Global Monitoring Concepts for Bridges

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ABSTRACT

Knowledge of the integrity of in-service structures on a continuous time basis is an ultimate objective for owners and maintenance authorities. The development of a life extension and/or replacement strategy for highway structures is a crucial point in an effective bridge management system. A key component of such a bridge management system is a means of surveillance techniques and determining the condition of an existing structure within the normative and budgetary constraints. Recent advances in sensing technologies and material/structure damage characterization combined with current developments in computations and communications have resulted in a significant interest in developing diagnostic technologies for monitoring the integrity of and for the detection of damages of structures. 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.

Keywords: Structural Health Monitoring, Field Instrumentation and Data Acquisition, System Modeling and Analysis, Serviceability and Reliability, Assessment and Safety Evaluation

1. INTRODUCTION

Over the years of civilization, the inventory of civil infrastructure systems has been accumulating in developed countries, especially in the last decades of our century. The performance of many of these in-service structures has decayed and the inherent level of safety can be shown to be inadequate relative to current design documents. After years of maintenance-free operation, owners and maintenance authorities require rational decision criteria to assign the budgets for maintenance and repair. In a world where public safety is paramount and the financial and other consequences of failure are great, an effective management system for civil infrastructures is a crucial point in the development of a life extension and replacement strategy. The fundamental of structural integrity and durability aspects is to develop continuous monitoring concepts for structural components and for the global behavior[14]. A structure is said to have general structural integrity if localized damage does not lead to widespread collapse. Structural integrity has to be guaranteed by the structural safety under ultimate and serviceability conditions and by ductility as well as redundancy of load paths. So far, the most commonly applied concept of maintenance included the periodical inspection which usually starts with a visual inspection. The advances in today's transducer, data acquisition and information technologies allow very complex monitoring and surveillance tasks to be realized with good cost effectiveness[13]. Today we can monitor highly instrumented structures continuously and remotely, at a high degree of automation, versatility and flexibility. Nevertheless, instrumentation is only the start of monitoring field performance. Interpretation of the acquired data and consecutive decision making is equally important.

In the present paper a description of the various measurement methods and their physical principles as well as their application for a global monitoring concept will be described. This includes the observation of deformations as well as environmentally induced processes. Thus we are interested in an adequate instrumentation for the measurement of strains, linear and rotational displacement, slopes, acceleration, etc. Further we have to consider climatic variables like temperature, humidity and wind loads. A central point in our monitoring concept consists in the observation of the chemical parameters[6] in the form of electrochemical potentials, resistivitiy, and penetration processes[5]. The present paper will provide an outline for a global monitoring concept for bridges by the discussion of the different types of measurements that can be made. However,

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an almost complete instrumentation of all imaginable physical phenomena would exceed the reasonable amount of financial efforts. Additionally, a waste 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 safety, serviceability, and durability[19].

2. INSTRUMENTATION

The definition of the objective of the instrumentation program usually follows the realization 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 behavior 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. Instruments can be installed in trouble spots, such as points where it is expected that there will be large stress concentrations or points where it is supposed that deficiencies have already initiated. Alternatively, the instruments can be placed at a number of representative points or zones of the structure[3]. After testing, the taking of the readings and their processing and analysis must be carried out in a systematic, organized way[19].

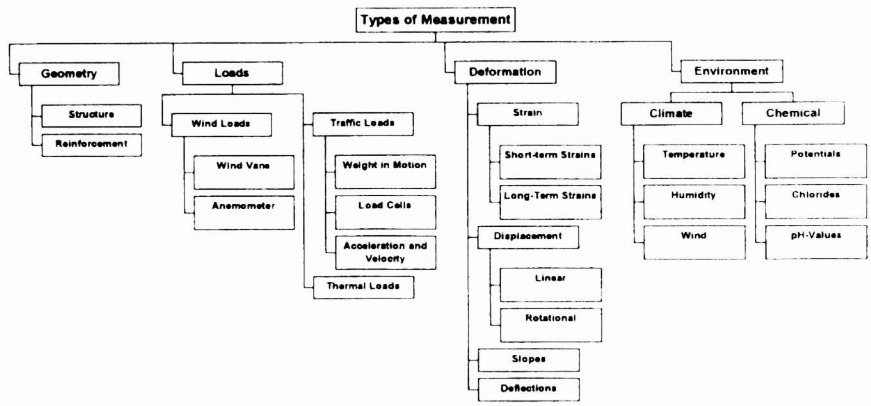


Fig. 1 Hierarchical classification of the different types of measurements

3. MEASUREMENTS

Generally, the different types of measurements that are of interest can be classified in methods that measure geometrical quantities, mechanical, dynamical, and chemical-environmental ones[14] (Fig. 1). But the phenomena that occur on a structure like a bridge and resulting failures are not always the same and depend on the function and type of structure of the bridge as well as on the used materials. This and the environmental conditions have to be considered when planning the instrumentation of a monitoring system. In the following sections we will describe the several types of measurements that are useful in the field of bridge monitoring and that can be performed by common transducers for which the technology is well established[9]. However, apart from the transducers discussed in this paper, there may exist a variety of other devices that find use in engineering practice[8]. To give the reader some vivid idea of our work, we will shortly discuss some implementation issues related to the health monitoring project of the Colle d'Isarco viaduct on the Italian Brenner-Highway A22, which is currently going to be ready for full operation[13]. 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. 2. 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. This large dimensions require a measurement system that is able to collect widely distributed sensing units.

