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Chapter 3. Current codes and guidelines

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ABSTRACT: This chapter reviews the existing codes and guidelines for load testing of structures. A summary of the main requirements of each existing code is provided with a focus on the determination of the required load and measurements. The requirements for load testing of bridges and buildings are revised, for new and existing structures. An international perspective is given, revising the practice from Germany, the United Kingdom, Ireland, the United States, France, Switzerland, the Czech Republic, Slovakia, Spain, Italy, Switzerland, and Poland. The chapter concludes with a short overview of the current developments and with a discussion of the different available codes and guidelines.

1 INTRODUCTION

Load testing practices originated as part of the bridge engineering profession, to demonstrate to the traveling public that a given bridge is safe for use. Over time, load testing practices for the assessment of existing bridges were also developed. This chapter gives an overview of the load testing practices and regulations internationally. Not all countries have guidelines for diagnostic and proof load testing of bridges and buildings. In some countries, the guidelines are only applicable to structures of a certain material, e.g the German guidelines were originally developed for proof load testing of concrete buildings, and the ACI guidelines are only applicable for proof load testing of concrete buildings. These guidelines have been included into this section, since few bridge codes deal in detail with proof load testing.

In a proof load test, a high load is used that is representative of the factored live load. The determination of the magnitude of this load is different across the available guidelines for proof load testing. Therefore, in the description of the codes that allow for proof load testing, the determination of the target proof load is discussed. Since high loads are used in proof load tests, it is important to identify when the test should be terminated, even though the target proof load has not been reached yet. The criteria that are used to identify if a test should be terminated are called stop criteria. In the ACI codes and guidelines, the term acceptance criteria, for criteria that should be fulfilled and checked after the test, is used. These criteria are defined based on the measurements on the structure. Stop criteria generally are defined based on strain, deflection, stiffness, crack width and other responses that can be monitored in real time during the proof load test. If a stop criterion is exceeded, further loading is not permitted. The structure is then approved for the highest load level that was achieved before exceeding a stop criterion.

Since the goal of diagnostic load testing is to gather information about the structural response of the tested bridge, the magnitude of the applied load is less important in a diagnostic load test. The load should be large enough so that the structural response can be measured by the applied sensors and be representative of service load levels. The measured structural response is then used to update the analytical model that was used to develop predictions of the structural responses. The measurements should be followed during the load test, but since the applied loads are much smaller than in a proof load test, the risk for causing irreversible damage to the structure is smaller. Therefore, codes typically do not define stop criteria for diagnostic load tests.

Even though the German and ACI guidelines have been developed for buildings, their contents are discussed in this chapter, since the proposed stop and acceptance criteria in these guidelines have been important for the further development of stop criteria for concrete bridges. Whereas the focus of this chapter and book is on load testing of bridges, regardless of their building material, for concrete structures, the definition of stop criteria may be more convoluted than for steel structures, where strain measurements can indicate directly how far away from the yield strain the occurring strain is. For fracture- and fatigue-critical steel structures, the current codes do not permit testing. Future research should focus on developing safe guidelines for testing of these types of steel structures. For shear-critical concrete bridges, recent research has focused on developing stop criteria that allow for the safe execution of proof load tests on these types of structures.

2 GERMAN GUIDELINES

2.1 General

In Germany, a guideline for load testing (Deutscher Ausschuss für Stahlbeton 2000) of plain and reinforced concrete structures is available. The guideline cannot be used when a brittle failure mode can occur in the proof load test, and thus does not allow testing of shear-critical structures. The original scope of the guideline was proof load testing of buildings.

Prior to the load test, the structural system, geometry and material properties need to be known. The data should either be taken from the available documentation, or should be determined by measurements and/or testing of the actual structure. A visual inspection, with additional destructive and non-destructive testing is required prior to the test. The structural capacity needs to be determined prior to the load test, using the following partial factors:

- permanent loads: γ_G =1.15
- concrete: γ_C = 1.4
- reinforcement steel: γ_S = 1.1

According to the German guideline, load testing is permitted in case of insufficient knowledge on the calculation models, the composite action and load distribution among structural members, the effect of material damage, and the effect of repair actions. During the preparations of the load test, the following elements need to be determined: the measurements expected during the test, the effect of changes to the state or system (effect of uncracked versus cracked section, the effect of changes in temperature), the expected stresses and strains for the applied load, and the effect of the load test on the substructure.

The position of the load in a proof load test has to be such that it is representative of the most unfavorable loading position. In a diagnostic load test, the position of the load has to correspond with the property under study. The German guideline prescribes a cyclic loading protocol for proof load tests. In a proof load test, the load has to be applied in at least 3 steps, and after each step unloading is required at least once.

After the load test, the results need to be analysed and compared with the calculations made before the test. Similar structures to the tested structure can be assessed based on the load test as well, when their equivalence can be shown through all essential details and properties.

2.2 Safety philosophy and target proof load

The guideline specifiies the following loads:

- the limiting load level F_{lim}: the load at which a stop criterion is reached, indicating that further loading would cause permanent damage to the structure,
- the total target load F_{target}: the planned maximum load prior to the load test, and

- the applied target load $ext.F_{target}$: the externally applied proof load, without the present permanent loads.

The German guideline prescribes two scenarios that can occur in a load test:

1. The target load $ext.F_{target}$ is applied to the structure, and none of the stop criteria are exceeded. The load test has shown successfully that the structure can carry the applied load.

2. Prior to reaching the target load $ext.F_{target}$, a stop criterion is exceeded at a load level F_{lim}. Further loading is thus not permitted. The results of the load test may be used to conclude that the structure can carry loads at a load level up to F_{lim}.

This safety philosophy is illustrated in Figure 1. The concept is illustrated based on the load-displacement diagram, here more generally shown as the relation between action and effect in the experiment. The value of F_{lim} is shown as the onset of nonlinear behavior. The permanent loads G_1 are shown on the diagram, as well as the total capacity $effR_u$, which corresponds to the maximum action. The value of F_{lim} can be subdivided into the effect of the permanent loads G_1 and the externally applied load $ext.F_{lim}$. The target load should correspond to the considered load combination of the factored permanent and live loads. The applied load $ext.F_{target}$ is then the target load F_{target}, minus the occurring permanent load G_1: $G_{dj} + Q_d$. As shown in Figure 1, two scenarios are possible: $F_{target} \leq F_{lim}$, which means that the structure has been shown to fulfill the requirements, and $F_{target} > F_{lim}$, which means that the load test has to be terminated at a lower load level than the target load F_{target}.

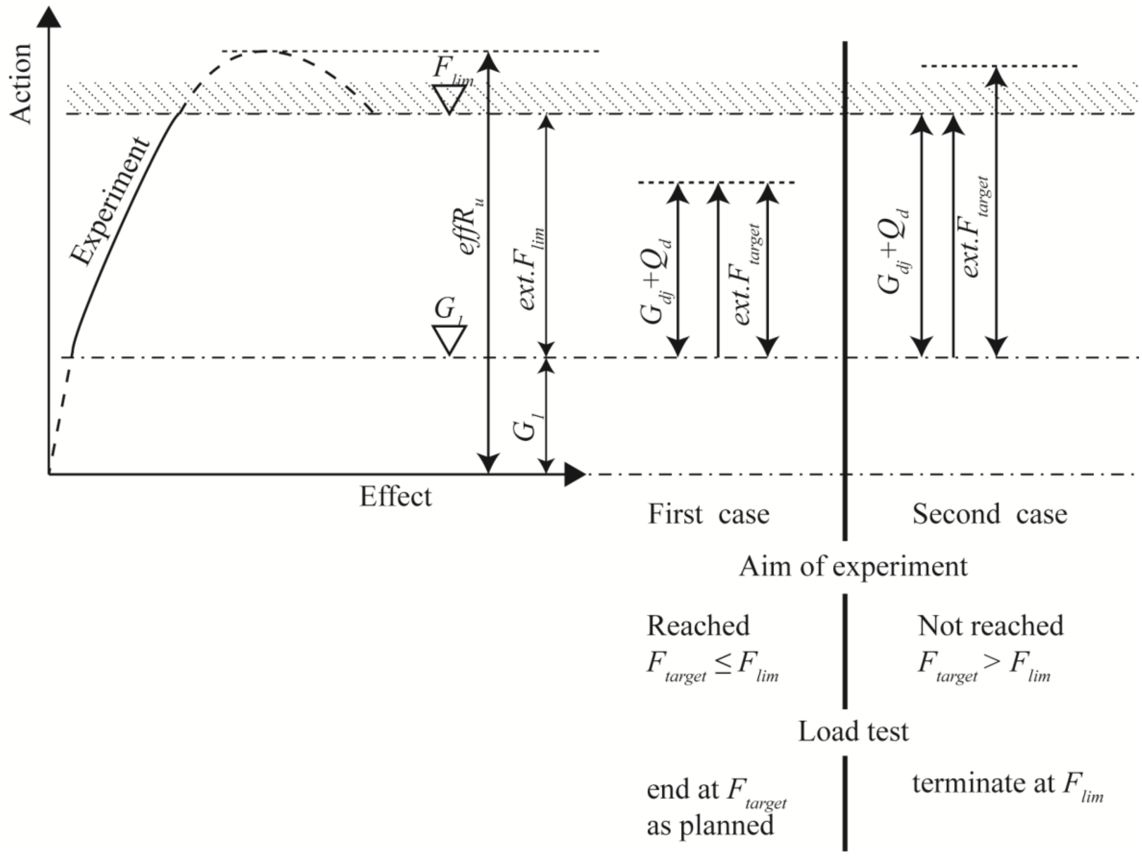

Figure 1: Safety philosophy of the German guideline (Deutscher Ausschuss für Stahlbeton 2000), showing the two possible scenarios. Reprinted with permission from (Lantsoght et al. 2017).

In the German guideline, the applied target proof load $ext.F_{target}$ is determined as follows:

$$ext.F_{target} = \sum_{j>1} \gamma_{G,j} G_{k,j} + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \psi_{Q,i} Q_{k,i} \quad (1)$$

with

$$0.35 G_{k,1} \leq ext.F_{target} \leq ext.F_{\lim} \quad (2)$$

The defined loads are $G_{k,1}$, the characteristic value of the permanent loads occurring in the load test, $G_{k,j}$, the characteristic value of the permanent loads occurring after the load test, $Q_{k,1}$ and $Q_{k,i}$, the characteristic values of the live load for the governing load 1 and other loads i. The defined load factors are $\gamma_{G,j}$, the partial factor the permanent loads G, $\gamma_{Q,1}$ and $\gamma_{Q,i}$, the load factor for the governing live load 1 and other live loads i, and $\psi_{Q,i}$, the combination factor for the live loads Q. The partial factors and combination factor should be taken from the governing German codes. The values of $Q_{k,1}$, $Q_{k,i}$ and $G_{k,j}$ are not valid anymore when changes are made to the studied structure.

2.3 **Stop criteria**

The German guideline prescribes stop criteria to be used for proof load tests for structures that are expected to be flexure-critical. The limiting load F_{lim} from the safety philosophy illustrated in Figure 1 is reached when a stop criterion is exceeded. In total, five stop criteria are defined. The first stop criterion describes a limiting strain in the concrete:

$$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0} \tag{3}$$

In Equation (3) ε_c is the strain measured in the concrete during proof loading. This strain has to be smaller than the limiting strain of $\varepsilon_{c,lim} - \varepsilon_{c0}$. The value of $\varepsilon_{c,lim}$ equals 0.6 ‰ in general, and can be increased to 0.8 ‰ when the concrete compressive strength is larger than 25 MPa (3.6 ksi). The strain ε_{c0} is the analytically determined short-term strain in the concrete caused by the permanent loads that act on the structure before the application of the proof load.

The second stop criterion describes a limiting strain in the reinforcement steel. The value is determined as:

$$\varepsilon_{s2} < 0.7\frac{f_{ym}}{E_s} - \varepsilon_{s02} \tag{4}$$

When the stress-strain relationship of the steel bars is known, Equation (4) can be replaced by:

$$\varepsilon_{s2} < 0.9\frac{f_{0.01m}}{E_s} - \varepsilon_{s02} \tag{5}$$

In Equations (4) and (5), ε_{s2} refers to the measured strain in the steel, and ε_{s02} is the analytically determined strain (assuming that the concrete cross-section is cracked) in the reinforcement caused by the permanent loads that act on the structure before the application of the proof load. The value of f_{ym} is the average yield strength of the tension steel. If the stress-strain relationship of the bars is known, the more precise $f_{0.01m}$ can be used, with $f_{0.01m}$ the average yield strength based on a strain of 0.01% in the steel. E_s is the Young's modulus of the reinforcement steel.

