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Paper SHM 2002-001

Health Monitoring of a Long-Span Bridge by a Supervisory Data Acquisition and Control System

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The goal of the paper is to introduce the motivations for health monitoring of long-span bridges, describe the issues and technical challenges that need resolution and formulate long-term research and applications by taking advantage of an example demonstration on Commodore Barry, a long-span bridge spanning the Delaware River.

The principal advantage we expect from the new paradigm of infrastructure health monitoring is to be able to proactively manage the overall structural health of these infrastructures just as in the medical realm. Through diagnostic procedures, deterioration and damage can be detected prior to or at their onset. Timely detection and effective response can be achieved to prevent operational incidents, accidents, and natural hazards from occurring.

Presently, we discover deterioration and damage by visually observing the signs they exhibit only after they progress and take their toll on the structural integrity. In the case of long-span bridges, the effectiveness of visual inspection in reaching all the critical locations and in finding all of the possible defects poses a great deal of uncertainty. The biannual visual inspection of a major bridge such as the Brooklyn Bridge in New York is reported to last for over three months and costs can reach as high as $1 million. Another recent study done by the FHWA revealed that at least 56% of the average Condition Ratings were incorrect with a 95% probability resulting from visual inspection. It follows that if visual inspection was coupled with advanced Health Monitoring techniques there may be a mitigation of these current shortcomings. Such an improvement would motivate bridge owners to take advantage of this paradigm. There are also many other additional incentives for the implementation of infrastructure systems Health Monitoring techniques to current management procedures, which will be discussed in the paper.

It is noted that Health Monitoring requires and deserves its generalized theory and associated guidelines and standard specifications similar to design and construction, in addition to the specifics of the particular infrastructure systems or components that are considered. In general, Health Monitoring of an entire infrastructure's meta-system as opposed to its individual components is more meaningful and desirable, as this will permit an integrated, holistic and optimum management of the entire system's health. However, until a generalized theory is developed and demonstrated, we have considered highway bridges as critical system-wide nodes of the highway transportation system and therefore will focus on component-level Health Monitoring of highway bridges. Presently, there does not exist an apparent association between operational and structural maintenance management of long-span bridges. Health monitoring may serve as a natural integrator of operational and maintenance management.

Writer and his associates have been demonstrating Health Monitoring on both short-span and long-span bridges in Ohio and Pennsylvania in the last two decades. The proposed paper will focus on a demonstration project that has been ongoing on a long-span bridge since 1997. A supervisory control and data acquisition (SCADA) system has been developed with 300 sensors utilizing a high-speed fiber-optic network. The data includes environmental inputs such as wind, temperature, humidity, radiation, etc., traffic through high-speed streaming digital camera images and a weigh-in-motion device, and, bridge movements, tilts, accelerations and strains at critical locations. Both real-time and legacy data are available through the Internet, by taking advantage of a data and information management system.

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Paper SHM 2002-002

Prestressed Concrete Bridge Beam Health Monitoring in Michigan

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Introduction

The first prestressed concrete (PC) I-girder highway bridge was constructed in 1958 in the State of Michigan. A predominant number of the PC I-girder bridges (345 out of a total of 699) was constructed between 1960 and 1970. Bridge management in Michigan is performed using a relational database integrated under a software program called "Pontis". Inventory, operation, inspection and management data is collected in the relational database. According to the inventory data, there are 5902 bridges under the jurisdiction of Michigan's Department of Transportation (MDOT). Out of this total 2632 are prestressed concrete with design types of an I-girder, box girder or spread box girder of which, 699 are PC I-girder bridges. PC box girders are designed for spans up to 43 meters. AASHTO type PC I-girders are also designed for spans up to 32 meters, and a Wisconsin Type I-girder with a depth of 1800 mm can achieve a span of 46 meters using 48 MPa concrete. Furthermore, prestressed concrete girders are now the choice in freeways bridges subjected to severe exposure conditions with I-girders being the most preferred type. In earlier designs the girders were simply supported on neoprene or steel pads with an unshored composite concrete deck having expansion joints between each span. More recently the deck is cast continuously with the approach pads and monolithically with sizable diaphragms over the piers and the abutments. The girder ends are waxed during the casting of the diaphragms, assuming that rotational freedom is provided. On the deck surface, control joints are cut at the inflection point locations in order to prevent cracking. The primary reason for this detail was to eliminate the leaky joint in order to provide a roof over the beam-ends and pier caps for protection from heavy applications of deicing salts.

An earlier study focusing on the condition of Michigan's PC bridges revealed that while most were in fair or better than fair condition, older structures were beginning to show signs of significant deterioration at the ends of the PC beams. Newer structures (less than 20 years old) utilize joint details that help to deter the deterioration as described above. Major concerns observed with older structures included the corrosion of prestressing strands and high chloride concentrations in concrete. It was reported that the deterioration level was influenced by the location of the bridge, traffic volumes, load limits, and de-icing salt usage. The study brought out the need for clear health monitoring guidelines in appraising the vulnerability of the PC I-girder to deterioration. A careful review of 500 PC I-girder inspection reports showed that 110 bridges exhibit cracking, corrosion and delamination at the girder ends within the first meter. A detailed inspection of 20 such bridges constructed between 1964 and 1998 was conducted and their condition documented. Detailed review of the inspection data indicated that the girder-ends are often cracked as early as the time of erection.

The specific goals of this research were to develop a health monitoring procedure for PC I-girder bridges primarily based on visual inspection and to develop/recommend protection and repair techniques corresponding to each state of health. The primary expectation from the health monitoring procedure is to identify the PC I-girders vulnerable to tendon corrosion. The health monitoring procedure is being based on extensive analysis of the Pontis data, a multi-state survey in the US to learn about the experience of other State Highway Agencies, and the detailed field inspection of twenty highway bridges. It is also important to note that the bridge work activities in Michigan are funded under four categories specified as "Capital Scheduled Maintenance (CSM)", "Capital Preventive Maintenance (CPM)", "Rehabilitation (R1)" and "Replacement (R2)". CPM activities are for sustaining the current condition of the bridges, CSM is to address the needs of bridges in fair condition, and R1 and R2 are for improving the condition of the bridges. The health monitoring procedure is needed to designate the condition states compatible with the funding categories. The protection/repair procedure recommendations are currently being developed. These procedures will be based on what is reported in the literature and analytical FE studies of a typical PC I-girder bridge.

Health monitoring and Vulnerability Assessment Recommendations

In Michigan, health monitoring of bridges is based on the visual inspections performed every two years. Inspection is performed on each bridge component. Specifically for PC I-girder bridges, rating and comments are provided for the barriers, expansion joints, deck, stringers, diaphragms, bearings, piers, abutments and the drainage system. The rating is a condition state and assigned for each of the inspected components. At this time, two independent instruments are used in defining the condition state. The first instrument is described in the Michigan Pontis Bridge Inspection Manual and primarily intended for fleet management tasks such as scheduling preventive maintenance. The second instrument is described in the Michigan Structure Inventory and Appraisal Coding Guide, used for National Bridge Inventory System (NBIS inspections) with a primary purpose of safety assessment. Pontis has defined pre-determined assessment criteria for an inspector to follow for assigning a condition state and potential feasible actions. In contrast, the Michigan Structure Inventory and Appraisal Coding Guide allows for greater latitude in assigning condition ratings to a structural element. In a Federal Highway Agency manual (Manual 90) for the training of bridge inspectors, it is required that inspectors rate bridge elements, including prestressed concrete I-beams, as a whole, rather than allowing individual locations of distress to lower an element's rating. However, inspectors are expected to modify the condition rating accordingly if an isolated distress (possibly beam end deterioration) influences the load carrying capacity or serviceability of the element. The NBIS inspection condition rating for a superstructure element, such as a prestressed concrete I-girder, is based on a scale of 0 to 9. However, a uniform damage severity classification is not provided for various concrete distresses and assessment is left to the judgment of the bridge inspector.

The PC I-girder vulnerability was defined based on the distress observed at the girder ends. The primary reason for the girder-end distress was the expansion joint and/or the drainage system failure. As a result the surface water together with dissolved deicing salts drain over the girder ends. With sufficient time deicing salts reach and initiate corrosion of the reinforcement and the tendons. The field inspection performed concentrated on documenting the condition of the beam end for the purposes of developing a health monitoring procedure for the corrosion prone beam-ends. A total of twenty bridges between the ages of 3-40 years were inspected. After reviewing the inspection data consisting of 828 girder ends and an equal number of bearings and sole plates, a pattern of deterioration was identified. Five of the bridges were of more recent vintage incorporating the continuous joint detail cast monolithically with the diaphragm and deck. The behavior of newer bridges is significantly different due to the lack of water infiltration (no leaky joint) and lack of subsequent restraint at the pier and abutment reduce sole plate and tearing corrosion. However, the vertical cracking observed at the abutments is perhaps due to the restraining effect of the end diaphragm. The bridges designed before 1980 are truly simply supported systems with expansion joints over each pier. Over the abutments, the girder ends are encased in diaphragms monolithically cast with the deck and approach slab, except that the girder end with the expansion joint is expected to provide the movement capability. Over the piers, the girders are connected near the ends with partial diaphragms. The partial diaphragms depths are not uniform, always ending above the bottom flange but sometimes extending to the deck.

Currently we are developing detailed analytical models of PC I-girder bridges of typical configurations to develop a clear understanding of the bridge response under the complexities and the variations of the structural system. Using the models, a three dimensional finite element (FE) analysis will be conducted in order to evaluate the restraints imposed on the girders due to the continuous deck and diaphragms. The FE model also includes the concrete barriers located on both sides of the deck surface are often cast with anchor rebars going into the deck.

Utilizing the inspection data, a preliminary vulnerability assessment measure has been developed. The measure is based on the state of girder-end cracking in excess of 0.0025 mm, expansion joint condition, functionality of the bearing pads and the state of corrosion of the sole-plate. The vulnerability can directly be determined from the bi-annual visual inspection reports.

Paper SHM 2002-003

Health Monitoring of Cable-Stayed Bridges Via Modal Intervals Techniques

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This paper deals with the problem of health monitoring of a class of cable-stayed bridges. It is well known that this kind of bridge exhibits complex behavior due to the strong coupling between the translational and torsional modes. Generally speaking, little expertise has been accumulated on the health monitoring of very flexible structures such as cable-stayed bridges and the research has not been extended in depth as it has been done with the buildings. In this sense, the health monitoring of cable-stayed bridges represents a new, challenging, difficult and unique problem not only to the fault detection and diagnosis but also to the structural control community, with many complexities in modeling, control design and implementation.

