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RECENT ADVANCES IN THE FIELD OF BRIDGE LOAD TESTING

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Load testing of bridges is commonly used to verify the performance of a bridge prior to opening as well as for the assessment of existing bridges. This paper reports on recent advances in the field of bridge load testing, based on experimental work carried out in Europe as well as international collaboration efforts. The experimental, numerical and analytical work that has been carried out in these past years is summarized. The main findings are: 1) modern instrumentation techniques (such as acoustic emission measurements and digital image correlation) can be combined with traditional measurements to gain more in-depth insights during and after the test; 2) for load testing to be fully compliant with current codes, a probabilistic substantiation of the methodology is needed; and 3) international collaboration is key in order to successfully update current codes and guidelines and develop recommendations and sets of best practices. The recent advances in North America and Europe have also resulted in improvements to the practice of bridge load testing in Latin America (in particular in Costa Rica and Colombia). To conclude, load testing is an important tool for engineers faced with the task of assessing existing bridges. The aforementioned efforts will result in improved recommendations for the assessment of concrete bridges by load testing to be included in codes and guidelines in Ecuador and other countries in Latin America.

Keywords: Assessment, Design codes, Diagnostic load testing, Field testing, Proof load testing.

1 INTRODUCTION

In evaluating existing bridges, particularly those with significant uncertainties, analytical methods exhibit limitations. It becomes necessary to adopt conservative assumptions, often leading to overly conservative assessments. A pertinent example is the evaluation of reinforced concrete slab bridges for shear (Lantsoght *et al.* 2013). In such assessments, the calculation methodologies typically overlook the transverse redistribution capacity of these structures. Additionally, these bridges are generally without shear reinforcement, resulting in their classification as shear-critical and potentially non-compliant with current codes upon assessment. Another notable source of uncertainty is the influence of material degradation and deterioration on the structural capacity, which tends to yield conservative capacity estimations.

To tackle these uncertainties, conducting field tests on a bridge is a viable assessment strategy. Generally, there are two types of field tests, each with distinct methods and objectives: diagnostic load tests and proof load tests. Diagnostic load tests aim to refine an analytical assessment (Olaszek *et al.* 2014). These tests involve applying a relatively low load and measuring the structural response. The results of these measurements are then compared with the analytically predicted response, often derived from a linear finite element model. To align the field data with the analytical model, the latter is adjusted to develop a field-validated model. Possible modifications include aspects like composite action effects, continuity at supports, structural stiffness, and the contribution of non-structural elements to overall behavior (Alampalli *et al.* 2019). Proof load tests involve applying a load equivalent to the factored live load (Lantsoght and Okumus 2018). The test is deemed successful if the bridge can withstand this load without distress, demonstrating compliance with code requirements and eliminating the need for further assessment. Given the high loads in proof load tests, it is critical to instrument the bridge. The monitoring should happen in real-time to evaluate the bridge's response under increasing levels of load. It is also essential to establish "stop criteria", thresholds indicating the start of irreversible damage, before conducting a proof load test. If these thresholds are exceeded during the test, it must be halted immediately and the bridge must be unloaded.

Both diagnostic and proof load tests can be used for assessment. Assessment by diagnostic load testing results in an improved analytical (often, numerical) model. The process of proof load testing offers a direct method for assessment. It is important to note that this method stands apart from the diagnostic load tests typically conducted in Ecuador prior to bridge opening. The load levels applied in proof load tests are substantially higher. These loads are intended to simulate the factored live loads, or a load combination that incorporates the factored live load.

This paper outlines recent advances in bridge load testing in Europe, the Netherlands, North America, and Latin America, and outlines a path forward for Ecuador to use bridge load testing for the management of its existing bridge stock.

2 BRIDGE LOAD TESTING RESEARCH IN EUROPE

Recent research in Europe has focused on applying diagnostic load testing on railway bridges in combination with radar interferometry in Poland (Olaszek *et al.* 2021), the development of radar interferometry in Italy (Gentile *et al.* 2009), and the use of proof load testing for existing bridges in Poland (Halicka *et al.* 2018), Denmark (Christensen *et al.* 2023), and Sweden (Bagge 2020), and for existing buildings in Germany (Schacht *et al.* 2016). These insights have resulted in updated codes and guidelines in Poland (Research Institute of Roads and Bridges 2008), Hungary (Hungarian Chamber of Engineers 2013), Germany (Deutscher Ausschuss für Stahlbeton 2020), and expected new documents in Denmark and the Netherlands.

