A full-scale loading test of a highway bridge in Finland

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ABSTRACT: We report here on a full-scale loading test of Jeesiöjoki Bridge located in Sodankylä, Finland. With three spans each about 20 m long, Jeesiöjoki Bridge incorporates four steel girders and a concrete deck. It was originally built in the 1950's and has since been renovated, e.g. by building additional pedestrian lanes on both sides. The bridge has no particular load carrying problems as far as normal traffic is concerned, the maximum allowable load for which is 60 tons in Finland, but occasional special transport loads may exceed 200 tons, which, according to the Finnish Transport Agency, is likely to exceed the load carrying capacity of the structure.

In the actual loading test two vehicle cranes and one full trailer truck were used for loading while both the static and dynamic behaviour of the bridge was recorded using FBG strain sensors and deflection in the main girders was measured using a newly developed DMM method based on a rotary laser transmitter and optical sensor units. In addition, linear position sensors were used for monitoring displacement between the girders and the deck. A comparison of the measurement results with a FEM model is also included in this report.

1 INTRODUCTION

The Finnish road network has approximately 14 600 bridges, most of which are steel concrete structures of various kinds (60%) or steel culverts (21%). The remainder include tensioned concrete bridges (8%), steel bridges (6%), wooden bridges (4%) and masonry bridges. A considerable proportion of these bridges were built in the 1950's and 1960's, when the design loads were smaller than today, and most of these are now at or approaching an age at which renovation must be considered.

All public bridges are inspected regularly according to instructions issued by the Finnish Transport Agency. There are three inspection routines: annual, general and special inspections. In annual inspections a bridge is inspected visually on the surface by a contractor or company who is specialized in providing this service. This is a rapid procedure during which only the most significant deficiencies or instances of damage are documented.

Approximately once in five years a bridge is subjected to a general inspection. During this procedure all points of damage are carefully documented with photographs in a specific bridge register maintained by the Finnish Transport Agency. Large bridges are typically inspected with a specially designed bridge crane that allows careful examination and photographing of the structural elements beneath the deck. In these cases various research methods can be used that justify the procedure being called an extended general inspection.

A special inspection is performed if a general inspection reveals any notable problems or if more specific information is needed for planning repairs or renovation. A wide variety of research methods can be used in special inspections to assess the condition of a bridge, the most typical methods in the case of concrete bridges being the measurement of carbonization depth and chloride content from test samples, the surveying of crack widths and the determination of microstructures.

A loading test is one special inspection routine which can be carried out if a mathematical analysis, e.g. a finite element model (FEM, Zienkiewicz et al 2005) indicates that there is deficiency in load carrying capacity. Real changes measured with a known test load allow calibration of the mathematical model which improves the reliability of the loading analysis. Especially bridges on routes of special transportation are tested since they are frequently subjected to extremely high loads.

The purpose of this article is to describe a typical loading test carried out in Finland, using the Jeesiöjoki Bridge as an example. The focus will be on careful description of the measures taken and equipment used, while less attention will be paid to the mathematical analysis. As a part of the loading test, we will also present a new method for measuring vertical deflection, the Deflection Multi Meter (DMM) method, which differs from the frequently used levelling instrument or tachymeter methods (Russell et al 1995) in that it gives real-time information on vertical deviations at a number of locations. The main difference relative to long gauge-length optical fibre sensors (Braunstein et al 2002, Inaudi et al 1999) is that DMM gives direct deflection information while with fibre sensors deflection is calculated indirectly from the strain result. This feature speeds up the making of conclusions in the field and improves the confidence level of the loading analysis.

2 JEESIÖJOKI BRIDGE

Located in Sodankylä in the northern part of Finland, Jeesiöjoki Bridge on the E75 highway has three spans, each about 20 m in length and incorporates four steel girders and a concrete deck (Figure 1). It was originally built in 1950's and has since been renovated, e.g. by building additional pedestrian lanes on both sides. The bridge has no particular problems as far as normal traffic is concerned, maximum allowable load for which is 60 tons in Finland, but special transportation loads may exceed 200 tons, which, according to the Finnish transport agency, is likely to be beyond the load carrying capacity of the structure.

Figure 1. Jeesiöjoki Bridge.

