis. The final step can be a non-linear resistance assessment combined with a probabilistic analysis where the model uncertainties are considered further. Input values can be refined by the use updated properties from testing (such as concrete core and reinforcement testing results, etc.) (Christensen, 2023, Vejdirektoratet, 2024) When applying the approach presented in Christensen, (2023), there is no final step with assessment or updating of the resistance. It is a direct load assessment, which ensures that the bridge can carry a load with a return period corresponding to the desired probability of failure.

The approach is based on the work of prEN 1990-2, where it is defined that two approaches may be applied:

1. To apply a load that induces a load effect equivalent to one that may occur with a probability matching the desired failure-probability.

Table 1. Classification of vehicles in Denmark (Damsgaard et al., 2024; Vejdirektoratet, 2017).

Class	Axle configuration (loads in ton, spacings in [m])
100	7,0 7,0 9,5 9,5 11,5 11,5 11,5 15,1 15,1 11,5 1,4 3,2 1,4 6,0 1,4 1,4 1,4 1,4 1,4
150	7,0 7,0 9,5 9,5 11,5 11,5 11,5 15,1 15,1 11,5 1,4 3,2 1,4 6,0 1,4 1,4 1,4 1,4 1,4
200	7,0 7,0 9,5 9,5 11,5 11,5 11,5 15,1 15,1 11,5 1,4 3,2 1,4 6,0 1,4 1,4 1,4 1,4 1,4

2. To apply a load that (following a successful proof load test) allows the probability of failure to be updated to match the desired failure-probability.

It is thus the first approach that is applied. The target proof load in this method is higher and therefore sets are higher demand for the bridge, but in cases where there is limited documentation on the bridge or uncertainty regarding load redistribution, support conditions, and other parameters influencing the bridge behaviour, this method is highly applicable.

Proof load testing in Denmark is carried out to align with the Danish classification system, using specified axle loads for each vehicle A (Schmidt et al., 2020; Vejdirektoratet, 2017; Vejdirektoratet - The Danish Road Directorate, 2017). Both vehicles A and B are applied to the bridge during a proof load test, whereas the uniformly distributed load is typically not applied (for short bridges). This approach can directly demonstrate that a given bridge can carry the considered load class. An analytical or finite element assessment may be carried out prior to the proof load test; the engineer is free to decide how this assessment is to be done as a function of the available information.

2.6. Italy

In Italy a large number of bridges were designed and built between 1955 and 1975 with a simply supported static scheme resulting in an approximate frequency of one bridge every two kilometres along the main highways. Assessment of bridges received a strong impulse after the tragic collapse of the Polcevera bridge in 2018, resulting in multiple fatalities (Bettiza, 2023; The Guardian, 2019). In 2020, the Italian High Council of Public Works issued new guidelines for classification and risk management, safety checks and monitoring of existing bridges (Cosenza & Losanno, 2021; Ministero delle Infrastrutture e dei Trasporti - Consiglio Superiore dei Lavori Pubblici, 2020a; b).

Apart from diagnostic load test, proof load testing is considered for a 'temporary operational' condition for a maximum period of 60 days only (meanwhile, a conventional safety check is carried out, i.e. based on partial safety factors method) whose target load effect should be a magnification of the vehicle class to be admitted. If the test is passed, the permitted vehicle class can be posted on the bridge for a limited period of time. Dump tracks are commonly adopted and applied in different steps (usually from 2 to 4) while measuring bridge deck deflections in a number of points usually through deal gauges or laser scanner. Measurement points are commonly set at midspan of each girder and along the edge girder at 1/3 and 3/4 of the span to visualise deck deflections both in transverse and longitudinal direction. Settlements at supports are also measured to be filtered out when calculating girders deflection. For a succesfull test, deflections should increase almost linearly with increasing load effect while residual displacements upon unloading should not be larger than 5% of peak measured deflection.

An application not described in the guidelines is the use of acceptance load tests after retrofitting of a bridge as per new bridges. For these applications, dump trucks are commonly used that create a load effect consistent with the unfactored Eurocode LM1 in accordance with the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti, 2018). Nowadays many bridges managed by municipalities and local authorities are lacking design drawings and reports thus resulting in potentially higher costs and conservatism in conventional safety checks. Among many ongoing research projects dealing with the assessment of existing concrete bridges in Italy, in a project funded by the HCPW to the Italian university network Reluis, work package 4.7 is aiming at developing methodologies and protocols for proof load testing in order to add specific suggestions to the next version of the guidelines. Ongoing research is attempting to define the correlation between target proof load as a function of LM1 and increased safety levels of the bridge posterior to the test since WIM data are barely available.

2.7. The Netherlands

In the Netherlands, the bridge type that has received most attention for assessment are the reinforced concrete solid slab bridges, as these bridges do not have shear reinforcement and many of these bridges are found to be shear-critical upon assessment according to the currently governing Eurocodes (Lantsoght et al., 2013; 2017c). The governing document for the assessment of bridges owned by the Ministry of Infrastructure and Water Management—Rijkswaterstaat, i.e. the highway bridges, is the Guidelines for the Assessment of Existing Bridges, known as RBK (Richtlijnen Bestaande Kunstwerken) (Rijkswaterstaat, 2022). In general, the governing codes for existing structures in the Netherlands are the NEN 8700 codes (Normcommissie 351001, 2011a; b). The RBK allows various approaches of assessment, denoted as AI, AII and AIII. All three approaches use the traffic loading for existing bridges from NEN 8701 (Normcommissie 351001, 2011a) but have different assumptions for the layout of the lanes in the road, and thus the position of the design tandem.

When evaluating a bridge typology, a staggered approach is used in the Netherlands, to help identify those bridges that require further attention. This method is based on the principles of the Levels of Approximation, as first introduced in the *fib* Model Code 2010 (fib, 2012), resulting in Levels of Assessment (LoA). LoA I is a first triage of the subset of bridges, based on a spreadsheet-based calculation that compares the load effect as obtained with a hand calculation to the factor code-prescribed capacity, resulting in a 'Unity Check' (UC, ratio of factored demand to capacity). If the UC $\leq$ 1, it is found that the critical section, and by extent the bridge, fulfils the code requirements and no further analysis is necessary. If the UC exceeds 1, LoA II can be used, in which the load effect is determined using a linear finite element analysis, and this result is combined with the code-prescribed capacity to determine the UC.

If a next LoA is necessary, LoA III includes probabilistic analyses or the use of nonlinear finite element models according to the Dutch Guidelines for Nonlinear finite element analysis of concrete structures (Rijkswaterstaat, 2012). If none of the calculation methods can demonstrate sufficient capacity but there are reasons to expect additional capacity in the structure, a proof load test can be considered in exceptional cases.

Bridge load testing for assessment is not commonly used in the Netherlands. Most research interest is geared towards proof load testing (Lantsoght et al., 2017e), and some companies have developed methodologies for flexure (2017; Waarts et al., 2015; Cement, 2017). However, before these insights can be put to practice, fundamental research on stop criteria (Zarate Garnica et al., 2024b) and the probabilistic substantiation of proof load testing (de Vries et al., 2025) needs to be carried out.

2.8. Poland

According to Polish law, managers of roads and railway lines are obliged to maintain bridges in proper technical condition. For this purpose, periodic inspections are carried out in annual and five-year cycles. The technical condition of the bridge should be checked every year and a more extensive inspection should be carried out every five years. There are appropriate inspection instructions developed by managers of national roads and railway lines. Currently, there are no detailed guidelines related to the assessment of the load-bearing capacity of road and rail bridges, but work is underway to develop recommendations - Guidelines for determining the load-bearing capacity of road bridge structures.

An important element of bridge maintenance is acceptance tests performed after the completion of construction or renovation. For many years, test loads have been performed in Poland to confirm the quality of works or design assumptions regarding load-bearing capacity. In recent years, there have been more and more voices in the scientific community related to changes in the approach to performing acceptance tests under test load by changing the purpose of performing the tests. Acceptance tests should be treated as an element of bridge diagnostics. They should constitute a specific metric of the bridge and be used to update the numerical model of the bridge and as a reference to tests performed during operation.

In 2021, at the initiative of the Road and Bridge Research Institute (Ministry of Infrastructure, 2021), the recommended scope of mandatory acceptance tests of road bridges was reduced by excluding non-prestressed reinforced concrete bridges, soil-shell and masonry bridges, as well as overpasses for animals and pedestrian bridges under static load. In the case of structures not mentioned above, it was left mandatory to perform tests under static and dynamic load only with a theoretical span length of 30 m or more (instead of the previous 20 m). Additionally, a reduction in the value of internal forces achieved during acceptance tests under static load was introduced. In the case of railway bridges in 2023, (Technical standards, 2023) introduced a reduction in the scope of mandatory acceptance tests under static load by introducing a span limit of greater than or equal to 20 m (instead of without span limits) and an increase in the scope under dynamic load by changing the span limit from a larger 21 m to 15 m.

2.9. Slovenia

Apart from newer motorways, most of the Slovenian road bridges date back to the early and mid-twentieth century, with an average age well over 50 years. A comprehensive bridge inspection system was implemented in the late 1980s. All state bridges are visually inspected at least every three years and comprehensively every six years. A damage-based bridge condition rating is calculated after each inspection and serves as the basic indicator for future actions by road operators. Typically, safety recalculations are performed if a bridge falls into the worst, 'critical' class. Bridge assessments were traditionally conducted using design codes and principles. The advancements and expanded applications of weigh-in-motion (WIM) systems, which collected realistic traffic loading information, led to bridge assessment recommendations in 1999. These recommendations replaced the design code-based loading schemes with assessment or rating WIM-based schemes. In 2009, they were assessed based on more available WIM data and due to a substantial increase in freight traffic after Slovenia joined the European Union.

