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Bridge Load Testing: State-of-the-Practice

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Abstract

Bridge load testing can answer a variety of questions about bridge behavior that cannot be answered otherwise. The current governing codes and guidelines for bridge load testing in the USA are the 1998 NCHRP *Manual for Bridge Rating through Load Testing* and Chapter 8 of the AASHTO *Manual for Bridge Evaluation*. Over the past two decades, the practice of load testing has evolved and its intersections with other fields have expanded. The outcomes of load tests have been used to keep bridges open cost-effectively without unnecessarily restricting legal loads, when theoretical analyses cannot yield insights representative of in-service performance. Load testing data can be further used to develop field-verified finite element models of tested bridges to understand these structures better. Additionally, structural reliability concepts can be used to estimate the probability of failure based on the results of load tests, and non-contact measurement techniques capturing large surfaces of bridges allow for better monitoring of structural responses.

Given these developments, a new TRB Circular, *Primer on Bridge Load Testing,* has been developed. This document contains new proposals for interpreting the results of diagnostic load tests, loading protocols, and the determination of bridge load ratings based on the results of proof load tests. In addition, included provisions provide an estimation of the resulting reliability index and the remaining service life of a bridge based on load testing results. The benefit of load testing is illustrated based on a cost-benefit analysis. The current state-of-the-practice has demonstrated that load testing is an effective means for answering many important questions regarding bridge behavior that are critical to decisions on bridge maintenance or replacement. Load testing has evolved over its history, and the newly developed TRB Circular reflects this evolution in a practical way.

CE database subject headings

bridge maintenance; bridge tests; codes and guidelines; instrumentation; field tests; load testing

Introduction

Load testing was originally used to convince the traveling public that a bridge was safe for use (Schacht et al., 2016). While some countries still require a load test on all or certain cases of newly constructed bridges, now load testing is mostly used for the assessment of existing bridges where routine analysis methods fail to represent their in-service performance. Recent applications of load testing also include developing of field-verified finite element models (Barker, 2001), evaluating the effect of material damage on bridge performance (Koekkoek et al., 2015), assessing bridges without design plans (Aguilar et al., 2015; Anay et al., 2016; Shenton et al., 2007), evaluating strengthening measures (Nilimaa et al., 2015; Puurula et al., 2015; Shifferaw and Fanous, 2013), analyzing heritage bridges (Coletti, 2002; Moen et al., 2013; Orban and Gutermann, 2009), evaluating the contribution of additional load-carrying mechanisms such as arching action (Taylor et al., 2007), evaluating new materials (Alampalli and Kunin, 2002; 2003; Alampalli and Hag-Elsafi, 2013; Hag-Elsafi et al., 2002; Hag-Elsafi et al., 2004), determining remaining fatigue life (Alampalli and Lund, 2006), and verifying design assumptions of new bridges (Yannotti et al., 2000).

Depending on the load application, static and dynamic load tests can be distinguished. Two types of static load tests are generally used: diagnostic load tests and proof load tests (Lantsoght et al., 2017b). Diagnostic load tests (Fu et al., 1997; Hernandez and Myers, 2018; Jáuregui and Barr, 2004; Kim et al., 2009) are used to measure structural responses under known (externally applied) loads. These responses can then be interpreted to gain insight in the overall behavior of the bridge, determine specific elements of the bridge behavior (composite action with the deck, transverse distribution etc.), and/or to develop a field-verified model for its capacity/demand ratios or rating. Proof load tests (Aguilar et al., 2015; Anay et al., 2016; Casas and Gómez, 2013; Lantsoght et al., 2017a) apply a target load to directly demonstrate that a bridge can carry the code-prescribed live loads without signs of distress. If the bridge shows signs of distress before the target proof load is reached, then the bridge may still be able to remain in function for lower load levels, depending on the maximum load that could be applied during the proof load test.

The provisions for load testing in the USA are given in Chapter 8 of the Manual for Bridge Evaluation, MBE (AASHTO, 2016), which is based on the 1998 Manual for Bridge Rating through Load Testing, MBRLT (NCHRP, 1998). The 1998 document in turn is based on research from the late 1980s and 1990s. Since then, the practice of load testing of bridges has changed significantly. Improvements related to cellular communications technology, wireless techniques, and sensing and data acquisition technology have made gathering, sending, and storing data (such as structural responses) more accessible. In addition, the more widespread use of finite element models in conjunction with higher-speed computing has resulted in vastly improved methods for combining analytical models and field tests. Advances in the development and use of sensors that take distributed measurements (or a large collection of point measurements to approximate a distributed measurement) have resulted in the ability of capturing the structural response of an entire line or surface of a structure during a load test, instead of a single measurement point. Finally, unifying codes based on a probability of failure of a structure also has resulted in combining the concepts of structural reliability with applied proof loads. The current provisions for load testing do not reflect this state-of-the-practice. Therefore, members of TRB Standing Committee on Testing and

Evaluation of Transportation Structures (AFF40/AKB40) have developed the *Primer on Bridge Load Testing* as an updated guidance document. This paper describes the need for a document such as the *Primer*, the current state-of-the-practice, recent advances in bridge load testing research, and how these elements are summarized in the *Primer* to form a practical guidance document.

Current governing codes and guidelines

Manual for Bridge Rating through Load Testing

The Manual for Bridge Rating through Load Testing (MBRLT) (NCHRP, 1998) is based on research carried out during the late 1980s and the 1990s. This manual describes procedures for conducting a nondestructive load test and load rating of a bridge based on a load test. The aim of the MBRLT was to establish realistic safe service live load capacities for bridges. This goal can be achieved through diagnostic or proof load tests. The outcome of the test is then used for rating the bridge under consideration. The MBRLT discusses factors that influence the load-carrying capacity: unintended composite action, load distribution, participation of parapets, railings, curbs and utilities, differences in material properties, unintended continuity, participation of secondary members, the effect of skew, the effects of damage and deterioration, the unintended arching action due to frozen bearings, and the load-carrying capacity of the deck. The MBRLT also contains an extensive discussion of available equipment for measuring structural responses during a load test, reflecting the state of the practice in the 1990s. Examples are included, and the background for determination of the target proof load based on concepts of structural reliability is included as an attached technical report.

Manual for Bridge Evaluation – Chapter 8

The MBRLT forms the basis of Chapter 8 of the Manual for Bridge Evaluation (MBE) (AASHTO, 2016). Using the concepts of load and resistance factor rating (LRFR), the rating factor *RF* becomes:

$$RF = \frac{C-(\gamma_{DC})(DC)-(\gamma_{DW})(DW)\pm(\gamma_P)(P)}{(\gamma_{LL})LL(1+I)} \tag{1}$$

where the capacity *C* for the Strength Limit States is determined as:

$$C = \varphi_c \varphi_s \varphi R_n \text{ with } \varphi_c \varphi_s \geq 0.85 \tag{2}$$

In Eq. (2), R_n is the nominal member resistance as inspected. For the Serviceability Limit States, the capacity *C* is determined as:

$$C = f_R \tag{3}$$

where f_R is the allowable stress specified in the LRFD Code (AASHTO, 2015).

For diagnostic load tests, the rating factor based on the test result is determined according to comparison of the analytically determined strain to the measured strain at the position of the maximum measured strain. The procedure for determining the rating factor based on diagnostic load test results RF_T is based on multiplying the rating factor prior to the test RF_C with an adjustment factor *K*:

$$RF_T = RF_c \times K \tag{4}$$

The adjustment factor *K* is calculated by multiplying K_a, the benefit derived from the load test, and K_b, a factor that accounts for differences between the actual behavior of the bridge and the revised analytical model with regard to lateral and longitudinal load distribution and the participation of other members.

$$K = 1 + K_a \times K_b \tag{5}$$

The benefit from the load test K_a is determined based on the ratio of the maximum measured strain during the test ε_T and the corresponding analytically determined strain ε_c.

$$K_a = \frac{\varepsilon_c}{\varepsilon_T} - 1 \tag{6}$$

The factor K_b for the differences between the actual behavior of the bridge and the revised analytical model contains the contributions of K_{b1}, which reflects if the test measurements can be directly extrapolated to bridge performance at higher load levels, K_{b2}, which accounts for the ability of the inspection time to identify problems that could invalidate the test result, and K_{b3} for the presence of critical structural features which cannot be determined in a load test.

$$K_b = K_{b1} \times K_{b2} \times K_{b3} \tag{7}$$

Alternatively, a proof load test may be used to update a load rating. The rating factor at the Operating Level RF_O after a proof load test is determined as:

$$RF_O = \frac{OP}{L_R(1+I)} \tag{8}$$

with L_R the comparable live load due to the rating vehicle for the lanes loaded. The capacity at the operating level OP is determined based on the maximum applied load during the proof load test L_P, with k_O = 1.0 when the target proof load L_T is achieved and k_O = 0.88 if the test was stopped prematurely because distress or nonlinear behavior was observed:

$$OP = \frac{k_O L_P}{X_{PA}} \tag{9}$$

The target proof load L_T is determined on L_R and the magnification factor X_{PA}:

$$L_T = X_{PA} L_R \left(1 + I\right) \tag{10}$$

with the magnification factor X_{PA} between 1.3 and 2.2. The factor X_{PA} equals $X_P = 1.4$ multiplied by adjustments Σ% as given by the MBE:

$$X_{PA} = X_P \left(1 + \frac{\Sigma\%}{100}\right) \tag{11}$$

International practice

Several countries have national codes or guidelines for load testing. Some of these national guidelines are application specific. The German guideline (Deutscher Ausschuss für Stahlbeton, 2000), was developed for proof load testing of plain and reinforced concrete structures that are flexure-critical. The guideline for load testing from the United Kingdom (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges, 1998) only deals with diagnostic load testing (called supplementary load testing in the UK guideline) as an integral part of the overall assessment procedure for existing bridges. This guideline was originally developed to assess existing bridges when the 40 tonne (88 kip) truck was introduced in the UK. Similarly, the Irish manual for load testing (NRA, 2014) considers diagnostic load testing of older metal and concrete bridges as an accompaniment to assessment calculations. In Switzerland, load testing is used for assessment of existing bridges and is included in the SIA 269:2011 code (SIA, 2011). Poland has guidelines (Research Institute of Roads and Bridges, 2008) to verify if a vehicle of “abnormal weight” above the design live load can be carried by a certain bridge (Halicka et al., 2018). In Hungary, the serviceability of existing structures can be verified through load testing (Hungarian Chamber of Engineers, 2013).