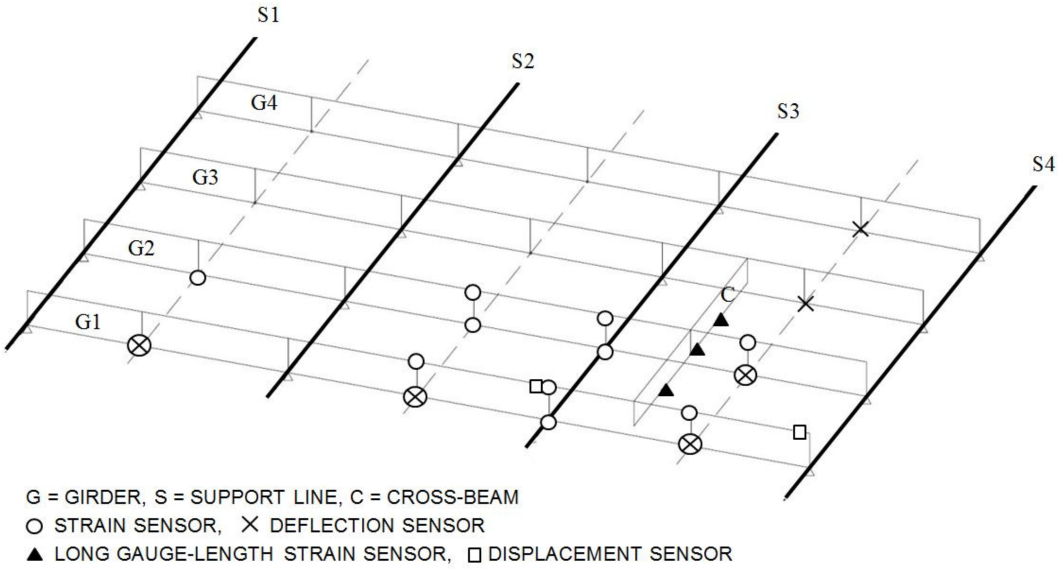


Figure 2. Schematic drawing of Jeesiöjoki Bridge showing the location of each sensor. To simplify the figure, not all the crossbeams are shown in the drawing.

3 MEASUREMENT EQUIPMENT

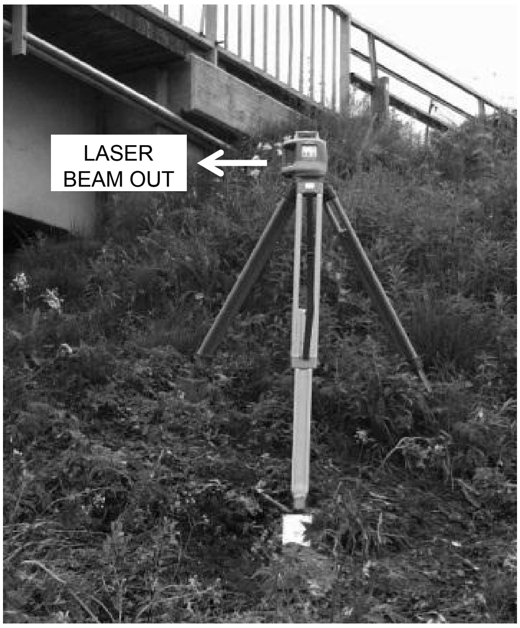
An already available FEM analysis indicated that altogether 25 sensors were needed to characterize the loading behaviour of the bridge. Various strain and deflection sensors were placed on the main girders and crossbeams, as shown in Figure 2, and displacement sensors were used for measuring slide between the main girders and the deck in a longitudinal direction with respect to the bridge.

3.1 Deflection sensors

In order to reveal structural stiffness and to assess the distribution of the load over the cross-section of the bridge the main girders were provided with six deflection sensors, as illustrated in Figure 2, deflection being measured by the new DMM method as developed by Dimense Ltd, Finland. This method is based on a rotary laser transmitter which forms a fixed reference plane and a number of optical sensor units which move vertically with respect to the reference plane when the bridge is loaded. With a measurement range of 0 - 160 mm, a DMM sensor has a single-pulse (sweep) precision of 0.5 mm at a sampling rate of 10 Hz. For static measurements the precision can be improved to 0.1 mm by means of low-pass filtering or averaging methods.

