APPROACHES AND METHODS OF EVALUATION FOR COMPOSITE MATERIALS: CURRENT TRENDS AND THE FUTURE

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Abstract

Critical structures and components utilised in applications such as Aerospace, need special attention in terms of evaluation and establishment of integrity, in particular, in view of the requirements of utmost safety, quality and reliability of performance. Consequently, evolutionary approaches have been imminent and have been taking place since the time of implementation of non invasive methods in their primitive forms utilizing physical principles. However, the approach had taken a totally different direction since the introduction and utilization of newer materials such as composites for primary structural components in aerospace, automotive and several other applications. But, while in practice, the utility and the applicability of the conventional methods and procedures are severely constrained by several factors such as the type of loading, operational environment and more than any other a number of uncertainties associated with real life structures. One simple example is the variation in the mechanical properties of a material. Hence, the approaches that have been followed and are being considered from time to time needed a thorough understanding and development which has been the basis for the evolution of NDT to NDE and currently to SHM. In fact, though SHM is the most recent method of evaluation complementing the existing approaches, it still does not take care of the uncertainties. Thus, some of the recent work oriented towards solving this problem is presented in this paper.

***Key Words**: Composites, Non-destructive Evaluation, Structural Health Monitoring, Adhesive Bonding, Digital Image Correlation*

Introduction

The timely and accurate detection, characterization and monitoring of structural cracking, corrosion, delamination, material degradation and other types of damage are of major concern in the operational environment. Along with these, stringent requirements of safety and operational reliability have lead to evolutionary methods for evaluation of structural integrity. As a result, conventional non destructive evaluation methods have moved towards a new concept, Structural Health Monitoring (SHM). SHM provides in-situ information about the occurrence of damage if any, location and severity of damage and residual life of the structure and also helps in improving the safety, reliability and confidence levels of critical engineering structures. While the concepts underlying SHM are well understood, development of methods is still in a nascent stage which requires extensive research. In our recent work which is discussed in this paper, investigations were undertaken with an integrated approach using Ultrasonic (active) and Acoustic Emission (passive) methods for SHM of metallic and composite plate structures(typical to Aerospace) using distributed array of surface bonded circular Piezoelectric Wafer Active Sensors (PWAS) [1]. Besides the complex damage mechanisms, composites are prone to relatively high material property variations compared to isotropic materials. The greater uncertainty levels in composites are because of a larger number of parameters involved and the tolerances set in their manufacturing and fabrication process which ultimately leads to uncertainties in their structural response. The analysis and design of a composite structure should therefore consider the randomness of the material properties. Furthermore, development of damage modeling and detection methods on composite structures should distinguish material property uncertainty effects from effects caused by damage [2]. One part of the work presented in this paper aims at investigating the effect of uncertainty due to variation of mechanical properties in composites. Adhesive bonding is an effective method of assembling complex structures, particularly those made from different materials. Provided the joint is well designed, the adhesive bond ought to be one of the strongest aspects of the structure and most certainly should not be the life limiting factor.

This of course pre-supposes that the joint has been correctly executed. The major factors determining the integrity of an adhesive bond are selection of the most appropriate adhesive, joint design, preparation of the bonding surfaces, strict quality control in production and condition monitoring in service. Adhesives have become increasingly important in assembling many of the multi-material structures which make up contemporary aircrafts both civil as well as military. These aircraft have become increasingly dependent on structural fibre reinforced plastic materials and around 50% of their weight consists of fibre reinforced plastics and the appropriate adhesives to facilitate fabrication. Many of these structures operate under high stresses and are often exposed to aggressive environments like high temperature and humidity, leading to a degradation of adhesive quality in the joint. Consequently any failure in these structures leads to catastrophe resulting in the loss of human life. In this context non-destructive evaluation becomes extremely important which has been well investigated and reasonably well established. However, while determination of strength though occupies pre-eminence it is still under extensive investigation to be established quantitatively. Thus, the variation of properties associated with the adherand, adhesive and the interfaces add further complexity making the development of methodologies formidable. In the next part of the work discussed here in dealing with the uncertainties associated with real life structures, an attempt is made to solve this problem through Finite Element modelling using ANSYS and experimental Digital Image correlation data with Monte Carlo simulation. Some preliminary results obtained on the determination of Coefficient of Variation of the adherend are presented in this paper [3].