Until recently, all new or reconstructed bridges longer than 10 m had to undergo an acceptance diagnostic static and dynamic load test. Figure 2 shows an example of such a diagnostic load test, on the tallest viaduct in Slovenia, using 48 overloaded trucks to apply less than 70% of the design load. In the 1990s, Slovenia began verifying the structural safety of its deficient bridges and soon integrated dynamic testing and monitoring techniques to better understand bridge behaviour under traffic loads. One of the key advancements was the development of the SiWIM® system, a bridge weigh-in-motion (B-WIM) technology (Žnidarič et al., 2018) pioneered by Slovenian researchers that enabled engineers to measure the effects of real traffic loads on bridges without requiring test vehicles.

The research in several European research projects at the turn of the century resulted in the development of the Soft Load Testing (SLT) approach (Casas et al., 2009). SLT applies B-WIM measurements, which not only provide axle loads and spacings for developing the traffic load models but also measure three bridge performance parameters: influence lines, load distribution factors, and dynamic amplification factors from all vehicles that cross the bridge (Žnidarič & Kalin, 2020). These are statistically evaluated and can be used in structural analyses at any level of complexity. In most cases, a deterministic Rating Factor approach—similar to the one outlined in the AASHTO Bridge Evaluation Manual—is used to assess structural safety. This method incorporates a capacity reduction factor that accounts for the condition index, which is derived from bridge inspection results. This methodology allows engineers to determine the structural integrity of ageing bridges while avoiding unnecessary closures.

Figure 2. Example of diagnostic load test from Slovenia, 2008.

The approach is particularly beneficial for single-span older concrete and steel bridges, where original design documentation is either incomplete or unavailable and whose performance, due to missing expansion joints and faulty bearings, is far more favourable than in theory (Žnidarič & Lavrič, 2010). An SLT limitation is that it is valid at serviceability limit states only, but is quick, cost-effective, does not necessitate road closures, a critical factor for many existing bridges, and provides information for a reliable answer to a common question: 'Is the bridge safe for the present traffic?'. From 2004 to 2016, Slovenia used SLT in combination with material testing and step-by-step analyses to assess 154 structurally deficient bridges. Finally, only 13 of the 154 bridges were reconstructed or replaced; the rest were just repaired to extend their service life.

2.10. Spain

In Spain, there are not specific guidelines or standards for the safety assessment of existing bridges. For highway bridges, at the national level, there are two recommendations or guidelines for the assessment of the bridge condition based on basic (or routine) and principal inspections (Ministerio de Fomento, 2009, 2012). The basic inspection is defined in Ministerio de Fomento, (2009) as a visual inspection that can be carried out by an inspector without specialisation. The principal inspection is also mainly visual, but with deeper observation of the condition of different parts of the bridge, but open to further requirements (optical devices, cameras, … .) and also it should be carried by specialised personnel with knowledge on bridges. Based on the result of the principal inspection, normally performed every 5 years, a condition index of the bridge is obtained. The classification is as follows: Based on the severity, extension and type of damage, a condition index between 0 and 100 is obtained and 5 condition levels are defined according to Table 2. Different recommendations are used in the case of railway bridges although with similar background and characteristics (ADIF, 2019, 2020, 2021b).

Table 2. Condition index used in Spain.

Score range	Condition	Description
0–20	Very Good	No consequences on durability or safety. No action.
21–40	Good	Minor defects that should be monitored in the near future.
41–60	Fair	Moderate defects that can reduce durability, serviceability, and safety. Some repairs necessary in the mid-term.
61–80	Poor	Important defects that can affect performance in a short-term period. Short-term repair needed. Depending on the type of defect, a special inspection may be necessary.
81–100	Very Poor	Safety may be in jeopardy. Very important defects. Requires a special inspection and immediate intervention (repair). In some cases, traffic restrictions should be imposed.

Load testing for assessment is carried out both for highway and railway bridges. In the case of highway bridges, a guideline was issued by the Ministry of Public Works, containing recommendation for both static and dynamic load testing (Ministerio de Fomento - Direccion General de Carreteras, 1999). Both can be classified as diagnostic load tests and no standard or recommendation is available concerning the proof load assessment. The static test is mandatory for any bridge with a minimum span-length of 12 m after construction and before to be opened to traffic. Although there is no declared and regulated prohibition in the Spanish codes for the execution of proof load tests, they are not particularly exploited systematically. At the present time there is no public information on proof load test performed in a bridge in operation in Spain. Proof load tests have been carried out at a research level in the case of bridges that were deemed to be removed due to important deterioration or because of new planning requirements. In the case of railway bridges there is also a guideline for the execution of load tests (ADIF, 2021a). Both static and dynamic tests are included in this guideline, which is applicable for both cases: new bridges before opening to the traffic and existing bridges to assess the static and dynamic performance for the safety evaluation.

2.11. Sweden

Sweden owns approximately 30,000 bridges, of which about 4,500 are railway bridges and the remaining ones are road bridges, organised into the bridge management system 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 both private or public companies and different 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.

Inspection of bridges is carried out regularly in accordance with Trafikverket's infrastructure regulation (Trafikverket, 2020), and the results are classified using a four-level condition framework called Tillståndsklasser (TK), ranging from TK0 to TK3. TK0 indicates that no intervention is needed within the next 10 years, TK1 requires action within 10 years, TK2 within 3 years, and TK3 requires immediate action. Importantly, these condition classes do not necessarily imply structural deficiencies. A TK3 classification may, for instance, result from a corroded but non-load-bearing railing needing repainting, a pothole in the asphalt surface, or rail sleepers disconnected from rails—issues that affect functionality or safety without compromising structural capacity.

The TK classification serves as a functional assessment system that supports prioritisation for maintenance and follow-up investigations. It is not a numerical condition index nor a rating factor. Moreover, this classification framework is not limited to bridges: it applies to a variety of infrastructure types managed in Trafikverket's BaTMan system, including quay walls, ferry docks, snow galleries, and noise barriers (Trafikverket, 2020, Section 2).

2.12. Switzerland

Switzerland has been a pioneering country in the assessment of existing structures, with the first code published specially for this purpose in 2011, as described in Brühwiler et al., (2012). This code mostly provides information on the evaluations of structural verifications with deterministic and probabilistic methods. It puts emphasis on the actualisation of material properties (i.e. the evolution of concrete properties in time) and actions (i.e. reduced alpha factor for traffic load model). The assessment is expressed as the structural-safety evaluation, and is quantified as the ratio between resistance and loading (in design values) for any limit states.

Load testing and, more broadly, monitoring activities are recommended as a measure to update actions and structural properties. These activities are considered only as additional measures, if assessment calculations indicate that the code requirements are not met, and sources of additional capacity or stiffness can be reasonably expected. Due to this approach, bridge load testing is currently only performed extraordinarily. It must be added that, in the past, a load test was performed on each new bridge in the network in collaboration with a research institute, such as 200 load tests made between 1970 and 1990 by EPFL (Burdet, 1993) and 356 dynamic load tests documented by EMPA until 1983 (Cantieni, 1983). This practice is discontinued.

2.13. United Kingdom

Bridge assessment in the UK has a long history based on combinations of visual inspection and numerical calculation. The principles of design theory and factors of safety are applied in the first instance, progressing through simple assumptions and linear models, advancing to detailed considerations and finite element models where necessary to reduce conservatisms. The assessment of a highway bridge outputs a verification of the safety for use to a level of Assessment Live Load (ALL)—the maximum weight of vehicle permitted to pass over the bridge. Rail bridges are similarly output with a Route Availability (RA) level at a stated maximum travelling speed.

Deterioration of aged structures poses significant problems, particularly for cast iron or early steel structures of the rail network, reinforced concrete structures (including half-joints, hinge joints and post-tensioning) of the trunk road networks and masonry arch bridges. The limitations of finding and quantifying defects through visual inspections is a known problem including a failure at Stewarton (Department for transport, 2009), and those which came close such as Hammersmith Flyover and the Forth Road Bridge. These led to recent research and publications including guidance for detection of hidden defects (Collins et al., 2017), structural health monitoring (Sparkes & Webb, 2020) and non-destructive testing (Mckibbins et al., 2022).

Load testing for bridge assessment was formalised in the UK, as publication by the Institution of Civil Engineers in 1998 (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges, 1998). More recently, load testing has been further promoted for the assessment of bridges in the standard CS463 (Highways England, 2019). Supplementary (or 'diagnostic') load testing is promoted to 'assist the strength assessment of bridges … for bridge types which contain features where hidden strength reserves can be found'. Stiffness is measured under the imposing of a controlled load less than the daily maximum vehicles, for the purpose of detecting restraints and load sharing behaviours. Proving (or 'proof') load tests are permitted only for bridges that could otherwise be closed to traffic or demolished.

Despite having national standards and guidance available, load testing is seldom used in the UK for road bridge assessment and even less so for rail bridges. Disruption to traffic is avoided as far as possible and safety concerns of testing can be prohibitive. Assessment relies more often on extensive calculation, modelling and assumptions progressively refined though inspection and non-destructive testing. In many cases, it is possible for the asset owner to accept deviations from the standards to lower the factors of safety, which is often favoured for financial limitations rather than to load test. Over 3000 highway structures in the UK are considered sub-standard (RAC Foundation, 2022) of which 80% are associated with limitations of resources to rectify. Remote condition monitoring is typically used as a means of detecting measurable changes and providing warning on such structures.

2.14. India

In India, there are separate code-making bodies for bridges, namely Indian Roads Congress (IRC) for Highways, Bureau of Indian Standards (BIS) for all structures, and Research, Design and Standards Organisation (RDSO) for Railways. It is estimated that about 25% of the existing bridges are in some form of distress, and the majority of existing bridges in India are vulnerable to earthquakes as they were not designed according to any seismic design criteria or using old codes with different seismic detailing requirements as compared to current codes. Therefore, strength assessment, considering flexure, shear, torsion, buckling, and serviceability aspects are required for assessment, and the IRC works with a load factor for the assessment of strength (Garg & Kumar, 2006). The outcome of assessment is:

a. to evaluate the safe load carrying capacity of the bridge,
b. to provide information about rating and posting of bridge to owner clients and authorities.
c. assessment also includes recommendations for dealing with over-dimensioned and over-weight vehicles, which ply on the roads occasionally.