In other countries, load testing is primarily used to demonstrate that an as-built structure performs as it was designed. In France, all new bridges (including pedestrian bridges) must be subjected to a diagnostic load test prior to opening (Cochet et al., 2004). Simplified procedures for rigid frame bridges, slab bridges, and girder bridges are provided. Similar requirements for load testing prior to opening and after widening or rehabilitation exist in Spain (Ministerio de Fomento - Direccion General de Carreteras, 1999; Ministerio de Fomento, 2009; 2010) for highway and pedestrian bridges. In the Spanish practice, static load tests are required for all bridges longer than 12 m (39 ft), dynamic load tests are required for concrete bridges with a span length over 60 m (197 ft), pedestrian bridges, bridges with an unusual design, and bridges using new materials. Diagnostic load testing of road bridges prior to opening is common in Italy as well (Veneziano et al., 1978; Veneziano et al., 1984a; b). In Switzerland, every major bridge is load tested prior to opening (Moses et al., 1994).

Extensive guidelines (Frýba and Pirner, 2001; Kopácik, 2003) for static and dynamic load testing of railway and road bridges (upon opening and for assessment purposes) exist in the Czech Republic (Český normalizační institut, 1996) and Slovakia (Slovak Standardization Institute, 1979). These guidelines contain both stop criteria and acceptance criteria, and apply to reinforced concrete, prestressed concrete, and steel bridges.

Practical need for updating current codes and guidelines

Most highway bridges in the United States are required by federal law (US Code of Federal Regulations, 2011) to be inspected on a biennial basis. The primary purpose of these bridge inspections is to provide public safety through assuring that bridges have enough capacity to carry the loads allowed on them (Alampalli and Jalinoos, 2009). Hence, during these inspections, most owners document the changes to bridge condition (such as increased weight due to overlays) and bridge deterioration (such as section loss) that can affect the bridge capacity. Using this data, live load carrying capacity of the bridge is updated and compared to the effect of live loads allowed on it. In the case of demand exceeding capacity, a bridge is restricted to less than what would otherwise be legal loads for the highway it serves (known as “load posting”, or simply “posting”); or, if needed the bridge is closed to traffic until improvements are made to increase its capacity. Such disruptions can cause inconvenience and increased costs to public due to detours or congestion. Thus, estimating the capacity of the bridge in its existing condition is very important to assure the ongoing safety and mobility of the traveling public.

As noted in earlier sections, structural analysis is generally used for load rating existing bridges. In some cases, where owners believe that analysis does not represent the true capacity of the structure (due to, for example, limitations in ability to model a particular deterioration mode in software, or a lack of as-built plans or other documentation needed to build a usable computational model), load testing provides an alternative means to obtain the capacity of the structure in its current condition. A survey (Wang et al., 2009) conducted for the Georgia Department of Transportation in 2009 found that only fourteen of the forty-one responding states performed some form of load testing as part of bridge evaluation practice. Five other states reported that they had once performed very few load tests for the reason of academic research; the remaining states had never used load testing as a tool for bridge condition assessment. Most of the load tests mentioned in survey responses were performed (1) to re-evaluate the capacity of bridges in good condition, but with sufficiently low capacity per typical analysis methods as to require load postings, (2) to evaluate bridges constructed using novel materials such as fiber reinforced polymers, or (3) on bridges without as-built plans or design documentation, or with serious deterioration that prevented an accurate theoretical strength calculation. The report also found that methods based on the NCHRP (1998) report were still in use by many respondents; only one state employed the AASHTO LRFR Guide Manual (2003).

Even though load testing is widely recognized as a load rating method, as noted above, its use has been relatively limited by many highway agencies. This suggests that an update is required to the NCHRP 1998 based methodology to incorporate knowledge gained since its writing and also to illustrate its use through case studies to encourage owners to perform load testing, as needed, as an alternate method of load rating. Furthermore, in the absence of a clear value proposition for load testing, the initial costs of testing may deter some owners. As previous guidance documents have not included a method to calculate the value of load testing, a simple, rational way to perform a benefit-cost analysis is needed. Given that all highway agencies use the LRFD approach and are moving towards the LRFR approach, guidance to update the reliability index after a load test, considering the uncertainties associated with the structure performance as well as load test, is also needed, along with a method to estimate remaining service life.

Current practice of bridge load testing

Diagnostic load testing

In diagnostic load testing, see for example **Figure 1**, the actual responses of key structural components, in terms of measured strains, deflections, rotations, etc., to known test loads are measured. Typically, an analytical model, based on best available information, is developed for comparison with the load test results. After the analytical model is adjusted and validated against the test results, it can be used to predict structural behaviors for a variety of purposes, including to assess the maximum load effects of dead load and all required rating vehicles. In order to calculate refined bridge load ratings through diagnostic load testing, member capacities must still be quantified based on section and material properties per construction documents, field measurements, or through in-situ material testing. Load factors must also be applied according to the applicable code.

Figure 1. Diagnostic load test on a rural one-lane concrete slab bridge

Diagnostic load testing has gradually gained wider acceptance among bridge owners as a refined method for bridge load rating, especially when simplified analytical methods suggest unreasonably low ratings or the need for load posting in conflict with the actual condition and loading history of the structure. Diagnostic load testing has also been used to identify specific structural behavior concerns such as live load distribution, connection stresses, unintended composite actions, support conditions, and so on.

Proof load testing

Proof load testing (see for example **Figure 2**) physically demonstrates the bridge's ability to carry its full dead load plus some magnified live load. Test loads are applied to the bridge in multiple steps using loading and unloading process in a progressively increasing manner towards a predetermined target proof load. The target proof load is established to be sufficiently higher than the rating vehicles in order to include a live load factor for the required margin of safety and to account for the effects of dynamic impact. During each loading and unloading step, key responses of the structure are measured and monitored for possible signs of distress or non-linear-elastic behavior. Upon successful completion of a proof load test, the highest applied load provides a lower bound on the true strength capacity, which leads to a lower bound bridge load rating after incorporating proper load factors and dynamic load allowance.

Compared with diagnostic load testing, proof load testing yields more reliable results on the load carrying capacity of the tested structure. It requires a reduced level of structural analysis without the need to calculate section capacities or the maximum force effects of dead and live loads. The primary result from a proof load test is to conclude whether the rating factor for a specific vehicle type exceeds 1.0 at the operating level of reliability. However, if load ratings for vehicle types other than the test vehicle are needed, a structural analysis will be required to compare the load effects of the rating vehicles with those of the test vehicle.

Figure 2. Proof load test on bridge with cracks in overlay along joints of the box beams

In-service application of bridge proof load testing is less common than diagnostic load testing, primarily due to the following reasons: first, test loads exceeding the service load level involve risks; second, implementation of a multi-step loading and unloading process using high loads requires proper planning, suitable equipment, close monitoring, as well as knowledge, experience and judgement.

Recent advances in bridge load testing

Integration with structural reliability

Structural reliability analysis provides a rigorous framework to quantify and compare the safety margins of different structural designs (Ang et al., 2007). It has been widely used to develop and calibrate design guidelines for bridge structures. Uncertainties associated with structural capacity may arise from design models, material properties, and fabrication and construction processes, among others. Uncertainties associated with structural demand may stem from the weight and configuration of heavy vehicles, operating speed, and road surface, among others. Structural reliability analysis considers uncertainties involved in both structural capacity and structural demand to evaluate the probability of failure. Mathematically, this probability of failure can be expressed as

$$P_{fb} = \Pr[R - S < 0] = \int_{0}^{+\infty} \big(1 - F_S(r)\big) f_R(r) dr \tag{12}$$

where R and S are the random variables representing structural capacity and structural demand, respectively; $F_S(\cdot)$ and $f_R(\cdot)$ are the cumulative distribution function (CDF) and the probability density function (PDF) of R and S, respectively. Due to the low probability of failure of civil structures, this probability as determined in Eq. (12) is usually expressed as the reliability index β. The relation between the probability of failure and the reliability index is:

$$P_{fb} = \Phi(-\beta_b) \tag{13}$$

Where, $\Phi(\cdot)$ is the CDF of standard normal distribution.