An Integrated Approach for Structural Health Monitoring of Typical Aerospace Structures Using Active and Passive Wave based Method

As mentioned in the introduction, in an attempt to develop a methodology for the integrated approach experimentation and analysis has been carried out step by step to reach the final goal for detection and location of defects and damage "off-line" using Ultrasound and "on-line" by using Acoustic Emission techniques. And, another important consideration in this work has been the development of the methodology for components of complex geometries which makes the work directly applicable to real life structures. In ultrasonic method, PWAS are used for actuation and reception of Lamb waves in plate structures. The damage detection is based on the interaction of waves with defects resulting in reflection, mode conversion and scattering. In Acoustic Emission (AE) technique, the same sensor is used to pick up the stress waves generated by initiation or growth of defects or damage. Thus, both the active and passive damage detection methods are used in this work for detection, location and characterization of defects and damage in metallic and composite plates with complex geometries and structural discontinuities. And, thus the strategy adopted is to use time-frequency analysis and time reversal technique to extract the information from Lamb wave signals for damage detection and a geodesic method for detection and location of damage.

Development and Implementation Time Frequency and Time Reversal Methods and their Utilization on Metal and Composite Specimens

To start with experiments were conducted on aluminum plates to study the interaction of Lamb waves with cracks oriented at different angles and on a titanium turbine blade of complex geometry with a fine surface crack (Fig.1). Further, the interaction of Lamb wave modes with multiple layer delaminations in glass fiber epoxy composite laminates was studied (Fig.2).

The data acquired from these experiments yielded complex sets of signals which were not easily discernable for obtaining the information required regarding the defects and damage. Thus, to resolve the complexity, Time-Frequency analysis of a number of simulated and experimental signals due to elastic wave scattering from defects and damage using Wavelet Transform (WT) and Hilbert-Huang Transform (HHT) [4]. And, a comparison of their performances in the context of quantifying the damages has given detailed insight into the problem of identifying localized damages, dispersion of multi-frequency non-stationary signals after their interaction with different types of defects and damage, finally leading to quantification. Conventional Lamb wave based damage detection methods look for the presence of defects and damage in a structure by comparing the signal obtained with the baseline signal acquired under healthy conditions.

The environmental conditions like change in temperature can alter the Lamb wave signals and when compared with baseline signals may lead to false damage prediction. So, in order to make Lamb wave based damage detection baseline free, in the present work, the time reversal technique has been utilized. And, experiments were conducted on metallic and composite plates to study the time reversal behavior of A0 and S0 Lamb wave modes. Damage in the form of a notch was introduced in an aluminum plate to study the changes in the characteristics of the time reversed Lamb wave modes experimentally.

This experimental study showed that there is no change in the shape of the time reversed Lamb wave in the presence of defect implying no breakage of time reversibility (Fig.3). Time reversal experiments were further carried out on a carbon/epoxy composite t-pull specimen representing a typical structure. And, the specimen was subjected to a tensile loading in a Universal testing machine. PWAS sensor measurements were carried out at no load as also during different stages of delamination due to tensile loading. Application of time reversed A0 and S0 modes for both healthy and delaminated specimens and studying the change in shape of the time reversed Lamb wave signals has resulted in successful detection of the presence of delamination. The aim of this study has been to show the effectiveness of Lamb wave time reversal technique for damage detection in health monitoring applications.

