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Chapter 7. Post-processing and bridge assessment

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ABSTRACT: This chapter discusses the aspects related to processing the results of a load test after the test. The way in which the data are processed depends on the goals of the test. As such, the report that summarizes the preparation, execution, and post-processing of the load test should clearly state the goal of the load test, how the test addressed this goal, and what can be concluded based on an analysis of the test results. Typical elements of the post-processing stage include discussing the applied load, the measured structural responses, and then evaluating the bridge based on the results of the load test.

1 INTRODUCTION

The final step in a load test is the post-processing of data obtained during testing, and using this data to verify the bridge response and thus fulfil the aims identified before testing. This step includes developing the deliverables from the load test (often a technical report) which includes an assessment of the tested bridge.

For a diagnostic load test, a comparison between the analytically predicted responses and the measured responses can be used to update and improve the analytical model, so that an improved rating or assessment of the bridge results. After a diagnostic load test with a specific goal, such as verification of stress transfer, deflections, transverse distribution, unintended composite action etc., the data obtained during the field test should be analyzed to address this specific goal.

After a successful proof load test in which the bridge has carried the target load without exceeding any stop criteria, it can be directly concluded that the bridge can carry the code-prescribed loads. In this case, the post-processing stage is limited to discussing the way in which the target load was determined, showing placing and description of the loading, presenting the graphs of the measured responses in a report, demonstrating that no stop criteria were exceeded, and writing down the conclusion that the bridge can carry the pre-defined target loads. Additionally, a proof load test can be used to verify bridge response assessments, based on extensive analytical models. The proof load test then serves to confirm the assumptions regarding material modeling, geometries, structural element interactions, load separation, boundary conditions etc. For bridges with material degradation and deterioration, the proof load test can be used to evaluate the deterioration model assumed in the analytical model.

In all cases, it is necessary to develop a report after a load test for future reference and bridge management decisions. When calibrating a finite element model based on field test results is one of the goals, the improved model should be submitted with the report, so that for future decisions (for example, checking if a super load can be allowed passage over the bridge) this improved model is available.

2 POST-PROCESSING OF MEASUREMENT DATA

2.1 Applied load

A first element that should be calculated if not directly available and reported is the magnitude of the total applied load. When the load is applied with vehicles, the weight of these vehicles is measured on site. The weight per axle and distance between axles should be included in the report of the load test. Depending on the goals of the load test, the position of the vehicles may be measured as well. Post-processing of these measurements could include developing plots of the loading protocol in terms of position of the load versus time. If different vehicles and configurations of these vehicles are used, resulting in a number of loading scenarios, then these scenarios should be documented and the report of the load test should contain such information.

When hydraulic jacks are used, the applied load should be measured, by using for example load cells. If the same load should be applied on all wheel prints, the measurements that show that this goal was met during the test should be post-processed and shown in the report, see for example Figure 1. If the load is applied to represent a truck with different axle loads, the measurements that show that this goal was met during the test should be post-processed and shown in the report. Additionally, the sum of the externally applied load should be made. The total applied load is the sum of all separate loads (on the separate wheel prints), as well as the weight of the jacks and other elements that are used for load application. The weight of the elements used for load application should be provided by the engineers responsible for the loading procedure.

The position of the wheel prints on site should be measured carefully so that it corresponds to the sensor plan as close as possible, and any changes from the originally determined positions should be explained, reported, and changed on the final drawing of the sensor plan for the report.

