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Paper SHM 2002-041

Seismic Damage Identification of a Tested Tall Building Model Using Hilbert-Huang Transform and Novelty Detection Technique

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Recent natural and man-made disasters have demonstrated the need for real time damage assessment of civil structures. In this study, a novel method based on a combined use of Hilbert-Huang transform (HHT) and novelty detection technique is developed for seismic damage identification of tall buildings. The HHT is superior to the conventional Fourier transform due to its adaptive ability in dealing with nonlinear and non-stationary signals. Moreover, the HHT provides time-frequency information which makes it possible to construct novelty detection networks just from one measurement. The proposed method follows three steps. The first step is to decompose each time-domain response sequence into a finite and often small number of intrinsic mode functions (IMFs) using the empirical mode decomposition (EMD) technique. This decomposition is based on direct extraction of the energy associated with various intrinsic time scales and is therefore applicable to nonlinear and non-stationary processes. In the second step, the HHT is applied to each IMF to construct the time-frequency-energy distribution of the signal, designated as the Hilbert spectrum, from which instantaneous amplitudes and frequencies are calculated. The third step is to use the instantaneous information for training novelty detection neural networks and for damage identification. In the present study, only the instantaneous frequencies are adopted to construct the novelty index for damage detection. The proposed method has two salient advantages: it needs no structural model, so it is applicable to tall building structures of arbitrary complexity; it uses only response signals (stationary or non-stationary) without need of excitation signals, so it is applicable for field ambient vibration measurement.

The proposed method is experimentally verified by shaking table tests of a 1:20 scale 38-storey building model. The tested structure is subjected to successively enhanced earthquake acceleration excitations on the shaking table. Accordingly, the structure incurs trifling, moderate, severe and complete (nearly collapsed) seismic damage respectively. After experiencing damage for each level, a 3-minute white-noise random excitation with low intensity is applied to the structure and the corresponding structural responses are measured for damage detection. A total of 27 accelerometers are deployed along the building height to collect acceleration responses in both east-west and south-north directions. Based only on the response accelerations, the EMD and HHT are implemented to extract the first 10 instantaneous frequencies. The instantaneous time-varying frequency sequences obtained in the intact state are used to train auto-associative neural networks, and those obtained in the subsequent states are presented on the trained neural networks to obtain novelty indices for damage alarming and quantification. Results of the case study show that the constructed novelty indices can clearly alarm the damage occurrence in all trifling, moderate, severe and complete damage cases, and indicate the relative damage severity among the cases.

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Paper SHM 2002-043

Principal Component Analysis of Piezo-Sensor Array for Damage Localisation

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It is well known that experiments produce noisy data due to numerous sources of scatter and uncertainty that are inherently present in all physical systems, and similarly in their numerical simulation models. Moreover, the increasing complexity of structures involves prohibitive size models for a direct correlation between analysis and test data. The problem of damage detection is then best approached on statistical grounds with a comparison between two sets of experimental data.

The general trend of smart structure shows an increase of the number of distributed sensors. The spatial information given by the distributed sensors (e.g.: piezoelectric laminates) can be used to forecast structural damage on localised critical spot. It is well known that localised structural damage with relative small amplitude do not affect significantly the modal response of the structure, at least at low frequencies. Nevertheless, structural damages, produced by fatigue or by exceeding the maximum stress, occur by failure propagation. It is then logical to expect that the crack propagation will affect the interface between the structure and a distributed sensor. A local delamination or an electrode deterioration at the distributed sensor level will show significant changes on the response of the sensor by modifying its apparent electromechanical coupling.

Assuming that the number of sensors is greater that the number of involved structural modes, local structural damage, with a relative small amplitude, will only affect a particular distributed sensor without affecting significantly the response of the others. By applying a principal component analysis (PCA) on the sensor time responses, it is possible to see that any change of one particular sensor properties will affect the subspace generated by the complete sensor response set. The subspace generated with the damaged structure can then be compared with the subspace of an initial state in order to diagnose damage or not. The principal component analysis can also be performed for every potential subset of damaged sensors in order to identify which sensor is injured, and therefore where the structure begins to be damaged. This damage detection and localisation technique is illustrated on a plate instrumented by several piezo-laminates and submitted to external loads.

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Paper SHM 2002-044

Design of optical fibre sensors for smart concrete structures

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One often speaks about the « in situ » experiment, insinuation of the experiment of the specialist man. Force is to note that an important part of our inheritance results from constructive provisions established starting from rules of dimensioning and know-how transmitted from generation to generation. Today, the improvement of knowledge and the provision of powerful tools of design, manufacture and control contributed to make evolve these practices. The request of the « customer » diversifies and the requirements become increasingly pointed. To the concept of object comes to be added that of service, of service level and functionality. As an example, one is not satisfied more than one « passive » material sold with meter-cubic or the ton, but one wishes to know some, at the same time, the history and to become it, i.e. the origin, the manufactoring processes, transportation, the implementation, conformity compared to the imposed specifications, the behaviour of use to short, average and long term. The recourse to total quantifiers to characterize each significant phase of the process belongs to a step overall « quality » required frequently maintaining in the schedule of conditions.

To meet these new needs, the tools and means of assistance to management and the decision have to be fitted. One wishes to have access to exploited information, the means to arrive there having to remain transparent for the user. The sensor thus becomes the link of a more or less complex chain which one associates: working of the signals, their validation, the extraction of the relevant data, the local or off-set treatment, the exploitation and the use of this information for if required ordering an action. They are thus systems.

In fact, the integrated equipment within structure does not seem only any more like one occasional means of monitoring of " pathological " cases, but an help with the «real time » assessment of the state of a structure during its existence. According to the service level of the tools and chosen exploitation modes compared to the use considered, it is possible to make a structure sensitive or to affect a certain more or less advanced controllability to it, that some do not hesitate to call « intelligence ».

The concept of “smart structure” is a natural evolution of our need for better control of field data processing, structural testing feedback and maintenance. Equipped with an automated network of reliable sensors, the structure permanently delivers, in real time, its mechanical behaviour, load bearing capacity and supplies information on its defects, reflecting its actual state. This cumulated knowledge will enable more efficient maintenance of existing structures and optimum design of future ones.

In concrete structures, optical fibre sensors, can collect data on the material core and surface. These measurement techniques are, in fact, a technology transfer from telecommunication systems, with regard particularly to interfacing, setting in sensor networks, and signal multiplexing and real time data processing. Besides, several sensitive elements (transducers) can be fused to a single multiple sensors, thus allowing a distributed metrology on a greater base, describing the whole structural behaviour.

These NDT physical tools, integrated within a control loop, offer possibilities for driving actuators. Nevertheless, difficulties may arise and depend on the required relevance and validation levels of the “rough” data especially when converted to suitable physical quantities. It is, thus, essential to know the behaviour of an embedded sensor and its response fitting the required parameter. The control of the intrinsic and extrinsic optical fibre sensor characteristics is not direct because it requires a good knowledge of the behaviour of involved materials and mechanisms governing the various interfaces existing between medium and the active part of the measuring element.

Indeed, the delivered sensors output information, are influenced by the coupling between the concrete material, the conditioning of the sensor body and the optical fibre. This leads to an approximate representation of the true concrete strain due to inclusion effect of the embedded sensor. Under these conditions, the knowledge of the “filtering” function is essential for access to the true quantity. Moreover, the remark can apply to a great number of transducers.

Local concrete heterogeneity is likely to influence the sensor response, according to its nature, to various degrees developed by micrometrical size of the optical fibre body. Furthermore, the discontinuity of the elasticity modulus at the aggregate-binder interface can cause punching and modify instrumentation performances.

In short, the control of the “filtering” functions will make out of the technology a key too satisfying our present need for smart structures (especially with regard to strain monitoring). To this end, studies were conducted through theoretical modelling and experimental testing. Results are discussed.

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Paper SHM 2002-045

Three–Dimensional Finite Element Analysis of composite patches with embedded optical fibers – Selection of Optical Fibers Paths and Sensors Locations

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A classical cracked metallic structure repaired with a “smart” bonded composite patch has been studied using finite element analysis, to select appropriate optical fibers paths and Bragg Grating sensors locations. The patch is bonded over a cracked aluminum plate by means of a thin adhesive layer. External loads were applied on the metallic structure, as in a real repair case. The primary loading axis of the metal was assumed to be parallel to the direction of the optical fibers. Different optical fiber paths and sensor positions were considered, in order to study their ability to measure the developed strain field and to trace the position of the crack tip. It was concluded that a fiber optics network is capable of tracing the critical parameters required for the on line monitoring of the structural integrity of composite patch reinforced structures (i.e. strains developed at the patch and position of the crack tip). However, the optical sensors should be located according to certain rules, in order to acquire reliable results. At least two Bragg Grating sensors should be used at each side of the crack per optical fiber, to enable adequate monitoring of the strain field and the crack tip location. For the case of one-sided patched structures, optical sensors should be located 2-3mm far from the crack axis and repeated at regular intervals of 2-5mm away from the crack tip, (depending on the required accuracy) until the predicted crack propagation limit. For the two-sided patched structures the optical sensors should be placed closer to the crack axis (i.e. only 1mm away) keeping the same periodicity. The second row of sensors should be located approximately 5-7mm far from the first.

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Paper SHM 2002-046

Damage Behavior Analysis Using CFRP Laminates with Embedded SMA Foils under Quasi-Static Uniaxial Tension Load

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The authors have been conducting research and development of the damage suppression systems by using the recovery stress of SMA foil actuators for weight reduction of next generation aircraft. In former studies, the authors confirmed the suppression effects of damage onset and multiplication through the results of load-unload tests and fatigue tests using CFRP laminates with embedded SMA foils [1]. However, their studies were not sufficient for application to the actual aerospace structure because of the simple sequence laminates.

Therefore, the authors have further discussed the effects of recovery stress of SMA and the mechanism in order to prove the damage growth suppression effects on quasi-isotropic CFRP laminates ([+45/0/-45/90]s) using T300/F593 prepreg system in this paper. Then, the authors conducted the load-unload test using the specimens, which is manufactured with the several different kinds of interface conditions. After that, the damage behavior was discussed about transverse crack onset strain and crack density.

Furthermore, this paper described stress distribution of 90 degree ply by FEM analysis to simulate the effects of SMA with respect to damage growth suppression of CFRP laminates. Then, the analysis was conducted for 2 cases, when the SMA embedded to CFRP laminates and when the embedded SMA heated up to over Af temperature. The analysis was found to agree well to the test results. Therefore, it was concluded that the damage growth suppression effects of SMA was generated by the both recovery stress and embedded effect of SMA.

Reference

[1] T.Ogisu, M.Nomura, N.Ando, J.Takaki, M.Kobayashi, T.Okabe and N.Takeda, “Development of damage suppression system using embedded SMA foil in CFRP laminates”, *Proc. of 8th SPIE Smart Material and Structural System*, Vol.4333, pp.387-398, 2001.

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Paper SHM 2002-047

Monitoring the Surface Condition under Cyclic Loading at the Location of a Circular Hole

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It would be of very great advantage to practical engineering if it were possible to detect on the surface of a structure a warning just before the structure was about to rupture. It is plausible that rupture takes place after the material has reached yield point and has gone through the process of forming a crack. If it were possible to detect yield stress, it would serve to predict a rupture. When a carbon steel plate undergoes yield stress it manifests Lüders' lines on the surface. It is very easy to detect the striped patterns of Lüders' lines with the naked eye. As the load increases the Lüders' lines gradually assume an orange-peel. We have reported that a similar phenomenon takes place in the case of cyclic loading. By using Lüders' lines as a smart sensor it is possible to apprehend the inception of the yield area on the surface of the plate, brought about by cyclic loading, in real time. In this case, no special instruments are necessary; simply by polishing a fixed area to a smoothness of less than Ra:0.2ì m, observation can be made with the naked eye.

If there is a circular hole in the member, the stress concentration induced by cyclic loading will take place there, and thereafter bring about yielding. As a concrete example to illustrate the utility of Lüders' lines as a smart sensor, direct observation was made of the changes on the surface of a flat bar made of carbon steel, when cyclic loading of different load ratios were applied to the vicinity of the circular hole. The yield area appearing in the vicinity of the circular hole changed into an orange peel, after which a crack appeared, and thereafter the bar broke at the same place. The yielding in the vicinity of the circular hole at a load ratio of 0 was similar to that of monotonic loading, but at a load ratio of –1 the states of the two plates were clearly different. The stress distributions at the vicinity of the circular holes was gathered and compared by means of FEM analysis. The stress distributions obtained by FEM and by experiment were the same only under limited conditions. Comparison was made of the change in the Vickers hardness and the surface roughness as monotonic loading with a load ratio of 0, and cyclic loading with a load ratio of –1 were applied to the specimens. It was obvious that in the case of cyclic loading the stress concentration factor had no appropriate application. It is possible to use Lüders' lines as a visible smart sensor in real time to monitor the outbreak of a yield area and predict fracture.

Figure A exhibits the yield area in the vicinity of the circular hole at the time of load ratio:0. Figure B exhibits the yield area at the time of load ratio:-1.

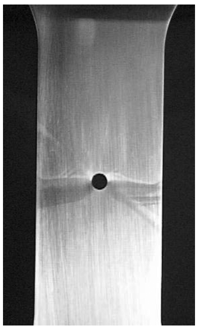

Figure A: load ratio: 0

Figure B: load ratio :-1

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Paper SHM 2002-048

Identification of the Critical Components in a Transportation Network: a Case Study

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Transportation infrastructures are networks made by structural components linked each to another by earth-works. In the European context, it is quite difficult to meet infrastructures of recent constructions (and/or of recent upgrading) which do not interact with a pre-existing network resulting from the centuries of man actions on the environment. As a consequence to manage a transportation infrastructure does not mean to work on the designed infrastructure but on the complex system which arises from many overlapping networks.

This paper reports the progress of an investigation covering an Alps valley linking a large town with its winter sport resort. It also represents one of the trade traffic ways between two neighboring countries (see Figure 1).

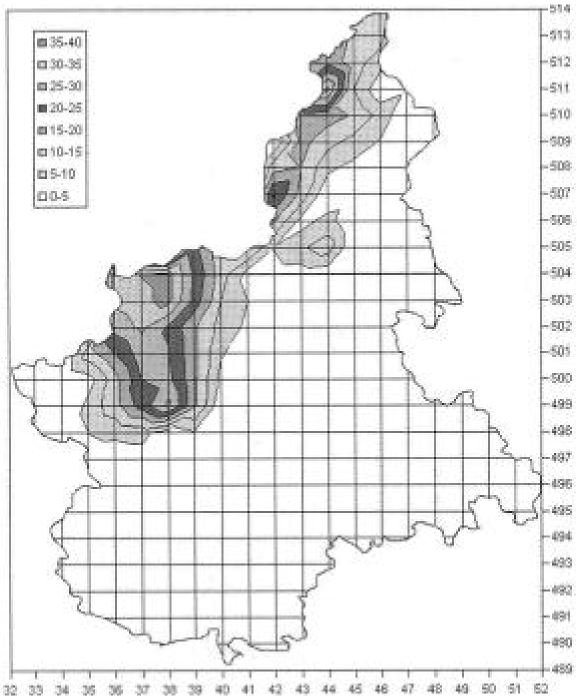

Figure 1 – Characterization of precipitations in the valley under investigation during a catastrophic event of 1993.