Proposal and Establishment of a New Algorithm and Software for Geodesic Approach for Location of Defects in Metallic and Composite Components with Discontinuities and of Complex Geometries

The next step in SHM is to identify the damage location after the confirmation of presence of damage in the structure. Wave based acoustic damage detection methods (UT and AE) employing triangulation technique are not suitable for locating damage in a structure which has complicated geometry and contains structural discontinuities. And, the problem further gets compounded if the material of the structure is anisotropic warranting complex analytical velocity models. In this work, a novel geodesic approach using Lamb waves is proposed to locate the AE source/damage in plate like structures. The approach is based on the fact that the wave takes minimum energy path to travel from the source to any other point in the connected domain. The geodesics are computed numerically on the meshed surface of the structure using Dijkstra's algorithm [5]. By propagating the waves in reverse virtually from these sensors along the geodesic path and by locating the first intersection point of these waves, one can get the AE source/damage location. Experiments have been conducted on metallic and composite plate specimens of simple and complex geometry to validate this approach. And, the results obtained using this approach have demonstrated the advantages for a practicable source location solution with arbitrary surfaces containing finite discontinuities. And, by locating the first intersection point of these waves, one can get the AE source/damage location (Fig.4). Experiments have been conducted on metallic and composite plate specimens of simple and complex geometry to validate this approach.

The drawback of Dijkstra's algorithm is that the geodesics are allowed to travel along the edges of the triangular mesh and not inside them. To overcome this limitation, the simpler Dijkstra's algorithm has been replaced by a Fast Marching Method (FMM) which allows geodesic path to travel inside the triangular domain [6]. The results obtained using FMM showed that we can accurately compute the geodesic path taken by the elastic waves in composite plates from the AE source/damage to the sensor array, thus obtaining a more accurate damage location (Fig.5).

Assessment of Uncertainty by Monte Carlo Simulation of Composites for Estimation of Coefficient of Variation (COV)

For structural engineers to become confident in the use of FRP composites and for them to be widely accepted in structural engineering applications, the process for setting nominal strength and stiffness for design must be consistent.

A consistent method for stipulating nominal design is necessary which reflects the statistical uncertainty that results from small sample sizes. The main factors that affect the consistency are the material properties. Therefore, the following variables are considered viz., longitudinal Young's modulus E_{xx}, transversal Young's modulus E_{yy}, Poisson's Ratio v. Monte Carlo simulations are performed with each factor being considered stochastic one at a time to evaluate their influence.

Finite Element Modelling Using ANSYS

For the purpose of FEM modeling the substrate (adherand) was modeled as an orthotropic material. with Ex=140Gpa, Ey=Ez=10.7Gpa, exy=exz=0.31, eyz=0.43, Gxy=Gxz=4.5Gpa, Gyz=3.6Gpa adhesive is modeled as an isotropic material. And the joint was completely constrained at one edge. Uy=0, Uz=0 at the other end. A load of 50N was applied. A fine mesh was created near joint area (Fig.6).

Evaluation of Bond Strength of an Adhesive Lap Shear Joint Using Digital Image Correlation Technique

Digital Image Correlation (DIC), sometimes called electronic speckle photography has been used for obtaining the strain change on the surface specimen through speckle interferometry [7]. The camera was positioned approximately 500 mm from the specimen in the loading position, perpendicular to the specimen surface. The camera was carefully focused and Images were recorded and analyzed using VIC2D software. By using this technique full field measurements made on the specimen can be analyzed. Images were taken at different load intervals till failure and the data thus recorded was analyzed using VIC2D. Once calibrated, the DIC software is able to calculate the displacement field of a specimen at any point during loading with a corresponding image. A strain field is obtained by differentiation of the associated displacement field. The displacement field is calculated by comparing the loaded and reference images. Using the software, first a reference image, called a base image with the unloaded specimen was selected. Using the software tool, a small area of interest was chosen on the specimen in order to reduce computation time and define the region to be analyzed. Finally, the rest of images of the specimen over the entire loading sequence, called the deformed images, were selected for comparison with the base image for calculation of each of their respective strain fields which can be seen in Fig.7.