Traditionally, evaluation of existing bridges follows a deterministic approach where the aforementioned uncertainties are not explicitly considered. The MBE (AASHTO, 2016) allows for allowable stress rating (ASR), load factor rating (LFR), and load and resistance factor rating (LRFR). ASR and LFR are inherited from the 1994 edition of the Manual for Condition Evaluation of Bridges (AASHTO, 1994). These deterministic approaches lack structural reliability analysis and, consequently, may not ensure a consistent level of safety margins across different bridges and different limit states. On the other hand, LRFR, though still following a deterministic procedure, is a semi-probabilistic approach that does consider uncertainties involved and uses structural reliability analysis to calibrate load and resistance factors. The clear emphasis on LRFR in the 2018 MBE indicates the intended integration of structural reliability and load rating.

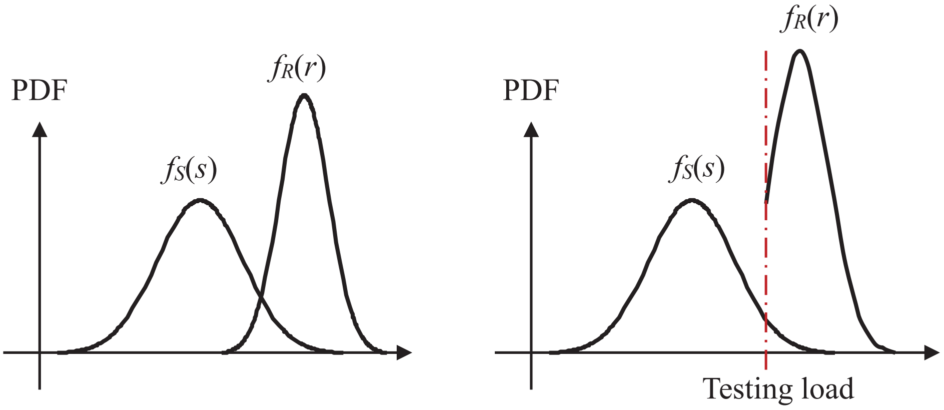

Figure 3. Effect of load testing from structural reliability standpoint

The most direct effect of load testing on structural reliability is to reduce the uncertainty of structural capacity. Passing a load test indicates that the structural capacity of the tested bridge is at least equal to the load effect associated with the testing load. This information can be used to refine the distribution of structural capacity (as illustrated in Figure 3) and ultimately update the probability of failure of an existing bridge. The benefit of load testing to structural reliability can be represented as follows (Frangopol et al., 2019):

$$P_{fa} = \Pr\left[R - S < 0 | R > s_p\right] = \int_{s_p}^{+\infty} \left(1 - F_S(r)\right) \frac{f_R(r)}{1 - F_R\left(s_p\right)} dr \qquad (14)$$

where P_{fa} is the probability of failure after passing a load test; s_p is the load effect associated with the testing vehicle.

Cost-benefit analysis of load testing

Comparing Eqs. (12) and (14), it can be realized that by providing confirmative information on structural capacity, a load test can reduce the probability of failure of a bridge. This increased confidence in structural safety can be converted to an economic benefit using risk analysis. In particular, the value of passing a load test (V_{LT}) can be quantified as:

$$V_{LT} = Ri_b - Ri_a = \left(P_{fb} - P_{fa}\right)C_F \tag{15}$$

where Ri_b and Ri_a are the risks of structural failure before and after passing a load test; C_F is the failure cost. Other benefits of load testing may include validation and calibration of structural models and gaining public confidence in structural safety.

Despite the various benefits of load testing, it may bring in additional cost in the form of direct operation cost and indirect failure/damage risk. The former includes expenses associated with preparation, execution, and analysis of a load test, while the latter represents expected losses due to potential structural damage/failure during a load test. The overall cost associated with a load test can be expressed as:

$$C_{LT} = C_{op} + \sum_{i=1}^{n_d} p_{d,i}C_{d,i} + P_{fd}C_F \tag{16}$$

where C_{op} is the direct operation cost associated with a load test; n_d is the number of damage states that are likely to be reached after an unsuccessful load test; $p_{d,i}$ is the probability of falling into damage state i after the load test; $C_{d,i}$ is the remedy cost associated with damage state i; P_{fd} is the probability of failure during a load test.

For a prescribed design service life, a proof load test during the service life of a bridge can be more informative than that at the beginning (Ellingwood, 1996; Faber et al., 2000; Olaszek et al., 2014). This is particularly true when a service load history is available, e.g. from weigh-in-motion (WIM) records (Fiorillo and Ghosn, 2014). Therefore, a cost-benefit analysis for planning load tests should be incorporated into the life-cycle cost analysis of a bridge. The total life-cycle cost of a bridge can be expressed as (Frangopol et al., 1997):

$$ELCC = C_T + EC_{PM} + EC_{INS} + EC_{REP} + EC_F \tag{17}$$

where $ELCC$ is the expected life-cycle cost; C_T is the initial cost; EC_{PM} is the expected cost of routine maintenance; EC_{INS} is the expected cost of inspections; EC_{REP} is the expected cost of repair; EC_F is the expected failure cost (i.e. failure risk). Decisions on maintenance activities in the structural service life should minimize the expected life-cycle cost while keeping or maximizing the safety margin of a structure. This optimization problem is usually analysed using an event-tree model and solved with multi-objective evolution algorithms (Yang et al., 2019). Load testing costs can be assimilated into inspection costs since both can provide information related to structural capacity. Nonetheless, the difference between a load test and an inspection action is that the former may induce structural damage or even failure. This possibility should be included in the event-tree model of life-cycle analysis.

In recent years, cost-benefit analysis of infrastructure projects has been moving towards a sustainability-informed approach in which social and environmental costs are also taken into account in addition to the traditional economic cost (Frangopol and Soliman, 2016; Frangopol et al., 2017). The social cost includes the delay and detour costs for traffic users as well as the derivative costs from the reduction in accessibility (e.g. loss of business). Estimation of social cost usually requires analyses of road networks and the surrounding communities (Yang and Frangopol, 2018). The environmental cost usually includes evaluation of climate change potential in terms of greenhouse gas emissions (García-Segura et al., 2017), energy consumption (Sabatino et al., 2015), as well as project-related pollution to soil, water, and air (Wang et al., 2019). Although there is a lack of consensus on how to conduct sustainability-informed asset management, multi-attribute utility theory has proven to be an effective tool to combine all three aspects of sustainability based on the risk perception and risk attitude of decision-makers (Liu et al., 2018; Sabatino et al., 2015; 2016).

Advances in measurement techniques

Recently, significant advances have occurred in the areas of data measurement, collection, storage, and visualization. Many of these advances improve the process of performing a specific bridge test, and others help to minimize errors and general difficulties of field testing.

For example, self-identifying transducers and wireless transducers can aid in speed of setup for any test. Data acquisition systems have improved in both precision and speed of measurement. Perhaps of greatest aid to the field-testing engineer are improvements in analysis software and real-time visualization. On-the-fly data processing and analysis supported by these tools help to reduce, or even eliminate, common data collection or post-processing problems that may be otherwise revealed after demobilization from field testing.

It is useful to examine instrumentation, data acquisition, and data aggregation developments from related fields such as long-term structural health monitoring (SHM), geotechnical instrumentation, surveying/geodesy, geographic information systems (GIS) and so on for synergies with bridge load testing. Types of measurements required, and, accordingly, appropriate data acquisition rates and intervals, may vary considerably between bridge load testing and these and other related fields, but many underlying principles are relevant. For example:

- **Consideration of long-term stability of sensors.** Typically, bridge load tests are conducted over relatively short time spans (hours) compared to long-term structural or geotechnical monitoring projects. Such long-term exposure to the elements and service loads may serve as a kind of overall durability test for sensors and sensing technologies employed in bridge load tests – with the caveat that long-term SHM deployments do not entail repeated application and removal of sensors as is likely to occur over years of periodic short-term bridge load tests. Statistical methods (e.g. (Chen et al., 2014) have been proposed to monitor performance of sensors themselves within the context of structural monitoring.
- **Development of robust data aggregation strategies**. Long-term structural/geotechnical monitoring systems for complex projects may include tens or hundreds of individual measurement devices based upon varied sensing technologies and data acquisition schemes. For example, an SHM system might include different sensors – or readings from the same sensors at different sample rates – to capture different kinds of structural outputs (e.g. strain, rotation, displacement), or quasi-static versus dynamic structural response (e.g. (Kosnik, 2012; Kosnik and Dowding, 2015)). Similarly, a load test on a complex structure, or with complex stop conditions, requires careful consideration of multiple signal types: for example, a test based mostly on strain, but with a deflection-based stop criterion, would require both strain and displacement measurements. Integration of these measurements into a synoptic view of structural response is not

particularly difficult if designed into the load test a priori. However, waiting until the data are taken and the field team is de-mobilized before considering a data aggregation plan may make data interpretation unnecessarily complicated, and could even make trends less visible to analysts.

