Characterization of matrix micro-cracking in composite laminates using built-in piezo-electric sensors.

Cecilia Larrosa[1], Fu-Kuo Chang[1]

[1] *Department of Aeronautics and Astronautics, Stanford University, Stanford, Ca, 94305, U.S.*
clarrosa@stanford.edu
fkchang@stanford.edu

1. INTRODUCTION

The increased use of composite structures in aircraft and aerospace applications and the desire to reduce inspection schedules has lead to the requirement for in-situ damage diagnosis and prognostics for condition based maintenance scheduling. In the condition based maintenance approach, the current damage of the structure is known, this information is used as the input for a prognostic tool that estimates damage propagation. With this information a maintenance decision can be made. The described approach has the potential to reduce maintenance costs as well as increase the safety of the vehicle (Mueller, 2009).

Composite structures are constructed of stacked plies (or lamina). There are two main damage types that occur in composite structures: matrix micro-cracks and inter-laminar delamination. Matrix micro-cracks first develop in the matrix through the ply thickness direction, creating stress concentration at the plies' interfaces. As more cracks develop, the interfacial stress increases up to a point where delamination is initiated and is propagated along the ply interface. Delamination significantly degrades the strength of the structure and is generally the ultimate cause of failure in composite structures. An efficient condition based maintenance schedule for composite structures can be achieved through knowledge of the current damage type and its extent. In the case when only matrix micro-cracks are present, delamination initiation can be prevented. If it is known that delamination has already developed, delamination propagation could be avoided.

Matrix micro-cracks and delamination can occur in any of the plies, resulting in 'invisible damage,' which can be missed in visual inspections. There are many non-destructive inspection techniques available that could potentially solve the 'invisible damage' issue such as X-ray or acoustic emissions (Djordjevic, 2009). Most of these techniques require the structure to be disassembled into its components, which is time consuming and labor intensive. In-situ damage diagnosis addresses these issues by attaching a network of sensors to the structure that are able to rapidly inspect the structure. Many techniques using different types of sensor networks have been developed previously (Su, 2006; Pierce, 2000). An active piezo-electric-sensor network has been shown to be a very good technique to generate guided Lamb waves through composite structures (Lin, 2001; Worden, 2001). Once a sensor network has been attached, the data acquired by the sensor network needs to be interpreted into damage classification, quantification and location into an integrated damage diagnosis.

After a literature review of existing guided Lamb waves diagnostic techniques for composite structures, it has come to the authors' attention that a lot of the research studies conducted to date have focused on locating damage, particularly delamination, holes and simulated damage [Su, 2006; Pierce, 2000, Ihn, 2004 & 2008; Moll, 2011). Some research (Toyama, 2003 & 2005; Seale 1998) has reported results on the effect of matrix micro-cracks on Lamb wave propagation, in particular how it affects wave velocity, but has not directly quantified matrix micro-cracking density or developed a matrix micro-cracking diagnosis.

Many models for damage propagation and transition from matrix micro-cracks to delamination have been proposed (Beaumont, 2006; Narin, 1999; Shahid, 1993; Choi, 1990). Shahid and Chang, 1993 have used a ply based fracture mechanics approach that makes it very robust to layup configuration. But the model has been applied and validated for static loading only, which is helpful for design purposes but not for lifetime predictions.

2. PROBLEM STATEMENT

The goal of this research is to detect, quantify and diagnose matrix micro-cracking on a composite plate with attached piezo-electric sensors. This diagnostic data will then be transferred to an analytical model that will estimate future matrix micro-cracks propagation and strength degradation.

3. METHOD OF APPROACH

To accomplish the aforementioned goal, composite plates of different layups with surface mounted PZT sensor networks were subjected to tension-tension fatigue experiments. Through these experiments, sensor signal changes due to matrix micro-cracking will be studied. Once signal parameters sensitive to matrix micro-cracks have been found, develop a method to quantify and diagnose matrix micro-cracks.

The second part of the research will be to modify an existing static matrix micro-crack propagation model into a fatigue matrix micro-crack propagation model and analysis. These modifications include the capability of introducing current damaged diagnosed from the attached sensors' signals. The fatigue tests mentioned above will help validate the applied model and analysis.