The third stop criterion limits the width w of new cracks that can occur during the load test, as well as the increase in crack width Δw of existing crack widths during the load test. Limitations are given both for the maximum value of the crack width, as well as the residual crack width after removal of the load. This stop criterion is given in Table 1.

The fourth stop criterion is related to the measured deflection. This stop criterion is either exceeded when a clear increase of the non-linear part of the deformation is observed, or when more than 10% permanent deformation is found after removing the load.

Table 1: Requirements for crack width w for newly developing cracks and increase in crack width Δw for existing cracks.

	During load testing	After load testing
Existing cracks	$\Delta w \leq 0.3$ mm = 0.12 in	$\leq 0.2\Delta w$
New cracks	$w \leq 0.5$ mm = 0.20 in	$\leq 0.3w$

A final stop criterion is only applicable to beams with shear reinforcement. For this case, the strains in the shear span are further limited: for the stop criterion from Equation (3), the maximum strain is taken as 60% of the maximum strain given in Equation (3), and for the stop criterion from Equation (4), the maximum strain is taken as 50% of the maximum strain given in Equation (4).

Additional conditions that require the termination of a load test in the German guideline (Deutscher Ausschuss für Stahlbeton 2000) are:

- when the measurements (for example: the load-deflection curve or acoustic emission measurements) indicate critical changes in the structure, which are expected to cause damage when the load is further increased;
- when the stability of the structure cannot be further guaranteed;
- when critical displacements occur at the supports.

To evaluate the stop criteria, the instrumentation of the structure needs to be able to measure the input necessary for verifying these stop criteria. Furthermore, the effect of the environmental conditions (temperature, humidity, and wind) needs to be known.

3 BRITISH GUIDELINES

3.1 General

In the United Kingdom, a guideline for load testing is available (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges 1998). This guideline was developed as a consequence of the implementation of the 40-tonne vehicle (88 kip vehicle) in 1988, for which a large number of existing bridges did not have sufficient capacity. The guideline is suitable for showing sufficient load-carrying capacity of apparently understrength bridges, as well as for checking the performance of newly constructed bridges. Load tests according to this guideline can be used to aid assessment by calculation.

The nomenclature used in the British guidelines slightly differs from what is used throughout this book. The British guidelines describe the following types of load tests:

- supplementary load tests: load tests to supplement the analytical methods of assessment based on calculation and the use of codes of practice (called diagnostic load tests in this book),
- proof loading: load tests to validate the design method and design assumptions for newly constructed bridges, with loading levels to the serviceability limit state (called diagnostic load tests in this book),
- proving load testing: load tests to provide a safe load-carrying capacity without further theoretical analysis, where the load is increased to some predetermined maximum or until the structure shows signs of deterioration or distress (called proof load tests in this book), and
- dynamic load testing: load tests using ambient or forced vibrations to measure the stiffness (called dynamic load tests in this book).

The British guideline is limited to supplementary load testing (diagnostic load testing) as an integral part of the overall assessment procedure for existing bridges. The results of such a load test can be used to improve the existing finite element model based on the field measurements. The updated model is then used for the assessment.

The described procedures can be used for structures and structural elements. The guideline does not recommend testing when a brittle failure mode can occur, such as failure in shear or bearing at the support. Additionally, a structure in poor condition (with excessive deterioration or significant deflections) should not be load tested. It must be verified prior to deciding if a load test is suitable that the instrumentation can be applied where required, and that the results of the load test can be used to improve the analysis. While the British guideline encompasses all types of bridges, it seems to be based mostly on work on masonry arch bridges. The reinforced concrete bridges that were tested (some to failure) to calibrate the proposed method were the Dornie bridge (a beam-and-slab type bridge) (Ricketts and Low 1993) and a series of filler beam bridges (Low and Ricketts 1993).

If possible, load testing should be carried out at night when there is less traffic and bridge deck temperatures are most stable. At a time of the year when the ambient temperatures are high, the surfacing stiffness will be low. This consideration should be kept in mind.

3.2 Preparation and application of loading

An assessment is required prior to the field test in the British guideline. For this assessment the actual dimensions of the bridge elements are to be used. The actual dimensions should be based on site measurements, with due allowances for corrosion and other forms of deterioration.

One difficulty in load testing that is highlighted in the British guideline is that it is often difficult to separate the influence of the different effects that contribute to the overall response. However, supplementary load testing (diagnostic load testing) does provide a way of improving the accuracy of the analytical model used in structural analysis so that it more closely models the behavior of the real structure. The following effects on the structural behavior can be assessed through load testing:

- transverse load distribution;
- composite action: eg. when no shear connectors are provided between the girders and the deck;
- restraints at the supports: continuous surfacing over buried joints or friction in the bearings can provide some rotational and translational restraint;
- pin-joint fixity: in truss members, there is always a certain amount of restraint in the connections;
- transverse compression, or arching action: this effect can occur in concrete deck slabs of beam-and-slab type bridges.

The applied loading during the load test should reflect the current vehicle construction and use regulations, including allowances for overloading and the dynamic behavior of the vehicles. The magnitude of the load used during the load test is determined based on the following criterion: the applied load should produce measurable elastic deformations, such as deflections or surface strains, without causing permanent damage. Possible methods of load application that are suggested in the guidelines are:

- dead weights or kentledge blocks as distributed or concentrated loads, applied directly on the deck or on a frame spanning the structure to apply concentrated loads to the deck by jacking against the dead weight;
- flexible water bags that provide dead weight for testing;
- jacking systems reacting against ground or rock anchors;
- an HB single-axle trailer which holds kentledge units symmetrically about the axle and can provide single axle loading of maximum 45 ton (99 kips);
- loaded vehicles, indicated as the most commonly used method of bridge testing, usually 30 or 32 ton (66 or 73 kips) four axle rigid aggregate lorries, filled to the desired load and weighed at a weighbridge or with portable weigh pads;
- railway loading for railroad bridges with locomotives as static or moving loads.

3.3 Evaluation of the load test

For the interpretation of the test results, the obtained measurements (of strains and/or displacements) are used to determine an improved value of the safe load-carrying capacity of the structure. A first step in the analysis deals with the comparison of measured and calculated results in terms of:

- Linearity: changes in the loading should correspond to pro-rate changes in deflections and strains. All measured responses should return to zero when the load is removed.
- The effect of the dead load on the structure and the proportion of the load-carrying capacity required to carry these loads needs to be determined.
- The tested stiffness needs to be compared to the stiffness assumed in the calculations and finite element model.

- Local effects should be considered. For example, if concentrated loads are applied on the deck, and strain measurements are taken around the load, it can be evaluated if membrane action occurs.

In terms of estimating the structural capacity and ultimate limit state, the guideline clearly states: “It is this relatively complex and unique nature of most bridge structures that makes it impossible to derive a safe load capacity directly from load tests in the elastic range with any degree of confidence. The most effective role of supplementary load testing is in providing a better understanding of the global and local behavior of a particular structure and hence in improving the analytical model so that it more closely mirrors that of the real structure.” Extra strength can be attributed to the structure for the following cases:

- If relevant data from collapse tests is available, and the structural actions could be arrived from these collapse data, and they can be reliably used at the ultimate limit state.
- If the structural actions are identified by analysis, and can be shown to be reliable.
- If the structural actions are identified by analysis, and the unreliable actions can be retrofitted.
- If the structural actions are identified by analysis, and the unreliable actions can be monitored.
- If the structural actions are identified by analysis, and the unreliable actions can be verified periodically with load tests.

4 IRISH GUIDELINES

4.1 General

In Ireland, a manual for load testing is available (NRA 2014). This manual is suitable for older metal bridges and older concrete bridges that may be found to be substandard when assessed using the calculation methods from the currently governing assessment standards. Load tests can be used to increase the assessed capacity, so that sources of reserve capacity can be taken into account. Only diagnostic load tests are permitted by the Irish guidelines. Such load tests should be considered an accompaniment to the assessment calculations. When upon assessment a bridge is found to be insufficient for shear, load testing is not recommended, or the load levels should be limited. Proof load tests, which are a self-supporting alternative to a theoretical assessment, are not permitted.

Load testing should only be used for bridges that have insufficient capacity according to an assessment, and where there is a realistic possibility of improving the assessed capacity to a level of significant benefit.

4.2 Recommendations for applied loading

The applied loading in the field test can be one or more vehicles, axle or patch loads, or combinations thereof. A single procedure that should be followed for the prescribed diagnostic load tests is not provided and each case has to be treated individually. The loading can be used to generate the bending moments produced by the assessment live loading, for example, and should be applied in increments. The structural responses should be kept within the elastic range of the bridge flexural behavior.

The loading needs to reflect the traffic of the day in a safe and conservative way. Increases in the assessment live load to take into account include the following:

- axle impact effects;
- overloading of vehicles; and
- bunching of vehicles for bridges with loaded lengths less than 50 m (164 ft).

The load levels in the tests should not exceed those caused by the loads carried by the bridge on a day to day basis.

4.3 Evaluation of the load test

After the field test, the measurements of strains and deflections can be used to assess the hidden reserve capacity in the bridge, and each possible source of hidden strength should be examined, possibly based on knowledge gained in earlier collapse tests on similar bridges. This additional source of strength can then be implemented into the assessment calculations. Extrapolation from load tests at fairly low load levels to ultimate limit state conditions is not recommended, unless earlier collapse tests have been carried out on bridges with similar materials and details.

5.1 Bridges: Manual for Bridge Rating through Load Testing

5.1.1 *General*

The “Manual for Bridge Rating through Load Testing” (NCHRP 1998), used in North America, links the concepts of load testing and bridge rating. The manual is valid for all types of bridges, except long span bridges, shear-critical concrete beam bridges, bridges with an extremely low capacity analytically, bridges with frozen joints that could cause a sudden release of energy, steel bridges with fracture-critical members, and bridges on poor soil and foundation conditions. The concepts from this manual are also repeated in the Manual for Bridge Evaluation (MBE) (AASHTO 2011).

The Manual describes diagnostic load tests as tests in which the load is placed at designated locations and the effects of this load on individual members of the bridge are measured by the instrumentation attached to these members. The measurements are then compared to computed effects. Proof load tests are described as tests in which the bridge is loaded up to its elastic limit, when the test is stopped and the maximum load and position are recorded. In some cases, a target proof load is established prior to the test, and the load test is stopped when this goal is reached. Note that all other codes and guidelines require the determination of the target proof load prior to a proof load test.

The goal of the Manual is to establish realistic safe service live load capacities for bridges. For load rating, the MBE (AASHTO 2011) currently prescribes the following expression to determine the rating factor *RF* for LRFR (Load and Resistance Factor Rating):

$$RF = \frac{C-(\gamma_{DC})(DC)-(\gamma_{DW})(DW)\pm(\gamma_P)(P)}{(\gamma_{LL})(LL+IM)} \tag{6}$$

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

$$C = \varphi_c \varphi_s \varphi R_n \text{ with } \varphi_c \varphi_s \geq 0.85 \tag{7}$$

In Equation (7), R_n is the nominal member resistance as inspected. For the Serviceability Limit States, the capacity *C* is determined as:

$$C = f_R \tag{8}$$

with f_R the allowable stress specified in the LRFD Code (AASHTO 2015). In Equation (6), *DC* is the dead load effect due to structural components and attachments, *DW* is the dead load effect due to wearing surface and utilities, P is the effect from the permanent loads other than dead loads, LL is the live load effect, and IM is the dynamic load allowance. The following load and resistance factors are defined in Equations (6), (7), and (8): γ_{DC} is the LRFD load factor for structural components and attachments, γ_{DW} is the LRFD load factor for wearing surfaces and utilities, γ_P is the LRFD load factor for permanent loads other than dead load, which equals 1.0, γ_{LL} is the evaluation live load factor, ϕ_c is the condition factor, ϕ_s is the system factor, and ϕ is the LRFD resistance factor.

