SMAR 2017

Structural response of full-scale concrete bridges subjected to high load magnitudes

Philip S. Halding[1], Jacob W. Schmidt[2], Thomas W. Jensen[3], and Arne H. Henriksen[4]

[1] Technical University of Denmark, Kgs. Lyngby, Denmark
[2] Technical University of Denmark, Kgs. Lyngby, Denmark
[3] Technical University of Denmark, Kgs. Lyngby, Denmark, and COWI Denmark
[4] Danish Road Directorate, Skanderborg, Denmark

ABSTRACT: A project concerning full-scale testing of concrete bridges was initiated in September 2016 in Denmark. Four bridges were tested, and the structural response of the bridges evaluated. Two bridges consisted of overturned concrete T-beams (OT-beams), and two bridges were constructed by joining L-shaped concrete elements.
The test method is outlined in the paper, which includes a description of a novel test-rig used to apply a high magnitude loading. It was shown that the test rig could perform controlled testing in only one day, which is an important aspect, since available time (due to traffic disturbance) often is an issue when testing on site. Also, different types of measuring equipment such as lasers, LVDT's and DIC-cameras was investigated, in order to evaluate the deformations during loading of one of the OT-beam bridges. The monitoring equipment was studied to verify if such equipment efficiently could be used for in-situ measurements. The load was applied semi-deformation controlled by a combination of dead load and hydraulic jacks. The novel high magnitude loading-rig worked well. It was also possible to achieve good readings from the monitoring equipment in combination with the applied loading.

1 INTRODUCTION

Concrete bridges, consisting of different geometries and material compositions, have been subject of various types of full-scale load tests and monitoring in the past decades. One of the earliest reported failure tests on existing concrete bridges were from 1952 in the UK (Unknown (1952)). Uniformly distributed dead load was apply to failure of a pedestrian bridge, and deflections were monitored by deflection gages. This loading method has also been applied more recently, e.g. Isaksen (1998) and Zhang et al. (2011).

In Switzerland Rösli (1963) performed a test on a 23 m (main span) bridge. He was the first to apply load via jacks positioned between transverse steel loading beams, and the road surface. The transverse beams were then anchored in bedrock (earth anchoring) via some very large threaded rods through holes in the bridge deck. Cracks and deflections of the bridge were monitored mechanically.

Rösli's loading method with the earth anchoring to counteract the large jacking force on the bridge surface was often used in later full-scale tests such as Gosbell et al. (1968), Goodpasture et al. (1973), Plos (1995), and Bergström et al. (2009), where Goodpasture et al. (1973) seem to have been the first to apply strain gages for monitoring of concrete surface strains.

Jorgenson et al. (1976) was the first to suggest a load application method with longitudinal loading beams. The loading beams were fixed to the bridge piers, and the load was applied via jacks between the loading beams, and the bridge surface. Jorgenson et al. (1976) also introduced deflection measurement by land surveying. In Germany, Slowik et al. (2004) altered the loading method by presenting a load truck, Belfa. The truck could quickly extend a loading beam over the bridge in the longitudinal direction. Ballast was then applied both ends of the beam, and the bridge was loaded by hydraulic jacks between the beam and the bridge surface.

The monitoring methods for in-situ bridge testing have developed significantly since the early failure tests in the 50s and 60s. Now, the state-of-the-art equipment include electrical strain gages, LVDT's, inclinometers, fiber optic sensors, etc., with the most commonly used equipment being strain gages and LVDT's.

Non-contact measuring methods are often faster to apply in-situ and operate, but they are more rarely seen in the literature of full-scale bridge testing. Crack detection by Digital Image Correlation (DIC) has hardly ever been performed in regard to full-scale concrete bridge testing. Schmidt et al. (2014) used a DIC-system to monitor cracks in a local failure test on a bridge wing in Denmark, and McCormick et al. (2014) measured crack development in critical areas of a bridge during non-destructive load testing in the UK without painting high contrast patterns on the surfaces. Furthermore, DIC has also been used to measure deflections on the side of bridges with high contrast patterns and regular camera lenses, e.g. Yoneyama et al. (2006).