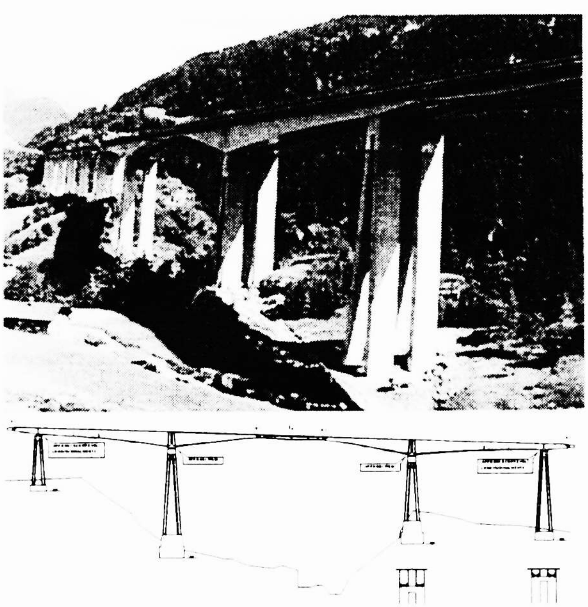
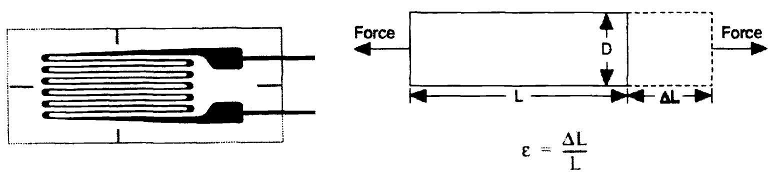


Fig. 2 Monitored section of the viaduct on the A22

3.1 Deformation and Displacement Measurements

When forces are applied to a structure, the components of the structure change slightly in their dimensions and are said to be strained and they may even underlie a certain translational or rotational displacement. Creep, shrinkage, and seasonal temperature changes may result in overall length changes of a bridge or components of a bridge. In order to compare this effects with calculated length changes it is necessary to measure this quantities. The measurement of deformation can be approached either from the material or from the structural point of view[3]. On the one hand, observation of local material properties made by a series of short base-length strain sensors can be extrapolated to the global behavior of the whole structure. If some a-priori knowledge about the most interesting and representative locations to be analyzed is available, it can be assumed that the rest of structure or parts of it will behave in a similar way. Strain gauges provide the technical basis for common systems to measure the motion of solid-body systems and the determination of applied forces. In the past, the electrical resistance gauge[9] was the most common and reliable transducer for these measurements (Fig. 3). When pulled or compressed, a metal wire changes its electrical resistance as a result of change of its length L, its cross-section and its specific resistivity ρ. The relative change of resistance ΔR referred to the basic resistance R is proportional to the strain ε, where ν is the Poisson's ratio, and GF the gauge factor of the sensor. Equation (1) describes the relationship between the change in resistance of the wire, strain, and the change in resistivity of the wire:



$$GF \cdot \varepsilon = \frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L}(1 + 2\nu) \qquad (1)$$

Fig. 3 Foil strain gauge and strain gauge equation

While metallic foil strain gauges are widely used, strain gauges can also be constructed from semiconductor materials. Semiconductor strain gauges, which are also used as sensing elements in pressure and acceleration transducers, have the advantage of a higher gauge factor than foil gauges. As the technology for this type of sensor is well established and as there exists a vaste number of different configurations (single gauges, rectangular rosettes, equiangular rosettes, quarter-, half- and full-bridge configuration, etc.), we will not discuss this sensor in detail. At least it should be said, that due to their low-level outputs and the inherent sensitivity to electrical noise, these types of sensing elements require appropriate signal conditioning such as excitation, amplification, filtering, etc. In combination with fiber optical strain sensors[2], electrical resistance strain gauges were applied on the Colle d'Isarco viaduct[13] for the instrumentation of the reinforcement and the prestressing cables.

Recent advances in fiber optic technologies led Bragg grating[22] and Fabry-Perot strain sensors to become an alternative to classical resistance gauges. These sensors are widely immune against rough environmental conditions and show good long-term performance. A widely distributed fiber optic sensor technology is the in-fiber Bragg grating technology, where a permanent periodic modulation of the refractive index in the core of a photosensitive optical fiber can be produced by transverse illumination with an interference pattern created by a pair of strong UV beams. This creates a Bragg grating in the core of the optical fiber, which acts essentially as a wavelength selective mirror. By means of its strain and temperature sensitivity, the in-fiber Bragg grating (Fig. 4) is an effective sensor for many applications. One of the most challenging tasks in the adaptation of fiber optic sensing technology for engineering applications is the production of durable and consistent sensors at a reasonable cost. The fiber optic grating acts as a wavelength selective mirror for incoming light. The reflected portion of the light consists of a narrow spectral band while remainder is simply transmitted through the grating[22] (Fig. 4). The transmitted light is simply lost or, as e.g. in serial multiplexing schemes, it is used to interrogate gratings further long in the fiber. The center wavelength λ_0 of the reflected spectral band is defined by the Bragg condition (2). Fiber optic grating sensor response arises from two sources, namely the induced change in pitch length (Λ) of the effective core refractive index (n_{eff}). The sensor response can be described by the linear relation (3):

$$\lambda_0 = 2 \cdot n_{eff} \cdot \Lambda \qquad (2)$$

$$\frac{\Delta\lambda}{\lambda_0} = (1 - \frac{n_{eff}^2}{2} \cdot \rho_{12}) \cdot \varepsilon_1 - \frac{n_{eff}^2}{2} \cdot (\rho_{11} \cdot \varepsilon_2 + \rho_{11} \cdot \varepsilon_3) \cdot \beta \cdot \Delta T \qquad (3)$$

In this relation ε_1 is the axial strain, and ε_2 and ε_3 are the principal strains in the cross sectional plane at the core of the optical fiber. Together with the temperature change ΔT and wavelength shift Δλ, these represent excursions from a reference condition corresponding to the center wavelength λ_0. The photoelastic coefficients ρ_{11} and ρ_{12} represent the elasto-optic effect and are commonly taken as ρ_{11} = 0.113 and ρ_{12} = 0.252 although they are known to vary somewhat with fiber type. The coefficient β is the sum of both the thermo-optic component and the thermal expansivity of the optical fiber and has the nominal value $6 \cdot 10^{-6}/°C$. For practical purposes the fiber grating sensor response is well represented by the simplified expression (4), wherein the strain gauge factor GF is introduced. Further compensation for the thermal apparent strain contribution by the host material can be performed. These sensors are available with gauge lengths between 2 and 20 mm, or in an extensometer configuration for greater lengths. However, such sensors can only be used in combination with special readout units and are still quite cost-intensive.