The approach illustrated in the paper can be summarized in the following steps:

1) adopt a satellite image with high resolution (i.e.. of the Ikonos class with 1m of resolution) as basis for the Geographical Information System (GIS); repeated image acquisition (twice per year, for instance) allows one a real time update of the global information;
2) build over the satellite image an integrated database, by collecting all the existing material in terms of: i) structural component design and maintenance status; ii) earth work in terms of characteristics and actual maintenance; iii) surrounding basins and relevant hydro-geological data base; iv) seismic (if any) catalogue and any other source of hazard for the system under investigation;
3) adopt graph theory techniques to identify the critical components in the global system consisting of the main infrastructure but also of the interacting local traffic transportation branches. They offer desirable loops in the case of failure of single components;
4) monitor by standard techniques the few structural and non-structural components which result from the previous prioritization step;
5) start damage assessment schemes on the monitored components.

In particular this paper provides adequate details on steps 1) and 2) on which deep expertise was already gained in a previous research within the project RADATT (Gamba P. and Casciati F., 1998, GIS and Image Understanding for Near-Real-Time Earthquake Damage Assessment, Photogrammetric Engineering and Remote Sensing, 987-994) of the Telematic Program of the European Union..

Coupling the more hazardous areas with the network structural components is the main purpose of this preliminary study.

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Paper SHM2002-049

Structural Damage Detection Based on Dynamic Response Identification

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It is well known that current practice of aseismic design relies on the ability of a structural system to dissipate energy by undergoing local damage.

The after event task is then to test the structure in order to identify the actual damage. An optimum damage threshold for repair can be defined as the damage value for which the life-cycle expected total cost of the structure is a minimum. Such expected total cost involves the expected repair cost after each damaging earthquake occurs. The threshold can be estimated a priori by introducing the exceeding probabilities in computing the expected repair cost after each earthquake occurs, so that the life-cycle expected total cost can be obtained and, hence, the optimum damage threshold.

In this paper a multi-degree-of-freedom nonlinear structural system is numerically modeled and analyzed. This results in a variety of post event damaged structural systems: on them standard tests are applied. The purpose is to build a mapping between actual damage and test results. When a one to one correspondence cannot be established, a sort of testing re-iteration is used to solve the indeterminacy.

The after event tests one proposes are mainly of two types. The drastic drop of a horizontal force is used to generate a transient response whose parameters give the bases for assessing the initial damage. On the other side a sinusoidal force is applied at different locations and the resulting steady state responses are used to identify the initial damage.

A basic role is played in such an investigation by the definition of damage. Standard scalar definitions are useful but does not allow a unique solution in terms of suggested repair policy. A vector definition of damage is much better but its estimation requires a significant testing effort.

The two parameters which determine the rate of stiffness reduction as a consequence of deformation amplitude and cyclic response, respectively, are the main ingredients of the damage. They are considered uncertain in order to take into account uncertainties in the structural properties.

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Paper SHM 2002-051

Use of electrical potential as a damage detection technique in Carbon fibres reinforced polymers

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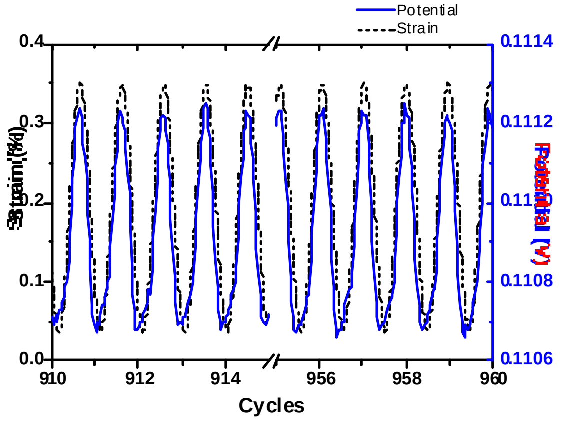
Carbon-fibre-reinforced polymers (CFRP) are increasingly used as structural parts, especially in the aircraft industry. Despite their excellent mechanical strength and stiffness, CFRP are susceptible to impact damage in service. If the damage is of sufficient size, both strength and service durability of the structure are degraded. A wide range of techniques have been proposed for in service detection, location and characterisation of delaminations and fibre breaks in CFRP materials. Amongst them, measurement of electrical potential differences on the composite component before and after damage looks very promising. Damage in the form of fibre breaks, splits and delaminations will cause local changes in the distribution of electrical resistance in a composite. The advantage of this technique is the use of carbon fibres as embedded sensors for in service detection with on board measurement systems.

In order to assess the capability of this technique for practical damage detection, it is important to understand the role played by factors in addition to mechanical damage in changing electrical resistivity. Cyclic loading tests have been conducted on unidirectional T300/914 CFRP composite materials. The dimensions of this sample were 280x30x2 mm. The following aspects were investigated:

- Effect of current input attachments on the distribution of electrical potential in the sample
- Effect of damage on the sample resistivity change

Two different types of current input were manufactured. Current wires were attached using a high viscosity carbon cement, and secondly, silver dag- a low viscosity dispersion of silver particles in a liquid. Current was input at two locations (a) across the sample width at the sample ends, and (b) at points on the sample surface. Electrical potential was measured on the sample surface both across the width and at separate points, and was used to monitor resistivity changes on cyclic loading.

It was found that, the longitudinal resistivity change in the sample was out of phase with the strain changes when carbon cement was used. However, when silver dag was used to attach the current leads, the strain history was in phase with the resistivity changes. A microscopic inspection of the contact surface between specimens and current input showed that the silver dag creates a continuous contact with the specimen edge. However along the interface between the specimen and the carbon cement there were many gaps. To show the effect of such gap on the potential changes, a discontinuous surface contact was deliberately created in silver dag.



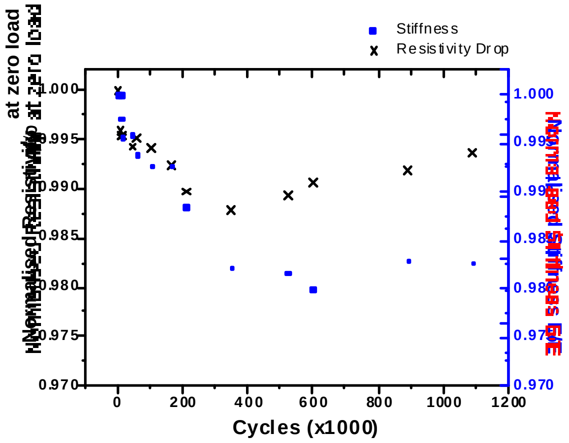


Figure 1 – Potential changes with strain level in the longitudinal direction after 1000 cycles

Figure 2 – Measurement of the longitudinal resistivity change from the minimum to the maximum loading and stiffness drop against the cycling loading number

When the potential probes are located in line with the current contact points, the potential is always in phase with the strain (figure 1). However, if the potential is measured on probes which are not located in the line of current flow, the electrical potential change is out of phase with the strain change.

Finally, up to 10^6 cycles were applied to the sample in order to investigate change of resistivity with fatigue induced changes in the stiffness of the sample. As is shown in figure 2**,** there are two different stages of the change of resistivity. At the beginning the resistivity decreases with decreasing stiffness. Later, there is an increase in the resistivity. The results are discussed in terms of the conduction processes occurring in carbon fibre composites, and the degradation caused by fatigue cycling.

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Paper SHM 2002-052

Application of Small-Diameter Fiber Bragg Grating Sensors to Health Monitoring of Composite Materials and Structures

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Small-diameter fiber Bragg grating (FBG) sensors have been developed by Hitachi Cable Ltd. and the authors. The outside diameter of polyimide coating is 52 m, and the cladding is 40 m in diameter. Thus, embedding of the sensors into carbon fiber reinforced plastic (CFRP) composite prepregs of 125 m in thickness does not deteriorate the mechanical properties of the composite laminates. In this research, the small-diameter FBG sensors were applied to detect transverse cracks and delamination.

First, for the detection of transverse cracks in 90-degree ply of a CFRP cross-ply laminate, the small-diameter FBG sensor was embedded in a neighboring 0-degree ply of the laminate, and the reflection spectrum from the FBG sensor was measured at various tensile strains. The spectrum became broad and had some peaks with an increase in the transverse crack density. Furthermore, the theoretical calculation reproduced the change in the spectrum very well. Thus, it was confirmed that the change in the form of the spectrum was caused by the non-uniform strain distribution due to stress concentrations around crack tips. Secondly, the delamination originating from a tip of a transverse crack in a cross-ply laminate was detected using a similar technique and also theoretically supported. These results show that the small-diameter FBG sensors have a potential to detect the occurrence of transverse cracks and delamination through the change in the form of the spectrum, and to evaluate the transverse cracks and delamination length quantitatively.

Moreover, as an application for actual composite structures, this damage detection techniques using small-diameter FBG sensor was applied to composite sandwich panel used for satellite structures. This panel consists of two CFRP face sheets and an aluminum honeycomb core including heat pipes. Since thermal expansion coefficients are very different between CFRP and aluminum, microscopic damages are introduced in the CFRP face sheets by thermal stresses when temperature changed over a permissible range. The small-diameter FBG sensor suits to the detection of these damages, because the face sheet is very thin, which is formed from only 4 plies as $[0/90_2/0]$. Thus, the small-diameter FBG sensor was embedded in the CFRP laminate, and the laminate was adhered to an aluminum square pillar at 120 degrees C, which is the cure temperature of the epoxy adhesive. During the cooling process to the room temperature, the reflection spectrum from the FBG sensor deformed. This is because microscopic damages occurred in the CFRP laminate because of thermal compression stress, such as buckling in 0-degree ply and delamination at 0/90 interface, and these damages caused non-uniform strain distribution in the embedded small-diameter FBG sensor. Hence, it was found that the damage detection method using the small-diameter FBG sensor could be applied for CFRP sandwich panel of satellite structures.

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Paper SHM 2002-053

Identification of Crack Location in Composites Using Fiber Bragg Grating Sensors

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The authors have applied fiber Bragg grating (FBG) sensors for the detection of transverse cracks in carbon fiber reinforced plastic (CFRP) laminates. The crack density can be evaluated quantitatively by the change in the width of the reflection power spectrum, because the form of the spectrum is deformed by the non-uniform strain distribution due to stress concentrations around crack tips. However, locations of the cracks cannot be identified by this technique. Hence, in the present research, two novel methods were proposed to identify the crack locations.

One method is the inversion from a complex reflection spectrum. First, the complex reflection spectrum from an embedded FBG sensor, which consists of a power spectrum and a phase spectrum, is measured. The phase spectrum can be obtained using a tunable laser and a network analyzer. Then, the profiles of the grating period and the average refractive index in the FBG are reconstructed from the measured complex reflection spectrum using an inverse scattering algorithm. From the profiles, the crack locations can be identified, because the positions of the peaks in the profiles correspond to the crack positions.

The other method uses chirped FBG sensors. Since the reflection power spectrum from a chirped FBG is expressed as a function of the position along the grating, the spectrum from the chirped FBG embedded in a composite laminate has dips corresponding to positions of the cracks. Thus, the crack locations can be identified directly from the positions of the dips in the power spectrum.

These two methods were applied to CFRP cross-ply laminates. First, a uniform FBG sensor was embedded in 0-degree ply on the border of 90-degree ply where transverse cracks appear, and the complex reflection spectrum was measured at various tensile strains. Then, the crack positions were identified through the inversion from the complex reflection spectrum. The obtained positions were compared with the observation at a polished edge surface of the specimen using an optical microscope. As a result, this inversion technique was found to be able to identify the crack locations precisely. Next, the chirped FBG sensor was embedded in the same location in the laminate, and the reflection power spectrum was measured. The measured spectrum had dips corresponding to crack positions observed by the optical microscope. Moreover, this change in the form of the spectrum could be confirmed by theoretical calculation. Hence, the chirped FBG sensor can also be applied to crack location identification.

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Paper SHM 2002-054

Corrosion damage identification on plates by optimisation algorithms

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The average age of commercial airplanes is increasing each year, with more than 25 percent of these airplanes over 20 years old [1]. The principal problem due to structural aging is directly related to corrosion detection [2]. Corrosion is the electrochemical deterioration of a metal, due to its chemical reaction with the surrounding environment. Studies on corrosion show that localized pitting corrosion work as crack generator and causes early crack formation and the beginning of fatigue crack growth. It can significantly reduce the service lives of structural components. Therefore, the safety of plane structures can be compromised by corrosion. The visual inspection is the most common technique to identify corrosion in aircraft. But not all areas affected by corrosion are easily accessible. In order to permit the identification of corrosion in these zones, several methodologies were developed. Two basic ways can be identified to provide information on corrosion problem [3], the engineering data and operational data. Engineering data is related to identification of changes in physical dimensions or material properties of structures. The main techniques are based on acquisition of the structure response after an excitation that could be ultrasonic or acoustic and so on [4]. Operational data is based on monitoring of changes in the corrosivity on structures by information gathered using insert probes and chemical analysis [5].

This paper presents a numerical simulation coupled to an experimental campaign, aimed at identifying location and severity of corrosion. The identification of damage of the members of a structure from measured response characteristics is an inverse process. The identification process was carried out comparing the modal characteristic of numerical model and the damaged structure. This identification process was performed using an optimisation algorithm of Ansys commercial code.

In the optimisation process the correct choice of the objective function and the design variables has great importance to identify corrosion damage successful. At this aim, the objective function was based on COMAC (Coordinate Modal Assurance Criterion) while as design variables the element thicknesses were chosen. The location and severity of corrosion damage were identified by changes of element thicknesses.

In order to reduce the computational time, the identification process was divided in two steps. In the first step the damaged macro-areas were detected by major thickness changes, in the second, after a subdivision of the detected damaged zone in smaller areas, a more precise corrosion identification is obtained by considering as design variable only the elements of the previously identified macro-area. Different damaged configurations were considered. Single and multi-site damaged configurations were studied. Damage location and severity was successfully identified showing significant improvement towards a corrosion prevention and control program.

Indeed, the above figures show as the corrosion was identified in two different damaged configurations. In the first configuration, the area indicated in figure 1 was damaged by decreasing of 20% thickness. Results of the two identification process phases represented in the figures 3 and 4 as percentage changes of area thicknesses identify clearly the damage position and its severity (15% instead of 20%). An example of multi-site damage identification is shown in figure 2. The plate was damage as location shown in figure 4 by decreasing thickness of 20%. In the first phase of optimisation process (fig. 5) the damaged macro areas are identified, while in the second phase (fig. 6) a more precise localization and severity of corrosion damaged was obtained.