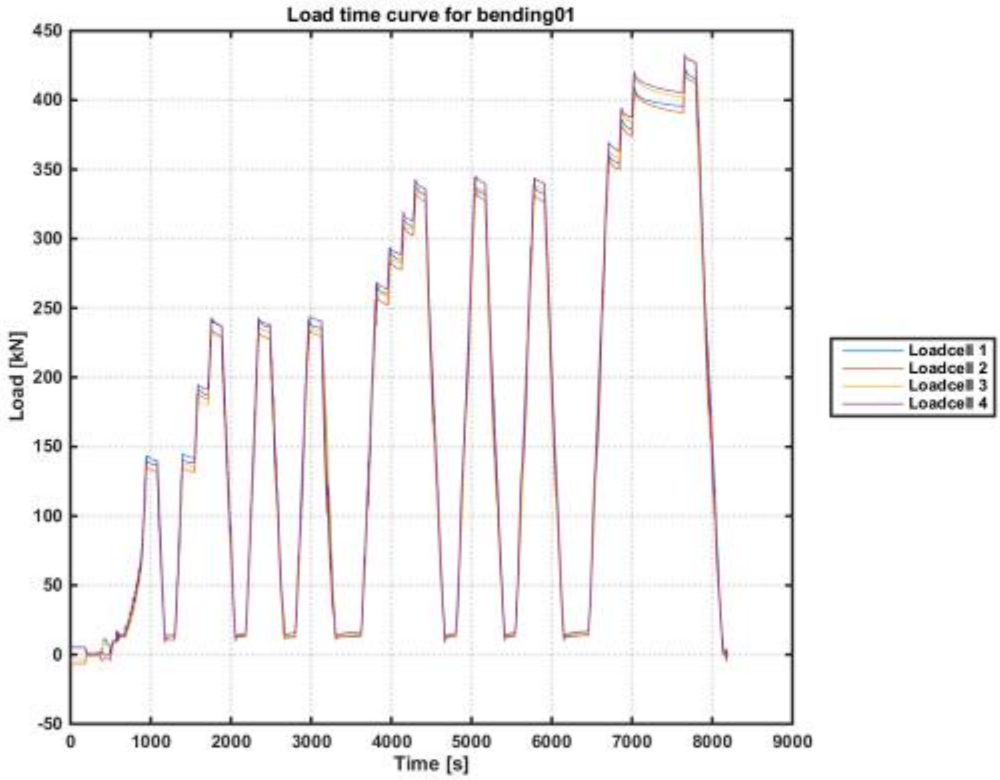

Figure 1. Comparison between four load cells on which the same load should be measured. Conversion: 1 kN = 0.225 kip.

2.2 **Verification of measurement data**

After a load test, all measurements should be post-processed. A first step here is to develop plots of all measured structural responses versus time or versus load, and check these plots for anomalies in the data. If such anomalies are observed, an explanation should be sought. Possible explanations include a sensor running out of its available measurement range, effects of wind on the structure on which sensors are mounted, etc. Special attention should be paid to the measurement data that are used to meet the goals of the load test. Using two independent measurement methods for the same output could be one of the means to understand discrepancies related to monitoring and responses.

The data should also be checked based on the expected structural response determined analytically prior to the test. The cause of significant differences between prediction and measurements should be determined as good as possible. Additionally, the symmetry, linearity, and reproducibility of the data should be checked. Symmetry of the measured structural responses means that for symmetry of geometry or load application, similar responses should be measured. Linearity of the measured structural responses means that for equal increases in the load, equal increases in the structural response should be measured. Reproducibility of the measurements means that when a load case is repeated, similar structural responses should be measured. When these requirements are not met, possible explanations could be:

- Differences in the structural responses as a result of the influence of changes in temperature and humidity,
- Sensor malfunction,
- Imperfections in the structure, or
- Small misalignments with the method of load and sensor application or on the load path when vehicles are used.

The engineer should also address the quality of the data based on the amount of noise in the measurements.

2.3 Correction for support deformations

When elastomeric bearings (Figure 2) are used, these bearings can be compressed during the load test. This deformation should be measured during the load test. Consequently, the measured deflections of the superstructure can be corrected for the support deformations to find the net deflection of the superstructure.

Additionally, for bridges on soft soils, the settlement of the supports during the load test should be measured, and the measured deflections of the superstructure should be compensated with the support settlement to find the net deflections of the superstructure. The plots of the measurement data that should be included in the report of the load test should show the deflection measurements corrected for the effect of the support deformations.