No condition index is used to adjust the results. The outcome of the assessment is a capacity-to-demand ratio, using the sectional capacity of the structural member.

Railways have issued a guideline for load testing of bridges (Government of India - Ministry of Railways, 2024). The load tests described in this clause are intended as checks on the quality of the units and should not be used as a substitute for normal design procedures. Where members require special testing, such special testing procedures should be in accordance with the specification. Test loads are to be applied and removed incrementally. The test loads to be applied for the limit states of deflection and local damage are the appropriate design loads, i.e. the characteristic dead and imposed loads. When the ultimate limit state is being considered, the test load should be equal to the sum of the characteristic dead load plus 1.25 times the characteristic imposed load and should be maintained for a period of 24 h. If any of the final dead load is not in position on the structure, compensating loads should be added as necessary.

It is made clear in this guideline that the primary objective of performing load test is to understand bridge's response to static and dynamic loadings. The levels of loading necessary should be such that they are sufficient to obtain measurable responses from the structure without causing any permanent structural damage. Acceptance criteria is given in terms of crack width and deflection for reinforced concrete structure), though for pre-stressed concrete structures, there should be no cracks. Recovery of deflection after release of load shall be 85%. For highways, there are 2 guidelines published by IRC which have reference to load testing of bridges:

- IRC:SP:51 2015 titled 'GUIDELINES FOR LOAD TESTING OF BRIDGES' (Indian Roads Congress, 2015).
- IRC:SP:37 2010 titled 'GUIDELINES FOR EVALUATION OF LOAD CARRYING CAPACITY OF BRIDGES' (Indian Roads Congress, 2010).

SP:51 deals with load testing of Superstructure for Highway Bridges, excluding arch type of bridges. The Guideline deals with Proof Load Test. The nomenclature used for proof load test in this guideline differs from the nomenclature used in several countries (e,g. USA and Europe), but is aligned with the British guideline, where the term proof load test is used for an acceptance test, or diagnostic load test prior to opening a bridge. Testing for shear capacity is not considered. Load test as per this guideline is not intended to assess ultimate load carrying capacity of bridge superstructure. The acceptance/rejection of bridge as per this guideline is only on the basis of live load deflection and recovery after unloading. SP: 37 covers load testing of existing bridges for rating and posting purposes. Load testing for rating is applied when it is not possible to determine the rated capacity of a bridge due to lack of essential details. Load Test for posting is done when details required for verifying the strength of all elements of existing structure by analytical methods is not possible due to lack of reliable data.

3. Bridge load testing for assessment

3.1. General concepts

When analytical assessment calculations indicate that a given bridge does not fulfil the code requirements for existing bridges as defined differently across countries, various types of refinements are possible: analytical, numerical, and experimental, see Figure 3. One of the options to obtain additional information for assessment is through bridge load testing. Load testing can be particularly interesting for short-to-medium span bridges, where the contribution of the live load to the factored load effect is significant.

Diagnostic load testing can be used to obtain information on actual bridge behaviour, including load distribution and global stiffness (Alampalli et al., 2021; Bridge Diagnostics Inc., 2012; Commander, 2019; Fu et al., 1997; Hernandez & Myers, 2018), as well as reserve structural capacity (Bayane

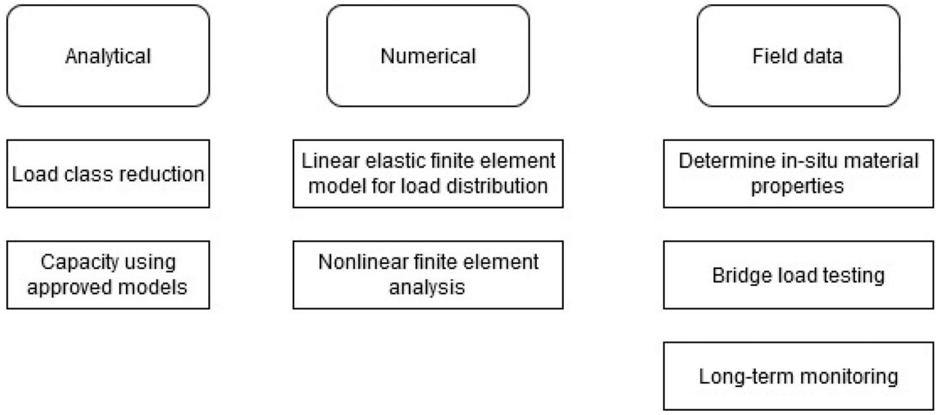

Figure 3. Options to improve assessment, based on (Ensink, 2024).

et al., 2021; Bertola et al., 2023; Proverbio et al., 2018). A diagnostic load test involves collecting data from a bridge subjected to a controlled and known load. This data serves as the foundation for refining a finite element model of the bridge. Subsequently, the refined model is utilised to determine the safe load-carrying capacity of the bridge. Diagnostic load testing is primarily employed as an assessment tool when the current load rating of the bridge falls below a safe level determined through conventional assessment methods and when the bridge geometry and type lends itself to a diagnostic test. Important in diagnostic load testing is to apply a controlled load that causes a measurable response, and to interpret this response in the light of the open questions for the assessment of the existing bridge. In practice, the interpretation of the response is carried out using a linear finite element model, and the field data are used to develop a field-validated numerical model that then can be used for assessment.

Proof load testing, on the other hand, can be used to directly assess a bridge by demonstrating experimentally that the bridge fulfils the safety requirements of the code (Lantsoght et al., 2017b; 2017d; Moses et al., 1994; Olaszek et al., 2012; Ransom & Heywood, 1997; Saraf et al., 1996). These requirements can be achieved by applying a load that creates the same sectional effect as the code-prescribed factored load combination, or by directly using the load test information to update the reliability index and compare this value of the required target reliability index for the considered bridge (Casas & Gómez, 2013; de Vries et al., 2021; 2022; 2024; 2024).

When the first method is used, generally large-magnitude loads need to be applied for the proof load test, which involves a higher risk to the testing procedure. Therefore, careful instrumentation and interpretation of the measurements during the test becomes crucial. In practice, this interpretation is carried out based on stop criteria, which are predetermined thresholds to the structural response that warn the test engineer that further loading could result in permanent damage to the structure (Christensen et al., 2022; Lantsoght et al., 2019; Olaszek et al., 2016). As such, loading past reaching a stop criterion is not permitted. For the second approach, especially when the measured information is used to update the reliability index during the test, lower loads (although still larger than the characteristic value), can be used in practice.

Finally, collapse tests are a type of bridge load tests that can be used to obtain valuable information on the behaviour and ultimate capacity. It can be decided to test one bridge, potentially one that will be decommissioned anyway, to better understand the overall behaviour of a certain bridge type. This is relatively rare and requires careful execution due to the risks involved, and may result in an unexpected failure type (Bagge et al., 2018). For assessment, the advantages of bridge load testing include the ability to map the actual behaviour of the bridge in its current condition (using diagnostic load testing) and obtaining a direct experimental assessment (using proof load testing). The disadvantages include: the high cost, the high risk involved with proof load testing, and the necessity to actually instrument the bridge. Therefore, before deciding to use bridge load testing for assessment, a cost-benefit analysis is required (Alampalli et al., 2019).

The variety in bridge load testing practices observed internationally aligns with the broad range of assessment practices in various countries. In some countries, diagnostic load testing and/or proof load testing may be part of the assessment practice, whereas in other locations such field tests are uncommon. Proof load testing in particular for assessing existing concrete bridges is highly country-dependent in terms of application, methodologies, loading method, stop criteria, and target loads. Due to the higher risk involved, traffic disruption, and uncertainties on the procedures, as well as a lack of generally accepted codes and guidelines, this method may be underutilised at the moment, and bridge owners may be reluctant to apply the method. Therefore, analysing international experiences with diagnostic and proof load testing is valuable. Figure 4 gives an overview of the different load magnitudes that can be used in the different types of bridge load tests. A current trend is to move towards a more integrated interpretation of load testing results, in combination with other types of field data (Lantsoght et al., 2025), and to develop frameworks to address bridge assessment and examination from a more holistic point of view (Bertola et al., 2024).

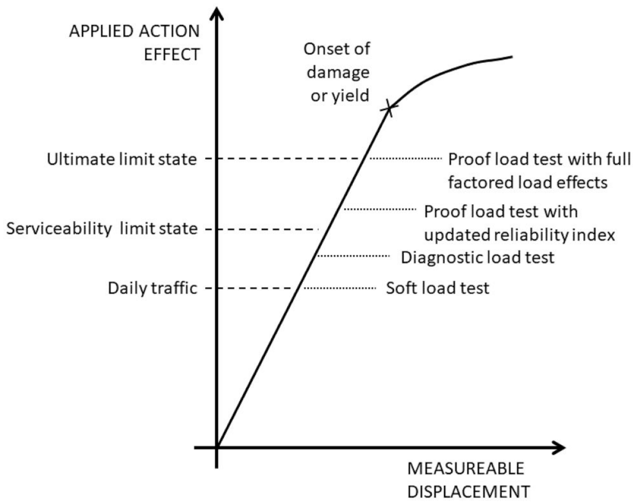

Figure 4. Comparison between different load magnitudes in bridge load testing.

3.2. Practical applications

Table 3 gives an overview of the cases for which bridge load testing is used, how often bridge load testing is used, what the local limitations are for the countries considered, the governing documents, reported examples of load tests and their references, and gives an estimate of the number of bridges that have been assessed using load testing. Additional details of successful applications are mentioned in the subsequent paragraphs.

