INTEGRAL BRIDGES

Bridges without joints and cushions – so-called integral bridges – have several advantages over conventional structures. Dilation joints (road surface transitions) and cushions always represent weaknesses in a structure. Nowadays bridges are dimensioned for a service life of up to 100 years. Eliminating joints – which may well have a much shorter service life, depending on the impact of traffic and weather – has a positive effect on the durability and the maintenance costs of a bridge. In addition, the frame effect leads to increased load capacity in many cases.

Under the conditions obtaining, though, integral bridges are supported in a statically indeterminate way, so changes in temperature, support displacement, pre-stressing and long-term effects cause constraints – particularly compression forces – that are hard to quantify and normally undesirable. That is why joints and cushions have been used without reservations in bridge construction until now.

From the engineering and economic point of view the integral approach has so many advantages that it has become indispensable for short bridges. Bridge engineers are therefore currently concerned to make these advantages available in the case of longer structures, too. However, this involves a wide variety of problems, and many questions about this type of structure have yet to receive a definitive answer. Specific measurement programs can aid in providing some answers and suitable input variables for dimensioning.

ABSTRACT: With their considerable advantages in construction and maintenance, integral bridges (which do without cushions and intermediate structures completely) are being implemented more and more often in actual practice. The structures in question are monolithic: superstructure, abutments and foundation form a functional whole, embedded in the ground. Temperature influences both from the structure and from the ground are thus in play, and therefore act as constraints. In view of the economic advantages, there is a general trend today towards adopting the integral-bridge approach even for very long structures. On the other hand reservations about this approach are still widespread, which is why various monitoring systems have recently been installed on structures of this kind, to make it possible to assess their long-term performance and to draw inferences for future dimensioning. This paper presents details of the design and implementation of monitoring systems on selected bridges.

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Monitoring Experiences on Integral Bridges

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2 BRIDGE MONITORING

Modern methods of measuring are increasingly being employed to monitor built structures, particularly in the field of bridge maintenance. One highly ambitious aim in the past was to make statements about the condition of a bridge on the basis of actual measurements carried out on the structure in conjunction with recalculations conducted in parallel. For a long time attempts were made to establish these monitoring procedures as an alternative to the tried and tested conventional methods of bridge testing, too. But this idea has – quite understandably – failed to gain acceptance among practising bridge engineers, although some promising results have been obtained in research projects. The information content of conventional bridge testing, including special surveys, goes well beyond what measuring and analysis can achieve, assuming that the monitoring methods are employed cost-effectively.

However, scientific experiments have demonstrated beyond doubt that monitoring procedures can detect damage. In such experiments, though, the unknown parameters – such as extent of loading, effects of changes in temperature, earlier damage, geometry of the built structure, material characteristics etc. were either left out of account or also investigated in detail. So practical applications normally need to take a large number of unknowns into account – and the influence these have on the data obtained is of the same order as that of significant damage, or even greater (e.g. effect of temperature).

In the author’s view it is essential to provide various definitions in connexion with monitoring, which are listed in the next chapter:

As a general rule, monitoring built structures is taken to mean performing data-based investigations on an existing object.

These investigations involve gathering data for a wide variety of parameters selected to match the current assignment. The parameters in question may be static, as in the case of deformation, inclination, stress etc., or dynamic, as in the case of vibration: here vibration velocity or vibration acceleration are the relevant parameters.

It is also important to distinguish between global and local methods. With global methods the assumption is that measuring at relatively few points suffices to describe the behaviour of the system accurately, whereas local methods are confined to a limited area of the built structure, which they investigate in detail. As an example of global methods, measuring vibration response with a small number of sensors is typical; in contrast, ultrasonic testing methods or simply measuring crack widths are examples of local methods.

As regards duration, a distinction is also to be made between long-term and short-term (occasional) measuring activities. For long-term measurements a system is installed on a built structure more or less permanently, and the relevant parameters are observed continuously. For occasional measurements data are gathered only at certain times. However, the distinction is not hard-and-fast, since intermediate cases, e.g. permanently installing sensors that are in sleep mode most of the time, are possible. In such cases the system is activated by hand or automatically at defined intervals, in order to collect data.

Monitoring built structures sometimes involves comparison with calculations based on finite-element modelling, to refine the analysis, or the data collected are used to improve an existing model. This way of updating models is a subject in its own right; as things stand a great deal of further research is needed here.

