OPTICAL EXPERIMENTAL METHODS AS USEFUL TOOLS IN REMOTE CONTROL AND SUPERVISING LARGE ENGINEERING STRUCTURES

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Abstract

With concern to large engineering structures of high risk-potentials in case of failure or damage the question must be answered, whether only deterministic methods to predict strain and stress states in the design-phase of structures are furtheron are acceptable and sufficient to yield reliable information on safety against failure, hazardous damage, ultimate load capacity and on the service-life of such structures. And it is of increasing importance to control at least periodically, whether changes in utilisation, time-depending response, ageing and fatigue of materials, environmental conditions etc. might affect the structural response as e.g. stability, safety and service-life adversely. Controlling and supervising such structures is of outmost importance not only for safety but for economical reasons also.

Therefore it is necessary to develop respective strategies in order to get truthful knowledge on the behaviour of structures over the whole life-span. Such strategies have to be based on measurements, no matter whether the measurements should be carried out permanently or periodically. Reievant measurement techniques, sensors, transducers, data-recording-, data-evaluation-techniques including techniques for teletransmission of measured signals are available nowadays. However as yet mainly methods of electrical measuring mechanical quantities are used in a variety of combinations. But meanwhile different optical methods are available also, mainly based on coherent light, on optical fiber technique and laser-based tachymetric methods.

Such methods are very useful in long-range monitoring of any kind of structures, being reliable in the long run because they are relative insensitive against external influences. Their resolving power is high, they are applicable in static, dynamic and real-time measurements as well. Data-acquisition and data-transmission is less problematic, their installation is easy and compared to other methods more cost-effective.

An overview on different optical methods will be given, their physical principles will be described as well as their implementation into complex measuring systems. Finally the inverse problem of recalculating the actual structural parameters from measured quantities will be considered.

1. INTRODUCTION

At first it must be asked for the definition of "safety". According to an English dictionary "safety" has been defined as "Avoiding of failure and/or protection against risks". However, this definition seems to be too strictly, possibly misleading because one may draw the conclusion that the notion "safety" might be valid absolutely and every risk could be excluded in contradiction to all experiences, that there will exist residual risks always, no matter how large the "residue" might be. Restricting the considerations on the anthropogeneous risks, especially on technical risks in the sense of safety science, "safety" can be defined as follows: "A technical state or process can be considered as safe, if the risk is smaller than a prescribed acceptable limiting value.

Such a quantitative classification at any rate demands a quantitative conception of risk despite the uncertainty, which sets the limiting values and with which intention and what is the meaning of "acceptable". Therefore, risk will be defined as the product of damage and the probability the damage can occur. Thus the risk concept is materialised by the notion "damage", which anew will be determined by the failure mode of a technical system and the consequences, e.g. whether and how many human beings might be afflicted by a failure.

With concern to large engineering structures of high risk potentials like multistoried buildings, TV-Towers, wide spanned bridges, dams, installations like for instance in power stations and chemical plants, containments of nuclear reactors, tanks etc, the question must be answered whether only deterministic methods for pre-dicting strain and stress in the design phase are sufficient to yield reliable information on the safety against failure and/or damage, ultimate load capacity and on the life span of such structures. Moreover, it must be checked whether changes in the utilization, time-depending response of materials, fatigue, environmental conditions etc. might influence the factor of safety of the structures and their stability respectively.

Furthermore, not only because of safety measures and risk-minimizing but also because of economical reasons assessment of the structure conditions and their monitoring must be considered as of outmost importance. The infrastructure in many countries of the world is ageing. And there is an increasing awareness of the need to assess the severity of the damage occuring to infrastructure. Limited resources preclude the replacement of all structures that need repairs or have exceeded their life times. Methods to assess the amount and severity of failure and damage are crucial to implementing a systematic, cost effective approach to repair and/or replace the damaged structures. The importance of inspection, maintenance and longevity of infrastructure must be underlined explicitly with concern to economics.

The challenges of inspecting ageing structures without impairing their usefulness rely on a variety of technologies and techniques for nondestructive evaluation, the purpose of which is the prevention of potentially costly or destructive consequences from failure of structures. And especially with concern to civil-engineering structures it has been stated "that for too long it has been underinvested in maintaining and renewing them, although it should have been clear the state of physical infrastructure health to be closely linked to the nations economic productivity" [1].

