Bridges tested to failure in Sweden

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Abstract

Five bridges of different types have been tested to failure and the results have been compared to analyses of the load-carrying capacity using standard code models and advanced numerical methods. The results may help to make accurate assessments of similar existing bridges. There it is necessary to know the real behaviour, weak points, and to be able to model the load-carrying capacity in a correct way.

The five bridges were: (1) a strengthened one span concrete road bridge - Stora Höga ; (2) a one span concrete rail trough bridge loaded in fatigue – Lautajokk; (3) a two span strengthened concrete trough railway bridge - Övik; (4) a one span railway steel truss bridge -Åby; and (5) a five span prestressed concrete road bridge - Kiruna. The unique results in the paper are the experiences of the real failure types, the robustness/weakness of the bridges, and the accuracy and shortcomings/potentials of different codes and models for safety assessment of existing structures

Keywords: Test to failure, bridges of concrete and steel, Assessment, Strengthening, Monitoring, Bending, Shar, Torsion, Bond, Fatigue, Carbon Fibre Reinforced Polymers (CFRP)

1 Introduction

Load testing is one of the oldest ways to check the quality of a bridge, Bolle *et al.* [1]. The deformations of a bridge during loading summarize its general condition and stiffness. Thus, the deformation can be identified as a key performance indicator as studied in e.g. COST 1406 [2], [3].

In this paper some examples and experiences are given from load tests to failure in Sweden; how quality control and management of bridges can be improved and how numerical models may be calibrated.

2 Service and ultimate load levels

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 (Lantsoght *et al*. [4]-[6]):

I. Diagnostic tests to update the analytical model of a bridge so that the allowable load can be better defined. Here often the stiffness of a bridge is determined in the linear elastic stage.

II. Proof loading tests to demonstrate that a bridge can carry the loads it is intended for, Casas, Gomez [7]. 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 [4].

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, Bagge *et al.* [8]. Load testing to failure is often more expensive than diagnostic and proof tests where standardized load rigs or trucks with known weight can be used.

3 Examples of load testing

In Sweden, numerous bridge tests have been carried out, Elfgren *et al.* [9]. Some examples are given in Table 1. The overall aim has been to investigate and evaluate the safe function of the bridges for increased loads at the serviceability and ultimate limit states and to improve modelling.

The main result of the tests 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. In numerical models, boundary conditions are often hard to predict correctly but can after calibration to test results present a more correct picture of the behaviour.

Similar experiences from load testing have been obtained in e.g. Finland, Raunio [10] and Norway, Statens Vegvesen [11]

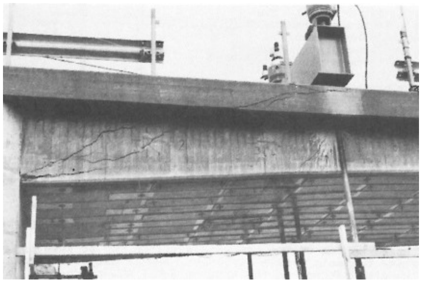
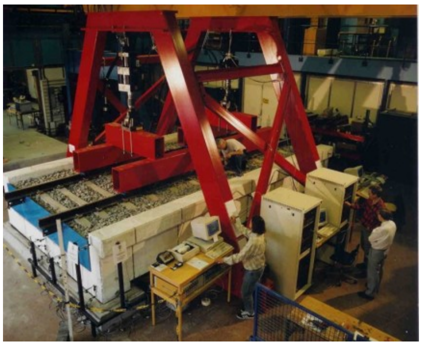
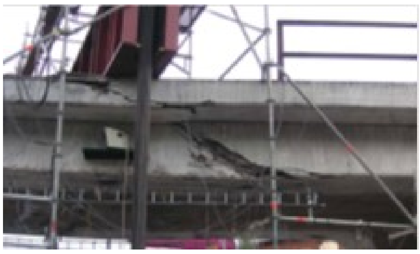
4 Calibrating numerical models

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, Bagge [10], Hendriks *et al.* [11]. In numerous studies, see e.g. Bagge *et al.* [9], 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 Örnsköldsvik Bridge. 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 (Puurula *et al*. [12]-[14]. 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, Bagge [10], Paulsson *et al.* [15]

