Lessons Learnt from Full-Scale-Tests of Bridges in Croatia and Sweden

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Lessons learnt from Full-Scale Tests of Bridges in Croatia and Sweden

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Abstract

Load testing is a way to control the capacity and function of a bridge. Methods and recommendations for load testing are described and examples are given from tests carried out in Croatia and Sweden. In order not to damage the bridge being tested, the load must be limited, often to be within the serviceability limit state (SLS). Numerical models can be calibrated by load tests and then be used to check the carrying capacity for higher loads than what has been tested. Need for further work and recommendations are discussed. By effective planning, costs can be saved and a more sustainable use of bridges can be obtained.

Keywords: Load testing, proof loading, collapse, deformations, serviceability limit state (SLS), numerical modelling, stiffness

1 Introduction

Load testing is one of the oldest ways to check the quality of a bridge [1]. The deformations of a bridge during loading summarize its general condition and stiffness. Thus, the deformation is identified as a key performance indicator in the COST Action TU1406 "Quality specifications for roadway bridges, standardization at a European level", [2], [3]. In this paper some examples and experiences are given from load testing in Croatia and Sweden; how quality control and management of bridges can be improved and how numerical models may be calibrated.

Load testing can be performed at (a) service-load levels and (b) loads to check the ultimate capacity (failure) of a structure. Testing for service-load levels (a) are often divided into two groups [4]:

- Diagnostic tests in the linear elastic stage to update the analytical model of a bridge so that the allowable load can be better defined.
- Proof loading tests to demonstrate that the intended loads can be carried. Higher loads are usually used than in diagnostic tests.

Recommendations for proof loading are given in some codes and stop criteria are given to prevent damage. The criteria often prescribe maximum values for concrete and steel strains, crack widths and residual deflections. Brittle failures are feared so bridges with a risk for shear failure are usually not allowed to be proof loaded.

Testing to failure (b) can be used to increase the knowledge of the real function of a type of structure and how well codes can predict the load-carrying capacity [5]. Load testing to failure is often more expensive than diagnostic and proof

load tests where standardized load rigs or trucks with known weight can be used.

2 Experiences from Croatia

On the evening of March, 30, 2009, an unexpected collapse occurred for the railway bridge Jakuševac in Zagreb when a locomotive with 26 wagons was passing over it. Due to a high level of the Sava River and many years of scouring of bed material, one of the pillars suffered a partial collapse [Figure 1 & Figure 2], [6].

Figure 1. Partially collapsed bridge Jakuševac over the Sava River, side view [6]

The Jakuševac Bridge is a typical riveted double track bridge built in 1968. The static system consists of two main continuous I-girders (height 3,8 m, transversal distance 9,1 m) over three main spans (34,6 m + 65,9 m + 34,6 m = 135,1 m) with cross girders and bracings.

Figure 2. Plastic deformation of the bridge

Due to the lowering of the support, the bridge was subjected to excessively high compressive and tensile stresses, especially in the zones where the initial bending moment was close to zero. This region was not designed for large stresses, so a plastic zone developed [Figure 3]. Furthermore, due to self-weight of the structure and the new

static system (continuous girder with a plastic hinge) one of the two main girders at an end span was lifted and no longer supported by the column S4. This further increased the bending moment on the support S5. In addition to the vertical movement, the bridge suffered a horizontal shift and serious damage of the bottom secondary members.

Figure 3. Resulting moment distribution a) initial and b) after lowering of the inner support

The damage required a demanding rehabilitation project [7, 8], which was staged in the following three steps: (a) construction of temporary working supports, (b) positioning of the bridge at its design centre line, (c) strengthening of the damaged bridge elements (main and secondary steel elements, column and foundation S6).

2.1 Measurements during the lifting

When the construction of the temporary supports was finished, the bridge was lifted to its design centre line [Figure 4]. During the lifting, the strains were recorded in the two weakest cross sections close to the pinned support (S5) and close to the plastic zone.

Figure 4. Lifting stage using temporary supports

Figure 5. Measuring locations for strain recording

During each stage of the lifting, the bridge was raised 5 to 10 cm with hydraulic jacks. It took three days.

Based on the measured strains, stresses were calculated as a function of time [Figure 6], using Young's Modulus $E = 200 \text{ GPa}$. Each peak in the graph presents one of the lifting stages of the structure. According to the recordings, the bridge behaved in an elastic manner during the lifting.

Figure 6. Stresses for lifting steps

2.2 Diagnostic load testing

After successful positioning of the bridge at its design centre line and after strengthening of all the damaged bridge elements, a diagnostic load test was performed. According to current legislation in Croatia (HRN U.M1.046) [9] all new and repaired railway bridges with a span greater than 10 m, have to be subjected to a load test in order to verify their response to static and dynamic loads.

