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Recent Austrian Activities in Bridge Monitoring

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ABSTRACT: In addition to conventional methods of assessing the condition of bridges, more and more measuring and monitoring concepts for structures have been introduced in recent years with the intention of providing information on the way the condition of bridges changes with the passing of time at the same time as promoting bridge structure analysis by means of recording objective data. However, these technologies have not yet reached the desired degree of acceptance, although the potential of these technologies is huge considering the questions engineers are always faced with during design, construction and maintenance of such structures. Recent experience has shown that tailor-made and problem oriented monitoring concepts and systems have the potential for a much wider application in the field of civil engineering and shall become standard tools to support decision making processes.

1 HOW TO ENSURE THE APPLICATION OF SHM

Experience gained in Austria over the past decade regarding monitoring has taught us that for a more widespread and successful application of this technology we need to branch away from previous strategies because only very few projects have been monitored so far, and in many cases the focus was on research projects. Based on practical experience in recent years, 3 key theses according to Geier et. al. (2008) have been deduced that are of core significance to increasing the implementation of monitoring systems.

(1) Monitoring may not replace conventional inspection. This technique should be a supplement to determine structural condition and load bearing capacity. Moreover monitoring may present a tool to determine specific load bearing conditions during construction processes or specific load cases during erection and/or operation (refer to chapter 3).

(2) 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, ensuring 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 (refer to chapter 4).

(3) Objective data are collected as input parameters for further investigations. Apart from the application described before, measuring procedures can be employed particularly to gather the necessary basic data on load-bearing structures in a realistic way. The resulting data can be used for further analysis, e.g. to aid in adapting existing computer simulations to the actual behaviour of a structure or to verify assumptions taken during design process (refer to chapter 5).

Following successful application during reference projects in which the above theses were consistently followed and explained to the relevant clients, it was possible to create a platform to promote increased acceptance of monitoring in the construction sector. This platform also made it possible to introduce a directive on the subject of monitoring as a supplement to Austrian guideline RVS 13.03.11 that is binding in a similar way to a standard. This directive is explained in the following chapter.

In addition to observing the above theses, it was also deduced that monitoring systems offer high performance in respect to identifying damage according to Cunha (2010), although the results are often very difficult to assess for construction engineers due to the complexity of interacting factors - e.g. between measuring parameters and other influences such as temperature, traffic etc. and subsequent evaluation. The human factor in this respect is often to reject things that are difficult or impossible to understand. This phenomenon has been observed on several occasions in recent years. Moreover, such applications involve considerable investment in the measuring system and subsequent evaluation and analysis.

In addition to observations on the above theses, the following aspects in particular are significant in the long-term success of structural monitoring:

(1) Acting as a reliable consultant: try and provide client with objective consultation regarding opportunities and limitation of monitoring systems. Do not insist on a potential monitoring project if other methods (conventional inspection etc.) are more likely to achieve better results. The risk of damaging the reputation of this relatively new technology is too high if the application of monitoring is unsuccessful. Keep the costs of the technology package (measuring system and engineering services) transparent and tuned to the objective in hand. Costs should be roughly the same as a convention inspection or a special inspection.

(2) Promote understanding and involvement: use measures that are as easy as possible to understand when addressing the problem with the intention of promoting understanding and gaining the client/administrator's confidence through their involvement in the project. Attempt to focus on direct measurement of the variable parameters so that peripheral influences can be disregarded. Involve the client to increase their interest and encourage their participation as a result.

(3) Refer to practical issues: by keeping in touch with companies involved in planning and construction, tackle issues that arise in the course of planning and construction in order to verify them conclusively using subsequent measurements.

(4) Be a comprehensive service provider: focusing on measurements and data evaluation alone is not enough. Together with the client and other specialists involved, a status report and follow-up action list need to be developed so that the monitoring results can be integrated into the ongoing process of maintaining the bridge.

(5) Create a professional platform: by observing the above points it is possible to create a positive echo in the sector. This platform can then be used to focus on compiling specifications and regulations. A client will always find it easier to accept and apply a specific service if applicable regulations are available.

