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OVERVIEW OF EUROPEAN ACTIVITIES IN THE HEALTH MONITORING OF BRIDGES

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Abstract: *Infrastructure management is becoming one of the key issues in the approach to sustainable development of modern countries. In Europe, most of the transportation networks like highways and railways, as well as ports and inland navigation facilities, have been built decades or centuries ago and are subject to ageing and obsolescence.*
In particular, owners of highway systems are developing increasing interest in experiencing advanced methods for surveillance and monitoring. The aim of these activities is first of all to detect the deterioration process already in its initiation phase and to investigate and identify the causes of deterioration. In this framework, health monitoring is representing one of the most valuable tools for the decision making process concerning maintenance of bridges.
After giving a broad view of the consistency of the European stock of road bridges, the paper discusses some experiences that are being conducted and their possible contribution to the improvement of existing practices.

1 INTRODUCTION

The process of forming the European Union as a real political entity out of a plurality of independent national states is now coming to a new phase after the establishment of the common currency, and because of the foreseen extension of the membership to several formerly East-European countries. It is expected that this new phase will further produce a significant social and economic development and, therefore, it will also create new demand for the mobility of persons and freights both inside the Union and with the rest of the world.

In the above scenario the internal transport network, especially for those lines interconnecting large ports, metropolitan areas and industrial districts, will play a key role in the European economic and social development. Cross-Alpine transport sub-network will represent, in particular, a very delicate component. Because of this reason, the Swiss transport system shall be considered as well.

Although the need for making this development compatible with environmental requirements will continue dispatching an increasing percentage of traffic on railways and local shipping, most part of this mobility will still be sustained by the road network, because of its higher level of service and flexibility. For these reasons, traffic on the road is expected to increase in the next years at a rate of 4-5% each year.

As a consequence the road network must be enhanced, and existing infrastructure shall be put in a condition of maintaining its level of safety and functionality with as little inconvenience as possible to users. In this view it is necessary to plan carefully maintenance, repair and/or rehabilitation operations, with the constraint of often limited available funding.

Bridges may be considered as the most vulnerable elements of the infrastructure as their condition of out-of-service causes great losses in terms of costs both for users (delays and detours) and for road owners and operators.

Special attention is therefore focussed on maintaining them in a serviceable condition. The problem is quite complicate as it is function of their age, variety of structural types, different processes of deterioration and increasing volume and composition of traffic.

From this viewpoint, surveillance and monitoring have already become a widely used standard. The aim of these activities is first of all to detect the deterioration process already in its initiation phase and to investigate and identify the causes of deterioration.

Secondly, by monitoring the progress of deterioration on the different parts of the structure it is possible to give an input for actions aiming at keeping the safety and functionality of the structure within acceptable limits by performing adequate repair actions.

Instrumental monitoring is gaining more and more attention as a convenient tool to follow, on a long-term scale, the global performance or the local variations of relevant properties of structures.

Mostly developed in the last 10-15 years, this type of approach even not common practice, has been and is used on both new and existing structures to keep under control bridges of strategic importance or very deteriorated structures whose critical conditions may require continuous attention. Starting from a review of the European consistency and status of road bridges, this paper is focussing some aspects of the global approach to health monitoring of bridges in view of the application of instrumental monitoring systems.

2 THE EUROPEAN ROAD BRIDGE STOCK

The number of road bridges existing in European countries (e.g. in the central north-south corridor), together with their length, and the percentage of bridges repaired each year can be obtained from available studies in OECD countries [1]. This data is reported in Figure 1.

Countries	Number	Total length (km)	% Bridges repaired per year
Former West Germany	28170	1125	4,9
Belgium	3848	230,1	5,2
Denmark	1983	72,1	1,5
Finland	11714	178	1,2
Italy	3000	250	1,6
Netherlands	4479	134	2,2
Sweden	11350	375	4,4
Switzerland	2976	238	5
USA	578000	22164	-
Japan	651869	8897	-

Table 1 : Consistency of the bridge stock versus percentage of repaired bridges

The information has been completed with the global data on the US and Japanese networks. Apart from the scatter that may reflect different conditions in land and climate characteristics, infrastructure characteristics, and management approaches, it appears that the range in the percentage of repaired bridges is very wide.