In a diagnostic load test, the live load effect from Equation (6) is measured directly during the test in one or more critical bridge members. These values are then compared with the values computed by an analytical model. The difference between the theoretical and measured load effects is used to update the analytical model, and then to determine the load rating for a bridge member. The difference is caused by uncertainties about bridge behavior (material properties, boundary conditions, effectiveness of repairs, unintended composite action, and effect of damage and deterioration) or as part of routine parametric determinations (e.g. load distribution, impact factors). The contribution from nonstructural components (non-composite deck slabs or parapets) may cease at higher load levels, so that the applied load should be "sufficiently high".

In a proof load test, on the other hand, the capacity of the bridge to carry live load, which is the numerator of Equation (6), is measured. According to the Manual for Bridge Rating through Load Testing, a test should be terminated when:

1. a predetermined maximum load (the target proof load) has been reached, or
2. the bridge exhibits the onset of non-linear behavior or other visible signs of distress.

Moreover, the Manual for Bridge Rating through Load Testing mentions other types of non-destructive load tests, such as:

- load identification (based on WIM data);
- tests for unusual forces (effects of stream flow, ice, wind pressure, seismic action and thermal response, which are not part of the usual rating procedures);
- dead load effects (by using residual stress gages for steel members, or by jacking, which is a dangerous procedure);
- dynamic effects to determine the bridge frequency and damping (by using moving loads, portable sinusoidal shakers, sudden release of applied deflections, sudden stopping of vehicles by braking, or impulse devices);

- impact (influence by the surface roughness of the deck and bumps on the bridge approach);
- fatigue for steel highway bridges.

5.1.2 *Preparation of load tests*

The first step in preparing a load test, is identifying if a load test is a suitable procedure to determine the unknown information necessary for the bridge load rating. The types of bridges that have been identified in the Manual for Bridge Rating through Load Testing as interesting for load testing are:

- slab bridges, for which a load test can be used to determine the transverse load distribution;
- multi-stringer bridges, to determine the distribution of the load to the stringers, the effect of composite action, and the effect of restraints at the stringer and girder supports;
- two-girder bridges, where the structure is made partially continuous because the deck slab is made continuous over the transverse floor beams;
- truss bridges, to quantify the restraint in the joints;
- masonry arch bridges, which typically are rather old;
- rigid frame bridges, where proof load tests can establish a safe service load;
- timber bridges, in which the material properties are time-dependent.

When a load test seems to be useful for the bridge under consideration, the next step required by the Manual for Bridge Rating through Load Testing is an inspection of the bridge. This inspection should determine the condition of the bridge, determine occurring damage, and help assess the actual dead loads by, for example, measuring the thickness of the asphalt layer. These results are then used for a preliminary rating, according to Equation (6). In this phase, it is determined if load testing is a feasible alternative for establishing the load rating. If the rating factor is larger than one, a load test is unnecessary. If the rating factor is much smaller than one, it is unlikely that a load test will be able to bring the rating factor up to a value larger than or equal to one. Therefore, the most suitable candidate bridges for load testing are those with a rating factor smaller than one, but close to one. The initial calculations are also necessary for defining the sensor plan.

5.1.3 *Execution of load tests*

The elements of the execution of load tests that are discussed in the Manual for Bridge Rating through Load Testing are the target load, the loading system, and the possibilities for sensors.

The required load depends on the type of load test. For a diagnostic load test, the load levels are around service levels, and usually involve one or two loaded dump trucks. The test load should stress all critical elements that need to be evaluated in the load test. The required load during a proof load test is higher, and is closely related to the rating factor. It will be discussed in §5.1.5.

The loading system can be stationary loading with heavy blocks or with jacks, or moveable loading with test vehicles that simulate the legal vehicles, and that move at crawl speed or at normal operating speeds. The loading system should fulfill the following requirements:

- it should be representative of the rating vehicles;
- the load should be adjustable in magnitude;
- loads should be maneuverable;
- loads should allow for repeatability to check the linearity of the bridge response and return of response to zero.

The Manual also states that for multiple-lane bridges, a minimum of two lanes should be loaded concurrently.

The Manual for Bridge Rating through Load Testing does not rigidly prescribe a certain loading protocol. Critical test load cases should be repeated at least two times or until correlation between each repetition is obtained. This correlation between the results for repeated load positions generally indicates elastic behavior and provides assurance that the test instrumentation is performing correctly. For proof load tests, the first-stage loading should not exceed 25% of the target load. and the second stage should not exceed 50% of the target load. Smaller increments of loading may be warranted, particularly when the applied proof load approaches the target load.

During a load test, displacements, strains, rotations and crack widths must be measured. These measurements are taken at the start of the load test and the end of each load increment. The measurements should then be compared to the predicted response from the preliminary calculations to detect unusual behavior. The load-deformation response and deflection recovery should be monitored very closely to determine the onset of nonlinear behavior, which is used as a stop criterion for proof load tests in the Manual for Bridge Rating through Load Testing. In a standard proof load test according to the Manual, only the applied loads and resulting displacements are monitored. If more extensive instrumentation is applied, the test is considered a mixed test, including elements from diagnostic load testing. The Manual also contains an extensive description of possibilities for load test instrumentation, albeit outdated.

5.1.4 *Determination of the rating factor after a diagnostic load test*

For a diagnostic load test, the rating factor after the test can be updated based on the observations made during the load test. One has to be careful when extrapolating the results of the diagnostic load test to higher load levels. The Manual for Bridge Rating through Load Testing proposed the following equation to update the rating factor prior to the test RF_C from Equation (6) to the rating factor based on the test results RF_T:

$$RF_T = RF_c \times K \tag{9}$$

In Equation (9), K is an adjustment factor resulting from the comparison of measured test behavior with the analytical model, given as:

$$K = 1 + K_a \times K_b \tag{10}$$

The factor K_a accounts for both the benefit derived from the load test, if any, and considerations of the section factor resisting the applied test load. K_a captures the test benefit without the effect of unintended composite action, which cannot be extrapolated to higher load levels. The value of K_a can be determined as follows:

$$K_a = \frac{\varepsilon_c}{\varepsilon_T} - 1 \tag{11}$$

In Equation (11), ε_T is the maximum member strain measured during the load test, whereas ε_c is the corresponding theoretical strain due to the test vehicle and its position on the bridge which produced ε_T. The value of ε_c can be determined analytically as:

$$\varepsilon_c = \frac{L_T}{(SF)E} \tag{12}$$

In Equation (12), L_T is the calculated theoretical load effect in member corresponding to the measured strain ε_T, SF is the member appropriate section actor (area, section modulus…), and E is the member modulus of elasticity.

The second factor in Equation (10) is the factor K_b. This factor K_b takes differences between the actual behavior of the bridge and the revised analytical model into account, specifically with regard to lateral and longitudinal load distribution and the participation of other members, and consists of several elements:

$$K_b = K_{b1} \times K_{b2} \times K_{b3} \tag{13}$$

The factor K_{b1} in Equation (13) takes into account the analysis performed by the load test team and their understanding and explanations of the possible enhancements to the load capacity observed during the test. K_{b1} = 0 reflects the inability of the test team to explain the test behavior or validate the test results, whereas K_{b1} = 1 means that the test measurements can be directly extrapolated to performance at higher loads corresponding to the rating levels. Intermediate values can be derived based on the test vehicle effect T and the gross rating load effect W, see Table 2.

The second factor, K_{b2} takes into account the ability of the inspection team to find problems in a timely manner to prevent changes in the bridge condition that could invalidate the test result. The value of K_{b2} depends on the type and frequency of inspection, and can be found in Table 3.

The last factor, K_{b3} accounts for the presence of critical structural features which cannot be determined in a diagnostic test, and which could contribute to sudden fatigue, fracture, or instability failure of the bridge. The value of K_{b3} is determined as given in Table 4.

Table 2: Determination of K_{b1}

Can member behavior be extrapolated to 1.33W?		Magnitude of test load			K_{b1}
Yes	No	$T/W < 0.4$	$0.4 \leq T/W \leq 0.7$	$T/W > 0.7$	
x		x			0
x			x		0.8
x				x	1
	x	x			0
	x		x		0
	x			x	0.5

Table 3: Determination of K_{b2}

Inspection		K_{b2}
Type	Frequency	
Routine	between 1 and 2 years	0.8
Routine	less than 1 year	0.9
In-depth	between 1 and 2 years	0.9
In-depth	less than 1 year	1.0

Table 4: Determination of K_{b3}

Fatigue controls?		Redundancy?		K_{b3}
No	Yes	No	Yes	
	x	x		0.7
	x		x	0.8
x		x		0.9
x			x	1.0

5.1.5 *Determination of the rating factor after a proof load test*

For a proof load test, the maximum applied load is a lower bound on the live load capacity of the bridge. The target proof load should cover uncertainties, in particular the possibility of bridge overloads during normal operations, as well as the impact allowance. The goal of the target proof load is to result in a rating factor of one after the proof load test. The rating factor is one if the test safely reaches the legal rating plus the impact allowance magnified by the target live load factor X_{pA} during the proof load test, which is determined as:

$$X_{PA} = X_P \left(1 + \frac{\Sigma\%}{100}\right) \tag{14}$$

In Equation (14), X_P is the factor prior to adjustments, which equals 1.4. This factor is adjusted as follows (represented by Σ% in Equation (14)):

- X_p needs to be increased by 15% if one lane load controls the response.
- For spans with fracture critical details, X_p shall be increased by 10%.
- If routine inspections are performed less than every 2 years, X_p should be increased by 10%.
- If the structure is ratable, i.e. has no hidden details, X_p can be reduced by 5%.
- Additional factors including traffic intensity and bridge condition may also be incorporated in the selection of the live load factor X_p.

The resulting value for X_{pA} lies between 1.3 and 2.2. Once X_{pA} is known, the target proof load L_T can be calculated as:

$$L_T = X_{PA} L_R \left(1 + I\right) \tag{15}$$

L_R is the comparable live load due to the rating vehicle for the lanes loaded, and I is the AASHTO specifications impact allowance.

The maximum load applied during the proof load test is L_p. This value can be the target proof load L_T when the test is successful, or a lower load level if nonlinearity occurred prior to reaching L_T. The capacity at the operating level is then determined based on L_P as follows:

$$OP = \frac{k_O L_P}{X_{PA}} \tag{16}$$

The value of k_O equals 1.0 if the target proof load was achieved during the test, and equals 0.88 if the test had to be terminated because nonlinear behaviour was observed. The rating factor at the Operating Level is then calculated as:

$$RF_O = \frac{OP}{L_R \left(1 + I\right)} \tag{17}$$

From the previous analyses, it can be seen that for X_P = 1.4 the rating factor at the operating level equals 1.0. This analysis at the operating rating level corresponds to a reliability index of 2.3. The lower beta value is justified as it reflects past rating practice at the operating levels. The factor X_P = 1.4 is derived to match this reliability index, based on a first order reliability approach.

5.2 **Buildings**

5.2.1 *ACI 437.1 "Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria"*

For load tests on buildings in the USA, ACI provides a number of documents that will be discussed in this chapter since these documents have influenced the discussion on the determination of the target proof load and the stop criteria for proof load testing of bridges. For new and existing structures, ACI 437.1R-07 (ACI Committee 437 2007) describes the procedures, the target proof load, the load testing protocol, and the acceptance criteria. Similar provisions can be found in ACI 318-14 (ACI Committee 318 2014) for new buildings. For existing structures, ACI 437.2M-13 (ACI Committee 437 2013) describes the procedures, the target proof load, the load testing protocol, and the acceptance criteria. Similar provisions can be found in ACI 562-16 (ACI Committee 562 2016) for existing buildings. ACI 562-16 fully refers to ACI 437.2M-13 for load testing.

This section summarizes the provisions for load tests on structures that are given in ACI 437.1R-07 (ACI Committee 437 2007). This report provides the background to a new proposal of ACI Committee 437 with regard to the target proof load, so that the proof load testing procedures can be aligned to changes made to the ACI building code in its 2002 version. The recommendations from the report can be applied to normal strength concrete structures and buildings, but not to bridges. The goal of the proof load tests described by ACI 437.1R-07 (ACI Committee 437 2007) is to "show that a structure can resist the working design loads in a serviceable fashion where deflections and cracking are within limits considered acceptable by ACI 318."