2. GENERAL REFLECTIONS ON MONITORING AND REMOTE CONTROL SYSTEMS [2]

In engineering branches as for instance in automotive- and aircraft industry the structures, designed by means of theoretical/numerical models, are tested very thoroughly in experimental procedures. Thus it is proved whether the project fits to reality before the product is released to be used generally. Measurement techniques and methods of experimental mechanics are playing a decisive role. Besides different instructions for users periodical supervisions are performed during the whole life-span. However on the other hand numerous engineering projects are prototypes as a rule without the possibility of comprehensive transfer of experiences. Each multistoried building, each bridge, each silo works, each dam represents an unique project. Experimental tests are possible at best or practically meaningful to prove the results of theoretical/numerical analysis of separate structural elements or of reduced-in-size "iconic" models only. In structural engineering research such separate tests and parametric studies are carried out to obtain basic information on endurance, fatigue, fracture strength, on phenomena of vibration, on the resistance against environmental influence as the basis of mathematical modelling. Also in the construction phase methods of measurement and testing are of increasing importance to control whether the construction runs according to plan, to guarantee the quality of materials, the reliability of joints. The measured real data and the reactions respectively then are to compare with those layed down in the design. If needed corrections are to undertake. Finally it is necessary to supervise the finished structures or structural systems respectively to observe their response under real utilization (Fig. 1) [3]. Measurements can be applied temporarily to already existing structures in order to obtain information on the real material response considering ageing, on the stress-strain state, on the remaining service-life and thereby the safety relevance of extraordinary influences and changes in utilization, furthermore to prove and control the effectiveness of retro-fitting, of restoration and maintenance measures.

With concern to structures of high damage potential and hazardous risks in case of failure it is necessary to develop systematic control and supervising strategies, which are effective for the whole period of utilization. The behaviour over time of the constructions owing to continuous loading, fatigue, time depending response of material etc. should be recorded in order to detect the beginning of failure or the loss of usability eventually and/or to assess the residual strength and the possible residual life-span too.

With the modem achievements in measurement techniques, measuring instruments and systems, data acquisition and recording, date transmission and far-reaching automated evaluation based on electronic computing remote monitoring - and control - systems can be installed to observe the response and state of even complex structures either permanently or as to time limited. The variety of the measurement methods is large, e.g. different mechanical, electrical, piezoelectrical, optical, acusto-thermo-emission, ultrasonic, radiographic and even satellite-based methods allow statical and dynamical measurements. The choice of the best-fitted methods depends on the respective structure, situation, external conditions, the relevant data to rate the state of the structure and on the finally wanted information.

It is necessary to select the method of measurement as well as the areas and the points respectively where to measure, so that the apparently critical areas are under consideration and data of reliable evidence are obtained. To design a more or less automated control and supervising measuring system a combination of different methods with different sensors have to come into question as a rule (Fig. 2). The originally measured signals are recorded in situ, converted into digital data and then transmitted to a control station for further evaluation.

It can be differentiated between permanent and temporarily (possibly mobile) installation of a measuring system, the latter one as a role for screening already existing, in most cases aged structures (Fig.3).

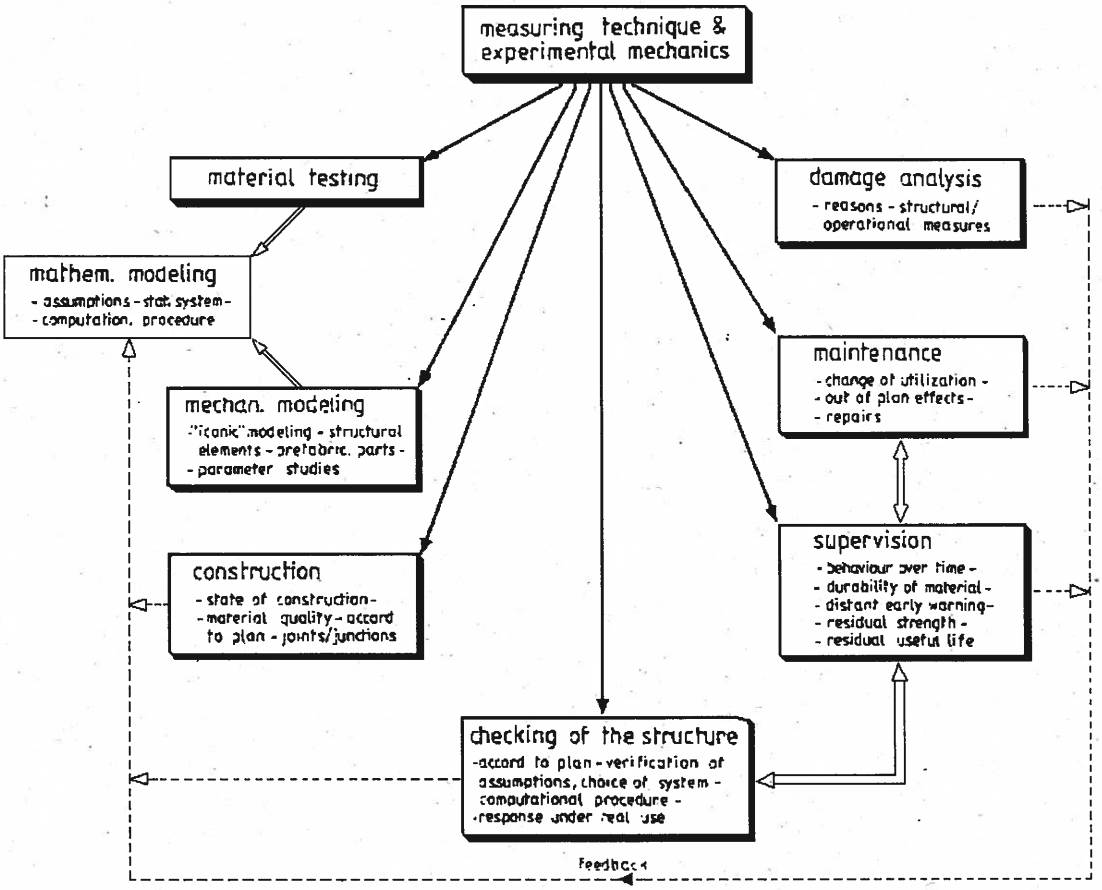

Fig 1 Application of measuring techniques to safety control of risk-sensitive engineering structures