A further contribution to the understanding of the European situation can be obtained by considering the chart of Figure 1, where bridges are subdivided per year of construction with respect to the same countries reported in Table 1. The above information dates from 1990, but this is not a limitation because, for the purpose of discussing about maintenance, younger infrastructure is not relevant.

From the plot it is clearly visible that Italy and Switzerland form a similarity group, while the other European countries are forming a different group, and Sweden stays slightly apart. It is noticed that, despite of the similarity in the age of existing bridges, the percentage of repaired bridges per year still differ substantially within the same group.

The above described situation suggests the consideration that maintenance approaches differ substantially among European countries.

Indeed, the solutions implemented in the various European countries concerning property of road infrastructure, toll policies, safety regulations, design and inspection standards (e.g. Italy [2]) have been very different.

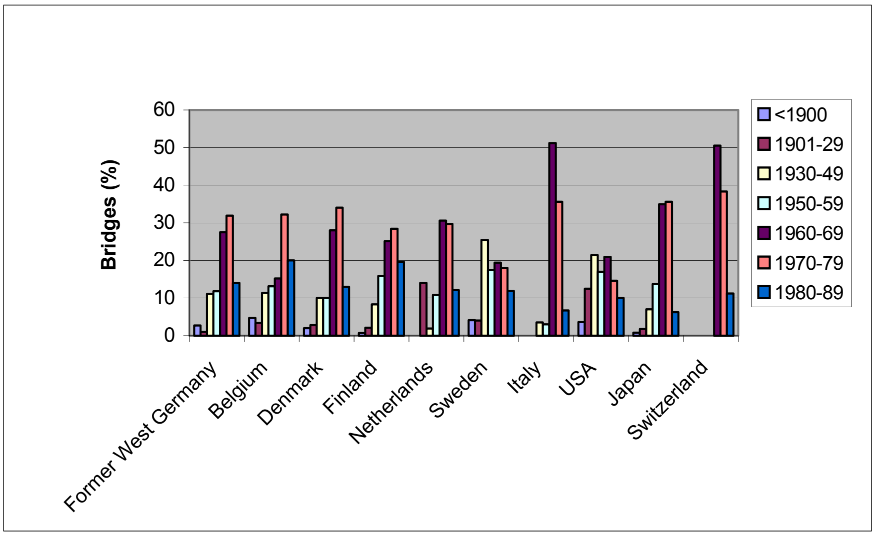


Figure 1: Bridge stock per year of construction

It has to be noted that, while the establishment of common design standards has been the subject of direct actions at the Union level since a long time (Eurocodes), efforts devoted to establishing a reference framework for the management of bridges on the European road network are relatively recent. The BRIME project [3], part of the 4th Framework Programme, as well as the SAMCO [4] network, part of the 5th Framework Programme, are among these efforts.

3 HEALTH MONITORING STRATEGIES AND TOOLS

As seen in the previous paragraph, a global approach to health monitoring is needed in order to establish a reference framework of common knowledge upon which uniform bridge management procedures could be developed.

Extensive discussions on the above subject may be found in the European literature [5] and elsewhere [6]. A review is clearly outside the scope of the present paper. A few basic concepts will be however recalled.

According to Aktan et al. [6] health monitoring may be defined as "*the measurement of operating and loading environment and the critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies, and/or deterioration or damage indicators that may affect operation, serviceability, or safety reliability*". Bridge management systems that have been realised by most infrastructure owners up to know do implement this concept by means of heuristic approaches, substantially based upon:

a) visual inspection techniques;
b) spot NDE techniques;
c) data processing and interpretation techniques;
d) information retrieval systems;
e) ranking systems based on qualitative condition indices.

It is pointed out, without any criticism, that existing procedures simply represent the rationalisation of a very traditional civil engineering approach to facility management, just taking advantage of the tools that modern electronics and information technology deliver on the market. Of course, the use of sophisticated instrumentation, data manipulation and modelling techniques may also be occasionally involved in such procedures.

In the recent years, both long-term and short-term instrumental monitoring are being proposed. Although these techniques are encountering increasing interest among infrastructure owners, extensive application is still lacking. When instrumental monitoring is used, comparison between forecasted and observed behaviour becomes a key issue in the determination of global condition indices and in the detection of the insurgence of local damaging. Advanced data processing and modelling techniques are therefore needed.