$$\frac{\Delta\lambda}{\lambda_0} = GF \cdot \varepsilon_1 + \beta \cdot \Delta T \qquad (4)$$

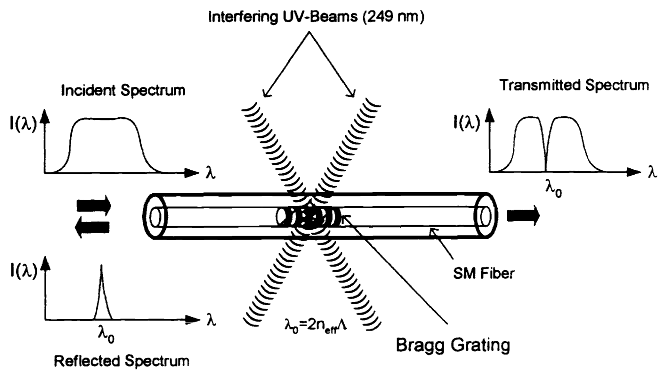


Fig. 4 Bragg Grating fabrication technique and operation principle

Another approach is to observe the structure from a geometrical point of view[3]. In this case the use of long base-length sensors allows to gain information about the deformations of the whole structure or parts of it. While strain sensors are usually used for material monitoring rather than structural monitoring, long-gauge sensors give information on the behavior and response of structure. Material degradation like cracking are only detected when they have an impact on the form of the structure. Further, longer base-lengths help to reduce misleading measurements stemming from material inhomogenities.

A good representative of long base-length fiber optic sensors is the SOFO measurement technique developed by Inaudi et. Al.[1,2] .This measuring system is based on the principle of low-coherence interferometry. The infrared emission of a light emitting diode is launched into a standard single mode fiber and directed, through a coupler, towards two fibers mounted on or embedded in the structure to be monitored (Fig. 5). The measurement fiber is in mechanical contact with the structure itself and will therefore follow its deformations in both elongation and shortening. The second fiber, called reference fiber, is installed free in the same pipe. Mirrors, placed at the end of both fibers, reflect the light back to the coupler which recombines the two beams and directs them towards the analyzer. This is also made of two fiber lines and can introduce a well known path difference between them by means of a mobile mirror. On moving this mirror, a modulated signal is obtained on the photodiode only when the length difference between the fibers in the analyzer compensates the length difference between the fibers in the structure to better than the coherence length of the source. Each measurement gives a new compensation position reflecting the deformation undergone by the structure relatively to the previous measurement points. The readout unit can therefore be disconnected and used to monitor other fiber sensors and other structures. This type of sensor allows active measurement lengths in the range of 0,25 to 10 m with a sensitivity of 2 microns. Common to most fiber optic sensors is the insensitivity to temperature, humidity, vibrations, corrosion, and electromagnetic fields. Additionally, this sensors are easy and fast to install, embeddable in concrete, mortars, surface mountable on concrete, metallic or timber structures.

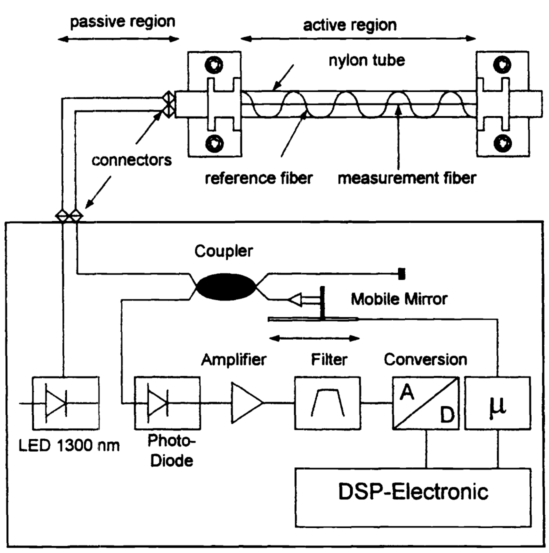


Fig. 5 Low coherence interferometry sensor SOFO™, SMARTEC

Another family of sensors to measure deformations and displacement are vibrating wire transducers[8]. A length of piano wire held in tension will vibrate at its natural frequency, when plucked. Small relative movements of the end fixings cause changes in the measured frequency. Vibrating wire transducers pluck the strain gauge and return a frequency signal to a readout unit where the signal is converted to units of microstrain or period. This sensors usually incorporate a temperature sensor, which supplies data for temperature compensation. Gauge lengths from 50 to 250 mm are commercially available with a measurement range greater than 3000 $\mu\varepsilon$ and a resolution better than 1 $\mu\varepsilon$. Equation (5) describes the fundamental operation principle of vibration wire transducers. F denotes the force in the wire, L the length between the supports, f the modal frequency, μ the mass per unit length of the cable, n the mode number, and g the acceleration due to gravity.

Since the force in the wire can be expressed as a function of the strain, we can obtain strain as a function of the modal frequency of vibration of the wire. Finally, the most common devices for measurement of linear and angular displacement are electrical transducers such as linear potentiometers, and linear and rotary variable differential transducers[8] (LVDT). On the Colle d'Isarco viaduct 16 LVDTs were installed to measure both bearing movements and crack growth.

$$F = \frac{4L^2 f^2 \mu}{ng} \qquad (5)$$

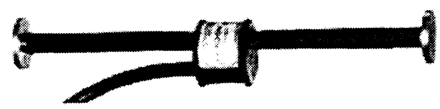


Fig. 6 Typical vibrating wire strain gauge

Apart from the use of transducers to measure the motion and the strain of a body it is a central point to have temperature measurements and temperature compensation when either the transducer or the physical behavior of the structure is sensitive to changes in temperature. Beside the two traditional electric output devices for measuring temperatures, thermocouples and resistance temperature detectors (RTDs), there exist a number of semiconductor and fiber optic devices that find applications in the measurement of temperature. Thermocouples (Fig. 7) are very rugged and inexpensive and can operate over a wide temperature range. A thermocouple is created whenever two dissimilar metals touch and the contact point produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as Seebek voltage[8]. A resistance temperature detector (Fig. 8) is a device whose resistance increases with temperature. An RTD consists of a wire coil or deposited film of pure metal. RTDs can be made of different metals and have different resistances, but the most popular RTD is platinum and has a nominal resistance of 100 Ω at 0°C. RTDs are known for their excellent accuracy over a wide temperature range[9].