In ACI 437.1R-07 (ACI Committee 437 2007), the target proof load, called "test load magnitude" is redefined. Parameter studies showed that defining the test load as a constant percentage of the required design strength results in the fact that the relationship between the proof load applied to the structure and the service live load is not apparent and is not a reasonably constant ratio. Moreover, defining the test load as a combination of a factored dead and live load makes the relationship between the target proof load and the service live loads variable. For this reason, it is recommended to separate the dead load into the components that do not vary (the dead load due to self-weight D_w) and those that vary (the dead load due to weight of construction and other building materials, i.e. the superimposed dead load D_s). For the dead load due to self-weight D_w, a load factor of 1.0 is proposed, whereas for the superimposed dead load D_s a factor greater than 1.0 is proposed, since these loads may change over time depending on the owner's use of the facility, and construction and maintenance means and methods. If only portions of the suspect areas of a structure can be tested, a higher test load is recommended to improve the level of confidence that significant flaws or weaknesses in the design, construction, or current condition of the structure are made evident by the load test. The resulting recommendation for the test load magnitude *TLM* for the case when all suspect portions of a structure are to be load tested or when the members to be tested are determinate and the suspect flaw or weakness is controlled by flexural tension is that the test load magnitude *TLM* shall not be less than:

$$TLM = 1.2\left(D_w + D_s\right) \tag{18}$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.4L + 0.4\left(L_r \text{ or } S \text{ or } R\right) \tag{19}$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.4\left(L_r \text{ or } S \text{ or } R\right) + 0.9L \tag{20}$$

In Equations (19) and (20), L_r is the live load on the roof, S is the snow load, and R is the rain load.

When only part of suspect portions of a structure is to be load tested and members to be tested are indeterminate, the test load magnitude *TLM*, including the dead load already in place, shall not be less than:

$$TLM = 1.3\left(D_w + D_s\right) \tag{21}$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.6L + 0.5\left(L_r \text{ or } S \text{ or } R\right) \tag{22}$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.6\left(L_r \text{ or } S \text{ or } R\right) + 1.0L \tag{23}$$

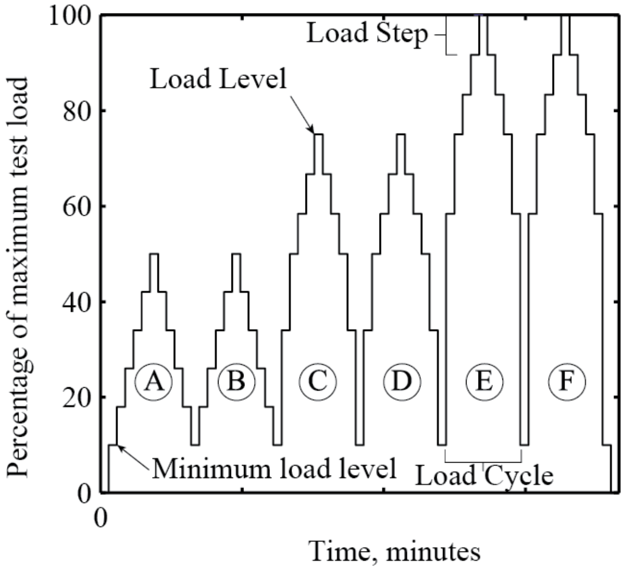

Figure 2: Cyclic loading protocol from ACI 437.1R-07. Reprinted with permission from ACI.

The load can be applied as a uniformly distributed load with dead weights, or with a series of concentrated loads to simulate the effects (bending moment and shear forces) of a uniformly distributed load by using patch or strip equivalent loads. Two loading procedures are allowed: monotonic loading, and cyclic loading, see Figure 2. For monotonic loading, at least four load increments are used. No sketch of the monotonic loading protocol is given in ACI 437.1R-07. Cyclic loading has the advantage that parameters such as the linearity of the structural deflection response, repeatability of the load-deflection response, and permanency of deflections can be measured. The load cycles at low load levels also help the engineer to better understand end fixity and load transfer characteristics of the tested member by comparing the actual deflection responses with the calculated deflection responses. The duration of loading at the maximum load can be 24 hours, which is the traditional ACI approach, or a shorter duration (approximately 2 minutes). Planning a cyclic load test involves more engineering effort and interpretation, and requires more insight in the structural behaviour, including effects of load sharing and end fixity. The advantage of a cyclic loading test is that it takes less time and that it allows the engineer a real-time assessment of the performance of the structure. At least six loading and unloading cycles should be used. Each load cycle consists of five load steps, see Figure 2. A minimum load P_{min} of at least 10% of the total test load should be maintained between the cycles to keep the test devices engaged.

The acceptance criteria for the 24-hour monotonic load test are based on a set of visual parameters (no spalling or crushing of compressed concrete is evident) and one of the two following expressions with regard to deflections must be satisfied:

$$\Delta_{\max} \leq \frac{l_t^2}{20000h} \tag{24}$$

$$\Delta_{r,\max} \leq \frac{\Delta_{\max}}{4} \tag{25}$$

In Equations (24) and (25), Δ_{max} is the maximum measured deflection, $\Delta_{r,max}$ is the maximum residual deflection, l_t is the span length, and h is the member depth. Equation (24) is unrelated to modern material strengths, deflection limits, degree of fixity that may be present in the structural member being tested. Furthermore, ACI 437.1R-07 mentions that new acceptance criteria for deflection should be developed, which include the maximum deflection under the full test load compared with the calculated theoretical maximum deflection at that load level, recovery of deflection upon full removal of the load; and linearity of deflection response during loading and unloading. Moreover, it is recommended in ACI 437.1R-07 to replace Equation (24) with:

$$\Delta_{\max} \leq \frac{l_t}{180} \tag{26}$$

It is also proposed that the residual deflection should be less than 25% of the corresponding absolute maximum deflection immediately upon unloading or 24 hours afterwards. No check on the deflection recovery is required if the absolute deflection is lower than 1.3 mm (0.05 in) or if the deflection as a percentage of span length is less than $l_t/2000$.

For a cyclic load test, three acceptance criteria are defined. The first acceptance criterion is the repeatability index I_R, which measures the similarity of behaviour of the member or structure during two twin load cycles at the same load level. It is a measure of the recoverable elastic deflection and load-deflection response in general. The repeatability index is calculated with the definitions from Figure 3 as follows:

$$I_R = \frac{\Delta_{\max}^B - \Delta_r^B}{\Delta_{\max}^A - \Delta_r^A} \times 100\% \tag{27}$$

A value of I_R in the range of 95% - 105% is considered satisfactory.

The second acceptance criterion is the permanency index I_P, which is the relative value of the residual deflection compared with the corresponding maximum deflection. The value of I_P should be less than 10%. Higher values indicate that load application has damaged the member/structure and that nonlinear effects are taking place. The value of the permanency index I_P is determined based on the deflections shown in Figure 3 as:

$$I_P = \frac{\Delta_r^B}{\Delta_{\max}^B} \times 100\% \tag{28}$$

The last acceptance criterion for cyclic load tests is the deviation from linearity, which represents the measure of the nonlinear behaviour of a member/structure being tested. Linearity is defined as the slopes of two secant lines intersecting the load-deflection envelop as shown in Figure 4. The linearity at any point *i* on the load-deflection envelope is the percent ratio of the slope of the secant line to point *i*, expressed by $\tan(\alpha_i)$ to the slope of the reference secant line, expressed by $\tan(\alpha_{ref})$, with the angles as shown in Figure 4. The linearity is thus expressed as:

$$Linearity_i = \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} \times 100\% \qquad (29)$$

The deviation from linearity index I_{DL} is then given as:

$$I_{DL} = 100\% - Linearity_i \qquad (30)$$

The value of I_{DL} should be less than 25% and should be monitored continuously during the cyclic load test. When a member/structure is initially uncracked and becomes cracked during the load test, the change in flexural stiffness as a result of a drastic change in moment of inertia can result in a very high deviation from linearity that is not necessarily related to degradation in strength. It is suggested that I_{DL} should only be computed for the member/structure under cracked conditions.

An additional advantage of the cyclic load protocol is that it can be used for load rating. Loading can be continued until one of the acceptance criteria fails. That load level can then be used to calculate the safe live load level. A qualitative acceptance criterion is also formulated: the structure should show no signs of impending failure such as concrete crushing in the compressive zone or concrete cracking exceeding a preset limit. The maximum deflection at the second load cycle that reaches the target proof load should be less than the deflection calculated according to the ACI 318 building code, to make sure the engineer has made a prediction given the available information and that such a prediction be used to interpret the experimental results.

At the service load level, crack spacing and width should be analysed. The variable nature of cracking and the challenges in accurately measuring and predicting crack width make the corresponding limits difficult to implement. The engineer should determine a limiting crack width. The maximum measured deflection should not exceed the permissible values from ACI 318.

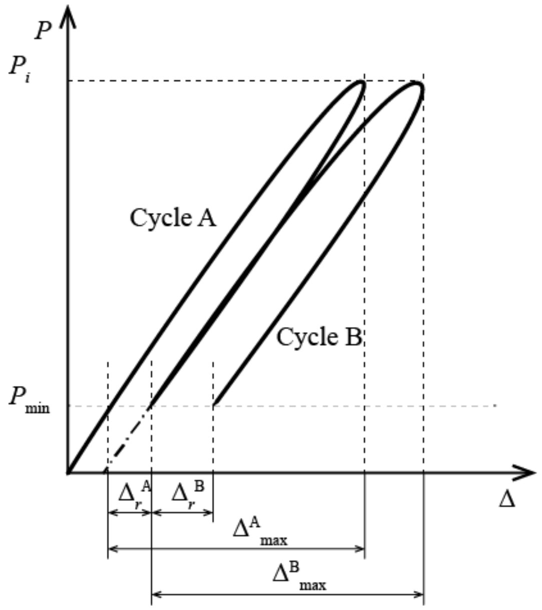

Figure 3: Load-deflection curve for two cycles at the same load level, used to determine the repeatability index I_R and the permanency index I_p, from ACI 437.2M-13 (ACI Committee 437 2013). Reprinted with permission from ACI.

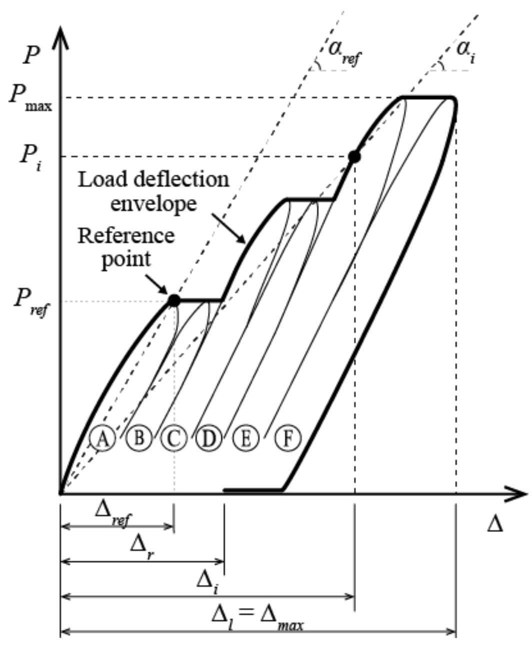

Figure 4: Load-deflection curve for six cycles, used to determine the deviation from linearity index I_{DL}, from ACI 437.2M-13 (ACI Committee 437 2013). Reprinted with permission from ACI.

5.2.2 *New buildings: ACI 318-14*

The ACI 318-14 Building Code (ACI Committee 318 2014) discusses strength evaluation by load testing in §27.4, where the focus is on the evaluation of new buildings through load tests.

These provisions are based on the recommendations from ACI 437.1R-07 (ACI Committee 437 2007). The total test load T_t, including dead load already in place shall be at least the greatest of:

$$T_t = 1.3D \tag{31}$$

$$T_t = 1.15D + 1.5L + 0.4\left(L_r \text{ or } S \text{ or } R\right) \tag{32}$$

$$T_t = 1.15D + 1.5\left(L_r \text{ or } S \text{ or } R\right) + 0.9L \tag{33}$$

with D the dead load, L the live load, L_r the live load on the roof, S the snow load, and R the rain load. The live load L can be reduced in accordance with the general building code.