- **Novel, or at least new-to-load-testing measurements.** Non-contact measurement devices from surveying and geodesy, such as total stations, differential GPS, and laser rangefinders, may facilitate acquisition of deflection data on bridges over deep gorges or other situations where there is not a convenient, stable reference for deflection measurement
- **Full-field measurement techniques**. As the resolution and performance of field-ready cameras and image processing equipment improves, it may be practical for full-field measurement techniques such as structured light imaging or digital image correlation to be widely adopted. These methods can provide two- or three-dimensional analyses of strains or displacements, as well as characterize cracking or spalling – a useful complement to the point measurements provided by strain gauges or displacement sensors. Full-field techniques may be particularly useful on concrete and masonry, where material heterogeneity makes it necessary to employ long gauge lengths to obtain reasonable measurements of average strain.
- **Visualizing results in space and time.** On large bridges, or on networks of bridges serving a given transportation corridor, it may be useful to visualize the load test data using GIS tools or other spatially-aware database systems. In the GIS scheme, sensors (or their corresponding measurements) are associated with a particular physical location,

with measurements varying over time and displayed accordingly. This approach may promote faster identification of areas of note and may also promote interoperability with bridge owners' existing asset management software. Examples of highly scalable GIS-aware infrastructure and environmental monitoring include the US Army Corps of Engineers National Levee Database (US Army Corps of Engineers, 2019) and the US Geological Survey National Streamflow Information Program (Eberts et al., 2019), respectively.

- **Archival data and data interoperability.** Particularly with publicly-owned infrastructure such as highway bridges, test data should be reported and stored in well-documented open format that will be readily digestible by future users, as opposed to (for example) data formats unique to a particular proprietary software suite for which support might end before the data are used again. A variety of schemes based on XML, e.g. SensorML, promulgated by the Open Geospatial Consortium (Open Geospatial Consortium, 2014), or relational databases (e.g. (Kosnik and Henschen, 2013)) have been proposed, each with particular advantages and disadvantages. Whatever scheme is adopted for data archival, care should be taken to ensure that the next team to conduct a test on a particular bridge will have practical access to past instrumentation data.

Introducing the *Primer on Bridge Load Testing*

Proposed approach for diagnostic load testing

The diagnostic load testing approach presented in the *Primer* on Bridge Load Testing differs significantly from the current AASHTO MBE – Chapter 8 (AASHTO 2016) guidelines. The MBE

Chapter 8 approach is based upon calculation of an adjustment factor *K* from load test results. *K* represents the ratio between the estimated analytical strain versus the measured strain, as was shown in Eq. (6). This “K-factor” approach was derived from an NCHRP study (Lichtenstein, 1993) that produced the MBRLT. The K-factor approach is relatively simple as it was based on a limited number of tests and a limited number of measurements per test. At the time most bridge analyses consisted of a beamline and distribution factor, digital data acquisition had more limited capabilities, and sensors were expensive. Load ratings obtained through load tests were therefore based on a few strain and deflection measurements. The “K-Factor” approach was not widely adopted within the industry as it was overly subjective. As discussed by (Commander, 2019), the load rating adjustment factor (*K*) relies heavily on the accuracy (or inaccuracy) of the analytical approach with no generally accepted guidelines for identifying and verifying the discrepancies between the measured responses versus the analytically derived responses.

Now, with the abundance of advanced modeling programs, load ratings are often performed using planar and 3-D finite element models. Advances in field-ready instrumentation and data acquisition allow for load tests to produce higher quality and much higher quantity of response measurements. Processing and comparing the massive amount of data that can now be generated was unthinkable twenty years ago but can now be used to validate models using high powered computers and machine learning algorithms. The diagnostic load testing approach, outlined in the *Primer on Load Testing*, takes advantage of the technology available today.

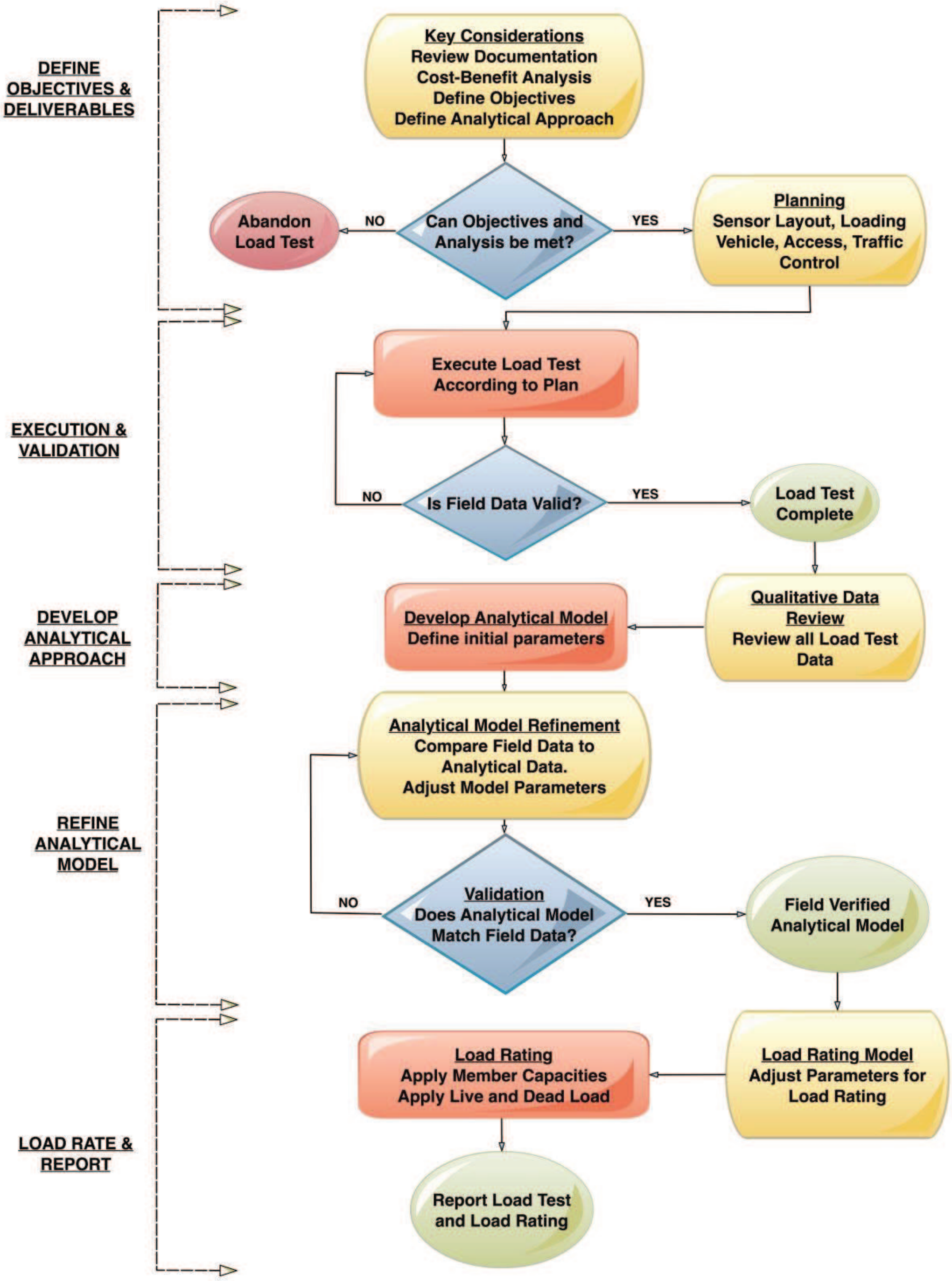

Figure 4: Diagnostic Load Testing Process

The diagnostic load testing approach is a more thorough integrated approach (Halfawy et al., 2002; Wipf et al., 2003) than the K-factor approach. The proposed approach compares measured structural responses (strain, deflection, rotation, etc.) to calculated or predicted responses with the expressed purpose of refining and validating the analytical approach. This is the core of the diagnostic load testing approach; however, there are several steps that need to be considered prior to undertaking a diagnostic load test. The entire diagnostic load testing process outlined in **Figure 4**, and described in more detail in the steps below is the current state of the practice.

Step 1: Define Load Testing Objectives, Deliverables, and Planning

While the most typical reason for conducting a diagnostic load test is to develop a more accurate load rating using structural response data, there are several other reasons for undertaking a diagnostic load test. They range from a full FEM based analysis resulting in an accurate load rating as well as better understanding of structural behavior to simply evaluating specific structural element responses to determining performance characteristics based on secondary element contributions such as parapet walls, sidewalks, guardrails, etc. Among these varied scenarios, the common element is to measure the structure's ability to carry and distribute load.

Whether undertaking a load test using in-house staff or hiring a consultant, the objectives and deliverables should be well defined upfront so that all stakeholders understand the purpose of the test. Once the objectives and deliverables are defined, a cost associated with the diagnostic load test can be established; this cost should be compared against all reasonable alternative solutions so that a cost-benefit analysis can be conducted before proceeding with the load test.

Assuming there is a net financial benefit to conducting the diagnostic load test, the next step is to develop a load testing plan. Planning a diagnostic load test involves a few items, the first of which is the instrumentation plan. The instrumentation plan should be designed around the objectives of the test, so for example, if the objective is to use the load test results to refine and validate a FEM for the purpose of load rating, then the focus of the instrumentation should be in load response and distribution behavior. Alternatively, if the load test is intended to identify stress levels of a particular member, then instrumentation should be focused on that member (and possibly connected members as well) to help identify the in-service load paths.

The second step is to define the loads/loading-vehicle(s) and their positions. Since diagnostic load tests are generally employed to validating an analytical model, a vehicle near the legal weight limit is typically sufficient and is commonly used. The vehicle dimensions, along with the individual axle weights, should be recorded.

