Monitoring of Bridges and Concrete Structures with Fibre Optic Sensors in Europe

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Summary

The use of fibre optic sensors is becoming a valuable practice in sensory systems for the health monitoring of structures. The paper presents a few significant case studies in which fibre optic sensors have proven their effectiveness. Implementation of the sensory system as well as data analysis and interpretation are discussed.

Keywords : Health monitoring, Fibre optic sensors, Bridges, Concrete Structures, Data Analysis and Interpretation

1. Introduction

In the last decade, an increasing shift from investments in the construction of new infrastructures to the maintenance and lifetime extension of the existing ones has taken place. In Europe, for example, most of the transportation network, such as highways and railways, is completed and in service. A similar situation is encountered in ports and maritime infrastructure, where most of the facilities have been built 30 to 80 years ago. By the other hand, the establishment of a common economical and political *european space* larger than ever is pushing the demand for free circulation of people and freights, but the concern for the impact created by the construction of new facilities in delicate natural and architectural environments is also increasing. Therefore, the authorities managing civil infrastructure face the challenge of maintaining the transportation network in a satisfactory state, using a limited budget and with little perturbation to its normal use. This task is far more complex than that of building new structures and requires new management instruments.

Due to the loads, ageing of materials and environmental action, the performance of many in-service structures has decayed and the inherent level of safety can be shown inadequate relative to current design standards. Structural health monitoring is certainly one of the most powerful tools for infrastructure management, as witnessed by the recent technical and scientific literature (e.g. [1]). In what we call *the information age*, structural health monitoring seems to close the gap between the traditional world of structural engineering and the frenetic one of information technology.

Monitoring includes the observation of deformations as well as environmentally induced processes. Climatic variables like temperature, humidity and wind loads shall be considered as well. A central point consists in the observation of the chemical parameters in the form of electrochemical potentials, resistivity, and penetration processes. However, an almost complete instrumentation of all imaginable physical phenomena would exceed the reasonable amount of financial efforts. Additionally, a larger number of collected data might not necessarily improve the quality of the drawn conclusions. Therefore, the identification and observation of the decisive parameters is fundamental for the development and calibration of consistent engineering models describing the deterioration mechanisms threatening ultimate limit state, serviceability, and durability [2].

The definition of the objective of the instrumentation program usually follows the realisation that something about the structure is not known well enough and that measurements of a number of quantities at a certain location would be desirable for the sake of economy or safety. The first step is to reflect on all possible ways the construction might behave and to chose which quantities to measure, where to measure them, and to select adequate instruments to do so. This requires an estimation of the magnitudes of changes in the quantities to be measured, which allows the definition of the range, resolution, accuracy, and sensitivity of the instruments selected to measure them. In much the same way, the temporal behaviour of the observed phenomena might be a criterion for the dynamic requirements for both the instruments and the readout units. As next the instrument positions and the number of instrumented sections have to be determined. After testing, the taking of the readings and their processing and analysis must be carried out in a systematic, organised way [2].

This paper is intended to discuss the experiences gained by the Authors in the application of fibre optic sensor systems in monitoring massive and beam-like concrete structures in the marine and in the alpine environment. Structures, as well as sensory systems, are subjected to a great threat in such regions, and special care shall be given to durability and reliability problems in the long term.

In the last few years, innovative fibre optic sensors have made a slow but significant entrance in the sensor panorama because in certain cases they are able to provide an additional value with respect to conventional sensors. The additional value can include an improved quality of the measurements, a better reliability, the possibility of replacing manual readings and operator judgement with automatic measurements, an easier installation and maintenance or a lower lifetime cost. Before going on with the paper, a brief summary of the basic principles of the sensors used will be given.

1.1 Long-base fibre optic sensors for strain measurements

Recent advances in fibre optic sensing has led several technologies to become an alternative to classical electrical, mechanical or vibrating wire strain gages [3]. Among them, Bragg grating and Fabry-Perot sensors are available to provide local strain measurements, but SOFO sensors can provide a very accurate and reliable measurement of the relative displacement of any two points chosen in a structure at distances from 20 cm to 30 metres.