4. PRELIMINARY RESULTS AND FUTURE WORK

Tensile-tensile fatigue experiments in composite plates were designed and are being conducted in collaboration with NASA Ames to achieve the aforementioned goals (Saxena, 2011). The generation of guided Lamb waves is achieved by a surface mounted piezoelectric active sensor network (Acellent's SMART Layers ®). The sets of sensors serve as a signal generator and receiver pair. At the end of every N cycle, sensor data along with X-radiography of the sample are recorded. The X-ray images provide the real damage type and quantity.

4.1 Matrix micro-cracks diagnosis.

A preliminary study of the data revealed a parameter that was highly correlated to matrix micro-cracking, but this same parameter is also affected by delamination. In order to separate the effects of delamination and matrix micro-cracking, different classification algorithms with different combinations of features were applied and compared on all samples tested. Gaussian Discriminant Analysis (GDA) and a combination of Time and Frequency domain features yielded a 20% delamination prediction error per actuator-sensor path. The next step was to assess the sensitivity of the classification to different laminate configurations, which decreased the prediction error to 17% per path (Larrosa, 2011). Once we had the delamination classification model we were able to find a relationship to matrix micro-crack density using a probabilistic regression method (Larrosa, 2011). The current methods have not taken into account the effect of material anisotropy which could be a cause of the resulting errors. The next step is to add the effect of anisotropy, introducing Lamb wave propagation physics that could improve algorithm accuracy. The final step would be to merge all the information gathered per actuator-sensor path into one diagnosis that images the damage type and quantity present in the composite laminate.

4.2 Matrix micro-cracks Fatigue Progressive Failure Analysis.

A progressive failure analysis model, originally derived by Shahid and Chang, 1993 for the simulation of damage in bolted composite joints, was adopted and extended. A Hashin-based failure criterion (Hashin, 1990) was selected to predict the damage during the evolution of load history. When the criterion is fulfilled damage is introduced or propagated. It accounts for matrix micro-cracking, and uses degradation factors to account for other damage mechanisms, it does not predict delamination. Upon damage the stiffness and strength of the laminate are degraded following a degradation model developed based on fracture mechanics. The model was implemented as a user defined material subroutine (UMAT) in the Finite Element package ABAQUS/Standard.

The current modified version of the analysis accounts for low cycle fatigue loads. The analysis is based on a fracture toughness wear out model dependent on the material system used, and it predicts matrix micro-cracking initiation and propagation as a function of fatigue cycles. In order to validate the proposed analysis, results of the numerical analysis were compared to experimental data acquired during the fatigue tests previously described. The preliminary results show a good match between experiments and predicted matrix micro-cracks propagation. The next step is to include a capability to introduce damaged elements. The elements (location) and damage type and quantity information would be the result of the diagnosis algorithm described above.

ACKNOWLEDGMENT

The authors would like to acknowledge the *National Aeronautics and Space Administration (NASA)* for supporting this work under grants ARMD/AvSafe NRA-07-IVHM1-07-0061, NRA-07-IVHM1-07-0064, as well as Space Act Agreement SAA2-402292. We would like to thank Richard W. Ross (NASA LaRC) as the program monitor of the grants, as well as Kai Goebel and Abhinav Saxena (NASA Ames, PCoE) for assistance with experimental planning and support in interpretation of the data. The authors are also grateful for Acellent Technology's assistance with the active sensing system.

REFERENCES

Beaumont, P.W.R, Dimant, R.A. and Shercliff, H.R. (2006). Failure processes in composite materials: getting physical. *Journal of material science* 41:6526-6546.

Chang, F.-K. and Qing, X. L. (1997). Recent advances in structural joints and repairs for composite materials. *Edited by L. Tong and C. Soutis, Kluwer Academic Publisher, 101-140*.

Choi, H. (1990). *Damage in graphite/epoxy laminated composites due to low-velocity impact*. Dissertation, Department of Aeronautics and Astronautics, Stanford University.

Djordjevic, B.B. (2009). Nondestructive test technology for composites. *The 10th International Conference of the Slovenian Society for non-destructive testing*. September 1-3, 2009. Ljubljana, Slovenia

Harris, A. (2003). *Fatigue in composites*. Woodhead Publishing.

Hashin, Z. (1980). Failure criteria for unidirectional fiber composites. *Journal of Applied Mechanics, 47: 329-334*.