In the United States, the predominant methodology employed for bridge load testing is the diagnostic load testing approach. Furthermore, the primary objective of these tests is to assess bridges with low load ratings. The bridges that typically derive the most significant benefit from diagnostic load testing are short- to medium-span structures that incorporate elements that enhance stiffness (e.g. substantial parapet walls, sidewalks, etc.), as well as structures that exhibit superior lateral load distribution compared to what is permitted by an analytical bridge assessment. The diagnostic load test gained significant traction in the United States not only for its accuracy but also for its practicality. A diagnostic load test can typically be completed on a short- to medium-span bridge within a single day, minimising disruptions to normal traffic. The results of a diagnostic load test not only provide a more precise load rating of the bridge but also serve as a baseline for future assessments.

In India, assessment of existing bridges can include the load testing prescribed in code checking the bridge is performing elastically for the service live loads. Overloading the structure to test the performance of bridge beyond the characteristic live load is not permitted in current codes. Figure 5 shows a typical load test of a reinforced concrete bow string girder bridge performed recently in Lucknow (U.P, India). There is no bridge management system prevalent in India currently, and therefore no data is available regarding the number of load tests done for assessment. However, the Indian Bridge Management System is currently under development and will be implemented in the very near future. Once IBMS is in place, it would be possible to keep a record of load tests that have been carried out for assessment.

Successful proof load test campaigns have been carried out in Denmark. A first campaign considered bridges between Herning and Holstebro, focusing on gaining experience with the methodology, handling measurement equipment, and achieving insights on the bridge behaviour and ability to carry the loads (Schmidt et al., 2018). Lessons learned regarding the use of laboratory equipment on-site and carrying out the test during the short available bridges of class 80, and using proof load testing to upgrade these bridges to class 100. All testing was carried out in three days, and resulted in an upgrade of the road stretch, allowing heavier vehicles to pass all bridges (Christensen et al., 2023). In the Netherlands, proof load tests have been carried out for research purposes. The main goal was to see if proof load testing can be used to assess existing reinforced concrete slab bridges that are found to be shear-critical upon assessment.

In the UK, supplementary load tests have proven useful in several abnormal assessment schemes (Collins et al., 2017; Cousins, 2017) and after construction of more complex structures (Cousins et al., 2025; Parker et al., 2003). Proof load testing in the UK is rare, and even less frequently made public. In Spain, load tests on new bridges of the high-speed railway network are mandatory. Figure 6 shows a drone view of load testing at El Tajo Viaduct (July 2021).

An example of a diagnostic test for bridge acceptance in Poland is that of a railway bridge conducted in 1996. The bridge consists of free supported spans with a theoretical span of 16.7 m (Figure 7(a,b)). First, dynamic tests were performed after the construction was completed using two locomotives at speeds from 10 to 100 km/h. During the run at 100 km/h, significant forced vibrations were recorded. The increase in extreme vertical displacements at a speed of 100 km/h in relation to the displacements at a speed of 10 km/h was approximately 41%, most likely related to the impact generated when the locomotive entered the bridge. It could have resulted from a large difference in the stiffness of the track and substructure on the span and on the approach.

Operating the bridge in such a condition (without track adjustment) could have led to instability of the ballast (Olaszek et al., 2021). After the load test, the bridge was operated with a speed limit of 50 km/h. The tests were repeated after track adjustment and after seven months of operation of the facility. Now, only an 8% increase in vertical displacement was observed between the 100 km/h and 10 km/h runs (Figure 7(c)). This example confirms the validity of dynamic acceptance tests of railway bridges and the possibility of assessing the degree of reduction of the dynamic effect in relation to the results of these tests during subsequent diagnostic tests. It should be noted that about 780 bridges have been tested over 25 years by one laboratory (while tests are also performed by a few more independent laboratories). Most of these theses were acceptance tests of new bridges, and only a small percentage of these were

Table 3. Application of bridge load testing for assessment internationally.

Country	Application and extent of application	Local limitations	Governing documents	Examples	# of bridges assessed
United States	Diagnostic and proof load testing for assessment	Depends on local Department of Transportation	AASHTO Manual for Bridge Evaluation (AASHTO, 2016) + TRB e-circular 257 (Alampalli et al., 2019)	Documented in TRB e-circular 257 (Alampalli et al., 2019)	over 2500[a]
Chile	Damaged bridges and permit vehicles.	Used for service load testing on special bridges, and Proof load testing on existing bridges.	Spanish guidelines (Ministerio de Fomento - Direccion General de Carreteras, 1999)	Seminario Bridge, Toltén Bridge (Márquez et al., 2021) CauCau Bridge (Valenzuela & Márquez, 2024) KayKay Treng Treng Bridge	around 20[a]
Ecuador	Acceptance tests prior to opening of new bridges	Not used for assessment. Proof load testing is not used.	Spanish guidelines (Ministerio de Fomento - Direccion General de Carreteras, 1999) + AASHTO Manual for Bridge Evaluation (AASHTO, 2016)	Villorita and Los Pajaros bridges (Bonifaz et al., 2018)	Not used for assessment.
India	Applicable for Highway & Railway Bridges	Not applicable for Arch Bridges & Shear Critical Bridges	IRS CBC 1997, Cl. 18 (Railways) IRC:SP:51-2015 (Highways) IRC:SP:37-2010 (Highways)	Figure 5, Lucknow test.	unknown
Denmark	Proof load testing of bridges to upgrade to higher vehicle class.	Linked to national vehicle classification approach; no diagnostic load testing; single-span bridges	Danish guideline for proof load testing (Vejdirektoratet (The Danish Road Directorate), 2025)	Examples of high magnitude load testing (Schmidt et al., 2018) and proof load testing (Christensen, 2023)	About 10 as part of ongoing research[a]
Italy	Monitoring existing bridges; temporary operational existing bridges; acceptance criteria of retrofitted bridges.	Not to be used for safety assessment.	Italian building code (Ministero delle Infrastrutture e dei Trasporti, 2018); Guidelines for safety assessment of existing bridges (Ministero delle Infrastrutture e dei Trasporti - Consiglio Superiore dei Lavori Pubblici, 2020a).	Acceptance load tests on retrofitted bridges; Monitoring and comparison with load test results at the time of construction.	Order of magnitude: hundreds of bridges[a]
the Netherlands	Proof load testing for flexure in some cases, mostly research applications	No governing national document or code available	Eurocodes, National Codes for Assessment NEN 8700:2011 (Normcommissie 351001, 2011b), NEN 8701:2011 (Code Committee 351001, 2011) and RBK (Rijkswaterstaat, 2022)	Viaduct Zijlweg (Lantsoght et al., 2017d), Viaduct de Beek (Lantsoght et al., 2017a), Halvemaans Bridge (Fennis & Hordijk, 2014)	20–30[a]
Poland	Diagnostic (static and dynamic) and proof load testing	Currently in progress switching from proof to diagnostic load testing	Polish guidelines (Research Institute of Roads and Bridges, 2008), updated in 2021 (Ministry of Infrastructure, 2021)	Railway bridge shown in Figure 7	Mostly acceptance tests of new bridges
Slovenia	Soft and diagnostic load testing	No proof load testing.	Methodology for determining and controlling the load capacity of road bridges, Road Infrastructure Agency, 2009	Examples in Žnidarič & Kalin, (2020)	154 bridges tested between 2004 and 2016, 143 approved
Spain	Acceptance tests prior to opening of new or rehabilitated bridges	No proof load testing	Ministerio de Fomento - Direccion General de Carreteras, 1999	Viaducto de Valdelinares Viaducto de la Plata,	>5000 bridges[a]

(*continued*)

Table 3. Continued.

Country	Application and extent of application	Local limitations	Governing documents	Examples	# of bridges assessed
			ADIF. Pruebas de carga ferroviarias en puentes de ferrocarril. NAP 2-4-2.0. 2021. Madrid	see Figures 13 and 14	
Sweden	Proof load testing is a recent topic of research.	No explicit restrictions	Assessment using national code (TRVINFRA-00331, 2023)	Kalix bridge (Agredo Chávez et al., 2024)	More than 20 bridges[a]
Switzerland	Mostly load testing linked with research activities	No proof load testing	No governing document	Bridge load testing occurs while research is ongoing on data-interpretation, sensing technologies or structural intervention validation (Bertola et al., 2023; Michels et al., 2016; Pasquier et al., 2016; Reuland et al., 2023)	See note in text
United Kingdom	Occasional for assessments of complex aged or deteriorated structures.	Preference for numerical assessment. Guidance excludes masonry arch bridges. Proof load testing only permitted for structures otherwise condemned.	Design Manual for Roads and Bridges CS463 Load Testing for Bridge Assessment (Highways England, 2019). Bridge Testing Guidelines for Supplementary Load Testing 1998 (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges, 1998)	Multiple case studies available: Ciria C768 (Collins et al., 2017), Ciria C788 (Sparkes & Webb, 2020), (Cousins, 2017), (Cousins et al., 2025)	about 10-20 bridges each year[a]

[a]estimated values.

Figure 5. Example of load test in India.

performed to assess the load-carrying capacity of existing bridges.

For Switzerland, there is no database of load tests. Due to its decentralised nature, estimating the number of load tests used for assessment is difficult. Moreover, as load testing upon opening was common practice in the past, baseline data is available, but no statistics are available to date. In research projects, 10-15 load tests have been published in recent years, but the number of bridges tested by practitioners is expected to exceed this number.

Figure 6. Load testing at El tajo Viaduct.