Figure 2. Example of elastomeric bridge bearings in laboratory conditions

2.4 Correction for influence of temperature and humidity

The influence of temperature and humidity on the measured structural responses can be important, as discussed in Chapter 5. Temperature and humidity can influence both the structural response as well as the sensor function- and sensitivity. The latter effects can sometimes be mitigated with correction factors that are provided by the manufacturer of the sensor. The first effect can be mitigated by measuring the structural response caused by only temperature and humidity changes at a position that is not affected by the applied load (for example, see Figure 3) or by using “zero load” cases. The measurements that are affected by the influence of temperature and humidity should be corrected for these effects. The discussions in the report of the load test should address the effect of temperature and humidity, and the plots of measurements data in the report of the load test should be corrected for the effect of temperature and humidity.

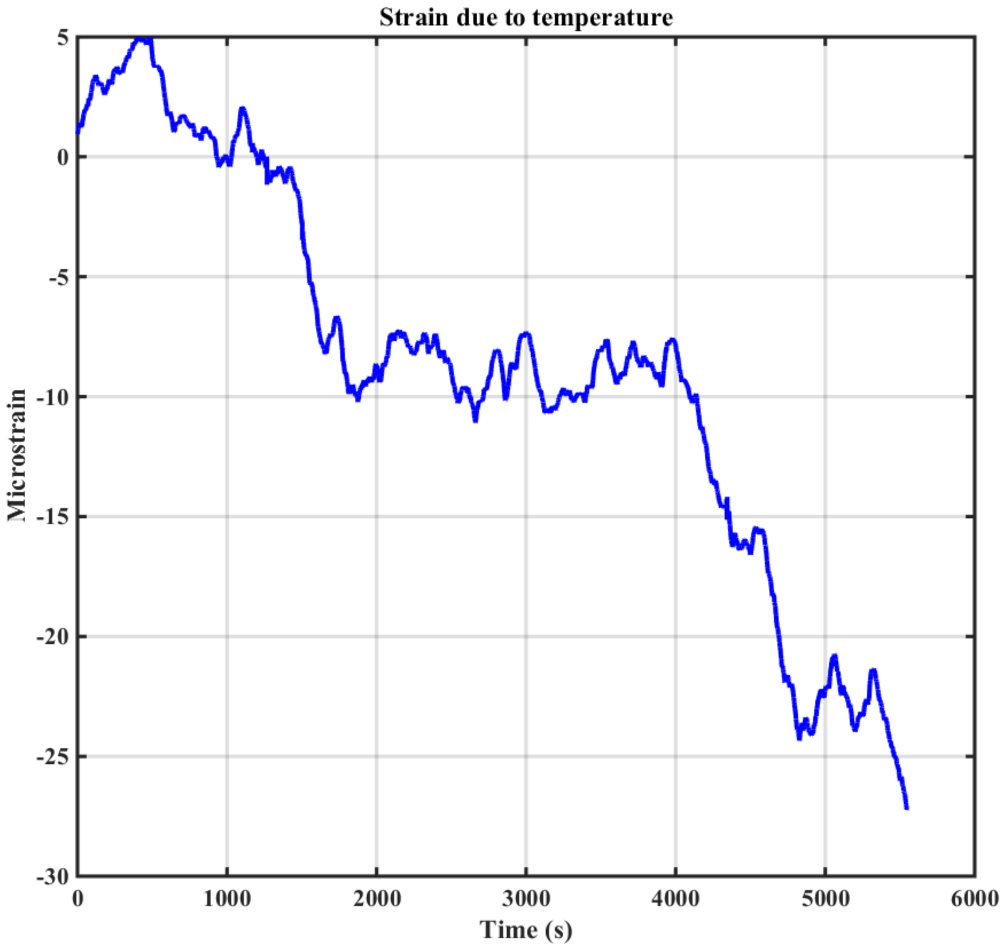

Figure 3. Strain measured at position not influenced by the applied load: strain development over time due to changes in temperature and humidity.