The above strategy may be appropriate for new as well as for existing structures, in which it is supposed that the design hypotheses have been fully reproduced during construction, commissioning, and initial stage of operation. In this case the target reliability is ensured until some degradation phenomena develop inside structural materials or the evolutions of usage and environmental conditions produce some modification of the design assumptions.

The possibilities offered by modern instrumental monitoring techniques are however offering a wider interpretation of the health monitoring, including the *construction phase* into the behavioural fields that may be investigated by observation. In particular, embedding sensory systems for long-term static monitoring in reinforced concrete structures during construction or retrofitting works may introduce a new type of knowledge into the health monitoring process. This possibility will be discussed further.

4 LIFE-CYCLE INSTRUMENTAL MONITORING: A TECHNOLOGY BREAKTROUGH ?

For most structures, the behaviour observed from long-term instrumental monitoring often introduces difficulties and questionable subjects in data analysis and interpretation [7]. Structural malfunctions are, in several cases, disclosed by the in-service response even for loading conditions that are not comparable with the design intensity.

In general it is very difficult to interpret such response, and to identify and refer malfunctions to proper causes in due time. It is believed that long-term static monitoring data can provide an efficient tool for facing this aspect in most cases. However, long-term monitoring implies that, in case of malfunctions, the structure should be kept into operation at least for some time.

Structural malfunctions originating in bridge structures may be likely due to some inconvenient occurring during the construction phase. Therefore, the possibility of extending monitoring activities to the entire life-cycle of a bridge will introduce a significant technological improvement. On the other hand, this will render data analysis and interpretation even more complex.

To make an example of the type of information that can be gathered from structural monitoring during construction of a bridge, the case study of the Siggenthal arch bridge in Switzerland [8] will be discussed.

The Siggenthal Bridge is a concrete arch bridge with an arch span of 117 m, built over the Limmat river in Baden, Switzerland. The bridge also includes two approaches with one span on one side and three spans on the other. The total length of the bridge is of 217 m. The bridge is presently under construction and Figure 2 depicts the scheme of the scaffolding that has been used for arch construction (left) and a picture of the finished arch (right).

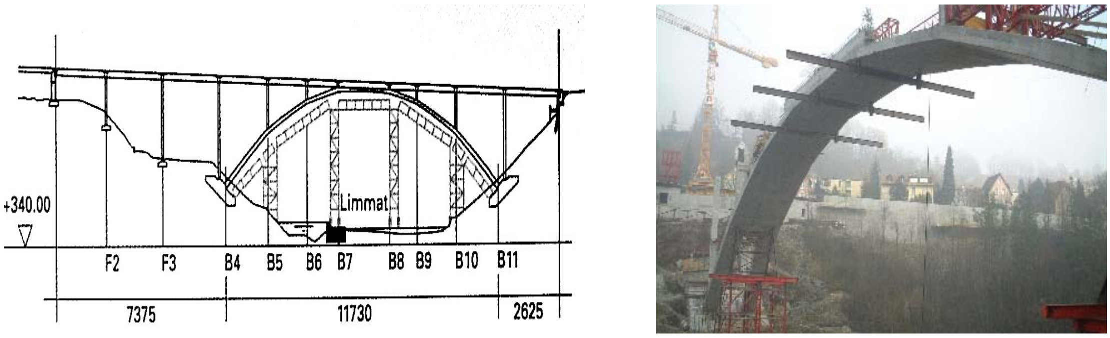


Figure 2 : scaffolding during arch construction (left) and finished arch (right)

The arch has a variable width from 10 m at the ends, where it doubles in two parallel and distinct arch segments, and 8 m at the top. Its thickness is 0.8 m at the top and 1.4 m at the feet.

The arch curve is made of 7 segments with inflexion points under the columns supporting the deck and slightly curved in between. The arch construction proceeded in five successive concrete pouring phases, executed symmetrically and starting from the feet. After construction of the arch the scaffolding was removed. The arch has been stabilised by temporary steel towers under the first columns to continue construction of the bridge.

A monitoring system composed by 2 inclinometers, 8 temperature sensors, and 58 long-gage (between 3 and 5 m) SOFO™ fibre optic sensors [9], placed in pairs at the interior of the arch in order to measure curvatures (Figure 3). From the measurement of curvatures, vertical displacements can be retrieved by double integration [10]. SOFO sensors are low-coherence temperature compensated sensors that can provide measurements of the variations of the base-length in the micron range.