The SOFO sensor, originally developed by Inaudi et Al. [4], consists of a pair of single-mode fibres installed in the structure to be monitored. One of the fibres, called measurement fibre, is in mechanical contact with the host structure itself, while the other, the reference fibre, is placed loose in a neighbouring pipe. All deformations of the structure will then result in a change of the length difference between these two fibres.

To make an absolute measurement of this path unbalance, a low-coherence double Michelson interferometer in tandem configuration is used. The first interferometer is made of the measurement and reference fibres, while the second is contained in a portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-known path unbalance between its two arms. Because of the reduced coherence of the source used (the 1.3 micron radiation of a LED), interference fringes are detectable only when the reading interferometer compensates the length difference between the fibres in the structure.

The precision and stability obtained by this set-up have been quantified to 2 micron and a precision of 0.2%, independently from the sensor length and over more than five years. Even a change in the fibre transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

1.2 Distributed strain and temperature fibre optic sensors

Brillouin scattering sensors show an interesting potential for distributed strain and temperature monitoring [5]. Systems able to measure strain or temperature variations of fibers with length up to 50 km with spatial resolution down in the meter range are now demonstrating their potential in the first field trials. Brillouin scattering is the result of the interaction between optical and sound waves in optical fibres. Thermally excited acoustic waves produce a periodic modulation of the refractive index. Acoustic waves can also be generated by injecting in the fibre two counter-propagating light waves.

The MET (Metrology laboratory) group at Swiss Federal Institute of Technology in Lausanne (EPFL) have proposed a sensing system based on the above principles [6]. It consists in generating the two scattering waves from a single laser source using an integrated optics modulator. This arrangement offers the advantage of eliminating the need for two lasers and intrinsically insures that the frequency difference remains stable independently from the laser drift. A system called

DITEST, based on this set-up, is commercialised in Switzerland. It features a measurement range of 25 km with a spatial resolution of 0.8 m (over 2 km range). The strain resolution is 20 $\mu\varepsilon$ and the temperature resolution 1°C. The system is portable and can be used for field applications. These values are close to the theoretical limits for a Brillouin system.

2. Monitoring of Massive Concrete Structures

Massive concrete structures present characteristic behavioural parameters very difficult to observe by means of conventional sensors. Moreover, they undergo phenomena that are only detectable by long-term observation.

First of all, local strain fields are not very meaningful in deriving state conditions in massive structures. As a consequence, the use of long-base strain sensors with very high precision and stability over long periods of time is required. Secondly, thermal phenomena may be very important for structural integrity and develop very complex transient fields.

Massive structures are not easily modelled through conventional structural mechanics approaches. Consequently, interpretation of monitoring data seldom takes advantage of known analytical models only, and it shall also be based upon statistical system identification procedures. Two case studies are presented in the following.

2.1 Deformation monitoring of a quay wall

A large-scale monitoring programme is being conducted by the Port Authority of Genoa to assess safety and operability of existing structures and to keep records of the effects of service conditions as well as of the effects of retrofitting activities. In the framework of this programme an application useful for the present discussion is represented by the installation of a monitoring system along the east quay wall of the San Giorgio pier [7].

The San Giorgio pier actually measures 400 m in length and it is used for coal import. The facility has been built in the 1920s and the vertical walls delimiting the quays are made of heavy concrete blocks. It has been planned to dredge the nearby basin, increasing the water depth from 11 m to 14 m; this planned work has required strengthening of the wall. The structure has been underpinned with jet-grouting columns, and the blocks have been connected by means of vertical steel rods; stability has been improved with permanent active tendons installed along the entire length of the pier. In order to monitor the displacements eventually caused by the dredging activities, the quay wall has been equipped with 72 SOFO sensors of 10 m base length, located in a service tunnel along the top blocks, in such a way to have 3 sensors in each measuring section (Fig. 1, left).