Examples of other non-contact monitoring methods include photogrammetry (Jáuregui et al. (2003)), deflections by land surveying (Halding et al. (2016)), distance lasers (Bergström (2009)), laser scanning (Fuchs et al. (2004)), and deflections by GPS (Figurski et al. (2007)).

1.1 New concrete bridge load testing project in Denmark

The present paper focuses on the evaluation of the practical performance of the monitoring equipment used in Denmark in 2016 for full-scale concrete bridge tests. The monitoring equipment was used in a unique combination with a newly invented loading rig, described later.

The initial goal in the Danish bridge testing project is to develop a test method which meets the requirements to fast-, precise- and high magnitude full-scale testing of one-span bridges up to 12 m and develop advanced monitoring systems, which can be used in conjunction with such testing. Consequently, the output can be used to calibrate theoretical modelling related to a certain bridge type. The proposed test method is primarily for bridges where limited information is available regarding the load carrying capacity, and it is deemed faster and more inexpensive to perform than e.g. structural health monitoring approached.

The project was initiated in September 2016 where the first four bridges were tested, and the structural responses of sub- and superstructures were evaluated. The initial tests were done on two bridges of overturned T-beam elements, and two bridges of joined L-elements. The longest span was 11 m. The project is a collaboration between the Danish Road Directorate, The Technical University of Denmark, and COWI A/S.

2 APPLYING THE HIGH MAGNITUDE LOADING

A novel loading rig was developed in the project to insure that loading was applied in accordance with the relevant regulations for special vehicles with high magnitude axel loads (European committee for standardization (2009), Vejregelrådet (2010)). In the regulations, a vehicle A and a vehicle B should be positioned adjacent to each other on the bridge.

Vehicle A is positioned in the most critical lane, where the weight can reach up to 507 tonne with a maximum axle load of 23.7 tonne (4979 kN and 233 kN respectively - without safety factors).

The weight of vehicle B is fixed to 53.1 tonne with a maximum axle load of 11.8 tonne (521 kN and 116 kN respectively - without safety factors) and it is positioned in the lane next to vehicle A. For bridges of shorter span, the vehicles in the codes are longer than the bridge, and therefore only the heaviest axels are applied in order to represent the most critical load configuration.

The total load from vehicle A in conjunction with vehicle B, with applied safety factors, should be less than the bridge capacity, if passing should be allowed.

Axle loads representing both vehicle A and B were therefore applied via loading frames, see Figure 1. For vehicle B the maximum load was approximately 73 tonne with an axle load of approximately 24 tonne (717 kN and 239 kN respectively corresponding to an applied safety factor of approximately 2), and the loading was applied as dead load directly on a three axle loading frame.

Figure 1: Positioning of loading frames (3 axels) for vehicle B next to the most critical lane prior to full-scale load test of bridge.

In order to simulate vehicle A, the load was applied via a combination of dead load and (primarily) hydraulic jacks. The jacks were placed between the loading frames and two large loading beams, which were part of the loading rig, see Figure 2.

This loading system ensured (semi-) deformation controlling of the applied load. An EnerPac hydraulic controller unit was used when performing a stepwise increase of the load on vehicle A from the jacks. Each load step was pre-defined and was limited by a certain deflection rate. If the bridge started to deflect too quickly, the load (hydraulic pressure) would decrease. In this way a potential uncontrolled collapse could be avoided. The deflections of the jacks were measured by string potentiometers between the loading frames and the loading beams. The total load output of one of the OT-beam bridges is given as an example in Figure 3.

Figure 2: Top. Loading rig with ballast in the sides, and jacks to apply load from the loading beams to the loading frames. Bottom. Close-up of the hydraulic jacks between loading beams and loading frames.