In this paper, the technique of modal intervals has been applied to the health monitoring of cable-stayed bridges. An interval mathematical model is presented to describe the dynamic behavior of the cable-stayed bridges such that the bounded parametric uncertainties can be taken into account. In this way, the simulation based on the interval model can exhibit the possible real dynamic behavior of the bridge structure under normal circumstance and can give an envelop in which the real dynamics of a cable-stayed bridge will be involved. By using the methodology of modal intervals, it is able to detect and identify the possible structural faults, such as the stiffness weakening, to make the prediction of the future dynamic behavior of the cable-stayed bridge due to the material aging and to find also the bounds of the structural parameters within which the cable-stayed bridge can maintain its satisfactory dynamic behavior. Numerical simulation is done by using a benchmark model based on a cable-stayed bridge that is currently under construction in Cape Girardeau, Missouri, USA, in which appropriate evaluation criteria and real constraints are adopted in terms that are meaningful for cable-stayed bridge structures. The obtained results have verified the effectiveness of the proposed modal intervals based fault diagnosis strategies.

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Paper SHM 2002-004

Development of Smart Monitoring System and Algorithm for the Maintenance of Long-Span Bridges

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This research aims to develop a basic model of smart monitoring system for the maintenance of long-span bridge. This could be possible by setting a database model for restoring the data of the long-span bridge and by studying on the application to the monitoring system for the measurement of the bridges existing and to the general system for the maintenance by using smart monitoring.

On this purpose, a basic model for the construction of the database is suggested based on the case studies of the real monitoring systems applied to some of the existing bridges. In addition, various systems installed for bridges around the world are investigated.

For this study, a basic model for the optimal smart monitoring system should be suggested with an algorithm for the maintenance of long-span bridge. Also, an algorithm and judgement for an abnormal behavior of long-span bridge using response characteristics of monitoring data is founded on the inspection of optical fiber sensor using cyclic response.

To the conclusion, a relationship and a device for the integration between the judgement for an abnormal behavior of long-span bridge with the algorithm could be earned.

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Paper SHM 2002-005

Health Monitoring of Composite Bonded Repairs by using a Novel Bragg Grating Optical Fibre System to Detect Changes in Residual Strains

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With the increasing use of composite bonded repairs to ageing aircraft there is a growing need to monitor the health of these repairs in service. One approach is to incorporate various in-situ health monitoring systems within the repair (ie the 'Smart Patch' Concept). This paper reports on an ongoing collaborative program, between the Australian Defence Science and Technology Organisation (DSTO) and Monash University (as part of the DSTO sponsored Centre of Expertise in Structural Mechanics) which aims to use Bragg grating optical fibre sensors to monitor the thermal residual strain in bonded composite repairs for disbond detection.

In order to optimise embedded fibre Bragg grating strain sensor placement, and therefore Smart Patch performance, research was undertaken to investigate typical distributions of thermal residual strain (TRS) in various geometries on laboratory skin doubler composite bonded repair specimens. A simplified approach to predicting TRS levels and distributions in similar specimens is proposed and validated by numerical and experimental studies. Finite element modeling was undertaken for various geometries of boron epoxy skin doubler repair, and trends in the distribution of stress in the specimens could be observed (as shown in Figure 1), which help to simplify one's understanding of the effect of change of temperature on the residual stress field. This was able to help with sensor placement design for experimental work, which could then target regions of low strain gradient, but high residual stress levels. This approach leads to an ability to quickly approximate the level and distribution of TRS in repairs, which allows optimal placement of surface mounted or embedded optical fibre sensors.

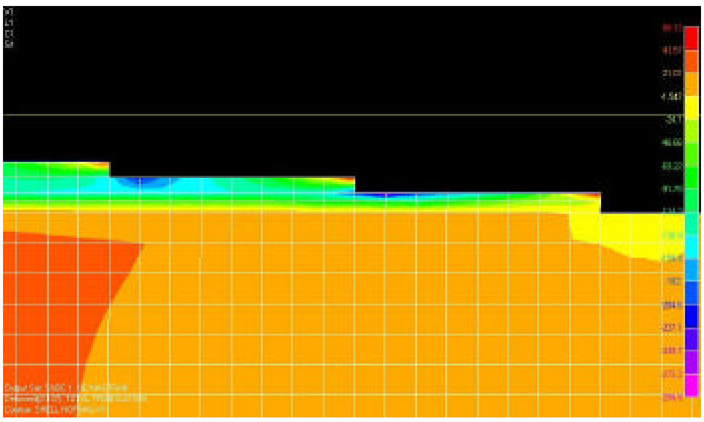

Figure 1: Longitudinal residual stress distribution at the edge of a composite bonded repair.

Experimental work involved both surface mounted and embedded fibres, and results were compared to determine when embedding may provide advantages over surface mounted fibres, particularly in the tapered region. These were further compared with surface mounted strain gauge results, which were located adjacent to the Bragg grating sensors.

Discussion also includes comments on the disadvantages/advantages in embedding the fibre for these repair geometries, compared with surface mounted fibres. While concerns may exist with embedding sensors in repairs this study shows that embedded optical fibre sensors offers enhanced reliability and sensitivity compared to other techniques.

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Paper SHM 2002-006

Bridge Classification Based Upon Ambient Vibration Measurements

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Bridges are essential for the transportation infrastructure of any country. The peak of construction of the European Transportation Infrastructure happened in the 1970s. It is estimated that nowadays 760,000 bridges are serving within the Trans-European Network (TEN) and the primary and secondary road networks. Owners of bridges expect that the critical age where rehabilitation and retrofit works at bridges become essential starts after 30 years of service. Considering the time of construction a huge peak of repair and retrofit investment is expected for the years starting from 2005 onwards. Studies carried out show that the required effort should be more than tripled compared to present values. In times of shrinking budgets, as prevailing now, alternative methods to deal with this problem are necessary.

Therefore different monitoring systems based on the analysis of the dynamic characteristic were developed recently. Owners of concrete bridges require assessment tools for those components which cannot be inspected visually. Brimos provides additional information for the bridge inspector to carry out an accurate assessment of the condition and the remaining lifetime of the bridge.

In the scope of the dynamic tests a classification system is established. This classification was drawn up on the basis of experience gathered from more than 80 assessed bridge structures. The results of artificial damages on real prestressed concrete and reinforced concrete bridges were integrated as an important basis for the establishment of the system. From this classification system the urgency of any required rehabilitation measures can be derived, which enables an optimum control of the existing financial sources with simultaneous maintenance of a maximum safety level for the users. Damaged structures can therefore be identified quickly and cost-effectively.

The intended paper shall demonstrate that ambient vibration monitoring is a powerful tool for the assessment of complex structures and structural elements.

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Paper SHM 2002-008

Damage Detection in Composites by a Wavelet-Coefficient Technique

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The wavelets were used in an active system for the damage detection of aerospace composites. The active system was based on the generation and reception of Lamb waves by two embedded piezoceramic transducers. The wavelets post-processed the Lamb wave response collected by an embedded piezoceramic transducer used as sensor in a composite plate. The wavelets were used to decompose the Lamb wave response into wavelet coefficients. The decomposition performance was improved by utilising more adapted wavelets, based on the recurrent waveforms of Lamb waves. The changes in the Lamb waves meeting with damage in the plate were successfully characterised by this wavelet technique, through the amplitude change of the wavelet coefficients. Besides, this wavelet technique showed great sensitivity in detecting damage of small sizes. This technique was found straightforward for detection of impact damage and evaluation of the damage size.

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Paper SHM 2002-009

Influence of Traffic on Modal Properties of Bridges

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A construction can be identified by vibration measurements, from which are derived the intrinsic properties of the structure like eigenfrequencies and modeshapes. Heavy structures like bridges, buildings and dams, having very low natural frequencies, are difficult to put into vibration. In this case ambient vibrations, caused by wind, traffic, micro-tremors… are generally used. One of the advantages is that normal operation is not disturbed by the measurement.

Substantial damage will affect these properties: so their use for health monitoring is an interesting and intensively explored research topic. However, the measured values do not necessarily return the exact properties of the bridge. Under the influence of environmental factors, like e.g. temperature and humidity variations, the dynamic properties will undergo changes.

In this paper the influence of traffic loads on the identified modal parameters will be investigated. For this purpose, finite element simulations are used, in which a vehicle moves over a bridge model. Different vehicle-models are considered. Using the simulated bridge response, the eigenfrequencies and modeshapes of the bridge vehicle system are determined by the stochastic subspace identification method and afterwards compared with those of the original, unloaded structure.

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Paper SHM 2002-010

An Experimental Validation of a Modal Model based Approach in Damage Detection and Localization

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This paper reports an experimental validation of a modal model based approach to structural damage detection and localization. The proposed technique uses output only vibration data as measured on the structure in operational conditions. It allows detecting structural damage, based on the variations occurring in the experimentally identified structural dynamic model of the structure under analysis. In addition, the technique provides a simple method to identify the location where damage has occurred provided that a numerical model of the structure is available.

In a first stage, the measurements carried out on the structure in healthy conditions, allows identifying the nominal model of the undamaged structure. Successively, new output-only time data are acquired on the structure in healthy conditions. The new time data (not necessarily reduced to modal parameter) are compared with the nominal model using a statistical test procedure. This procedure provides a calibration factor for the statistical test, which identifies the undamaged structural condition.

In a second stage, several different damage scenarios are artificially introduced on the structure and new experimental measurements are performed for each scenario. When new data are processed, the statistical test is performed again and if the test's result sensibly exceeds the calibration factor, it indicates that damage has occurred on the structure.

Assuming that a FE model of the structure is available and that the sensitivity matrix of selected FE parameters (e.g. proportional stiffness) to the modal parameters, has been estimated, the method allows identifying the FE parameters that give the highest reaction in the statistical test, suggesting where the damage occurs.

The technique has been validated on a geometrically simple test article designed, assembled and tested dynamically under impact and random shaker excitation. The test structure consists of a number of cylindrical bars connected in 4 spherical joints through specially designed screwed bolds. The method has proven powerful and fast, it allows detecting damage in an early stage and it does not require the extraction of the modal parameters from each newly acquired measurement data set. This characteristic is very well suited for health monitoring purposes, the technique does not need continuous user interaction and it can easily be made automatic.