2 AUSTRIAN MONITORING GUIDELINE

The ready for publication supplement of the Austrian Guideline RVS 13.03.11 (inspection of structures) from 2010 is based on several monitoring projects implemented successfully in recent years and is dedicated to monitoring of bridges and other civil engineering structures.

A dedicated working group under the leadership of the relevant Austrian ministry was set up to create this guideline. The working group consisted of construction company representatives, engineering offices as well as monitoring technology providers. The objective was to establish a legal framework for the commissioning, planning and implementation of monitoring systems with a wide range of capabilities and high level of acceptance.

Having defined monitoring and factors for compiling a specification, a work process was introduced as per the flowchart shown in Figure 1, giving potential users a clear overview of outstanding issues and the contents of the specification. The individual subject fields of the flowchart were then processed for integration into the practice-oriented guideline.

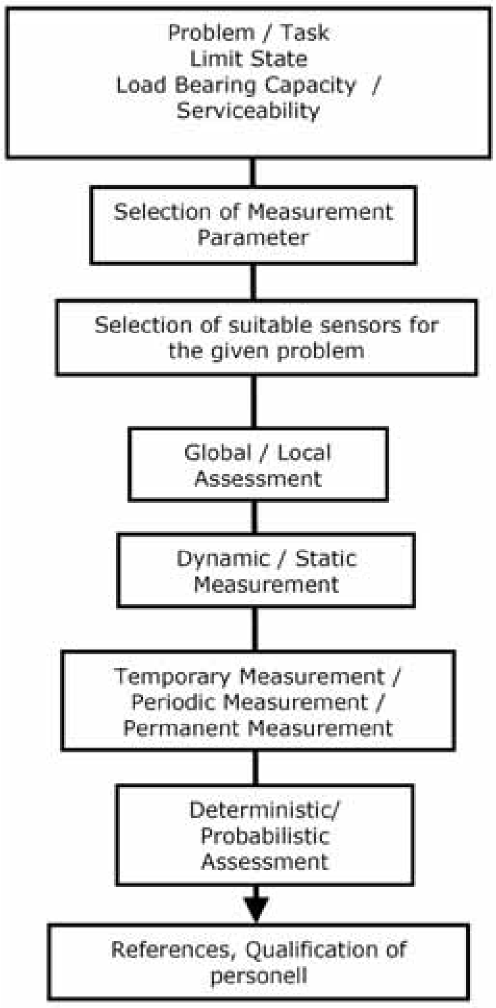

Figure 1. Flowchart of the Austrian monitoring guideline

The backbone of the guideline was the formation of a matrix with specifications of suitability criteria for defined sensors for a range of measuring methods for issues found in practice. Differentiation was made between "highly suitable", "suitable under certain circumstances" and "not suitable" for each measuring task, taking into consideration static and dynamic measurements. A large part of the guideline consists of a collection of possible application areas for monitoring with explanations of the measuring methods used and the results achieved. This complied with the construction engineers' and structure administrators' wishes to make this partially abstract subject more accessible so that they can refer to this "catalogue" of reference values and quality criteria when describing similar monitoring services in their specifications.

3 CABLE FORCE DETERMINATION

The determination of the acting tensile force in stay cables as well as the assessment of proneness in contrast to vibration excited by wind or traffic is both relevant, if safety of the structure is of major concern. As early as the beginning of the 1950s attempts were made to evaluate the cable force by the simple approach of sensing the basic mode of vibration by hand. For calculation of the stress the simple coherence function between basic eigenfrequency and tensile force was used. The accuracy of course, was not sufficient to fulfil the requirements of civil engineering practice. Currently the main part of cable force measurements is performed by static means or periodic frequency measurements. Lift-off testing by hydraulic jacks is an approach, although it is not applied in civil engineering practice very often.

Technologies which are based on the analysis of the dynamic response of a cable under tension are very well known. Based upon ambient vibration testing according to figure 2 quick and reliable evaluation of cable forces are possible. In general, the dynamic response of a cable is a function of tensile force and bending stiffness of the cable cross section. Depending on the cable type, the length and mass of the tendon, different developments of the natural frequencies have been observed.