ACI 318-14 (ACI Committee 318 2014) describes a monotonic loading protocol. The test load T_t is applied in at least four approximately equal increments. If a uniformly distributed load is used, arching must be avoided, since this effect results in a reduction of the load near the mid-span. T_t must remain on the structure for at least 24 hours, unless signs of distress are observed. Response measurements such as deflection, strain, slip, and crack width shall be made at locations where maximum response is expected, and these measurements must be recorded after each load increment and after T_t has been applied to the structure for at least 24 hours. The last set of measurements is taken 24 hours after T_t is removed.

The acceptance criteria in ACI 318-14 are the following:

1. The portion of the structure tested shall show no spalling or crushing of concrete, or other evidence of failure, including distress (cracking, spalling, or deflection) of such magnitude and extent that the observed result is obviously excessive and incompatible with the safety requirements of the structure. Local spalling or flaking of the compressed concrete in flexural members related to casting imperfections need not indicate overall structural distress.

2. Members tested shall not exhibit cracks indicating imminent shear failure, i.e. when crack lengths increase to approach a horizontal projected length equal to the depth of the member and widen to the extent that aggregate interlock cannot occur, and as transverse stirrups, if present, begin to yield or display loss of anchorage so as to threaten their integrity.

3. If no transverse reinforcement is available, structural cracks inclined to the longitudinal axis and having a horizontal projection greater than the depth of the member shall be evaluated, as these may lead to brittle failure.

4. In regions of anchorage and lap splices of reinforcement, short inclined cracks or horizontal cracks along the line of reinforcement shall be evaluated. These cracks can indicate high stresses associated with the transfer of forces between the reinforcement and the concrete, and may be indicators of impending brittle failure of the member.

5. The measured deflections Δ_l (maximum deflection after 24 hours of load application) and Δ_r (residual deflection 24 hours after removal of the test load) shall satisfy:

$$\Delta_1 \leq \frac{l_t^2}{20000h} \tag{34}$$

$$\Delta_r \leq \frac{\Delta_1}{4} \tag{35}$$

In Equation (34) l_t is the span of the member, taken as the shorter span for two-way slab systems and h is the overall thickness of the member.

Retesting 72 hours after removal of the loads is allowed if the deflection criteria are not satisfied in the first test. The acceptance criterion for deflection in the retest becomes a function of Δ_2, the maximum deflection during the retest after 24 hours of load application:

$$\Delta_r \leq \frac{\Delta_2}{5} \tag{36}$$

If the deflection criteria are not satisfied, the structure shall be permitted for use at a lower load rating.

5.2.3 *Existing buildings: ACI 437.2M-13*

ACI 437.2M-13 (ACI Committee 437 2013) gives the code requirements for load testing of existing concrete structures. This code prescribes procedures and acceptance criteria for load testing of existing concrete structures, and is valid for application where ACI 562-13 governs. It cannot be applied to bridges. The code is valid for prestressed and reinforced concrete, provided that the concrete compressive strength is not larger than 55 MPa (8.0 ksi).

The test load magnitude *TLM*, when only part of the portions of a structure are suspected of containing deficiencies or that have been repaired or rehabilitated and whose adequacy is to be verified, and the members are statically indeterminate, is the larger of:

$$TLM = 1.3\left(D_W + D_S\right) \tag{37}$$

$$TLM = 1.0D_W + 1.1D_S + 1.6L + 0.5\left(L_r \text{ or } S \text{ or } R\right) \tag{38}$$

$$TLM = 1.0D_W + 1.1D_S + 1.6\left(L_r \text{ or } S \text{ or } R\right) + 1.0L \tag{39}$$

In Equations (37), (38), and (39), D_w is the self-weight based on a density of 24 kN/m^3 (150 lb/ft^3), D_s is the superimposed dead load, L is the live load due to use and occupancy of the building, S is the snow load, R is the rain load, and L_r is the live load on the roof produced during maintenance by workers, equipment, and materials, or during life of the structure by moveable objects such as planers and people.

When all suspect portions of a structure are to be load tested, or when the elements to be tested are determinate, and the suspect flaw or weakness is controlled by flexural tension, the following equations are used to determine the test load magnitude *TLM*:

$$TLM = 1.2\left(D_W + D_S\right) \tag{40}$$

$$TLM = 1.0D_W + 1.1D_S + 1.4L + 0.4\left(L_r \text{ or } S \text{ or } R\right) \tag{41}$$

$$TLM = 1.0D_W + 1.1D_S + 1.4\left(L_r \text{ or } S \text{ or } R\right) + 0.9L \tag{42}$$

For the evaluation of serviceability, the following test load level has to be included in the loading cycles:

$$TLM_{SLS} = 1.0D + 1.0L + 1.0\left(L_r \text{ or } S \text{ or } R\right) \tag{43}$$

If the ratio of service live loads to service dead loads exceeds 2.0, and if the suspect deficiency is tension-controlled, the load factor applied to the live load L in Equation (38) can be reduced to 1.4 and in Equation (41) to 1.3. Similarly, the load factor applied to roof live loads, snow load, or rain loads (L_r or S or R) in Equation (39) can be reduced to 1.4 and in Equation (42) to 1.3.

As in ACI 437.1R-07 (ACI Committee 437 2007), two loading protocols are described: a monotonic loading protocol and a cyclic loading protocol. The monotonic loading protocol uses at least four approximately equal increments, see Figure 5. The applied sustained load should be +- 5% of the full applied test load *ATL*, which is applied for 24 hours. The deflections are measured after applying each load level until stabilization of the deflections, i.e. when the difference between successive deflection readings maximum 2 minutes apart does not exceed 10% of the initial deflection. Each load step is held constant at least for 2 minutes. Measurements are taken at the beginning and end of the 24-hour loading time, and the last set of measurements is taken 24 hours after removing the load.

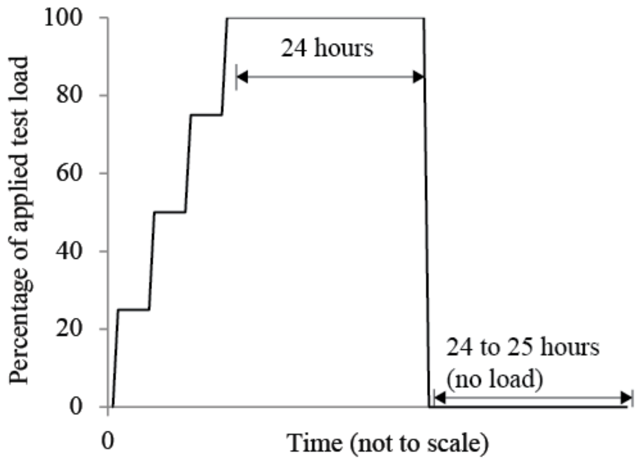

Figure 5: Loading protocol for monotonic load test procedure from ACI 437.2M-13 (ACI Committee 437 2013). Reprinted with permission from ACI.

The cyclic loading protocol is identical to the protocol described in ACI 437.1R-07, and shown in Figure 2. At least six cycles are used, with cycles A and B at the serviceability load level or 50% of *ATL*, cycles C and D halfway between cycles A and B and 100% *ATL* and cycles E and F at 100% *ATL*. A +- 5% tolerance for the applied load for each load cycle is acceptable. A minimum load level of 10% – 15% of *ATL* should be used to keep the test devices engaged. The load is typically applied through hydraulic devices. This method allows to understand end fixity and load transfer characteristics of the tested member, especially for statically indeterminate structures. The same criterion for the stabilization of the deflections governs as for the monotonic loading protocol.

For a load test, the measurements must be taken where maximum responses are expected, and must have a resolution no larger than 1/100 of the expected deflection. A sampling rate of 1/s during the test and 1/min for the 24-hour loading time is recommended. The structure must be visually inspected after each load level.

The acceptance criteria that are used depend on the chosen loading protocol. For both protocols, the first acceptance criterion is that the structure shows no evidence of failure. When deflections exceed the calculated deflections, when cracking is observed, or when distress is observed that could result in a brittle failure type (anchorage failure, bond failure, shear failure …) the test should be terminated.

For monotonic loading, the quantitative acceptance criterion is based on deflections, and uses the maximum deflection Δ_l, the span length l_t, and the residual deflection Δ_r:

$$\Delta_r \leq \frac{\Delta_l}{4} \tag{44}$$

$$\Delta_l \leq \frac{l_t}{180} \tag{45}$$

The deflections are considered as non-existent if the maximum deflection during the test Δ_l is less than 1.3 mm (0.05 in) or l_t/2000. If the criteria from Equations (44) and (45) are not met, re-testing can be permitted, minimum 72 hours after removal of the test load for the first test. For a retest, the deflection Δ_{rrt} at least 24 hours after removal of the load has to fulfill:

$$\Delta_{rrt} \leq \frac{\Delta_{l2}}{10} \tag{46}$$

with Δ_{l2} the maximum deflection measured during the second test relative to the position of the structure at the beginning of the second test.

For a cyclic loading protocol, acceptance criteria are defined that require the use of the loading protocol as shown in Figure 2. These criteria follow the same basic idea of the acceptance criteria from ACI 437.1R-07 (ACI Committee 437 2007), but are defined slightly different. The first acceptance criterion is the deviation from linearity index, I_{DL}, which is based on the slope of the reference secant line for the load deflection envelope, tan(α_{ref}) and the secant stiffness of any point i on the increasing loading portion of the load-deflection envelope, tan(α_i), see Figure 4. The acceptance criterion for the deviation from linearity index I_{DL} is:

$$I_{DL} = 1 - \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} \leq 0.25 \tag{47}$$

If the load test induces cracking, the test may be restarted. The second stop criterion is based on the permanency ratio I_{pr}. I_{pr} is determined for each pair cycles of a cyclic loading test. The acceptance criterion for the permanency ratio I_{pr} equals:

$$I_{pr} = \frac{I_{p(i+1)}}{I_{pi}} \leq 0.5 \tag{48}$$

where I_{pi} and $I_{p(i+1)}$ are the permanency indexes calculated for the i-th and (i+1)-th load cycles, see Figure 3 (replace "A" with "i" and "B" with "i+1" in the figure):

$$I_{pi} = \frac{\Delta_r^i}{\Delta_{max}^i} \tag{49}$$

$$I_{p(i+1)} = \frac{\Delta_r^{(i+1)}}{\Delta_{max}^{(i+1)}} \tag{50}$$

The third stop criterion that is used for a load test with a cyclic loading protocol deals with the residual deflection Δ_r, measured at least 24 hours after removal of the load. This deflection should fulfil Equation (44). If the acceptance criteria are exceeded, the structure shall be considered to have failed the load test. If the maximum deflection from Equation (45) is fulfilled, retesting is permitted at least 24 hours after complete removal of the test load. Then, the new residual deflection should fulfil Equation (46). If a structure does not fulfil the acceptance criteria, the structure can be used at a lower load rating, except if the load test caused significant damage.

6 FRENCH GUIDELINES

6.1 General

In France, all new bridges have to be load tested to show that the delivered work complies with the contract between the owner and the building party (Cochet et al. 2004). The French National Annex to the Eurocode includes the requirements of quality control of a structure, including load tests. Since the aim of the load test is to relate the structural response to the calculations and modeling, the load tests described by the French guidelines are diagnostic load tests.

For bridges of less than 10 m (33 ft), simplified load tests can be carried out. For these tests, it is not required to measure load effects. When it is necessary to monitor all responses, the following effects can be measured:

- deflections,
- settlements (of the supports),
- horizontal displacements at the supports, abutments, or pylon heads,
- flexural rotations (at the top or bottom of supports),
- strains (on steel members),
- curvatures, and
- tension forces (in hangers).

For rigid frame bridges, slab bridges, and girder bridges, general guidelines are provided. For slab bridges, two trucks of 26 tons (57 kips) per lane are required. The trucks have to be placed so that the maximum support moments and maximum span moments for each support and span are reached. For bridges with spans more than 40 m (131 ft), special requirements are in place, and the preparation has to be carried out on a case-by-case basis.

When a large number of similar bridges are being delivered, at least 10% of these and at least one have to be load tested. For the other bridges, the results of the tested bridges can be extrapolated. For repaired bridges a load test can be used to compare the behavior of the bridge to its original state.

6.2 Recommendations for load application

In France, both dead weight (ballast blocks) and trucks are used for load testing. The maximum load that is applied during the load test should correspond to traffic with a return period between one week and one year. In practice, this load is situated between the frequent traffic loads on the structure and 75% of the live load model from NEN-EN 1991-2:2003 (CEN 2003). The load should never be smaller than the uniformly distributed load on the carriageway of 2.5 kN/m^2 (0.05 kip/ft^2). For bridges that carry exceptional very heavy convoys (French load classes D and E), a different type of load test may be more suitable.