Once verified the strong dependence of damage identifiability with sensor positions, particular attention was put in the optimal sensor placement. At such aim the Effective Independence method (EFI) [6] was used (fig 7).

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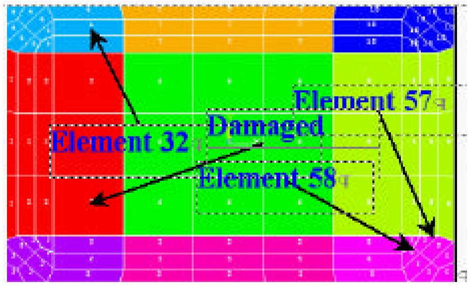

Figure 1 – One location damage

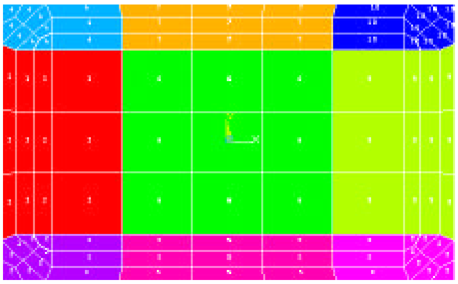

Figure 2 – Multi-location damage

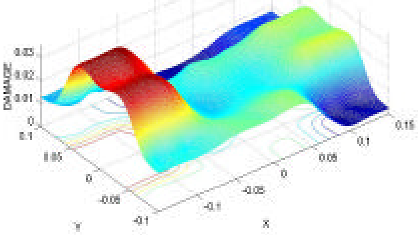

Figure 3 – First step identification

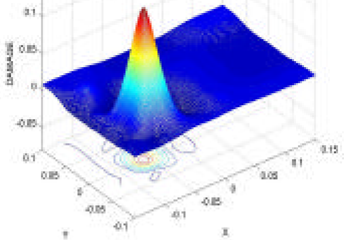

Figure 4 – Second step identification

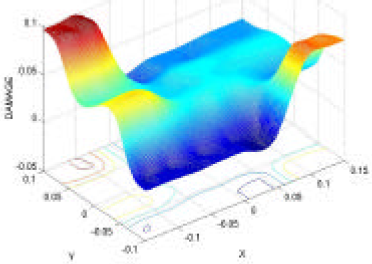

Figure 5 – First step identification

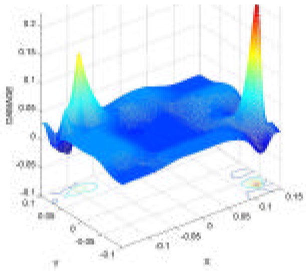

Figure 6 – Second step identification

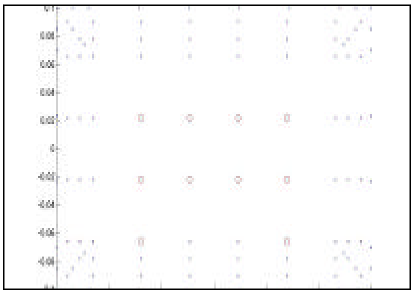

Figure 7 – optimal sensor placement by EFI

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Paper SHM 2002-055

Life Time Assessment of existing Bridges

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The prediction of the realistic fatigue life cycle of steel bridges is an important task nowadays. The classical approach consists of a model chain: a load model, a system-transfer model and a damage model is needed. Because the results of one model serve as an input for the next model, the systematic and the random errors of all models are multiplied. To avoid the errors of the load and the system transfer model the random strains at the critical points are monitored. Using a multi step Markov-process, including the past and the expected trends of the future traffic, synthetic time series of the local strains are generated which includes the real statistics of the process and cluster effects induced by truck convoys.

This synthetic time history of the local strains is used as an input for the controller of the test rig in which the same detail is tested, so the usually unreliable damage model is avoided.

The results of the method are very promising. The assessment of the life cycle of a structure is better in an order of magnitude.

If a structure is monitored right from the beginning, the procedure is straightforward. To predict the remaining fatigue life of an *existing* structure, time histories from the past would be required. Using the estimated statistical data of the distributions of traffic loads (i.e. heavy trucks, light trucks, cars and other vehicles), time histories of the traffic load from the past can be generated, which meets the statistical conditions.

The second problem is the simulation of the dynamic response of the bridge under the generated moving traffic loads, including the roughness of the road. The bridge is first modeled by the Finite-Element-Method and a modal analysis is carried out. The subsequent dynamic analysis includes the movement of the bridge (in modal space), coupled with the moving traffic loads under consideration of the roughness of the road. This roughness is considered in physical coordinates as a random stationary process and characterized by a power spectral density, discrete bumps can also be taken into account. The vehicles are modeled by a damped spring mass system of two degrees of freedom for each wheel. Three types of vehicles are distinguished up to now. The nonlinear bridge-vehicle interaction forces are iteratively calculated in the time domain. The calculated responses under different traffic conditions are used as an input for the above mentioned synthetic time histories.

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Paper SHM 2002-056

Fast and Reliable Technique for Optical Fibres Bragg Grating based Sensor Systems

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Fiber Bragg Grating Sensors are becoming a “state of the art” for new sensing techniques. Many applications have been developed and demonstrated to be a powerful concentration of precision, embed ability, EMI immunity, and multifunction devices.

From a point of view of interrogation techniques, typical responses do not match the extreme resolution supported by FBGS themselves. Even if it can avoid the interferometric disadvantages with new Optical filtering, which solve also the slow response of Optical Spectrum Analyzer solutions, something is missing. Phase Drift, Expensive and complex schemes are always present in any of State of the Art concurring commercial available interrogation devices.

We propose a novel technique namely: Broadband Interrogation and Bragg Grating Based Optical Filtering, which is characterized by High Resolution, Robustness, Dynamic Measurements, Low Cost. After theory exposition, a proper normalization provides a robust immunity of the sensor response to intensity fluctuation, optical losses, microbendings along the optical chain is shown. Experimental Sensor Response graphs show the 0.1 °C Temperature and 1 Micro Static Strain Resolution Measurements. Sensor Bandwidth experimental graphs are limited only by the electronic circuitry (up to 1000Hz). Actual studies promise to cover Band Width Sensor both for Modal Analysis and Acoustic Emission Testing Techniques.

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Papers SHM 2002-057

Damage Detection and Repair Quality Assessment in Stiffened Aircraft Panels via Vibration Testing

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The combined problem of *skin damage detection* and *repair quality assessment* in stiffened aircraft panels based upon vibration testing is considered. The panel examined[1] is from a Vought A-7 Corsair aircraft, and weighs 887gr. Initially it is in healthy condition, then damaged by a user-imposed 25mm long sawcut on its skin, and finally repaired by using a composite material patch[2,3,4].

Vibration testing is based upon free-free panel suspension and application (via an electromagnetic shaker) of a random force on the panel skin and measurement of both the force (via an impedance head) and the resulting vibration acceleration (via lightweight accelerometers) at three skin locations [Figure 1].

The vibration based methodology for skin damage detection and repair quality assessment is formulated based upon parametrically (using Vector AutoRegressive with eXogenous excitation – VARX - models) and non-parametrically (using Welch spectral estimates) obtained transfer function (Frequency Response Function) interval estimates[5,6,7]. The interval estimates incorporate the probability density function of the estimated quantities and allow the formulation of statistical hypothesis tests for proper damage detection in the presence of experimental uncertainty. Damage detection is thus based upon the statistical detection of changes in FRFs and global modal parameters in two distinct frequency ranges: The “lower” frequency range which accounts for the panel’s “global” behavior, and the “higher” frequency range which accounts for the panel’s “local” behavior. An additional criterion that is formulated for effective damage detection is based upon statistically significant changes in the estimated coherence function, and in particular in its measure obtained by the coherence integral over the frequency range of interest (“coherence measure”, or equivalently its complement designated as the “coherence residual” – see Figure 2).

The results of the study indicate that *skin damage* may be reliably detected based upon detection of statistically significant changes in the FRFs, or global modal parameters, or coherence function estimates. As it may have been expected, the “higher” frequency range – as opposed to its “lower” counterpart” - is considerably more sensitive to skin damage and may be effectively used for this purpose.

Repair quality assessment – that is assessment of the panel’s proper restoration – is a more difficult problem due to the fact that the composite material patch significantly increases the local mass (the total mass is increased by 3.5%). The “lower” frequency range characteristics of the repaired panel correspond nicely to its original (healthy) condition, but – as a result of the mass increase – this is not the case with the “higher” frequency range characteristics. Yet, the coherence function may be effectively used in this case, as the coherence is generally reduced with damage and then drastically improved (very often to a level even better than that of the original / healthy panel) following repair (this is due to the actual “strengthening” of the panel’s elasticity). A typical result is shown in Figure 3, where the coherence residual is significantly reduced for the repaired panel at three different measurement locations.

In summary, the proposed vibration testing based methodology, which properly accounts for experimental variability, appears promising for the effective detection of skin damage and the proper assessment of skin repairs in light aircraft panels.

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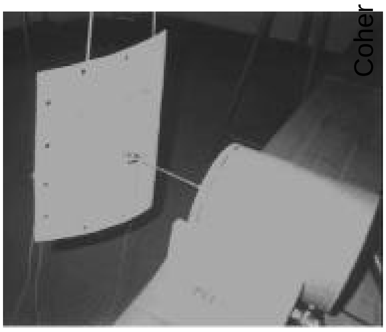
Figure 1: The experimental setup.



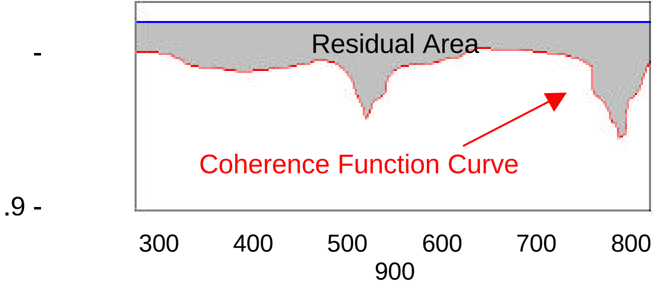


Figure 2: The residual area.

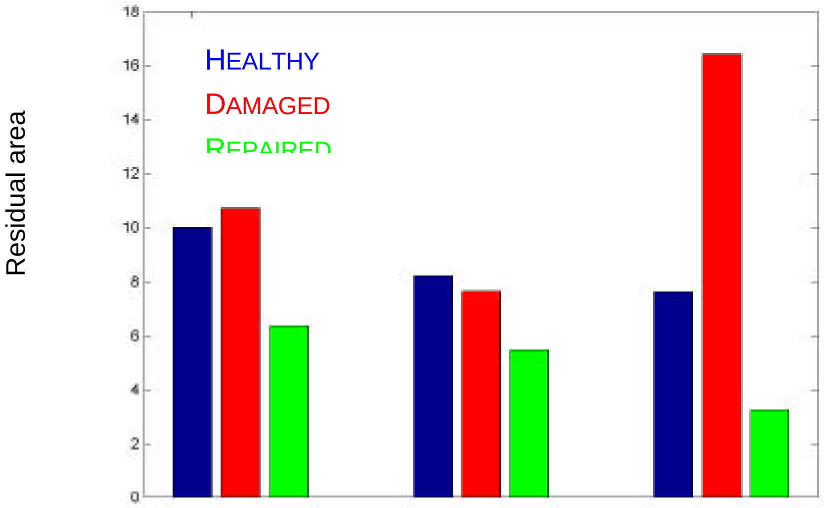


Figure 3: Coherence Function between the applied force and the accelerations at three different

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Paper SHM 2002-58

Measurements and Modelling for the Monitoring of Damaged Laminate Composite Structures

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Metallic structure monitoring has proved its capacity to reduce both the risks of accident and maintenance costs. Designing monitoring systems of damages on composite structures is hard, because of the complexity of the material's behaviour.

Existing systems [1] generally use piezoelectric transducers integrated into the structure in order to measure mainly the damage created by impacts. We are interested in the damages created not only by impacts but also by static and fatigue loading. This measurement allows us to determine the kind of damage produced, whether they be, diffuse (microcracks), ply fractures or delamination, and to locate and measure their levels (figure 1). The monitoring presented here consists not only measuring damages but also in predicting their evolutions with modelling tools.

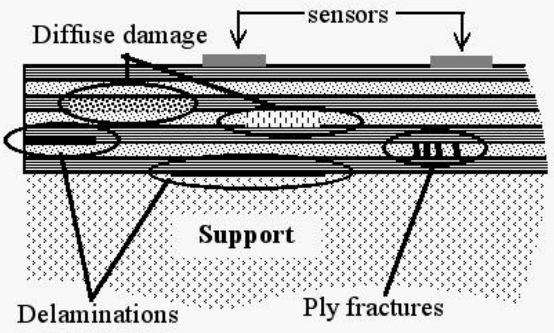

Figure 1

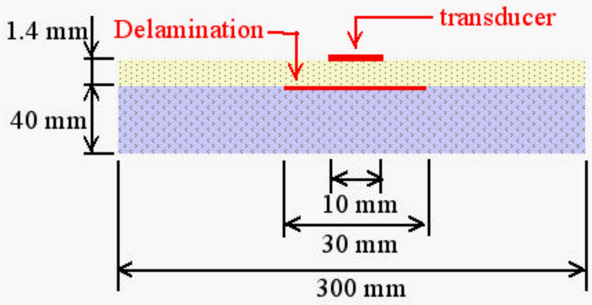

Figure 2

Various methods using piezoelectric transducers make it possible to highlight the appearance of degradations within a laminate:

- Lamb waves transmission between two transducers [2]: change in propagation velocity and attenuation, wave diffraction, …
- Electrical impedance response of a piezoelectric transducer coupled with the structure [3]: change in spectrum.

Both measurement methods can be carried out with the same transducers. Damage in a structure is not uniform and therefore the local character of measurement is very significant. Only the impedance measurement gives access to the damage characteristics close of piezoelectric without a complex information processing: inverse problems, neural networks.

Thus, our work concerns the identification and the measurement of diffuse damage, delaminations and ply fractures by electrical impedance measurement of piezoelectric transducers and Lamb waves transmission between two piezoelectric transducers stuck to a carbon-epoxy laminate.

We simulated these various damage using a finite element software application (ABAQUS) and analytical models (1-D and beam) to highlight the phenomena that generates impedance modifications. These simulations also allow us to design the optimal measurement system, by analysing the influence of the form and the position of the transducer, dimensions and the elastic characteristics of the laminate.