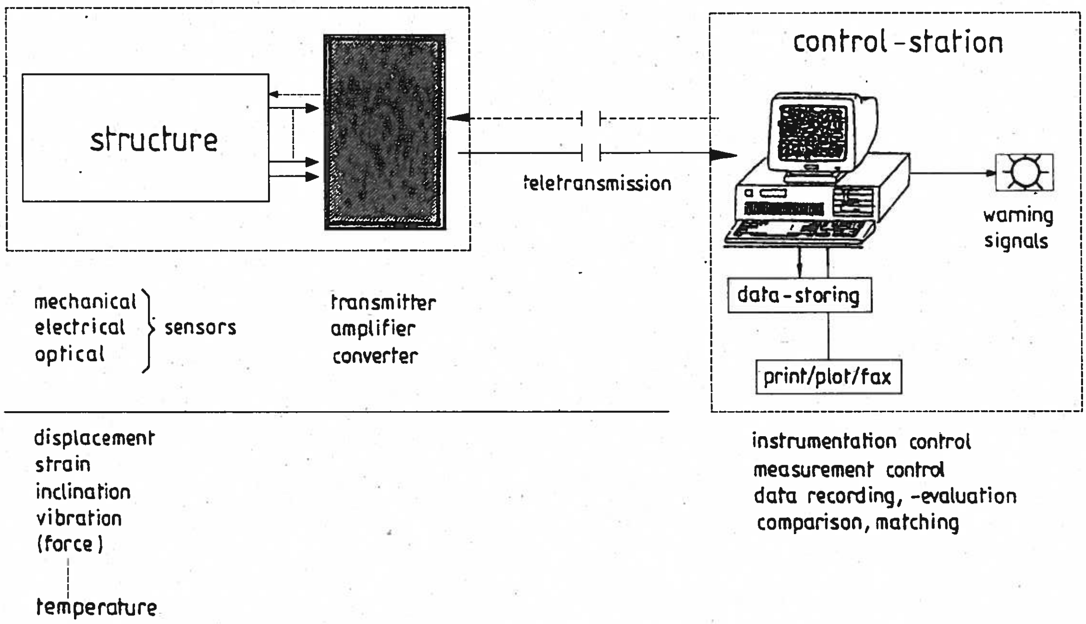

Fig 2 Principle of automated remote control systems

According to the respective purpose of the measurements and with reference to the finally wanted results different possibilities exist to evaluate the originally data, i.e. the originally recorded and digitised optical phenomena (Fig. 4). Proper algorithms are to develop and to translate into computing models to evaluate the observed phenomena, i.e. the originally measured data. The results of evaluation are then to introduce into mathematical/numerical reference models to determine the actual state of the structural stability. If states are detected which endanger stability, direct operational measures can be taken to avert risks and/or decisions may be taken with reference to retro-fitting. Although the amount of measured data might be extremely large the number of points of observation will be restricted generally and will be much less than e.g. the nodal points of the design-model, assumed this to be based on discrete computing methods. Therefore, a reference model must enable gaining response spectra over the whole structure from the evaluated measured data and correlating them to the results of the theoretical design model and perhaps of a simulation model.