The third item, site-specific planning, is easily overlooked but quite important. Specific aspects of site planning include access to the structural elements of interest and maintenance and protection of traffic; the latter must follow local regulations or requirements. With instrumentation, load testing, site access, and safety plans developed, all stakeholders in the project should approve the plan before proceeding with executing the diagnostic load test.

Step 2: Execute Load Test and Validate Results

With proper planning in-place, executing the load test should be reasonably quick depending on the size of the load test (both bridge size and instrumentation quantity) and access/traffic constraints. Experience has shown that for most short to medium-span bridges, a diagnostic load test can be carried out in a single day. Instrumentation installation is typically 60% of the work, while conducting the load test and removing the instrumentation is the remaining 40% of the field work.

When conducting the load tests, traffic will need to be temporarily shut down, so no other loads are on the bridge at the time of load testing. Diagnostic load tests are typically conducted with the loading vehicle traveling at crawl speed (< 5 mph = 8 km/h), to mimic a static test, so as to not induce any dynamic effects. The load tests are also conducted with the test vehicle starting position being completely off the bridge and end again with the vehicle completely off the bridge (or far enough down so there is no loading influence on the spans that are being tested) at the other end of the bridge. The vehicle position should be recorded so that data can be presented in terms of loading vehicle position (i.e., as influence lines) rather than exclusively in terms of elapsed time.

This loading process is important for several reasons: 1) it allows for a quality check on the data being collected with respect to values starting at zero and ending again at zero, and 2) the data is a complete response history that will indicate how the structure is responding to the loading vehicle at all longitudinal positions. If there is some sort of non-linear response (e.g., non-composite behavior when directly loaded), that behavior might be missed if the data isn't collected continuously. Since each test itself is generally of short duration, traffic can be cleared between test runs, reducing the overall impact to the traveling public. Data must be collected at a frequency not to miss the peak values of parameters being measured.

If dynamic (high speed) live-load tests are desired for the purpose of measuring the dynamic impact on the structure, careful consideration is required to ensure that the load test results in a reasonable estimate of the dynamic allowance. The impact generated for a higher speed test is typically more related to the road roughness and bridge approach than to the geometry of the bridge. This type of test does not account for the possibility of a live-load impact due to sudden braking or some other action on the structure. Once again, sound engineering judgment must be employed when assessing dynamic allowance.

It is valuable for the test engineer to be able to validate the data in real-time. The data acquisition system and software should be configured to present sensor data in an useful manner, i.e., in terms of engineering units rather than the raw reading of the sensor. Rapid visualization enables the test engineer to evaluate incoming data not only in terms of the data quality but also in terms of structural response, such that the engineer can recognize unusual responses or possibly non-linear behaviors that would warrant changes to the load testing process or even halting the load test.

Step 3: Develop the Analytical Approach

The analytical approach itself was identified in Step 1; this step refers to initial revisions of the analytical model based on the qualitative assessment of the load test data. Typically, the load test data is reviewed by the person conducting the analysis for the purpose of identifying the data files that will be used to refine the analytical model and validate the quality of the data. This may include some post-processing of the data to eliminate noise or temperature effects identified during execution phase of the project. During this qualitative review, the engineer should be evaluating the structural responses which might affect the analytical modeling parameters so that reasonable initial parameters can be established.

With an initial qualitative review being completed, the initial analytical model (such as FEM) can be developed and initial modeling parameters entered. The main goal in this analytical approach is to recreate the diagnostic test within the analytical approach so that a direct comparison can be made between the load test data and the analytical model data. If a FEM is the chosen route for the analytical approach, the model geometry is developed based on field-verified as-built plans.

The loading plan should be recreated to mimic the continuous loading vehicle positions. Data should be extracted from the model at the same locations where sensors were installed in the field so that a visual and analytical comparison can be made.

Step 4: Refining Analytical Model

Refining of the analytical approach is often the more difficult process in a diagnostic load test and takes an experienced engineer to not only understand the differences between an initial model prediction and the measured responses but to also understand what parameters should and can be adjusted to yield a truly accurate field-verified model. Since the development of the analytical approach includes setting up the model to output data (such as strain, deflection, and rotation), at the same location and orientation as where the sensors were installed on the bridge during the load test, the data generated by the model can be plotted with the data that was collected during the load test. Additionally, the data can be analytically compared in terms of errors between the data sets and correlation coefficient between the data sets. It is very common that the initial model predictions do not agree closely with the load test measurements in magnitude; however, if there are significant differences in the data alignment, there may be issues with the model geometry or load application that need to be addressed prior to beginning the parameter adjustments.

With the initial model geometry and loading validated, it is then down to adjusting parameters within the model so that the model predictions match the load test data. This is generally accomplished through an iterative process based on engineering judgement. Modeling parameters identified in the *Primer* as being commonly adjusted are listed in **Table 1**; this list is by no means exhaustive, but provides a reasonable starting point for refining a model.

Table 1: Common Adjustment Parameters for Refining an Analytical Model (Alampalli et al., 2019)

Adjustment Parameters	**Refinement of Analytical Model for Improved Agreement with Load Test Results**
Element Type and Mesh Size	Strain or stress output, depending on the element type and mesh size at sensor locations, must be comparable to the gage length and orientation of strain sensors used in load test.
Secondary Members	Secondary members such as barriers, sidewalks, diaphragms, etc., need to be properly included for their geometrical, material, and stiffness properties.
Bearing Support Conditions	Typical bridge bearings, of fixed or expansion, provide a rectangular patch support to the superstructure. Expansion bearings usually have frictional resistance. Use of idealized fixed or roller point or line supports in the analytical model may cause discrepancies with load test measurements due to simplifications.
Elastic Modulus of Concrete (E_c)	E_c is usually estimated from concrete compressive strength (f_c') using an empirical formula. In reality, most concrete mixes are placed at a higher strength than design requirements; and concrete continues to gain strength over time. When modelling the sectional stiffness, both the effect of the concrete strength and the provided reinforcement are considered. If test data is available, using the actual material properties instead of nominal values will improve the fidelity of results from the model.
Link Members for Eccentricities	Use of line or planar elements in a FEM requires the use of link members to address the eccentricities between intersecting or connecting bridge members. Proper definitions of the stiffness properties of the link members are important to properly simulate the overall behavior of the structural system, including intended or unintended composite actions between adjacent members.

While several methods exist for refining a model, it is critically important to use engineering judgment throughout this process so that when a final field-verified model is achieved, all final parameters are realistic values and the method for arriving at those values is backed up by sound engineering principles and can be repeated. It must be noted that depending on the structure and the mechanism that is being verified through diagnostic load testing, development of an analytical model may also be completely unnecessary. Type of analytical model, effort required for developing and refining the model, and its value should be carefully evaluated during the test planning as it can add to the project cost considerably. Several transportation agencies have structural analysis models developed using software such as AASHTOWare Bridge Rating (BrR), and these can be used instead of analytical models, where appropriate, instead of developing detailed finite element type of models.

Step 5: Load Rating and Reporting Results

A field-verified analytical/structural model is a powerful tool that can be used for many purposes such as determining in-service load paths, forces in all elements, bending moments, shear stresses, and ultimately evaluate how the structure will respond when other loads are applied to the model. When using the model for load rating, it is important to determine the reliability of the refined parameters in terms of whether the final parameter values should be used in the load rating process or if they should be adjusted to reflect a potential future condition of the bridge. For example, if a partially-fixed support is lowering the mid-span moment of a girder significantly, should that support fixity be counted on in the load rating process if there is a chance this situation might change at higher loading events or due to possible maintenance/rehabilitation in the future. It would seem imprudent to rely on fixity in this example; the final parameters should be revisited and adjusted based on the engineer's judgment.

One of the differences between a proof load test and a diagnostic load tests with regard to calculating the load rating is that the capacity of all elements to be load rated must still be calculated based on the applicable code and current condition of the bridge element. If as-built plans are not available, nondestructive testing techniques can help identify material properties and a variety of field techniques are available to measure the bridge geometry.

Another consideration is application of live load versus dead load when load rating the bridge using an analytical model. Depending on how the bridge was constructed, certain dead loads may need to be applied to an adjusted model (e.g., dead load of a concrete deck should be applied to a non-composite model while dead load of an asphalt overlay should be applied to a composite section). When applying the live load to the model, the live load paths, multiple-lane paths along with all load factors are all applied according to the applicable code (e.g., AASHTO MBE). The output from the analytical model should be load ratings along with factored responses for each element that a capacity was assigned. This provides a great deal of resolution into the critical locations of the bridge.

The report following a diagnostic load test should include a summary of the results of the analytical approach, which typically takes the form of an updated load rating identifying the controlling elements within the structure. Additionally, all pertinent information regarding the load testing procedure, analytical approach, model refinement methodology, and final model results should be included. The report should allow other engineers to follow through the process and understand the decision making and judgments along the way. There should be clear and concise justifications for all the modeling parameters that were developed and used in the analytical approach.

It is again important to note that a diagnostic test is not intended to replace standard NBIS type inspections or traditional load rating; it is a tool that can be implemented in cases where inspections and/or traditional load ratings result in load posting the structure. Hundreds of diagnostic load tests have been conducted over the last 20+ years and it is a proven method for developing a more accurate load rating for a bridge. **Table 2** outlines the estimated improvement in load carrying capacity of common bridge types.