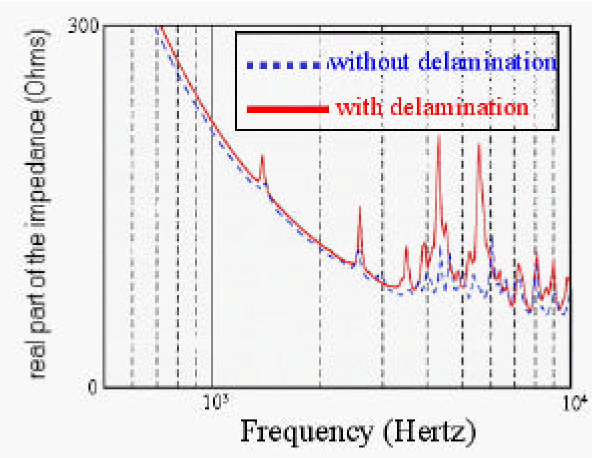

Figure 3

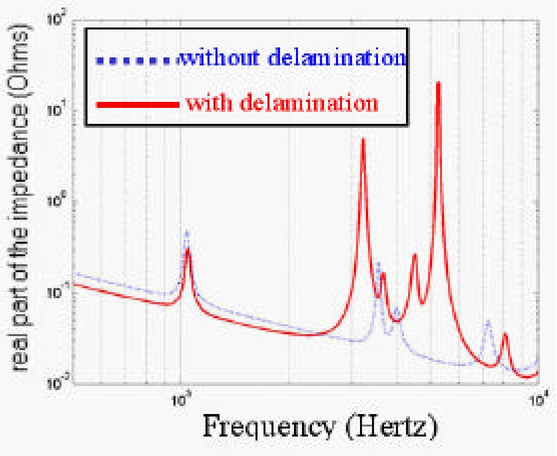

Figure 4

Delamination monitoring:

The structure which we studied is a carbon-epoxy laminate stuck onto a foam polyurethane support (figure 2). A delamination between the composite and the support is created during manufacture. The impedance measurement makes it possible to visualize the modes modified or created by the presence of delamination (figure 3). F.E. simulation (figure 4) also shows the presence of two modes related to delamination. The first mode caused by delamination (f#4000 Hz) corresponds to the first flexural mode of a 30 mm length embedded beam of the same laminate: thus measurement allows us to determine the delaminaton length.

Diffuse damage monitoring :

The goal of this monitoring is to measure the level of diffuse damage in order to readjust a predictive structure damage model (for monotonous and fatigue loading) [4, 5]. Diffuse damage leads to a decrease in rigidity (down to 50%) in some of the material's directions and an increase in damping. Because taking measurements locally produces significant results, two methods are then possible:

- amplitude measurement of local modes (high frequencies) with the use of impedance method which depends on the damping level,
- propagation velocity measurement of Lamb waves which is proportional to the square root of the rigidity modulus.

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Paper SHM 2002-59

Real-time Damage Detection of a Composite Cantilever Beam Using Wavelet Transforms

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There has been a growing interest in developing systems to monitor structural integrity of composite structures in real-time, especially in civil, aerospace and maritime structures. The reason being that as structures get larger and are built from more complex materials (such as composite panels) the costs of inspection and maintenance in terms of time and money increase significantly.

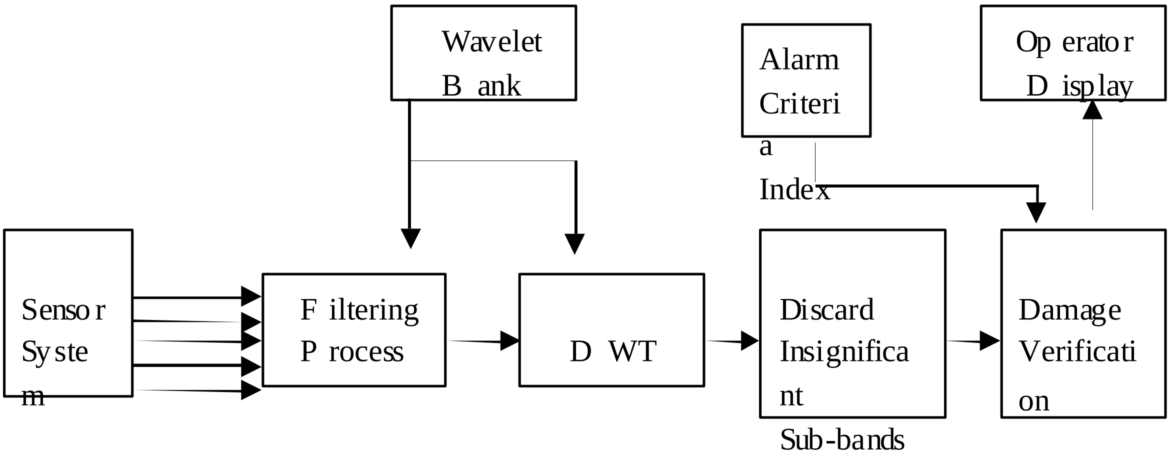
Structures which have these type of systems integrated into them can provide

- Information about damage and its location
- Monitor load in real-time to provide feedback so that performance can be adjusted to make sure the structure is not overloaded
- Improve performance and safety of the structure
- Reduction in maintenance and inspection times
- Verification of new structures and inspect how the monitored load it experiences compares with the simulated design
- Information on service lifetime of the structure based on analysing long term load history that can be recorded and stored

This research paper outlines the technique of using a composite cantilever beam as an example to demonstrate a real-time damage detection system. Fibre-optic Bragg grating strain sensors are embedded in strategic locations along the beam to measure internal strain.

A novel technique has been developed to gradually introduce damage inside the beam in the form of a de-lamination so that the progress of the damage between the ply's can be identified. The signals obtained from the Bragg grating sensors are generally affected by noise due to the thermal effects, so Wavelet Transforms are used to initially to filter the signals from the Bragg grating strain sensors so that a discrete version of the Wavelet Transform(DWT), implemented in hardware, can divide the signal into different sub-bands in-order to discard the insignificant sub-bands and analyse the rest for anomalies among the frequency components due to damage. A block diagram of the system components can be seen below.

An index such as an alarm criteria can be developed so that if a critical level has been or is about to be reached an indication of damage or impending damage can be displayed on an operator display.



Block Diagram of On-Line Damage Detection System Using Wavelet Transforms

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Paper SHM 2002-060

New general signal processing approach for health monitoring

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A new general signal processing approach was proposed [1-6] for those cases when one or multidimensional Fourier transforms are used for health monitoring, diagnostics, and prognostics. This approach consists of using simultaneously the real and imaginary components of the Fourier transforms as features. This is in contrast to most published applications concerning health monitoring, diagnostics, and prognostics where the power spectral density and phase spectrum are used.

In the presented paper mentioned approach is utilized for health monitoring in frequency domain using vibroacoustical signals. The comparison of the health monitoring effectiveness between the proposed features and power spectral density is done, taking into account covariance between the proposed features.

Covariance and the correlation coefficient between the proposed features are obtained for the first time for *arbitrary* stationary vibroacoustical signals.

It is shown that generally the power spectral density and phase spectrum are not an optimal features and represent only a particular cases of the likelihood ratio of the proposed new features.

The vibroacoustical health monitoring, based on Gaussian zero mean signals, is considered. It is shown that the use of power spectral density is optimal if simultaneously: (a) the correlation coefficient between Fourier components is equal to zero and (b) the standard deviations of these components are equal.

The use of the proposed features provides a gain in health monitoring effectiveness in comparison with the power spectral density. This gain is reached for arbitrary values of correlation coefficient between the features and the difference between the feature's variances. Health monitoring effectiveness gain increases as correlation coefficient departs from zero. It is shown that accounting for the covariance between the proposed features improves the health monitoring effectiveness.

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Paper SHM 2002-061

General adaptive decision-making technique for health monitoring

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Usually health monitoring is carried out under the presence of the nuisance parameters of the tested objects and environment. A new general adaptive approach for decision-making was proposed [1-2] to preserve health monitoring optimality in these cases. The basis of this approach is to define and measure the nuisance parameters and use the adaptive likelihood ratio to decrease the influence of these parameters on the health monitoring effectiveness. The adaptive likelihood ratio [1-2] depends on the diagnostics features and also on the measurable nuisance parameters. This is in contrast to most published applications concerning health monitoring, where the classical likelihood ratio is used.

In the presented paper mentioned approach is utilized for the vibroacoustical free-oscillation method of the fatigue crack monitoring. The adaptation consists in the variation of the likelihood ratio with the estimates of the nuisance parameters of the tested object.

It is shown that the use of the proposed technique provides a gain in health monitoring effectiveness in comparison with the classical likelihood ratio.

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Paper SHM 2002-062

Structural Health Monitoring of Draglines Using Lamb Waves

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The Australian coal industry operates a large number of draglines, 30+ draglines by the BHPBilliton Mitsubishi Alliance alone. The average age of the fleet is ~25 years. Although some of the machines have passed their design life, there is pressure to increase the duty and extend their operational life. Unfortunately several large mining structures have recently collapsed, due to fatigue related component failures. It is essential that tools for assessing and monitoring the structural health of draglines be developed if they are to be managed safely and economically

In recent years there has been an increased use of smart structures concepts for assessing structural integrity, e.g. [1-4]. However, the use of these techniques has generally been limited to aerospace and military applications. The use of piezoceramics to produce Lamb waves for use in damage detection has been reported by numerous authors [3]. These devices are used to detect damage at the high end of the frequency spectrum, i.e. ~1 MHz. Lamb waves can propagate over long distances, giving the possibility of inspecting several metres of structure in a single test. This paper will show that by using Lamb waves, and by studying both the transmitted and the reflected waves, we can both determine the onset and monitor cracking in a typical weld cluster. This technique has the advantage that it can be performed automatically without increased downtime or the need to continually access hard to reach regions.

Figure 1: Dragline, and a typical weld cluster

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Paper SHM 2002-063

Permanently Installable, Active Guided-Wave Sensor for Structural Health Monitoring

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Most sensors considered for structural health monitoring such as fiber optics, stain gauges, thermometers, and accelerometers are passive. They detect environmental conditions the structure is subjected to that may be useful to infer the integrity and safety of the structure. The reliability and confidence of structural health monitoring would be significantly improved if active, instead of passive, sensors are used that, when actuated, can inspect critical load-bearing areas of the structure and detect and locate actual damages in the structure such as cracks, debonds, and corrosion wastage. This paper describes an active guided-wave sensor that can be used for periodic and long-term inspection and monitoring of structures for structural degradation such as crack formation and growth and corrosion material loss. The sensor, based on the magnetostrictive sensor technology developed and patented by Southwest Research Institute, is low-profile, inexpensive, and permanently attachable to structural surface. The sensor can inspect and monitor large areas of a structure and provide quantitative information on the condition of the structure. By multiplexing multiple sensors installed at strategic locations on a large structure (such as airplane, ship, bridge, offshore platform, large storage tank, building, etc.) from a single data acquisition station, the entire structure can be quickly inspected for damaged areas and trending that are needed for structural integrity assessment and determination of remedial action if necessary. Examples of the use of this sensor for structural health monitoring are given.

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Paper SHM 2002-064

Experiment study on the relationship between the angle and the resonant wavelength by using the SPRE

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According to the Surface Plasma Resonant Effect of the Kretchmann model , the paper discusses the sensitivity of the resonant wavelength to the variance of the incident angle, thus we provide the providence to make a new angle-measuring sensor.

1.Introduction

Nowadays, there are many means used to measure the variance of the angle such as the mechanic means, electronic means and optic means. One of the optic means to measure the variance of the angle by the theory of the surface plasma resonance [1] is to compare the intensity of the P light with the intensity of the S light [2]. Almost all of the optic measuring means are to measure the relative light intensity or absolute light intensity. Due to measuring the light intensity, the means require that the light source be very stable. In fact, however it is very difficult or very expensive to obtain the highly stable light source.

In the paper, we find that the incident angle is closely correlated with the resonant wavelength after analyzing the reflective light spectrum of the two layers of the film and the surface plasma resonant effect. And the phenomenon is proven by experiments.

2.Theory

In the following discussions, we used the Kretchmann model to describe the relationship between the angle and the resonant wavelength. In Figure 1, P is a prism which has two 45 degrees angles and one 90 degrees angle. M is a very thin layer of silver covered on the bottom of the prism. Under the silver layer there is the air. The surface plasma wave appears at the interface of the silver layer and the air at a special incident angle when the horizontal component of the wave-vector of the incident light is equal to the wave-vector of the surface plasma wave.

According to the Kretchmann model , the reflective index is:[2]

$$r_p = \frac{r_{01}^p + r_{12}^p \exp(2ik_{1z}d)}{1 + r_{01}^p r_{12}^p \exp(2ik_{1z}d)} \qquad (1)$$

where:

$$r_{01}^p = \frac{\dfrac{e_0}{k_{0z}} - \dfrac{e_1}{k_{1z}}}{\dfrac{e_0}{k_{0z}} + \dfrac{e_1}{k_{1z}}} \qquad r_{12}^p = \frac{\dfrac{e_1}{k_{1z}} - \dfrac{e_2}{k_{2z}}}{\dfrac{e_1}{k_{1z}} + \dfrac{e_2}{k_{2z}}}$$

$$k_{0x} = \frac{w}{c}\sqrt{e_0}\sin q$$

$$k_{0z} = \sqrt{(\frac{w}{c})^2 e_0 - k_{0x}^2} \qquad k_{1z} = \sqrt{(\frac{w}{c})^2 e_1 - k_{0x}^2} \qquad k_{2z} = \sqrt{(\frac{w}{c})^2 e_2 - k_{0x}^2}$$

r_{01}^p is the reflective index of the interface between the prism bottom and the metal film, r_{12}^p is the reflective index of the interface between the metal film and the air , d is the thickness of the metal film e_0 e_1 e_2 are the dielectric constants of the prism silver film air, respectively .

$k_{i,j}$ (i=1,2,3,j=x,z) are the wave vector in the three kinds of dielectrics, c is the velocity of the light and ω is the light frequency.

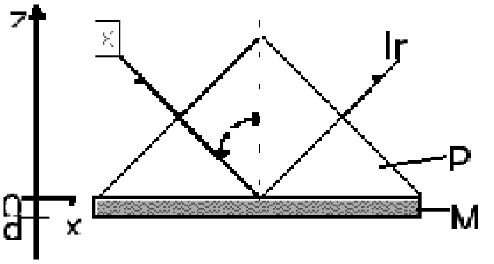

Figure 1 the Kretchmann model

The wave vector of the Surface Plasma Wave (SPW) is as following: [3]

$$k_{sp} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_p\varepsilon_m}{\varepsilon_p-\varepsilon_m}} \qquad (2)$$

Surface Plasma Wave Resonance (SPWR) appears when k_{sp} is equal to k_{0x}. As ε_0, ε_2, c, t (temperature) are constants and ε_1 is related with the λ closely, thus we have:

$$\varepsilon_1 = \varepsilon_1(\lambda) \qquad (3)$$

$$r_p = r_p(\lambda,\theta) \qquad (4)$$

3. Experiment

The experiment system is shown in Figure 2.