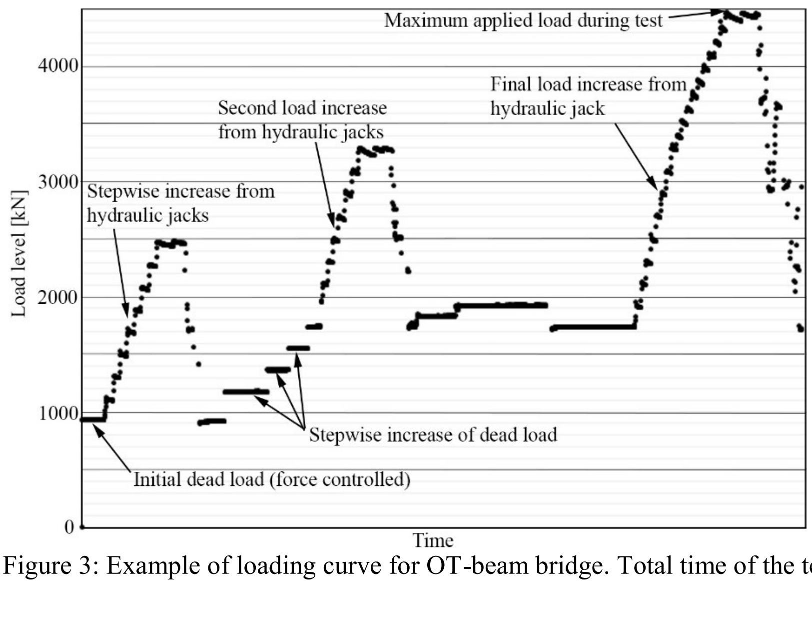

Figure 3: Example of loading curve for OT-beam bridge. Total time of the test was six hours.

Two of the bridges reached axle load levels, which were higher than the highest vehicle classes described in Vejregelrådet (2010). The prospect was to load the two OT-beam bridges to a very high magnitude and consequently failure. However, the loading procedure resulted in an extremely high load level where no more ballast weight was available and the capacity level of the test rig was reached at an axle load of approximately 100 tonne.

3 OPERATED MONITORING EQUIPMENT

The monitoring equipment used in the initial four full-scale bridge tests is presented in the following with a brief evaluation of the potential of the applied methods. The objective of using the equipment during testing was to reach monitoring data in specific locations for comparisons to analytical calculations and calibration of numerical models (not within paper scope).

Normally, in-situ monitoring- and testing is significantly more demanding than laboratory testing, economically and technically. Some of the general challenges were as follows:

- No electrical outlets at the site (had to rely on a generator).
- Weather conditions and protection of weather (light, moisture, temperature, etc.) sensitive devices.
- A very limited period for the setup of the apparatus and cabling (the road is often closed during testing). Very limited time for fine-adjustments or extra checks of the devices.
- Preparatory work carried out both above and below the bridge simultaneously.
- Difficult access to the underneath bridge surface (with a small lift on an uneven road surface).
- A small space for the crane to operate during assembly and disassembly of the loading rig.
- Uneven surface where the loading frames were positioned.

"Real time monitoring" is a relevant parameter when evaluating the future perspective of the types of equipment in bridge testing when loading to high magnitudes. "Real time monitoring" is to evaluate the bridge response during the load test. This means that data should be directly available, and data evaluation should be performed by more or less automatic procedures. Also, this data output can be uploaded during the test so that externally located experts may follow the development live.

Another relevant term is "Remote access monitoring". Here, the data acquisition happens with least possible personnel interference after calibration has been conducted. For high magnitude load tests in-situ, this is important for safety reasons.

3.1 Land surveying instrumentation

Land surveyor equipment was used on all four bridges. A land surveyor measured the deflection at mid-span under vehicle A, and at the supports. The land surveyor was measuring from a distance outside the bridge. Measurements were performed at each load step. An example of the output is given in Figure 4.

- Data collection: Manually, slow.
- Accuracy in the specific tests (approx.): ±0.1 mm.
- Difficulty: Requires a trained land surveyor and land surveying equipment.
- Calibration: Relatively fast.
- "Remote access monitoring": No, a person must perform each reading.
- Potential of "Real time monitoring": No. However, data can be collected by manually entering directly into a computer.

- Wireless: Yes.