This research was performed in the frame of the EC BRITE-EURAM "SAM" project (Structural alternatives in Machinery). SAM project aimed at reducing the structural weight of machinery tools while keeping their dynamics and working safety. The support of the EC is gratefully acknowledged.

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Paper SHM 2002-011

Neural Networks Approach to Structural Damage Assessment

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Over the past 30 years damage identification in a structure from changes in global dynamic parameters has received considerable attention from the civil, aerospace and mechanical engineering communities. The basis for the approach to damage identification is that changes in the structure's physical properties (i.e., stiffness, mass and/or damping) will, inturn, alter the dynamic characteristic (i.e., resonant frequencies, modal damping, and mode shapes) of the structures.

A neural network-based approach is presented for the detection of changes in the characteristics of structure. Neural networks have been viewed as potential saviors for solution of the difficult problems in damage location. Neural networks are able to treat damage mechanisms implicitly, so that it is not necessary to model the structure in so much detail, the method can also deal with non-linear damage mechanisms easily.

A way of choosing the patterns representing the characteristics of the structure, which are to be used as the input to neural networks, is one of the most important subjects in this approach. Different modal-based damage features such as natural frequencies, mode shapes, curvature mode shapes, modal flexibility, frequency respond functions are used as input patterns in this study, analyzing the various input patterns to neural networks respectively, which shows that different have different sensitivities to the location and extent of the damage. The combined features are presented as the input features of neural networks in structural damage identification in this paper. It is shown, through simulation studies indicate that the combined damage features will more suitable for the input patterns of neural networks than either the other features alone.

It is also shown, through a simulation, that this method is verified to be practical for the location and extent of structural damage identification.

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Paper SHM 2002-012

Damage Detection of A Bridge-type Truss Employing Ambient Vibration

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Health monitoring methods based on the flexibility matrix have recently been shown to be promising for damage detection. Bernal (2001) proposed a flexibility-based Damage Locating Vector (DLV) method to localize the damage for the case in which the input can be measured. Numerical simulation showed quite good results. Later, Bernal (2001) extended his method to handle the ambient vibration case. However, the proof of this approach for the general case, that is, when not all DOFs and modes are measured, seems illusive. Gao, et al. (2002) proposed an alternative approach for addressing the ambient vibration case using the DLV method, which looks promising. However, until this point, experimental verification of the DLV concept and related methods has not been carried out.

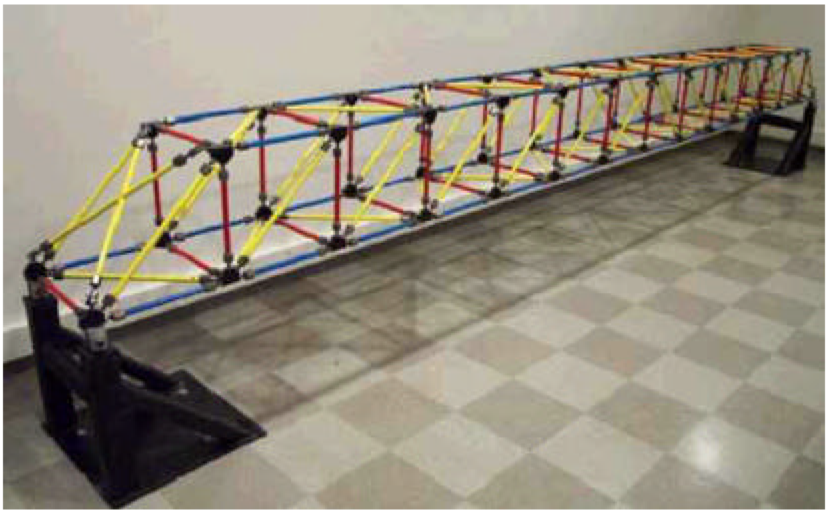

Figure 1 – 14-bay truss

Fig. 1 shows the 14-bay bridge type truss, which will be employed as the experimental set-up for the verification. The truss is designed and constructed in such a way that the user can easily remove and replace any member from the truss without dissembling the whole truss. The truss is excited by a permanent magnetic shaker attached under the truss. Band-limited white noise is selected to simulate the ambient vibration. Accelerations are collected with the aid of a 12-channel Data Acquisition System. This Data Acquisition System has anti-aliasing filter in each channel and allows simultaneous sampling. The Natural Excitation Technique (NExT) (James et al. 1993) in conjunction with ERA (Juang, 1985) is employed to obtain the modal parameters for ambient vibration case (Dyke et al. 2000). The proposed approach for ambient vibration case using DLV method (Bernal 2001, Gao et al. 2002) is applied to detect the damage in the truss.

Damage is simulated by totally removing the member. Single and multiple damage case will beconsidered. Experimental results will be presented and discussions are followed. The paper is then concluded by the evaluation of this proposed DLV related method (Gao et al. 2002) for damage localization.

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Paper SHM 2002-013

Evaluation of Delamination in Laminated Composites Based on Lamb Wave Modes: FEM simulation and Experimental Verification

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The fundamental Lamb wave modes have the significant potential to be used for broad range non-destructive inspection. In this study, interaction between the individual Lamb wave mode and the delamination in CF/EP composite laminates was investigated using the numerical simulation. A 3D asymmetric finite element model was proposed, imitating the full-scale structure involving internal defect, and performed with the ABAQUS/EXPLICIT FEM code. The FEM results were then verified experimentally with an inhouse active real-time damage diagnosis system. Both the theoretically calculated and experimentally measured structural dynamic response signals were processed with the wavelet-based time-frequency analysis for the detection of singularity, and a good agreement has been achieved. The results show that the dynamic response in the time-frequency domain is considerably sensitive to the delamination location, which makes the quantitative damage identification applicable. The ultimate efforts of this research aim at developing a damage detection (*inverse problem*) technique using a combined approach based on numerical and experimental analyses.

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Paper SHM 2002-014

Detection of Delaminations Using Spectral Finite Elements

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Damage detection systems are based on the known fact that material discontinuities affect the propagation of elastic waves in solids. Wave frequencies that are most sensitive to damage depend on the type of structure, the type of material, and the type of damage. Elastic waves are generated and sensed by an array of transducers either embedded in or bonded to the surface of the structure.

This paper presents a method, which can be used to detect small delaminations in beam-like structures. Figure 1 is a schematic of a conceptual damage identification system that can estimate the location and evolution of damage using the measured signals from the sensors built into the structure. The plate is instrumented with four pairs of piezoelements bonded to both faces of the plate. Each of these pairs can be used as a transmitter or as a receiver. Local actuators dynamically excite the structure while sensors measure its response. A processor compares the response to a baseline measured earlier from the undamaged structure. If the response differs, then the structure may be damaged.

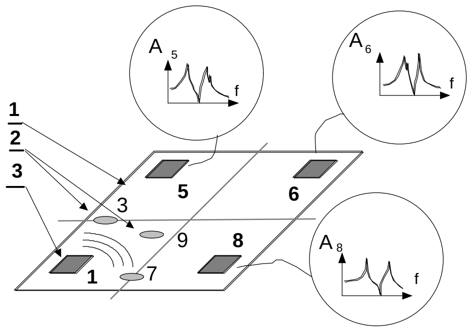

Figure 1 Damage identification concept

The frequencies used in this technique are much higher than those typically used in modal analysis based methods but are lower than in ultrasonic testing. At such high frequencies, the response is dominated by the local mode and the wavelength of the excitation is small enough to detect incipient or potentially significant damage.

In this approach, the measured dynamic responses of the structure are compared to those calculated using a new spectral finite element which contains a delamination. Differences between the measured and calculated values of the responses at several points of the structure are used to formulate an objective function. This objective function is used by a genetic algorithm, which quickly and accurately identifies the size and location of a delamination. The delaminated region of a structure is modelled by three spectral finite elements (I, II and III), which are connected at the delamination crack tip where additional boundary conditions are applied (Fig. 2).

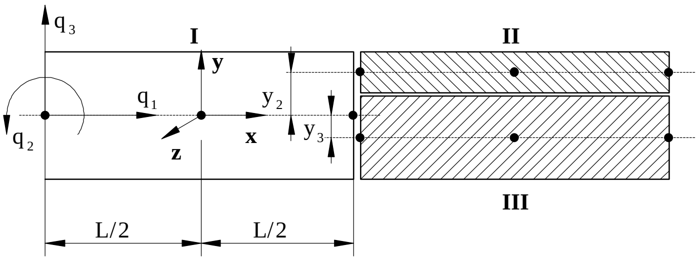

Figure 2 Damaged region of a structure modelled by spectral finite elements

Each element has two nodes with two degrees of freedom (transverse displacement, q_3, and rotation, q_2). Nodal spectral displacements have the following form:

$$v(x) = A_1 e^{-i k_n x} + A_2 e^{-k_n x} + A_3 e^{-i k_n (L-x)} + A_4 e^{-k_n (L-x)}$$

for x∈<0, L>

$$k_n = \sqrt{w_n} \left(\frac{r\,A}{E\,J} \right)^{\frac{1}{4}}$$ (ω_n- bending natural frequency)

where: *r* is the density of the beam material, *A* is the area of the element cross section, *E* denotes Young's modulus, *J* denotes the geometrical moment of inertia of the element cross-section and w_n is the natural frequency in bending. By considering the boundary conditions the frequency dependent dynamic stiffness matrix for the damaged region can be calculated.

The searching process uses a genetic algorithm, the objective function of which is based on changes in t he dynamic responses of the structure. The objective function compares measured values of dynamic responses (displacements, velocities or accelerations) with those obtained from calculations for delaminations of various location and size. The form of the objective function depends on the number of points at which dynamic responses are measured.

Numerical calculations were carried out for a cantilever beam. The structure was excited by transverse force vibrations, which were of triangular shape modulated by a sine function. During analysis, the signals were affected by random noise, the magnitude of which was up to 5% of the virgin signal.

The obtained results indicate that the current approach can successfully detect delaminations that are of very small size, even in the presence of considerably high measurement errors. Consequently, the method proposed here appears to be better than methods that are based on measuring changes in modal parameters.