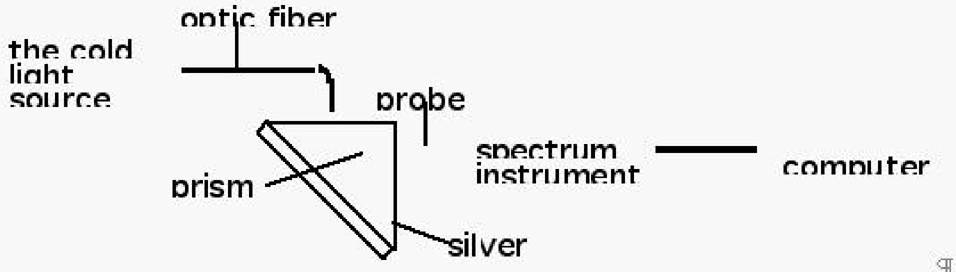

Figure 2 the experiment system

In the experiment, the spectrum range of the light source is between 480nm and 600nm. When the wavelength is the same as above, the refractive index of the prism is equal to 1.520 and the refractive index of the air is equal to 1. The light spectrum instrument used is EPP2000_UV manufactured by the Stalas Corporation in USA, whose light stitch is 25um and the probe sensor is made of CCD .We mainly measure the influence on the resonant wavelength produced by the angle variance .In the experiment ,the thickness of the silver film is 30nm .The reflective light from the interface between the prism bottom and the silver film is not a single color spot and there is some colorful stripes in the middle of the spot .This may be the result of the SPRE .To verify the thought we use the light spectrum instrument to measure the light spot and analyze it .The curves showing the relationship between the reflective index and the wavelength are shown in Figure3. In Figure 3, each curve is correspondent with a special incident angle. It is not difficult to draw the curve which shows the relationship of the incident angle and the resonant wavelength according to the data of the Figure 3, which is shown in Figure 4.

From Figure 3,one can find that the resonant wavelength changes greatly from 500nm to 600nm when the incident varied less than 3 degrees. One can measure the angle variance baseed on the reflective light spot diagram (Figure 3) .The way to measure the angle is accurate. On the other hand, due to use of the cold light source whose spectrum is very stable, the way to measure the angle variance overcomes the demerit existing in other ways in which the variance of the angle is determined by measuring the light intensity.

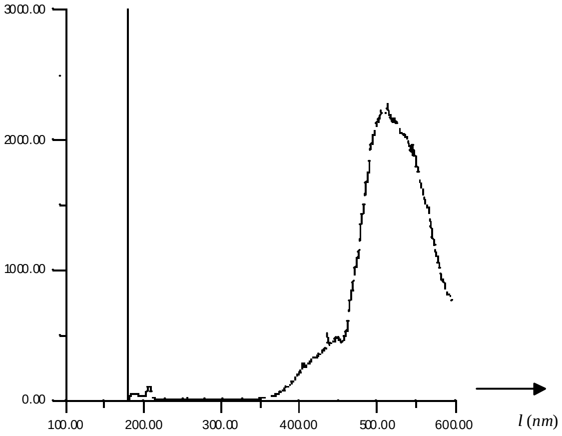

Figure 3 the curve lines of the reflective index and the wavelength

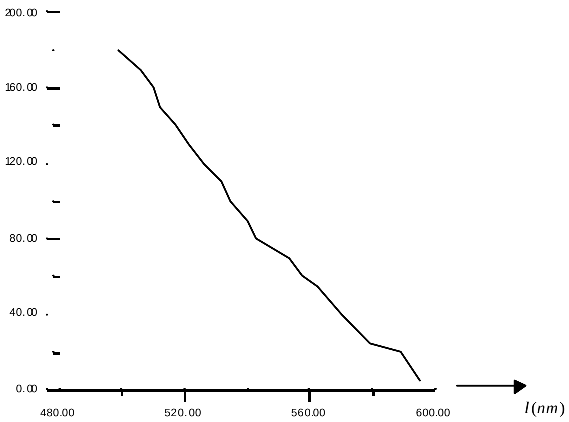

Figure 4 The curve of the incident angle and the resonant wavelength (The unit of angle is cent)

4. Conclusion

Based on the results reported here in, one find that the resonant wavelength and the incident angle have a definite relation when all other parameters are constant (In fact it is easy to realize) after studying and analyzing the SPW resonant character and the spectrum of the reflective light in the Kretchmann model, thus a new way to measure the variance of the angle is proposed ,the influence produced by the instability of the light intensity is eliminated by measuring the resonant wavelength.

5.Acknowledgement

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Paper SHM 2002-065

Electric Resistance Change Method for Monitoring of Embedded Delaminations of Quasi-isotropic CFRP Laminated Plates

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Laminated composite plates fabricated by stacking unidirectional plies have superior specific mechanical properties to the mechanical properties of the conventional metallic materials. The laminated composite plates, however, have a weak point at delamination resistance. The low delamination resistance causes delamination cracks by slight impacts. Since the delamination cracks are usually invisible, the delamination causes low reliability for primary structures of laminated composites. In order to improve the low reliability, detection systems for delamination cracks in-service are required. Health monitoring system to detect the delamination cracks is one of the appropriate technologies for practical laminated composite structures.

In the present study, an electric resistance change method is attempted to identify embedded delamination cracks. The electric resistance change method does not require expensive equipment. Since the method adopts reinforcement carbon fiber as delamination detection sensors, this method does not cause strength reduction, and applicable to existing structures. Therefore, the electric resistance change method has been adopted by several researches.

A research group of authors has already investigated the applicability of the electric resistance change method for monitoring of internal delamination crack using beam type specimens. For the beam type specimens, five electrodes are required to precisely identify delamination location and size. Analyses of electric resistance changes were performed using FEM, and the appropriate electric charging direction has been confirmed to the fiber direction of the surface ply. Using the plate type specimens made from cross-ply laminates, embedded delamination cracks were identified.

In the present paper, an effect of stacking sequences on delamination crack identifications is experimentally investigated using quasi-isotropic laminated plates. The specimen configuration is shown in Fig.1. As shown in Fig.1, ten electrodes were mounted on a specimen surface made from a CFRP plate. These electrodes were made from copper foil of 200µm thickness, and the electrodes were co-cured during curing process. The stacking sequence of the plate is [0/45/-45/90]s. An actual delamination crack was created in the specimen with the indentation loading using a cylindrical supporting jig. Electric resistance changes of the all segments were measured with electric resistance bridge circuits. Actual delamination crack size and location was measured with a scanning acoustic microscope.

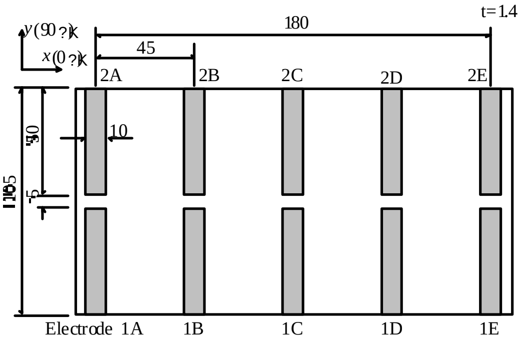

Fig.1 Specimen configuration

After the creation of the delamination crack, electric resistance change was measured. Sixty-four experiments were conducted with changing delamination location and size. As the tool for solving the inverse problem to identify delamination location and size from the measured electric resistance changes, we employed response surfaces. We made response surfaces to identify delamination location and size using the measured electric resistance changes.

The estimation results obtained from the response surfaces are shown in Table 1 by comparing with the results of the cross-ply laminates. As shown in the table, estimation reliability itself is lower than the case of the cross-ply laminates, although the reliability is high enough for practical use. This lower estimation reliability is supposed to be caused by the smaller electric resistance changes for the quasi-isotropic laminates. The smaller electric resistance changes were caused by the fact that the delamination crack location in the thickness direction was far from the surface in the quasi-isotropic laminates.

Staking sequence			$[0_2/90_2]_S$	$[0/45/-45/90]_S$
Number of electrodes			10	
Space of electrodes			45mm	
Number of experiments			64	
Number of data for regression			192 (64?~3)	
R_{adj}^2	Location	*x*	0.920	0.845
		y	0.826	0.755
	Size		0.753	0.843
Estimation reliability	Used in RS	Location (absolute)	86.5%	81.5%
		Location (practical)	99.5%	96.9%
		Size	81.3%	89.1%
	Not used in RS (12data)	Location (absolute)	66.7%	33.3%
		Location (practical)	100.0%	100.0%
		Size	58.3%	41.7%

Table1 Estimation results

The high estimation reliability is observed in the specimen middle points. When the delamination crack locates in the specimen edge, the estimation error is high. When the delamination crack locates in the middle of the specimen, the estimation agrees well. This is completely contract to the estimation results of the cross-ply laminates. This is caused by the difference of electric current in the specimen. This means that the stacking sequence has large effect on the electric current flow.

As a result, the electric resistance change method for the delamination monitoring is experimentally shown to be effective even for the quasi-isotropic laminates. This method is applicable without loading and for the existing structures by the low cost. This method is quite efficient for the improvement of CFRP structures.

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Empirical Models of the Non-linear Vibration of Cracked RC Beams

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Over the past twenty-five years there have been many studies into the application of modal and dynamic testing for the detection of damage in structural systems. The key principle underlying this technique is that damage to a structure - such as cracking or even the loss of one or more components - will result in a loss of stiffness, which is then detected as a change in modal properties. An overall reduction in stiffness will result in a reduced natural frequency whereas a change in distribution of stiffness through localised damage will result in a change in mode shape. The use of modal testing to detect these changes in stiffness has two distinct advantages over other forms of non-destructive testing. First, the modal characteristics provide a global picture of the structural system. Second, it is simple to monitor changes in these modal properties using relatively few sensors strategically placed on the structure.

There are, however, several problems in applying these methods in practice. For example, there may be confusion between the distribution and severity of stiffness loss. Also, for severe damage, comparing modal properties before and after is questionable as the modes are really “new modes” not “changed modes”. Most critically, it is often difficult to obtain reliable data free from other influences, such as environmental conditions and temperature. For Civil Engineering structures these issues can be especially important. A particular problem that occurs with reinforced concrete (RC) structures is that they can exhibit non-linear behaviour, even with relatively low levels of damage [1,2,3]. This in turn can make it difficult to make a reliable estimate of modal properties for use in damage detection/health monitoring.

To better understand this behaviour and the mechanisms that cause it, a series of studies have been performed at the University of Nottingham. Whereas earlier studies have focussed on simply confirming the presence of this non-linear behaviour [3] more recent work has concentrated on understanding more about the behaviour using non-linear system identification [4]. These studies have shown that the non-linearity is not due simply to the opening and closing of the cracks (so-called breathing behaviour) but is governed by the transition between crack open and crack closed. A simple phenomenological model of this transition considered the change in stiffness to be defined by a hyperbolic tangent function [5]:

$$k = \frac{(1-m)}{2} k_0 \tanh(ax+b) + \frac{(1+m)}{2} k_0 \qquad (1)$$

Where a and b are parameters defining the transition and k_0 and μ define the intact stiffness and stiffness reduction. The corresponding force displacement relationship is given by:

$$p = \frac{(1-m)}{2} \frac{k_0}{a} \ln(\cosh(ax+b)) + \frac{(1+m)}{2} k_0 x \qquad (2)$$

In this paper the authors compare the vibration behaviour of cracked RC beams with simulations made using the hyperbolic tangent model. The results show that the experimental variation of non-linearity with damage level (Figure 1) parallels the variation in non-linearity from the hyperbolic tangent model as parameter a is varied (Figure 2).

To establish the correct model parameters for the RC beams the restoring force surface method was first used to determine the non-linear force displacement relationships for the modal response. A curve fit was then performed on these data to determine parameters a, b, m and k_0 in Eqn 1 using an iterative least squares approach. These results confirm the suitability of the hyperbolic tangent model of stiffness transition.

In conclusion, although the variation of non-linearity with damage level is not sufficiently repeatable to be considered as a damage indicator, the phenomenon still needs to be understood if vibration data are to be used for damage assessment or structural health monitoring. The model developed here fits the experimental data and provides a method for dealing with non-linearity in monitoring data.

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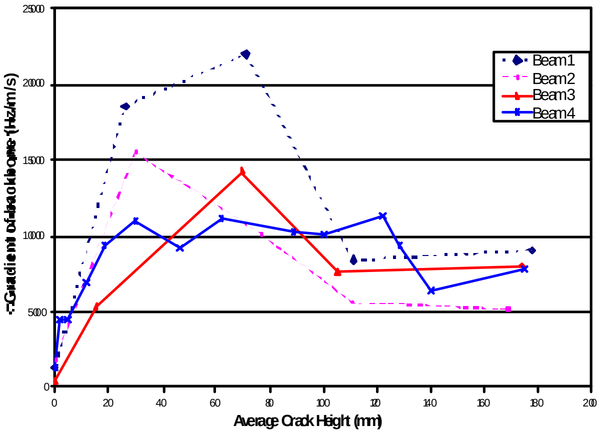

Figure 1 Experimental variation of non-linearity linearity with damage level

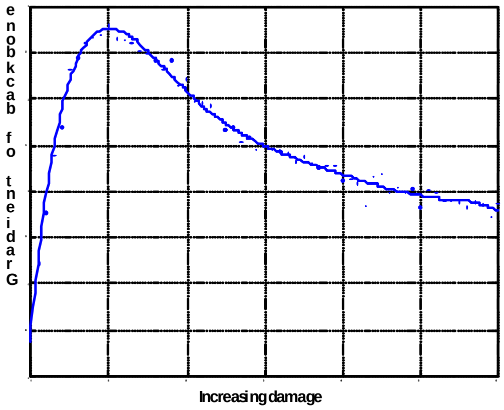

Figure 2 Predicted variation of non-with damage level

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Paper SHM 2002-067

Damage Detection in a Steel Bridge using Artificial Neural Networks and Signal Anomaly Index

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The purpose of this study is to develop a practical method to identify damage location and severity in steel bridges. A signal pattern recognition technique adopting artificial neural network is applied in this study. A parameter named as signal anomaly index (SAI) that quantifies the change of frequency response is also suggested for the development of modeling error tolerant damage localization method.

Signal anomaly index (SAI) is conceptually defined as a Euclidean norm of the difference between frequency response function (FRF) of intact and damaged structure. SAI values calculated for each measurement location and interesting frequency region form a SAI vector. Since the shape of SAI vector is unique for a specific damage location, and numerical model shows a similar shape of SAI vector to that of physical model, SAI application is effectively used for the identification of damage location with pattern recognition technique. In addition, use of SAI vector can contribute to avoid the performance degradation due to modeling error because it is hardly affected by modeling error.

A series of experimental tests for a model bridge has been performed in order to verify the suggested method. The model bridge consists of three steel girders, a steel slab plate and several lateral beams and added masses. Saw-cuts and loosening of bolts on main girders with several levels are imposed as damages. Acceleration and dynamic strain are measured for every damage levels. The feasibility of SAI vector for the identification of damage location has been verified using experimentally acquired signals and numerically simulated signals

The suggested method would be practically applied to real bridge with following advantages: 1) This method requires relatively short computation time, 2) This method is tolerant of remaining modeling error, 3) This method does not need modal analysis procedure to express the change of dynamic characteristics. The applicability and effectiveness of the suggested method will be examined with experimental test for real bridges in near future.