In the Netherlands, a number of pilot proof load tests (see Figure 1) have been carried out between 2009 and 2016 to study the potential of proof load testing for the assessment of existing bridges, and in particular reinforced concrete slab bridges (with cracking caused by alkali-silica reaction, with cracking caused by overloading, and with limited observed damage) and girder bridges with corrosion damage (Lantsoght *et al.* 2017a). From these pilot proof load tests, it was found that: 1) proof load testing can be a suitable method for assessment of existing bridges, and 2) a system with a load spreader beam, counterweights, and hydraulic jacks can be used to apply the load in a controlled manner. However, discussions remained open on the following topics: 1) influence of loading speed during the load test; 2) required number of cycles per load level; 3) required proof load magnitude; and 4) stop criteria to alert for a potential shear failure.

The uncertainties regarding the loading speed and loading cycles were addressed by laboratory testing of slab strips (Lantsoght *et al.* 2017b). These slab strips also served to develop theoretically-based stop criteria for flexure, and to propose shear stop criteria (Lantsoght *et al.* 2019). However, it was found that slab experiments are necessary to develop shear stop criteria for testing reinforced concrete slab bridges.

The uncertainties regarding the required proof load magnitude require a study of the probabilistic substantiation of proof load testing (de Vries *et al.* 2022). The stop criteria for shear and the probabilistic substantiation are topics of current research at Delft University of Technology.

Figure 1. Overview of tested bridges: (a) Halvemaans Bridge; (b) Viaduct Zijlweg; (c) Viaduct Vlijmen Oost; (d) Viaduct de Beek.

3 BRIDGE LOAD TESTING IN NORTH AMERICA

In North America, recent research has focused on the combination of diagnostic load testing with damaged bridges (Russo *et al.* 2000), the use of new materials (Hernandez and Myers 2018), and more advanced computational methods (Ohanian *et al.* 2017). As bridge load tests in the United States are typically carried out by the industry, companies have also geared their efforts towards better describing their load testing practices, to reach consensus (Commander 2019). This consensus is reflected in the TRB Primer on Bridge Load Testing (Alampalli *et al.* 2019) and ASCE state-of-the-practice paper (Alampalli *et al.* 2021). These documents, as developed by TRB AKB40 (Testing and Evaluation of Transportation Structures), lie at the basis of the changes to Chapter 8 of the Manual for Bridge Evaluation (AASHTO 2016) which have been approved and will be implemented at the next code change cycle.

4 LOAD TESTING ADVANCES IN LATIN AMERICA

In Latin America, load testing is commonly done prior to opening of new bridges to demonstrate to the traveling public and the bridge owner that the bridge behaves as designed (Bonifaz *et al.* 2018), see Figure 2. Load testing of assessment is less commonly used. However, the particular climatic conditions, loading conditions, and (lack of) maintenance and management strategies require the necessary adjustments to the load testing practices for assessment.

In Costa Rica, the TRB Primer on Bridge Load Testing (Alampalli *et al.* 2019) lies at the basis of the chapter on load testing in the bridge assessment code. In the United States, this topic is addressed by Chapter 8 of the Manual for Bridge Evaluation (AASHTO 2016). The next update of the MBE will contain also the recommendations of the TRB Primer.

In Colombia, diagnostic load testing is used as a strategy for the assessment of existing prestressed concrete planless bridges with cracking (as determined by visual inspection) (Castellanos-Toro *et al.* 2022). The combination of diagnostic load testing and numerical modeling has been shown to be a powerful tool, and it can help address some of the challenges related to poor bridge management and the loss of archives with plans over time.

Figure 2. Diagnostic load test in Ecuador prior to bridge opening (Bonifaz *et al.* 2018).

5 PATH FORWARD FOR ECUADOR

Ecuador had a large expansion of the road network in the early 2000s. At the same time, the lack of redundancy in the road network, especially in the Andean highlands, means that one bridge closure results in detours of several hours. Some bridges in remote areas are essential for the access to certain communities. As such, proper maintenance and management of the existing bridges is crucial for the functioning of the country.

For Ecuador, load testing of existing bridges can be a tool for the assessment of these bridges. However, the first step should be to develop a national inventory of the existing bridges, the (estimated) year of construction, construction type and materials, length, width, number of spans, combined with an initial visual inspection. Then, a simple risk-based ranking system should be applied to identify the most critical bridges. Efforts can then be geared towards a more in-depth assessment of these bridges. Load testing can be one of many tools to support such an in-depth assessment.

6 SUMMARY AND CONCLUSIONS

This paper gives an overview of recent advances in bridge load testing, both diagnostic and proof load testing. Particular attention is paid to research related to proof load testing in the Netherlands, Europe, North America and in Latin America. The following conclusions can be drawn:

- Load testing is a valuable tool for the assessment of existing concrete bridges.
- Modern instrumentation techniques (such as acoustic emission measurements and digital image correlation) can be combined with traditional measurements to gain more in-depth insights during and after the test.
- For load testing to be fully compliant with current codes, a probabilistic substantiation of the methodology is needed. Research in the Netherlands is addressing this need.
- In Ecuador, load testing of existing bridges can be used within a package of measures to improve the management and maintenance of the existing bridge stock.

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