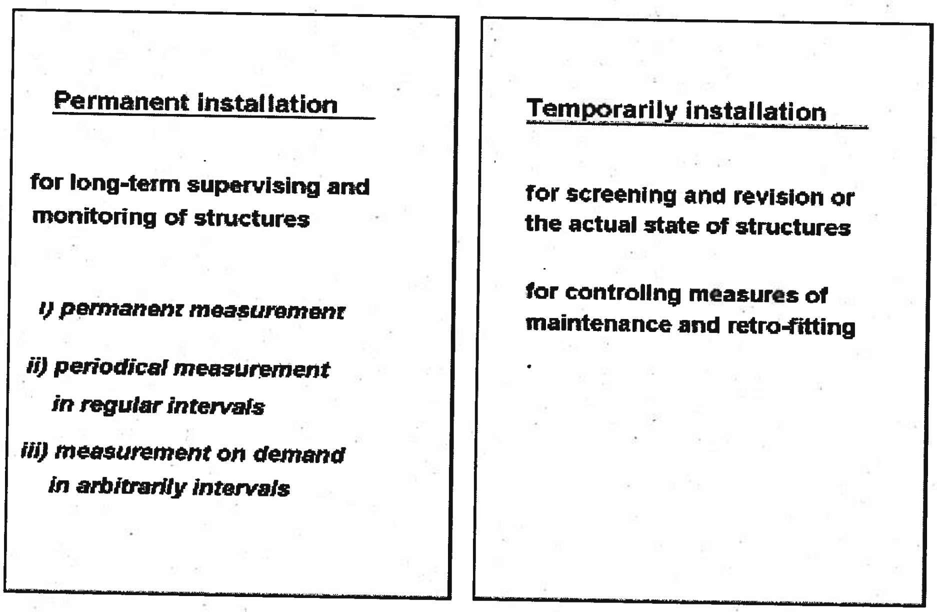

Fig. 3:Permament/temporary installation of remote systems control.

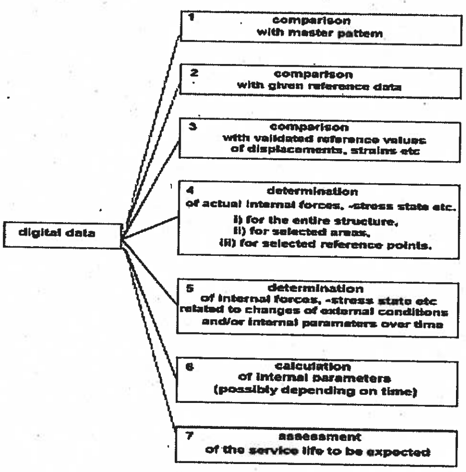

Fig. 4:Different paths to evaluate the optical data

In the following two examples are given of complex measuring systems to control the effectiveness of retro-fitting and to check the carrying capacity and stability at hand.

Because of subsurface erosion some years ago severe damage has occurred at the Reuss-Bridge in Switzerland and the question has been raised, whether the bridge should be renewed completely or could be repaired perhaps. After thorough considerations it has been decided to prefer retro-fitting. An ingenious measuring and supervising system has been worked out and installed (Fig. 5) to control the reconditioning measures and to observe for some years after the reactions of the bridge and its stability. Displacements and forces are measured by different electrical sensors, the signals transmitted to a local measuring station, where the data are recorded and evaluated thus providing reliable information on the response of the structure over the time of observation [4].

At the Baiersdorf-Bridge, a prestressed reinforced concrete structure, crossing the Main-Danubia-channel, considerable defects had been detected, beside other reasons mainly caused by deficient concrete quality, corrosion of the reinforcement, incomplete pressing of injection mortar into the encasing pipes of the prestressed rods. Therefore the responsible authorities had made up their minds to scrutinize the superstructure of the bridge by measuring technique. A very complex system had been worked out, mainly based on different electrical sensors, supplemented by acoustic emission measurements, deflection measurement by means of laser technique and by electric hose-levelling instrumentation. Figure 6 demonstrates the system assembly [5].

The evaluation of the data measured under test loads has proved, that the bridge could be released for utilisation for the originally planned payloads. However, affirmation of the life span to be expected hasn't been possible, hence a permanent observation should be recommended, which requires the installation of a more or less automated remote control system.

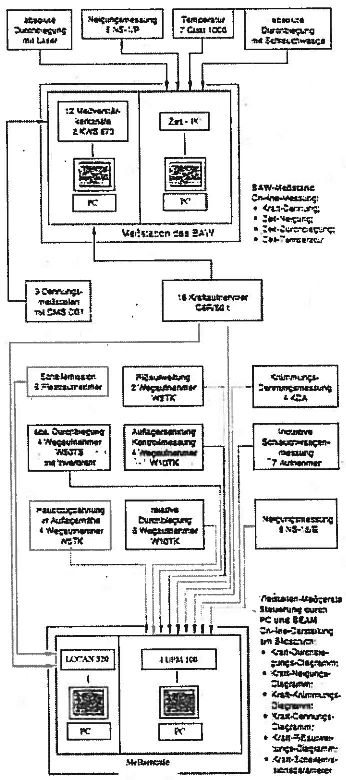

Fig. 6 Baiersdorf-Bridge, bloc-diagram of the measuring and evaluation assembly.

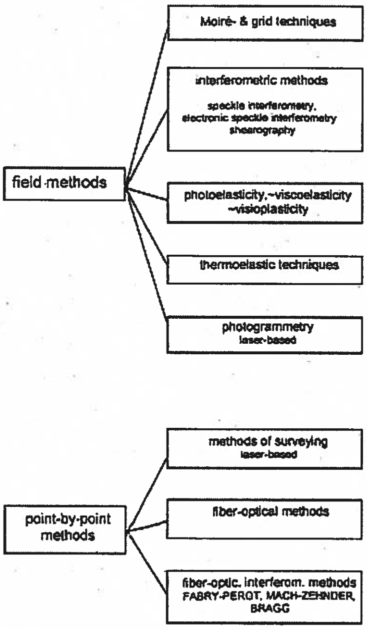

Fig.7: Measurement by field/point-by-point measurement.