The critical section in the span and over the support needs to be determined, to define the path for the loading vehicle. To limit the necessary number of test vehicles, the maximum load effect caused by the test vehicles as compared to the frequent traffic can be 10% lower. The dynamic forces are covered by using vehicles, and the effect of braking forces can be verified if vehicles of more than 19 ton (42 kips) are used.

Unlike other guidelines which typically focus on highway bridges, the French guidelines also include pedestrian bridges. Of all bridge types, the sidewalks, if present, also should be load tested. These types of load tests are typically carried out with ballast blocks.

6.3 Evaluation of the load test

For the evaluation of the load test, the responses from the analytical models are compared with the measured responses. To make this comparison, an extensive preparation is required. The calculations and hypotheses need to be mentioned, and the sensor plan and driving scheme for the vehicles should be developed based on the critical cross-sections. It also has to be determined how the loads and the measurements will be correlated, and how the load position will be measured. If the inspection prior to the test has identified defects, these can be instrumented during the load test.

After the load test, the analytical model and the measured responses are compared. The measured load effects cannot be larger than 1.5 times the calculated load effects. An inspection after the load test has to be carried out, and the results of this inspection should be compared to the inspection carried out prior to the load test.

7 CZECH REPUBLIC AND SLOVAKIA

7.1 General requirements

In the Czech Republic and Slovakia, load tests of bridges are used to check the quality of structures (Frýba and Pirner 2001). Since the tests compare theoretical assumptions with the actual behavior of the bridge, the types of tests that are carried out are diagnostic load tests (CSN 1996). The code prescribes static, dynamic, and long-term tests of bridges.

Static load tests are required for new bridges with spans greater than 18 m (59 ft). They can also be carried out if demanded by government authorities or by the designer of the bridge. The applied load is determined together with the designer, and the load distribution, measurements points and experimental method are defined prior to the test. An inspection prior to the test is required. The vertical deflections are measured where the effects are expected to be largest, as well as the settlements of supports and the squeeze of bearings. Additionally, it is recommended to measure the temperature of the ambient air and the structure, the strains and stresses, the deformations of other parts of the structure, the development of cracks, and the stability of compressed elements of the bridge.

The load can be applied with locomotives, wagons, rail cranes… for railway bridges, and trucks, track vehicles, building machines, water cisterns... for highway bridges. The applied load should be between 50% and 100% of the standard load including the standard dynamic impact factor. The loading protocol requires a minimum loading time of 30 min on concrete bridges and 15 min on steel bridges. The measurements are recorded at least twice before loading, immediately after loading, and at maximum 10 minute intervals during the test. The loading is usually repeated twice.

7.2 Acceptance criteria

The Czech and Slovak code describes three acceptance criteria, which are expressed based on the total S_{tot}, the permanent S_r and the elastic components S_e of all measured values. The relation between these values is:

$$S_{tot} = S_r + S_e \tag{51}$$

The first acceptance criterion for a load test is the condition of elastic deformation, with S_{cal} the calculated value:

$$\beta < \frac{S_e}{S_{cal}} \leq \alpha \tag{52}$$

The values of α and β depend on the bridge type and are given in Table 5. The second acceptance criterion looks at the condition of permanent deformation:

$$\frac{S_r}{S_{tot}} \leq \alpha_1 \tag{53}$$

with α_1 as given in Table 5. The third acceptance criterion is related to maximum crack widths for concrete bridges, as given in Table 6.

Table 5: Determination of parameters per bridge type (Frýba and Pirner 2001).

Bridge Type	α	α_1	α_2	α_3	β
Prestressed	1.05	0.2	0.5	0.1	0.7
Reinforced	1.10	0.25	0.5	0.125	0.6
Steel	1.05	0.1	0.3	0.05	0.8

Table 6: Limitations to crack widths that can occur in a load test (Frýba and Pirner 2001). Conversion: 1 mm = 0.04 in.

Bridge type	Environmental class	Maximum crack width
Reinforced concrete	1 (dry)	0.4 mm
	2, 3 (humid)	0.3 mm
	4, 5 (aggressive)	0.1 mm
Partially prestressed	1 (dry)	0.2 mm
	2, 3 (humid)	0.1 mm for post-tensioning
		0 mm for prestressing
	4, 5	0 mm
Fully prestressed	any	0 mm

Equation (53) can be modified for new bridges. The loading may be repeated if the effects of the first loading comply with:

$$\alpha_1 < \frac{S_r}{S_{tot}} < \alpha_2 \tag{54}$$

with α_1 and α_2 as given in Table 5. The condition of the permanent deformation now becomes:

$$\frac{S_r}{S_{tot}} < \alpha_3 \tag{55}$$

with α_3 as given in Table 5. If Equation (55) is not fulfilled upon retesting, a third test can be executed, which needs to fulfil:

$$\frac{S_r}{S_{tot}} \leq \frac{\alpha_1}{6} \tag{56}$$

If the measured values do not comply with any of the acceptance criteria, a special investigation and/or long-term observation and/or dynamic testing becomes necessary.

7.3 Dynamic load tests

Dynamic load tests in the Czech Republic and Slovakia are carried out by using railway of highway vehicles or a group of vehicles moving at a constant speed along the bridge. The speed is first 5 km/h (3 mph) and is increased for the next runs of the vehicles or the bridge. Other options for loading are an exciter with a varying frequency for modal analysis, a rocket motor which gives a controlled impulse, and a standard track irregularity for testing highway bridges. For pedestrian bridges, a group of pedestrians can be used.

The acceptance criteria for dynamic tests are as follows. The product of the standard dynamic impact factor δ and the k_{dyn} must fulfil:

$$\delta k_{dyn} \leq 1 \tag{57}$$

with

$$k_{dyn} = \frac{U_{dyn}}{U} \tag{58}$$

U_{dyn} is the response to the test load and U is the response to the standard load without δ at the measured point. The acceptance criterion for the natural frequencies is based on the calculated deviation:

$$\Delta_{(j)} = \frac{f_{(j)theor} - f_{(j)obs}}{f_{(j)theor}} \times 100 \tag{59}$$

with $f_{(j)theor}$ the calculated natural frequency and $f_{(j)obs}$ the measured frequency. The limits to the deviation are given in Table 10. The last acceptance criterion related to the dynamic impact factor is used for railway bridges:

$$(\delta_{obs} - 1)k_{dyn} \leq \delta - 1 \tag{60}$$

with δ_{obs} the measured dynamic impact factor:

$$\delta_{obs} = \frac{S_{\max}}{S_m} \tag{61}$$

and S_{max} is the maximum dynamic response due to the load at the measured point, and S_m is the maximum static response due to the same load at the same point. For the acceptance criterion from Equation (60), a minimum of 10 runs of railway vehicles is required, for which 90% of the tests have to fulfil the acceptance criterion.

Table 7: Limitations to deviation between measured and calculated frequencies (Frýba and Pirner 2001).

Frequency	$f_{(1)}$	$f_{(2)}$	$f_{(3)}$	$f_{(4)}$	$f_{(5)}$
$\Delta_{(j)}$ (%)	-15 to +5	-15 to +10	±15	±20	±25

8 SPANISH GUIDELINES

8.1 General considerations

The Spanish guidelines (Ministerio de Fomento - Direccion General de Carreteras 1999) focus on diagnostic load testing of bridges prior to opening, to confirm proper functioning. A representative service load should be applied. The guidelines mention that the same methods can also be used for existing structures. The guidelines cover static and dynamic load testing. For railway bridges (Ministerio de Fomento 2010), diagnostic load testing prior to opening is also required.

The Spanish guidelines cover highway bridges and pedestrian bridges. Static load tests are compulsory prior to opening a new bridge, whereas dynamic load tests can be used for checking vibrations in structures that require such checks. For all bridges with a span length of larger than or equal to 12 m (39 ft) load testing is obligatory, whereas for shorter bridges the decision lies with the project director. Dynamic testing is required for all concrete bridges with a span length larger than or equal to 60 m (197 ft), as well as for bridges with unusual design, bridges built with new materials, and footbridges. The same criteria are valid for steel and composite bridges. Load tests are required prior to opening as well as after widening or rehabilitation of bridges.

For railway bridges (Ministerio de Fomento 2010), a diagnostic load test is required for every bridge with a span larger than or equal to 10 m (33 ft). The load test should be static and dynamic. When the outcome of the load test is that the observed behavior does not correspond to the analytically predicted behavior, further analyses are required before the bridge can be opened to the traveling public. Moreover, a load test of the bridge, prior to installation of the railway track is recommended (Ministerio de Fomento 2009) to verify the behavior of the structure. Since the railway track is not yet installed, this load test is carried out with trucks.

At the end of the load test, a report needs to be developed, which contains the following information:

- the date of the load test, start and end time of the load test, and personnel present during the load test;
- reference to the project number of the structure and of the load test;
- description of the structure and its condition prior to the load test;
- detailed description of the vehicles used and the different load configurations;
- description of the measurements in terms of range of sensors, selected instrumentation, and numbering and positions of sensors;
- information about the development of the test (starting time of each loading configuration, time between loading and unloading, number of load steps…);
- measurements obtained during the test;
- comparison between analytically determined structural responses and measurements, and verification of acceptance criteria;
- elements observed during the technical inspection before, during, or after the load test;
- additional information: photographs, weather conditions, reference points of surveying if determined, incidents during load test…

The report lies at the basis of the official minutes of the load test, which should be signed by the director of the construction project, the director of the load test, and a representative of the contractor.

8.2 Loading requirements

The load is applied with vehicles. Two standard vehicles can be used: a 26 ton (52 kip) truck with three axles, or a 38 ton (76 kip) truck with four axles. The structure type and geometry, as well as the goals of the load test, then define the number and position of the trucks that are used during the test.

The load should be representative of service load levels with a return period of the load of 5 years. The load should be causing around 60% of the ultimate limit state (ULS) load effect based on the load combination prescribed in the code, and should never cause load effects exceeding 70% of the ULS load effect. A deviation of ±5% from the planned load is accepted for the trucks when they are weighed prior to the load test.

The load should be applied in at least two steps, and complete unloading of the structure after each load step is necessary. The total load (i.e. the target load) should remain on the bridge until stabilization of the measurements occurs.

For pedestrian bridges, distributed loads are recommended, but these loads can be replaced by concentrated loads, provided that they cause the same load effect.

For simply supported bridges, the load should be applied span per span, and every span should be subjected to a load test. For continuously supported bridges, the loading configuration should consider the overall bridge behavior. Loading can be carried out by placing trucks in contingent spans, or by loading alternate spans.

For curved and skewed bridges, the position of the load in the transverse direction becomes important. For such structures, asymmetric loading cases should be added to study the torsional effects.

Where necessary, loading cases to study the transverse distribution should be included in the load test.

Simplified load tests can be carried out for certain cases. For bridges with a number of similar simply supported spans, one in every four spans should be tested with a full load test, and the other spans can be subjected to a simplified load test. For bridges with a number of similar continuous spans, the two end spans should be tested with a full load test, as well as one in every four of the center spans. The remaining spans can be subjected to a simplified load test. Spans are considered similar if no more than 10% of difference in the span length occurs. The full load test should study the maximum flexural response at both supports of the span as well as at mid span. When a number of similar bridges are built during a project, ≤50% of these can be subjected to a simplified load tests, whereas the rest should be tested with a full load test in at least two spans. A simplified load test has the following characteristics:

- the load is applied in one load step;
- a minimal amount of measurements are taken;
- the number of loading configurations is reduced, and can be simplified to a quasi-static test with a truck speed of 5 km/h (3.1 mph)

8.3 Stop and acceptance criteria for static load tests

The Spanish guidelines describe recommended stop and acceptance criteria. Moreover, the guidelines mention that different acceptance criteria are allowed if they are defined during the preparation stage of the test.

The required measurements are the deflection at midspan and the support settlements. For box girder bridges, it is recommended to measure the deflections in the transverse direction for the evaluation of torsional effects. For slab-on-girder bridges, it is required to measure the deflections at three positions in the transverse direction: on the tested girder and then on each side of this girder. For steel and composite bridges, strain measurements should be added. Real-time monitoring of the measurements is recommended.