4. Recent research on bridge load testing

4.1. United States

Research related to bridge load testing in the United States has been greatly extended over the past 30 years. During the onset of diagnostic load testing as a solution for assessing bridges, the research focused on the application of

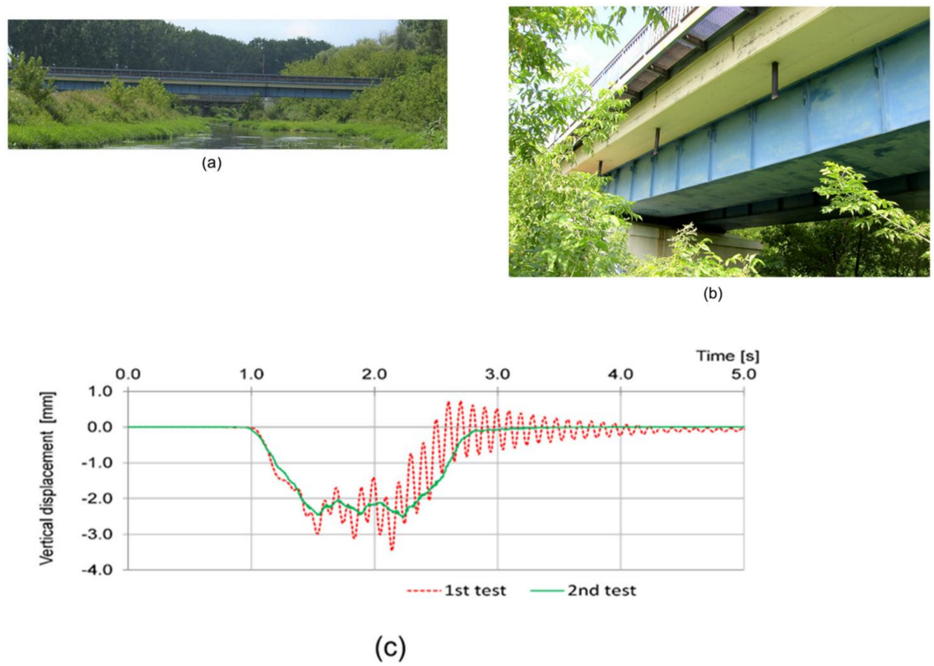

Figure 7. Diagnostic tests of the railway bridge: (a) general view of the bridge, (b) details of the structure, (c) summary of the displacement time history recorded during the passage of 2 locomotives at a speed of approx. 100 km/h during the 1st test (acceptance) and the 2nd test (diagnostic) carried out after the track adjustment on the approach and after 7 months of operation (Olaszek et al., 2021).

diagnostic load testing to various structure types. The research completed has added significant value to the acceptance of diagnostic load testing as an assessment tool and is widely used throughout the United States today. More recently, the advancement of Non-Destructive Testing (NDT) tools for the purpose of material assessment has greatly improved the accuracy of load tests as results can provide a much more accurate representation of the material properties, used in the model refinement parameters. In addition, recent research has focused on the use of proof load testing for the serviceability limit state (Jauregui et al., 2019), which is often governing over the ultimate limit state for prestressed concrete bridges with bonded tendons.

4.2. Chile

Static and dynamic load tests were carried out in Chile by the academia and the Ministry of Public Works Laboratory for the development of minor bridges, i.e. slab-type bridges with a free span of no more than 15 metres. These tests were carried out considering lightened bridge slabs, of both in-situ construction and prefabrication (San Martin & Valenzuela, 2016).

4.3. Ecuador

In Ecuador, research has been carried out on the topic of proof load testing, in line with developments in the Netherlands (Benitez et al., 2018; Paredes & Lantsoght, 2018; Rodriguez & Lantsoght, 2018). Recent research on the vulnerability of existing bridges considers load testing as one of the methods to obtain field data and validate numerical models (Cervantes et al., 2025).

4.4. Denmark

Research on proof load testing for existing bridges in Denmark has been carried out for half a decade. One project has been successfully completed and a follow-up project is ongoing. In collaboration between government (Danish Road Directorate), industry (COWI A/S), and academia (Technical University of Denmark (DTU) and Aalborg University (AAU)). The research focuses on combining experimental work, probabilistic approaches, and theoretical response evaluations.

The first project focused on applying concepts of proof load testing in alignment with the Danish classification system. Methods were developed that are economically competitive, successful and quick on site, and that explore the use of novel monitoring techniques during testing. The optimised multidisciplinary approach seemed to work well where advanced monitoring could be optimised and reduced to an extent that enabled several pilot proof load tests. These approaches were applied to single-span bridges, Figure 8 with a particular focus on inverted T-girder bridges. Testing and numerical work showed large interaction between the girders and an overall slab-like behaviour, resulting in improved capacity overall, demonstrating that these bridges are excellent candidates for proof load testing.

The second project focuses on multi-span bridges, and an improvement of the stop criteria from the first project (Christensen et al., 2022), with a focus on reinforced concrete slabs without shear reinforcement and prestressed concrete bridges. This research is supported by a series of collapse tests to better understand the ultimate behaviour of slab elements in bridges, see Figure 9 and Figure 10.

(a) (b)

Figure 8. (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.

Figure 9. Partial testing of bridge slab, (june 2024, Denmark) (Schmidt et al., 2024).

4.5. Italy

Current research in Italy has mostly focused on proof load testing of I-type simply supported prestressed concrete bridges. The research aims at substantiating the proof load testing reproducing the load effects of Eurocode Load Model 1 (LM1) (CEN, 2003). An I-type highway bridge has been considered as case study where an acceptance load test had been performed recently (Addonizio et al., 2024). The bridge deck underwent retrofit interventions for bending at midspan in some beams. Reliability analyses are investigating the sensitivity of the load test on different failure mechanisms with different demand-to capacity ratios (DCRs) for the longitudinal edge beam. Due to the lack of weight-in-motion data at regional level, the traffic load model is defined with an extreme value type distribution properly fitted on the characteristic value of the LM1 having a return period of 1000 years. Based on analytical models, the edge girder at the end region was shear critical with a DCR higher than unity under the ultimate limit state traffic load combination.

The proof load testing was performed with a total of 8 dump trucks of 42tonnes each imposed in four increments (i.e. two per step) aiming to reproduce the LM1 effects both in terms of bending moment at midspan and shear at supports. The test was passed with no cracking along the girder, no residual displacements and with a linear trend of deflections across the deck, confirming the design assumptions. A reliability-based analysis demonstrated that after the proof load test, the reliability index in shear attained satisfactory value thus preventing further strengthening interventions. Ongoing research aims to demonstrate the effectiveness of proof load testing on different case study bridges in order to develop a comprehensive methodology for future applications.

4.6. The Netherlands

Two main topics of research are ongoing in the Netherlands related to proof load testing for assessment of existing bridges (Lantsoght et al., 2017g). The first topic relates to stop criteria for shear in members without shear reinforcement such as reinforced concrete solid slab bridges, and the second topic to the probabilistic substantiation of the practice of proof load testing. In addition, in recent years collapse tests have been carried out on a reinforced concrete slab bridge (Lantsoght et al., 2016; 2017f) and a post-tensioned slab-between-girder bridge (Ensink et al., accepted for publication), which are being analysed to improve the proof load testing practice.

For the research related to stop criteria, three sets of experimental data are used: 1) existing data from experiments on slab strips tested under cycles of loads, 2) experiments on straight slabs under concentrated loads, and 3) experiments on skewed slabs under concentrated loads. This approach has allowed stop criteria to be developed first theoretically based on concepts from the Critical Shear Crack Theory (Muttoni & Simões, 2023) and the Critical Shear Displacement Theory (Yang et al., 2016), and subsequently to be validated on experiments on beams without shear reinforcement (i.e. slab strips) (Zarate Garnica et al., 2024b). In a next step, the effect of the wavy shape of the shear crack in the width direction was taken into account, resulting in updated shear stop criteria for wide members, such as reinforced concrete slabs (Zarate Garnica et al., 2024a). For this purpose, 25 experiments failing in flexure and shear on six reinforced concrete slabs of $5\,m \times 2.5\,m \times 0.3\,\mathrm{m}$ were tested. The slabs were subjected to a loading protocol similar to that used for proof load testing to study the behaviour under cycles of loading, indicators prior to failure, and develop and validate stop criteria.

Finally, for the skewed slabs, the experiments were carried out with the load near the edge, so that the stop criteria developed for beams are governing (Lu et al., 2025) and can be validated under different loading conditions. In this series of experiments, seven slabs of different skew angles are

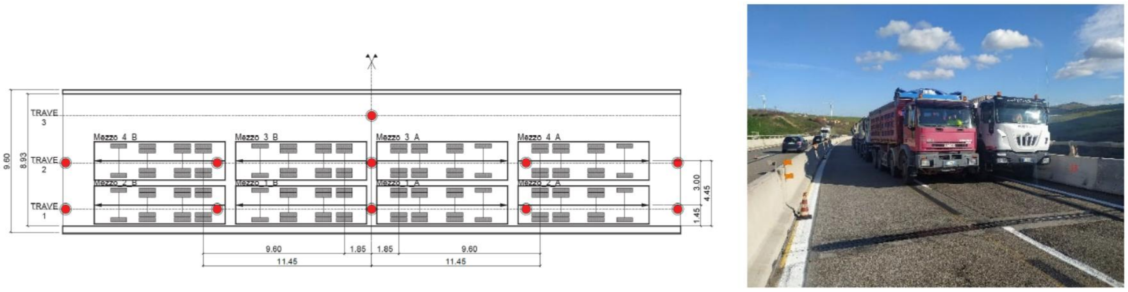

Figure 10. (a) Plan view of the proof load layout for the case study bridge; (b) picture of the eight loaded dump tracks.

Figure 11. Skewed slab testing at delft University of technology.

tested, see Figure 11. Besides validating the stop criteria, the experiments on skewed slabs also serve to evaluate the procedures to determine the shear capacity of skewed slabs in the obtuse corner, to inform assessment practices in the Netherlands.

To develop a probabilistic substantiation of proof load testing, four key aspects are studied: 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.* 2024), 3) using stop criteria and measurements during proof load testing for the probabilistic analysis (de Vries et al., 2025), and 4) spatial variability to extrapolate results between sections, spans, and objects.