3. DEVELOPMENTS IN OPTO-ELECTRICAL MEASUREMENT TECHNIQUES.

Beside the as yet mainly used electrical measurement techniques of mechanical quantities optical methods are applied more and more; they especially are useful in systems of long range monitoring of large structures, being more durable and reliable, because they are relatively insensitive against external influences e.g. temperature, moisture and aging. Furthermore, the resolving power is higher, installation easier, costs are lower and acquisition and transmission of measured data less problematic, they are applicable to real-time measurements too. In principle it can be differentiated between techniques of field measurement and of point-by-point measurement (Fig. 7). In the following some recent achievements in opto-electrical techniques will be reported, which are suitable for monitoring systems, focussing on the measurement of deformations.

3. 1. Position sensitive detector

Displacements, especially deflections, absolute or related to at least two reference points can be measured using one-dimensional arrays of diodes, so-called position sensitive detectors (Fig. 8) [6]. These sensors yield the position of the light intensity maximum with the exactness of one pixel and thus the difference of the displacement between two succeeding states as well as the cumulated values. This method can be used for statical and real-time dynamical measurements as well.

3.2. Optical fiber sensors

Optical fibres, known from communication technologies, are applied with increasing tendency in measurement techniques. Undesired effects in communication technique, i.e. the influence of mechanical strain on the transmitted signals, are explicitly used as sensor effects. Such sensors are suitable in supervising systems to measure small deformations and strain as well as to detect cracks and to observe crack propagation and width.

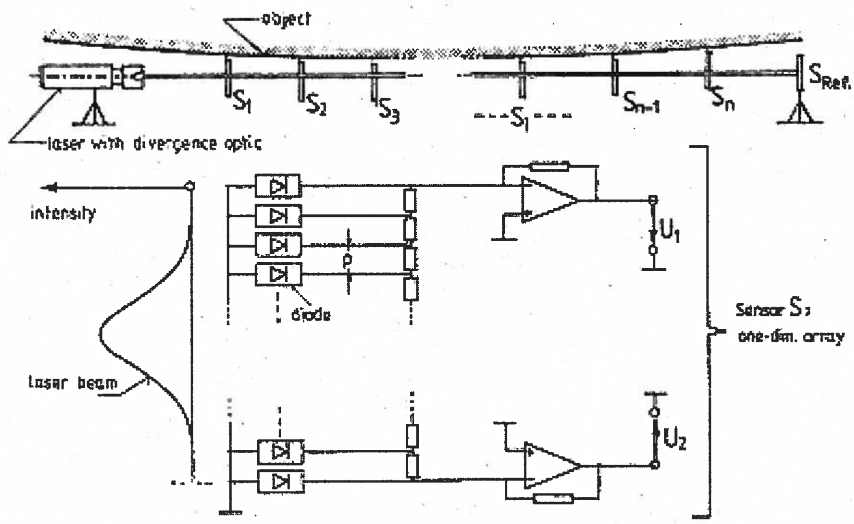

Fig.8: Laserbased deflection measurement by means of Position-Sensitive Diodes.

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As an example Fig. 9 shows a sensor to control the width of cracks. The loss of light-intensity caused by the curvature change of the fibre loops yields permanent information on the changes in the crack opening [7].

Sensors of optical fibres, so-called "optical strings" (Fig. 10) [8], [9] are used to measure displacements under static and dynamic conditions, related to the gauge length L (L<10 m). Such strings consist of some twisted optical fibres. The principle of measurement is based on the amplitude modulation of light by the effect of micro bending; the monochromatic light will be emitted from LED's into the single fiber. Each sensor is calibrated and fixed at both ends to the structure. The optical signals are digitised by an opto-electronic converter and transmitted to a computer system for further utilisation.

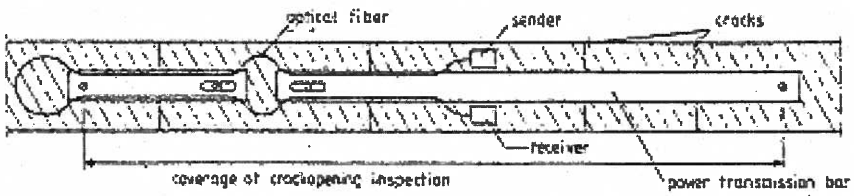


Fig. 9: Crack and crack-opening detecting sensor

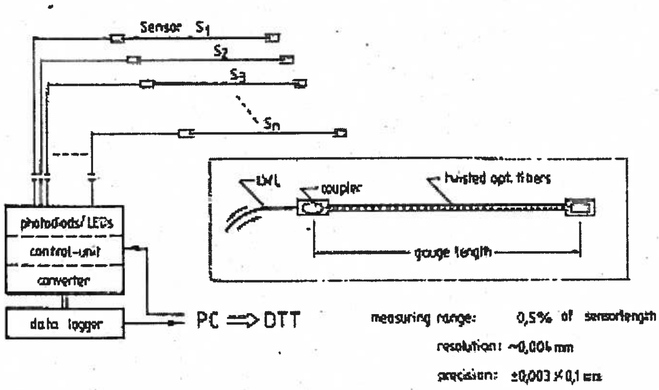


Fig. 10: Method of the "optical string" for displacement/strain measurement.