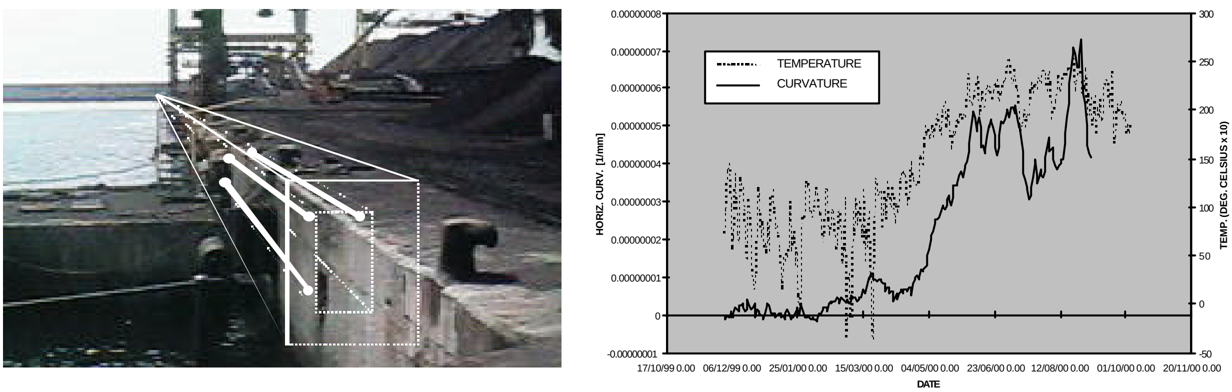

Fig. 1: San Giorgio Pier, general view and sensor placement sketch (left); Typical curvature vs. temperature plot in a measuring section (right)

With this arrangement it is possible to compute the linear strain at the three corners, as well as the curvatures in the vertical and in the horizontal planes. The monitoring programme has been set up in this phase to identify a *normal* structural behaviour, in order to interpret deviations from this behaviour as a possible indication of distress at a later stage, when dredging will be performed.

The system is operational since fall 1999. Time histories of strain and curvatures have been found to be correlated to the environmental temperature (Fig. 1, right). No correlation has been detected yet with the activities taking place at the terminal. Interpretation of the mechanics of the wall by means of analytical techniques is very cumbersome due to the complexity of the interaction among blocks and the uncertainties in the condition of joints. Characterisation of the response by means of statistical models is being conducted.

2.2 Distributed temperature monitoring in a dam abutment

As noted, distributed temperature measurements are highly interesting for structural monitoring of large structures. In the presented application, the MET-EPFL group used the DITEST system to monitor the temperature development of the concrete used to build a dam [8]. The Luzzone dam in Switzerland was recently raised by 17 meters to increase the capacity of the reservoir. The raising was realised by successively concreting 3m thick blocks. The tests concentrated on the largest block to be poured, the one resting against the rock foundation on one end of the dam. An armoured telecom cable installed in serpentine during concrete pouring constituted the Brillouin sensor. The temperature measurements started immediately after pouring and extended over 6 months. The measurement system proved reliable even in the demanding environment present at the dam (dust, snow, and temperature excursions). The temperature distributions after 15 and 55 days from concrete pouring are shown in Fig. 2. Comparative measurements obtained locally with conventional thermocouples showed agreement within the error of both systems. This example shows how it is possible to obtain a large number of measurement points with relatively simple sensors. The distributed nature of Brillouin sensing make it particularly adapted to the monitoring of large structures were the use of more conventional sensors would require extensive cabling.