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Paper SHM 2002-068

Autonomous On-line Health Monitoring System for a Cable Stayed Bridge

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Automatic measurement of instrumented civil engineering structures is becoming more common for behaviour monitoring during construction in field as well as long-term monitoring for life time assessment. In order to deploy a successful monitoring system, the considerations necessary are: proper instrumentation, reliable signal processing and knowledgeable information processing. Since instrumentation which includes sensory device and data acquisition systems (DAQs) obtains raw data from the real structure, sensor technology is of critical importance in the development of a monitoring system.

A number of sensors and sensing techniques have been developed in recent years which have been the potential for meeting the eventual need of an automatic monitoring system. These fall into the domain of remote sensing and non-destructive testing. Selection and installation of proper sensors are key considerations. Beyond the sensory system itself, some additional facilities need to be located in the field as well as in the remote control space. These facilities consists of data acquisition systems, temporal data storage devices, telecommunication facilities, and some auxiliary devices.

Sensor signal must be processed and interpreted. Immense volume of often noisy signals generated by a multiple-channel sensory system should be manipulated concurrently and interpreted intelligently in both hardware and software considering each of the following:

- sensor network to support the safe and fast transmission of the data,
- an appropriate data acquisition and storage system, and
- signal processing to convert raw signals to useful data for monitoring and diagnosis.

The signal processing procedure consists of a number of operations such as signal acquisition, generation, and interpretation. In order to assess the current condition of the structure based on the signals, which is called as information processing, it is necessary to devise appropriate computational Paperions and support environments. To develop comprehensive computational environments for these purposes, a model of the information describing the system is required. This model must support a meaningful and computable representation of the components and their complex inter-relationships that are characteristic of engineering systems, such as physical configurations, sensors, signal processing, and diagnostic knowledge (Chen and Kim 1995).

This paper describes these three considerations: instrumentation, signal processing, and implementation of signal management program based on an ongoing real application to a cable-stayed bridge, Seohae Bridge, which was constructed to cross Asan bay between Pyongtaek and Dangjin in Western Korea in 2000.

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Paper SHM 2002-069

Fuzzy Logic and Piezoelectric Sensors for Materials Elastic Properties Analysis

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In this work a novel approach for unknown material recognition based on a smart tactile sensor is presented. It has been realized through the adoption of piezoelectric bimorph tactile sensors. The approach adopted is based on the idea of recognizing the material an object is made of, by analyzing the signal produced at the moment of touching and stressing it. The bimorph piezo-ceramic elements, used as actuators and sensors, allow for both stimulating the unknown surface and sensing the response signal. Two tactile probes, shown in Figure 3 and Figure 4, have been realized and a lot of signals have been gathered highlighting relevant differences in the elastic responses of various materials, as shown in Figure 1 both in time and frequency domain.

A functional block scheme of the whole system is represented in Figure 2. It is highlighted as two different strategies are considered for the problem taken into account. The "off-line" approach based on both time and frequency domain signal processing, allow to identify suitable numerical models that allow to classify the various surfaces.

The "real-time" strategy, based on the processing of spectral power densities of sensor signals in different frequency ranges, has allowed to realize an automatic measuring system, which allow to classify the elastic properties of a given material as a reaction to a given mechanical stimulus. In fact, all the materials examined presented different values of these energies of the signal in the frequency ranges chosen. A Switched Capacitors band pass filter bank and an analog circuit for computation of the V_{RMS} of each filter output has been used. Finally a classification algorithm, based on fuzzy logic and implemented on a dedicated micro controller, elaborates these input data in order to realize the on line material recognition.

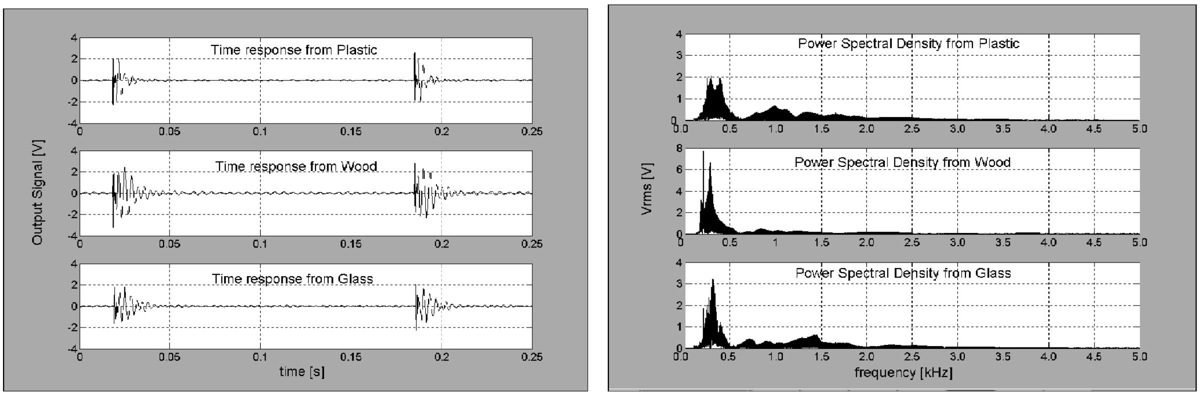

Fig.1: (a) Time responses and (b) Power Spectral Densities of signals related to three different materials.

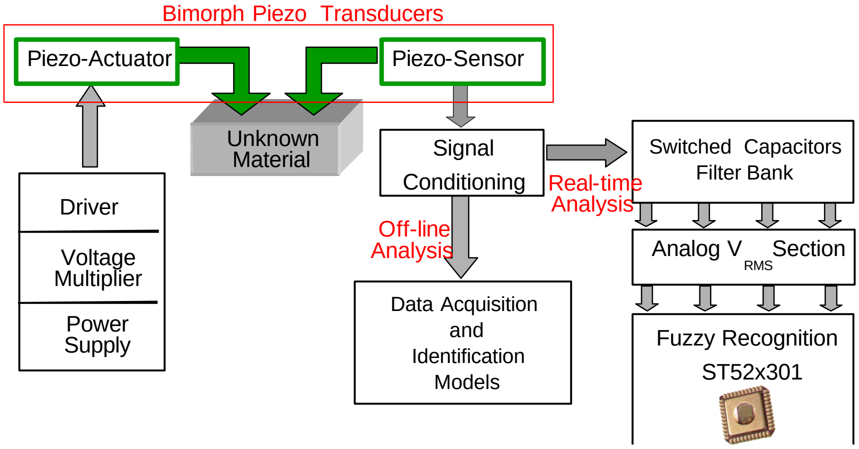

Fig. 2: Functional block scheme of the smart measuring system.

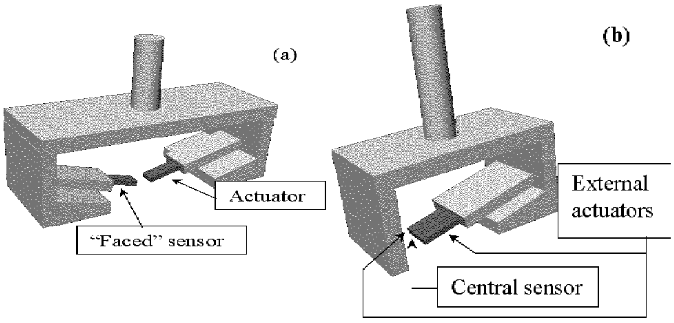

Fig.3: 3D Model of the two different probes developed and experimentally tested: (a) "faced" sensors and actuators and (b) "three-finger" bivalent probe.

Fig. 4: Pictures of the tactile probes realized. The **"faced"** structure is realized by placing the piezo actuator and sensor one in front to the other such to have high sensitivity to longitudinal waves. The actuator stimulates the unknown surface and the sensor gathers the elastic response to extract the material properties. In the **"three-finger"** system the external piezo realize actuation while the central one acts as sensor. Also in this case the elastic material reaction is monitored.

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Paper SHM 2002-070

Modal Characterisation of Civil Structures

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Extensive structural health instrumentation systems have been installed on a variety of civil structures, in particular, suspension bridges and offshore oil/gas installations. Modal parameters of the structures are computed from data recorded by a distributed array of vibration sensors. The structures are subject to two types of loading: (1) forced excitation using a shaker system, or (2) ambient excitation from environmental conditions (i.e. wind, waves). The instrumentation systems also record the input loading or environment. The modal and environmental parameters are used to provide indicators of structural health. These can be produced by automated data processing to give continuous information on structural health. In other applications, the modal parameters are used for design verification after construction or modification works. In this paper, some consideration is given to the relative merits of forced and ambient testing schemes.

First European Workshop on Structural Health Monitoring
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Paper SHM 2002-071

In-Situ Damage Detection of Composite Materials using Lamb Wave Methods

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Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to improve reliability and reduce life-cycle costs. The greatest challenge in designing a SHM system is knowing what “changes” to look for and how to identify them. The characteristics of damage in a particular structure plays a key role in defining the architecture of the SHM system. The resulting “changes,” or damage signature, will dictate the type of sensors that are required, which in-turn determines the requirements for the rest of the components in the system. Non-destructive evaluation techniques (e.g. ultrasound, radiography, infra-red imaging) are available for use during standard repair and maintenance cycles of composite structures, however by comparison to techniques used for metals these are expensive, time-consuming and can be unreliable. Cost-effective and reliable damage detection is critical for the utilization of composite materials in structural applications. This paper presents part of an experimental and analytical survey of candidate methods for in-situ damage detection of composite materials, along with guidelines and recommendations drawn from this research to assist in the design of a structural health monitoring system for a composite vehicle.

Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries. Two groups of waves, symmetric and anti-symmetric, satisfy the wave equation and boundary conditions for this problem and can propagate independently of each other. The present work utilizes piezoelectric patches to excite the first anti-symmetric Lamb wave (A_0 mode) in composite specimens. This wave was chosen since it can propagate long distances with little dispersion, and no higher modes are present to clutter the resulting response waves. First, a collection of analytical expressions which described the propagation of Lamb waves was used to calculate the optimal operating parameters for the testing procedures. These parameters, which include driving pulse shape and frequency, and actuator dimensions, were then experimentally verified with narrow laminated coupons. Using this procedure, results are presented for the application of Lamb wave techniques to rectangular quasi-isotropic graphite/epoxy test specimens containing representative damage modes, including delamination, transverse ply cracks and through-holes. PZT piezoelectric patches affixed with thermoplastic tape were used as actuators and sensors for both sets of experiments, as seen in **Figure 1**, so that the specimens could be re-used for testing using other non-destructive methods. The group velocity of a Lamb wave can be determined by measuring the time of flight (TOF) between two sensors of known separation. This information can then be used to locate damaged areas along a specimen, without using any analytical models, by observing the disturbed wave between the sensor and actuator. The Lamb wave’s group velocity essentially varies by a similar equality to that of a structure’s resonant frequency, as $(E/\rho)^{½}$, where E is modulus and ρ is density, so as a wave travels across an area of reduced stiffness it will slow down. Another phenomenon associated with damage is analogous to traveling acoustical waves; upon reaching a region of dissimilar wave speed, a portion of the wave is reflected proportionally to the difference in their stiffness and density. From these two pieces of information, good correlation with damage location and magnitude can be determined. Linear wave scans were performed on the narrow coupon specimens, as well as sandwich panel specimens in order to evaluate the effectiveness of detecting disbonds using various core materials such as Nomex, Rohacell and Aluminum honeycombs of assorted densities. The most significant result of the present research was a “blind test.” Four high density aluminum beam specimen were tested, one of which had a known delamination in its center, while of the remaining three specimens it was unknown which contained the circular disbond and which two were the undamaged controls. By comparing the four wavelet coefficient plots in **Figure 2**, one can easily deduce that the two control specimens are the ones with significantly greater energy in the transmitted signals, while the third specimen (Control C) obviously has the flaw that reduces energy to a similar level to that of the known delaminated specimen. This test serves as a testament to the viability of the Lamb Wave method being able to detect damage in at least simple structures. Several experiments were also performed on composite built-up structures, such as plates with bonded ribs and a large cylindrical composite structure. Finite element models were produced to simulate the experimental results for each of these configurations.

Lamb wave techniques have proven to provide more information about damage type and location than frequency response techniques and have demonstrated suitability for structural health monitoring applications since they can travel long distances, can be applied with low power and conformable piezoelectric actuators and sensors (under 10 volts), and they can provide useful information about the state of a structure during operation. Overall, the present research provides guidelines which may be useful in the design of future structural health monitoring systems. The advantages, disadvantages and limitations of Lamb wave methods are highlighted, and recommendations are offered for implementation of these techniques in the framework of a SHM system. The piezoelectric patches used for these experiments could also be used as multipurpose sensors to test using a variety of other methods such as acoustic emission and strain based methods simultaneously by altering driving frequencies and sampling rates. Integrated reliable SHM systems in composite structure will be an important component in future designs of air and spacecraft to increase the feasibility of their missions, and lamb wave techniques will likely play a role in these systems.

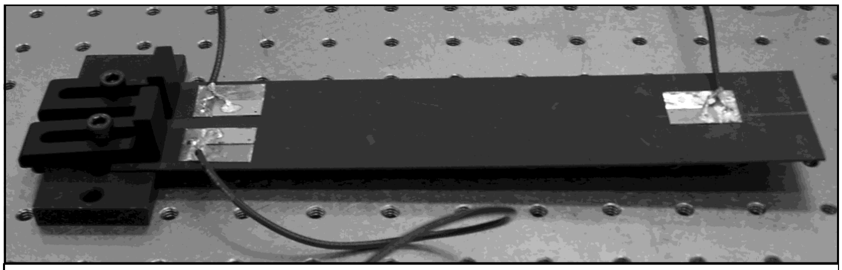

Figure 1: CFRP specimen (250mm x 50mm) with piezoceramic sensors

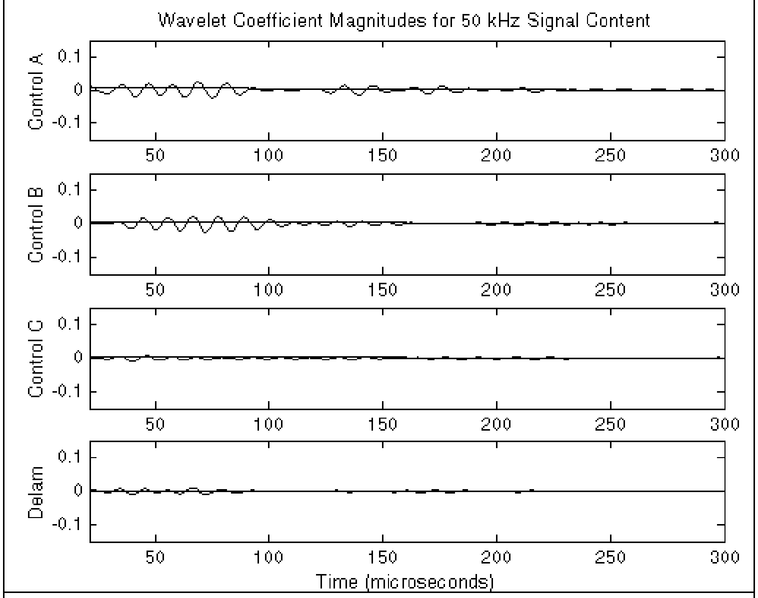

Figure 2: Wavelet coefficient plots for beam "blind test" compares 50 kHz energy

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Paper SHM 2002-072

Structural Health Monitoring Using Self-Sensing Conventional E-Glass Fibre Sensors

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This paper reports on the design and development of a novel low-cost sensor system based on conventional E-glass fibres. This sensor system is based on the conversion of E-glass fibres to act as waveguides that are capable of being used as (i) chemical sensors for cure monitoring and (ii) large-area damage detectors.