Paper SHM 2002-015

Computational and Experimental Validation Enabling a Viable In-Flight Structural Health Monitoring Technology

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An important and challenging technology aimed at the next generation of aerospace vehicles is that of structural health monitoring. The key problem is to determine accurately, reliably, and in real time the applied loads, stresses, and displacements experienced in flight, with such data establishing an information database for structural health monitoring.

The present effort is aimed at developing a finite element-based methodology involving an inverse formulation that employs measured surface strains to recover the applied loads, stresses, and displacements in an aerospace vehicle in real time. The computational procedure uses a standard finite element model (i.e., "direct analysis") of a given airframe, with subsequent application of the inverse interpolation approach. The inverse interpolation formulation is based on a parametric approximation of the loading and is further constructed through a least-squares minimization of calculated and measured strains. This procedure results in the governing system of linear algebraic equations, providing the unknown coefficients that accurately define the load approximation.

Numerical simulations are carried out for problems involving increasing levels of structural complexity. These include beam and plate bending examples and an aircraft wing box. Accuracy and computational efficiency are discussed in detail.

The experimental validation of the methodology by way of structural testing of an aircraft wing is also undertaken. The structural component used in this study is a Grumman C-1A Trader left half stabilizer that represents a typical semi-monocoque structure. Strain gauges are mounted on both the lower and upper surfaces, while linear extensometers are installed on the upper wing surface to measure surface-normal displacements. The extensometer measurements are used to verify the accuracy of the computed displacements by way of the inverse interpolation method. The applied forces are monitored via load cells. The results of the proposed computational-experimental methodology are correlated and quantified using the test data.

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Paper SHM 2002-016

Frequency-change-ratio-based Frame Structural Damage Identification

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Development of health monitoring system becomes an important theme for structural damage identification. Damage generally produces changes in the stiffness of a structure. These changes are reflected by changes in some of the dynamic properties. The variation of structural frequency before and after the damage is believed to be a most available and widely used modal parameter because of its easy testability and high measure precision. Based on frequency sensitivity analysis, a damage parameter identification method has been put forward. The method used only frequency measurement before and after damage occurred to locate the damage location and quantify the severity of the damage. For the inter-story shear building, most of the frequencies can be measured. Several frame models have been made and studied using vibration test. A lot of cases have been considered including single-damage and multi-damage with different severity and locations. Test results show that for shear buildings, damage severity and location can be calculated using frequency change ratio method from structural frequency measurement.

Paper SHM 2002-017

First structural damage identification on FRP laminates using an Acoustic Emission System

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In spite of the large use of fiber reinforced polymers (FRP), at present the mechanisms of damage initiation and propagation in FRPs are still not completely explained and are therefore hardly predictable. This is mostly due to the peculiar nature of such materials which lack of homogeneity and are characterised by high anisotropy. Moreover, even when a very accurate structural analysis is carried out on components, nevertheless often the damage starts at large distance from the most stressed points, and in particular near defects or flaws. In this regard, the topic of health monitoring of FRP structures (i.e. damage evolution monitoring) is, of course, of great interest. At present the most reliable monitoring systems are based on the use of non destructive testing (NDT) in order to point out existing damages, even when they are not visible. Among various NDT, AE was tested to be very effective in monitoring the onset of damage in FRP structures.

Aim of the present research is to investigate damage initiation and growth in FRP laminates by means of AE technique. In previous papers the authors correlated the onset of damage in CFRP laminates to the elastic modulus degradation found when performing cyclic tests. In this research, the same cyclic tests are repeated introducing AE acquisition. The goal is to be able to correlate mechanical (decrease of elastic modulus) and AE data, so the AE data can be used to evaluate a damage threshold at which mechanical properties of the material start to decay.

The experimental set-up consisted of mechanical tests carried out together with AE acquisition.. At this purpose, cyclic tensile tests have been carried out in order to monitor damage initiation in FRP specimens.

The following cyclic test procedure was performed:

- loading until a fixed value
- loading maintenance by 5 minutes,
- unloading,
- cycling to higher strength

results had shown a good correlation between AE data and the change of mechanical properties. In conclusion, the applied AE system was tested to be very effective for on-line monitoring of FRP components.

Paper SHM 2002-018

Development of a Practical Acoustic Emission Based Structural Monitoring System

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Acoustic Emission (AE) systems have been applied to the monitoring of structures for well in excess of three decades. During this time commercial AE systems have grown in both signal processing capability and complexity and this presents a significant barrier to the newcomer in view of the specialised experience and interpretative skills necessary for them to be used effectively. In the field of structural monitoring this, together with the high associated costs, has limited the wider exploitation of AE techniques.

Our experiences in the application of AE techniques to the health monitoring of rotating machinery have shown that it is possible for simpler solutions to have great impact in terms of end-user acceptance despite reduced functionality. Over the last two years we have explored whether this philosophy can be usefully applied to the field of structural health monitoring. Our ultimate goal in doing this work has been to make additional information accessible to civil and structural engineers through the creation of a practical AE based structural monitoring system.

In specifying such a reduced functionality system great care has to be taken to ensure that measurement integrity and inherent detection capability are not compromised. In addition consideration needs to be given to conceptual simplicity, ease of output interpretation and minimisation of the skills necessary for system installation and set-up. In this paper we discuss our progress along these lines and present experimental findings that illustrate the capability of a system that has been developed to address these issues.

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Paper SHM 2002-019

Health Monitoring of Smart Structures Using Fiber Optic Sensors

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A fiber optic based health monitoring system was developed for composite structures, using multiplexed Bragg gratings for strain and temperature sensing. The program was sponsored by the Israeli MOD, under the coordination of Dr. S. Gali. All aspects of the technology have been thoroughly investigated including the embedding process, the integration of the opto-mechanical interface, connectors, the analytical evaluation of the impact of the fiber presence on the composite, as well as various optical issues such as birefringence effects and their elimination.

The development of the embedding process included the following:

A. Selection of specific optical fiber for optimum compatibility between the fiber coating, composite matrix resin and the manufacturing process parameters.
B. Splicing of bragg sensors and splice protection.
C. Novel termination methods to protect the optical fiber at the exit locations from the composite.
D. Industry standard optical connectors, adapted to composite structure and manufacturing processes.

Numerous tests were performed in order to establish the feasibility and reliability of measuring strains using multiplexed Bragg strain sensors, embedded in composite structures under load. Specimens with both uniform and variable strain fields were tested. Excellent correlation between the Bragg sensor readings and conventional electrical resistance strain gage data was obtained (see fig 1)

Analytical evaluation of the effect of the embedded optical fiber on the mechanical properties of the structure and on the stress and strain distributions was performed. A Finite Element model was generated representing the fiber, fiber coating and surrounding composite (see figure 2). The model is based on advanced P-Element analysis capable of detecting high stress gradients combined with accurate geometric modeling.

The health monitoring system is now being applied to a demonstrator comprising the Israel Aircraft Industries commercial A/C Galaxy aileron. The aileron was instrumented with an embedded optical fiber net incorporating multiplexed Bragg sensors, in order measure strains and temperature in real time.

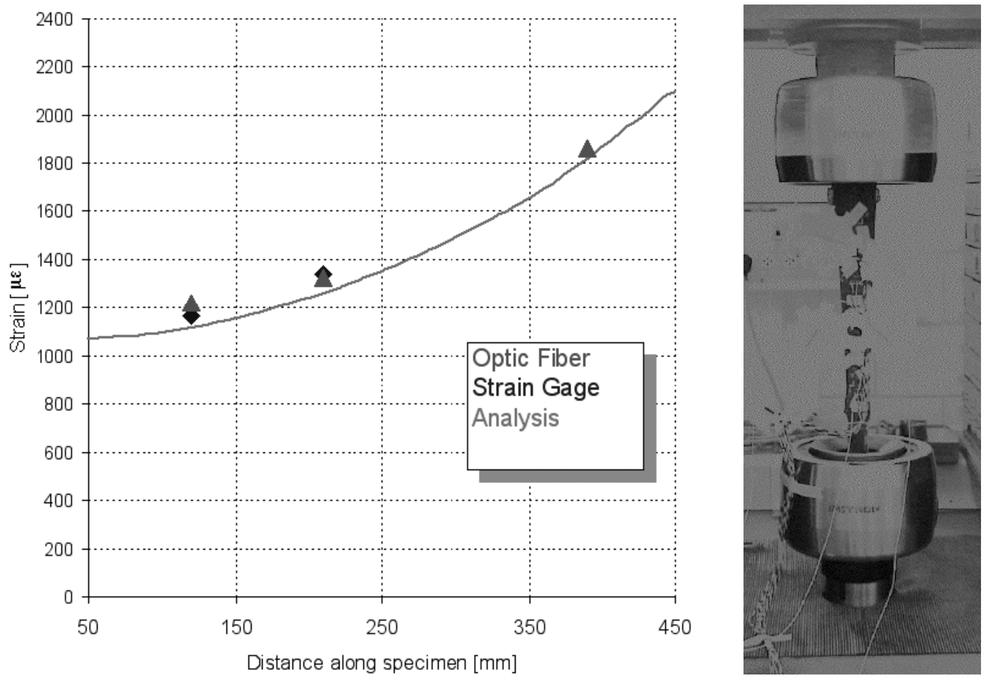

Fig 1 – Non-uniform strain field test data and anlytical correlation

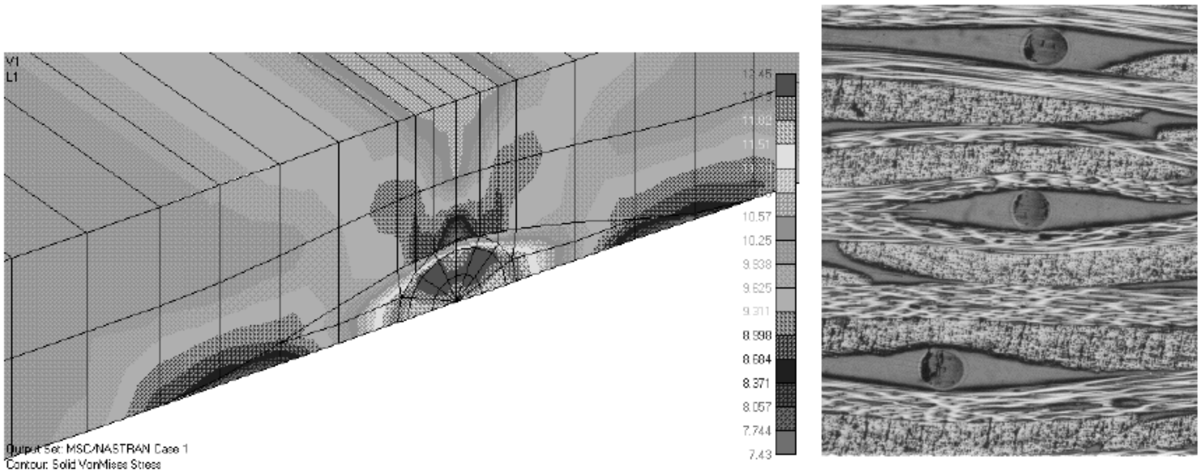

Fig 2 – Finite element model model of embedded fiber

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Paper SHM 2002-020

Magnetoelastic Transducers for Non Destructive Evaluation of Strands

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Evaluation and maintenance of structures are an important task in the field of civil engineering. Reliable and unexpensive methods are required for health monitoring of these structures. Nondestructive evaluation methods can be a solution to give information on the degradation of structural components such as steel members. Primary causes of steel cables and bars alteration being corrosion or mechnical fatigue.