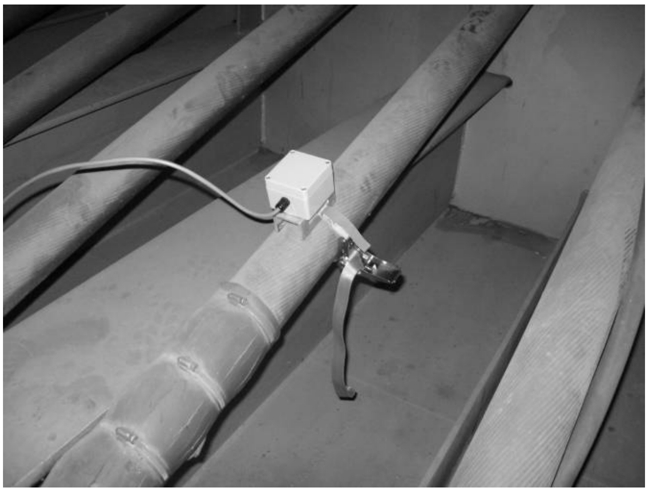

Figure 2. Acceleration sensor on stay cable

By considering these effects it is possible to determine an idealized frequency and a bending stiffness based on the measured basic and higher order modes. The application of this method was tested on several stay cables and the results have been compared to the design cable forces as well as to reference measurements in Geier (2004). These tests have shown that the accuracy of determining the cable force is considerably improved compared to conventional testing. One recent application, which is also related to the first thesis of chapter 1, is the Neckartal bridge in Weitingen / Germany.

Figure 3. External Cables at Neckartal Bridge

The bridge leads the motorway BAB A81 in the sector Stuttgart–Singen in Horb along the Neckar river, four-lane across the Neckar Valley. A distinctive feature of this 950 m long bridge are the first and the last span which are supported with cables with span width of 264 m and 234 m respectively (refer to figure 3). In this way they were able to dispense with pillars in the landslip endangered area of the valley slopes. Construction of the bridge began in 1975 and the bridge was opened to traffic in 1978.

The cables are essential bearing elements of the bridge and are supposed to provide the unrestricted stability and durability of the structure during its entire service life. In the framework of the partial maintenance works started in 2009 the cables are supposed to be corrosion coated again. Prior to these works the client thought of carrying out a magnetic-inductive analysis for all cables in order to evaluate their condition taken into consideration that ever since their construction they had only been visually checked according to DIN 1076. The very expensive magnetic-inductive analysis revealed the necessity for an early vibration verification of all cables.

The measuring aimed at determining the effective cable tension through evaluation of the eigenfrequency considering the bending stiffness according to figure 4. In addition parameters for the evaluation of the cable condition should be derived from the investigation and an assessment in terms of structural condition of cables and anchors should be performed. These investigations finally should lead to specific recommendations e.g. in terms of further and deeper investigations.

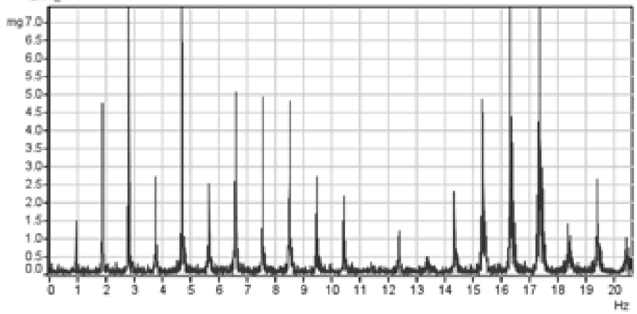

Figure 4. Typical frequency spectrum of one cable

The results of the analysis showed that on the basis of the parameters used for evaluation only 3 out of 48 cables displayed peculiar behaviour. And it was only related to these cables that further ultrasound verifications of the anchor-heads were suggested. In such a way a cost effective and technically reliable evaluation could be done to the benefit of the bridge administrator.