2.5 Reporting of measurements

Once the structural responses are corrected for the influence of support deformations and the influence of temperature and humidity, the plots of the measurements can be developed for the report. The measurements that are included in the final report of the load test depend on the goals of the load test. The structural responses necessary to address the testing aims should be included in the report, and the verification of these aims should be based on the observed structural responses.

Depending on the goals of the load test and type of load test, the following measurements can be included in the report:

- Monitoring plan, describing the location of each monitoring device and justification for the use (see also Chapter 5 which describes the development of the sensor plan).

- Loading scheme: The measured loading scheme should be similar to the planned loading scheme, and the report should address deviations from the plan, if any. Depending on the method of load application, the measured loading scheme can include the measured weights of the vehicles, the measured positions of the vehicles versus time during the load test, or the measured applied load on each jack when a system with hydraulic jacks is used. For more information on the required data for the report regarding the applied load, see §2.1.

- Load-displacement diagram at representative positions. The displacement is often the vertical deflection, but measurements in the horizontal direction can be used to verify out-of-plane movements of bridge elements, supports etc. If cycles of load are applied, the envelope as well as the full load-displacement diagram should be added to the report.

- Plots of deflections: if lines of deflection sensors are applied in the longitudinal and transverse direction, the resulting deflection plots at selected magnitudes of the load can be used to show the linearity of the overall structural response. Figure 4 depicts an example of a longitudinal deflection plot at different load steps.

- Strain profiles: if strains are measured over the height of girders, the resulting strain profiles should be drawn at selected magnitudes of the load. The position of the neutral axis should be determined for selected magnitudes of the load.

- Strain measurements: besides using the strain measurements to derive strain profiles, these measurements can also be reported as a function of the time and as a function of the applied load. These plots can be used to evaluate the linearity and reproducibility of the data, and to verify stop criteria for proof load tests.

- Crack width measurements: for concrete bridges, existing cracks and related opening can be monitored during a load test, or if a proof load test induces new crack development to the structure, these cracks can be monitored and followed as a part of the stop criterion evaluation. The post-processing of the data of crack width measurements can include plots of the crack width versus time, crack width versus load, drawings of the damage to the bridge before and after the load test, and the comparison of the measured crack widths to stop- or acceptance criteria for proof load tests.

