Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

REVIEWS

Structural Health Monitoring of Composite Structures

Ramadas Chennamsetti

Abstract | Structural Health Monitoring (SHM) aims at evaluation of structural performance by regularly monitoring various physical parameters captured by a network of sensors. In-service SHM plays a significant role, especially in composite structures, where a majority of damages are invisible and inaccessible. In this article, the recent research and development work carried out in the field of sensors and instrumentation for SHM applications and damage detection algorithms have been critically reviewed. Implementation of SHM strategy on various composite structures has also been discussed.

Keywords: *structural health monitoring, PZT, fibre bragg grating sensor, algorithm, lamb wave, strain*

1 Introduction

Use of composite materials for structural applications has grown substantially over the past few decades due to their high specific strength, high specific modulus, corrosion resistance and tailorability of the material as per external loading. Typical damages that occur in composites are matrix cracking, fiber breakage, inter-ply disbond (delamination), disbond between fiber and matrix etc. These damages are more severe and devastating when compared to damages that occur in metals. Moreover, sub-surface damages in composites are difficult to identify visually, and some of them are completely inaccessible. This makes inspection of composite structure for defects quite difficult putting structural integrity under threat. Moreover, prevailing Non-destructive Evaluation (NDE) techniques are off-line, not robust, and to some extent fail to identify the damages in composite structures. Hence, Structural Health Monitoring (SHM),[1–4] of composite materials is important in the life cycle management of composite products.

SHM has brought a paradigm shift in composite structures. With technological advancement in material processing, sensors, communication systems, computational tools etc., attempts are being made to carry out periodic on-line and/or off-line SHM of structures. The main focus of SHM is to (a) identify location of damage and (b) quantify severity of the damage. Another aspect of SHM is damage prognosis. Once all features of the damage in a structure are known, one can employ damage prognosis algorithms to predict remaining or residual life of the structure.

The key components required for SHM of any structure broadly are—sensors, data acquisition, signal processing, and the damage detection algorithm. Various techniques based on Lamb waves, strain, vibration, impedance etc. are available in literature for health monitoring. Selection of a technique is very vital for the success of SHM. Some techniques, such as vibration,[5] are sensitive to global changes in the structure, whereas, Lamb waves can give local measurements/changes in structural parameters.[2] It was found that combining various techniques can enhance efficacy of damage detection. As an example, Ramadas et al.[6] combined four different damage features, two each from Lamb wave and vibration, to identify damage in a cross-ply composite beam structure. Nevertheless, no extensive research on combining various SHM techniques to develop hybrid SHM schemes has been reported in literature. This article discusses some latest research and development, and implementation work carried out on SHM in composite structures. Interested readers can access references[1–3] for more details.

2 Sensors

For SHM, a network of sensors is deployed on the surface of a structure or embedded within the structure. For health monitoring applications,

Research and Development Estt (Engineers), DRDO, Pune 411 015, India.
rd_mech@yahoo.co.in

sensors have to be reliable and light weight, and size of a sensor should be as small as possible. Moreover, sensors deployed in a structure should not affect performance of the host structure. These sensors can be active or passive. In active sensor network, the sensors can give actuation and sense, for e.g., piezo (PZT) patches etc., whereas in passive sensor network, the sensors can only sense, for e.g., accelerometers and strain gauges. Selection of a sensor for any SHM applications is crucial aspect of the whole process.

Lamb waves can be excited and received through various means. Ultrasonic contact probes are traditionally being used for transmission and reception of the waves. Ultrasonic contact probe along with an angle shoe (a perspex wedge) is also used to excite a particular or single Lamb mode. Electro-Magnetic Acoustic Transducers (EMATs) are suitable to transmit and receive Lamb waves in metallic (conducting) structures. For use of contact probes, in general, a couplant is required for efficient coupling of energy between the probes and specimen. Amplitude of Lamb wave depends on thickness of the couplant. When contact between specimen and probe is a not permissible and/or to avoid the effect of couplant thickness, non-contact probes can be employed for generation and capturing of Lamb waves. In non-contact probes either water (liquid) or air acts as couplant. However, transducers discussed above are difficult to deploy and integrate with a structure for SHM applications. This is because of the fact that these transducers are bulky and also add some parasitic mass to the host structure. Piezoelectric, Piezoelectric Wafer Active Sensor (PWAS), Polyvinylidene fluoride (PVDF), Fiber Bragg Grating (FBG) sensors etc. are viable choices for SHM applications.