A total of 10 specimens were subjected to tensile loading and the DIC data was recorded and analyzed to obtain strain maps. The data collection was done in two steps. Thus a total of 100 strain values were considered for the Monte Carlo simulation. When plotted the strain data showed a normal distribution using which the simulation was carried on the computed modulus using ANSYS. Fig.8 shows the variation of E_1 (substrate) with (a) normal stress and (b) shear stresses for a confidence interval of 95%. As can be observed from the figure the variation in the cumulative probability with respect to stress shows a near linear relationship. Further to understand the uncertainties associated with adhesive bonding DIC experiments were performed with specimens consisting different levels of deterioration in terms of adding 10 to 40 percent of PVA to the adhesive. The results obtained from these experiments are presented in Fig.9. As can be observed from the figure except for very low and high stress values, the variation of cumulative probability distribution with respect to both normal and shear stress shows a near linear variation as in the case of the substrate.

Conclusions

The work reported in this paper presents investigations of an integrated approach using Ultrasonic (active) and Acoustic Emission (passive) methods for SHM of composites using distributed array of surface bonded circular piezoelectric wafer active sensors (PWAS) considering Time Frequency analysis and Time reversal techniques for detection and Geodesics with FMM for location of defects and damage. The results obtained indicate the effectiveness and efficiency of the methods developed for evaluating structures with finite discontinuities and of complex geometries. Further, results of preliminary investigations attempted using ANSYS for simulation and analysis of experimental data obtained by Digital Image Correlation considering the variation in the mechanical properties of composites show the utility of the Monte Carlo approach to deal with uncertainties in real life structures.

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References

1. Gangadharan, R., Murthy, C.R.L., Bhat, M.R., Sen, A., Das, N and Seal, A., "Embedded Piezoelectric Wafer Sensors for Sensing Acoustic Emission in Thin Plates Wafer Sensors", Review of Progress in Quantitative NDE, Portland, 30th July - 4th August, 2006.

2. Shinozuka, M and Wen, Y.-K., "Monte Carlo Solution of Nonlinear Vibration", AIAA Journal, 10, 39-40, 1972.

3. Vijayakumar, R.L., "Experimental and Numerical Studies on Evaluation of Bond Strength in Composite Adhesive Lap Joints", Ph. D Thesis (under preparationIndian), Institute of Science, Bangalore, India.

4. Gangadharan, R., Murthy, C.R.L., Bhat, M.R and Gopalakrishnan, S., "Time Reversal Technique for Health Monitoring of Metallic Structure Using Lamb Waves", Ultrasonics, 49, 696-705, 2009.

5. Gangadharan, R., Prasanna. G., Bhat, M.R., Murthy, C.R.L and Gopalakrishnan, S., "Acoustic Emission Source Location in Composite Structure by Voronoi Construction Using Geodesic Curve Evolution", Journal of Acoustical Society of America, 126 (5), 2324-2330, 2009.

6. Gangadharan, R., "Some Studies on Structural Health Monitoring of Thin Plate Like Structures Using Active and Passive Wave Based Methods", Ph. D Thesis, Indian Institute of Science, Bangalore, India, July 2010.

7. Stutton, M.A., Orteuand, J.J and Shreier, H.W., "Image Correlation for Shape, Motion and Deformation Measurements", Springerscience+Bussiness Media, LLC, 2009.