Besides deflection, a DMM unit is capable of measuring tilt and acceleration in two dimensions, and also temperature. It similarly provides three external inputs for various sensor types such as a strain gauge or linear sensor. Since it incorporates 24-bit D/A converters and uses a sampling rate of 4.8 kHz a DMM unit is a feasible data logger for bridge monitoring and other SHM applications. DMM method uses a RS485 bus, but a WLAN option is also available.

In order to achieve good visibility for each DMM unit, one laser was located on each river bank so that the distance from the DMM sensors varied between 20 and 40 m. One of the lasers together with a DMM sensor mounted on the lower flange of a main girder by means of a clamp holder is shown in Figure 3. A DMM sensor can easily be adjusted to the optimal height with respect to the reference plane by means of super-magnets.



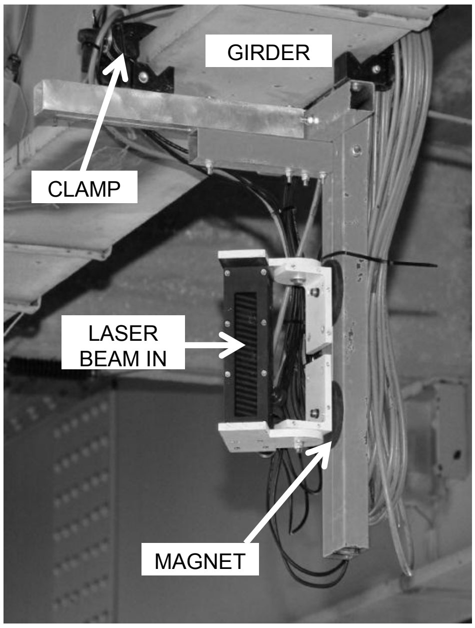


Figure 3. Left, the rotary laser (Sokkia LP410) used for deflection measurement; right, a DMM sensor mounted to the lower flange of a main girder.

3.2 *Displacement sensors*

Two displacement sensors were used for measuring slide between the main girders and the concrete deck. P103.25 linear sensors manufactured by Positek were attached close to the bearings on supports S3 and S4, as shown in Figure 2. This sensor type has a measurement range of ±12.5 mm when the plunger is adjusted to the middle position, and its resolution is infinite, being restricted only by the electronics of the data logger. In the present case the sensors were read with a DMM unit, so that the resolution was about 10 micrometres while the measurement speed was deliberately restricted to 10 samples / s. A displacement sensor together with its mounting structure is shown in Figure 4. A triangular holder is attached to the steel girder with magnets and an L-profiled counter piece pressed against the plunger is fixed to the concrete deck with an anchor.

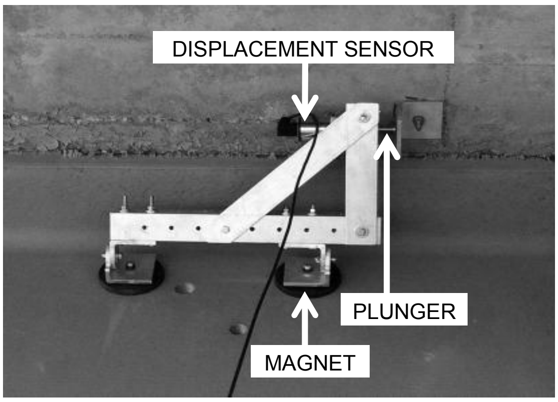


Figure 4. The Positek P103.25 linear sensor used for measuring slide between a main girder and the concrete deck.

3.3 Strain sensors

In order to obtain information about the behaviour of the bridge as a composite structure and to determine the maximum tension in the cross-section of a girder, a total of 17 strain sensors were attached to the main girders and cross-beams at various locations, as shown in Figure 2. The strain in each steel girder was then measured with os3155 fibre Bragg grating sensors (FBG, Kersey et al 1997) as manufactured by Micron Optics, Inc. (Figure 5). According to the datasheet, this temperature-compensated sensor has an accuracy of less than 1 με when used with an interrogator from the same manufacturer. The gauge length of the os3155 is 50 mm and the measurement range is ± 2500 με.

