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Chapter 4. General Considerations

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ABSTRACT: This chapter discusses aspects that should be considered prior to every load test. The first question that needs to be answered is: “Is this bridge suitable for load testing? If so, what are the goals of the load test?” To answer these questions, information must be gathered, and preliminary calculations should be carried out. In order to evaluate if a bridge is suitable for load testing, different types of testing are shown, the topic of when to load test a bridge is discussed, and structure type considerations are debated. Finally, some safety precautions that should be fulfilled during a load test are discussed.

1 INITIAL CONSIDERATIONS

1.1 **Introductory remarks**

Load testing of bridges can be a desirable method to show:

- that a newly built bridge behaves in the way it was designed,
- to improve the analytical assessment of existing bridges, or
- to directly show that a bridge can carry the code-prescribed loads without causing permanent undesirable damage.

This part of the book deals with the topic of preparation, execution, and post-processing of load testing. The particularities of diagnostic load tests are discussed further in Part III. Part IV focuses on proof load testing.

Prior to preparing load testing, the decision needs to be taken whether or not such testing can answer the open questions regarding the overall performance or specific response of the structure. In addition, sufficient preparation related to these questions is essential for the execution and post-processing of information leading to decision linking to the stop criteria and target load (depending on the type of load test). Several investigations are needed before the final decisions about field testing can be done. This information provides the decision basis and are essential elements that need to be addressed prior to deciding the execution methodology.

1.2 Load test types and their goals

It must be decided which type of load test is required to meet the aims of the test. To evaluate the design assumptions prior to opening of a new bridge, and to update the analytical model used for the assessment of an existing test with field measurements of unknown properties, diagnostic load testing can be used. To demonstrate directly that a bridge can carry the code-prescribed (factored) loads, a load that is representative for the code-prescribed (factored) loads can be applied to the bridge in a proof load test. If the bridge can carry this target proof load without signs of distress, than it has been shown directly that the code requirements are fulfilled. Only collapse tests (also called failure tests), which are a type of destructive testing, can answer questions with regard to the ultimate capacity of a given structure.

1.3 Type of bridge structure or element

In-situ full-scale load testing is a method which can be used for several types of bridge structures. However, the vast number of bridge type combinations containing new bridges, existing bridges, bridge sections, damaged/deteriorated bridges etc. (as well as the large number of reasons why one could decide to load test a bridge) often makes projects where full-scale testing is used, unique. However, the loading procedures which reflect traffic loading, described in guidelines or codes, are unaffected by the structural type. The way of applying a load configuration with a related target load, including the evaluation of a stop criterion should however be uniquely addressed for each full-scale bridge type or bridge element. It is in such applications normally seen that target loading is used for proof loading whereas stop criterions are used to find the highest acceptable loading rate. Diagnostic testing can address other uncertainties on the structural behavior.

Some of the considerations concerning steel bridges, reinforced concrete bridges, prestressed concrete bridges, masonry (arch) bridges, and timber bridges, are given in section 4 of this chapter. The limitations and points of attention for diagnostic testing and proof load testing of the individual structure types are discussed separately for the given bridge types. Further considerations per bridge type are given in Part III for diagnostic load tests and in Part IV for proof load tests.

1.4 Structural inspections, background codes and literature

Prior to deciding to proceed with a load test, a few elements need to be checked which are also discussed in the British guidelines (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges 1998). This guide provides a flowchart to assess if a bridge is a good candidate for a load test. During the preparation stage, the engineer should decide if load testing is the most suitable option to answer the open questions regarding the structural performance. In some cases, advanced modeling tools, such as probabilistic analyses or nonlinear finite element models can be used to analyze the critical elements in more detail. When ambient traffic loading can be sufficient to create the required structural responses, short- or long-term monitoring can be applied to the structure. For other cases, load testing is the best method to address the concerns related to the structure. The decision-making process prior to deciding on a load test is reflected in Figure 1.

In addition to the flow chart from Figure 1, it should be noted that a technical inspection of the object and an inspection of its surroundings are essential as background knowledge. If there are site-specific restrictions that inhibit the application of the required sensors or access to the structure, it must be evaluated if the load test can still be used to answer the open questions regarding the performance of the structure. When that is not the case, the load test should be abandoned. When the risks for the structure, the personnel on site, and the traveling public are too large, the load test should be abandoned or re-evaluated.

For proof load tests, the Unity Check in an assessment of the critical failure mode, should be only slightly larger than 1. If the differences between the Unity Check (or Rating Factor) in an analytical assessment and the target value with the test are too large, the engineer should evaluate if a test can be carried out. This decision will depend on the possible sources of additional capacity that are not considered in the assessment, and their estimated contribution. Such contributions depend on the type of structure - i.e. in reinforced concrete slab bridges more transverse redistribution than expected could be observed whereas girder bridges might develop less redistribution.

An inventory of the available information about the bridge structure should be made. If information is lacking, an evaluation-based decision should be taken regarding the properties that are unknown. If needed, these properties can be estimated or measured on site with destructive or non-destructive testing techniques.