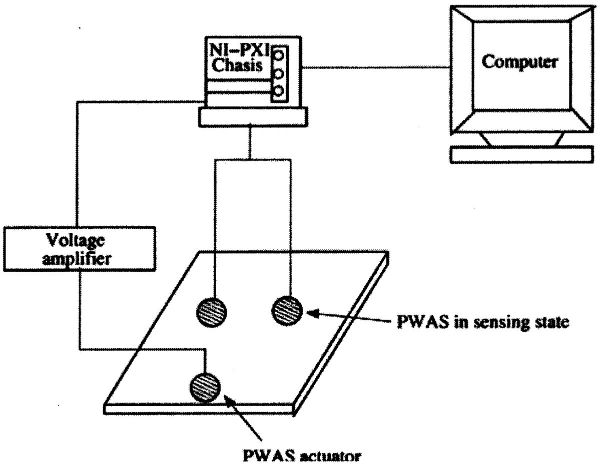


Fig.1 Schematic Diagram of the Experimental Setup

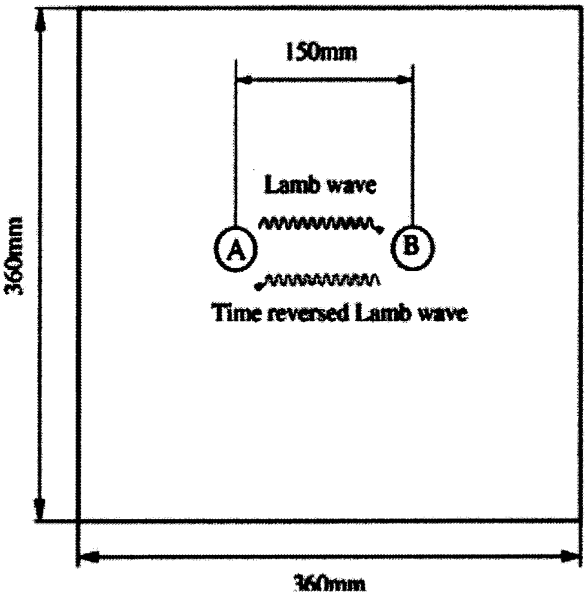
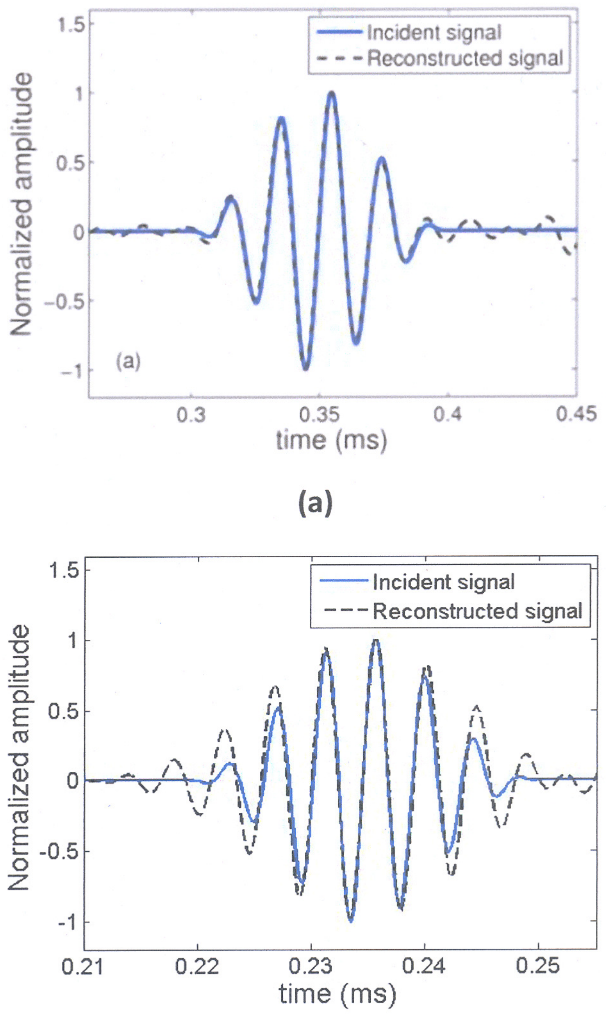