Besides the measurements of the structural responses, two reference sensors outside of the loaded span(s) should be used to measure the influence of temperature and humidity. Surveying of the bridge prior to opening should be done after the load test.

As mentioned in §8.2, the load should be applied until the measurements are stabilized. Stabilization of the measurements should be evaluated when the total load is on the structure, as well as after unloading. Stabilization of the measurements is first evaluated after 10 minutes with the following expression:

$$|f_{10} - f_0| < 0.05|f_0| \qquad (62)$$

with f_{10} the measurement after 10 minutes and f_0 the instantaneous measured structural response. If the criterion from Eq. (62) is fulfilled, then the measurements are considered as stabilized, and the loading case can be considered as finished, the load can be removed, and the next loading case can be executed. If the criterion from Eq. (62) is not fulfilled, then the stabilization of the measurements is evaluated after 20 minutes with the following expression:

$$|f_{20} - f_{10}| < 0.2|(f_{20} - f_{10})| \tag{63}$$

with f_{20} the measurement after 20 minutes. If the criterion from Eq. (63) is fulfilled, the measurements are considered as stabilized, and the loading case can be considered as finished, the load can be removed, and the next lading case can be executed. If the criterion from Eq. (63) is not fulfilled, the director of the load test decides if the load should kept for a longer period of time until stabilization occurs, or if the load should be removed and the test terminated. In the latter case, further analyses are required to study why no stabilization of the structural response was obtained, and retesting may be necessary to open the bridge to the traveling public. An example of the evaluation of the stabilization of measurements after application of the load is shown in Figure 6 and after unloading in Figure 7. A loading cycle is illustrated in Figure 8.

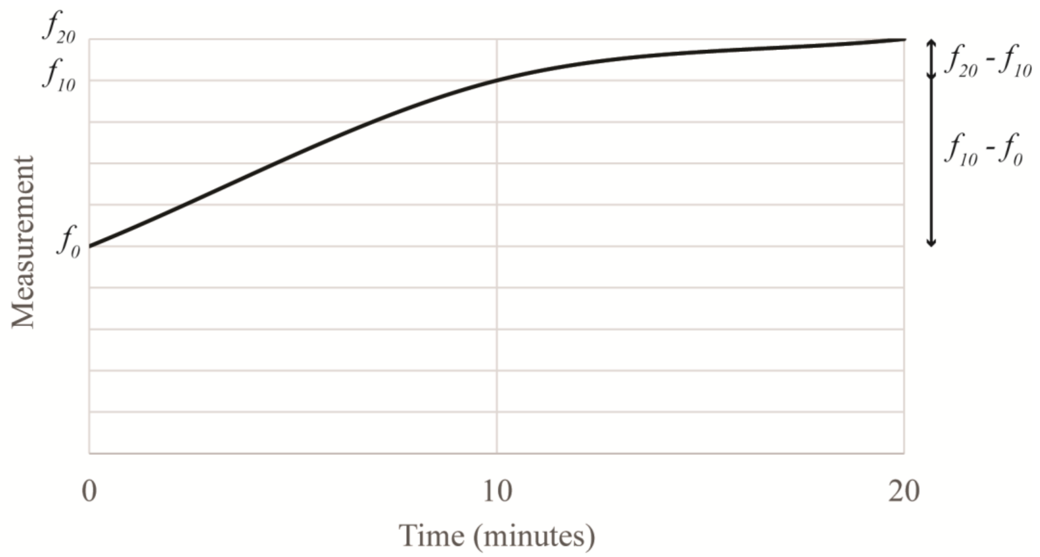

Figure 6: Illustration of procedure for evaluating the stabilization of measurements after application of target load (Ministerio de Fomento - Direccion General de Carreteras 1999).

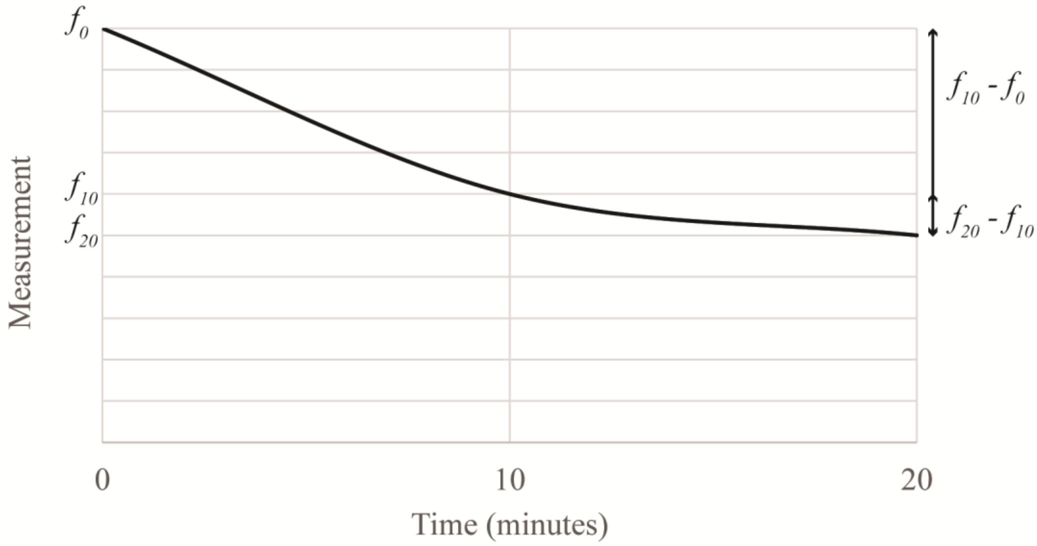

Figure 7: Illustration of procedure for evaluating the stabilization of measurements after unloading (Ministerio de Fomento - Direccion General de Carreteras 1999).

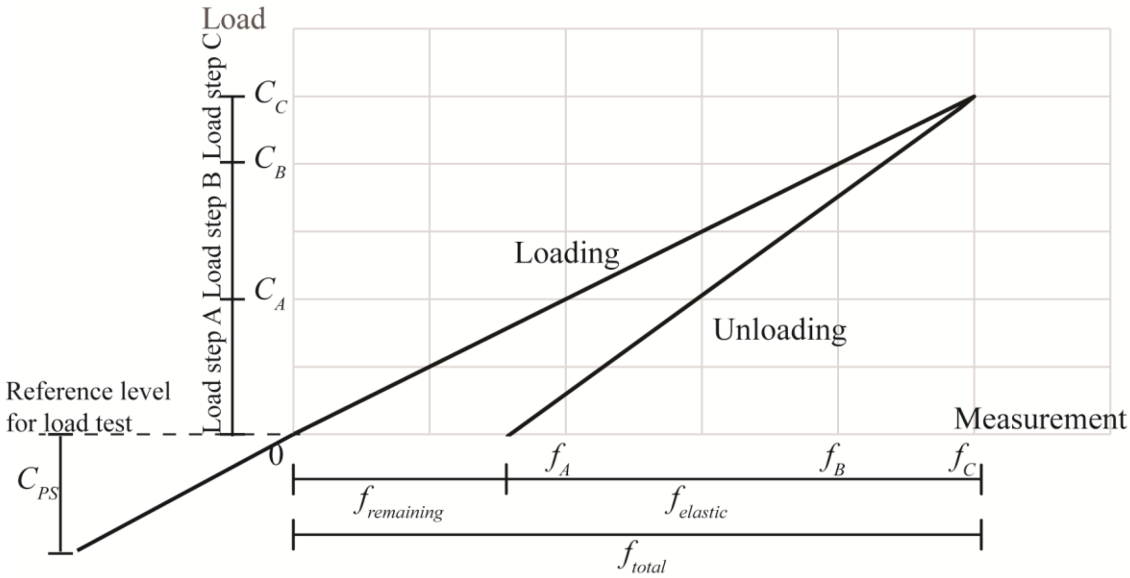

Figure 8: Cycle of loading and unloading. (Ministerio de Fomento - Direccion General de Carreteras 1999)

For static load tests, the stop criteria are defined based on the observed measurements during a load cycle, see Figure 8. The remaining measurement, or permanent measurement, f_r (abbreviated from $f_{remaining}$ in Figure 8) is used to calculate the remanence α:

$$\alpha = 100 \frac{f_r}{f} \tag{64}$$

with f the total measurement. The following limits are defined:

- α_{lim} = 20% for reinforced concrete bridges
- α_{lim} = 15% for prestressed concrete bridges or composite bridges
- α_{lim} = 10% for steel bridges.

In Figure 9, two load cycles are shown, with the measurement in the first cycle f, the remaining measurement after the first cycle f_r, the measurement in the second cycle f^*, and the remaining measurement after the second cycle f_r^*. The stop criterion for the remanence is defined as:

- if $\alpha \leq \alpha_{lim}$, the stop criterion is fulfilled,
- if $\alpha_{lim} < \alpha \leq 2\alpha_{lim}$, a second load cycle has to be applied, see Figure 9,
- if $\alpha > 2\alpha_{lim}$, the load test must be aborted because the stop criterion is exceeded.

When a second load cycle is required, the stop criterion becomes:

- if $\alpha^* \leq \alpha/3$, the stop criterion is fulfilled
- if $\alpha^* > \alpha/3$, the stop criterion is exceeded and further load testing is not permitted.

For this stop criterion, α is the remanence from the first load cycle, and α^* is the remanence from the second load cycle.

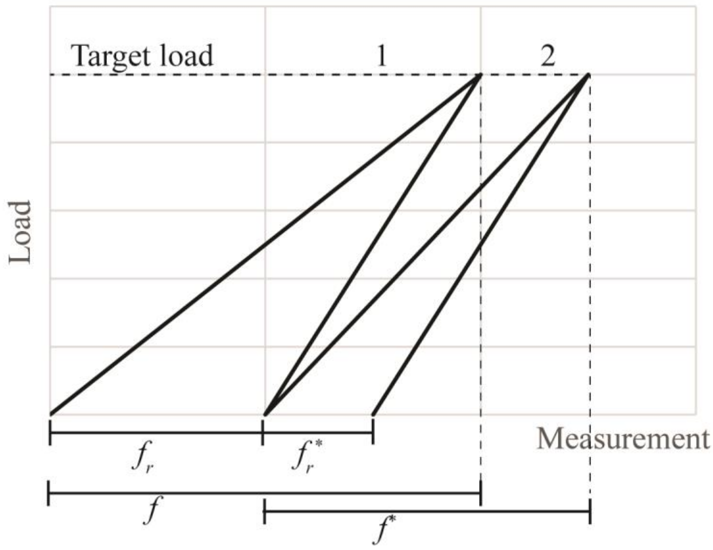

Figure 9: Determination of residual measurements (Ministerio de Fomento - Direccion General de Carreteras 1999).

Four acceptance criteria for static load tests are given. The following acceptance criteria are defined in the Spanish guidelines:

- For prestressed and steel bridges, the maximum measured deflection should not be more than 10% larger than the analytically determined deflection. For composite and reinforced concrete bridges, the maximum measured deflection should not be more than 15% larger than the analytically determined deflection. If the measured deflection is less than 60% of the analytically determined deflection, this discrepancy should be checked and explained.

- For simplified load test, the obtained results should not differ by more than 10% of the results obtained in a full load test. This result should be corrected for the difference in span length, if any. If this acceptance criterion is not fulfilled, a complete load test should be carried out.

- The maximum crack width should not exceed the crack width limits from the serviceability limit state of cracking prescribed by the governing code.

- No signs of distress and exhaustion of the bearing capacity of the structure should be observed.

8.4 Acceptance criteria for dynamic load tests

Dynamic load tests can be carried out to determine the following properties:

- influence lines
- accelerograms
- frequency spectra
- modes of vibration
- impact factor (dynamic amplification)
- damping

The results of a dynamic load test can be analyzed in the time domain or in the frequency domain. The Spanish guidelines define three speeds that can be used in a dynamic load test, depending on the goals of the test:

- slow speed: ≤ 5 km/h (3 mph) (quasi-static test)
- medium speed: between 30 km/h (19 mph) and 40 km/h (25 mph)
- fast speed: > 60 km/h (37 mph), provided that the site conditions allow driving at this speed.

An overview of the different goals of dynamic load tests, and recommendations for their execution is given in Table 8.