Table 2: Estimated percent improvement in Load Rating based on bridge type[11]

Bridge Type	**Influencing Factors**	**Estimated Percent Improvement**
Reinforced Concrete Slab	Greatest benefit, end conditions, edge stiffening, no longitudinal joints	30 to 60%
Beam/Slab	Ratings controlled by moment, Beam lines > wheel lines, End conditions and edge stiffening	20 to 40%
Beam/Slab	Ratings controlled by shear, No. of beam lines, edge stiffening.	0 to 15%
Culverts & Arches	Function of fill depth, end-conditions, span length	20 to 30%
Truss	Members in line with floor system	0 to 30%
Two Girder	No improvement in distribution. End conditions may influence ratings.	0 to 15%

Proposed approach for proof load testing

The following steps describe the proposed approach for bridge proof load testing in test implementation and results interpretation for load rating in accordance with the concepts and principles prescribed in the AASHTO MBE. The proof load process is summarized in the flowchart in **Figure 5**; a detailed description of each step follows.

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[11] Estimated presented in this table are based on the experience of BDI.

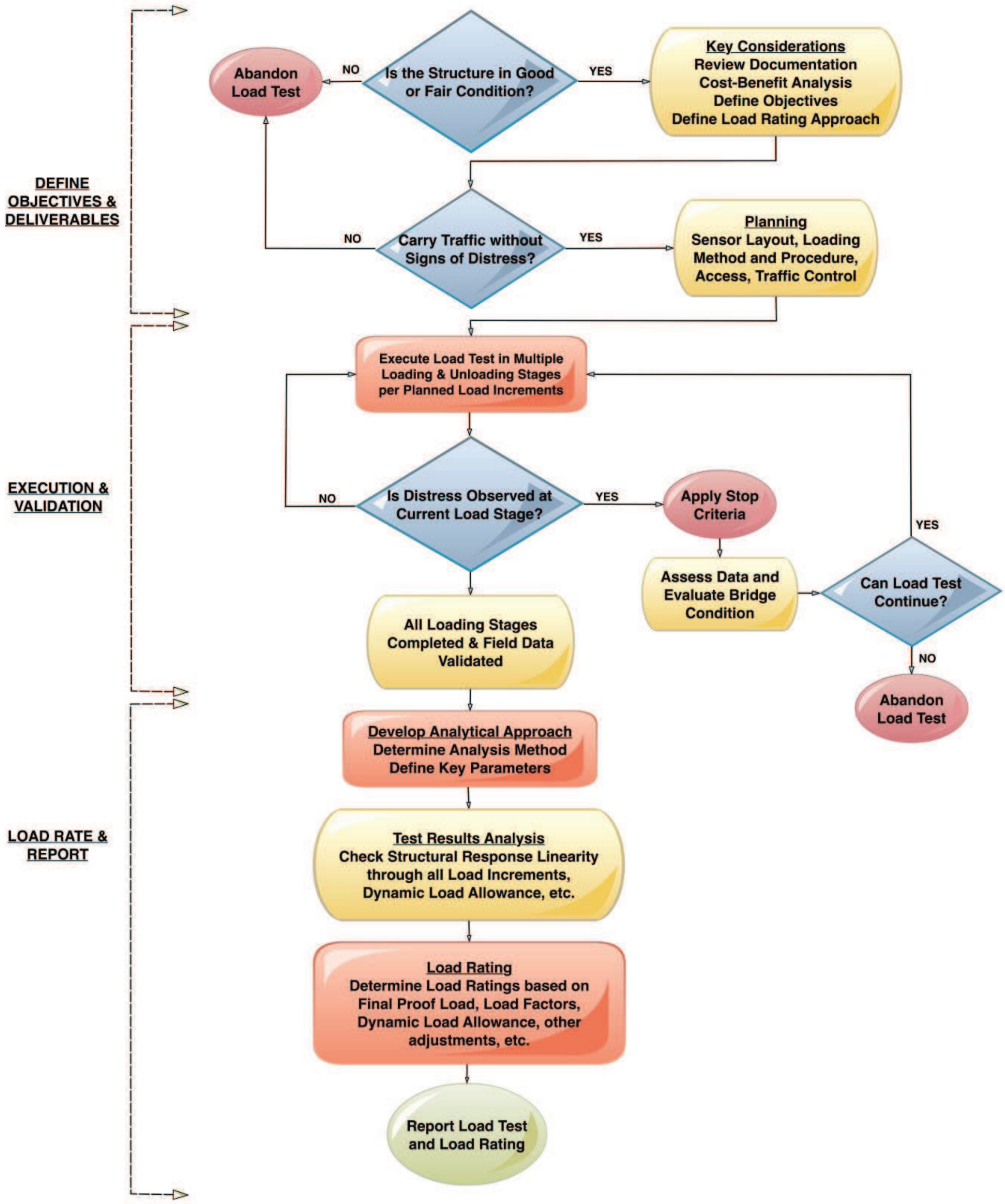

Figure 5: Proof load test procedure

Step 1: Test Planning and Preparation

Test planning, preparation, and assessing whether the subject bridge is suitable for proof load testing are very important. Preparation will require multiple considerations including: reviewing bridge structural information and performance history; understanding the primary and secondary load carrying mechanisms; developing an instrumentation plan for sensor layout, data collection and review including the timely capture of signs of distress; determining loading and unloading of equipment and logistics; establishing a traffic control plan at the bridge site; and last but not least, identifying potential risks and developing test stop criteria and an action plan.

Step 2: Establishing a Target Proof Load.

The target proof load is established in accordance with the procedures provided in the AASHTO MBE. The resulting target proof load L_T determined by Eq. (10) and Eq. (11) is for the governing load effect in bridge load rating, e.g., maximum bending moment at mid-span, maximum shear force at a support, etc. Before the execution of a proof load test using test vehicles, the target test vehicle weight, W_T, corresponding to the target proof load, L_T, must be determined in order to accomplish the proof test goals.

If the test vehicle has identical axle configuration (spacing and weight distribution) as the rating vehicle, the target test vehicle weight, W_T, is simply:

$$W_T = X_{pA}\, W_R\, (1 + I) \tag{18}$$

where W_R is the gross weight of rating vehicle, X_{pA} the factor explained with Eq. (11), and I the dynamic load allowance.

However, this is usually not the case in reality; there is often the need for assessing load ratings for multiple rating vehicles. As a result, it is necessary to determine a vehicle adjustment factor, f_V, for each rating vehicle to account for the axle configuration difference between the rating vehicle and the test vehicle. Thus, the target test vehicle weight should be determined as:

$$W_T = X_{pA} f_V W_R (1 + IM) \tag{19}$$

A structural analysis using a line model is generally sufficient to determine f_V for the test vehicle for equivalent governing live load effect L_R in load rating to each rating vehicle. The factor f_V is equal to 1.0 if the test vehicle is identical to the rating vehicle in axle configuration (spacing and weight distribution).

Step 3: Verifying Bridge Capacity

Verifying physical capacities of the subject bridge and developing test stop criteria are needed. As high loads are applied during proof load tests, an analysis should be performed to correlate the test load with the critical force effect for the predicted governing failure mode. The extent of this analysis should depend on the goals of the load test, the expected behavior of the bridge, and the level of maximum proof load relative to service load. For example, a more thorough analysis may be required for a shear-critical concrete girder bridge than a flexure-critical reinforced concrete slab bridge for assessing the maximum critical force due to test load with respect to estimated capacity.

The estimated critical forces due to test loads need to be compared with estimated corresponding physical capacities of the bridge based on known or assumed material properties. This assessment serves as a check against possible failures of load carrying members, or possible collapse of the structure under the target proof load. If the difference between the calculated capacity and the target test load is small, real-time measurements and data interpretations during the test must closely monitor the bridge response and condition change, and have a detailed plan for stopping the test if necessary. Stop criteria, in terms of limit values of measured strains, displacements, or other physical parameters should be established before the start of a proof load test. For in-service bridges, an examination of the weights and types of vehicles that cross the bridge provides reference information on the actual loading condition experienced by the structure. Such information can also serve as a reality check to the calculated physical capacities.

Step 4: Execution of the Proof Load Test

Execution of a proof load test involves applying the test load through a multiple-step loading and unloading process. Load levels are increased until the target proof load is reached while structural responses are closely monitored using sensors. Key considerations for executing proof load tests include: method of applying test load (test vehicles or a fixed loading system with hydraulic jacks); beginning level of test load based on actual traffic condition or analytical supports; load increments for all loading steps before reaching the target proof load; key response parameters of the governing failure mode(s) identified by analysis; instrumentation plan (sensor layout, data collection/processing/display methods, etc.); measurements evaluation criteria for proceeding to the next loading level (zero-return of individual sensor responses, linearity of response-test load correlations, etc.); and stop criteria for aborting the load test before reaching the target proof load.

For bridge proof load testing, the application of the loading protocol with loading and unloading steps can be carried out typically by repeating test truck positions, or by using a loading system with hydraulic jacks. Multiple loading and unloading steps of increasing load levels allow the engineer to check the linearity of the structural response to increasing load. A larger response to the same load increase on subsequent applications indicates that nonlinear behavior is occurring in the structure, or that the applied sensors are not properly functioning. In either case, the test should be stopped to investigate the cause of the observations. Small fluctuations in the response as the result of the influence of temperature and humidity can take place during the test. Engineering judgment is required to evaluate what constitutes a true nonlinear structural response versus response due to environmental changes.