Table 1. Bridges tested to failure in Swede

Location, Type	Photo	Tests and Results	References
Stora Höga Reinforced concrete (RC) portal frame road bridge with a span of 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 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 48% of the test value	Plos *et al.* 1990 [18], Täljsten 1994 [19] Plos 1995 [20] Bagge *et al. 2018* [8]
Lautajokk RC single-trough railway bridge with a span of 7.0 m. Built in 1967.		The axle loads on a 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. The shear capacity was studied of the connection of the slab to the longitudinal beams. After the cyclic loading, not resulting in any detectable damages, the load was increased to yielding of the reinforcement.	Thun *et al.* 2000 [21], 2011 [22] Elfgren 2015 [23]
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. Brittle bond failure of the CFRP was followed by shear-bending-torsion failure at 11.7 MN. The capacity with codes was 65 to 78% of the test value.	Sustainable Bridges 2007 [24] Puurula *et al.* 2012-2015 [14]-[16] Bagge *et al.* 2018 [8]
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. Fatigue cracking in some of the joints was expected but buckling occurred in the two longitudinal top chords for 11 MN. The bridge was designed for about 35 % of the failure load.	Mainline 2014 [25] Häggström 2016 [26] Häggström *et al.* 2017 [27]
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 then loaded in the middle of the 2nd span by hydraulic jacks anchored in the bedrock. Longitudinal non-pre-stressed 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 about 22 % of the failure load.	Bagge 2017 [10] Bagge *et al.* 2018 [8] Huang *et al.* 2016 [19]

5 Need for further work

Some lessons learnt from load testing to failure are presented in Bagge *et al.* [8]. 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 the 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.

Many tested structures had a considerable “hidden” capacity which can be disregarded during ordinary assessment processes and which is accounted for neither in standards nor in design guidelines. One reason is the high safety factors that are used both for loads and materials in the construction phase and which may not be necessary in an assessment process where geometry, materials and load may be better known, Paulsson *et al.* [17]. Probabilistic methods can be applied successfully to improve the study of reliability and safety of existing structures. More experience and acceptance of reduced reliability factors for different existing structures are needed.

Fatigue is an important factor when the load on a structure is increased. The rate of damage when the stresses are increased rise with a logarithmic factor that can be three to five times the stress increase. This means than an increase of stress range may cause a proportionally much larger reduction of the number of allowable load cycles. Methods to determine the remaining fatigue capacity would be very valuable both for steel and concrete bridges. The concrete fatigue capacity in shear is not as critical as many codes envision, Elfgren [23]. Shear stresses are in the design phase often converted to tensile and compressive stresses and the tensile stresses are mostly carried with reinforcement or eliminated by prestressing. Furthermore, concrete in compression seldom gives any fatigue problems.

Society may learn and save money from the experiences from “full-scale” failure tests. They can act as a complement to the experiences from unwanted and unexpected failures due to increased loads, scour, corrosion and other form of deterioration. It is therefore recommended that additional tests are to be carried out in order to further improve the understanding of existing bridges. The tests should as far as possible be based on realistic load cases, in order to optimize the outcome. Different bridge types can be tested to check their real capacity and give a background for establishing numerical models of them. As the tests are costly it is important that planning, preparations and analysis are done in a careful way - preferably in international cooperation.

Improved monitoring and numerical methods may in the future be used to determine hidden deterioration, Grip *et al.* [28], Huang *et al.* [29], Wang *et al.* [30].

An idea is also to create digital twin bridges which start their life (*in silico*) during the planning phase of a bridge, Bagge [12]. 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.

6 Conclusions

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.

This paper presents the experiences from bridges tested in Sweden. Most of the bridges had more capacity than the original design calculations indicated. Differences in e.g. load distribution, composite behaviour or support conditions may often result in extra “hidden” capacity to the bridge. In some cases, the result may be the contrary and reveal damages in the bridge superstructure which make the distribution even worse than calculated and the capacity of the bridge weaker.

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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