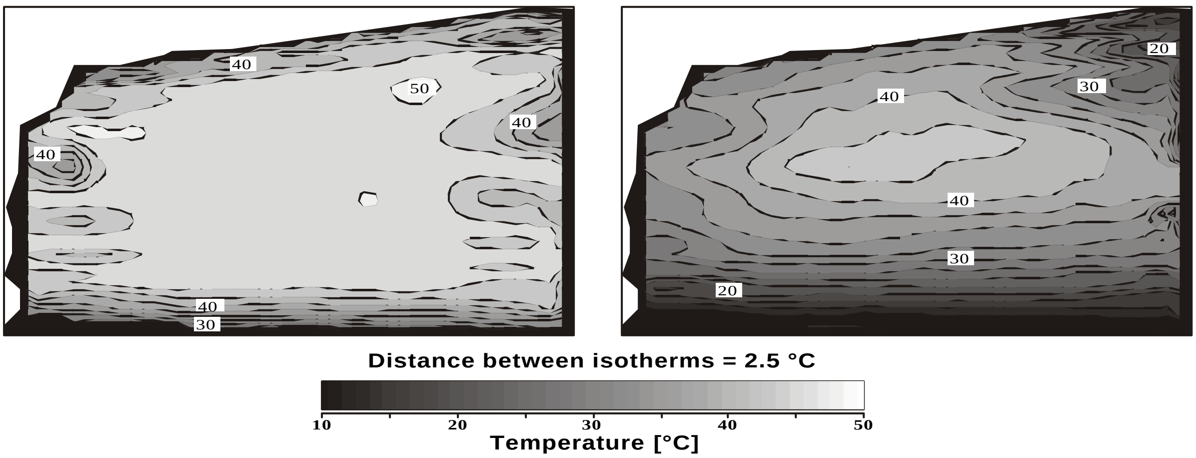

Fig. 2 Luzzone Dam: Temperature distribution measured with the DITEST system 15 and 55 days after concrete pouring (Courtesy of L. Thévenaz and P. Robert, MET-EPFL, Switzerland)

It is interesting to observe how interpretation of the measurements in terms of the state or condition assessment of the structure is an open problem. Indeed, although temperature fields induced in massive structures by the chemical process taking place in the concrete and by the thermal exchange with the environment is a well-known concern for structural engineers, detailed experimental measurements in real structures were never performed. This example allow to underline that the possibilities offered by new sensing technologies can provide a breakthrough in structural health monitoring.

3. Monitoring of Beam Structures

Long-term monitoring of beam structures is usually conducted to infer information on the damage state suffered by the structure. To this purpose, it is better to reason in terms of the deformed shape (either static or dynamic) under known loads, as damaging may more easily influence the overall geometric conditions than the local state of deformation. The use of SOFO fibre optic sensors, besides providing accuracy and stability over very long periods of time, is also very effective in producing an average deformation measurement over the base length (that eventually will include structural cracks), and in giving rise to analytical processing of the data able to reconstruct the deformed shape of the beam.
A special purpose algorithm named SPADS [9] is available to process SOFO sensors readings in order to produce the evolution of curvatures with time. This algorithm has been tested both in the

laboratory and in the field, in the framework of the monitoring activities performed over the Versoix Bridge in Switzerland. SOFO sensors have also been successfully installed over several bridges in Europe and abroad, but one of the most interesting applications, because of the generality of the architectural approach to the monitoring system, is represented by the project implemented over the Colle Isarco Bridge, on the highway linking Italy to Austria through the Brenner Pass. These two applications will be described in the following sections. A future implementation on a pre-stressed concrete pier in the Port of Genoa is also under study.

3.1 Monitoring of the Versoix Bridge

The North and South Versoix bridges are two parallel twin bridges. Each one supported two lanes of the Swiss national highway A9 between Geneva and Lausanne. The bridges are classical bridges consisting in two parallel pre-stressed concrete beams supporting a 30 cm concrete deck and two overhangs. In order to support a third traffic lane and a new emergency lane, the exterior beams were widened and the overhangs extended. The construction progressed in two phases: the interior and the exterior overhang extensions. The first one began by the demolition of the existing internal overhang followed by the reconstruction of a larger one. The second phase consisted to demolish the old external overhang, to widen the exterior web and to rebuild a larger overhang supported by metallic beams. Both phases were built by 14 m stages.
Because of the added weight and pre-stressing, as well as the differential shrinkage between new and old concrete, the bridge bends (both horizontally and vertically) and twists during the construction phases. In order to increase the knowledge on the bridge behaviour, SOFO sensors have been chosen to measure the displacements of the fresh concrete during the setting phase [10] and to monitor long term deformations of the bridge. The bridge was equipped with more than hundred SOFO sensors. The sensors are 6 m long and placed parallel to the bridge length. The first two spans of the bridge were subdivided into 5 and 7 regions (called cells). In each cell, 8 sensors were installed at different positions in the cross sections as shown in Fig. 3, left.