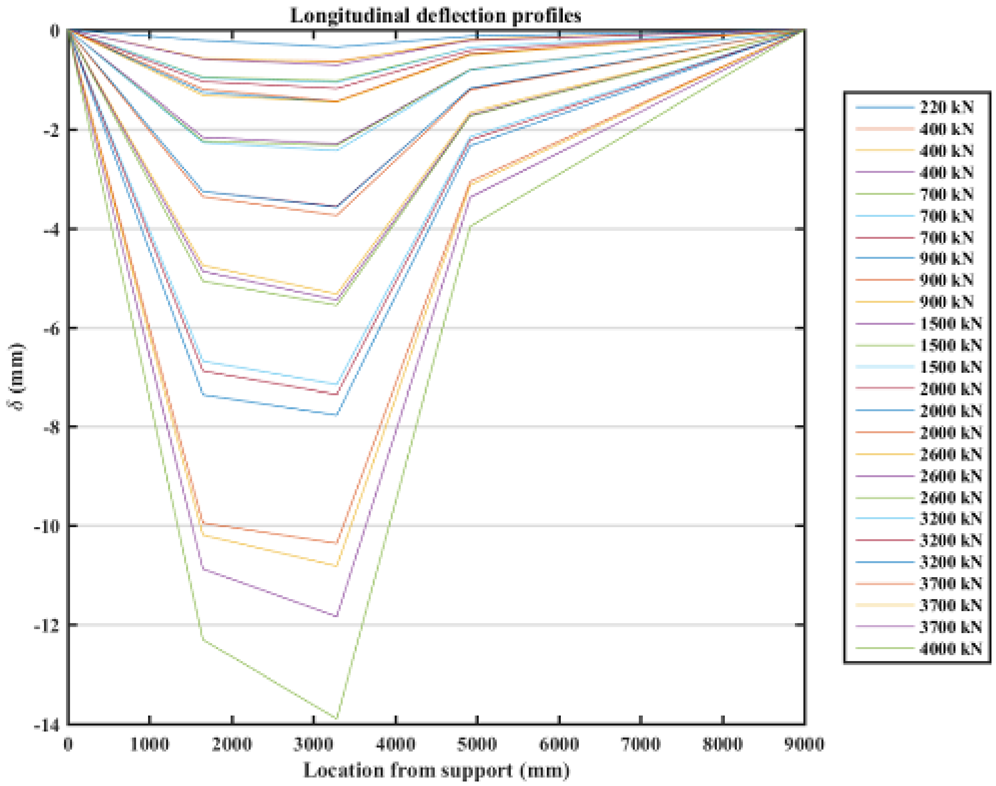

Figure 4. Longitudinal deflection profiles for different load levels. Conversion: 1 kN = 0.225 kip, 1 mm = 0.04 in.

For proof load tests, the report should restate the stop and acceptance criteria that were selected prior to the load test. The derived plots and measured structural responses can then be used to report that the stop criteria are not exceeded and to verify the acceptance criteria. Since the stop criteria are verified during the proof load test, their main importance is during the test. The post-processed data should be used to make a second check of the stop criteria. Acceptance criteria are verified after a proof load test to demonstrate that the structural behavior is within acceptable limits.

If a stop criterion is exceeded during a proof load test prior to reaching the target proof load, the outcome of the proof load test is that the bridge cannot carry the code-prescribed loads. Depending on the load level at which the stop criterion is exceeded, the bridge may fulfil the requirements for a lower safety level or for reduced traffic loads. Since the decision for posting this bridge then hinges on the stop criterion and the load at which it was exceeded, for such a case it is important to discuss this stop criterion and the measurements that were analyzed for this stop criterion in the report. This discussion should include the effect of the support deformations and influence of temperature and humidity. If it turns out that the corrected data show that the stop criterion was not exceeded, a retest may be necessary. For cases where a stop criterion is exceeded during the proof load, this step of post-processing should be done already in the field, so that (time permitting) a retest can be done.

3 UPDATING FINITE ELEMENT MODEL WITH MEASUREMENT DATA

The goal of a diagnostic load test can be to have a better understanding of the overall behavior of the tested bridge. A way to address this goal is by updating a finite element model with measurement data from a field test, so that the improved model can be used for the assessment. The details of these procedures are included in Part III. Barker (Barker 2001) identified the sources of differences between the measurements and the finite element model for diagnostic load tests on steel bridges as follows:

- frozen bearings, resulting in a restraint of deformations at the supports, which lead to sagging moments over the supports that were not included in the model,
- differences in the longitudinal distribution of bending moments,
- differences in the transverse distribution of bending moments,
- the stiffness of nonstructural elements such as barriers, curbs, and railings,
- the actual impact factor,
- the actual dimensions,
- unintended- or additional composite action.

In addition to the above discrepancies related to steel bridges, some additional differences could be the case for concrete bridges (Nanni et al. 1999), (Alkhrdaji et al. 1998), (Goodpasture & Burdette 1973), (Schmidt et. al 2018):

- actual influence of the steel reinforcement strain hardening magnitude,
- actual load distribution in the concrete bridge deck,
- effect of compressive and tensile membrane action,
- time-dependent effects on the concrete properties,
- confinement from the restraint of the bridge deck.

The differences between the dimensions in the finite element model and the actual dimensions should be limited after the visual inspection on site during the preparation stage of the load test. If there are doubts regarding certain dimensions, these dimensions can be measured on site. For concrete cross-sections, the difference between considering the cross-section as cracked or as uncracked should be evaluated.

Similarly, for proof load testing the field measurements can be used to update the finite element model that was used for the preparation of the load test. The improved model can be used for future load ratings of the bridge, or to evaluate its ability to carry a superload.