The feasibility of using these sensors for cure monitoring was demonstrated by monitoring the light transmission intensity through the fibres during curing (Fig 1). The variation in the transmitted light intensity during processing was correlated to the refractive index of the resins. This technology will permit the processing conditions used in the production of the composite to be related directly to its subsequent performance.

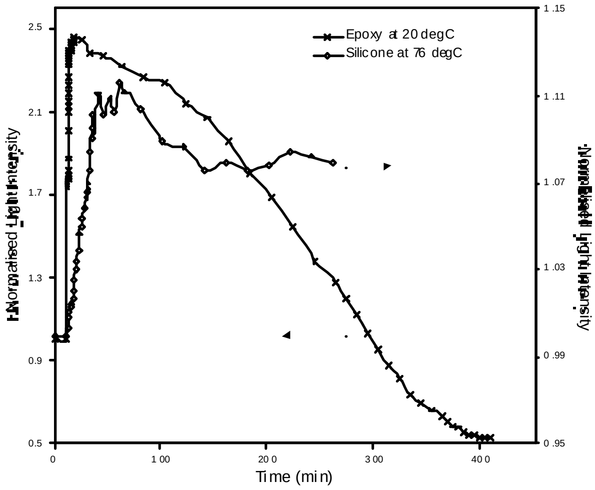

Fig. 1. Cure monitoring using E-glass fibres

Although tremendous progress has been made in the design and deployment of sensor systems for structural health monitoring, the introduction of a foreign body into the material can raise issues related to re-certification of the material.

The feasibility of using these sensors for conducting *in-situ* light transmission measurements while the E-glass fibres were tested in tension was successfully demonstrated (Fig 2). This technique was capable of highlighting differences in the macroscopic tensile failure modes of the fibre bundles.

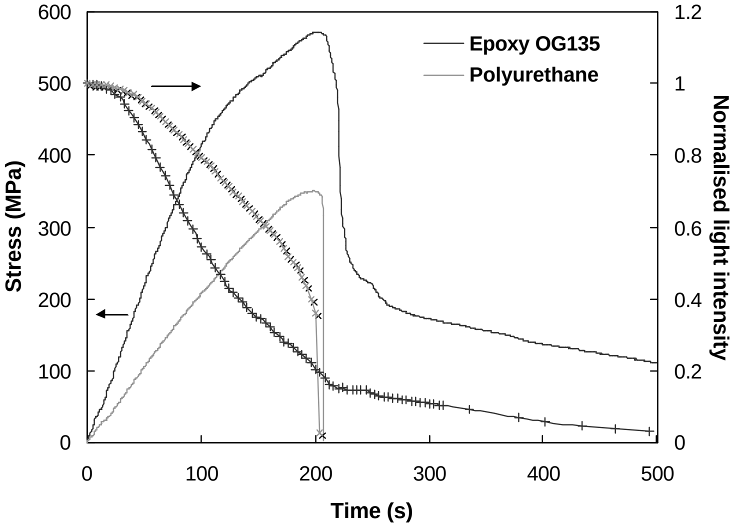

Fig 2. Tensile curves and light transmission variation of coated E-glass fibres.

In the final part of this study, the E-glass fibre waveguides were incorporated into GFRP composites in order to detect barely visible damage created by impact and indentation tests. The intensity of the light passing through the waveguides was recorded before and after impact and continuously during the indentation test. An attempt was made to correlate the reduction in the transmitted light intensity to the extend of damage incurred in the composites.

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Paper SHM 2002-073

Acoustic Monitoring of Bridge Cables Application to a pre-stressed concrete bridge

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The monitoring of degradations of the bridge cables (suspension bridges, cable stayed bridges) by acoustic monitoring system is operational since 1970.

Progress in electronics, data processing and telecommunications allowed evolutions improving the real time processing of the information collected (Smart sensors), the adjustment of the thresholds of alarms and the management of the in situ intervention autorities.

The chance for an acoustic monitoring to be installed on a prestressed concrete bridge (open to usual traffic) give the possibility to validate the effectiveness of the wire ruptures monitoring on the non accessible cables (for visual inspection). The automatic alarm devices, functioning in relation with the civil security services which operate the closing of the bridge, has been also certified in term of competence. The acoustic sensors installation, the monitoring and finally the real state of the bridge after dismantling are describedThe monitoring of degradations of the bridge cables (suspension bridges, cable stayed bridges) by acoustic monitoring is operational since 1970. Progress of electronics, data processing and telecommunications allowed evolutions improving the real time processing of the information collected (intelligent sensors), the adjustment of the thresholds of alarm and the management of the in situ intervention devices. The chance for an acoustic monitoring to be installed on a prestressed concrete bridge (motor vehicle traffic maintained) give the possibility to validate the effectiveness of the wire ruptures monitoring of the non accessible cables (for visual inspection). The automatic alarm devices, functioning in relation with the civil security services which operate the closing of the bridge, has been also certified in term of competence. The acoustic device installation, the monitoring and finally the real state of the bridge after demounting are described.

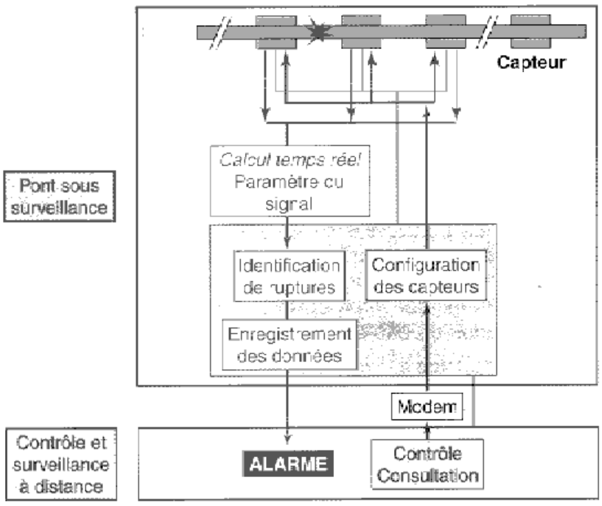

Figure 1 : Scheme of an acoustic monitoring system on a bridge.

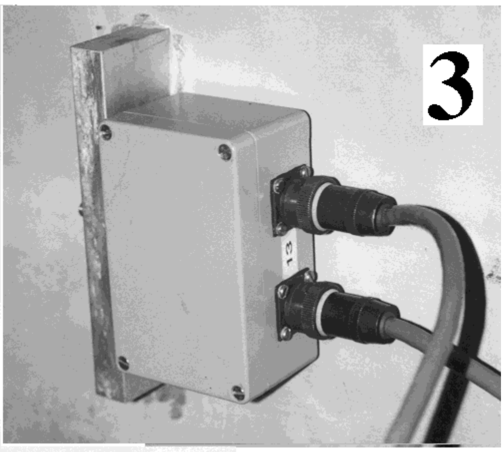

Figure 2 : Set up of sensors on a pre-stressed concrete beam.

Figure 3 : Smart sensor and his connections to the numerical line.

Figure 4 : Strands and their broken wires from the area located by acoustic monitoring

Paper SHM 2002-074

Fiber Optic System for Ship Hull Monitoring

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Summary

An autonomous fiber optic structure health monitoring system for ship hull monitoring, installed on steel and GRP sandwich vessels is presented. The system, with three installations in current operation and 6 additional installations programmed before the end of 2002, will be the first fiber optic SHM system for ship hulls with a wide user base. Results from the first installations will be presented.

Paper

Forsvarets Forskningsinstitutt (FFI) has been engaged in the application of fiber optic structure health monitoring (SHM) systems since 1995 [1-6], with a special focus on ship hull monitoring [7]. Fiber optic sensors are well suited for this application, due to their ability to withstand harsh environments, immunity to electromagnetic interference, and reduced cabling installation cost when employing wavelength multiplexing and multi-fiber cables. In addition, the reduced noise typically seen in fiber sensor installations, as compared to conventional strain gage techniques, improves the accuracy of advanced SHM data analysis methods.

The aim of the activity has been towards designing, building, testing and deploying complete SHM systems. Thus, it encompasses fiber sensor and sensor system design, interrogation hardware, data collection, analysis and presentation software.

In 2001, two important elements have been added to this system. First, a flexible Fabry-Perot filter based interrogation unit has been developed, replacing the unit contributed by the Naval Research Labs in previous collaboration projects. In addition, a new sensor package has been developed and qualified for use in harsh marine environments.

The integrated sensor packages facilitate easy installation onboard ships. Qualification tests of the packages have been carried out in cooperation with Telenor Fiber AS, Kristiansand, Norway and the classification society Det Norske Veritas, Høvik, Norway, showing that they meet the Hullmon ship hull monitoring class requirements.

The new interrogation unit is based on a Fabry-Perot filter gating a broadband source, detecting the intensity peaks as the transmitted spectrum match the sensor Bragg wavelength. The unit accommodates several sensors on each of its 8 independent channels, and a temperature stabilized wavelength reference. The sensor sampling rate is user selectable from 20 Hz to several kHz. For hull monitoring applications, the system is normally operated at a 680 Hz rate.

15 sensor systems were installed onboard the shuttle tankers Navion Oceania and Navion Europa in 2001. These installations were carried out by personnel from Telenor Fiber AS, demonstrating that the new sensor packages are well suited for industrial installations. These systems are designed according to the Hullmon 2 ship classification.

A 44 FGB system was installed onboard the Royal Norwegian Navy Mine Countermeasure Vessel Oksøy in 2001. The Oksøy is a twin hull surface effect ship (SES) made from sandwich panels with fiber reinforced polymer (FRP) skins. The new sensor package is installed in most locations, but FBG sensors embedded in the surface are also used.

Most sensors are located in an amidships cross-section of the hull. These sensors are used to estimate the most important global moments and forces acting on the hull by use of a transform developed in cooperation with FiReCo AS, Fredrikstad, Norway [4]. These moments and forces may then be directly compared to the design strength of the hull.

In addition to hull strain data measured by the fiber sensors, data from a GPS and a Motion Reference Unit are used to record the precise location, orientation, speed and acceleration of the vessel at all times. A microwave altimeter, acquired from Miros AS, Asker, Norway, measures the wave profile incident on the bow. The additional data enhance the possible use of the sensor system in that not only the effect on the hull, but also its cause, is recorded. This opens up for determining the response of the craft as a function of the operational parameters, which then can be used for operational and damage assessments.

The installed systems were operational in October 2001. The first data will be available for analysis at the end of November 2001, and presented in the paper. The system is commercially available.

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Paper SHM 2002-076

Unmanned Structural Health Monitoring via Internet with Unsupervised Statistical Diagnosis (Application for Damage Detection of Jet Fan)

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Structural Damage monitoring system requires a large number of sensors, and the structural integrity is monitored through the vast measured data. For the structural health monitoring (SHM) system, distributed optical fiber strain sensors are generally employed as sensors. However, multiple kinds of sensors like speed counters, leakage sensors, gas sensors, intensity-based non-distributed fiber optic sensors and CCD cameras are required for practical SHM systems. In some cases, actuators may be necessary for closing safety valves or activating vibration exciters. If these sensors and actuators are mounted on the structures using conventional analog lead wires, the system requires a large number of bundles of analog lead wires, and this cause cumbersome handling of the bundles of lead wires. The bundles of lead wire may cause significant increase of weight. In some cases, bundles of the lead wires make it impractical to replace some structural components when it requires repairs or arrangements. The Internet is generally adopted to transfer digital data packets for computer networks such as e-mail, multimedia information or Web data. To transfer analog data of sensors via the Internet has already attempted in several cases. Conventional cases employ conventional PCs for data acquisition and transfer. The present paper proposes new tiny tools for SHM via the Internet. One of the tools is a tiny size Smart terminal that has a network socket, a CPU, memory, a large capacity silicon disk tip, A/D converter, D/A converter and digital I/O ports. Linux operating system is adopted, and it has a web-server, mail-server and diagnostic methods for structural damage monitoring(Fig.1).

As an example, the present study deals structural health monitoring of jet-fan which installed to the tunnel on expressway as a ventilation fan(Fig.2). The damage are detected from the change of vibration data measured on the jet-fan(Fig.3). It uses response surface(RS) which shows relation of vibration condition of jet-fan. Damage is automatically diagnosed by testing the change of the RS by statistical methods. As a result, we succeeded in automatic damage diagnosis from the remote place using this method.

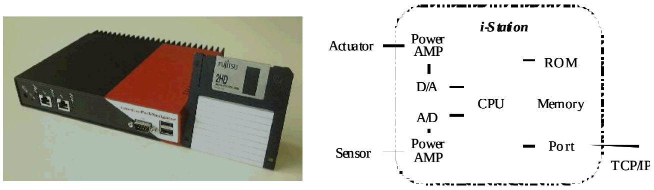
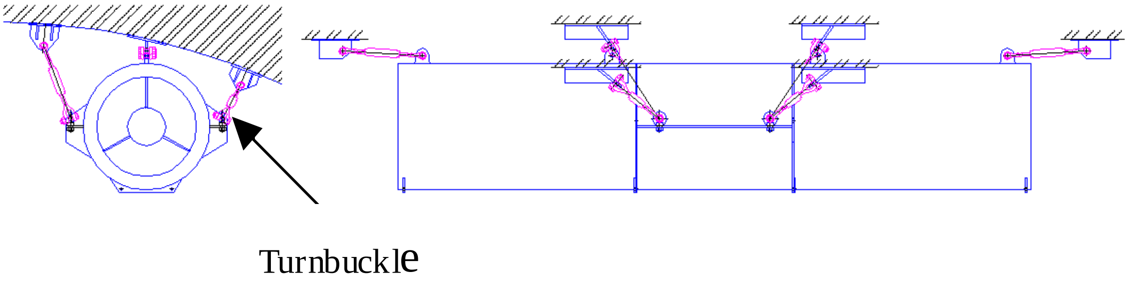
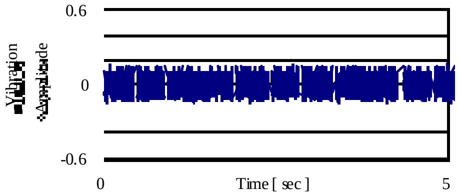


Fig. 1 Smart terminal

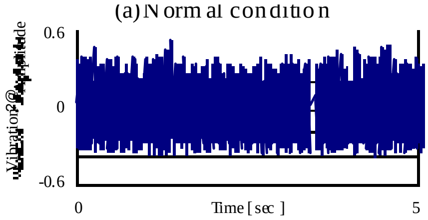


(a)Front view (b)Side view

Fig. 2 Schéma of the jet-fan



(a) Normal condition



(b)Damaged condition

Fig. 3 Vibration data of jet-fan

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Paper SHM 2002-077

Development of a New Type of Fibre-Optic Sensor for Detection of Acoustic Emission in Composites

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The detection of acoustic emission (AE) of composites can assist in determining the health of a structure made from such materials. Though generated by sub-surface sources, AE is usually monitored by manually placed surface-mounted piezo-electric (PZ) transducers. Such transducers are prone to electrical interference, unlike fibre-optic sensors (FOS), which are immune to such problems. Moreover, FOS can also be more easily embedded, so that continuous monitoring (e.g. of progression of damage) is possible. Such a feature is particularly desirable in difficult to access situations.