In the course of his activities in recent years the author has carried out numerous monitoring projects with varying aims and technology within the framework of research and commercial projects. The resulting findings may be summarised by the following three – possibly controversial – statements:

- Global monitoring methods do not permit early diagnosis of damage at acceptable cost. This applies particularly to vibration monitoring applying only a limited number of sensors.
- Data-based investigation is ideally suited to observing known problems or damage and changes in these over time. With monitoring focused on documenting a specific problem, the measuring program can be designed specifically to target the variable parameters, which ensures that the methods are employed cost-effectively. The aim must thus always be to develop a tailor-made concept for the particular structure and the assignment in question.
Objective data are collected as input parameters for further investigation. E.g. measurement results obtained are used for further finite-element calculations to improve simulation quality for more realistic results.

On the basis of these findings the author implemented several monitoring systems in recent years. The lessons learned in connexion with the layout of the monitoring systems, the selection of proper measurement equipment and software as well as long-term operation will be shown on selected (semi)-integral bridges.

3 MEASUREMENT TECHNOLOGY

To fulfil the demands from practice in terms of bridge monitoring using different types of sensors, a novel, high-quality Distributed Digital Monitoring System (Green Node) was developed by Aplica Advanced Solutions in cooperation with the author. The system is based on innovative hardware and software components and provides high reliability for continuous monitoring tasks, including automatic data transmission and on-line account to the measurement data. The system architecture provided permits application to all civil engineering structures with different types of sensors, to be selected according to the specific measurement task.

The design allows the combination of the advantages of a distributed field bus and a centralized measurement system, which is able to synchronize the polling of all sensors with an accuracy of 10 μs. A Linux-based monitoring server is the heart of the system, which collects and synchronizes the data from the digital sensors. In fast applications data acquisition (up to 1 kHz sampling) and synchronization of the digital signal is done by special real-time data concentrators which are connected to the monitoring server via Ethernet. Data concentrators may be located close to the monitoring server or somewhere on site. In slow applications (1 Hz and below) the acquisition and synchronization is done directly by the monitoring server.

The recorded data coming from the data concentrators are stored on a local hard disc using a novel, very efficient data format. Data download may be conducted via a modem connection, via GSM/GPRS modem or broadband internet access using FTP and TCP/IP. A small configuration file is used to customize file length, data format, triggered and/or continuous recording, automatic data transfer to a remote FTP server and much more. For each individual sensor it is possible to configure averaging and filtering stages to reduce noise and to get high precision data sets.

The digital sensor unit consists of the sensor itself (acceleration, temperature, displacement, etc.) and a 19-bit A/D converter in a very robust casing. Thus the length of the signal cables are very short, and long distances are bridged via digital bus or Ethernet connection. As an alternative a combination of central and local A/D conversion is possible based on the given boundary conditions.

The data are stored continuously using a hierarchical file structure without any interruption of the measurement process. The synchronization is accomplished in real time, using either a radio-based clock, a GPS system or an NTP signal (Network Time Protocol). As an alternative to continuous operation it is possible to run the system in a triggered mode, where only events of interest are permanently recorded.

The system described is the backbone of each monitoring system supplemented by a wide variety of sensor types selected for the measurement task in question. As monitoring integral bridges is focussed on some very specific measurements, three representative examples will be given in the following section.

4 MÜHLBRIDGE

The first integral bridge instrumented in Austria was the “Mühlbrücke” crossing the river Mühl in Upper Austria. This is a road bridge in integral construction, carrying two traffic lanes in all. The main spans are 12.60 m + 28.00 m + 12.60 m, making a total length of 53.20 m.

The purpose of this first project was to measure the development of earth pressure behind the abutment as well as temperature in the bridge superstructure. As an extension of the
measurement project an additional laser sensor was installed at the bridge to identify changes in
the main span due to temperature effects. Simple earth pressure sensors, temperature sensors
and a laser were selected. The monitoring centre and the software were designed according to
the DDMS described previously. As the cable lengths between sensors and base station are
rather short, it was decided to perform A/D conversion at the central unit and not in a
distributed way.

![Figure 1. View of the Mühlbridge](image1)

All in all five earth pressure sensors behind one abutment, six temperature sensors – five in
the backfill of the abutment and one in the superstructure – and one laser were placed on
characteristic locations which will be shown in the presentation. In order to enable proper
internet access to the bridge from remote locations a wireless network provider present in the
region of the bridge provided an access point with sufficient bandwidth directly on site. Fig. 2
below provides an impression of the hardware and how it was installed at the bridge.

The measurement program started in January 2008, and data were acquired continuously
except for a short period at the beginning where some hardware components were replaced in
the office. Since then the system has worked without interruption, which is evidence of the
great reliability of the components selected even under harsh environmental conditions on site.