3.3. MACH-ZEHNDER fiber sensor

In case of strain measurement according to the principle of MACH-ZEHNDER-interferometry two fibers are led parallel across the object, one reference fiber, the other one a sensing fiber, which is applied to the object surface along the gauge length L (L in the range of some millimetres to a few centimetres), and exposed to the strain over L ([10], [11]). A light beam, emitted from a laser or a LED, is split into two parts and injected into the two fibers. The two beams are recombined and made to interfere in what amounts to Young's fringes. These fringes can recorded either by a photodiode or projected to a screen and recorded by a CCD - camera (Fig. 11).

The methods using MICHELSON and polarimetric sensors respectively are almost analogue to the afore described technique [12]

3.4. FABRY-PEROT fiber sensor

Fig.12 shows the principle of strain measurement by an extrinsic interferometric sensor based on FABRY-PEROT interferometry [13], [14]. Two pieces of a monomode optical fiber are bonded in a glass tube, the fiber ends are partially mirrored to provide the necessary reflection for a low finesse FABRY-PEROT cavity. The light reflected from both the mirrors is interfering with each other thus yielding interference fringes. The strain is obtained from the sensor in much the same way as from a MACH-ZEHNDER sensor. However, the relationship between the number of fringes passing and the strain depends only on the wavelength of the light propagating and the gauge length of the sensor. If the cover tube is not connected with the fiber the sensor can be used also

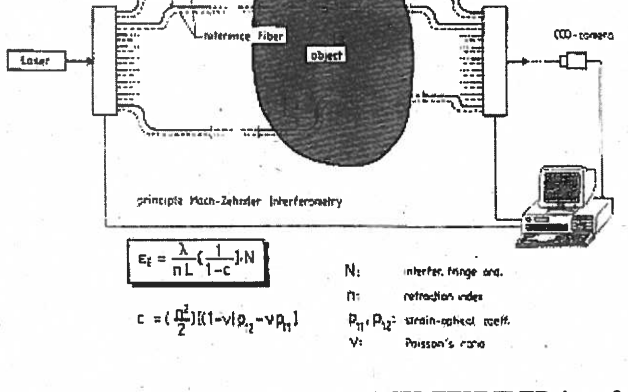
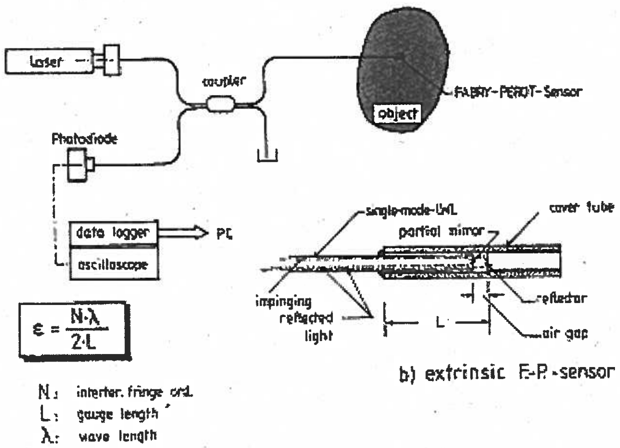


Fig. 11: Strain measurement according to MACH-ZEHNDER-interferometry.

to measure displacements. The small sensors can be embedded inside of structures, even if these consist of soft materials. Special types of such sensors enable measuring strain and displacements inside curing materials and they have been applied already effectively to get information on the process of concrete setting [15], [16].



a) Prinziple of FABRY-PEROT Interferometer

Fig. 12: Strain-measurement with sensors based on FABRY-PEROT-interferometry.

3.5. BRAGG sensors

One of the most promising technologies in fiber optics for strain measurement is based on in-fiber BRAGG-gratings, (17] to [20]. Such gratings are formed on a fiber e.g. by photo printing or "interference-printing" as a series of closely spaced lines along the fiber. They will in turn inhibit the transmission of light at a certain wavelength. Light propagating in the core of an optical fiber containing a BRAGG-grating will be reflected by the periodic variations of the refractive index, which comprise the grating. The centre wavelength, which will be affected by the grating, is proportional to the spacing n. It is possible to "write" many gratings of different spacing Λ_i , hence of different wavelength λ_i, in a single fiber at different locations. The fiber is illuminated with a LED, a broadband light source. The reflected light can be analysed using a spectrum analyser, providing the reflected signal as a function of wavelength, or by a tunable FABRY-PEROT filter, which allows multiplexing of numerous gratings. The centre wavelength and the reflection amplitude are sensitive to the strain of the fiber at the location of the grating (Fig. 13). The strain rate of such BRAGG gratings is limited by the limiting strain of glass; the resolution of the measured values is approximately about one micro strain. The fiber can be embedded into a structure or a structural element, e.g. in a concrete structure before casting the mould or can simply be applied on the surface of an already existing object. It must be mentioned, that there is a certain temperature sensitivity, which has been found to be different for different fiber material and fiber coating. If necessary the influence of temperature can be taken into account [21], (22], however in most cases of application the influence can be neglected.