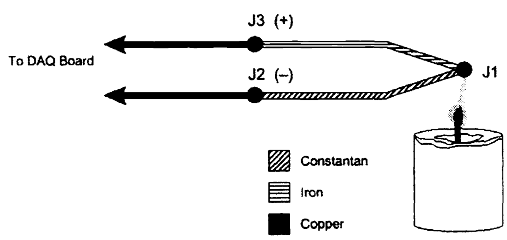


Fig. 7 J-type thermocouple

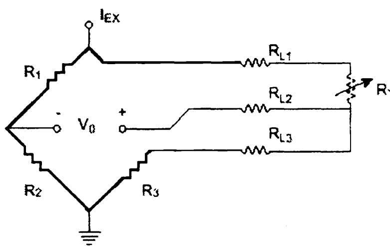


Fig. 8 Three-wire RTD in a Wheatstone configuration

The measurement of vertical deflections of long-span girders is a task for which no simple method or sensing unit exists. Current methods to measure deflections, such as e.g. triangulation, hydrostatic leveling, laser-based leveling, differential GPS, etc., are often tedious to install and require an accurate elaboration. The determination of deflection by the use of displacement transducers requires a stable accessible reference location for each measurement and is, for most bridges, not practical. However, results can be achieved by measuring the deflection at various points along the span relative to the ends of the girder. A more suitable method is described by Vurpillot et. Al.[1], where the vertical displacement and curvature profile can be measured by the use of a network of fiber optic deformation sensors placed on the structure. This approach was applied on the Colle d'Isarco viaduct, where 96 fiber optic SOFO-Sensors[2] with a measurement length of 10 m were installed parallel to the neutral axis of 4 box girders in order to determine the vertical, horizontal, and torsional deformations. Another 24 sensors of this type were installed on 2 piles of the bridge.

Another approach is to install a number of highly accurate inclinometers at selected points on the structure to determine the long-term deformations[17]. The changes in slope can be measured with tiltmeters or inclinometers[1,17]. There exist two types of tiltmeters. Biaxial tiltmeters measure rotations in two orthogonal directions, typically ranging from 0,5° to 80° with an accuracy from < 0,00001° to < 0,01°. Uniaxial tiltmeters are sensitive to only one direction. This sensing devices can be used for both short-term and long-term measurements. In order to compare this approach with the fiber optical sensor network as described above, 36 LCF-100-14.5 inclinometers from WPI-Instruments were installed on selected points of the monitored box girders. In any case, when monitoring deflections, it is important to remember that temperature gradients can have a large effect on camber changes. For this purpose, all deformation measurements should be taken just before sunrise when the temperature gradient is a minimum. To determine the temperature gradients and to compensate temperature influences on measurements, we installed 120 T-type thermocouples on the monitored structure[13].

On the Colle d'Isarco viaduct we renounced to measure the slip of strands at the ends of the girders, however we will shortly discuss one concept in this section. A small channel-shaped fixture can be attached to a strand at the end of the member. To measure the distance from the outer leg of the fixture to the concrete surface a digital depth gauge or caliper can be installed. Changes in the distance correspond to strand slip. Strand slip can be measured at detensioning, during the subsequent life of the girder, and during load tests.

3.1.1 Short-term and Long-term strains

When measuring deformations and strains it makes sense to differentiate short-term and long-term strains[14]. Short-term strains are those changes that can be observed over a period of hours whereas long-term strains are those occurring over months or years. Short-term strains are generally caused by changes in dead and live loads, daily temperature cycles, or wind loading. Long-term strains are caused by seasonal temperature changes and creep and shrinkage in concrete structures. Short-term strains can be measured using the different short base-length sensing devices presented in the previous paragraphs. Although these gauges can be mounted on the structures surface or attached directly to reinforcing steel in the field, the installation under field conditions might be quite difficult. Consequently, the gauges should be attached to separate lengths of reinforcement. This allows the gauges to be attached to the bars under laboratory conditions and permits proper attachment of leads and waterproofing. The gauged bars can be tied directly to the reinforcement cage. Electrical resistance strain gauges can be applied to hardened concrete surfaces. Depending on the character of a material surface, special techniques are needed to prepare the surface prior to application of the gauges. Weldable electrical resistance strain gauges are available for use on steel structures and large size reinforcing bars. These gauges are produced with leads and waterproofing attached and only require spot welding to the steel. However, the installation issues as described in this section do not only apply to electrical resistance gauges, the use of other types of sensors may prescribe other installation considerations.