In this paper we report the development of a new type of fibre-optic AE sensor for composite materials and structures. The device uses intensity modulation alone, giving it the potential to be cheaper and more reliable than other FOS. The sensing principle is based on the bi-conical fused tapered coupler concept, but including the facility for interaction with an incident acoustic wave. The sensor was designed to be compatible with an existing AE instrumentation system (the MISTRAS system from Physical Acoustics Ltd.). Fabrication and testing of sensor prototypes is described, including measurement of frequency response, sensitivity and noise.

Sensors were mounted on the surfaces of and embedded within glass-reinforced polyester laminates. Excited by pencil break tests and simulated AE signals, the sensors' performance is compared to that of conventional PZ AE transducers. Preliminary results obtained during mechanical testing of coupons containing embedded FOS are presented.

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Paper SHM 2002-078

Fibre optical in-situ evaluation of corrosion processes in reinforced concrete

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Concrete is an extremely durable material, if it is properly designed and produced for the environment in which it has to serve. But some environments exist in which no concrete is durable. Deterioration may occur through a variety of chemical or physical processes, whereas corrosion of reinforcement is probably the most widespread consequence. The expansion produced by rust formation causes the surrounding concrete to crack and spall. This can be prevented by a high pH-value of the pore solution in concrete, which stabilises an oxide film on the steel that inhibits further attack. The film is unstable at lower pH-values, which can result from carbonation, leaching or in the presence of Cl-anions.

We developed two principle ways to measure the corrosion damages. The first way is to measure directly the actual pH-value and the second is to measure one of the main causes, i.e. the concentration of the Cl-anions.

Both are based on the optical properties of indicator dyes, which show different absorption or fluorescence in different conditions in the concrete. They can be integrated in a suitable polymer matrix.

Such prepared sensor materials are capable of fibreoptical in-situ measurement of corrosion processes in reinforced concrete.

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Paper SHM 2002-079

Frequency domain analysis of distributed fiber-optic Brillouin sensors: a novel approach

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Besides the telecommunication field, optical fibers have also been used, since many years, for sensing applications due to their properties such as minimum invasivity, high sensitivity, immunity from the electromagnetic interference, high degree of integrability with the under control structures, resistance to corrosion and multiplexing possibility. Among optical fiber sensors, Bragg gratings allow for point measurements of temperature and strain with elevate accuracy (fractions of degree Celsius and microstrain sensitivity, respectively) and a spatial resolution as small as the size of the gratings theirselves. However, due to their millimetric length, Bragg sensors seem to be not particularly suitable for long range measurements, such as structural monitoring in large civil structures (dams, bridges, pipelines, etc.). In contrast, truly distributed fiber optic sensors are very attractive as they offer unmatched flexibility of measurement locations and the ability to monitor a virtually unlimited number of locations simultaneously. Several different types of distributed sensors exist, but various designs based on Brillouin scattering currently seem to be the focus of great attention. Stimulated Brillouin Scattering (SBS) based optical fiber sensors allow for distributed measurements of strain and/or temperature along sensing lengths of several kilometers, with a spatial resolution below 1m, and a temperature/strain accuracy of a few degrees Celsius and tens of microstrains, respectively [1].

Typically, measurements in SBS based optical fiber sensors are carried out by monitoring the interaction between a pulsed beam and a counter-propagating CW beam having an optical frequency slightly different from the pulsed one. When this frequency difference is around a characteristic frequency of the fiber, which is dependent on its strain and temperature conditions, there is a significant power exchange between the two beams. This power transfer is measured while the frequency difference between the lasers is stepped, producing the Brillouin gain spectrum of the sensing fiber. An alternative, effective approach involves the interaction along the sensing fiber between a CW lightwave and a amplitude-modulated one, while sweeping the modulation frequency of the latter between a few kHz and a few MHz. In such a way, the complex tranfer function of the fiber can be determined on the basis of narrow-band measurements, allowing larger signal-to-noise ratios when compared to the time-domain technique [2]. However, even by operating in the frequency-domain, strain and temperature profiles reconstruction is usually made by transforming the measured signals via IFFT, in order to produce the Brillouin Gain Spectra along the fiber.

In this paper, we propose a novel numerical technique for temperature/strain profiles reconstruction based on Brillouin Optical-fiber Frequency Domain Analysis (BOFDA) measurements. Such technique directly processes the Brillouin signals in the frequency domain, by making use of an original integral formulation which relates the Brillouin gain to the Brillouin signals. Unless the classical reconstruction procedure, where the assumption that a linear relationship between the Brillouin signal and the Brillouin gain limits the sensor performances [3], the proposed algorithm searches directly for the temperature/strain profile along the fibre that matches the measured data. In this way, long-range and high power level measurements are allowed, without leading to inaccurate strain and/or temperature determination due to nonlocal effects. The reconstructions are carried out by minimizing a cost-function representing the error between the measured and the model data. Such a minimization is effectively performed by representing the unknown (temperature/strain) profile with a finite number of parameters.

Several numerical simulations, even in presence of noise, have proved the capability of the proposed algorithm to compensate for some systematic errors suffered by classical approaches that are based on the direct reading of Brillouin power spectra.

As a preliminar example, we show, in Fig. 1, the results of a temperature profile reconstruction, where the generated synthetic data have been corrupted by adding an uniformly distributed noise, with a peak level equal to 2.5% of the complex transfer function mean value. The same figure also shows the reconstruction obtained by following the classical approach, i.e. by transforming the signals via IFFT and by looking for the maxima of the Brillouin loss spectra collected at each sensing section along the fiber. The comparison between the two reconstructions shows the capability of our algorithm to compensate for nonlocal effects, even if noisy data are processed.

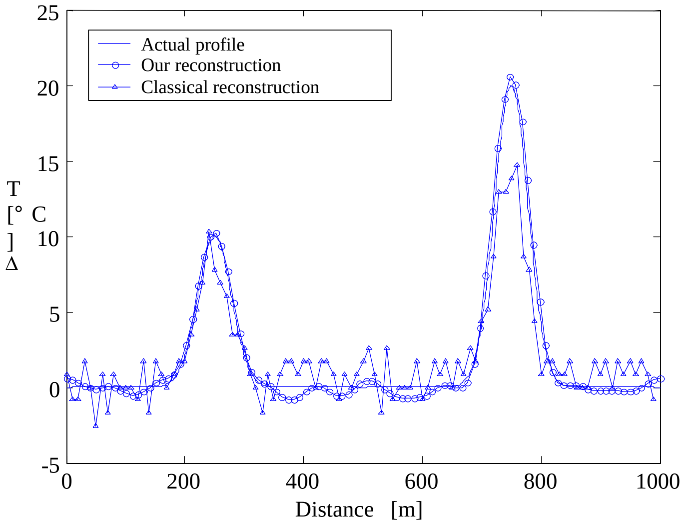

Figure 1. Temperature profile reconstruction:

Comparison between the classical approach and the proposed indirect technique

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Paper SHM 2002-080

Sensitivity Analysis and Damage Location over the Z24 Bridge

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Paper

The Z24 bridge became very famous in the scientific community in the recent past, due to the intensive tests carried on in 1998. Formerly, the tests were performed in the frame of a Brite-Euram project, but the data were lately used as one of the reference benchmarks in the framework of the COST F3 action "Structural Dynamics". A number of papers referring to this bridge can be found in scientific literature, some of those are also cited in the references of the full paper [1].

This paper is resuming the activity of the Mechanical Dept Dynamics Group on the Z24 benchmark; an overview of the identification procedure is given, focusing the attention to the up-dating technique to fit the FEM model and to look for the damage localisation.

The first task of the work, the identification aspect, has been achieved by adopting the well known CVA method applied to ambient, forced random and drop weight responses.

Introduction

One of the main concerns in the area of output-only identification is the apparent variability of the measurements and the uncertainty of extracted parameters; during the Z24 monitoring a particular care was devoted in measuring the accelerations over a large number of stations and under different excitation conditions. The temperature, a parameter which is frequently neglected, has also been registered, because of its high variations during the measurements.

This is an important task, being the frequency variations due to the temperature at least of the same order of magnitude of damage effects or boundary condition changes.

However, if the frequency shifts are taken into account together with a careful mode shape analysis, the results are more informative and a better chance to reach the desired identification target is given, as in the presented case.

Sensitivity analysis

It is based on the modal parameters extracted by CVA. The inverse eigensensitivity analysis [2] has been applied to a tri-dimensional FEM model of the Z24 bridge shown in figure 1. A first attempt was developed using a few macro-structures, i.e. splitting the system into two elasto-inertial macro-substructures (pavement, pillars) and into six elastic macro-elements fixed to ground. An overall of ten updating parameters of linear correction for the FEM model has been considered (*pm=2 , pk=8*) at this stage:

$$[M]=\sum_{i=1}^{pm} a_i [M_i] \; , \; [K]=\sum_{i=1}^{pk} b_i [K_i] \qquad (6)$$

where $[M_i]$, $[K_i]$ are the mass and stiffness matrices of substructure *i*.

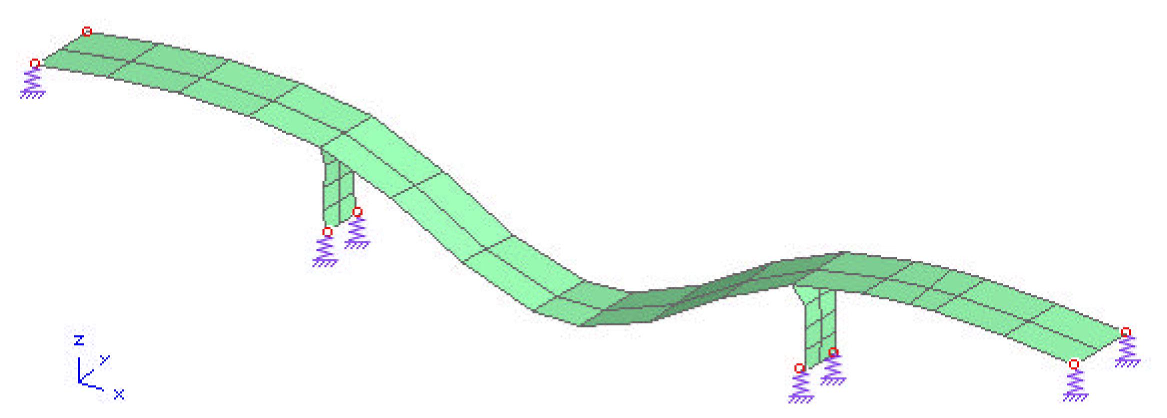

Figure 1: First mode with the elastic connections to ground used in the up-dating procedure

The FEM model has been developed by using the most significant experimental nodes and the computation has been performed by commercial computing codes and interfacing routines.

Only a few experimental modes of the undamaged structure have been updated, selected by using the MAC, and re-scaled with the norm of the corresponding analytical modes; the updating procedure has also shown the convergence of the modes outside those considered in the up-dating iteration.

The updating procedure has been achieved solving the following linear system, by balancing the sensitivity matrix S , $\{\Delta EigenV\} = [S]\,\{\Delta Par\}$, i.e.

$$\begin{Bmatrix} \dfrac{w_{1,\exp}^2 - w_{1,an}^2}{w_{1,an}^2} \\ \{\Phi_{1,\exp} - \Phi_{1,an}\} \\ \vdots \\ \dfrac{w_{r,\exp}^2 - w_{r,an}^2}{w_{r,an}^2} \\ \{\Phi_{r,\exp} - \Phi_{r,an}\} \end{Bmatrix} = \begin{bmatrix} \dfrac{\partial w_{1,an}^2}{\partial a_1}\Big/ w_{1,an}^2 & \cdots & \dfrac{\partial w_{1,an}^2}{\partial a_{pm}}\Big/ w_{1,an}^2 & \dfrac{\partial w_{1,an}^2}{\partial b_1}\Big/ w_{1,an}^2 & \cdots & \dfrac{\partial w_{1,an}^2}{\partial b_{pk}}\Big/ w_{1,an}^2 \\ \dfrac{\partial\{\Phi_{1,an}\}}{\partial a_1} & \cdots & \dfrac{\partial\{\Phi_{1,an}\}}{\partial a_{pm}} & \dfrac{\partial\{\Phi_{1,an}\}}{\partial b_1} & \cdots & \dfrac{\partial\{\Phi_{1,an}\}}{\partial b_{pk}} \\ \vdots & & \vdots & \vdots & & \vdots \\ \dfrac{\partial w_{r,an}^2}{\partial a_1}\Big/ w_{r,an}^2 & \cdots & \dfrac{\partial w_{r,an}^2}{\partial a_{pm}}\Big/ w_{r,an}^2 & \dfrac{\partial w_{r,an}^2}{\partial b_1}\Big/ w_{r,an}^2 & \cdots & \dfrac{\partial w_{r,an}^2}{\partial b_{pk}}\Big/ w_{r,an}^2 \\ \dfrac{\partial\{\Phi_{r,an}\}}{\partial a_1} & \cdots & \dfrac{\partial\{\Phi_{r,an}\}}{\partial a_{pm}} & \dfrac{\partial\{\Phi_{r,an}\}}{\partial b_1} & \cdots & \dfrac{\partial\{\Phi_{r,an}\}}{\partial b_{pk}} \end{bmatrix} \begin{Bmatrix} \Delta a_1 \\ \vdots \\ \Delta a_{pm} \\ \Delta b_1 \\ \vdots \\ \Delta b_{pk} \end{Bmatrix}$$

The convergence has been achieved by the SVD technique, through a limited number of iterations.

A dynamic equivalent FEM model has been updated starting from the unscaled experimental modal data; hence the new model has been used as a new base for the sensitivity analysis applied to the damage localisation.

References

[1] L. Garibaldi, A. Fasana, E. Giorcelli, D. Sabia, “ Z24 Bridge Dynamic Analysis by Time Domain Methods”, IMAC-XIX, Kissimmee (Florida), USA, February 5-8, 2001.

[2] Jung, H., Ewins, D. J., "Error sensitivity of the inverse eigensensitivity method for model updating", IMAC-X, San Diego (California), USA, February 3-7, 1992.