Depending on the goals of the load test and the available measurements, the strain and deflection profiles from the measurements can be compared to those predicted prior to the field test with a finite element model. If parametric studies were done by changing the uncertain properties in the finite element model, then the measured response should be compared to the predicted range of responses. This comparison can then be used to estimate the uncertain properties where these cannot be determined directly from the measurements during the load test. These insights can then be used to improve the available finite element model. The existing finite element model can be improved by using mathematical optimization functions. However, it is important for the bridge engineer who will evaluate the bridge and the field test to keep in mind the sources of the differences between the model and the measurements, so that the engineer can understand mechanisms behind the optimization of the model and the overall behavior of the bridge.

One element that requires further research is how finite element models can be used when only one span can be load tested. For bridges crossing the highway, it may not be permitted to carry out a proof load test on spans that are directly above the highway, as the risks involved are too large (Lantsoght et al. 2017, Lantsoght et al. 2018), and lane closures or complete closure of the highway would be necessary for safety reasons. If a span is proof loaded that is not the critical span, then the proof load test can only evaluate the tested span. A possible way to assess the critical span after the proof load test is by updating the finite element model based on the measurements from the load test, and then to use the updated model to assess the critical span. Future research should explore this method, and use probabilistic methods to quantify the uncertainties on such approaches.

4 BRIDGE ASSESSMENT

For existing bridges, load tests can be used for assessment. The method for assessment depends on the governing codes and guidelines. The way in which the information from the load test is used for an assessment depends on the type of load test. For diagnostic load tests, the AASHTO Manual for Bridge Evaluation (AASHTO 2016) presents a simple method based on the ratio between predicted and measured responses to update the rating of the considered structural elements, as well as a method to determine the target proof load so that the rating factor of the considered structural elements becomes larger than or equal to one.

In the assessment of the tested bridge after the load test, the differences between the applied loads and the loads required for assessment should be considered. In Europe, the load models from the Eurocode NEN-EN 1991-2:2003 (CEN 2003) that are used for assessment cannot directly be translated into a certain truck type. In the Americas as well as in some European countries, the assessment uses actual truck types. For such cases, the relation between the applied load and the load required for the rating is clear. For assessment using the NEN-EN 1991-2:2003 loads, an intermediate step is necessary. At this moment, this intermediate step is the use of equivalent sectional forces and moments. Future research should address this gap and embed load testing into the codes for assessment.

When an updated finite element model is used for the assessment after a load test, the bridge engineer should address questions about the applicability and extrapolation of the test results and updated model to higher load levels corresponding to the ultimate limit state and future ratings (Bridge Diagnostics Inc. 2012). If unintended composite action or boundary conditions e.g. (frozen bearings) are the source for differences between the responses in the model and the measured responses, these changes to the structure may not be valid for all load levels. For high loads, the unintended composite action may be lost, so it would not be conservative to take this positive effect into account for a rating at the ultimate limit state. If future maintenance activities include the replacement of bearings, the effect of this change on the assessment should be considered and discussed in the report of the load test.

5 FORMULATION OF RECOMMENDATIONS FOR MAINTENANCE OR OPERATION

The final step in using the results from a load test is making a decision regarding the future operation of the bridge. The bridge owner is responsible for this decision. This decision could be to keep the bridge in operation as it is, post the bridge, strengthen the bridge, or demolish (and possibly replace) the bridge. The owner is also responsible for the permit loads. The report of the load test can only include a recommendation for the future operation of the bridge based on the outcome of the test. If after the load test, certain elements of the bridge behavior are still uncertain, the bridge engineer can recommend further (material) testing, more advanced calculations based on more complex models, additional site inspections, possibly amplified with non-destructive testing techniques, or long-term monitoring of the structure.

6 RECOMMENDATIONS FOR REPORTING OF LOAD TESTS

After a load test, the report of this test should contain all relevant information related to test outcome as well as the resulting recommendations.

The report should contain the following information about the bridge:

- Name, location, year of construction,
- Overview photograph of the bridge,
- Type of structure.