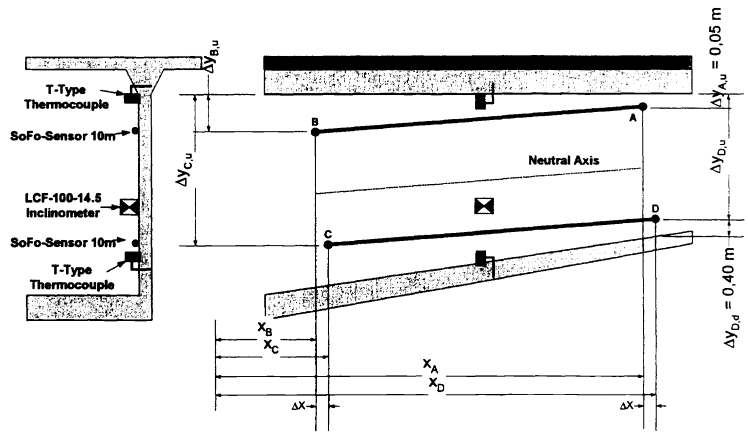


Fig. 9 Instrumented section of a girder box

Measuring long-term strains should be done with gauges designed specifically for this purpose. While electrical resistance gauges may not be recommended for this purpose, there exist other gauge technologies that are designed to have long-term stability, are robust for installation on site, and are provided with leads already attached. The gauges can be either installed directly in the structure or by casting them in concrete blocks and then cast the blocks in the concrete structure. The latter method is discussed because doubts about the effect of differential creep and shrinkage between the block and the concrete.

Long-term strain measurements are generally used to determine prestress losses. For this purpose, when positioning the gauges, it is necessary to consider the distribution of the prestressing forces. The determination of prestressing forces prior to transfer can be measured with load cells by positioning them on the strands at either the dead end or jacking end in the prestressing bed. Although calibrated hydraulic jacks are used to stress strands, they only provide the force before their release. For pretensioned members, load cells provide the force after release of the jack, during curing, and immediately prior to detensioning of the strand. Load cells may also be used on the ends of unbonded post-tensioning tendons and stay cables to measure the changes of force with time. Load cells are available as stock items from several manufacturers[9].

3.2 Load Measurements

While the dead load can be considered constant over the whole life time of a bridge, the traffic load may vary over this period. Beside static loading tests and the measurement of resulting deformations, a commonly accepted concept, we are interested in the characterization of the overall traffic loads. The continuous collection of traffic loads on bridges by a state of the art equipment enables us to classify load events into various categories (e.g. vehicle classes) and to compare them with available regulations and requirements. On the Brennerhighway, a system to acquire traffic loads is installed in the immediate neighborhood of the monitored Colle d'Isarco viaduct. A system description and a probabilistic concept to describe traffic loads and their effects to a bridge from acquired axle-load data on the Brennerhighway (Fig. 17) can be found in Bogath[10]. The measuring device is based on a monomer optical fiber. This fiber is double refractive, uncovered and lies between two metal strips which are weld together. If the sensor is loaded with a transversal force, the optical quality changes. The reason is the photoelastic characteristic of the fiber core and the surrounding material. Fig. 10 shows the layer structure of the sensor. This system has shown for several years to be reliable and will soon be integrated in the present monitoring project. A second approach to determine dynamic traffic loads could be the instrumentation of the bearings with load cells. For the determination of wind load and its intensity and direction an anemometer and a wind vane should be installed. The used WAA151 (Fig. 11) manufactured by VAISALA is a fast response, low-threshold anemometer. In the cup wheel it has three light weight conical cups providing good linearity over the entire operating range, from 0,4 up to 75 m/sec. Rotated by the wind, a chopper disc attached to the cup wheel's shaft cuts an infrared light beam 14 times per revolution, generating a pulse output from a phototransistor. This output pulse rate can be regarded directly proportional to wind speed. A heat element in the shaft tunnel keeps the bearings above the freezing level in cold climates. Optionally, this sensor can provide standard 0 to 5V signals as well. Temperature load and temperature gradients can be determined as already discussed in 3.1.1.

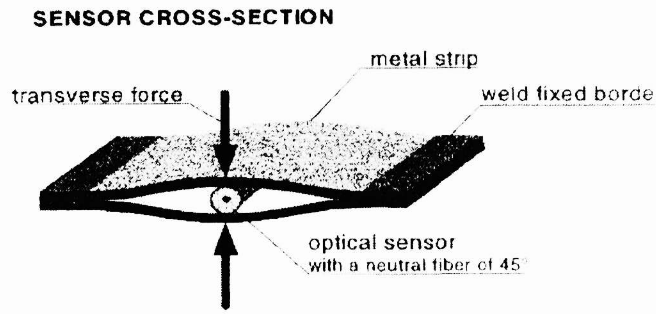


Fig. 10 Fiber optic 'Weight in Motion'- sensor


Fig. 11 Anemometer

3.3 Dynamic measurements

Dynamic measurements help to get information on the structural behavior of a bridge and can give indications of possible structural deteriorations and deficiencies. The measurement and subsequent analysis of structural vibration due to excitation loads permits to calculate the natural frequencies and the response behavior of a structure to an excitation. This is useful when identifying structural parameters that most effect the dynamic response and might have to be improved or modified. Increasing excitation at one of the natural frequencies due to growing traffic loads and a simultaneous decrease of structural fitness and damping results in high vibration amplitudes, dynamic stresses and noise levels[11]. The results of dynamic testing are subsequently used to compare the measured response with analytical models.

3.3.1 Forced and ambient vibration test

The system identification of a bridge is essentially achieved by extracting the dynamic characteristics of bridges from vibration data. Depending on the type of excitation that is used to gain a structural response behavior, we can differentiate forced vibration[20] and ambient vibration testing. In the first case, a controlled excitation is obtained by heavy shakers or drop weights. A method that is less cost intensive is the ambient vibration testing, where excitation is obtained by wind- or traffic-loads. Natural frequencies can be estimated by the analysis of averaged normalized power-spectral densities (ANPSD), which basically are obtained by the conversion of the measured acceleration in the time-domain by a Fast Fourier Transformation[11]. Accelerometers to measure vibration typically have ranges from ±2.5g to ±1000g, with an almost infinite resolution and a frequency domain of typically 10 to 1000 Hz. A bridge monitoring system for dynamic measurements can be found in Wenzel[11]. However, frequencies also vary with temperature and other factors and it may be very difficult to separate effects due to damage from other effects. Also damage may not necessarily lead to measurable changes in stiffness, therefore it is important to know the mechanism of damage to correlate changes in stiffness with the damage.