The purpose of this load test is to empirically quantify the load bearing capacity of the structure, i.e., to verify the theoretical model of the behaviour after reconstruction. The static and dynamic load tests were performed using six electric locomotives (three in each track line). Each of the four-axle locomotives had a total mass of 80 t (axle load of 20 t each).

2.2.1 Static load test

The static load test consisted of fifteen loading and unloading sequences [Table 1]. Ten loading sequences (T1 – T10) were applied in order to have both symmetrical and unsymmetrical loading conditions to obtain maximum load effects.

Figure 7. Maximum load effect at the middle span

The vertical displacements of the bridge were measured using geodetic methods, comprising 26 points located along the bridge [Figure 8]. A total of 22 LVDT's were installed to monitor the strains of the bridge in four cross sections. One LVDT was used to measure the horizontal displacement of the support S4 [Figure 9 & Figure 10].

Figure 8. Points for displacement measurements

The maximum measured displacement was 54 mm in loading stage T7 [10] for the maximum load in the middle span. Strain recordings during the static test for configuration T5 and T6 are presented in Figure 11, [10].

Table 1. Loading and unloading sequences

Test no.	Loading type	Span & number of Locomotives (*L)		
		S4-S5	S5-S6	S6-S7
UL1	Unloaded			
T1	Symmetric	4L		
T2	Unsymmetric	2L		
UL2	Unloaded			
T3	Symmetric			4L
T4	Unsymmetric			2L
UL3	Unloaded			
T5	Symmetric	2L	4L	
T6	Symmetric		2L	4L
UL4	Unloaded			
T7	Symmetric		6L	
T8	Unsymmetric		3L	
UL4	Unloaded			
T7	Symmetric	6L –pier S5		
T8	Symmetric		6L –pier S6

Figure 9. Sections for strain measurement

Figure 10. Points for strain measurement

2.2.2 Dynamic load test

In addition to information of the natural frequencies, modal shapes [Figure 12] and damping ratios of the bridge, the dynamic tests provide a picture of the variation in the dynamic amplification factor with speed [Table 2]. This test

Figure 11. Recordings of strains for T5 and T6

was conducted after the static load test by using two locomotives. The dynamic parameters were captured by using accelerometers in six points of the middle span.

At the end, all results were compared with theoretical values based on a FE-model of the bridge presented in [10]. The numerical model used for the structural analysis of the bridge was updated according to the measured displacements, strains and natural frequencies.

The bridge behaved elastic both during the static test and the dynamic test.

Table 2. Dynamic amplification factor

Number of locomotives	Speed [km/h]	Dynamic amplification factor
1	20	1,042
	40	1,066
	60	1,073
2	20	1,029
	40	1,043
	60	1,059

Figure 12. Measured first mode shape 3,03 Hz

3 Experiences from Sweden

Some examples are given in Table 3, [11].

Table 3. Examples of full-scale load testing to failure in Sweden.

Type	Photo	Tests and Results	Ref.
Stora Höga Reinforced concrete (RC) portal frame road bridge with a span 21.0 m Built in 1980.		The bridge was strengthened with externally bonded steel plates to avoid a bending failure. Loads were produced by using four hydraulic jacks anchored in the bedrock. Brittle shear failure at the supporting wall at a load of 4.6 MN. The theoretically assessed capacity with the Swedish code was only 48% of the test value.	Plos <i>et al.</i> (1990), [12] Täljsten (1994), [13] Plos (1995), [14] Bagge <i>et al.</i> (2018), [5]
Lautajokk RC single-trough railway bridge with a span of 7.0 m. Built in 1967.		The axle loads on an iron ore railway line was to be increased from 250 to 350 kN. In order to investigate the fatigue capacity, this bridge was tested with an axle load of 360 kN during 6 million load cycles using hydraulic jacks. The shear capacity was studied of the connection of the slab to the longitudinal beams, where no shear reinforcement was present. After the cyclic loading, not resulting in any detectable damages, the load was increased to yielding of the longitudinal bending reinforcement.	Thun <i>et al.</i> (2000), [15] Elfgrén (2015), [16]
Örnsköldsvik Continuous RC single-through railway bridge with spans of 11.9 m and 12.2 m. Built in 1955.		The bridge was strengthened with near surface mounted carbon fibre reinforced polymer (CFRP) bars to avoid a bending failure. The loading was produced by using two hydraulic jacks anchored in the bedrock. Brittle bond failure of CFRP followed by shear-bending-torsion failure at 11.7 MN. The theoretically assessed capacity with codes was 65 to 78% of the test value.	Sustainable Bridges (2007), [17] Puurula <i>et al.</i> (2012 - 15), [18-20] Bagge <i>et al.</i> (2018), [5]
Åby river Steel truss railway bridge with a span of 33 m Built in 1955.		The bridge was placed beside the original site at Åby river and loaded with two hydraulic jacks anchored in the bedrock. A failure initiated by fatigue was expected but instead buckling occurred in the two longitudinal top girders for 11 MN. The bridge was designed for about 35 % of the failure load.	Mainline (2014), [21] Häggström (2016), [22] Häggström <i>et al.</i> (2017), [23]
Kiruna Continuous PC girder road bridge with five spans of a total length of 121.5 m Built in 1959		The bridge was monitored for 8 years to check settlements due to mining. The bridge was thereafter loaded in the 2nd span by hydraulic jacks anchored in the bedrock. Longitudinal non-prestressed reinforcement and vertical shear reinforcement yielded. In the final stage, stirrups ruptured and the loading plate punched through the slab. The maximum load was 13.4 MN and the girder was designed for 22 % of the failure load.	Bagge (2017), [24] Bagge <i>et al.</i> (2018), [5] Huang <i>et al.</i> (2016), [25] Nilimaa (2015), [26]