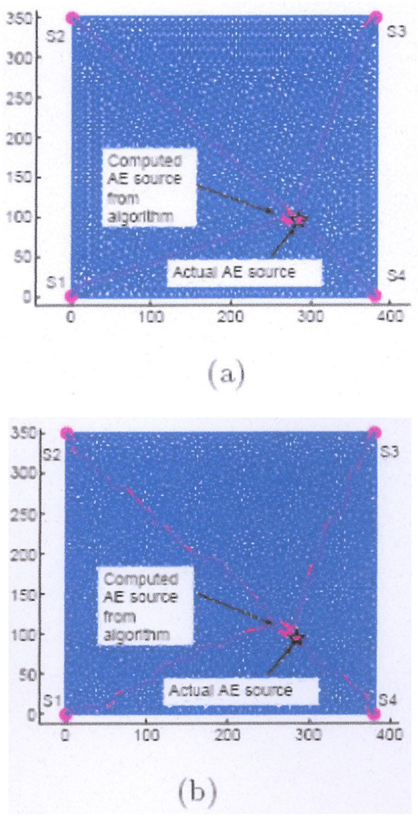
Fig.2 Schematic Diagram of the Composite Plate with PZT Sensors



(a)

(b)

Fig.3 Unidirectional Glass-epoxy Composite : Time Reversed Signal Picked up by Sensor A (a) A0 Mode (b) S0 Mode



(a)

(b)

Fig.4 Uni-directional Glass/epoxy Composite Plate : Source Location by Geodesic Propagation (a) Mesh Configuration (MATLAB) (b) Mesh Configuration (ANSYS)

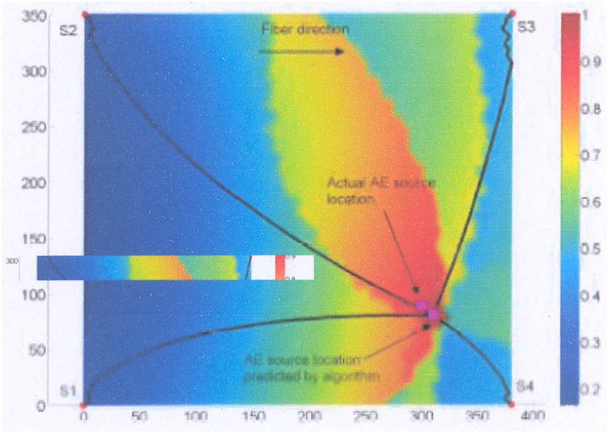


Fig.5 Uni-directional Glass/epoxy Composite Plate : AE Source Location by Geodesic Propagation Using FMM