For multiple-lane bridges, including those carrying one lane in each direction, a minimum of two loading vehicles should be used. The following loading protocol is recommended:

- Obtain two vehicles of the same axle configuration that are as close as possible to the rating vehicle of interest.
- Mark the bridge deck surface with lateral vehicle positions to properly check all loading position components.
- Determine a realistic weight for the loading vehicle (W_{Real}) that the bridge experiences on a regular basis based on a traffic survey, legal weights, any postings, or site observations.
- Establish a maximum vehicle weight increment to be one third of the difference between the target proof load and the realistic load, or $\Delta W = 0.33(W_T - W_{Real})$
- Repeat the following steps at each increasing vehicle weight (W_{Real}, $W_{Real}+\Delta W$, $W_{Real}+2\Delta W$, $W_{Real}+3\Delta W$, etc.):
    - Use one truck to cross the bridge at a crawl speed, or position it at a stationary location at all pre-marked lateral positions.
    - Review sensor measurements and visually inspect the structure for any signs of distress.

    - Use two trucks side-by-side to cross the bridge at a crawl speed, or position them at stationary locations at different combinations of lateral positions as allowed by deck geometry.
    - Review sensor measurements and visually inspect the structure for any signs of distress.
- If allowed by site condition and agreed by the vehicle owner and driver, repeat select single truck crossings by running the same truck at the speed limit, at the same lateral position, for assessing dynamic load allowance. This is usually practical and safe only at the lowest load level.

Step 5: Monitoring of Bridge Behavior During the Test

It is essential to monitor bridge behavior and be safety conscious during proof load testing. Since proof load tests need to apply test loads higher than the service load, the loading protocol and the limiting values for the stop criteria have to be determined prior to the beginning of the load test and communicated with all parties involved. Real-time monitoring of test measurement for timely discovery of non-linear structural behavior due to cracking, buckling or other physical damage is essential. The following quantities can be monitored: load vs. displacement diagrams to identify if non-linear behavior is occurring; strain responses in instrumented members to assess if elastic limits may be exceeded; width of existing cracks to see if cracks are activated in concrete bridges; and comparisons of test measurements with analytical predictions.

If non-linear behavior is observed, the test should be paused for additional checks. In particular, the instrumentation engineer should check for any indications of sensor malfunction. In the absence of indications of sensor malfunction, non-linear behavior may have taken place suggesting onset of irreversible damage to the structure and may warrant immediate termination of the load test. Quantitative stop criteria based on measurements should be determined prior to the test. Since loading beyond such stop criteria may result in irreversible damage, it is important that the load test be terminated immediately upon reaching any stop criterion, even if the target proof load has not been achieved. In exceptional cases, and only with the consent of the bridge owner and an analysis of the possible risks involved, further loading can be permitted.

Step 6: Interpretation of Results

The results of a proof test are used to determine the bridge load rating in accordance with the AASHTO MBE. A lower-bound bridge load rating for a rating vehicle based on the results of a proof load test can be determined using the following equation:

$$RF_P = (k_O)(W_P/W_R)(f_V)/[(\gamma_{LL})(1+IM)] \tag{20}$$

Where RF_P is a lower-bound rating factor derived from a proof load test, W_R is the gross vehicle weight (GVW) of rating vehicle, W_P is the final GVW of test vehicle upon completion of proof load test, γ_{LL} is the live load factor that varies with the load rating method and determines the load rating level of RF_P, as shown in Table 3.

Table 3. Live Load Factor (γ_{LL}) of AASHTO LRFR and LFR Methods

Load Rating Method	Load Rating Level	Live Load Factor γ_{LL}	AASHTO MBE
Load and Resistance Factor Rating (LRFR)	Design Inventory	1.75	Table 6A.4.3.2.2-1
	Design Operating	1.35	
	Legal	1.45 (ADTT ≥ 5,000)	Table 6A.4.4.2.3a-1 (linear interpolation)
		1.30 (ADTT ≤ 1,000)	
	Permit	1.10 to 1.40	Table 6A.4.5.4.2a-1
Load Factor Rating (LFR)	Inventory	2.17	Article 6B.4.3
	Operating	1.3	

The rating factor for a specific rating level for any rating vehicle based on equivalent maximum load effect to the final proof load in moment or shear is given by Equation (20). It should be noted that the current AASHTO MBE intends to use proof load testing to determine bridge load ratings at the LRFR Design Operating, LRFR Legal, or LFR Operating level, of a 2.5 reliability index, but not at the LRFR Design Inventory or LFR Inventory level, of a 3.5 reliability index.

Introduction of structural reliability concepts in the Primer on Bridge Load Testing

The *Primer* considers three reliability indices related to a load test (i.e. the reliability indices before, during, and after the test) in order to plan the load testing to minimize the expected life-cycle cost and to conduct cost-benefit analysis of a planned load test. In addition, the effects of structural deterioration (e.g. due to corrosion and fatigue) and increasing load effects can also be considered in the reliability analysis.

It should be noted that the increase of load effects can be gradual (e.g. due to increasing average daily traffic) or sudden (e.g. due to repurposing or posting of nearby bridges). To differentiate structural deterioration and increasing load effects, the latter is represented herein as a sudden increase at a future point-in-time, e.g. due to a repurposing of the roadway where the tested bridge is located.

Based on this simplification, Figure 6(a) and (b) illustrate the deteriorating structural capacity and a typical load history with one load test. The associated reliability index profiles are also shown in Figure 6 considering the effect of structural deterioration. Figure 6(c) represents the case where the bridge passes the load test without any signs of distress, while Figure 6(d) illustrates the opposite case where the load test causes structural damage.

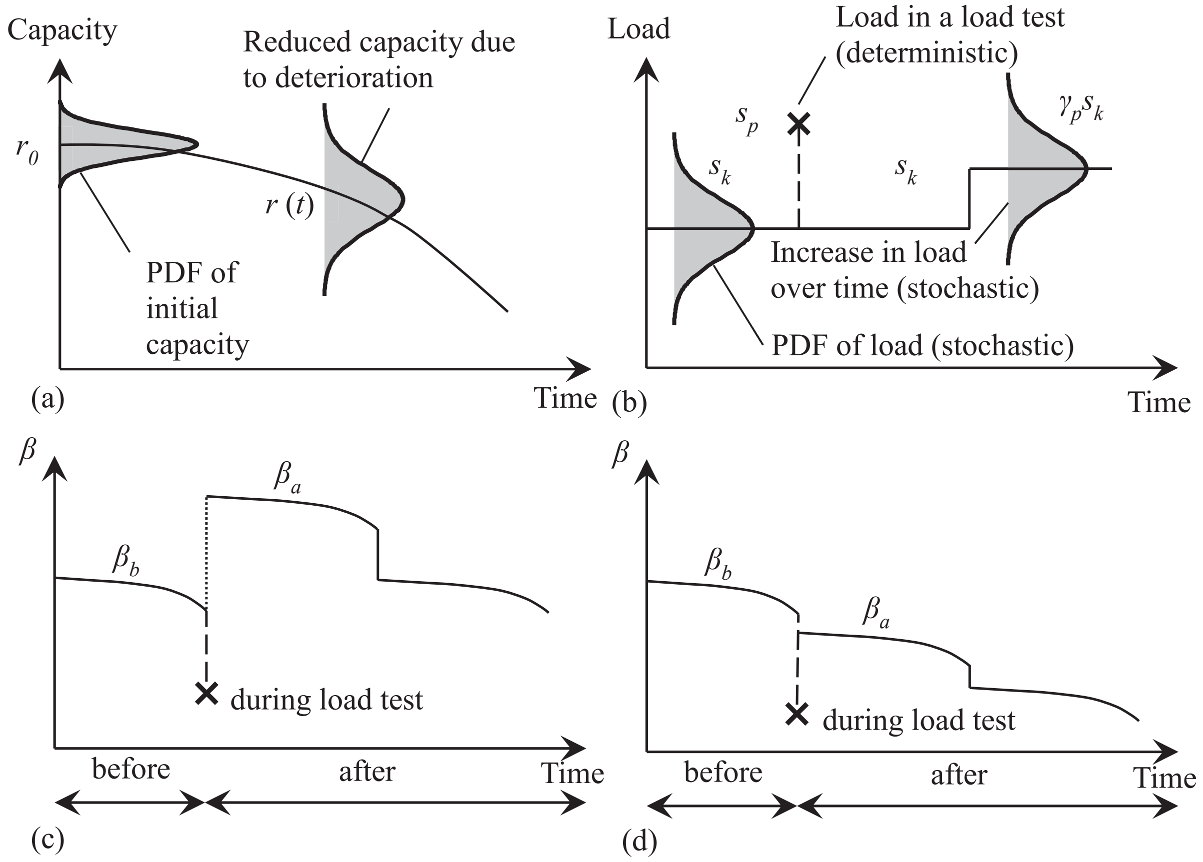

Figure 6. Change in reliability index before, during, and after load test: (a) reduced capacity due to structural deterioration; (b) load before, during, and after a load test; (c) reliability index profile if the bridges passes a load test; (d) reliability index profile if the load test causes damage

Based on the reliability index profiles, the remaining service life of the tested bridge up to a major corrective intervention or rebuilding can be estimated based on the target reliability index. The target reliability index in a reference period (e.g. five years in load rating at operating level) is related to consequences of failure and relative cost of safety improvement (Fischer et al., 2019). For existing structures, the target reliability index is lower than that used in the design specification since the relative cost of safety improvement is much higher than that in the design stage. Ideally, a cost-benefit analysis should be conducted to decide the optimal target reliability index. The *Primer* referenced the Dutch code (Rijkswaterstaat, 2013) and the Eurocode (Koteš and Vican, 2013) for the target reliability index used in load testing and load rating. Specifically, rating at the operating level may use a target reliability index of 2.3 (5-year reference period), while rating at the inventory level may use a target reliability index of 3.5 (75-year reference period).