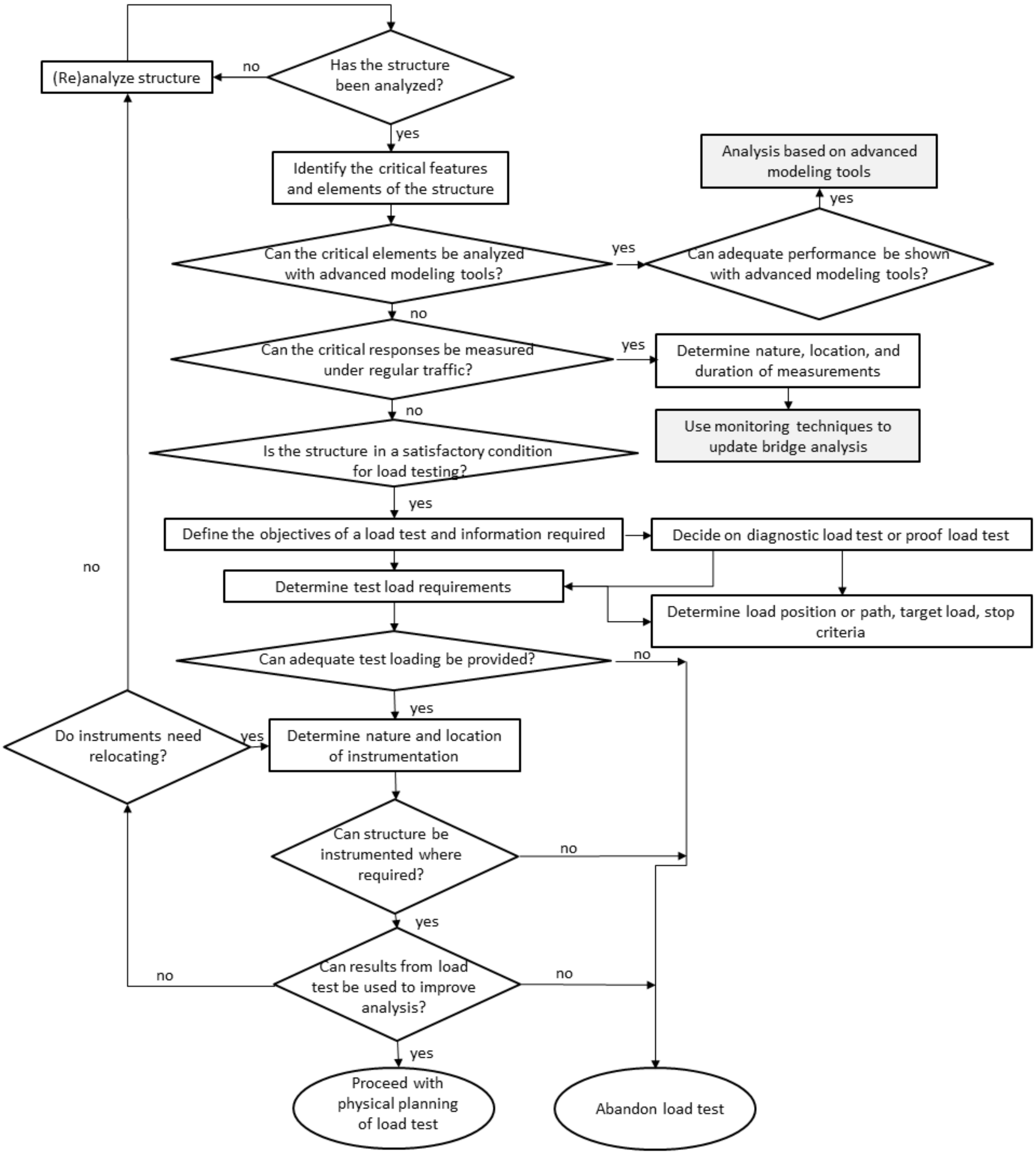

Figure 1. Flowchart to determine if load testing or other alternative can be used. Extended from the flowchart by (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges 1998).

Before the decision is taken whether or not a bridge is suitable for load testing, an exploratory study and/or report should be made to analyze the bridge and its state. This preliminary study and related documents, as well as the preparation of the load test (if it is decided to load test the bridge), should include the following:

- Information from the design stage of the bridge, encompassing the original design calculation reports, the design and as-built plans, and the results of material testing at the time of construction;
- Verification that the as-built information corresponds to the geometry and material parameters of the real in-situ structure;
- Evaluation reports, including periodical inspection reports, with the results of destructive and non-destructive tests carried out on the structure, and assessment reports of the structure;
- Information on changes to the structure, design reports of rehabilitation measures, and associated rehabilitation plans.
- Economical estimate of the testing project compared to other solutions, such as more detailed theoretical capacity estimations, strengthening methods etc.

As part of the preliminary analysis of the structure, a summary of the available information should be prepared. This summary should state which information is available and which information is missing. If information is missing, measures to obtain (some of) this information can be proposed. Moreover, the summary should include a discussion of the current state of the structure based on the available inspection and assessment reports. The summary of the current state serves as a summary of the available documentation, and can never replace a detailed on-site inspection of the bridge and the preparatory calculations, which are both required prior to load testing.

When crucial information about the structure is missing, these properties should be measured, estimated based on similar structures and experience, or calculated. When the properties are found, the validity of these assumptions should be discussed after the load test and in the light of the obtained measurements. When no information about the geometry of the bridge is available, the needed measures of the geometry should be determined. In addition, for concrete bridges, the amount of reinforcement and the layout of the reinforcement can be estimated and then be verified with reinforcement scanner methods.

When no information about the material properties is available, testing of the material properties can be done on samples from the bridge. To limit the number of samples that need to be collected from the bridge, it is recommended to supplement sample testing with non-destructive testing to determine material parameters. The outcome of material testing can be used to improve the initial assessment of the bridge and improve the preparations of the load test. For the post-processing stage of the test, having sufficient knowledge of the material properties will eliminate uncertainties, so that one source related to the uncertainties between the measured responses and the calculated responses can be reduced.

To determine the concrete compressive strength for concrete bridges, core samples can be drilled out, see Figure 2a. For core sampling, transportation, and testing, the guidelines provided by the bridge owner and/or national codes should be followed. The assessment methodology determines the number of required samples, and is for example explained in the Dutch Guidelines for the Assessment of Bridges RBK (Rijkswaterstaat 2013).

To determine the yield strength and tensile strength of reinforcement steel, samples can be taken and tested in the laboratory. When the steel grade is given on the structural plans, samples (see Figure 2b) can be taken to determine the average value of the yield strength and tensile strength. This additional testing can be interesting for older existing bridges, in which steel grades may be used that are not commercially available anymore. Testing of samples that have yielded is not recommended, as hardening will result in larger measured capacities. Similarly, for steel bridges, material samples can be taken.

(a) (b)

Figure 2. Examples of: (a) concrete cores and (b) reinforcement samples from an existing concrete bridge.