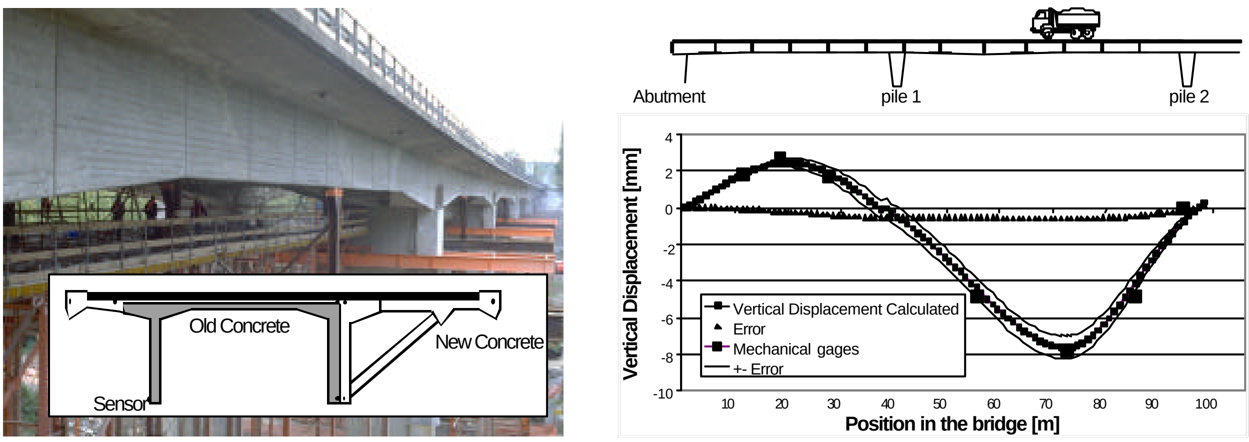

Fig. 3: Versoix Bridge, general view and sensor placement in a typical cross-section (left); vertical displacements calculated from SOFO curvature measurements compared with wire extensometers readings (Courtesy of S. Vurpillot, IMAC-EPFL, Switzerland) (right)

Thanks to this sensor network it is possible to follow both local and global displacements of the bridge. The sensors were first used separately to quantify the concrete shrinkage and study the performance of different concrete mix designs. Once the bridge completed, the sensors were used combined to calculate the horizontal and vertical curvature of each cell. By double-integration of these curvature measurements it is than possible to calculate the horizontal and vertical displacement of the whole bridge [10]. During a load test, performed in May 1998 after the construction was terminated, the vertical displacement of the bridge was monitored with mechanical gages and compared with the results of the computations performed from the sensor readings by means of the above mentioned procedure. The algorithm retrieved the position of the first pile and accurately reproduced the vertical displacement measured with mechanical gages. The comparison, together with the estimated error curve is shown in the plot of Fig. 3, right.

3.2 Monitoring of the Colle Isarco Viaduct

The development of a life extension and/or replacement strategy for highway structures is a crucial point in an effective bridge management system. An example of a global monitoring approach [11] in establishing a bridge management system is represented by the project of the Colle d'Isarco viaduct on the Italian Brenner-Highway A22, which is currently ready for full operation [12]. The section of the highway that is subject to monitoring activities includes four columns, each of them supporting asymmetrical cantilevers in the north and south direction as can bee seen in Fig. 4.