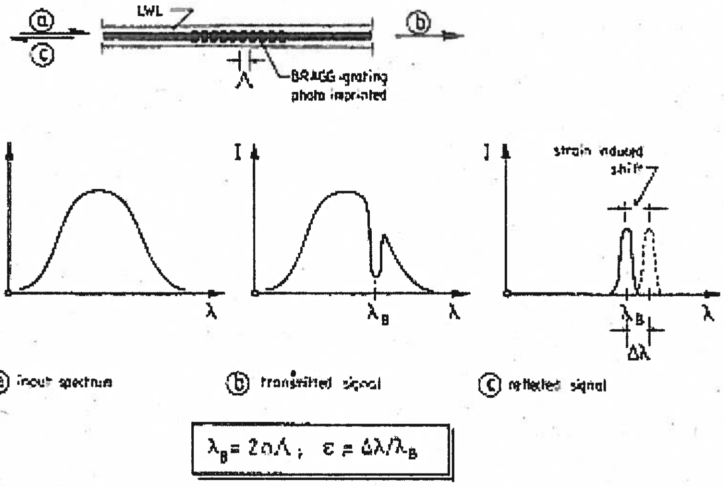


Fig. 13: Principle of strain measurement with optical febres and BRAGG-gratings.

4. OPTICAL FIELD METHODS IN MONITORING SYSTEMS

Also the field methods, (see Fig. 7), like grid-techniques, electronic shearography and electronic speckle interferometry and even photo elasticity [23], well known in experimental mechanics, can be implemented into control-systems, suitable also in real-time measurement.

As an example the principie of how to measure surface deformations, surface strains or how to detect surface cracks the Moiré-technique may be considered [24], [25], [26]. Different methods of this technique can be applied in measuring systems for the inspection of large structures. For that purpose the most practical ones are

i) the intrinsic Moiré or fixed grid technique, in which a grid is attached to selected areas of the object surface. As result the in-plane as well as the out-of-plane displacements are obtained and the formation of cracks can be detected;

ii) the projected Moiré technique, in which a grid is projected on a light diffusing object surface enabling the determination of the surface shape and the out-of-plane displacements. The grid projector and the recording camera are combined in a measuring head (Fig. 14). The images of the grid in the undeformed and the deformed state are recorded by a CCD-camera and

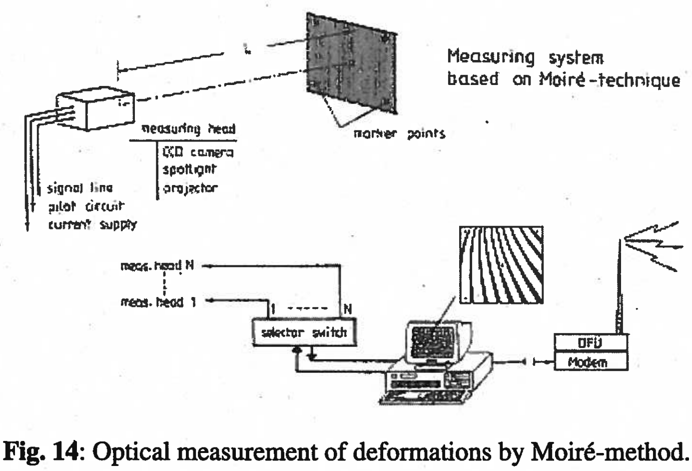


Fig. 14: Optical measurement of deformations by Moiré-method.

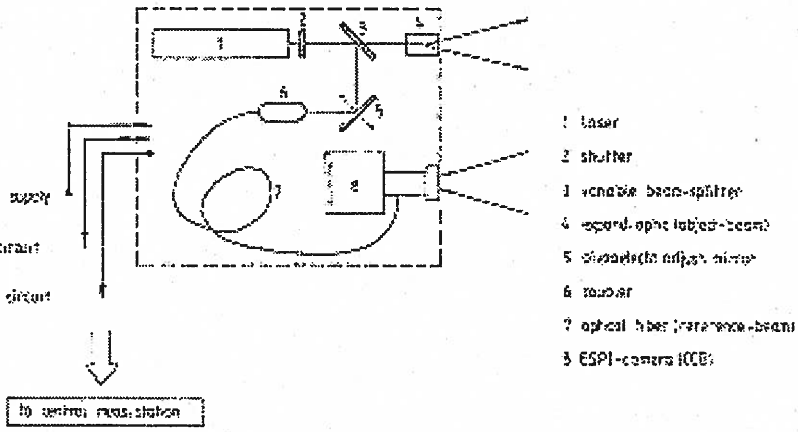


Fig. 15: Principle set-up of a compact measuring unf for shearography.

transferred as digital data separately to the control station and subtracted from each other in the frame grabber, thus yielding the Moiré pattern. The well-known image processing methods including phase shifting are used for further evaluation.