However, *in-situ* detection and monitoring of such degradations are still challenging problems.

The aim of the paper is to present a non-destructive low-ultrasonic pulse-echo method working with magnetoelastic transducers which could be considered as a complementary method to conventional ones such as magnetic flux leakage and acoustic monitoring methods. The ferromagnetic material under evaluation acts both as part of transducer and medium of propagation. The geometrical arrangement of the device is configurated for the production and detection of longitudinal mechanical waves.

The following technical aspects concerning:

(1) device operating conditions (polarizing field and dynamic field strength, excitation frequency content),
(2) guided wave propagation,
(3) defects detection

will be presented and analyzed through laboratory-based experiment results combining various geometries and types of materials.

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Paper SHM 2002-021

Near-Field Microwave Nondestructive Detection of Delamination Between Fiber Reinforced Polymer (FRP) Composite laminates and Concrete for Repair Quality Assessment

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Concrete Structural elements such as beams, slabs and columns may require strengthening during their life span. The need for strengthening may arise due to one or a combination of several factors including construction or design defects, increased load carrying demands, change in the usage of a structure, seismic upgrade, or meeting new code requirements. Studies have shown that fiber reinforced polymer (FRP) composites, in the form of sheets and laminates have emerged as a viable, cost-effective alternative to steel plates or other techniques for strengthening reinforced and prestressed concrete members. These advanced composites made of fibers embedded in a polymeric resin, known as FRP composite materials, have emerged as an alternative and practical solution to steel reinforcement and its inherent corrosion problems. The principal advantages of FRP sheets over steel include high strength-to-weight ratio, corrosion resistance and flexibility in its use. Repair and strengthening of structures with FRP reinforcement involves the use of externally bonded sheets, prefabricated laminates, and near surface mounted bars. For the application of externally bonded laminates or sheets, delaminations may occur shortly after the installation process or after installation due to environmental conditions such as weathering or fatigue.

From earlier experiences in the field applications, it was observed that during installation the presence of moisture vapor transmission or backside water ingress can cause air pockets or delamination under the FRP sheets. This phenomenon was related to the vapor transmissions resulting from entrapped moisture in the concrete after being exposed to high temperatures. Formation of air pockets prior to the full curing of the system will reduce the efficiency of the system and, if undetected and properly treated, can cause premature failure of the system. Furthermore, delaminations of moderate and large sizes can adversely affect the bond characteristics and structural performance of the repaired/strengthened system. Therefore, detection of delaminations is very important in the repair industry where FRP laminates are used. It appears that near-field microwave technologies hold promise for detection of such delaminations and voids.

Microwave signals penetrate inside of dielectric materials and are capable of interrogating their inner structure. In the past ten years, near-field microwave nondestructive testing and evaluation techniques have been extensively used for inspection of thin, thick and multi-layered composite structures as well as cement-based materials. Thus, the application of these techniques for detecting delamination in FRP wrapped concrete structures is quite viable. Recently, in a pilot study at the University of Missouri-Rolla (UMR), it was demonstrated that near-field microwave nondestructive inspection technology is capable of detecting delaminations and voids between a hardened cement-paste specimen and FRP sheets. Microwave technology also has the potential to examine the repair quality of delaminations using epoxy injection. To this end and to further this study into concrete structures, delaminations were introduced between a section of a concrete column and FRP sheets. Near-field microwave measurements were conducted to detect the delamination(s) and their spatial extent. Microwave images (scans) of these regions are produced to illustrate the capability of these techniques. Additionally, the delaminated regions are repaired using epoxy injection. Subsequently, the same microwave technique is used to show the capabilities of these comprehensive technique for detection and repair of delamination. The results of these investigations along with the capabilities and limitations of this microwave nondestructive inspection approach will be presented.

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Paper SHM 2002-022

Damage Detection in Truss Structures by Analysis of Wave Propagation

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The goal in recent infrastructure health monitoring and damage detection is to introduce the vibration methods into practice. Up till now many researchers have made significant strides in developing damage detection methods for structures based on traditional modal analysis techniques. These techniques are often well suited for structures, where the presence of damage leads to some low frequency change in the global behaviour of the system. On the other hand small defects, such as cracks, are obscured by modal approaches since such phenomena are high frequency effects not easily discovered by examining changes in modal mass, stiffness or damping parameters. This is because at high frequency modal structural models are subject to uncertainty. Increasing the order of the discrete model can reduce this uncertainty however, this increases the computational effort of modal-based damage detection schemes.

The spectral approach includes the advantages of the spectral element method and the precision and efficiency of the finite element method. The spectral element method resembles the finite element method, but in the spectral element method the elements of the stiffness matrix are determined in the frequency domain. It allows an exact assessment of the inertia of the system. Another advantage of the spectral element method is that from mathematical site it is only simple set of equations to solve. An important thing is that only one spectral element allows to calculate precisely an infinite number of frequencies and mode shapes of the examined structure. With the spectral element method it is also possible to compare the impact signal and the system response straight in the time domain. Differences in those signals give information about the state of structure.

Up till now there are models of a cracked beam in the literature available, however there is no spectral model of a cracked one. This paper presents a new finite spectral beam element with a transverse open and not propagating crack, which is applied for analysis of wave propagation in cracked truss structures. The crack was modelled with consideration of the influence of the plasticity zone around the crack tip. To prove the correctness of proposed model many exemplary results are performed. The process of damage detection included the usage of genetic algorithms with special fitness function, which used directly the information about the changes in waves.

From all numerical tests done one can conclude that the spectral approach is much sensitive for the damage introduction in the structure and the same allows to detect it on the very early stage. This fact is very promising for future work in the field of structural health monitoring.

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Paper SHM 2002-023

Long-Distance Identification of Corrosion Through Analysis of Piezo-Generated Impulse Transmission

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The damage detection systems based on array of piezoelectric transducers sending and receiving strain waves are intensively discussed by researchers recently. The signal-processing problem is the crucial point in this concept and a neural network based method is one of the most often suggested approaches to develop a numerically efficient solver for this problem.

The purpose of this paper is to propose an alternative approach to the inverse dynamic analysis problem. Generalising so called VDM (Virtual Distortion Method) approach on dynamic problems, a dynamic influence matrix D concept will be introduced. Pre-computing of the time dependent matrix D allows decomposition of the dynamic structural response on components caused by external excitation in undamaged structure (the linear part) and on components describing perturbations caused by the internal defects (the non-linear part). In the consequence, analytical formulas for calculation of these perturbations and the corresponding gradients can be derived. The physical meaning of so-called *virtual distortions* used in this paper are externally induced strains (non-compatible in general, e.g. caused by piezoelectric transducers, similarly to the effect of non-homogeneous heating). The compatible strains and self-equilibrated stresses are structural responses for these distortions.

Assuming possible locations of all potential defects in advance, an optimisation technique with analytically calculated gradients could be applied to solve the problem of the most probable defects' location. The considered damage can affect the local stiffness as well as the mass distribution modification. It is possible to identify the position as well as intensity of several, simultaneously generated defects.

The proposed methodology will be applied to corrosion detection (reduction of material thickness), and identification of its location in steel pipelines, using long-distance transmissions of impulses. The mechanical model can be reduced in this case to the isotropic one, with virtual distortions modelled through thermal-like, deviator-less tensor fields. This problem, similar to thermal shock propagation can be solved numerically cheaper than the general problem of elastic impulse propagation.

Theoretical background as well as numerical results and experimental verification will be presented.

The proposed approach can be also applied to identification of multi-impact location and intensity.

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Paper SHM 2002-025

Analysis and optimization of a magnet - based vibrating wire sensor

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Taking advantage of vibrating strings to measure relative displacements is a widely used technique in civil engineering. In France, thousands of vibrating wire sensor (VWS) are currently in use. The technique is based on the dependence of the ground natural frequency of a string with respect to its elongation. Excitation is usually achieved by means of an active coil, which is very close to the iron vibrating wire (2x10-4m). Extracting the natural frequency from the global response leads to the stretching of the wire. Current technology is limited to wires of very small length because of the necessary small dimension of the coil. Moreover, exciting the fundamental mode proves difficult because usually only one active coil is used, and also because this technique is very intrusive, although VWS aim at being fully embedded in structures.

The new VWS takes full advantage of an array of distributed passive magnets, which deliver a suitably shaped load distribution along the wire when the latter conducts an electrical current. An impulse current is imposed, thus leading to an impulse displacement of the wire according to Laplace's law.

Then the fundamental frequency of the wire is recovered by means of a zero counting technique applied to the current induced by the movement of the wire in the magnetic field according to Lenz ' law.

Above technique proves scalable and flexible. More than 500 sensors of this type, ranging from 10cm to 300 cm, have been designed and manufactured. They are being used in various investigations such as alcali-aggregate reaction laboratory testing.

The distribution of permanent magnets will be discussed. A solution based on the interpolation of the fundamental modeshape of the string will be analyzed. Error estimates between the ideal monochromatic electrical signal and the slightly polluted expected signal will be given. In practice, the proposed distribution of magnets yields a sufficiently pure signal, thus enabling scalability.

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Paper SHM 2002-026

Damage Detection in FRP Laminated Beams Using Neural Networks

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One of the promising research area in engineering applications is to detect the damage in real time so as to maintain the performance of the aircraft, marine and offshore structures. In case of composite materials, delamination and fibre breakage are the most typical examples of damages that significantly reduce the mechanical strength and cause an overall performance degradation in the structure.