For steel bridges, it can be necessary to estimate or measure the residual stresses in the members to improve the assessment. Non-destructive techniques based on ultrasound measurements (Li et al. 2016) can be used to measure the residual stresses. Additionally, hole drilling strain gauge methods can be used as an indication related to the residual stresses in steel bridge members (Bathgate 1968, Schajer 1992). More novel methods that are currently under investigation are laser ultrasonic measurements (Zhan et al. 2017) and magnetic Barkhausen noise (Vourna et al. 2015, Samimi et al. 2016).

In some cases, very limited information about a bridge is available. In such a case, a choice can be made to use load testing to gather the required information about the structural behavior. Examples of using load testing on bridges without structural plans are available in the literature (Aguilar et al. 2015, Anay et al. 2016). In some cases, it may be cheaper and easier to carry out material testing on the structure and measure missing dimensions, and to use this information as the initial input for the assessment calculations. With such calculations, it can be determined if the bridge is a suitable candidate for load testing, and to select the required type of load test depending on the questions that need to be answered with the field test. In other cases, a “quick and easy” proof load test can be used to demonstrate that the bridge fulfils the code requirements.

2 TYPES OF LOAD TESTS, AND WHICH TYPE OF LOAD TEST TO SELECT

In-situ load testing methods can differ significantly depending on the bridge type and project scope. It is often seen that the loading methods reflect the given national guidelines and standard methods, but that there are very strict demands to the testing time, since traffic often has to be redirected or stopped during testing. Consequently, these projects can be very costly and the in-situ test procedures have to be optimized to an extent which reduces the cost as much as possible. Depending on the goal of the load test, two different main types of load tests exist[1]:

- Diagnostic load tests (static or dynamic), mostly used for verification of the design assumptions of newly built bridges and to improve the analytical assessment of existing bridges.
- Proof load tests, loading of a structure (normally an existing structure) to a given target load (or to the load for which a stop criterion is reached) in order to verify a given response at higher load levels and demonstrate with a test that the bridge fulfils the code requirements.

These types of load tests are non-destructive tests. Additionally, failure testing (also called collapse testing or destructive testing) can be carried out on one bridge to evaluate for example a large subset of bridges or to understand the behavior up to the ultimate capacity of a certain

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[1] This terminology follows the AASHTO MBE (AASHTO 2011) definitions. In the UK and Ireland, a different terminology is used, see Chapter 3.

bridge type. Failure testing includes loading magnitudes that reach the damage regimes of the bridge structure where irreversible damage occurs as well as fully developed failure.

2.1 **Diagnostic load tests**

Diagnostic load tests (Moses et al. 1994, Russo et al. 2000, Farhey 2005, Jauregui et al. 2010, Olaszek et al. 2014) are the most common type of load test. Diagnostic load tests can be used to check a number of in-situ properties of a given bridge (Lantsoght et al. 2017f). This bridge can be a new bridge or an existing bridge. For new bridges, diagnostic load testing is used to verify the design assumptions and analytical models used for the design. Several countries, such as Italy (Veneziano et al. 1984), Switzerland (Bruehwiler et al. 2012), France (Cochet et al. 2004), and Ecuador (Sanchez et al. 2018) require a diagnostic load test upon opening of all bridges or certain types of bridges. The verification of the design assumptions is carried out by comparing the measured structural response and the analytically determined response. National codes describe the limits of the allowable difference between the response of the structure in the load test and the predicted response. If the difference is larger than allowed, a logical explanation for this difference should be sought. When the difference has an influence on the design calculations, the relevant calculations should be repeated with the inclusion of the information from the field test, and reported. For existing bridges, diagnostic load tests can be used to update the analytical model of the bridge and obtain a refined assessment of the structure.

The transverse flexural distribution (Ohanian et al. 2017) can be determined, as explained in ACI 342R-16 (ACI Committee 342 2016). The overall stiffness of the structure can be determined (Hodson et al. 2013). Testing prior to opening (Yang and Myers 2003), over time (Myers et al. 2012), and after rehabilitation (Alkhrdaji et al. 2000) can be used to compare the behavior of the bridge measured in the field to the design or assessment calculations. When a bridge is tested prior to opening, and after several years of service, the results of these load tests can be compared. The effect of deterioration and other time dependent changes can then be analyzed based on the reduction in stiffness between the newly opened bridge and the bridge after decades of service life. Dynamic tests can be used to determine the impact factor (Jiang et al. 2016) and the natural frequencies of the bridge (Frýba and Pirner 2001).

Since diagnostic load testing goes hand in hand with analytical modeling, the response measurements (strain/stress, crack widths, or deflections) play an important role. The measured responses (often based on strains) are compared to the analytically predicted responses, and the field test results can then be used to update the analytical model. In practice, the analytical model is often a finite element model (Bridge Diagnostics Inc. 2012, Sanayei et al. 2016).

The loads that are selected for carrying out a diagnostic load test must be large enough to result in measurable responses, but are significantly smaller than the loads involved with proof load testing. Known loads such as loading vehicles can be used for this purpose.

A challenging part of the post-processing of a diagnostic load test is to identify the effect of each different contribution to the overall structural response (Barker 2001). These contributions can be:

- the actual impact factor,
- the actual dimensions,
- the stiffness from non-structural elements such as curbs and railings,
- the actual lateral live load distribution,
- the effect of the flexibility of the supports,
- the actual longitudinal live load distribution, and
- unintended or additional composite action in composite sections.

Not all of these effects occur at the ultimate limit state. Certain effects only occur at small load levels, for example the interaction of some of the nonstructural elements. Therefore, it is recommended to carry out the load test with loads that can evaluate the behavior of the structure at the rating level. Other effects, such as unintended composite action and unintended support fixity, can be lost after cracking and/or at higher load levels. Therefore, it is important to analyze the sources of differences between the measured and analytical response, to see which elements can be used at the ultimate limit state, and can thus be used for the assessment.