The following information from the preparation stage of the load test should be included:

- Overview of the available information: plans, original calculations, inspection reports, reports of material testing…,
- Summary of the technical inspection carried out as part of the preparation of the load test,
- Results of assessment before the load test and models used to assess the bridge for an existing bridge, or summary of design assumptions and models used to design the bridge for a new bridge,
- Thresholds related to the load test such as target load and stop criteria (for proof load tests), and how the loading procedure will address these,
- Loading protocol (load paths and configurations if vehicles are used, or loading scheme when hydraulic jacks are used),
- Sensor plan with a link to the limiting thresholds of the load test,

- Expected structural responses, and when relevant, the expected capacity of the critical sections,
- Safety considerations.

From the execution of the load test, the report should include the following information:

- Date and time of the load test,
- Weather conditions during the load test,
- Personnel on site,
- Most important observations during the load test (the log of all observations can be added to the report as an Appendix).

The report should also include the following post-processing results:

- The actual loading protocol (and differences with the planned protocol should be addressed),
- Plots of the relevant measurements, with a discussion of the verification of the measurements (see section §2.2) and derivation of properties that follow from the measurements (location of member neutral axis, resulting stresses where strains are measured…),
- Verification of stop and acceptance criteria, when relevant (proof load tests)
- Comparison between predicted responses and measured responses, and updating of the analytical models, when relevant (typically diagnostic load tests),
- Parameter studies related to updating the finite element model or recommended actions if the outcome of the theoretical models differs from the test result of the real bridge structure and the parameter studies cannot identify the cause of these differences.

The final recommendations in the report can address the following elements:

- Assumptions used for the assessment of the bridge after the load test based on the experiences from inspections before the bridge test, identified critical areas during load testing, and information gained from the field test,
- Results of the assessment of the bridge after the load test,

- Recommendations for maintenance of the bridge, when relevant,

- Recommendations for posting or permit loads of the bridge, where relevant.

7 SUMMARY AND CONCLUSIONS

The final step in the project of a load test is to post-process the data gathered during the load test, and combine all relevant information into a report about the load test. The way in which the data are analyzed depends on the goals of the load test, the type of load test, and whether the tested structure is a new or existing bridge. For a diagnostic load test on a new bridge prior to opening, it may be sufficient to show that the differences between the measured and predicted responses are within acceptable limits. For a proof load test on an existing bridge, it can be sufficient to show that the bridge can carry the target load and thus fulfils the code-prescribed loads and load combination. For cases where the conclusion does not follow directly from the load test, all assumptions and calculation procedures should be discussed.

The report should include the relevant structural responses measured during the load test as well as the applied load. When the load is applied with vehicles, the magnitude of the load should be mentioned in the report, as well as the loading paths and combinations of trucks used for different scenarios. When the load is applied with hydraulic jacks, the measured forces should be reported. A next step should be to discuss the quality of the measurement data in terms of reproducibility, symmetry, and linearity, as well as in terms of noise on the measurements. These measured structural responses should be corrected for the effect of support deflections and the effects of temperature and humidity. The report should also include a comparison between the measured structural responses and the predicted responses, and should address the differences. All relevant measurements should be presented in a visual way after developing the most relevant graphs of the data.

In some cases, the goals of the load test cannot be directly met by analyzing the measurement data. For these cases, the finite element model that was used to prepare the load test can be updated with the measured structural responses, and through this process, the sources for the differences between the analytically determined responses and the measured responses can be identified. The updated model can then be used to improve the assessment of the bridge.

The bridge engineer can develop recommendations for the maintenance and decision-making for the tested bridge, but the responsibility for the operation decisions lies with the bridge owner. Based on the technical inspection, the field test, and the analysis of the field test data, the load test report should include an improved assessment of a bridge when the tested bridge is an existing bridge. For new bridges, the field test data can be used to identify differences between the actual structural behavior and the assumptions used during design. These differences should then be considered in future assessments of the bridge.

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