4 CONTINUOUS BRIDGE MONITORING

A typical application for thesis no. 2 is the Erdberger Bridge across the Donaukanal in Vienna which was built between 1968 and 1971 representing a milestone at the time in terms of bridge design and execution according to Vogler (1976). The bridge is the traffic junction between Ostautobahn A4 and the Vienna Südosttangente A23, conveying around 172,000 vehicles a day.

Figure 5. View of the Erdberger Bridge

The overall width of the bearing structure measuring 42.30 m provides space for six continuous carriageways plus four supplementary lanes. The bridge has an overall length of 147 m. The structural condition is ensured by means of a shell in form of a cylindrical barrel with parabolic opening (Figure 5). On the top of both cylindrical shells with variable thickness the deck slab with extensive long cantilever arms and a mid span of 12 m is situated. In order to reduce dead load of the structure cylindrical hollow bodies were put into the scaffolding before concreting the structure.

In 2007 the bridge administrator ASFiNAG had a bridge check done which revealed a bearing structure in a relatively poor condition with extensive damage. This prompted the bridge administrator to order a general repair of the structure. Against this background as well as taking into consideration the extremely important function of the bridge structure within the road network the decision was taken to monitor the evolution of the structure by means of a measuring system until the general repair was done. The monitoring system had to fulfil the following tasks: (i) Determination of the temperature of the structure over the seasons as a basis for the interpretation of all the other parameters. (ii) Monitoring of the horizontal shifts of the imposts, as they represent the critical parameter for the condition of the structure (superposition with length change through temperature essential), (iii) monitoring of the function of the buried backstay tendons at the abutment, (iv) connection of the existing mechanical extensometers to the electronic measurement system, and (v) automatic data backup via a measurement station at the bridge. In addition periodic reporting to ASFiNAG was required.

Starting from these requirements a tailor-made monitoring system was developed; its main idea was the realization of a preferably direct measurement of the decisive parameters. A direct and very reliable possibility for the monitoring of the horizontal shifts at the imposts resides in the measurement of the length change between the two bearing points. This measurement can be realized through an optical distance measuring through high-definition laser and reflector plates according to figure 6.

Figure 6. Laser sensor installation

The function of the tension tie can be monitored by means of displacement transducers between structure and abutment. Moreover, the connection of the existing mechanical extensometers to the electronic measurement system in which the transducers had been used as manual counter was done through displacement transducers.

The monitoring system was put into operation in a first stage in January 2009. The flexible hardware concept allows for the extension of the system at any time. The access of the contracting authority and of the operator to all data is done via a conventional web access (FTP log in) – all data are presented in a chart which makes changes in each parameter immediately noticeable. A web portal was also created where the current measured values of each sensor can be seen at any time (http://erdberg.selfip.net)

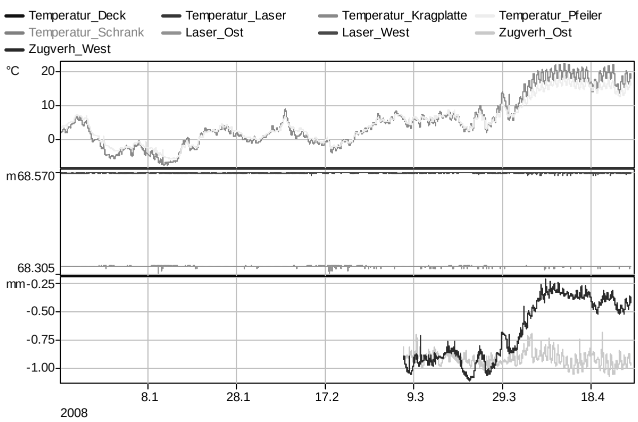

Figure 7. Results for temperature (top), arch distance (middle) and tendons (bottom)

5 INVESTIGATION OF RAILWAY BRIDGES

A typical application of monitoring in recent years applying the third thesis stated in chapter 1 is using the measurement data to calibrate a finite element model of railway bridges in terms of recalculation of vertical acceleration caused by high-speed train passage. In the following chapter a bridge of the Austrian federal railways has been selected for presentation of this approach. When trains cross bridges at high speed, the supporting structure may resonate causing high inertial forces exceeding the calculated ones based on the static load and the dynamic magnification factor. Therefore in EN 1991-2 a flow diagram is included, which divides the requirements of dynamic calculations into various groups.