2.2 **Proof load tests**

In a proof load test (Saraf and Nowak 1998, Faber et al. 2000, Casas and Gómez 2013, Arangjelovski et al. 2015, Lantsoght et al. 2017a, Lantsoght et al. 2017c), a load representing the factored load combination prescribed by the governing code is applied to the bridge. Since the load is applied during the test and all sensors are zeroed at the beginning of the test, a proof load test evaluates the net capacity of a bridge for carrying live load. If the bridge can carry the applied target load without signs of distress, the proof load test has shown directly that the bridge fulfils the code requirements. In the past, proof load testing was carried out on bridges prior to opening to show the traveling public that this new bridge is safe for use (Bolle et al.

2011). Nowadays, proof load testing is mainly used for a direct assessment of existing bridges, when a fully analytical assessment is not possible and/or lacks significant input information.

The lacking input can be related to the available information about the structure, for example the lack of structural plans (Shenton et al. 2007) and no means to develop these, related to the structural behavior such as transverse load redistribution in concrete slabs at higher load levels (Saraf 1998), or related to the effect of material degradation and deterioration on the capacity of the tested bridge (Lantsoght et al. 2017c). In general, several uncertainties can be identified, which can lead to an increased capacity, such as:

- Unintended composite behavior of slab-on-girder bridges (eg. steel girder bridges with a concrete deck),
- More desirable boundary conditions,
- Larger transverse redistribution than assumed during design and/or assessment,
- Arching action and direct load transfer,
- Compressive membrane action,
- Increased concrete compressive strength as a result of the ongoing cement hydration process,
- Stiffness and load-carrying capacity of non-structural elements,
- Unintended continuous behavior of simply supported girders with a continuous deck.

On the other hand, one can identify uncertainties resulting from deterioration mechanisms, material degradation, and damage that lead to a decreased capacity as well, such as:

- Corrosion-induced damage,
- Alkali-silica reaction,
- Environmental effects (chloride intrusion, frost/thaw, high/low temperatures, humidity, etc.),
- Leaching,
- Fatigue damage,
- Poor connection detailing,

- Ultraviolet and ozone damage in bridges made with plastic composites.

In addition, time-dependent damage can occur to:

- Joints and bearings,
- Substructures (settlements, scour…),
- Girders, caused by vehicle impact,
- Synergy effects which include several deterioration and damage mechanisms.

Since the loads have to represent the factored load combination, the applied loads in proof load tests are of a high magnitude. As such, the costs and risks involved with proof load testing are of a higher category than for diagnostic load testing.

In proof load tests, the measurements are important, as they need to be followed in real time during the experiment to verify that no irreversible damage takes place or that no collapse can occur. Threshold values for the structural responses, measured by the sensors, need to be determined prior to a proof load test. These threshold values are called the stop criteria. The stop criteria normally depend on the construction type, construction material, and expected failure mode. These stop criteria should be changed if the structural behavior is different than expected during preloading of the real in-situ structure. If a stop criterion is exceeded during a proof load test, further increasing of the load is not permitted, and the test should be terminated. It is then found that the bridge does not fulfil the requirements of the target load level. However, depending on the highest load that was achieved during the proof load test, the conclusion may be that the bridge can be used for a lower load level. Recommendations for posting of the structure can then be formulated. If the target proof load, which represents the factored load combination, is applied to the bridge without exceeding any of the stop criteria, it is shown experimentally that the bridge fulfils the code requirements. If the load is increased further than the target proof load, more information can be obtained about the behavior of the bridge at a higher load level. This practice is however typically limited to research applications.

The maximum load that is applied in a proof load test, i.e. the target proof load, can also be used as input for a probabilistic analysis (Lin and Nowak 1984, Rackwitz and Schrupp 1985, Nowak and Tharmabala 1988, Hall and Tsai 1989, Fu and Tang 1995). The target proof load can be used to truncate the probability density function of the resistance when the curves of load and resistance are used to determine the probability of failure. After a successful proof load test, it is known that the capacity is larger than or equal to load effect caused by the applied load.

Therefore, the probability density function of the capacity can be truncated as shown in Figure 3. To influence the probability of failure, the target proof load should be large enough.

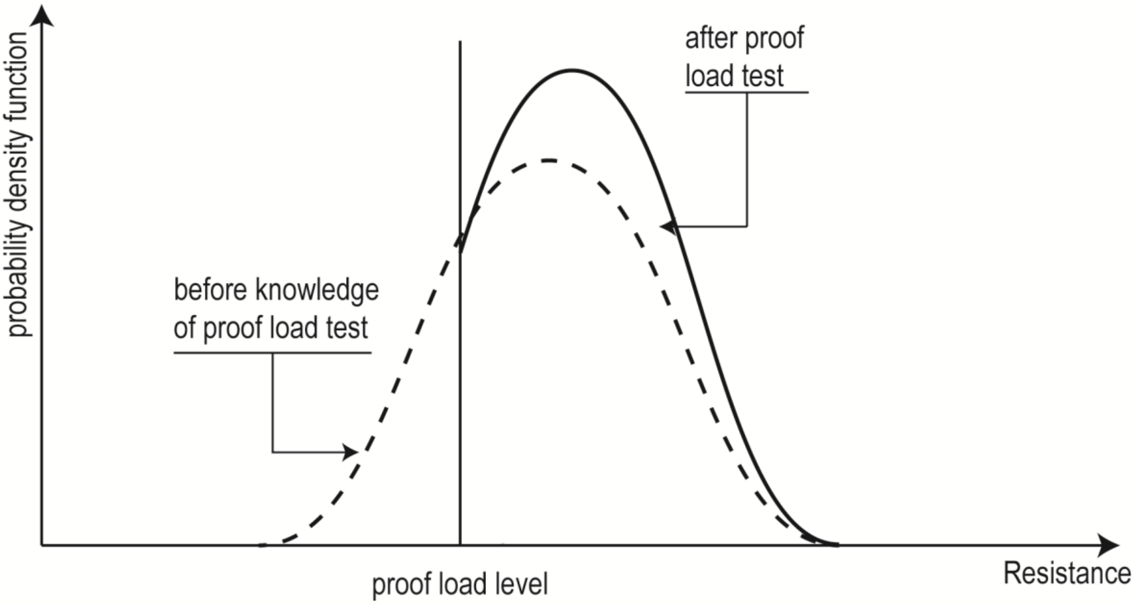

Figure 3. Truncation of probability density function of resistance after proof load test, based on (Nowak and Tharmabala 1988)