4.7. Poland

The Road and Bridge Research Institute, in cooperation with the Institute of Fundamental Technology Research, the Polish Academy of Sciences and the Kielce University of Technology has, between 2023 and 2025, conducted a project of diagnostics for prestressed and cable-supported bridges, including the selection of appropriate monitoring systems. The project was financed by the General Directorate for National Roads and Motorways, and the National Centre for Research and Development. As part of the project, the principles of using diagnostic test loads for periodic monitoring to determine the condition of the above-mentioned bridge structures were examined and defined. The project was characterised by an innovative approach to the diagnostics of damage to prestressing and suspension cables. Cracks in prestressing and suspension cables, caused by accelerated steel fatigue, are usually the result of their corrosion. The proposed solution is based on the coupling of mechanical tests, NDT methods and computer modelling. Mechanical tests included tests under local diagnostic static and dynamic test loads only with partial restriction of vehicle traffic on the tested bridges. Verification tests were carried out on two bridges - a prestressed post-tensioned bridge and a cable stayed bridge.

Figure 12. A proof-load test following a SLT on a test bridge in Slovenia.

4.8. Slovenia

Research in the 1990s and early 2000s focused on developing the Soft Load Testing methodology to assess bridge safety and performance (Mandić Ivanković et al., 2019). Many tests were performed in the laboratory and on-site to compare the results of SLT and traditional load testing methods (Figure 12). Special focus was given to the dynamic response of bridges due to traffic loading. The modern B-WIM systems can evaluate dynamic amplifications from every heavy vehicle that crosses the bridge. Consequently, the statistically evaluated data results in a realistic dynamic amplification factor, typically considerably lower than in the codes (Kalin et al., 2022). The numerous examples demonstrate that SLT can efficiently characterise bridge performance and provide valuable inputs for optimised bridge analyses.

In recent years, research has focused on using B-WIM systems equipped with conventional strain transducers and many other sensors for long-term monitoring and model updating of longer and more complex bridges. Several structures were equipped with accelerometers, strain and other gauges, and optic fibres to collect data on bridge behaviour under various conditions to better understand the

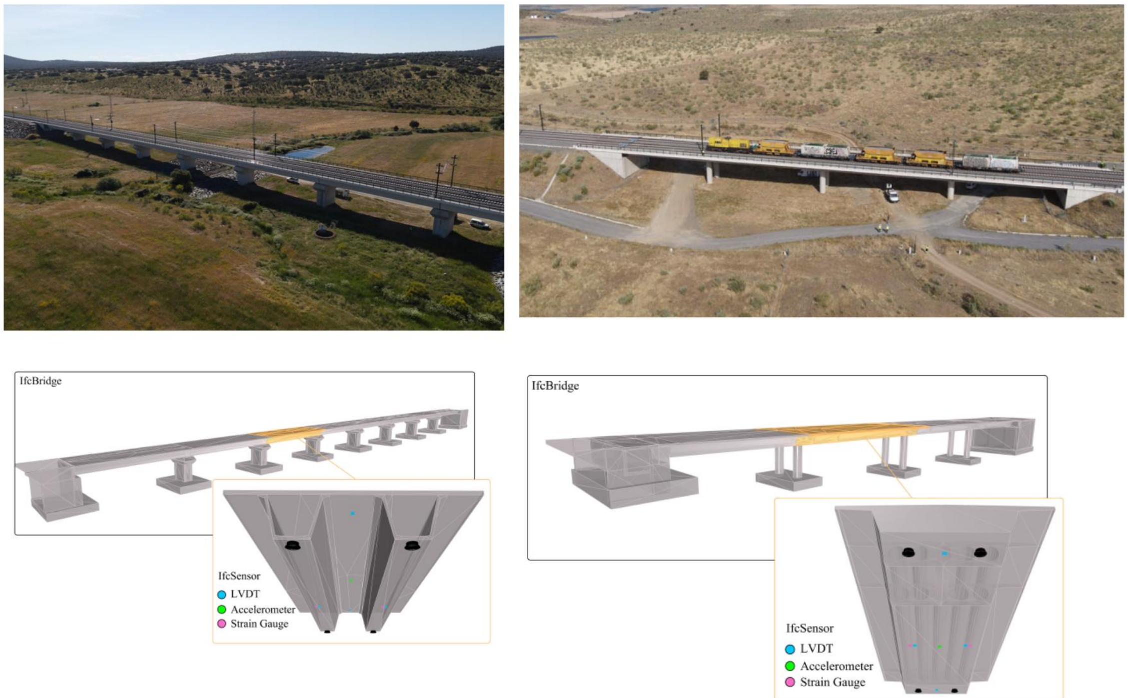

Figure 13. Asset and geometric representation of the IFC model of valdelinares (left) and La plata (right).

differences between the strain and frequency-based results (Hekič et al., 2024).

4.9. Spain

Recent load tests have been routinely conducted in Spain as part of infrastructure verification efforts. In 2021, tests were performed on the Plasencia-Cáceres section of the Spanish High-Speed Rail (AVE) network (Chacón et al., 2023b). These tests were carried out by the infrastructure authority ADIF in collaboration with the engineering firm formerly known as GEOCISA, now DRACE. While primarily aimed at ensuring compliance with regulatory requirements, these tests also provided an opportunity for parallel research initiatives focused on the systematic digitalisation of the process.

The objective of these research efforts was to explore the feasibility of using load testing as a basis for generating a validated digital twin of the bridge, based upon and ensuring consistency with national regulatory checks (ADIF, 2021a). The methodology involved integrating multiple data sources, including open BIM (building information modelling) geometry (IFC, industry foundation classes data format), measurement data stored on an internet-of-things (IoT) platform, structural analysis models, and comparative assessments between observed and predicted behaviour. This multi-layered information construct was then incorporated into a web-based platform built on knowledge graph systems, offering a structured approach to managing and interpreting different types of data (Chacón et al., 2023a; Ramonell et al., 2023). Two bridges from this rail line were digitised (see Figure 13) Valdelinares, an eight-spanned, prefabricated precast concrete box-girder with a simply supported configuration and La Plata, a four-spanned, cast in-situ, post-tensioned box girder.

Figure 14 presents the results of the developed platform, displaying the geolocated bridge within an interactive environment. The user can visualise the underlying hypotheses and comparisons between measured and predicted responses while also accessing detailed IFC-based geometric information and sensor data. This integration enabled a first semantic digitised version of these bridges in a twinned form for subsequent use during their life cycles. Both static and dynamic routine tests were included.

4.10. Sweden

During the last 30 years about fifteen tests on bridges have been conducted in Sweden, with five tested to failure (Elfgren et al., 2018). The work was primarily led by LTU (Luleå Technical University) and in collaboration with the Swedish Transport Administration and other universities. 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 numerical modelling. The results consistently showed discrepancies between code estimates, test results, and numerical simulations, thus prompting further developments.

The most recent work on proof loading of bridges in Sweden aims at identifying the true capacity of the existing bridges by developing tools and methods for life cycle assessment in areas of structural health monitoring (SHM), prediction simulations and tests, see Figure 15.

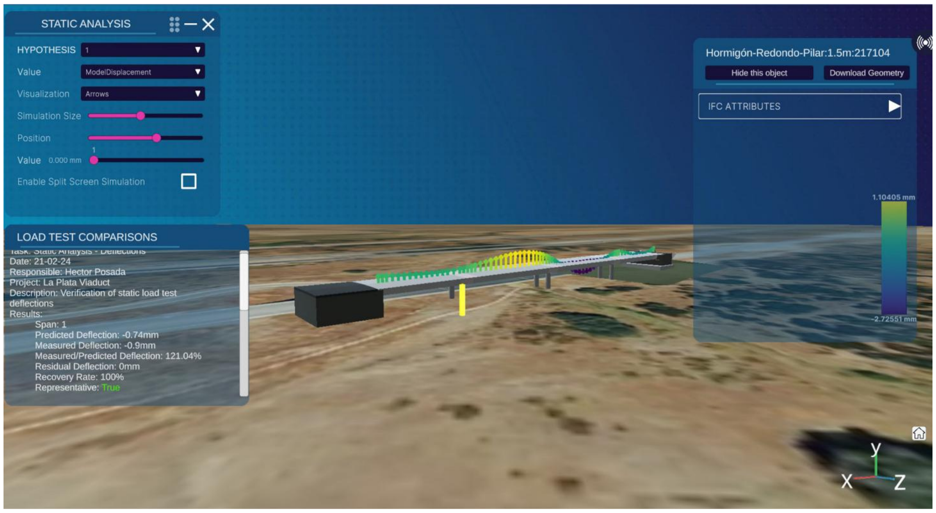

Figure 14. Digital twin of La plata Viaduct. User interface.

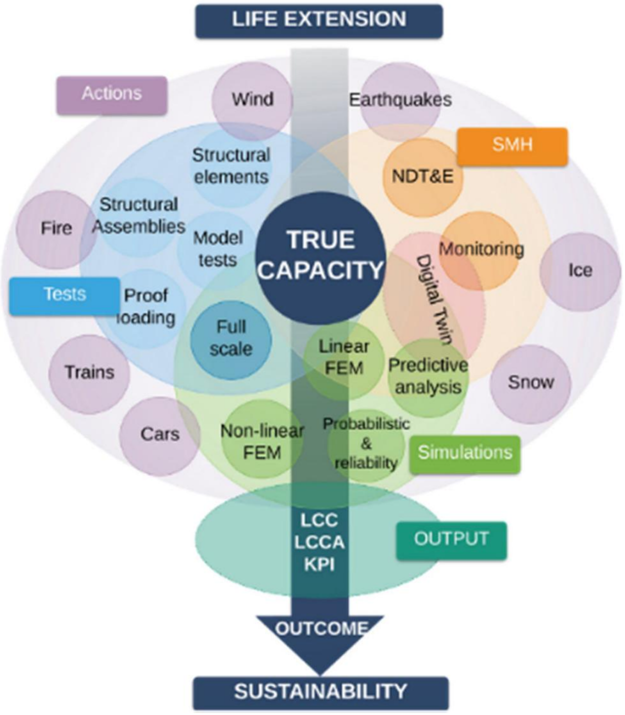

Figure 15. Concept used at luleå University of technology (LTU) for life extension of existing structures.