Fig. 4: Colle Isarco Viaduct on A22, view of the monitored section

The overall length of this section is 378 m. The height of the girders near the supports number 8 and 9 is 11 m, at the supports 7 and 10 the height is 4.50 m. The girders have a uniform width of 6 m, the arrangement for each road bed is approximately 11 m wide. A wide set of sensors have been installed, including both traditional and fiber optic sensors and, due to the large dimensions of the section, a data acquisition system able to collect widely distributed sensing units was also installed. A partial overview of the sensor types and placement, and data acquisition network is presented in Fig. 5

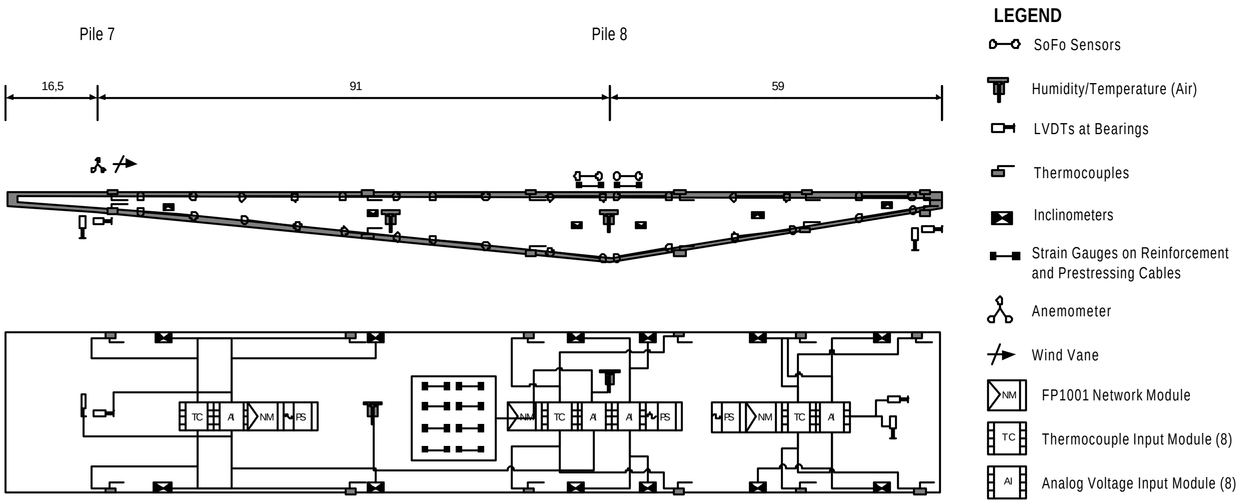

Fig. 5: Partial instrumentation scheme for one girder box

Typically an I/O-module in such a network has 8 to 16 thermocouple, RTD, voltage, current, or frequency inputs, 16-bit resolution, self-calibrating with stable onboard reference, rejection of 50/60 Hz noise, and a -40 to 70°C operating range. Wireless serial communication is used to transfer the measured data from the almost inaccessible locations on the bridge to the location of the personal computer used to evaluate the measured data. Finally, the readout-units that control transducers delivering non-standard signals, as e.g., fibre optic devices, vibrating wires, etc., have been integrated in the data acquisition network via the specified interfaces. The fibre optical SOFO system requires a separated signal processing and can therefore not be integrated directly in the data acquisition system. Each sensing fibre is addressed separately and subsequently multiplexed to a readout unit that performs the necessary interpretation of the optical effect to a discrete signal. This readout unit is connected to a PC running the evaluation algorithm described in [9].

In addition, a system to acquire traffic loads has been installed in the immediate neighbourhood of the viaduct. The measuring device is based on a monomer optical fibre. This system will soon be integrated in the monitoring project.

4. Analytical Modelling and Statistical Evaluation

To identify anomalies and deterioration processes, it is essential to understand the relationships between the signal measurements and the real occurred phenomena. Therefore, the comparison of measured and calculated data in order to tune and validate the mechanical and numerical model assumptions is an integral part of any system analysis. Finally, the interpreted results of all measurements should be the basis for the condition assessment and the safety evaluation of a structure to facilitate replacement and repair decisions.