The effects of the common damages on the structure are reduction in natural frequencies and increase in the damping. As the measurement of natural frequencies is much easier than that of changes in damping of a structure, damage can be detected from vibration based analysis using natural frequencies. These damages can be modelled as local area stiffness reduction by using finite element tools. Although reduction in natural frequency is an indicator for the existence and the severity of the damage, it does not give much information about the location of the damage. On the other hand, absolute difference between curvature mode shapes, which can be obtained from the displacement mode shapes, can be used as a possible candidate to find the location of the damage.

Since the determination of the severity and the location of the damage is an inverse non-linear problem, an intelligent algorithm is needed to perform the damage detection analysis. The purpose of this paper is to explain how this can be achieved by using neural networks. The inputs and the corresponding outputs (targets) required to train the neural network are obtained from the finite element analyses for different vibration modes of the laminated composite beam. The existing models are generally using normalised natural frequency information as input to the neural networks but in the present method, not only normalised natural frequencies but also maximum absolute difference in curvature mode shapes and the locations where the maximum absolute differences occur along the beam are taken into account as input to the neural network for higher accuracy predictions.

The preliminary results from the neural network which has been trained by using different damage scenarios using finite element analysis depict that severity and location of the damage can be predicted by just using as input the natural frequencies and curvature mode shapes.

Paper SHM 2002-027

Structural Damage Identification Using High-Definition Mode Shapes

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In this research, in-depth numerical feasibility studies of the mode shape curvature (MSC) method have been carried out, investigating the effects of experimental conditions that affect the accuracy of structural damage identification by this method. Results from these studies indicate that (i) measurement accuracy and spatial resolution of the mode shapes keys to reliable damage identification using vibration data and (ii) there are difficulties achieve the required standards with conventional measurement methods.

For practical implementation of the MSC Method with improved reliability, a new experimental method has been applied. The method involves the use of a scanning Laser Doppler Vibrometer (LDV) to measure mode shapes in much more detail than is current practice. Experiments have also been conducted to illustrate the significance of the various findings of this research.

It is concluded that (i) high-density mode shape data have to be used to perform practical reliable damage identification with the MSC Method and (ii) in this respect, the use of SLDV is recommended for experimental mode shape acquisition wherever applicable.

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Paper SHM 2002-028

Architecture and Design Technologies for the Emerging Nano-to-Micro Integrated Smart MEMSs

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While microfabrication technologies are approaching the capability of building microstructures with details well below the present limit of 100 nm, the increasing success of both solid state and molecular nanoelectronics as single-electron circuitries is reducing the size of the information bit. The application of all that downsizing to integration of nano- to micro-structures holds promise of technologies realising a level of merging of structure and function, i.e. of the chain "sensing - information processing - actuating" quite comparable to that observed in biological systems, subsystems, devices and components whose "smartness" in real situations and applications (aerospace devices, planetary exploration robots etc.) outweighs that of systems based on Artificial Intelligence. Accordingly, three problems are raised here and discussed for realistic near-term solutions concerning the technologies involved in the effort of realizing nano-to-micro integrated architectures for smart MEMSs and bioMEMSs, the latter as systems endowed with a high level of structure-function integration: 1) the materials technology that holds promise of embodying the recent theoretical achievements concerning our understanding of biological information processing capabilities; 2) the problem, dubbed here the "metasystem problem", arising in connecting the macroscopic physics world of micromechanics and microelectronics to the mesoscopic physics world of nanosystems, mainly of single-electron nanoelectronic systems involving the quantum mechanical world; and 3) the design technology that, contrary to usual design procedures which aim to assemble a system according to a roadmap that leads from components to devices, to subsystems and finally to systems, is to synthesize a system embodying as much as possible a structure-function unitary agency consisting of an architecture that is made up of a number of mechanical actuators/sensors/computing units. While it is stressed that the resulting products would span a wide terrestrial market (e.g. multipurpose monitoring techniques) in addition to the quite limited markets of aerospace and special space mission applications, so that a consequent recoup of heavy investment in aerospace development costs would be envisageable, some applications to miniature space robots like untethered flying observers, orbiters, landers, microrobot swarms etc. are briefly illustrated. The resulting general features of the most complex systems built by this nano/MEMSs integrated philosophy sum up to hyper-interspersed nano/MEMSs architectures made up of autonomous units realizing peripheral autonomous, nano/micro-structured macroscopic members (e.g., smart skins) in addition to a global action/motion level depending on instructions controlled by a central unit. The nanoscale and the cooperating microscale hyper-interspersed architecture make up the finely structured intelligent autonomous, biomimetic level working on and interacting with the external analogue reality locally, the corresponding information detection and processing going on through both nanoscale-level and microscale bulk "primitive components" interconnected into discrete pseudo-analogue networks, i.e. networks performing a form of computation decidedly different both from digital and analogue computation. They might solve problems on the same principles as those employed in digital computers but without transformation of information into discrete form. Such primitive components perform on both size-scales complicated information processing operations in addition to the simpler operations like parallel arithmetics, recognition, decision making, i.e. learning, keeping attention, intermixing

layer. In spite of recent successes in preparation of nanowires, electromagnetic field connections ("optical wiring") should be preferred because of capacitance problems that, as is shown, would interfere with the nanoelectronic device designed operation and because of the possibility of realizing more complex, 3D circuit topologies. The basic equations for the corresponding nanoelectronic network node dynamics, and some "metasystem" sketches are given and discussed, together with some basic sketches of single-electron tunnelling devices. It is also stressed that the latter, due to their underlying operational principle, also work under far-from-equilibrium conditions, so that they lend themselves to applications to control of open systems, like robotic devices. The concepts of "limiting environmental size" of each quantum mechanical node and of "single mesoscopic node addressing" are formulated, and possible nanoscale addressing techniques are discussed for suitable connection between the nano- and the macroscopic world. The basic concept in the design technology involves a change in the approach to system design according to the current philosophies; the change is from the current bottom-up process (from component to devices subsystem(s) and system) to a top-down process, in which the overall system requirements are first defined and then reduced to the component level specifications. The corresponding sequential process of concept exploration, synthesis, analysis and verification is discussed for a definite technology model intended for creating and building complex, highly integrated nano-micromechanical architectures for smart MEMSs.

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Paper SHM 2002-029

Development of an electromagnetic based sensor for measurement of mechanical force in pre-stressed steel cables and tendons

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The demand for maintenance of structural health and safety to acceptable standards poses challenges for research and development of effective technologies for monitoring and measurement of parameters governing safety and health of structures.

In this work, an electromagnetic based sensor has been investigated and developed for measuring force in pre-stressed steel cables and tendons. The change in magnetic permeability of a material caused by mechanical stress is exploited to measure force in the material. The sensor consists of a pair of sensing coils and a pair of reference coils. The sensing coils are wound around a stressed material while the reference pair are wound on a dummy specimen of same material as that under stress.

When sensing and reference primary coils are excited by same current simultaneously, both the stressed and dummy materials are equally magnetized by the magnetic field generated by the current, and voltage is induced in the sensing and reference secondary coils. The induced voltage in each secondary coil is dependent on a number of factors including the magnetic permeability of its core which is a function of the core magnetizing current, temperature and stress.

By suitably arranging the sensing and reference coils electro-magnetically, the effects of temperature and magnetizing current on the permeability of a stressed material can be eliminated in the output voltage of the sensor. The output voltage is a function of only the mechanical stress in the stressed material, and can be calibrated for determination of force in the stressed materials.

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Paper SHM 2002-030

Elimination of Environmental Influences from Damage-Sensitive Features in a Structural Health Monitoring System

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Vibration-based structural health monitoring is becoming an alternative to manual inspection in civil, mechanical, and aerospace engineering systems. Damage in a structure can be identified from changes in selected features extracted from the measurements. The same features are influenced also by other effects than damage, such as natural variations in temperature, humidity, wind, and traffic. If the effects are not taken into account, they can result in false identifications of damage and make vibration-based health monitoring difficult or impossible.

The problems in health monitoring due to environmental or operational variations include:

1. Long monitoring before automatic damage detection can be initiated.
2. Although temperature measurements are relatively easy to perform, the sensor locations may be difficult to determine.
3. Other environmental or operational quantities may affect the data. Some quantities may be forgotten or can be difficult to measure.
4. Each structure is individual. Models accounting for environmental effects may be complicated and need a lot of effort to develop separately for each structure.
5. Only part of the measurements can be utilized, for example data from similar conditions or features for which the model was developed.

In this paper an attempt is made to eliminate the effects of the environmental variation from the data and solve most of the problems above. The technique is based on factor analysis: it is assumed that there exist common, or latent, factors that have linear effects on all features. The common factors are the environmental variables. Their effects are removed from the observations and the unique factors remain. These unique factors are assumed to include the normal variation and the effects of structural damage excluding those of the environment.

The advantages of the method are:

1. The environmental variables need not be measured.
2. The underlying physical quantity need not even be known.
3. Two or more common factors can exist affecting the observations.
4. The same model can be used for different structures.
5. All monitoring data can be utilized regardless of present conditions.

The limitations of the method are that the relationship between the environmental variables and the features must be linear and that a multivariate feature vector must be used.

The first study was a simulation consisting of four natural frequencies monitored once a day during nine years under varying temperature. The variation of the natural frequencies occurred due to temperature, damage, and normal statistical fluctuation. Shewhart T control charts for the natural frequencies before and after factor analysis are shown in Figure 1, in which the improvement of the proposed technique can be clearly seen.