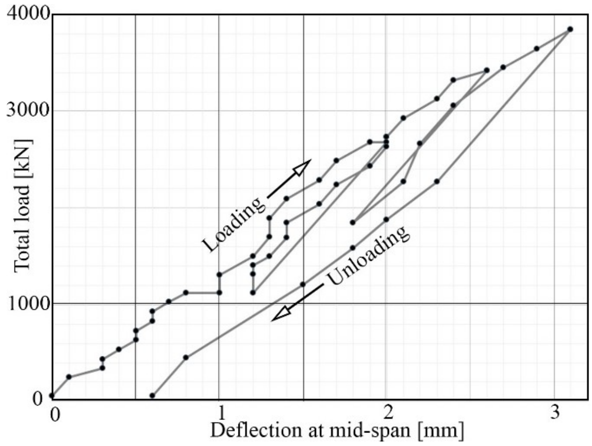

Figure 4: Land surveyor measuring at a distance (left) and deflection-load output at mid-span from a OT-beam bridge with a span of 5 m (right).

3.2 Linear Variable Differential Transformers (LVDT's)

A LVDT can measure deflections in a point in one direction. It consists of a stationary housing and a moving pin (see Figure 5). The pin of the LVDT touches the structure surface and moves together with the surface. The output of voltage change is calibrated beforehand, and corresponds to a change in movement of the pin.

- Data collection: Data logging, fast. 0 - 5 V output.
- Accuracy in the specific tests (approx.): ±0.02 mm.
- Difficulty: Requires precise calibration, a frame structure for the setup, and data collection expertise.
- Calibration: Time consuming – but can be performed beforehand.
- "Remote access monitoring": Yes.
- Potential of "Real time monitoring": Yes.
- Wireless: No.


Figure 5: LVDT attached to steel bar underneath OT-beam bridge (left), and close up of LVDT from lab test of beam sub-component of another bridge (right).

3.3 Digital Image Correlation (DIC) system

A DIC-system consist of a camera(s) and a computer software (GOM Correlate). The camera takes photographs of a specific area of a structure before and during loading. The software recognizes small (user-defined sized) sections, called facets, of the surface during loading and compares them to the same sections prior to loading. From that analysis, strains and in-plane deflections can be found on the surface.

A DSLR-camera with wide-angle lens was used to take photographs perpendicular to the bottom bridge surface in 2d without any modifications of the surface, see Figure 6. The position of the figure is directly underneath vehicle A. A method for correction for lens distortion, out-of-angle (non-perpendicular) points, and the deflection of the bridge (out of the 2d-plane) is currently being investigated to achieve a more precise output of strains by this novel method. Usually, DIC-systems are used on smaller areas, with a normal lens camera, and with a high contrast pattern painted on the surface.

- Data collection: Data logging, medium speed.
- Accuracy in the specific tests (approx.): Depends on the lens distortion and angle to the measured point.
- Difficulty: Requires a complex calibration method, and a pre-test of the surface quality, a good contrast surface, sufficient light.
- Calibration: Relatively time consuming.
- “Remote access monitoring”: Yes.
- Potential of “Real time monitoring”: It has a high potential, but with high complexity due to the corrections of the output, and the software.
- Wireless: Yes, if the camera has e.g. a Wi-Fi connection.

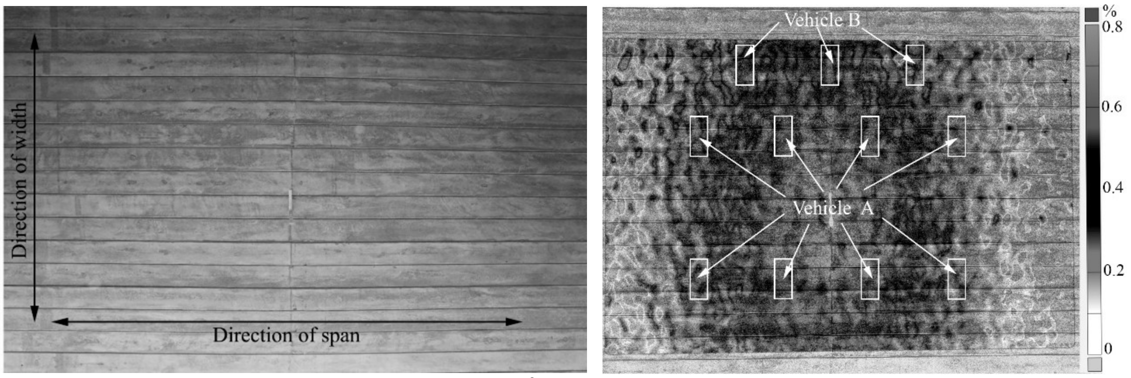

Figure 6: Reference photograph of approx. 50 m^2 (left) and non-corrected longitudinal strain plot during loading with vehicle wheel positions (right).