As previously mentioned, structural reliability analysis is usually conducted for limit states at the structural component level. For a majority of bridges, the structural capacity of the entire structural system is rarely controlled by a component failure due to load redistribution among components (Hendawi and Frangopol, 1994). This form of structural redundancy can be modeled using parallel-series system models that combine limit states associated with different structural components (Estes and Frangopol, 1999). The probability of failure of a bridge can then be determined with system reliability methods. The *Primer* includes such analysis in load rating through load testing, but it also states that further development is needed to streamline this system-level approach for reliability-based load testing analysis.

Based on results from structural reliability analysis, load testing can be integrated into the broader realm of optimal bridge management. As an intervention action, load testing can be planned in the service life of a bridge so that the expected life-cycle cost as defined in Eq. (14) is minimized while the safety margin of the bridge is maximized, or at least kept above the target value. For instance, reliability-based load testing planning can be formulated as the following optimization problem (Frangopol et al., 2019):

Given

Structural model of a bridge, deterioration conditions, and effects of maintenance actions,

Find

Time and technique of loading testing in the service life of the bridge

Such that

The total life-cycle cost is minimized

Subject to

(a) the lowest annual reliability index of the bridge in its life-cycle is higher than the target annual reliability index,

(b) the budget for load testing, and

(c) the budget for maintenance actions

Discussion

This paper gives the scientific background that lies at the basis of the recommendations in the *Primer for Bridge Load Testing*, and gives a brief summary of the recommended procedures. The reader is encouraged to consult the *Primer* to help identify whether a load test is the correct means to answer questions about a given bridge, to prepare for a load test, to select the correct load test type, and to interpret the load test results. In addition, the *Primer* contains example case studies of load tests. This paper is focused on the research behind the *Primer*, whereas the *Primer* itself is written to serve as practical guidance for an audience of practicing engineers and bridge owners.

When deciding the appropriateness of a bridge load test, it is important to make an informed choice. While recommendations are provided for the selection of test objectives and for the planning stage of a load test, it is important to maintain open communication between all involved parties. In particular, it is important that the engineer responsible for the load test discusses the needs of the client and the open questions regarding the bridge at an early stage to make sure the test adequately addresses these open questions. It is also important to remind all parties involved during, before, and after the load test of the objectives of the test, so that preparation, execution, and analysis are carried out with a common perspective.

Two parts of the recommendations in the *Primer* require further research. The first element that requires further research is the factor X_{pA} as used to determine the target proof load. This factor from the MBE and originally the MBRLT has not been changed in the *Primer*. It is recommended that reliability-based analyses are pursued to evaluate the currently used values for X_{pA}. A second element that requires further research is to more fully integrate structural reliability concepts with load testing, including case studies and practical applications. The *Primer* approaches from a theoretical perspective how to determine the target proof load such that a certain reliability index is demonstrated after a proof load test. It also discusses concepts related to life-cycle cost optimization (including sustainability considerations) and system reliability. However, practical applications of these concepts through pilot case studies will be necessary to further develop these recommendations.

Summary and Conclusions

A working group from the TRB Standing Committee on Testing and Evaluation of Transportation Structures (AFF40/AKB40) developed the recently published *Primer for Bridge Load Testing*. Given that the recommendations for load testing in the extant AASHTO Manual for Bridge

Evaluation are based on research carried out in the 1980s and early 1990s, the *Primer* is intended as practical guidance revised in light of research and experience gained since then. Additionally, the *Primer* identifies applications of recent advances in bridge engineering to load tests, with particular attention to integration with structural reliability, cost-benefit analysis methods, advances in measurement techniques, and advances in finite element modeling. The *Primer* also contains examples that can serve as references for practicing engineers and bridge owners.

The methods for load testing in the *Primer* are mainly diagnostic and proof load testing. While the focus of the *Primer* is on bridge load testing for bridge rating, other applications are identified and illustrated with examples as well. Short discussions on parameter-specific diagnostic load tests and dynamic testing are also provided.

When selecting the type of load test, it is important to refer to the test objectives and the relationship between the objectives and the required load level. If relatively low load levels can give insight into the structural behavior and additional load paths, a diagnostic load test can be recommended. If uncertainties on the bridge structural behavior and reliability of additional load paths under higher load levels are large, a proof load test may be a better option.

Given the recent advances in measurement techniques and analytical modeling, the recommendations for diagnostic load testing and proof load testing in the *Primer* differ from those in the MBE. For diagnostic load testing, the MBE uses a *K*-factor approach, which is based on a pointwise measurement of strains. In the *Primer*, this approach is replaced using multiple sensors (either pointwise contact sensors or a selected number of datapoints from full-field non-contact sensors) and comparison of measured structural responses to those predicted by an analytical model. For several test objectives, the recommended analytical model is a linear finite element model.

Through model updating based on the measured structural responses, a field-validated model can then be developed. By changing average material parameters to characteristic values, using the relevant live load model, and removing load-carrying mechanisms that are not reliable under higher loads, a model for bridge load rating can then be derived. For proof load testing, the MBE does not provide guidance on how to relate the use of a certain vehicle during a proof load test and the rating vehicle. Many times, the axle weight and spacing of the test truck will be different from the rating vehicle. The *Primer* has addressed this topic by introducing a factor that quantifies the difference in load effect between the test vehicle and the rating vehicle. In addition, the *Primer* gives guidance on how to select the different load levels that should be used during a proof load test.

This paper has combined the research from recent years that lies at the basis of the *Primer for Bridge Load Testing* and provides a summarized overview of the recommendations in the *Primer*. As such, this work gives the current state of the practice regarding bridge load testing, and points to topics for future research.

Notation List

The following symbols are used in this paper:

f_c'	specified concrete compressive strength
f_R	allowable stress specified in the LRFD Code (AASHTO, 2015)
$f_R(.)$	probability density function of the resistance
$f_S(.)$	probability density function of the load effect
f_V	vehicle adjustment factor
k_O	factor that takes into account if target proof load or stop criterion was reached

n_d	number of damage states that are likely to be reached after an unsuccessful load test
$p_{d,I}$	probability of falling into damage state i after the load test
s_p	magnitude of test load
C	capacity
$C_{d,i}$	remedy cost associated with damage state i
C_F	cost of failure
C_{LT}	cost of load test
C_{op}	direct operation cost associated with a load test
C_T	initial cost
DC	dead load effect due to structural components and attachments
DW	dead load effect due to wearing surface and utilities
E_c	modulus of elasticity of the concrete
EC_F	expected failure cost (i.e. failure risk)
EC_{INS}	expected cost of inspections
EC_{PM}	expected cost of routine maintenance
EC_{REP}	expected cost of repair
$ELCC$	expected life-cycle cost
$F_R(.)$	cumulative distribution function of resistance
$F_S(.)$	cumulative distribution function of the load effect
I	dynamic load allowance
K	adjustment factor

K_a	benefit derived from load test
K_b	adjustment for differences between actual bridge behavior and revised analytical model
K_{b1}	factor for ability of test team to explain differences between load test observations and analytical model, and to extrapolate test results to higher load levels
K_{b2}	factor for ability to determine problems in a timely manner with inspections
K_{b3}	factor for the presence of critical structural features which cannot be determined in a load test
LL	live load effect
L_P	maximum load applied in proof load test
L_R	comparable live load due to rating vehicle for the lanes loaded
L_T	target proof load
OP	capacity at the operating level
P	effect from permanent loads other than dead loads
P_{fa}	probability of failure after a load test
P_{fb}	probability of failure before a load test
P_{fd}	probability of failure during a load test
R	resistance effect
R_n	nominal member resistance as inspected
RF	rating factor
RF_C	rating factor before load test
RF_O	rating factor at operating level after proof load test
RF_P	lower-bound rating factor derived from a proof load test

RF_T	rating factor after load test
Ri_a	risk of structural failure after load test
Ri_b	risk of structural failure before load test
S	load effect
V_{LT}	value of the load test
W_P	final gross vehicle weight of test vehicle upon completion of proof load test
W_R	gross vehicle weight of rating vehicle
W_{Real}	realistic weight for the loading vehicle
W_T	target truck weight for load test truck
X_p	target live load factor prior to adjustments, = 1.4
X_{pA}	target live load factor after corrections
B	reliability index
γ_{DC}	load factor for dead load
γ_{DW}	load factor for superimposed dead load
γ_{LL}	load factor for live load
γ_P	load factor for permanent loads other than dead load
ε_c	analytically determined strain
ε_T	strain measured during load test
φ	LRFD resistance factor
φ_c	condition factor
φ_s	system factor
$\Phi(\cdot)$	cumulative distribution function of standard normal distribution

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