Shearography can be regarded as a "self-referencing" interferometric method, which yields information on the gradients of out-of-plane as well as of in-plane displacements under static and dynamic conditions [27], [28], [29]. The measuring set-up, as in principle shown in Fig. 15, is a quite simple and robust one. Therefore this method fits to in-situ measurements, even under rough environmental conditions. As a result of miniaturisation of light sources and of the electronic recording devices, i.e. CCD-cameras, including the technique of data-teletransmission the costs of the hardware nowadays are reduced remarkably. Because compact shearographical measuring units are already in the markets it could be taken into consideration, to implement several of such compact units in a complex supervising system for large structures together with other sensors depending in each case on the problems of inspection in question.

Similar statements can be made with reference to the method of electronic speckle interferometry.

5. REMARKS ON FINAL EVALUATION AND INTERPRETATION

As the measuring systems for remote control and supervising large engineering structures are comprehensive and very complex, it is of substantial importance not to look at the whole configuration of such a system as a "black box"! To assure reliability of the obtained information the relations between the original in-put signals and the out-put signals must be known, i.e. the flow of energy in the system must be traced very carefully [30]. The real transfer-functions, the impedances, the different signal/noise ratios as well as the extension of the measuring range of the single instruments in the configuration and their relation to one another must be regarded thoroughly. This is necessary to avoid uncontrolled changes or distortions of the original in-put signals (Figs. 16 and 17).

As yet there doesn't exist a technology generally accepted by the constructors to validate and to correct the theoretical models of the design by implementing data measured in reality. However, it is necessary to develop such mathematical/numerical procedures, which enable resulta of monitoring to be taken into account to get reliable information on the state of structure timely. The observed and recorded optical phenomena are evaluated to get information on the

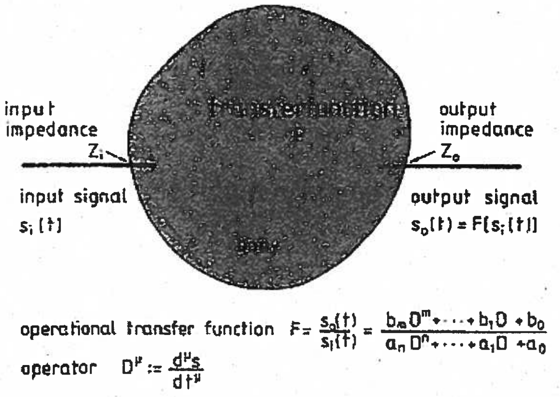


Fig. 16: Operational transfer function

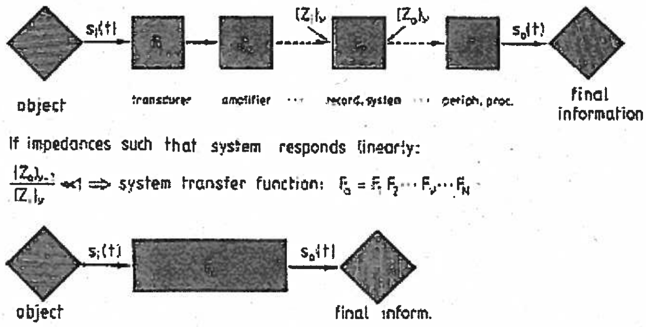


Fig. 17: System transfer function

mechanical quantities, in principle deformations, displacements, strains as well as vibration modes, -frequencies, amplitudes. But these quantities do not meet the finally wanted information, as eg. Information on stresses, internal forces, internal structural parameters with concern to the entire structure. Therefore the "measured" and the "processed" data must run through a further phase of evaluation, which demands proper algorithms to correlation and inversion for trustworthy and unequivocal interpretation of results. This means, that

i) numerous measured data, taken in a restricted number of measuring points, must be related to few calculated design data in numerous nodal reference points of the structure, for instance in the nodal points of a Finite-Element-Grid;

ii) inverse problems must be solved, to calculate causes and internal parameters from the measured effects [31], [32].

It must be pointed out, that as yet there exists a lack in reliable theoretical reference models to correlate the information taken from measurement to the results of the original design models and that it is necessary to derive mathematical/numerical models to solve inverse problems unequivocally.

6. CONCLUSION.

With regard to the necessity to monitor safety, stability and operability of large structures with high risk potentials in case of failure and with regard to the requirements for evaluating the actual stability and the service life of ageing infrastructure because of economical reasons, to take up maintenance measures and retrofitting activities timely and to control their effectiveness, remote control systems must be designed and installed. The modem achievements in measuring techniques, in data acquisition, on-line evaluation and teletransmission techniques are yielding the presupposition.

Some modem optical measurement techniques to measure deformations, displacements and strains in static and dynamic states or at least the principles of which have been presented without laying claim of entire numeration. It should be the aim of this paper to underline the necessity and to give reasons for remote control of large engineering structures as well as giving at least some references to technical possibilities and recent developments.

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