A 65-year-old prestressed box-girder concrete bridge in Kalix, northern Sweden, was demolished in 2022 (Figure 16). Prior to this, an experimental campaign was conducted to enhance understanding of the behaviour of such bridges. The work focused on three aspects: (1) condition assessment using non-destructive testing (NDT), (2) development of a proof loading method for assessing service limit conditions with standard convoys and SHM sensors, and (3) formulation of controlled demolition methods for prestressed concrete bridges. The bridge was decommissioned due to concerns about possible corrosion of the internal prestressing bars (Dywidag system), caused by a deficient waterproofing system in the deck slab. In addition, drivers of heavy trucks had reported over time a noticeable bouncing effect when crossing the midspan, where the cantilever tips joined, indicating potential issues with serviceability and excessive deflections.

Figure 16. View of the midspan of the kalix bridge under proof loading.

Figure 17. A section from the kalix bridge conserved for further testing.

The proof loading confirmed this linear-elastic response under service loads. However, no corrosion of the prestressing system was detected during post-mortem investigations, where material samples taken from various parts of the structure showed no significant deterioration. The NDT tools tested showed promise for detecting hidden defects, though further field validation is needed. The developed demolition process was successfully executed, ensuring safety and environmental cleanliness. A 45-tonne section of the Kalix Bridge (Figure 17) has been preserved to serve as a test object for future demonstration of NDT tools for condition assessment.

New research related to railway bridges began in 2021 with an investigation into potentially increasing axle loads from 30 to 32.5 and 35 tonnes on one of the most heavily

Figure 18. View of the full-scale trough bridge tested at the LTU lab.

utilised 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 ($7\,m \times 4\,\mathrm{m}$) in the LTU laboratory, Figure 18. A suite of sensors, including standard strain gauges, Linear Variable Differential Transformers (LVDTs), Fibre 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 utilised for benchmarking numerical analyses and subsequent parametric stochastic validation.

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. Results show that seasonal variations have great influence on the natural frequency of the bridges.

4.11. Switzerland

Recent research has been carried out on diagnostic load testing and more broadly structural health monitoring for data-informed structural safety assessment. Contributions involve the pioneering use of new sensing technologies, development of new data-interpretation tools, and information-gain prediction approaches. These methodologies almost always involved full-scale bridge applications for validation. The aim was to update safety evaluations such as

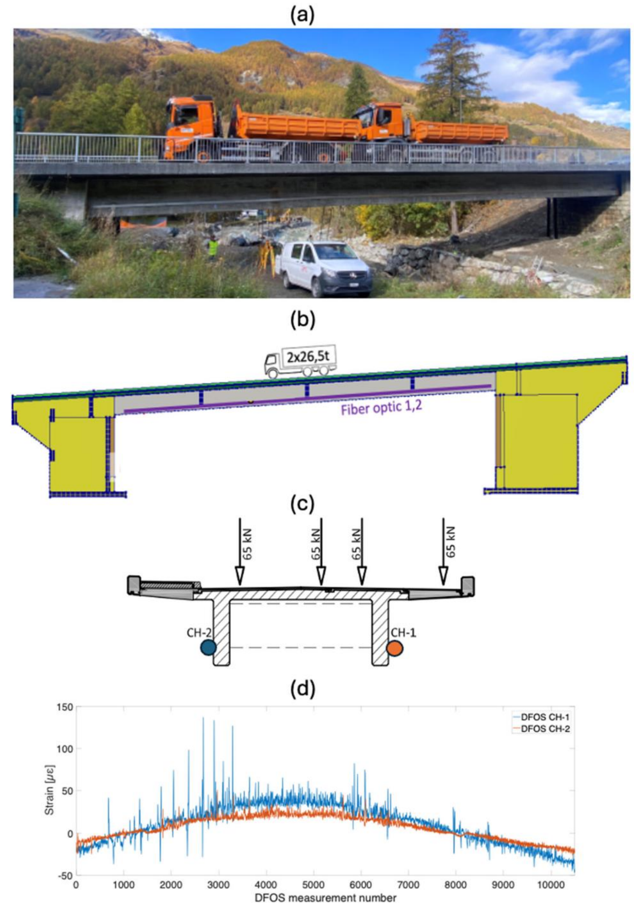

Figure 19. (a) Ferpècle bridge static load testing in october 2024, (b) bridge static scheme, (c) bridge cross-section and applied load, (d) distributed fibre optic (DFOS) datasets during the load testing.

for fatigue (Sawicki & Brühwiler, 2022), ultimate, and serviceability limit states (Bertola et al., 2023; Proverbio et al., 2018).

Novel sensing technologies, such as acoustic emission (Bayane & Brühwiler, 2020) or distributed fibre optic sensors (Bertola & Brühwiler, 2024a) have been employed on in-service bridges, see Figure 19. Several studies also enable the prediction of information gain from multiple sensing tools and monitoring goals. A sensor placement algorithm was introduced for evaluating information gain from load testing (Bertola et al., 2017). Frameworks for quantification of the value of information of SHM (Kamariotis et al., 2023), and structural identification based on load testing (Bertola et al., 2020), and combination of monitoring techniques for structural safety assessment (Bertola & Brühwiler, 2024b).

Once data are collected, new model-updating techniques (such as error-domain model falsification) have been introduced based on static diagnostic load tests, and performed multiple load testing campaigns in Switzerland and worldwide (Pai & Smith, 2022). Moreover, significant contributions have also been made on the field of vibration-based engineering for dynamic properties extraction and damage detection (Jin et al., 2022; Vettori et al., 2023). Pioneering approaches have also been introduced for physics-informed machine learning modelling of structures (Lai et al., 2021; Liu et al., 2022).

4.12. Summary of main research findings

The main research findings from the previously mentioned ongoing and recent research projects are as follows. Pilot case studies have shown that load testing of prestressed concrete bridges for serviceability limit state (USA, Italy, Poland), load testing of short-span slab bridges (Chile, the Netherlands), cable-supported bridges (Poland), strengthened bridges (Sweden, Italy) and inverted T-bridges (Denmark) is feasible. Combining diagnostic load testing with other methods for obtaining field data, such as NDE or SHM, promises to improve assessments (USA, Poland, Sweden, Switzerland). In addition, the combination of load testing with digital twins is promising (Spain).

Moreover, using concrete mechanics and laboratory experiments to derive stop criteria (the Netherlands, Denmark) makes proof load testing of shear-critical bridges without shear reinforcement possible, broadening the applicability of the methodology. In addition, novel instrumentation methods, such as acoustic emissions, digital image correlation, and fibre optic measurements, may result in richer data from a load test, which in turns improves the assessment and possibilities for insights after the test (Switzerland, Denmark, the Netherlands). Combining load testing methods and data with probabilistic analyses has been shown to successfully update the reliability index and thus directly assess the safety of a bridge (Denmark, the Netherlands, Italy). B-WIM can be used as a load testing method as well (Slovenia). These insights are used in Section 5 to identify the synergy in research and opportunities for further convergence on bridge load testing research and practice.

5. Collaboration

5.1. Role of IABMAS bridge load testing committee

The Bridge Load Testing Committee of IABMAS, the International Association for Bridge Maintenance and Safety, was inaugurated in June 2021. Its goals include, among others, exchanging information on the use of load testing in different countries, exchanging lessons learned and best practices, informing about case studies of bridge load testing, communicating load testing guides or standards that have been developed, unifying terminology and definitions associated directly with load testing of bridges, and establishing international collaborations.

To address these goals, and establish a baseline on proof load testing of concrete bridges, the IABMAS Bridge Load Testing committee is collaborating with *fib* TG 3.2 on Modelling of structural performance of existing concrete structures of the International Concrete Federation to develop a guidance document. Other committee activities include presenting information on recent research and applications of bridge load testing through the biannual committee meetings, developing mini symposia and special sessions for conferences on the topic of field testing of bridges, and collaborating with the other Technical Committees of IABMAS on topics of shared interest, such as the development of a workshop on Digital Twins for IABMAS 2026. This article reflects the recent discussions held in the IABMAS Bridge Load Testing committee and is a product of collaborations established through the committee. Interested readers can find the minutes of the activities, mission, goals, minutes of previous meetings, and current membership of the Bridge Load Testing Committee on the IABMAS website (IABMAS, 2021).

5.2. Document and code development in international collaboration

As a result of the renewed research efforts and practical interest in bridge load testing for assessment, various technical documents, codes and guidelines have been published in recent years that deserve to be highlighted here. Within the *fib* (international concrete federation), the increased interest in load testing, and in particular proof load testing (both for bridges and buildings) is reflected by a dedicated chapter in the recent *fib* Bulletin of TG 3.2 (fib TG 3.2, 2024). In addition, the latest version of the Model Code stipulates a baseline for load testing and proof load testing in §30.11.4, introducing this practice for the first time into the Model Code. For Europe, Annexe I.4.2.6.2 to prEN 1990-2 (Eurocode - Basis of structural and geotechnical design - Part 2: Assessment of existing structures) (CEN-TC 250-SC 10, 2025) will lie at the basis of the new Eurocode 0-2, which will form the overall basis for bridge load testing and associated standards in the countries where the Eurocodes are used.

Within ACI, the American Concrete Institute, the new ACI 437.2 M-22 (ACI Committee 437, 2022) code is a major change as compared to ACI 437.2 M-13 (ACI Committee 437, 2013). This document addresses proof load testing for the assessment of existing concrete buildings. The 2022 version of the code includes proof load testing of buildings for shear for the first time.