If a dynamic calculation is required in accordance with EN 1991, the vertical acceleration values need to be calculated inline with the criteria (3.5 m/s² ballast) and the dynamic cross-sectional values need to be checked against the static values. A problem that often crops up - especially with existing bridges - is that the acceleration limits based on the available drawings cannot be maintained at higher speeds and for different types of train resulting in the speed having to be limited for this section of the railway line, or the structure having to be replaced with a new bridge. Such measures are not cost-effective, especially for relatively new bridges.

However, based on experience gained from numerous dynamic measurements on bridges reported in Geier & Österreicher (2006), it is known that the eigenfrequency and as a consequence the rigidity of the physical structure is usually much higher than established in a calculation, and as a result a combined procedure consisting of measurements and calculations has been developed for such situations. The reason for these often very large differences in frequency is that the structural components that do indeed contribute to overall stiffness (edge beams, rails, track ballast and higher concrete strengths) but are not taken into consideration in the calculations. A method has therefore been developed together with Austrian Federal Railways (OEBB) that includes the actual physical construction properties in the calculation. In an initial step an oscillation measurement is performed to establish the eigenfrequency of the bridge as shown in Figure 8.

Figure 8. Acceleration Sensor on bridge girder

The measurement setup is chosen in such a way that a sensor in mid-span is especially suitable for determining the maximum values (acceleration, deformation) while two additional sensors at 35% of main-span are used to determine bending and torsional frequencies typically by a simple Fast-Fourier-Transformation (FFT).

In the next step a finite element model of the bridge can be modified in terms of natural frequencies to account for realistic (measured) conditions by simply increasing the modulus of elasticity, since only the frequencies are of concern in the calculation. This leads in consequence to higher structural stiffness and higher natural frequencies of the structure. Now the HSLM load models as well as operating trains may be assessed by the updated computer model up to a value of 1.2 times of the desired travelling speed. Figure 9 shows the difference between pure calculation and the combined approach. Here it can be seen that the limit for the train being analysed was 220 kph to start with, but could be moved up to over 270 kph as a result of the measurements so that a much higher travelling speed can now be used on this section of the track.

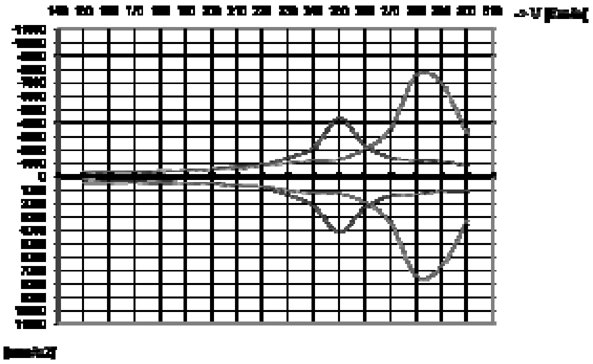

Figure 9. Comparison of calculation (left) and updated calculation (right)

6 SUMMARY

The objective of this paper was to present the efficient application of different monitoring tasks as well as the combination of conventional bridge inspection and subsequent specific monitoring based upon experience gained in Austria in recent years.

The wide range of application capabilities also demonstrates that while taking the conditions detailed in Chapter 1 into consideration, monitoring can be implemented very effectively for various structures and purposes and achieves a high level of acceptance with clients and administrators. Only by achieving this level of acceptance will clients and administrators be able to regard monitoring as an effective supplement to the daily tasks of professional engineers. In Austria, the introduction of the Austrian Monitoring Guideline (chapter 2) represented a milestone in the long-term success of monitoring.

7 REFERENCES

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