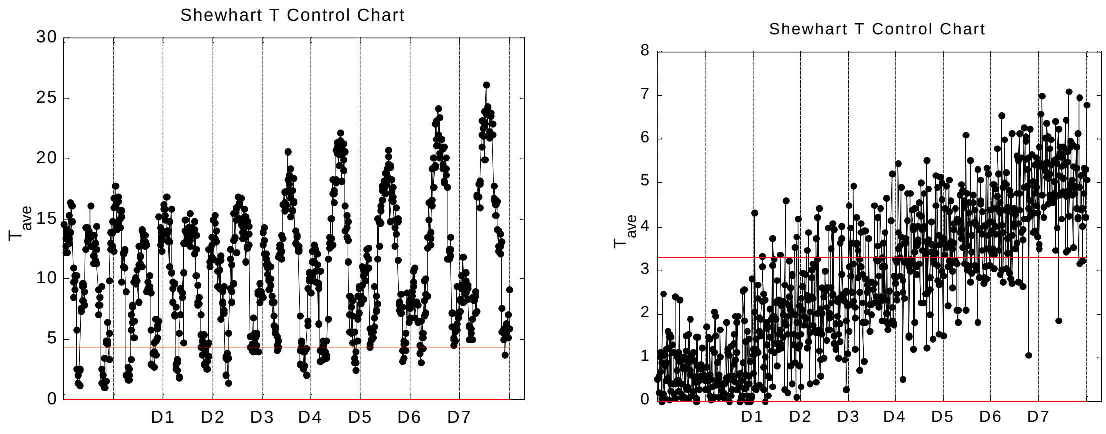

Figure 1. Shewhart T control charts for natural frequencies before and after factor analysis.

Environmental effects were also investigated with a monitoring system built in the laboratory. The structure was a wooden bridge model and the damage-sensitive features were the modal parameters of the structure, which were identified using the stochastic subspace technique. Multivariate Hotelling *T* control charts for the modal parameters before and after factor analysis are shown in Figure 2. Damage detection without factor analysis produced several false indications of damage, whereas the factor analysis resulted in superior results. All damage configurations were detected. Occasional false indications of damage were also present, suggesting that at least two successive outliers should be present before alarm signal is generated.

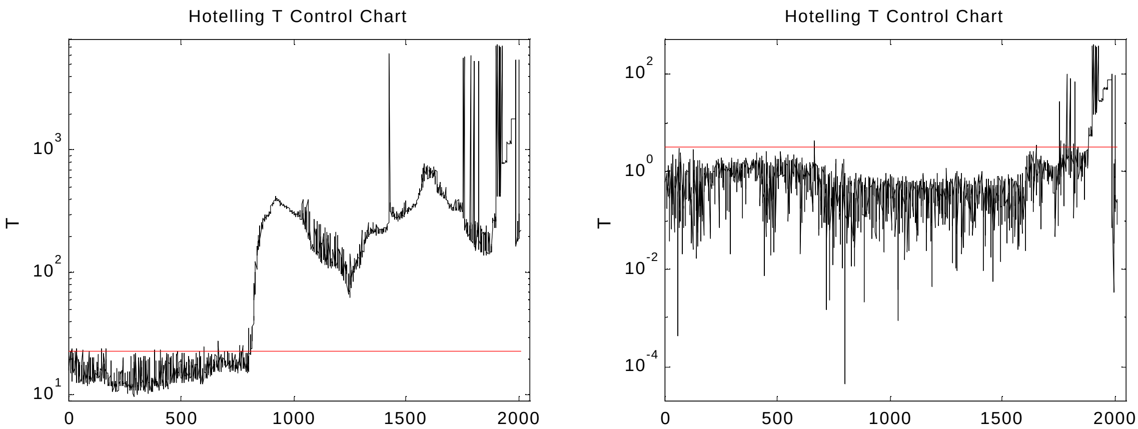

Figure 2. Control charts for modal parameters a) before and b) after factor analysis.

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Paper SHM 2002-031

A mathematical network approach to structural prognostic health management

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Evaluating the stresses ofg critical aircraft components is essential for advanced prognostic health monitoring. Aircraft stresses can be directly measured by strain gauges. Strain gauge monitoring systems only provide stress measurements at a small number of structural locations and their operational costs are often high. Recorded flight parameters can potentially indicate component stresses and at the same time describe the flight conditions that caused these stresses, and hence, they can form the foundation of advanced prognostic management systems where the effects (stresses) and their causes can be derived from a single source. Over the last three decades, recorded flight data has been extensively used to analyse aircraft incidents and accidents and, hence, there is a growing interest in using readily available flight data for prognostic management. Therefore, Smiths Aerospace has developed mathematical networks that combine mathematical formulae, Artificial Intelligence (AI) and engineering knowledge to synthesise stresses from flight parameters. Working with BAE SYSTEMS, their engineering knowledge was used to configure mathematical networks for their aeroplanes. Whilst the networks accurately synthesised the stresses of a number of components, a challenge remained to define a method for qualifying them. This paper describes the AI model-based approach used, reports the results of the mathematical networks and presents preliminary discussions regarding the qualification approach of such networks.

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Paper SHM 2002-032

Monitoring the damaging effects of aircraft rare events

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There is a growing interest in developing affordable structural prognostic management systems that can track how each individual aircraft is used and at the same time quantify the damaging effects of usage events. Whilst recorded aircraft flight parameters can indicate the stresses induced by complex manoeuvres, they cannot monitor damaging effects of rare events such as buffeting, hard landing and severe turbulence. Buffeting is an aeroelastic phenomenon, which occurs, in some circumstances, under manoeuvring conditions that involve high angle of attack (AOA) and can often consume the fatigue life of military aircraft fins. Flight parameters such as AOA, velocity and accelerations can only determine the likely situations during which buffeting may occur. Other factors such as air turbulence, wind speed, wind direction and gusts can have an influence on the phenomenon and, hence, for the same set of measured flight parameters, buffeting may or may not take place depending on other factors. Hard landing can also consume the fatigue life of undercarriage attachments. Smiths Aerospace has developed mathematical networks that combine mathematical models, Artificial Intelligence (AI) and engineering knowledge to synthesise stresses from flight parameters. Working with BAE SYSTEMS, a mathematical network was configured to monitor the damaging effects of rare events. The configuration of the mathematical network involved modal analysis and a simplified Eurofighter finite element model. This paper describes the AI model-based approach to rare event monitoring and reports its preliminary results.

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Paper SHM 2002-033

The evolution of FUMS^{TM}, a Health Prognostic Management System

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The initial developments of the Smiths Aerospace Fatigue and Usage Management System (FUMS^{TM}) have been motivated by the need to improve the fatigue management approach for military helicopters and by the growing interest to build into the MoD Health and Usage Monitoring System (HUMS) advanced fatigue management capabilities. In 1995, Smiths Aerospace recommended that cost effective fatigue management should consider monitoring flight parameters and also monitor and track all causes of failure. The failure of any aircraft component occurs as a result of component use, exposure of component to environment and component interactions with other components or objects. Since 1995 FUMS^{TM} has evolved as an affordable Prognostic Health Management system (PHM). The FUMS^{TM} framework combines mathematical models, Artificial Intelligence (AI) and aircraft engineering knowledge. It fuses information extracted from recorded flight parameters, on-condition monitoring sensors, maintenance observations and design information to provide meaningful diagnostics and prognostics. For example, FUMS^{TM} has successfully calculated, from flight parameters, military aircraft stresses, helicopter torque, aircraft all up mass, centre of gravity, and low cycle fatigue of aircraft and engine components. FUMS^{TM} delivers its prognostics by implementing mathematical networks, probabilistic graphical models, neural networks, fuzzy rules, mathematical models, if-then scenarios, and by providing tools for pattern recognition, data visualisation, data mining, knowledge discovery and decision support. Through its intelligent charts and management database, the framework provides different users with information consistent with their need and converts its complex set of math/AI tools to simple computer-mouse interactions. This paper describes the architecture of FUMS^{TM}, presents its fusion capabilities, gives brief background information about its math-AI framework and compares its results with measured flight data.

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Paper SHM 2002-034

State-of-the-art: Structural Health Monitoring in bridges, viaducts and concrete dams in Portugal

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This article is a state-of-the-art report regarding the Health Monitoring of Structures and Structural Monitoring Systems in Portugal. The notion of Structural Health Monitoring (SHM) is presented, SHM characteristics, as well as the most frequently used health monitoring systems and techniques for structures such as bridges, viaducts, concrete dams, etc. References about the actual current state of SHM in Portugal and smart structures are also presented.

SHM is a relatively new technology motivated by 1) the need to complement subjective visual inspection methods by objective non-destructive evaluation tools based on physical measurements and computer analyses, and by 2) the decreasing cost, high reliability, and high sensitivity of modern transducers, data acquisition systems and computer technology.

SHM is normally used to monitor and control the actual state of structures in order to assure structural stability or functions in a service state. The application domains of SHM are very ample. Health monitoring can be applied in bridges, viaducts, dams, historic monuments, buildings, tunnels, foundations, and excavations to name a few. Systems and the techniques of SHM depend on the type of structural monitoring and it's specificities. In this article a short description of the usual monitoring systems is presented for a few specific types of structures.

A structural monitoring project is defined by taking into account the stage or lifetime of a structure and the type of structural evaluation demanded. Thus a structure may be monitored during the construction or reception stages, in service, and in unplanned situations such as structural modifications, rehabilitations or reinforcements.

Monitoring systems of some Portuguese structures, in different stages of lifetime, are presented in this article. One of those structures, the Infante Bridge, Porto, is currently under construction and is monitored continuously through the use of electrical resistance strain gages and inclinometers. This bridge is also subjected, like other bridges, to dynamic testing. The actual monitoring system will be integrated in the future long-term monitoring system.

Monitoring systems can be classified into three categories: visual inspection, short-term monitoring, and long-term monitoring. Health monitoring techniques classified as local or global techniques are distinct from their purpose, characteristic, and advantages/disadvantages. These systems and techniques used in SHM for bridges, viaducts, and concrete dams can be applied to both new and aging structures. The selection of monitoring techniques is very dependent on the cost-benefit ratio. The most used local techniques described in this article are acoustic emission and radiography technologies, ultrasonic methods, and some expeditious methods that allow qualitative concrete evaluations of strength (hardness testing) and carbonation effects on concrete by the application of phenolphthalein. In regards to global techniques, static (load testing) and dynamic (ambient vibration and free vibration testing) methods are referred. Dynamic tests, which are currently very promising, allow a researcher to not only evaluate the global performance without individual inspection of the structural elements, but also the ability to identify local or global damages and degradations. The SHM systems will identify these items with the advantage of decreasing cost, high reliability, and high sensitivity of modern transducers, data acquisition systems and computer technology as compared to older SHM systems.

Considering the huge interest by the scientific community on smart structures, the article also presents a brief reference to the kind of structures that are candidates for a SHM system condition itself.