3.4 Electrochemical and Environmental Measurements

Beside the solid mechanical quantities described above, there exist a variety of other physical and chemical processes that take place. As mentioned section 3.1, it might be necessary to measure temperatures, humidity and other electrochemical phenomena. Steel embedded in good quality concrete is protected by the alkalinity of the concrete pore water. However, penetration of aggressive ions, as e.g. chloride from deicing salt or carbonate from acid rain, will destroy the passivation of the embedded steel. In the presence of oxygen and the right humidity level in the concrete, corrosion of the steel will start and develop continuously[15]. Humidity is a measure of the amount of water vapor in air and to measure it might be necessary in combination with a corrosion instrumentation. Water vapor in air affects the density, and humidity measurement is necessary to determine the performance of many systems. Humidity sensors have typical ranges of 20 to 90% relative humidity with an accuracy of ±3% relative humidity[8].

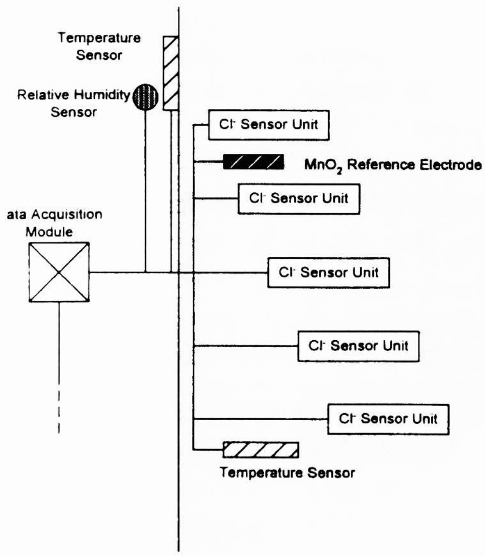


Fig. 12 Corrosion sensor unit[5,6] developed by Zimmermann, Schiegg, Elsener and Böhni

3.4.1 Electrochemical measurements

This category of measurements is based on the electrochemical nature of corrosive processes that is comparable to the anode and cathode principle[5]. Several methods have been developed for detecting and evaluating the effects of steel corrosion in concrete. These methods include visual inspection, chaining or sounding for delamination, pH level determination, potential measurements, polarization techniques, and x-ray spectography. However, many of these methods require concrete cores to be brought into the laboratory for testing. In addition, the laboratory methods require significant technical expertise to perform them. Additionally, the evaluation of the results from many of the tests rely on subjective or statistical interpretations from previously reported tests. Further, different researchers use different methods of testing and evaluating. In most instances no clearly reproducible results may be obtained, therefore an unequivocal comparison of the results may not be possible. Due to the high complexity of the phenomenon, reliable methods of corrosion detection and evaluation have developed slowly[6].

The easiest and most straightforward method for detecting steel corrosion in reinforced and prestressed concrete structures is the visual inspection for rust staining and cracking[11]. Rust stains that follow the line of reinforcement clearly indicate steel corrosion. When corrosion progresses further, cracking of the steel concrete cover occurs. Another approach is the chloride determination, a method that establishes the likelihood as to whether or not corrosion is occurring. The significance of a chloride analysis lies within the spectrum of simply determining that the concentration is sufficient to cause steel to change from a passive to an active corrosion state. Beyond the threshold value of chloride concentration necessary to cause corrosion, the rate of corrosion is a function of many variables, but in particular of moisture content. Therefore, even though a bridge slab may have more chlorides than the threshold value, it may not be in an active state when considering ambient and environmental factors which are necessary for corrosion. Likewise, if a bridge deck is in an active corrosion state, additional amounts of chlorides may have little effect on the corrosion[12].

For an electrochemical mechanism such as galvanic corrosion to occur, there must be a potential difference. Potential methods such as the half cell potential method rely on this known condition for corrosion detection. In particular, the half cell potential method measures voltage gradients or drops by use of a high-impedance voltmeter and a constant voltage reference cell. The reference cell possesses a constant internal voltage, which allows voltage changes existing on the reinforcement to be measured. This method provides both an effective means for determining if corrosion is occurring and the extent of corrosion distress. However, if corrosion has occurred and then was arrested by some means, the method proves ineffective in detecting this. Nevertheless, this method is applicable for members regardless their size or the depth of cover over the reinforcing steel. It can be used in structures which show no visible signs of distress to determine when corrosion initiates, or in a structure which shows sever corrosion distress to determine the extent of corrosion. On one selected pile of the Colle d'Isarco viaduct 12 electrochemical multiprobes (Fig. 12) were installed to determine the concentration of free chlorides, corrosion current and the electrochemical potential at different embedding levels. These multiprobes have been developed by Zimmermann[5], Schiegg, Elsener[6], and Böhni.

Of course there exist many other embeddable multiprobes for corrosion monitoring in concrete structures. Most of them are delivered in a standard version with 1 cathode and a series of anodes. The anodes electrodes are pointing towards the concrete surface, through which the penetration of the aggressive ions will take place. As the anodes are located at different distances from the concrete surface it is possible to monitor the rate of penetration and consequently the progress of corrosion through the depth. The cathode is usually integrated in the mulitprobe body.

4. DATA ACQUISITION

When selecting the architecture and the components of an automated data acquisition system, first the types of sensors and I/O signal types that should be used must be defined[13]. Many types of sensors and signals must be conditioned before connecting them to a data acquisition device. This includes the amplification of low-level signals, the isolation to avoid effects from environmental potentials, and filtering to remove unwanted noise from signals. Additionally, certain sensors often need external excitation. Finally, a linearization due to nonlinear responses of sensors to changes of a physical phenomenon might be necessary. In this context some considerations about the used sensors and their characteristics might be useful for an adequate selection. Often a multiplexing unit is needed for higher channel count. Criteria, such as accuracy, acquisition rates, number of channels, flexibility, reliability, expandability, ruggedness, and computer plattform are used to determine the best DAQ devices for the specific application. Finally, the choice of appropriate device drivers and application and/or programming software closes the cycle of selecting DAQ-components.