Table 8: Recommendations for the execution of dynamic load tests (Ministerio de Fomento - Direccion General de Carreteras 1999)

Goal of test	Loading configuration	Speed of load	Application of obstacle
influence lines	1 truck	slow	no
frequency	1 truck	medium and fast	optional
damping	1 truck	medium and fast	optional
impact factor	1 truck	slow, medium, and fast	no
acceleration	1 or more trucks	medium and fast	no

For special cases, the loading with trucks can be replaced by the application of a forced vibration, braking action, or dropping a weight. For pedestrian bridges, the applied load during a dynamic test should be a group of pedestrians. These pedestrians should cross the bridge by walking and by running. One person of average weight should be used for each meter (3.3 ft) width of the bridge.

The same instrumentation should be applied during a dynamic load test as during a static load test. Additionally, accelerometers should be used. The sampling rate of the sensors should be fast enough to capture the structural responses.

For dynamic load tests, no acceptance criteria are prescribed by the guidelines, given the diversity of types of structures and factors that may affect the structural response. Nevertheless, a few recommended acceptance criteria are summarize in the Spanish guidelines. These recommended acceptance criteria are subdivided between dynamic characteristics of the structure itself, and dynamic characteristics that depend on the applied load.

For the dynamic characteristics of the structure, frequencies and damping are analyzed. For frequencies, the recommended acceptance criterion is that the obtained principal frequency in the experiment should not differ significantly from the calculated value. For damping, the following definition is used:

$$\delta = \frac{1}{n}\ln\left(\frac{A_0}{A_n}\right) \tag{65}$$

with n the number of cycles of the interval with respect to the fundamental frequency, A_0 the dynamic response at the beginning of the interval, and A_n the dynamic response at the end of the interval. It is good practice to use at least 5 to 10 cycles. The values of A_0 and A_n should be obtained from the zone of free vibration of the structure, preferably based on deflections, and based on strains or accelerations if no deflection measurements can be obtained. A typical value of the damping, obtained according to Eq. (65) lies between 0.03 and 0.12. Damping can also be expressed as a percentage:

$$\zeta = \frac{\delta}{2\pi} \tag{66}$$

When damping is expressed based on Eq. (66), the values typically lie between 0.5% and 2%.

For the dynamic characteristics that depend on the applied load (or source of excitation), recommended acceptance criteria for accelerations and impact (dynamic amplification) are given in the Spanish guidelines. The limits to accelerations for pedestrian bridges and pedestrian walkways are classified as follows:

- The accelerations lie between imperceptible and easily perceptible when $a \leq 0.025g$
- The accelerations are clearly perceptible to disturbing when $0.025g < a \leq 0.075g$
- The accelerations are disturbing to very disturbing when $0.075g < a \leq 0.125g$

with a the maximum peak acceleration in gravity direction, and g the gravitational constant.

The second recommended acceptance criterion for the dynamic characteristics that depend on the applied load (or source of excitation) is the impact factor Φ, which is defined as:

$$\Phi = \frac{f_{dyn}}{f_{sta}} \tag{67}$$

with f_{dyn} the maximum dynamic response and f_{sta} the maximum static or quasi-static response, for both responses caused by the same action. The structural response can be based on deflections or based on strains. The impact factor is categorized as follows:

- low: $\Phi \leq 1.10$
- medium: $1.10 < \Phi \leq 1.30$
- high: $\Phi > 1.30$

9 OTHER COUNTRIES

9.1 **Italy**

In Italy (Veneziano et al. 1978, Veneziano et al. 1984a, 1984b), all road bridges are proof loaded prior to their opening to traffic to verify that the as-built stiffness and resistance of the deck is conform to the design specifications and applicable standards. Usually, heavy trucks are placed on the deck in a longitudinal arrangement to maximize the bending moment at midspan. To check the torsional stiffness of the deck and the transverse redistribution of the load, the trucks are often placed with maximum eccentricity in the transverse direction. During the load test, the applied stresses should be close to the design values. The measured response is the vertical displacement at various points of the deck, measured during and after loading. The measurements points are usually located across the midspan sections and near the supports. The difference between the support settlement and the deflection at midspan is the net deformation, which can be compared to theoretical predictions.

9.2 **Switzerland**

In Switzerland, provisions (SIA 269:2011 (SIA 2011)) are available for load testing of existing structures (Brühwiler et al. 2012). In addition to this, Switzerland has a long experience in testing new bridges prior to opening (Moses et al. 1994), since a load test is required for every major bridge. Sometimes, these bridges are then tested after several years in service as well to check their behavior. The interesting element of the Swiss practice is that it combines elements from diagnostic load testing and proof load testing. The applied load during a load test in Switzerland is 80-85% of the unfactored live load (serviceability limit state load level). Typically, four to eight dump trucks of 250 kN (56 kips) are used. This load is still significantly above the expected lifetime maximum traffic loading. During the load test, the displacements are compared to the analytical predictions for the displacements. Additionally, a dynamic test is carried out, in which moving vehicles and artificially created bumps are used to determine the impacts and frequencies. The deck is checked for cracks, and crack width measurements are carried out. In Swiss practice, the following acceptance criteria are defined:

1. There should be an agreement between the analytical and measured displacements. The measurements should be taken at several points along each girder.

2. The behavior should be linear and the residual displacements should be zero.

3. The measured crack widths should be within acceptable limits.

9.3 Poland

In Poland, the RIRB requirements (Research Institute of Roads and Bridges 2008) deal with load testing of bridges. This code requires the measurement of deflections (Halicka et al. 2018). The support deflections should be measured as well to find the net deflection of the bridge. In practice, during load tests typically also the settlements of the support and the compression of the bearings is measured (Filar et al. 2017).

The stop criterion that is prescribed in Poland is that no non-linear behavior is permitted to occur during the test. The residual deformations need to be verified as well. These are limited to 20% of the maximum deformation for reinforced concrete bridges, and 10% for prestressed concrete bridges.

The target load is determined based on a vehicle of abnormal weight Q_{abn}, which is larger than the design live load Q_{design}. This load is applied by using six load levels:

1. The load in the first step is maximum equal to the design load: $L_1 \leq Q_{design}$

2. The second step is an intermediate step with a load of $L_2 \leq Q_{design} + ¼(Q_{abn}-Q_{design})$

3. The third step is an intermediate step with a load of $L_3 \leq Q_{design} + ½ (Q_{abn} -Q_{design})$

4. The fourth step is an intermediate step with a load of $L_4 \leq Q_{design} + ¾ (Q_{abn} -Q_{design})$

5. The fifth step reaches the abnormal vehicle weight $L_5 \leq Q_{abn}$

6. The last step goes beyond the abnormal vehicle weight $L_6 \leq Q_{design} + 1 ¼ (Q_{abn} -Q_{design})$.

9.4 Hungary

In Hungary, load testing is used for verifying the serviceability of existing buildings (Hungarian Chamber of Engineers 2013). Two possible requirements can be checked for: if the structure is adequate or acceptable. A structure is considered adequate when all standard requirements are satisfied, and a structure is considered acceptable if:

- only minor defects can be observed,
- no brittle failure is expected,
- the structure has enough capacity to withstand at least the characteristic level of loads, regardless the fulfillment of deflection (stiffness) and crack width requirements,
- the deterioration of the structure is not faster than in usual cases.

An acceptable structure has a limited time for future operation, a limitation of its function, or should be periodically assessed by an independent expert. If a structure does not meet the requirements for being adequate or acceptable, it is considered dangerous, and action should be taken.

The target proof load to verify the adequate condition is calculated as:

$$P_{\max,d} = \left(1+\beta\left(a+b\gamma\right)\right)P_d \tag{68}$$

and for the acceptable condition it is calculated as:

$$P_{\max,k} = \left(1+\beta\left(a+b\gamma\right)\right)P_k \tag{69}$$

with $\beta = 1$ if a ductile failure mode is expected and $\beta = 1.5$ if a brittle failure mode is expected. The value of a is determined as:

$$a = 0.08\left(1-\frac{n}{2N^{0.5}}\right) \geq 0 \tag{70}$$

with n the tested number of elements and N the total number of structural elements in the complete structure identical to the tested component. The value of b can be determined as:

$$b = 5a + 0.16 \tag{71}$$

Equations (70) and (71) are replaced with $a = b = 0$ if $n = N$. If the loaded components are the weakest parts of the complete structure, $a = 0$ and $b = 0.15$. The value of γ is determined as:

$$\gamma = \frac{G}{G+P} \tag{72}$$

with G the permanent loads and P the proof load (P_d or P_k). The value P_k is the characteristic value of the proof load, which corresponds to the characteristic load intensity. The value P_d is the design value of the proof load, which corresponds to the design load intensity.

The stop criteria in the Hungarian guidelines are the following: fracture, rupture, yielding, damage of concrete under compression, buckling, deflections larger than 1/50 between points of inflection, cracks in concrete larger than 1 mm (0.04 in), cracks in steel, excessive deformations of the cross-section, extensive shell-buckling, and masonry cracks larger than 1 mm (0.04 in). For these cases, the structure will be assumed as failed.

In addition to the stop criteria, acceptance criteria are also formulated. The first acceptance criterion is a limit of the residual deformation to the maximum deformation, depending on the structure type, see Table 9. The second acceptance criterion is that the deflection under the characteristic proof load should not exceed the serviceability limit state criteria from the Eurocode. For concrete structures, a third acceptance criterion is that the crack width under the characteristic proof load should not exceed the limitations from Eurocode 2 EN 1992-1-1:2005 (CEN 2005).

Table 9: Limitations to deviation between measured and calculated deformations (Hungarian Chamber of Engineers 2013). The values between brackets are valid for $\gamma < 0.5$.

Type of structure	Ratio of residual and total deformation (in %)	
	$P_{max}=P_{max,k}$	$P_{max}=P_{max,d}$
Riveted steel structure	15	20
Welded steel structure	12	15
Steel with bolted connections	20 (25)	25 (30)
Prestressed concrete	20	25
Reinforced concrete	25 (30)	30 (35)
Steel-concrete composite	20	25
Timber structure	30	40

10 CURRENT DEVELOPMENTS

In several countries, currently efforts are geared towards the improvement of the current guidelines for load testing. These efforts include the following:

- unifying existing guidelines so that these cover all bridge types (reinforced concrete bridges, prestressed concrete bridges, steel bridges, timber bridges, masonry bridges,…)
- unifying existing guidelines so that these cover both diagnostic and proof load testing
- including guidelines for existing bridges
- including guidelines for bridges that can fail in a brittle manner such as shear-critical concrete bridges and fracture-critical steel bridges.

To achieve these goals, the following institutions and groups are currently revising codes and guidelines with regard to load testing:

- TRB Committee AFF40 is preparing an e-circular on load testing.
- The German guidelines for load testing are currently being revised, and the aim for the revision is to include testing for shear (Schacht et al. 2016).
- For the 2020 *fib* Model Code, which will include provisions for existing structures, load testing will perhaps be included. These provisions can then possibly lie at the basis for requirements that will be published as a Eurocode.

11 DISCUSSION

Load testing practices, as well as the available codes and guidelines, differ across countries, and are typically determined by the local demands and the country’s construction industry. In the past, most countries focused on developing guidelines for load testing of new bridges, to ensure the traveling public that the structure is safe. Nowadays, load testing of the existing infrastructure becomes increasingly interesting as a method for assessment. Some countries, such as the USA, have aimed at covering load testing in a holistic manner, by including diagnostic and proof load testing, for all bridge types. Other countries have geared their efforts towards a particular problem encountered upon bridge assessment. In Germany, the basis for proof load testing was laid by prescribing procedures for testing concrete buildings. Most other countries have focused on diagnostic load testing of bridges.

12 SUMMARY

This chapter gives an overview of the currently available codes and guidelines for load testing of bridges. Where the guidelines for buildings have played an important role for the practice of bridge load testing, the requirements from these guidelines have also been mentioned. The guidelines from Germany, the United Kingdom, Ireland, the United States of America (bridges and buildings), France, Italy, the Czech Republic, Slovakia, Spain, Switzerland, Poland, and Hungary have been summarized in this chapter.

From the presented discussions, it can be concluded that none of the available guidelines covers all bridge types, new and existing bridges, diagnostic load testing and proof load testing, a clear description of the target load, and stop criteria. For these reasons, several institutions are currently working on revisions of their guidelines and/or developing new guidelines.

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