Ihn, J-B., Chang, F-K. (2004). Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: I.Diagnostics. *Smart Materials and Structures*, **13**, 609–620.

Ihn, J-B., Chang, F-K.(2004). Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: II.Validation using riveted joints and repair patches. *Smart Materials and Structures*, **13**, 621–630.

Ihn, J-B., Chang, F-K.(2008). Pitch-catch active sensing methods in structural health monitoring for aircraft structures. *Structural Health Monitoring*, **7**, 5-19.

Johnson, P. and Chang, F-K. (2001). Characterization of matrix crack-induced laminate failure- Part I: Experiments. *Journal of composite materials*, Vol.35, No.22 .

Lafarie-Fernot, M. C. and Henaff-Gardin, C. and Gamby, D. (2001). Matrix cracking induced by cyclic ply stresses in composite laminates. *Composites Science and Technology, 61: 2327-2336*

Larrosa, C., Janapti, V., Lonkar, K., Shankar, S. and Chang, F-K. (2011). Damage classification and Quantification in composite laminates. *The 8th International Workshop on Structural Health Monitoring*.

Larrosa, C., Janapati, V., Roy, S. and Chang, F-K. (2011). In-situ damage assessment of composite laminates via active sensor networks. *The 2011 Aircraft Airworthiness and Sustainment Conference*, San Diego, Ca.

Lee, J-S., Park, G., Kim, C-G. and Farrar, C.R. (2011). Use of relative baseline features of guided waves for in-situ structural health monitoring. *Journal of intelligent materials and structures*, Vol. 0.

Lin, M., Qing, X., Kumar, A. and Beard, S.J. (2001). SMART layer and SMART suitcase for structural health monitoring applications. *Proceedings of SPIE* 4332, 98.

Moll, J., Schulte, R.T., Hartmann, B., Fritzen, C-P. and Nelles, O. (2010). Milti-site damage localization in anisotropic plate-like structures using and active guided wave structural health monitoring system. *Smart materials and structures* 19.

Mueller, I., Larrosa, C., S. Roy, Mittal, A., Lonkar, K. and Chang, F-K. (2009). An integrated health management and prognostic technology for composites airframe structures. *The annual conference of the Prognostics and Health Management Society*.

Mueller, I., Larrosa, C., Roy, S. and Chang, F-K. (2009). An integrated diagnostic to prognostic SHM technology for structural health management. Best paper Award. *The 7th International Workshop on Structural Health Monitoring*.

Narin, J. A. (1999). Applications of finite fracture mechanics for predicting fracture events in composites. *5th International Conference on Deformation and Fracture of Composites, London.*

Pierce, S.G, Culshaw, B., Manson, G., Worden, K. and Staszewski, W.J. (2000). The application of ultrasonic Lamb wave techniques to the evaluation of advanced composite structures. *Proceedings of SPIE* Vol. 3986 (2000)

Saxena, A., Goebel, K., Larrosa, C., Janapati, V., Roy, S. and Chang, F-K. (2011). Accelerated aging experiments for prognostics of damage growth in composite materials *The 8th International Workshop on Structural Health Monitoring*.

Seale, M.D., Smith, B.T. and Prosser, W.H. (1998). Lamb wave assessment of fatigue and thermal damage in composites. *Journal of Acoustical Society of America* 103 (5) 2416-2424.

Shahid, I. and Chang F.-K. (1993). *Progressive failure analysis of laminated composites subjected to in-plane and shear loads*. Department of Aeronautics and Astronautics, Stanford University.

Su, Z., Ye, L. and Lu, Y. (2006). Guided Lamb waves for identification of damage in composite structures: a review. *Journal of Sound and Vibration* 295 753-780.

Toyama, N., Noda, J. and Okabe, T. (2003). Quantitative damage detection in cross-ply laminates using Lamb wave method. *Composites science and technology* 631473-1479.

Toyama, N., Yashiro, S., Takatsubo, J. and Okabe, T. (2005). Stiffness evaluation and damage identification in composite beam under tension using Lamb waves. *Acta Materialia* 53 4389-4397.

Worden, K. (2001). Rayleigh and Lamb waves – basic principles. *Strain* Vol. 37 No. 4.