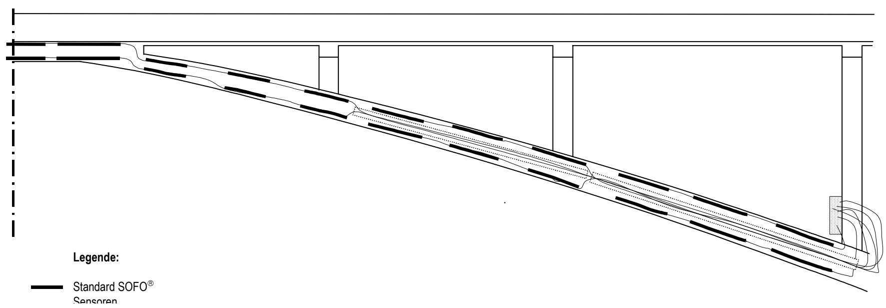
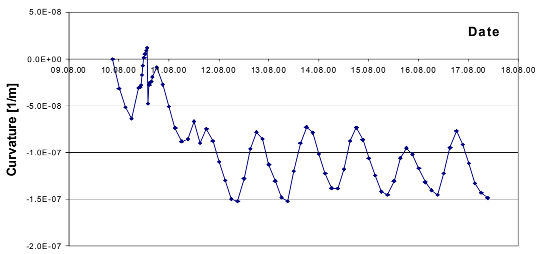


Figure 3 : Sensor position in the arch

The monitoring system is aimed at detecting local concrete deformations, measuring local curvatures in the vertical plane, and reconstructing the perpendicular displacements of the whole arch during the entire life-span of the bridge. The sensors have been installed before concrete pouring, for being interpreted with particular interest to the following phases: concreting of the different arch sections, removal of the scaffolding, free standing phase of the arch, installation of the temporary towers, construction of the supporting columns and of the deck, bridge testing, long-term in-service monitoring.

Already published results [8] show that important information on the behaviour of the as-built structure may be obtained. Figure 4 shows an example of the curvature readings and of the corresponding displacement reconstruction.



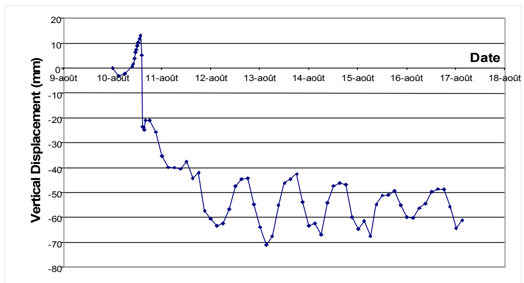


Figure 4 : Curvature readings (left) and vertical displacements at midspan in mm (right) during scaffolding removal and while free standing of the arch

The designers were able to compare with a high degree of accuracy the observed behaviour of the arch with the computed one. It has to be noticed that performance of the same comparison with arch displacements measured with traditional systems would have been more difficult because the readings would have taken some hours to be completed. In this time, temperature variations would have modified the state of displacement of the arch. By using fibre optic sensors, readings can be obtained in a few minutes for the whole array, and the effect of temperature variation is clearly recognisable and can be easily filtered out for separate analysis by means of signal processing techniques.

The above described example indicates that continuous life-cycle monitoring provides information qualitatively different with respect to traditional control systems. Instrumentation signal are rich of information that may reveal unwanted behaviours and allow intervention on a real-time basis.

5 CONCLUSIONS

The need for co-ordinated research and development on bridge monitoring systems in Europe has to be emphasised. Dissemination of new instrumental monitoring technologies among European infrastructure owners is indicated as a means to improve existing bridge management approaches.

It has also to be pointed out that instrumental monitoring techniques shall prove to be cost effective, provide simplifications of the current inspection practices and ensure that, in real conditions, the information necessary to assess the reliability of a bridge is available in the real time.

New sensor technology allows embodiment of deformation sensors inside reinforced concrete structures. These sensors are sufficiently reliable for being used over the entire life-cycle of the bridge. This possibility, actually demonstrated by the reported case study of the Siggenthal Bridge in Switzerland, is offering an interesting opportunity for rethinking the overall approach.

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