2.3 **Failure tests**

The only type of test that can answer questions with regard to the ultimate capacity of a structure is a failure test (Elmont 1913, Rösli 1963, Jorgenson and Larson 1976, Cullington et al. 1996, Haritos et al. 2000, Steinberg et al. 2011, Bagge et al. 2017b). Such testing is normally done on existing bridges that are functionally obsolete and serve to calibrate theoretical approaches as well as provide an indication regarding the actual response of a real-life structure. Often the capacity of real-life structures is higher than the predicted capacity due to rearrangement of the load path, interaction between the structural elements etc. However, one collapse test is often considered as insufficient for the predictions of other similar bridge structures. Consequently, a series of similar bridges need to be tested to answer capacity questions, which is rarely possible. Such testing provides, nevertheless, very important information concerning the responses and failure mechanisms at high loading magnitudes.

An example of this goal for a collapse test is testing of the Ruytenschildt Bridge (Lantsoght et al. 2017d) in Friesland to learn more about the behavior of reinforced concrete slab bridges, see Figure 4a. In Sweden, in the recent years, a number of bridges have been tested to collapse (Bieñ et al. 2007, Enochsson et al. 2008, Puurula et al. 2008, Taljsten et al. 2008, Zou et al.

2009, Puurula et al. 2014, Bagge et al. 2015a, Bagge et al. 2015b, Puurula et al. 2015, Puurula et al. 2016, Bagge et al. 2017a). In Denmark, open T bridges have been studied in failure tests (Schmidt et al. 2018, Halding et al. 2017), see Figure 4b. Collapse tests, however, are very uncommon and require thorough preparation in terms of execution and safety as well as much larger budgets than other types of field tests.

(a) (b)

Figure 4. Application of load for collapse test and high magnitude loading of (a) the Ruytenschildt Bridge in the Netherlands, and (b) Rosmosevej bridge in Denmark.

Selection of the load test type relates to client's needs and can thus differ depending on the unique project. Most available codes and guidelines do not permit the proof load testing of fracture- and fatigue-critical steel bridges, nor the proof load testing of concrete bridges that are shear-, punching-, or torsion-critical, as such tests involve larger risks. However, in current practice, such bridges are often found to be insufficient upon analytical assessment, and the client may wish to subject the structure to a proof load test. This application currently lies within the realm of research.

3 WHEN TO LOAD TEST A BRIDGE, AND WHEN NOT TO LOAD TEST

Economic estimations compared to competing bridge evaluation methods (recalculation of capacity, probabilistic evaluations, in-situ monitoring, etc.) need to be conducted, before an initial step toward full-scale bridge testing can be done. After determining the goal of the full-scale test, it is necessary to see if the bridge under consideration is a good candidate for the required type of load test. An inspection should determine if there are no site-specific limitations or restrictions to carrying out the load test. Coordination with the traffic authorities is required to see if (partial) closure of the bridge is possible during the test, and for how much time this closure can be in effect.

Depending on the available time to prepare the test on-site, it needs to be decided how contact and/or non-contact sensors can support the loading procedure and evaluate the expected response most efficiently. The number and type of sensors should be sufficient to gather the required information for updating the analytical model if a diagnostic load test is considered, or to monitor the bridge response and check the stop criteria if a proof load test is considered.

When a load test is considered for improving the assessment of a certain bridge, it is necessary that the analytically determined rating factor is slightly smaller than 1 or that the Unity Check is only slightly larger than 1. For proof load tests on reinforced concrete slab bridges (Lantsoght et al. 2017e), which have a large capacity for transverse redistribution, sections with a Unity Check between 1 and 1.3 are good candidates. For other bridge types, where less additional sources of capacity and redistribution are expected, sections with a Unity Check between 1 and 1.1 are good candidates for a proof load test, or a diagnostic load test. For these bridges, a diagnostic load test can be sufficient to determine parameters required to improve the analytical model used for the assessment, and thus refine the assessment.

When a detailed assessment of the bridge already results in Unity Checks smaller than 1 or rating factors larger than 1, a load test for assessment is not recommended. A detailed assessment can for example be an assessment based on a linear finite element model. Different codes and countries have develop methods based on Levels of Approximation (as used in the *fib* Model Code 2010 (fib 2012), see Figure 5) for assessment of existing bridges (Brühwiler et al. 2012, Shu et al. 2015, Lantsoght et al. 2017b), where load testing –if included- is considered as the highest level of approximation. A high level of approximation means that the expected results are more precise than for the lower levels of approximation, but that the required cost and computational time are much larger.

Other situations in which load testing is not recommended is when the safety cannot be guaranteed during the load test, for example, when there is a risk of a brittle failure during a proof load test. Besides the structural safety, the safety of the personnel involved on site and the traveling public should be considered before deciding on load testing a bridge. If there are serious concerns regarding the safety, the engineers should not proceed with the load test.