The sensors were attached to the I-shaped steel girders on top of the lower flange and under the upper flange and were assembled as close to the bearings as possible at the support lines. Prior to spot welding, the paint was mechanically removed from the area of approximately 10 cm x 20 cm, which was then cleaned with an alcohol-based detergent. Both ends of the strain gauge were attached with 10 spot welds using a Vishay Model 700 spot welding machine at weld energy of 50 Joules. After attachment the sensor was insulated from moisture with 4412N insulator tape and spray-type chassis mass 08888 from the 3M Company.

Apart from the main girders, strain was also assessed in the crossbeams, as shown in Figure 2. A long gauge-length os3600 sensor from Micron Optics was chosen for this purpose, as it allows strain measurement from the surface of concrete (Figure 5). The performance of the os3600 is similar to that of the os3155 with the exception that the sensor length is 25 cm. In addition, the os3600 needs field-made pre-tension to enable compression measurement. Altogether three such sensors were assembled on the crossbeams using stainless steel anchors and purpose-made flanges supplied by Micron Optics.

All the strain sensors were connected in series to form three sensor arrays, and measurements were taken with a Micron Optics SM125-500 interrogator at a sampling rate of 2 Hz.

Figure 5. Instruments used for measuring strain in the Jeesiöjoki Bridge. Above left, the os3155 sensor and below it the os3600 sensor. The SM125-500 interrogator is on the right. The photographs are not to scale.

4 LOADING VEHICLES

The loading was accomplished using two vehicle cranes, LTM 1130-5.1 and LTM 1100-5.2, manufactured by Liebherr (Figure 6). The basic axle weight of these 5-axle cranes is 12 tons, which was increased in two steps to 14 and 16 tons by means of the vehicle's counterweights. A typical 7-axle full trailer truck (60 tons) was also used for loading to obtain information about the behaviour of the bridge under the maximum allowable load.

Figure 6. Bridge loading using two vehicle cranes parked tail-to-tail.

5 SOURCES OF MEASUREMENT ERROR

A DMM system based on a rotary laser transmitter is susceptible to the same sources of error as all optical measurement equipment, e.g. a tachymeter. These are:

1) variation in air temperature and the effect of air turbulence on the optical laser beam,
2) non-ideal optics, and
3) movement of the rotary laser due to wind and/or soil vibration

The single sweep resolution of a DMM sensor is 0.5 mm. Error sources 1 and 2 induce small vertical fluctuations in the laser beam between successive sweeps, which appears as 0.5 – 2 mm peak-to-peak variations in the measurements as a function of distance.

The effects of wind and soil vibration on the stability of the laser beam are difficult to analyse and the resulting error cannot be easily removed from the measurements afterwards. Thus these effects should be minimized, e.g. by means of windbreaks and floating supports under the tripod.

In the case of mechanical sensors the manner of assembly plays a major role in measurement accuracy. The present strain sensors were assembled according to instructions provided by Micron Optics, which guaranteed strong attachment to the structure. This assumption was supported by observations made in the laboratory and in the field.

According to the datasheet, the instruments used for making the displacement measurements can tolerate a harsh environment and their performance is excellent. The mounting structure, as shown above, was made by the authors. Due to its rigid structure and strong attachment to the girders and deck, the error caused by its attachment can be assumed to be negligible.

Considering potential error sources, note should also be made of the uncertainty regarding the load. In order to minimize this effect and to achieve correct data for FEM analysis, the real axle loads were measured in the field with a calibrated weight gauge.

6 MEASUREMENTS AND FEM ANALYSIS

The actual loading procedure consisted of 22 phases in which one or more vehicles were parked on the bridge or drove across it slowly. Both lanes of the bridge were subjected to loading, and also the centre region, which is used for the transport of heavy loads. The vehicles were located on the bridge so that the maximum stress could be exerted on the support lines and the middle of each span.

Altogether 550 measurement curves were plotted as a result of the loading test, two of which are presented in Figure 7. In this example both vehicle cranes with an axle weight of 12 tons and the full trailer truck drove slowly across the bridge one behind the other. Strain and deflection were measured from the bottom flange of girder G2 in the middle span, between supports S3 and S4 (Figure 2). In this loading phase the maximum strain was 187 με and the deflection 7.6 mm, while the overall maximum values were 268 με and 13.6 mm, respectively.