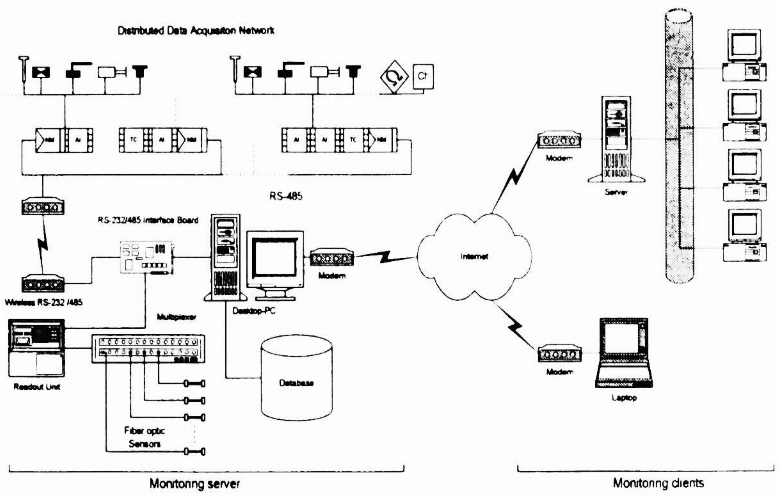


Fig. 13 Instrumentation and communication architecture of the monitoring equipment

In our case, the dimension of the highway bridge to instrument and monitor requires a data acquisition architecture that is able to collect the data of the transducers distributed by big distances over the structure. The proliferation of open, industrial networks has paved the way to move data acquisition and control functions out into the field via intelligent, distributed I/O products with robust network connections. Most of the transducers deliver electrical signals in terms of voltage or current. To collect this signals, RS-485 is a widely accepted industrial network using serial communications for distances up to 1,200 m. We have chosen a product which is is manufactured by the worlds leader in test an measurement technology, the National Instruments™ FieldPoint system (Fig. 14) that consists of three basic components - I/O modules, terminal bases, and network modules. Of course there exist a series of comparable products by other manufacturers on the market that would equally be adapted. A network module connects a bank of analog and digital I/O modules to an industrial network, such as RS-485. With this modular architecture we can mix and match the best combination of I/O modules, terminal base style and network. The latter can either be connected directly to the serial port of a PC (RS-232 network module) or to an add-in RS-485 board. This system provides an economical solution for monitoring and instrumentation applications and can be easily installed and maintained with a high degree of reliability. It includes an extensive fault and error detection, watchdog timers, and programmable power-up and failure mode states. Additionally, its adherence to extreme environmental specifications complies with the rough conditions a bridge monitoring system might be exposed to[13].

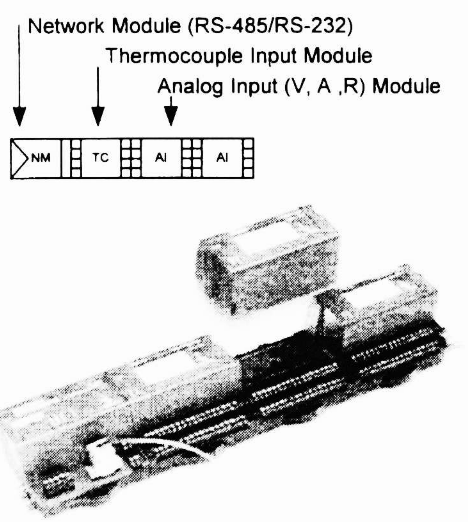


Fig. 14 Distributed data acquisition modules Field Point™, National Instruments

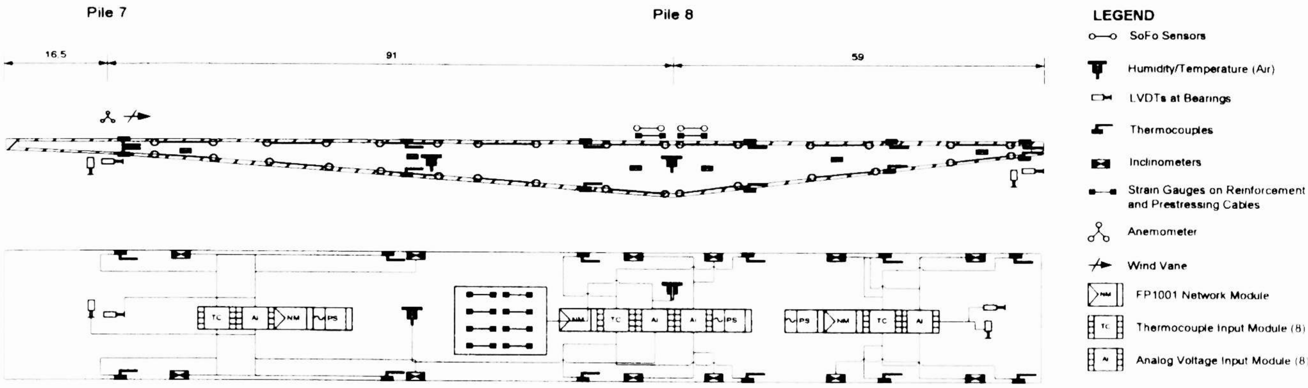


Fig. 15 Partial instrumentation scheme for one girder box

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. When 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, the transfer rates of the modems have to be taken into account when trying to acquire data at higher sampling rates. Finally, the readout-units that control transducers delivering non-standard signals, as e.g., fiber optic devices, vibrating wires, etc., have to be integrated in the data acquisition network via the specified interfaces. The fiber optical SoFo system[2] implemented on the Colle d'Isarco viaduct requires a separated signal processing and can therefore not be integrated directly in the data acquisition system described above. Each sensing fiber 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 appropriate evaluation algorithm[1].

5. ANALYTICAL MODELLING AND STATISTICAL EVALUATION

The installation of sensing elements and of an automated data acquisition system to collect measured data is only the start of monitoring field performance[20]. 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[19]. 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 analyze 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, the response of a virgin bridge 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[19].