The installation of sensing elements and of an automated data acquisition system to collect measured data is only the start of monitoring field performance. Interpretation of the acquired data is equally important, namely the comparison of measured and calculated data in order to validate the model assumptions or to verify the effectiveness and efficiency of the monitoring system [2]. For this purpose a finite element model of the monitored structure based on a linear or non-linear approach might be build. Comparing e.g. measured and calculated modal data helps to analyse the causes of discrepancies. The determination of stresses from short-term strains requires a determination of the modulus of elasticity of the concrete. Determination of stresses from long-term strains is considerably more complex and requires information about creep and shrinkage of the concrete. To calibrate the analytical state determination model for a bridge, the response of a virgin structure is first traced by the filament beam element to the ultimate load range. The initial stiffness of the service load level can be estimated by the fundamental frequency of the bridge structure obtained from vibration tests, static loading tests, and the major experimental information collected by the continuous monitoring system. The calibration of the analytical model is then adapted to the load-deflection response of the existing bridge structure. Once a calibration has gained a certain level of completeness, analytical prediction provides a quantitative knowledge and hence is a useful tool to support structural evaluation, decision making, and maintenance strategies.

However, measurement processes usually introduce a certain amount of variability or randomness into the results, and this randomness can affect the conclusions drawn from measurements. Randomness in measured variables can be accounted for by their probability density functions (PDF). In order to find the density function of continuous measured data, the so-called evaluation strategy (or genetic algorithms) may be applied [13]. Essentially, test data are classified into groups and subsequently the combined density functions are fitted by the use of evolution strategies such as mutation, recombination, and selection. The idea of this heuristic method is that small variations of the determining variables must lead to small changes in the evaluation of the fitness function. This method has been applied to the fitting of measured load data on the Brennerhighway [14].

In order to link measured data to the limits given by the design, limit state function for monitoring shall also be described and actual safety indices shall be finally computed. An ultimate limit state for durability should also be introduced.

Fig. 6 synthetically describes the process of comparing measured and analytical behaviours.

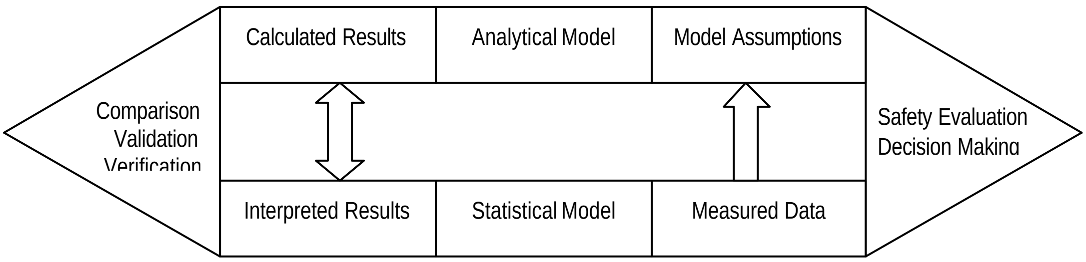

Fig. 6: Comparison of analytical and measured behaviour

5. Conclusions

Monitoring of new and existing structures is one of the essential tools for a modern and efficient management of the infrastructure network. Sensors are the first building block in the monitoring chain and are responsible for the accuracy and reliability of the data. In the recent years, fibre optic sensors have moved the first steps in structural monitoring and in particular in civil engineering. Different sensing technologies have emerged and quite a few have evolved into commercial

products. The applications of fibre optic sensors shown by the case studies presented in the paper demonstrate that this technology is now sufficiently mature for a routine use, especially in a severe environment, and that it can compete as a peer with conventional instrumentation.
Recent advances in sensing technologies and material/structure damage characterisation combined with current developments in computations and communications have also resulted in significant developments in diagnostic technologies for monitoring the integrity of and for the detection of damages of structures.

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