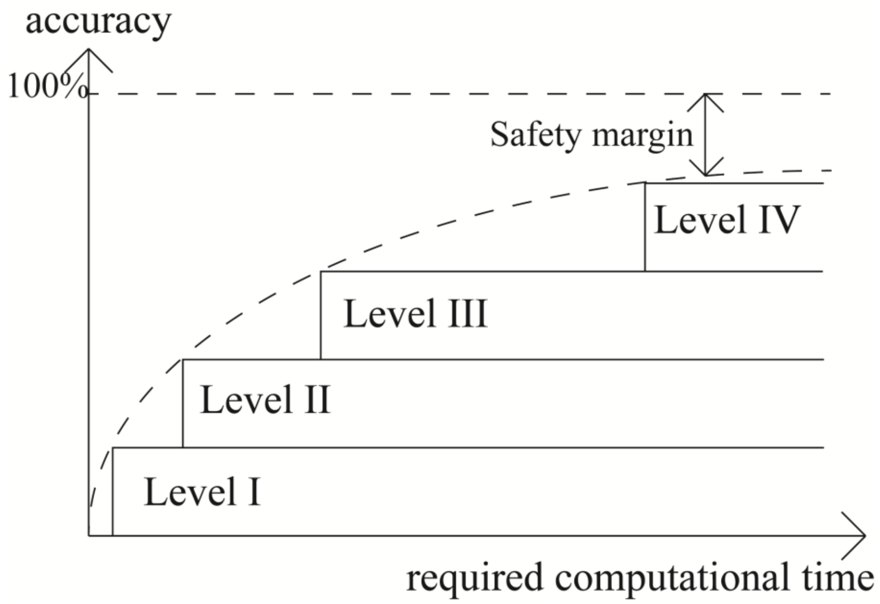

Figure 5. Levels of Approximation. Reprinted from (Lantsoght et al. 2017b) with permission.

4 STRUCTURE TYPE CONSIDERATIONS

4.1 **Steel bridges**

For steel bridges, measuring the structural response is straightforward when the residual stresses have been estimated. Contact sensors, such as strain gages or vibrating wire gages can be used to measure the structural response in terms of strains directly. The type of superstructure will determine where the structural responses (often strains) need to be measured, and will thus determine the required sensor plan.

Steel bridges are good candidates for diagnostic load tests, and methods to update the analytical models with the results from the field test are well-established (Barker 2001). Often, a diagnostic load test is sufficient for the assessment of steel bridges, as the isotopic material provides a structural behavior that is easier quantified compared to e.g. anisotropic concrete structures.

For proof load testing of steel bridges, special attention should be paid to fracture-critical members and members with fatigue damage (often cross-beams and connections). These elements need to be monitored closely during a proof load test, and relevant stop criteria should be defined prior to the test.

4.2 Reinforced concrete bridges

For reinforced concrete bridges, the type of structure will influence the sensor plan. For girder, tub, and box girder bridges, strains can be measured over the height of the structural elements. From these measurements, the strain profiles and thus stresses, and internal forces can be derived. For other structure types, such as slab bridges, applying sensors over the height of the structural element is not possible. For those cases, sometimes only the bottom face can be instrumented, see Figure 6 and Figure 7b.

In a diagnostic load test, a number of strain measurements over the element height (girder, tub, or box) can be used to calibrate the analytical models. When such measurements cannot be taken, such as for slab bridges, the calibration of the model should be carried out based on the measurements of strains on the bottom of the cross-section, or based on structural responses that are affected by a larger number of (unknown) parameters, such as deflection measurements. These measurements can be useful to evaluate transverse flexural distribution, but at times cannot cover all the unknowns required to improve the assessment.

(a) (b)

Figure 6. Monitoring with LVDTs, lasers, strain gauges, acoustic emission sensors, Digital Image correlation during a proof (a) and high magnitude (b) load test of a reinforced concrete slab bridge. Only the bottom face can be instrumented for these bridges.

In a proof load test, the onset of nonlinear behavior should be monitored with adequate stop criteria and sufficient sensors. When shear failures or other brittle failure modes can take place, stop criteria for these failure modes should be developed. At this moment, stop criteria for brittle failure modes in concrete are the topic of research (Schacht et al. 2016, Lantsoght et al. 2018). It has been shown that proof load testing can be used to evaluate shear-critical reinforced concrete slab bridges (Lantsoght et al. 2017c), but this type of tests should only be carried out by experts until codes and guidelines that include recommendations for the testing of concrete bridges for brittle failure modes are available.

4.3 Prestressed concrete bridges

For prestressed concrete bridges, which typically consist of girders, tubs, or box girders, the strains can also be measured over the height of the girders with contact sensors such as strain gages or vibrating wire gages.

(a) (b)

Figure 7. Instrumentation used during a test on a prestressed concrete bridge (a). Monitoring preparation for OT (overturned T-section) bridge (b).

Diagnostic load testing of prestressed concrete bridges is especially desirable since the measured strain profiles over the height can be directly used to calibrate the analytical assessment models. It is for such bridges seen that the cracking moment is larger than in non-prestressed reinforced concrete bridges. Consequently the occurrence of cracking in a field test is typically not acceptable in prestressed bridges. An example of instrumentation for a prestressed girder bridge is shown in Figure 7a.

In a proof load test, the definition of stop criteria is an important part of the preparation. If the occurrence of cracks would change the overall structural behavior of the tested superstructure, then cracking cannot be allowed during the proof load test. A stop criterion should then be defined to avoid exceedance of the cracking moment in a proof load test on a prestressed concrete bridge. In the currently available codes and guidelines, such a stop criterion is not available. Moreover, (brittle) failure modes, such as punching of the wheel prints through the deck should be avoided – especially if this undesirable failure mode is not related to the evaluation of the critical element during the test but is instead caused by the method of load application, when for example all load is concentrated at a single position. The stop criteria should also warn for the possibility of such a failure mode.

4.4 **Masonry bridges**

Masonry bridges are typically constructed as arch bridges. Their behavior is somewhat similar to the behavior of plain concrete and stone arch bridges. Therefore, the stipulations in this section are valid for all masonry, stone, and plain concrete arch bridges. These bridges are complex structures, and measuring the structural response often does not lead to a straightforward interpretation of the structural behavior. The overall behavior is three-dimensional, and results from the interaction between arch barrel and the spandrel walls (Fanning et al. 2005). Often, the measurements need to capture this overall behavior, and thus non-contact methods that follow the behavior of the entire structure such as radar interferometry (Mayer et al. 2012), total station, and digital image correlation (Bentz and Hoult 2016) can be used. Contact sensors (LVDTs, laser triangulation sensors) can be applied to measure deflections locally, and to calibrate the results of the non-contact methods. Measuring strains is typically not recommended for masonry and stone bridges, given the larger heterogeneity of the material. For plain concrete arch bridges, strain measurements can be used.