3.4 Analog distance lasers

Distance lasers measure the distance between the laser housing and an object. The measurement quality is dependent on the color, the angle and the roughness of the surface. The temperature and the level of light has an influence as well. The accuracy is increased as the measuring distance interval is decreased. On one of the OT-beam bridges, several lasers were used, see Figure 7, and they were adjusted to measure within a 200 mm interval at a distance of approximately 3.8 m.

- Data collection: Data logging, fast. 4 – 20 mA output.
- Accuracy in the specific tests (approx.): ±0.2 mm (can be improved with more experience)
- Difficulty: Sensitive to uneven and dark surfaces, but simple to set up. Must warm up before data logging.
- Calibration: Self-calibration, but must be manually adjusted to a new distance interval.
- “Remote access monitoring”: Yes.
- Potential of “Real time monitoring”: Yes.
- Wireless: No.

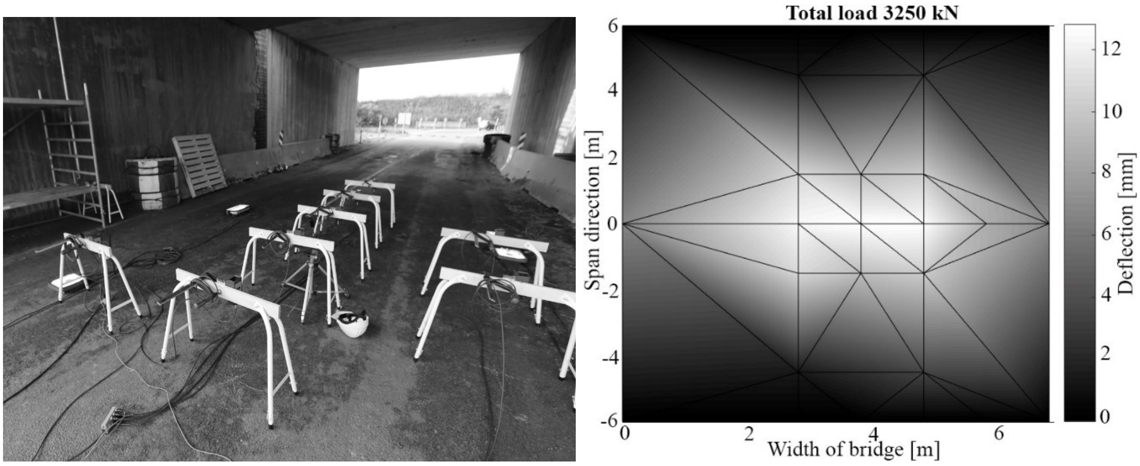

Figure 7: Lasers positioned under bridge (left) and example of contour plot of measured deflections during loading where symmetry around mid-span is used (right), where the measured points are the intersection of the lines and the contour is a linear interpolation between those points.

4 CONCLUSION

The load application method (with the novel loading rig) was successful in the sense that the high magnitude load was safely applied when using the semi-deformation controlled loading equipment. Each of the four full-scale load tests took less than a day to set up, run, and dismantle, and the applied load configuration followed the requirements for heavy special vehicles in the codes. The monitoring equipment was evaluated based on the method for logging data, the accuracy, the difficulty, and the future perspective use in connection to “Real time monitoring” and “Remote access monitoring”. The latter two have significant importance when developing a monitoring method for a controlled high magnitude loading of concrete bridges, where the test environment must be safe, and the test may have to be stopped before the bridge is damaged.
In practice, these experiences from the initial tests are significant milestones for the Danish full-scale concrete bridge project.