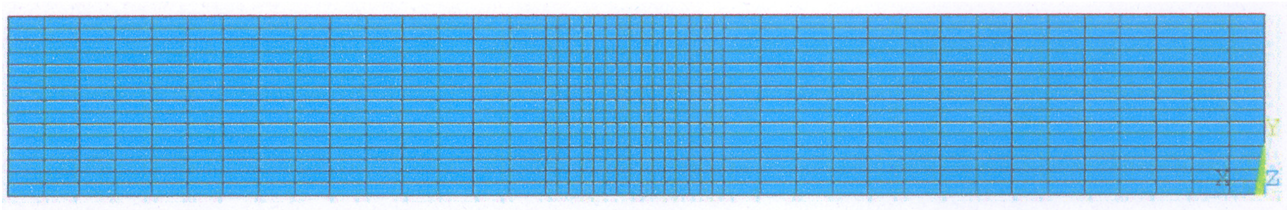


Fig.6 Finite Element Model

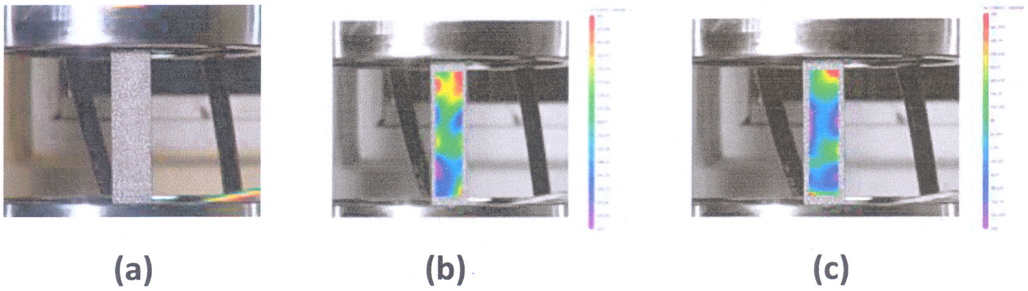
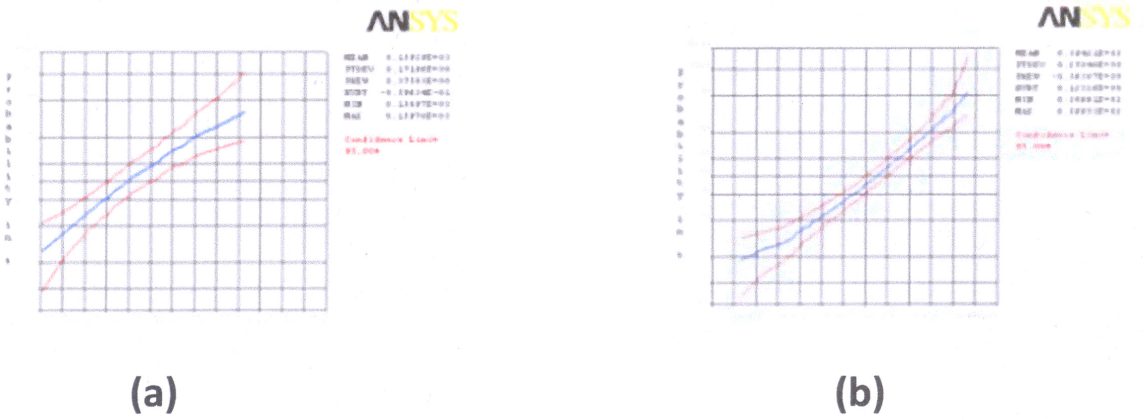
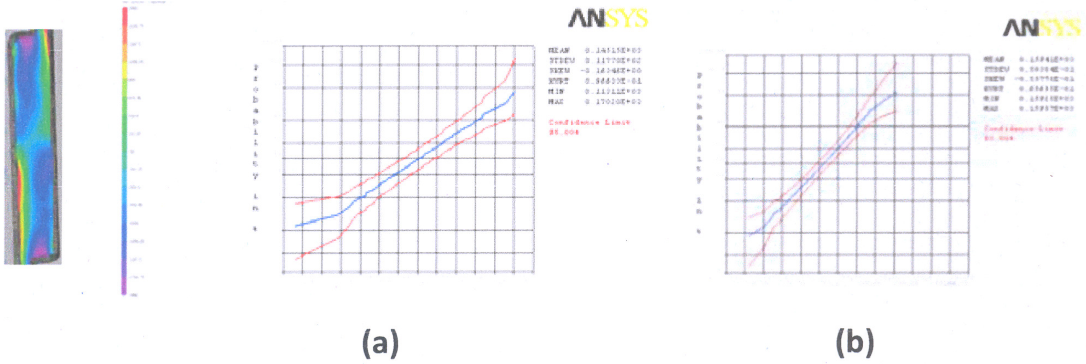

(a) (b) (c)

Fig.7 DIC Results Showing the Strain Distribution in the Substrate (a) No Load (b) Longitudinal (c) Shear



(a) (b)

Fig.8 Variation of E_1 (Substrate) with (a) Normal Stress and (b) Shear Stresses



(a) (b)

Fig.9 DIC Image and Variation of E_1 (Adhesive) with (a) Normal Stress and (b) Shear Stresses