Within AASHTO, the American Association of State Highway and Transportation Officials, the upcoming version of the Manual for Bridge Evaluation will include a new Chapter 8 on Load Testing (renamed from non-destructive load testing). The contents of the new chapter align with the contents of the Primer on Bridge Load Testing (e-circular 257) (Alampalli et al., 2019) as developed by TRB (Transportation Research Board) Standing Committee AKB40 on Testing and Evaluation of Transportation Structures. This contents has also been disseminated through a workshop at TRB, a TRB webinar, and a separate webinar for the FHWA (Federal Highway Administration).

In Denmark, a guideline for proof load testing has been published (Vejdirektoratet (The Danish Road Directorate), 2025). The guideline describes to perform a proof load test on a single-span bridge for assessment of existing Danish bridges in accordance with the Danish vehicle classification

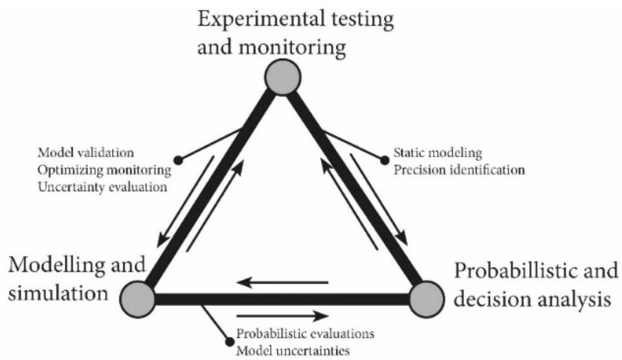

Figure 20. Synergy between research topics (Lantsoght et al., 2024).

system. This version of the guideline is expected to be updated with the insights from the second research project in Denmark.

Various international committees have included or are including load testing recommendations in their documents under development.

5.3. Synergy in research activities

Combining the discussions on recent research activities related to bridge load testing internationally, we can identify the following common themes: (1) integration with modelling of bridges, simulation aspects, and automated methods for condition assessment of existing bridges; (2) combining with new sensing techniques, laboratory testing, and monitoring aspects; and (3) research related to probabilistic aspects, decision-making and risk management. These three pillars, as identified in previous and ongoing research projects in Denmark, are sketched in Figure 20. The Danish research project has strong international collaboration, exemplifying the synergies discussed in this section.

These basic pillars of research activities carry over to applications of bridge load testing, such as novel integrations in assessment practices and validation of new bridge elements, bridge construction methods, strengthening activities, and expanding the range of applications of bridge load testing. All these activities require advanced engineering, and offer the opportunity to facilitate future studies on a tested bridges. As such, all load tests become a moment for a bridge to become digitally competent. In Chile, the research focus is on the use of new concrete components such as the use of Void former, instrumentation and data acquisition linked to BIM methodologies and studying the seismic effect and scour.

Other examples of synergy in research activities related to the application of bridge load testing include the interest in extending the application to larger bridge, such as post-tensioned bridges, evidenced by the collapse test of the Vecht Bridge in the Netherlands (Ensink et al., accepted for publication), the extension to cable-stayed bridges in Poland, and the application to prestressed bridges in Italy (Addonizio et al., 2024). Bridge load testing occurs under constraints of time and budget. As such, sharing experiences, as facilitated through the IABMAS Bridge Load Testing and through international collaborations, is to the benefit of all. In particular, a synergy of activities can be found between the researchers from the countries represented in this article for the following topics:

- solving practical challenges related to application of loading and sensors when multiple spans need to be tested, without needing to purchase large numbers of sensors;
- determination of the required number of load positions such that sufficient redundancy occurs in the data, without incurring large costs and lengthy bridge closures for the test,
- extrapolation of results from one span to another span for an assessment by studying the spatial variability and systems reliability considerations,
- 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, including the value of information from measurements during the test to lower the target proof load, and
- developing best practice guidance for different bridge typologies.

5.4. Embedding load testing research in bridge assessment and management

Various countries are working on implementing bridge load testing into their bridge management programs. Figure 14 shows the digital twin of the La Plata viaduct as developed in Spain. Soft Load Testing has since become an integral part of Slovenia's bridge management and monitoring efforts, complementing newer methods such as dynamic monitoring and advanced sensor networks. Today, Slovenia continues to leverage SLT and B-WIM technologies to ensure the safety and longevity of its bridge infrastructure.

In the Chilean programme, 'Monitoring Challenge', led by the Ministry of Public Works, an applied research programme was conducted for two bridges: Seminario and Tolten. The use of visual inspection, drones, satellite imagery, non destructive testing and structural health monitoring were combined to determine the current condition and remaining useful life. The incorporation of load tests was fundamental, providing baselines of the bridge condition. In particular, the Ministry carried out static tests, and then the university partner carried out dynamic tests that complement fatigue studies on the main beams of the bridge. This experience allowed it to be used as additional information for the bridge asset management platform, allowing authorities to make decisions. For these case studies, structural modelling was carried out, loading now to integrating these results into platforms using digital twins.

Future work related to combining field testing methods (including bridge load testing, non-destructive evaluation results, and long-term structural monitoring) and numerical models into a single platform is necessary to take full advantage of the generated information and to get a richer image through data fusion of the various sources of information

(Lantsoght et al., 2025). It is expected that such efforts, through the use of digital twins, will provide bridge owners better tools in the future to visualise the condition of their existing bridges.

6. Discussion

Comparing the assessment practices from various countries shows that a large variety of approaches are used. Some countries centre their assessment around numerical analysis, focusing on verifying if a certain bridge can carry the loads prescribed by the current codes, whereas other countries focus on condition assessment based on visible or measured signs of deterioration of the structure. The practice of bridge load testing is unevenly distributed between the various countries. We can distinguish between countries that have a long-standing tradition of load testing of bridges prior to opening, where engineers are more familiar with the practice of bridge load testing, yet universally we can identify the increased and renewed interest in bridge load testing, as a means to assess existing bridges.

Due to the higher risk involved, potential traffic impact, and uncertainties on the procedures, as well as a lack of generally accepted codes and guidelines for bridge load testing for assessment, this method may be underutilised at the moment. Bridge owners may be reluctant to apply the method, for example for non-shear-reinforced shear-critical concrete structures, as well as cast iron and arch bridges. However, the various examples of successful applications as highlighted in this article form a broad basis of the use of the methodology for different assessment purposes, abiding by different national practices. As such, the broad applicability demonstrated in this paper can form the basis for future unified guidelines as well as examples for bridge owners to show the viability of bridge load testing for assessment. Bridge load testing determines the effect of the traffic loading, or, for the case of proof load testing, determines the assessment of the critical section directly. In only very few cases is testing carried out to determine the effect of the self-weight. Jacking at the supports can be used to determine the support reaction, but requires very careful operation, is not carried out regularly, and will only in specific cases result in the necessary information to assess an existing bridge.

While national assessment methodologies, as well as requirements, vary broadly, there are general underpinnings that one can identify between the various countries presented in this paper. The importance of these topics is identified by the synergy between the ongoing research projects. Examples of these topics are:

- monitoring techniques and application of new sensor types during load testing,
- sufficient number of intermediate steps before reaching the target proof load,
- integration with numerical models and digital twins,
- embedment into a methodology for assessment (often based on various levels of approach),
- interpretation during the test and definition of stop criteria,
- alignment with data from other investigation methods (such as information obtained from visual inspections, inspections using NDT, and long-term monitoring campaigns), and
- linking the practice of proof load testing to the structural reliability requirements of the codes and standards.

Finally, this article shows the role of international collaboration in the field of bridge assessment, applied to the practice of bridge load testing. While national practices differ, comparing lessons learned and successful applications, as well as strong international collaborations (such as evidenced, among others, by the ongoing collaboration between Denmark and the Netherlands, including exchange of test data), are key ingredients to develop solid recommendations for practice. In turn, with solid recommendations for practice, bridge load testing can be implemented in countries that currently do not use this methodology for bridge assessment, and more bridges may be found not to need strengthening or replacement, resulting in significant economic and ecological benefits. It should be noted, however, that bridges may be demolished for other reasons than strength or performance criteria, such as for example those that have become functionally obsolete.

7. Conclusions

To avoid disruptions in the flow of traffic and goods, the management and maintenance of infrastructure is crucial. Bridge assessment to understand the status of an existing bridge is an important practice here, and both diagnostic and proof load testing are tools that bridge engineers can use. This paper introduces bridge assessment practices internationally, how bridge load testing in used in various countries, recent research internationally on the topic, and the path forward in finding synergy between these research efforts to develop practical recommendations for bridge owners as well as the industry.

Based on the insights collected in this collaborative paper, the following can be concluded:

- The use of bridge load testing as a tool for assessment is gaining more attention in recent years internationally. While originally used only for the acceptance of new bridges in certain countries, the methodology now has broader usage geared towards assessment of existing bridges internationally. And, while used originally mostly in a research context, we see a gradual shift to the industry.
- Various successful case studies and applications of bridge load testing show the usefulness of the methodology for the assessment of existing bridges.
- Generally, diagnostic load tests are more commonly used for assessment than proof load tests. However, recent research efforts in various countries have shown that

proof load tests can be cost-efficient for bridges with large uncertainties.

- The main topics of recent research include: monitoring techniques and application of new sensor types during load testing, integration with numerical models and digital twins, embedment into a methodology for assessment (often based on various levels of approach), interpretation during the test and definition of stop criteria, alignment with data from other investigation methods (such as information obtained from visual inspections, inspections using NDE, and long-term monitoring campaigns), and linking the practice of proof load testing to the structural reliability requirements of the codes and standards.
- To develop practical recommendations, collaborative efforts and exchange of ideas, as exemplified in this paper, are the way forward. In this context, the activities of the IABMAS Bridge Load Testing Committee can be highlighted, as this committee aims to foster international collaboration.

Finally, this paper may serve as a baseline of collecting information internationally about bridge load testing practices, and a foundation for increased convergence between the different national approaches.

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Data availability statement

No new data was generated for this research

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