For arch bridges, it is recommended to use a series of non-destructive evaluation methods during the inspection onsite as part of the preparation stage. Key input parameters required for the numerical analysis should be determined based on these non-destructive tests. The presence of internal voids, flaws, layering condition, and the mapping of non-homogeneity, moisture content, etc. need to be evaluated and determined prior to the load test and these results should be implemented in the analytical model used for the assessment and preparation of the load test (Orban and Gutermann 2009).

Diagnostic load testing of masonry, stone, and plain concrete arch bridges can be used to find an answer to particular questions, such as the overall stiffness of the structure or the influence of bearing restraint. However, the difficulty in the assessment lies in modelling of these types of bridges. Their complex three-dimensional behavior often results in a large number of unknowns and the necessity of a large number of assumptions, so that the developed analytical models can be subject to discussion.

In most cases, proof load tests are required for the assessment of masonry, stone, and plain concrete arch bridges (Orban and Gutermann 2009). With a proof load test, it can be assessed directly if the considered bridge fulfils the code requirements. Proof load tests are particularly interesting for arch bridges, as these bridges typically have a capacity that is found to be considerably larger in experiments than the capacity that is determined analytically (Orban and Gutermann 2009).

4.5 Timber bridges

Timber bridges are characterized by the change in behavior over time caused by the change in material properties due to environmental influences on the timber elements. Timber bridges are sometimes historic truss bridges with solid timber elements and sometimes new bridges with girders made of composite timber products (such as glulam), which are less subjective to environmental influences.

Since the properties of timber are heterogeneous, special attention should be paid to the positions where sensors are applied. It is recommended to focus on the overall structural behavior and to measure deck deflections or timber strains during a diagnostic load test (Gentry et al. 2007), which can be used to determine the performance, and static and dynamic load distribution characteristics of the timber bridge (Wipf et al. 2000). Diagnostic load testing of timber bridges can be used to determine the distribution of loads (Wipf et al. 2000) or to evaluate the performance of rehabilitation measures (Gutkowski et al. 2001). During the preparation stage of a diagnostic load test, the condition assessment is important to determine the state of the timber bridge and the used material prior to the test. This assessment can combine visual inspections, photographic and video documentation, and moisture content measurements to determine the extent of wood deterioration (Wipf et al. 2000).

Proof load testing of timber bridges can be used to directly evaluate if a given bridge fulfils the code requirements. When the effect of material deterioration cannot be assessed, a proof load test may be required to evaluate the bridge’s performance.

5 SAFETY REQUIREMENTS DURING LOAD TESTING

5.1 General considerations

A crucial part in the preparation of a load test, and an element that needs to be considered prior to taking the decision if a load test can be used to meet the requested goal, is assuring the safety during the load test. If the structural safety, and the safety of the personnel and traveling public cannot be guaranteed, a load test should not be attempted.

The structural safety, and risk of damage to the structure and collapse, should be carefully contemplated during the preparation stage of the load test. During the on-site inspection, special attention should be paid to structural and non-structural elements that have significant deterioration and of which the performance may be subpar. The analysis prior to the test should identify which members are fatigue- or fracture-critical, and which members could fail in a brittle manner. If such elements are present, it must be analyzed if measurements and stop criteria can be used to warn when a threshold of performance is surpassed. If it is not possible to test the bridge in a safe manner, the load test should not be attempted.

The integral safety during the load test is the responsibility of the party entrusted with the general safety considerations as agreed with the client. This party is responsible and liable for the preparation, preparatory calculations, determination of required measurements, load application, application and position of sensors, carrying out of the test, analysis and interpretation of the structural response during the test, delivering the report of the test, finalization and cleanup of the site after the test, and the safety of personnel, the structure, and the traveling public during the entire process. The responsible executing party can contract subcontractors for certain (sub)tasks of its responsibilities. When subcontractors are involved, the responsible executing party will then need to coordinate the activities with the subcontractors, arrange for meetings and communication between and with the subcontractors, communicate the safety requirements to all subcontractors, and communicate the tasks of the subcontractors to the client.

During the preparation stage, the party responsible for the safety should carry out the technical inspection. This inspection should be carried out in accordance with the governing guidelines for inspections, for example CUR 117 (CUR 1984) in the Netherlands. After this inspection a report should be written which summarizes the possible dangers, risks, and possible problems that may occur during the preparation, execution, and dismantling of the test setup on site. This risk analysis report should provide an overview of the possible risks, and provide solutions for these risks. Possible risks and situations that should be considered and evaluated include mechanical problems, electrical problems, electronic problems, failure or illness of personnel, and external factors (weather, local parties, press…). Where required, duplicate equipment (such as backup sensors and additional computers) should be included in the required equipment that needs to be transported to the test location. This report also needs to include an overall planning of the activities on site (preparation, execution, dismantling), as well as a detailed planning that identifies which tasks are consecutive, which tasks are parallel, and where the risk for delays lie. It is good practice to deliver the risk analysis and planning report at least five working days prior to the start of the activities on site. This report should be accepted by the client and owner of the bridge before activities on the site can be commenced. The report should also be distributed to all subcontractors and parties involved with the load test.

5.2 Safety of personnel and traveling public

As part of the initial considerations of the load test, an engineer responsible for the safety on site (here called the safety engineer) should be appointed. The safety engineer is responsible for the safety report of the test, which should consider the practical aspects of the execution of the load test. The report should include the means of communication that are used during the test (such as walkie-talkies). The safety requirements for during the test need to be added to this report: when can personnel –by exception- go under the bridge during the load test, and who decides after the load test that it is safe to go under the bridge again. In general, during a load test, nobody is allowed to go under the tested object, except when explicit permission is given. During the test, only the executing party is allowed on the bridge. Prior to the test, a list of people that are allowed to enter the test site should be drafted. Additional people can only be granted access in exceptional situations. Nobody is allowed to enter the site without attending the safety briefing by the safety engineer. This briefing should be given in a language that can be understood and spoken by all people involved with the test – a requirement that is particularly important when the load test is carried out by an international team or in multilingual countries. If necessary, the briefing should be given in multiple languages.