The overall aim has been to investigate and evaluate the safe function of bridges, as exemplified in Table 3, for increased loads at the serviceability and ultimate limit states and to improve modelling, [11].

The main result of the tests at service-load levels is that many bridges have a “hidden” capacity and could carry higher loads than what is obtained applying ordinary design rules. In these tests probabilistic analysis was also identified as a viable tool for the assessment

Numerical tools as linear and non-linear finite element methods have been shown to be useful for assessment, especially combined with material testing and step-wise refinements from linear to non-linear modelling of bending, shear and anchorage [24], [28].

In numerous studies, see e.g. [5], large differences have been demonstrated between standard structural assessment methods and more detailed analyses by using non-linear FEM. The differences have probably partly arisen from redistribution of loads during testing in statically indeterminate structures, from conservative load-carrying models, increased values of material properties and built-in properties of the supports.

Strengthening with carbon fibre reinforced polymers (CFRP) has been applied successfully in different cases. For instance, the load carrying capacity was substantially increased in the Örnköldsvik Bridge (see Table 3). Here, non-linear finite element models of the bridge were calibrated and used to simulate the structural behaviour in a good way. It was important to accurately model tension stiffening and support conditions [19], [20]. The concrete tensile strength and fracture energy were also identified as crucial parameters in numerical modelling. Often they are determined from empirical formulae from the concrete compression strength; however, more efforts should be taken to determine these properties directly from assessed existing structures.

The structural analysis and the verification of the required level of structural safety can be carried

out at several levels of increasingly complex approximation.

In addition to the choice of safety concept, the level of safety is an important issue for bridge assessment and should take into account what is already known about the structure and economical, societal and environmental risks associated with it [24], [26].

4 Discussion

Some lessons learnt from load testing to failure are presented in [5]. About 28% of full-scale tests on 30 bridges ended with a failure mode different to that predicted. In some cases, this was related to inaccuracies in the methods for determining the load-carrying capacity but, in the majority of cases, it was caused by a lack of insight into aspects shown to be critical, particularly associated with the shear and punching capacities and the boundary conditions. Consequently, there is a need of further studies in order to provide reliable codes and guidelines on how to accurately assess the capacity of bridges.

Scouring of bed material can be devastating to the function of a bridge. Improved monitoring and numerical methods may in the future be used to determine hidden deterioration [25].

An idea is also to create digital twin bridges which start their life (*in silico*) during the planning phase of a bridge [24]. The models may be integrated with monitoring of the *in situ* bridge to enable model updating and for later assessment of the quality and load-bearing capacity of the bridge during its life time.

5 Conclusions

This paper presents the experiences from a range of tested bridges in Croatia and Sweden. Most of the bridges had more capacity than the original design calculations indicated, and in several cases, a diagnostic load test was a cost-effective way to avoid strengthening or renewal of the bridge. Tests to failure may show differences, e.g. in load distribution, superstructures composite behaviour or support conditions, which often results in extra “hidden” capacity to the bridge. In a few tested

bridges, the result was the contrary. The tests revealed damages in the bridge superstructure which made the distribution even worse than calculated and the capacity of the bridge weaker.

The collapsed bridge in Croatia learned us in an expensive manner how not to manage bridges. This bridge was an example of lack of inspection and maintenance during ages. On the other hand, the well planned monitoring during construction and load testing was a complete success and a huge amount of interesting data was collected. This data is used by the authors to understand the static and dynamic behaviour of this structure as well as to produce an initial database of the undamaged repaired structure that can be used for future condition assessment of the bridge.

Load tests are a relatively easy way to get precise information about the behaviour of a bridge and also to provide useful information about different bridge types and their typical behaviour. Tests need to be designed carefully to achieve useful results and the results need be analysed and published in order to get a full insight of its implications.

Additional work is needed regarding recommendations for load testing, proof load levels, test set up and calibration of numerical models. Above all, more tests to failure of different bridge types are suggested to give a better base for reliable assessment of existing bridges in order to improve quality control, a cost efficient bridge management and a sustainable usage of the existing bridge stock.

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