ACKNOWLEDGEMENTS

The authors wish to thank our colleagues in the Danish Road Directorate and COWI for the excellent collaboration and good ambience in the project. In addition, we recognize the great efforts and practical expertise of the crane company BMS.

REFERENCES

Bergström, M., B. Täljsten, A. Carolin, 2009, Failure load test of a CFRP strengthened railway bridge in Örnsköldsvik, Sweden. *J Bridge Eng*, 14(5), 300–308. doi: http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000005.

European committee for standardization, 2009, EN 1991-2 DK NA Anneks A. *Danish Spandard*.

Figurski, M., M. Gałuszkiewicz, M. Wrona, 2007, A Bridge Deflection Monitoring with GPS, *Artificial Satellites*, 42(4). doi:10.2478/v10018-008-0010-3.

Fuchs, P.A., G.A. Washer, S.B. Chase, M. Moore, 2004, Laser-based instrumentation for bridge load testing, *J Performance of Constr Facilities*, 18(4), 213–219. doi:10.1061/(ASCE)0887-3828(2004)18:4(213).

Goodpasture, D.W., E.G. Burdette, 1973, Full Scale Tests to Failure of Four Highway Bridges, *American Railway Engineering Association*, 643(5), 454-472.

Gosbell, K.B., L.K. Stevens, 1968, Test loading of a full scale bridge, *A.R.R.B. proceedings*, 4(2), 2018-2041.

Halding, P.S., K.D. Hertz, J.W. Schmidt, B.J. Kennedy, 2016, Full-scale load tests of Pearl-Chain arches, *Eng Structures*, 131, 101–114. doi:10.1016/j.engstruct.2016.10.022

Isaksen, H.R., T. Kanstad, P. Olsen, 1998, Prøvebelastning av bru nr 02-1234 Smedstua bru – Forutsetninger, gjennemføring og måledata, *Statens vegvesen*, 98-11.

Jauregui, D.V., K.R. White, C.B. Woodward, K.R. Leitch, 2003, Noncontact Photogrammetric Measurement of Vertical Bridge Deflection, *J Bridge Eng*, 8(4), 212–222. doi:10.1061/(ASCE)1084-0702(2003)8:4(212).

Jorgenson, J.L., W. Larson, 1976, Field testing of a reinforced concrete highway bridge to collapse, *Transportation Research Record*, 607, 66-71.

McCormick, N., P. Waterfall, A. Owens, 2014, Optical imaging for low-cost structural measurements, *Proceedings of the Institution of Civil Engineers: Bridge Engineering*, 167(1), 33–42. doi:10.1680/bren.11.00055.

Plos, M., 1995, Application of fracture mechanics to concrete bridges, *Chalmers University of Technology*, Publication 95:3.

Rösli, A., 1963, Die Versuche an der Glattbrücke in Opfikon*, Eidgenössische Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe*, Bericht 192.

Schmidt, J.W., S.G. Hansen, R.A. Barbosa, A. Henriksen, 2014, Novel shear capacity testing of ASR damaged full scale concrete bridge, *Eng Structures*, 79, 365-374. Doi: 10.1016/j.engstruct.2014.08.027

Slowik, V., 2004, Combining experimental and numerical methods for the safety evaluation of existing concrete structures, *FRAMCOS5*

Unknown, 1952, Destruction of the Prestressed Concrete Footbridge at the South Bank, *Civil Engineers Review*, 6(8), 330-334.

Vejregelrådet, 2010, Broer – Vejledning til belastnings- og beregningsgrundlag. *Danish Road Directorate*.

Yoneyama, S., A. Kitagawa, S. Iwata, K. Tani, H. Kikuta, 2006, Bridge deflection measurement using digital image correlation, *Proceedings of the 2006 Sem Annual Conference and Exposition on Experimental and Applied Mechanics*, 4, 1720–1729.

Zhang, J.Q., H.W. Ren, B. Yu, 2011, Failure testing of a full-scale reinforced concrete Tgirder bridge. *Adv Mater Res,* 243–249(2), 1767–1773. doi: http://dx.doi.org/10.4028/www.scientific.net/AMR.243-249.1767.