![Figure 2. Earth pressure sensor (left) and laser unit (right)](image2)
The results obtained so far for earth pressure, ground temperature, temperature of the load-bearing structure and changes in length of the load-bearing structure do not contain anything out of the ordinary. As expected, the data for passive earth pressure do not reveal any special spikes or fluctuations. The reason is that the long-term effects of creep and shrinkage (once the structure has been completed) are crucial, and more or less made good the increase in length in the first year due to temperature.

In view of the structure’s exceptional rigidity (due to its relation with the two piers) there is no reason to expect significant changes in passive earth pressure; the data obtained in the next few years will confirm this assessment.

Unfortunately three of the earth-pressure sensors were knocked out by excess voltage when lightning struck the bridge, even though the measurement system itself was protected; so only the remaining earth-pressure sensors can be adduced for long-term interpretation – here the laser data provide valuable additional information for interpretation purposes.

The results also reveal that the sensor can determine the associated change in length of the load-bearing structure between the piers, and that this variable generally correlates closely with the load-bearing structure temperature. As expected, changes in temperature are also registered behind the abutments in the vicinity of the earth-pressure sensors, though they are less marked there than in the load-bearing structure. The ground also smooths out fluctuations in temperature.

Continued measurement of these long-term effects will give us a clearer picture of the extent to which changes in temperature and the associated change in length affect the development in earth pressure vis-à-vis the bridge structure.

5 ERDBERGER BRIDGE

A monitoring system was also designed for the Erdberger Bridge, which was at the date of erection an unusual structure – and is of great importance, due to its location in the road network. It forms part of a key motorway junction in Vienna, and carries six lanes plus additional linkage lanes. The structure has an overall width of 42.30 m and an overall length of
147 m. The structural engineering involves a compression shell of parabolic cross-section with draped tendons. The structure is curved, with span widths of 34.5 m + 73.0 m + 34.5 m.

After completion in 1971 the bridge was inspected in depth for the first time in 1976, when a good deal of damage, some of it severe, was discovered. In particular, the arch imposts had shifted horizontally – critical in view of the structural system. In the course of repairs the cause of these impost movements was remedied, and all other damage renovated to a considerable extent. A finite-element analysis – by the standards of the time innovative – was carried out; it was possible to detect an impost movement of 5 mm. The analysis revealed that another 5 mm of impost movement could be tolerated, but that anything more would lead to structural failure.

For this reason a permanent measurement program was initiated to monitor these horizontal movements; on one abutment side three extensometers were installed. These are to be read with a gauge at regular intervals (every six years at examinations of the bridge), and the data compared with previous readings.

During a main inspection in 2007, though, the load-bearing structure was found to be in poor condition: in particular, the inner face of the compression shell has cracks up to 0.9 mm wide, the bearings are damaged and the bridge is subject to relatively high dynamic loading. In addition, it was not possible to inspect the tension ties provided at both abutments to compensate for lift-off forces there (which could develop because the end sections are so short).

The authority responsible for maintaining this bridge therefore decided to aim for a full-scale repair. So as to be able to observe its reliability and general state, particularly the development of cracks and any horizontal movements of the imposts, until complete renovation was begun, the authority commissioned a monitoring system to perform the following tasks:
- Determine the temperature of the bridge structure throughout the year, as a basis for interpreting all other data
- Monitor horizontal movement of the imposts, as this is the critical factor as regards the state of the structure (in conjunction with changes in length caused by temperature).
- Monitor the functioning of the tension tie, so that it can be prevented from failing (in which case the bridge might lift off at the shorter end sections).
- Tie the existing mechanical extensometers into the electronic instrumentation system and correlate the data from them with the temperatures measured.
- Save data automatically by means of a monitoring station at the bridge.
- Transfer data via the internet, with a facility for displaying results without delay and without elaborate special software.

On the basis of the assignment, the bridge structure, accessibility and the utilities on hand (electricity, internet), it was decided to implement the monitoring system as follows.

Install a permanent monitoring system to measure the variables selected at regular intervals, using DDMS (as described in chapter 3).

Horizontal movement occurring at the imposts can be detected indirectly if the absolute change in length between the two fixing points is measured; this can be done by measuring the distance optically with a high-resolution laser. For each load-bearing structure a laser was situated at the Erdberg abutment end (to keep the connections to and from the monitoring station as short as possible). To achieve the required accuracy of measurement, suitable targets covered with reflecting foil were mounted at the opposite abutment end.
Displacement transducers between bridge and abutment monitor the functioning of the tension tie (here the abutment is the fixed point). Conventional temperature sensors at various locations detect seasonal changes in the temperature of the bridge. One temperature sensor is fitted in the shell, close to the abutments, another inserted in a drill hole in a part of the structure as thin as possible (end of cantilever plate).