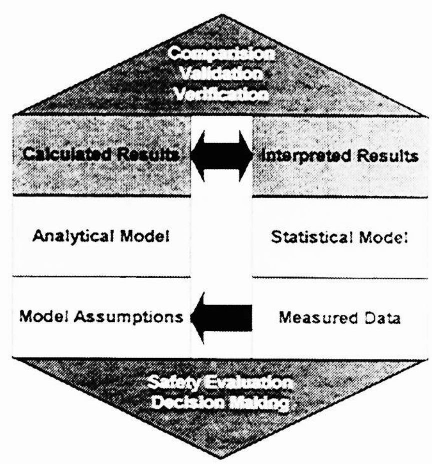


Fig. 16 Comparison of analytical and measured behavior

Measurement processes usually introduce a certain amount of variability or randomness into the results, and this randomness can affect the conclusions drawn from measurements[12]. In the classical approach for a limited quality of data the characteristic value may be based on the 5% fractile. If there is a complete lack of knowledge about the standard deviation, in equation (6) the value k_n has to be taken from the according line of Table 1 for the case that the standard deviation is unknown. If on the other hand the standard deviation is fully known from prior knowledge, the value of k_n has to be taken from line two of Table 1. In the given procedure (6) a normal distribution of the test results is assumed:

Standard deviation	n							
	3	4	6	8	10	20	30	∞
unknown	3,15	2,68	2,34	2,19	2,10	1,93	1,87	1,64
known	2,03	1,98	1,92	1,88	1,86	1,79	1,77	1,64

Table 1 Values of k_n based on a 5% fractile

αβ	P(Φ)	ν							
		2	3	5	7	9	19	29	∞
1,64	0,05	2,92	2,35	2,02	1,89	1,83	1,73	1,70	1,64

Table 2 Values of t_v

m_R mean value of the sample results
k_n coefficient depending on the number of results n
s_R standard deviation of the results
R_k characteristic value of measurement data

$$R_k = m_R \pm k_n \cdot s_R \qquad (6)$$

According to the Bayesian approach, given that a normal distribution of the test results is assumed, the characteristic value can be obtain from equation (7), where t_v is the coefficient of the Student distribution. The value of t_v follows from Table 2, where $\nu = n-1$. The product αβ corresponds to a fractile P(Φ) as indicated in Table 2. It is known that the Bayesian approach is sensitive for the value of the standard deviation, specially if only a small number of test results is available. Too small or too large standard deviations might result into unsafe or uneconomic design values. An advantage of the Bayesian theory is that the prior knowledge can avoid unrealistic design values.

$$Rd = \eta\left(mR \pm tv \cdot sR\sqrt{1+\frac{1}{n}}\right) \qquad (7)$$

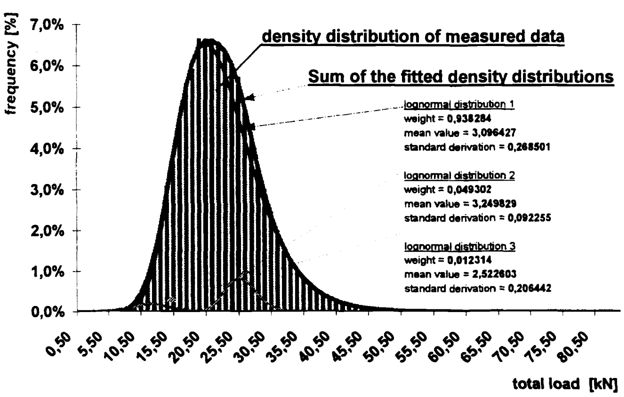


Fig. 17 Real axle load and fitted density functions[10]

In order to find the density function of continuous measured data, the so called evaluation strategy (or genetic algorithms) may be applied[18]. Essentially, test data is 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[10]. An example for the fitting of measured load data on the Brennerhighway is given in Fig. 17.

In order to link the measured data to limits given by thy design, the limit state function for monitoring is described as follows (8):

$$FM\left\{ \text{Monitoring Data} \leq \text{Limits}\begin{cases} \text{Ultimate Limit State} & \text{ULS} & \text{(loads)} \\ \text{Serviceability Limit State} & \text{SLS} & \text{(deformations)} \\ \text{Durability Limit State} & \text{DLS} & \text{(corrosion)} \end{cases} \right\} \qquad \frac{Li \pm mi}{Si} \geq \beta \qquad (8)$$

$$P_f = P[\, F_M(X_1, X_2, ..., X_n, a, b)] \qquad (9)$$

In equation (8) L_i are the limits given at the ULS, SLS, and DLS, m_i are the mean values of monitored data, and S_i is the standard deviation of acquired data. As the limit states have already been applied in the design phase, we have to guarantee that the measured data are in a safe range. Therefore we are interested in some safety indices as proposed in Table 3:

β	P_f	Risk
1,3	$1\cdot10^{-1}$	Small
1,8	$3{,}5\cdot10^{-2}$	Medium
2	$1\cdot10^{-2}$	High

Table 3 Safety indices

6. CONCLUSION

Monitoring the condition of an existing structure helps to ensure the safety of highway bridges with regard to life extension and replacement strategies. In this paper we presented a global monitoring concept discussing the different types of measurements that are of interest and may therefore be applied in the field of bridge monitoring. We also briefly lined out the major sensor technologies that may be used for instrumentation and that found application in the monitoring project on the Colle d'Isarco viaduct on the Italian Brennerhighway. We tried to line out the flexibility, versatility, and cost effectiveness of modern data acquisition and communication components in the field of long-term structural health monitoring. The result of all surveillance activities should be the basis for the condition assessment and the safety evaluation of a bridge. Therefore a comparison and combination of measured and analytically modeled behavior is useful to calibrate and tune the mechanical and numerical model assumptions in order to facilitate analytical prediction. Finally, structural monitoring and analysis should be the basis for decision making support in order to aid maintenance and repair activities.

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