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Paper SHM 2002-035

A Proposal for New Maintenance Inspection (tentative)

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Today, most maintenance inspection are done by periodically with using many nondestructive inspection(NDI) techniques. This ways of inspection, that is, periodical method is mainly caused by the large amount of parts to be inspected and the technical limitation of NDI. We know, however that there are keen criticism---labour intensive, time consuming, much human involvement and high expenditure. The worst deficit, the author thinks, is that it lacks a warning system for the occurrence of danger in the structure. The maintenance people in Japan set the expected goal of improvement as shown in Table 1. They did not show how to reach the final goal in this Table, but the goal of the improvement of maintenance inspection should be; 1)preventing occurrence of disaster by monitoring the structures to be inspected all the time, 2)equipping warning system for damage happening of the structures.

Table 1 Expected Steps of Progress in Maintenance Technology

1. Time Based Maintenance
2. Condition Based Maintenance
3. Predictive Maintenance
4. Preventive Maintenance

As for 1), putting many sensors on the structure inspected and make it so-called sensory one. For this purpose we should consider on the selection of sensors, distribution of them on the structure, how to attach them etc. And as for 2), we should think of the kind of warning system, kind of warning, how to decide threshold etc.

On the other hand, experimental mechanics, which is used as the basis of strength calculation of structures, has another role that is the monitoring and judgement of the safety of mechanical/civil structures in service. When experimental mechanics would step into, the author would like to promote this movement, this field, there will submerge many new study topics, for example, residual life estimation of partly broken structure---.

The final goal of maintenance inspection and the new field of experimental mechanics in near future would be the same one that the concept of structural health monitoring shows, the author guesses.

As examples of this movement, a new maintenance of 120 die-casting machines, tiny auto-piloted agricultural helicopter by YAMAHA etc. are introduced.

Key words

conceptual study, maintenance inspection, SHM, intelligent

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Paper SHM 2002-036

Strain Monitoring of Filament Wound Composite Tank Using Fiber Bragg Grating Sensors

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In this paper, we present strain monitoring of a filament wound composite tank using fiber Bragg grating sensors during hydrostatic pressurization. 20 fiber Bragg grating (FBG) sensors and 20 strain gauges were attached on the domes and cylinder of the composite tank. A wavelength-swept fiber laser (WSFL) was used as a light source to supply high signal power. From the experimental results, FBG sensors bonded on the cylinder and the skirt showed close agreement with the strain gauges, while there were some differences of measured strains between the FBG sensors and strain gauges on domes. The causes of differences of strains measured by FBG sensors and strain gauges were verified through the tensile test of an aluminum specimen which is under the state of strain gradient.

Fig. 1 *Filament Wound Composite Tank.*

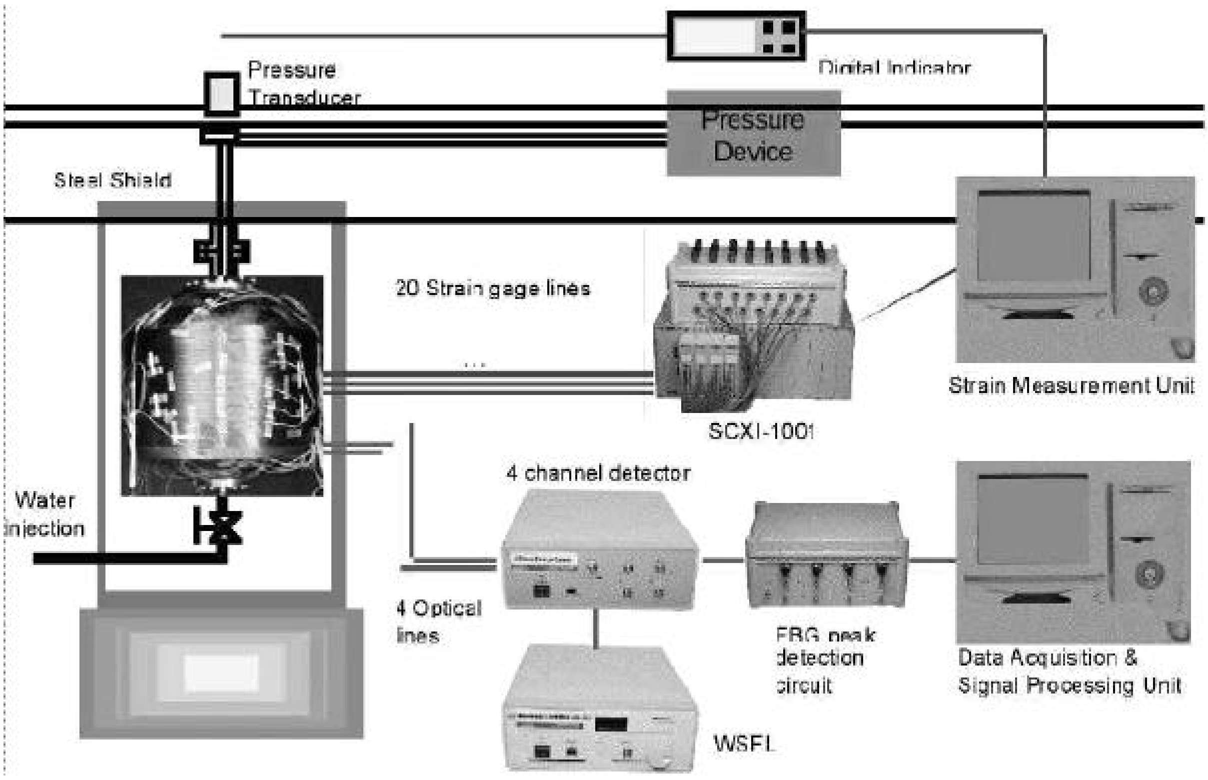

Fig. 2 Experimental set-up.

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Paper SHM 2002-037

Damaged Stiffness Matrix Identification of a Beam Structure Using Specified Loading and Measured Response Signals

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This paper is concerned with the damage identification of a simple beam structure in order to monitor the structural health condition. The damaged structural stiffness matrix is to be identified based on the specified loading and measured response signals. The finite element beam model is simplified to a substructure model according to the Guyan reduction method and the dynamic reduction method. The orthogonal polynomials approach is then used to extract the proposed distributed parameter model in question with noisy structural response data. The identified structural stiffness matrix for the reduced model with or without damage are furthermore transformed to the parameters which correspond to the global unreduced structural model by means of the back-propagation artificial neural network scheme. The unreduced damaged stiffness matrix is identified for a beam structure using sensors detected response signals when a specific loading is applied on the structure. Based on the identified damaged structural stiffness matrix, the damage locations and the degree of damage of the beam structure in question are then determined. A series of tests is also conducted in the laboratory in order to examine the adequacy and accuracy for the model proposed. Through the numerical validation and experimental verification, current identification process is capable of monitoring the structural health condition by using the time domain input and output signals generated and received by a set of embedded actuator and sensor.

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Paper SHM 2002-039

Impact Damage Location in Composite Structures using Genetic Algorithm

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Composite materials have become widely used in many areas of engineering applications, especially when performance and weight saving is important. These include the use of composite structures in aerospace, automobile, marine and rail industries. However, composite are susceptible to impact damage, which may occur during manufacture, service or maintenance. The problem of damage detection in composite materials can be related to the problem of impact detection and location. Although, the problem of damage detection has been addressed relatively well, a very small amount of applied experimental research has been done in impact location. Impact damage detection methods are in fact inverse problems. There exist two algorithms in the literature. The first algorithm involves system modelling ; the model of the analysed structure characterises its dynamic response subject to a known impact location. Measured sensor output are then compared with the estimated responses from the model. If the two responses are not identical, the algorithm revises the model to characterise the response to a different impact location. The process is iterated until the model response and the actual response of the structure converge. System modelling is not easy for complex structures, and this is the major drawback of the method. The second algorithm involves artificial neural networks which are capable of modelling extremely complex relationship between input and output data. Although, the location results are impressive, the method requires a significant amount of impact data for learning and clearly this is not always possible.

A new method is proposed to avoid the difficulties associated with modelling and learning. The method combines a classical triangulation procedure with an experimental wave velocity analysis and the optimisation procedure. The experimental analysis is used to obtain the information about the velocity of impact of wave propagation. This information is then combined with the Genetic Algorithm to estimate the impact location. The method is validated on a composite panel using the smart sensor technology.

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Paper SHM 2002-040

Nondestructive Structural Health Monitoring with Acoustic Emission Signal Processing

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Structural health monitoring has been drawing more and more attentions as many infrastructures are getting older or have quality problems in materials or constructions or even both. Comparing with other infrastructures, bridges are more vulnerable to ages and construction qualities as they suffer dynamic loads of traffic and expose to environmental loads day by day. In recent years, there were many reports on bridge collapse around the world. These events cost life and money, and often cause chaos to local traffic systems.

In recent years, many nondestructive methods for the structural health monitoring have been developed. Among them, vibration test methods have been studied most extensively. Approaches include natural frequency variation detections and finite element model parameter change identifications or model updating. In addition to the fact that changes in natural frequency only reflect global deterioration in a structure, recent studies have found that environmental factors, such as temperature and humidity, could change the vibration parameters of concrete structures. Besides heavy working load for building a finite element model, finite element analysis based methods often have such problems as vibration test methods and sensor placements.

Compared to vibration test methods and other traditional methods of health monitoring, the method with acoustic emission (AE) signal has significant advantages. First, AE signals detected are generated by the structure itself rather than being excited by an artificial source. Thus diagnosis by AE signals does not interfere with the normal operation of the structure and can be conducted on an on-line basis. Second, AE signals can be related directly to the damage in a structure. No intermediate quantification or processes are needed, in sharp contrast to methods such as modal parameter identification and model updating. Third, the problem of instrumentation associated with the AE method is not as serious as other methods. It should be pointed out that AE signals can travel relatively long distances inside a structure. For this reason, the number of sensors required is smaller than that of modal parameter identification and model updating. Properly developed, the AE method should be substantially more efficient and powerful in condition monitoring of concrete than any known competing method.

An important task of AE signal based method is to identify the source of an AE signal, as different damage will have different influence on the integrity of a structure. For example, damages of a steel reinforced concrete structure are steel bar corrosion, concrete crack and separation of steel bar from concrete. Some accidents showed that the steel bar corrosion is most harmful to the structure. In this paper, approaches of AE signal processing to the damage identification are discussed. Methods include wavelet transform, bilinear transform, cepstral analysis. An AE signal deconvolution method is also developed for the damage identification from the features of an AE signal source.