The existing extensometers (currently read by hand with a gauge) are connected to the existing measurement system by means of an electronic facility, using displacement transducers. For the measurement system to operate permanently without defects, it is essential for the cabling throughout the system to be implemented in the right way. For the Erdberger Bridge all cables were run in plastic pipes lined with aluminium. These pipes protect the otherwise vulnerable data cables against mechanical damage, while shielding them against static interference fields. This is vital in the case of sensors connected directly to a data logger, where A/D conversion does not take place at the transducer. All cables are secured on the bridge by means of pipe clips, and laid in the existing cable trays as far as possible.

All sensors have a robust steel plate housing to protect them against the weather, against getting too dirty and against vandalism. The central measurement unit is installed in a lockable enclosure in the Erdberg abutment. The system started operation early in January 2009, as has so far recorded data without interruption.

During the presentation details of component installation and of how the system has worked so far will be discussed.

6 SEITENHAFENBRIDGE

Planning is in progress in Vienna for the largest integral bridge in Austria, approx. 129 m long; the individual spans measure 32 m + 65 m + 32 m and the bridge will be 15 m wide. Since this is a structure of unusual length and design, the promoter has decided to commission a monitoring system with which to observe the bridge’s behaviour over an extended period, so as to compare it with the assumptions made in structural analysis.
Under the conditions obtaining the bridge is supported in a statically indeterminate way, so changes in temperature, the behaviour of concrete over time, pre-stressing and support displacement cause constraints that are normally undesirable. With increasing bridge length the stresses imposed by constraints can reach a level relevant for dimensioning. Given that certain stipulations were made at the planning stage as regards such stresses and the consequent constraints, the monitoring instrumentation should perform the following tasks:

- Determine the temperature of the bridge structure throughout the year.
- Determine the effect of changes in temperature on the length of the bridge and on the resulting earth pressure.
- Check the basis of the concept of a “flexible abutment” backed by elastic sandwich layers, with a textile-reinforced, stable backfill. This approach makes it possible to neglect stresses due to earth pressure during analysis.
- Determine the vertical distortion of the bridge at selected points throughout the year.
- Determine the behaviour of the flexible steel stays throughout the year, especially changes in their position, by measuring their slope.
- Determine maximum values for the vibration acceleration caused by traffic.
- Save data automatically and transfer data via an internet connection
- Ongoing reporting of the results obtained and comparison with the assumptions made in structural analysis

These tasks are handled by a variety of sensors. Changes in length are recorded by means of lasers, which have proved their worth; earth pressure sensors detect the pressures obtaining behind the abutment. These data are of special importance in the case of this particular bridge, since the concept of the flexible abutment has been implemented here (and exploited to the full in structural analysis).

It is also planned to install slope sensors at various points, so as to determine geometrical distortion in the bridge. Both the V-shaped steel stays and the pile structures beneath these have been earmarked for this. In addition, electronic level gauges are to provide data on changes in vertical position (with an eye to static sagging and to localized subsidence); for this purpose a sensor will be placed in the middle of the centre section, and more sensors at the top of the pile, with a reference transmitter close to the abutment.

To make it possible to identify the overall stresses occurring and to compare these with the owner’s criteria for dynamic loads, a three-dimensional acceleration transducer is to be installed in the centre section, where it is to record data continuously. Further, the dependence of the bridge’s natural frequency on temperature throughout the year is to be represented, to get an impression of how sensitive this natural frequency is in the case of integral bridges monolithically embedded in the subsoil. As currently envisaged, a number of temperature sensors and the central unit will complete the measurement system. The system is currently undergoing more detailed specification, in close collaboration with the planner responsible for the bridge. The final layout of the monitoring system, and subsequent steps leading to implementation, are to be explained in the presentation.

7 SUMMARY

The main aim of this paper is to present selected projects from Austria in the field of bridge monitoring. A further aim is to assess the potential and the limitations of measurement and analytical methods in a general way, and to offer a realistic perspective on useful applications.

It should be added that, as far as we can tell today, it is not possible – at reasonable cost – to diagnose damage early on by means of global procedures based on measuring vibration. So monitoring is no substitute for visual inspection; instead, its role is to provide objective data to aid the organization responsible in answering specific questions about changes in the state of the structure in question. Data-based investigations are also an excellent way to monitor known problems or special issues, as in the case of integral bridges. This field of application is particularly attractive, given that the organizations responsible for such structures also regard such investigations as well worth while to document the history of selected variables.

In general methods of monitoring built structures have great potential for preserving our civil engineering works.