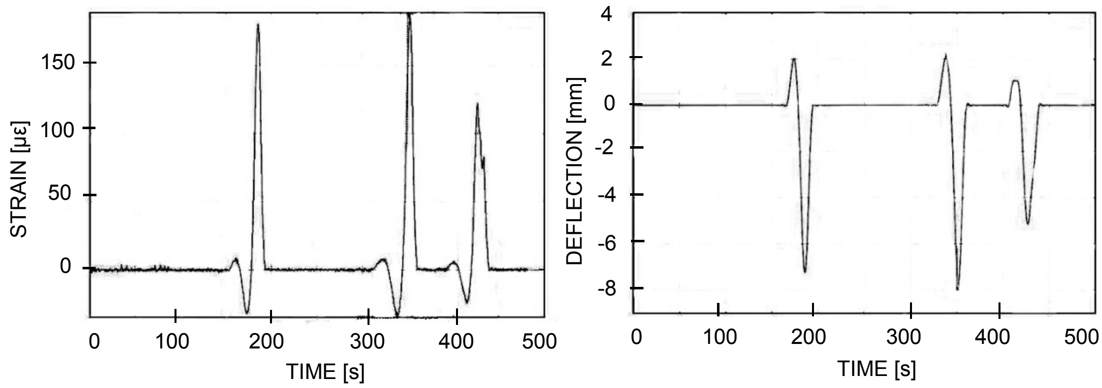


Figure 7. Measurements obtained in a loading phase in which two vehicle cranes and the full-trailer truck drove slowly across Jeesiöjoki Bridge one behind the other.

Comparison of the measurement results and the derived values with a FEM model shows a very good match, as presented in Table 1. This means that the theoretical model is very close to the real behaviour of the bridge and there is a need for only minor calibration. On the other hand, Table 2 shows a larger variation between the measured and calculated results in the case of crossbeam C (Figure 2). This is obviously due to severe cracks in the reinforced concrete, which necessitated adjustments to the FEM model.

Table 1. Deflection and stress as a function of load (girder G2 between supports S3 and S4, lower flange). Measured values versus the FEM model.

Load Axle weight [tons]	Deflection Measured [mm]	Deflection FEM [mm]	Stress Measured [MPa]	Stress FEM [MPa]
1 crane (12)	6.2	6.6	35	35
2 cranes (12)	7.6	7.6	36	36
2 cranes (14)	8.6	8.8	39	41
2 cranes (16)	9.1	10.1	46	46

Table 2. Stress in the centre of crossbeam C as a function of load. Measured values versus the FEM model.

Load Axle weight [tons]	Stress Measured [MPa]	Stress FEM [MPa]
1 crane (12)	3.1	4.3
2 cranes (12)	3.4	4.6
2 cranes (14)	4.1	5.4
2 cranes (16)	5.1	5.9

As regards slide between the concrete deck and the main girders, the displacement sensors revealed that these structural elements are tightly connected to each other, which makes the combination work in a composite fashion (although it was not planned to operate as such). As a consequence, the load carrying capacity of the bridge is somewhat higher than had been assumed at the beginning.

7 DISCUSSION AND CONCLUSIONS

This paper describes a typical bridge loading test as performed in Finland, taking the Jeesiöjoki Bridge as an example. All the measurement equipment is carefully described with especial attention to a new DMM method developed for deflection measurement by the authors.

In this case the measured values were generally in good agreement with the theoretical ones. According to the FEM analysis the stiffness of the bridge fulfils the Finnish regulations but there is a deficiency in load carrying capacity with respect to the special transportation of heavy loads. In the forthcoming renovation additional crossbeams will be added parallel to the existing ones to increase the stiffness of the structure.

This work was carried out in co-operation with the Finnish Transport Agency and Ponvia Ltd, and similar investigations were carried out on three other bridges in 2012. According to new regulations, the maximum weight limit for bridges in Finland will be increased from the existing 60 tons to 76 tons in 2013, which means that the number of bridge loading tests will possibly increase in the near future.

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