Moreover, the safety engineer is responsible for the safety on site and the safety and wellbeing of the personnel during the period of activities on site (preparation of the test on site, execution of test, and dismantling of the setup and cleanup of the site). Examples of risks and situations that need to be evaluated by the safety engineer are the possible presence of asbestos in the structure, and the presence of traffic on or next to the bridge (including shipping on rivers and canals).

The safety engineer should prepare the safety card, which contains the information of actions required in case of an accident, fire, or other type of calamity. This card should be displayed at a position where it can be seen by all personnel working on the site, should be accessible during all activities on site, and its contents should be communicated to all personnel before they start their activities on site. The safety card should include the phone numbers and addresses of the nearest hospital, general practitioners, and pharmacy, as well as the phone numbers of the emergency services, police, and firefighters. At all times, a first aid kit and at least one person with first aid certification should be present on the test site.

Besides the safety of the personnel involved with the load test, the safety of the travelling public and the safety of locals who may be curious about the load test and perhaps attempt at entering the test site should be guaranteed. An example of signaling used to show locals that they should not approach a bridge subjected to a collapse test is given in Figure 8a and an example of road closure in Figure 8b. For the safety of the travelling public, a traffic control plan and possibly a temporary detour should be developed together with the road authorities. This traffic control plan and possible detour should be communicated to the local communities with anticipation. When the interest of locals and possibly local press is expected, they should be referred to the communications expert of the road authority.

(a) (b)

Figure 8. Example of signaling for the traveling public during a collapse test. Translation: do not access – weakened structure caused by testing (a). Closure of a road leading under the bridge enabling a safe working area (b).

It is good practice to deliver the safety report and safety card at least five working days prior to the start of the activities on site, and these should be accepted by the client and owner of the bridge prior to the start of the activities on site. The safety report and safety card should also be communicated to all subcontractors and parties involved with the load test.

5.3 Structural safety

To guarantee the structural safety during a load test, a good preparation of the test and the measurements during the test are important. The preparation should consist of assessment calculations, calculations to predict the structural behavior during the test, an evaluation of the overall stability, a verification of the substructure, and design of loading configuration paying attention to its safety. The structural behavior during the test can be predicted with hand calculations to have a first estimate of the expected responses, or by using a numerical model. For this numerical model, assumptions need to be made regarding the boundary conditions, composite action, and the modulus of elasticity of the concrete (and the influence of cracking thereon). These preparatory calculations should be combined into a report. It is good practice to deliver this report at least five work days before the start of the activities on site to the client and bridge owner, and the report should be accepted by the client before any activities can be started on site. The report should also be shared with all subcontractors and other parties involved with the load test.

Especially for proof load tests, the structural safety should be an important consideration. During a proof load test, stop criteria are used to verify if no irreversible damage occurs in the bridge due to the test. To check the stop criteria, the measured structural responses should be displayed in real-time during the test, and should be followed carefully. It is good practice to have at least two engineers dedicated to following the measurements. The load should be applied in increments, and after each load cycle, the response measurements should be analyzed. Careful preparation and planning of the proof load test is important, and safety considerations should be thought through prior to the test to avoid damage to the structure or injury to personnel or the public. The response measurements should be analyzed by an experienced bridge engineer, who makes decisions about the structural safety and the possibility to increase the applied load on the structure.

6 SUMMARY AND CONCLUSIONS

This chapter discussed the general considerations that need to be considered prior to deciding on a load test. For that purpose, a number of questions should be explored.

1. Is all information about the structure available? If not, can this information be estimated or measured at the structure, with a non-destructive test or with a destructive test?

2. What is the aim of the load test? Which type of load test should be selected for this purpose?

3. Are there site-specific limitations and restrictions that should be considered and that require changes to the plan for testing the bridge? Can the test be carried out in a safe manner?

4. How does the type of structure affect the choices with regard to instrumentation and possible aims of a load test?

5. How can the structural safety, and the safety of personnel and the travelling public be guaranteed at all time during the activities on site? Who is responsible for the safety?

The first question was answered by carrying out an inventory of the available information of the bridge. If important parameters are unknown, these should be measured with destructive or non-destructive testing methods.

The second question was answered by considering the definitions of the different types of load tests. Diagnostic load tests can evaluate the overall stiffness, transverse redistribution, the effect of non-structural elements on the stiffness, the stiffness of the bearings, and unintended composite action between girders and the deck. When these properties are quantified, the analytical model used for the assessment of an existing bridge, or the analytical model used for the design of a new bridge can be updated. A proof load test, in which a load representative of the code-prescribed factored loads is applied to the bridge, can be used to directly prove that a given bridge fulfils the code requirements. In addition, proof loading can be used to evaluate the structural response up to a given stop criterion, which is a threshold before irreversible damage occurs.

The third question is essential to the decision whether or not to load test a bridge. An inspection of the site is necessary to see what the limitations and restrictions of the site may be. Afterwards, these limitations and their effect on the position of sensors, and all physical activities on site should be thought through. If the test cannot be carried out in a safe manner, or poses a risk for the traveling public, a load test should not be attempted. The results of the assessment should also have identified if the Unity Check (or Rating Factor) is close enough to one for a proof load test to be possible to demonstrate sufficient capacity.

The fourth question was answered in this chapter by highlighting the particularities of different structural types: steel bridges, reinforced concrete bridges, prestressed concrete bridges, masonry bridges, and timber bridges. Depending on the structural type and material, different locations and different types for the measurements may be recommended, and, for proof load testing, different stop criteria should be defined.

Finally, the fifth question was answered by discussing the different general elements of safety that need to be considered before the decision on load testing a bridge is made. Again it was stressed that a load test should not be attempted when this test poses a risk for the structural safety, the safety of the personnel on site, and the safety of the traveling public. To make sure all aspects of safety are considered, the project leader is made responsible for the overall safety. The project leader will then appoint a safety engineer to be responsible for the safety during all activities on site.

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