2.1 *Piezoelectric*

In general, for Lamb wave based SHM technique, a network of PZT sensors is bonded permanently to host structure, which is to be monitored. A pulser-receiver is required to power the piezo sensors, since power requirement for excitation of piezo patches is less, size of pulser and receiver comes down. Since PZT sensors are prone to Electromagnetic Interference (EMI) when deployed for SHM applications, layers were developed to shield the sensors from EMI.[7] The main disadvantage of Lamb wave based SHM, which uses PZT patches for transmission and reception of Lamb waves, is excitation of more than a single mode. This is because of the multi-modal characteristics of Lamb waves. These multiple modes may undergo interference and may affect each other. Therefore, to process the Lamb wave signals trans-received by PZT, robust signal processing tools are required.[2] To circumvent the multi-modal excitation problem, Piezoelectric Wafer Active Sensor (PWAS), which is an array of piezo wafers, can be used for tuning Lamb waves.[8] Amplitude of Lamb wave signal transmitted/received using PZT patches depends on various parameters, such as adhesive thickness and stiffness, PZT diameter and thickness, and on PZT sensor signal amplitude. Numerical and experimental studies were conducted[9] to understand the effects of these parameters and design criteria were proposed to maximize the signal amplitude. Because of brittle nature of PZT patches, it is difficult to deploy them in curved composite structures. In such instances, PVDF[10,11] piezoelectric film is a viable solution. Another promising sensor for SHM applications is PWAS. This sensor can be surface mounted or embedded in the host structure. More details on tuning of Lamb waves with PWAS for SHM applications can be found in Ref. 8.

In the recent past, SMART layer[R 12] with built-in piezosensor network was developed for SHM applications. The layer is embedded in a composite structure during fabrication, thus avoiding bonding of any sensor on surface of the structure. Embedment also helps in reduction of EM noise. Since piezosensors are in-built on a flexible layer, the layer can assume any shape of composite structure. It is also possible to integrate other sensors such as fiber optic and strain gauges, over the SMART layer.

2.2 *Fiber bragg grating*

Another promising sensor for SHM applications is based on fiber optics. Crane and Gagorik[13] were the first to use fiber optic based sensor for damage assessment in Fiber Reinforced Plastic (FRP) composite structure. Attempts were also made to use Fabry-Perot strain sensor (FP)[14] for measurement of strain/temperature. It was observed that Fiber Bragg Grating (FBG)[15,16] sensors are better than FP sensors. Since then, FBG sensors have been used for measurement of strain and temperature in structural applications. Nowadays, FBG has become an important sensor for measurement of strain in SHM applications and damage detection. More details on applications of FBG sensors for damage identification/detection can be found in.[17,18] This sensor has several advantages, such as consumption of low power, integration with laminated composites during manufacturing, no EM noise, multiplexing, good bandwidth, flexibility to integrate with curved composite structures, high sensitivity etc. Moreover, since dimensions of FBG are compatible with composites, effect of embedment of the sensors does not influence significantly mechanical properties of the host structure. It is anticipated that strain measured by surface bonded FBG sensor is same as that of host structure. But, because of protective layer over the sensor and adhesive bonding between the protective layer and host structure, the strains are different due to shear deformation.[19] Lau et al.[20] developed a model to estimate strain transferred to fiber optic sensor and validated the estimates through experiments based on Mach-Zehnder interferometer.

When FBG sensor is used for measuring high frequency ultrasonic waves, the sensor has to measure high frequency but low intensity strain instantly.[2] To acquire the high frequency ultrasonic Lamb waves using FBG, optical equipment using a tunable laser device was developed.[21] High sensitivity and high sampling rate up to 5 MHz of the equipment (FWHM: Full Wave Half Maximum) was also demonstrated. Other issues related to FBG sensors is directivity. A circular PZT sensor can capture an ultrasonic wave in all directions with same amplitude, but, an FBG sensor is more sensitive to strain in fiber direction. Hence, an FBG can capture, with good amplitude, a Lamb wave propagating in the direction of fiber. It has less sensitivity to the Lamb wave propagating in a direction perpendicular to that of the fiber.[22] To overcome this issue, FBG rosette, similar to strain rosette, was developed.[23] Three FBG sensors arranged at 120° angle (similar to equilateral triangle) are bonded/embedded in the structure. Amplitude of signal captured by each FBG sensor in rosette depends on direction of propagation of Lamb wave and fiber direction. This rosette can also be used for damage localization.[2]

2.3 *Other sensors and instrumentation*

Efforts have been made for developing instrumentation and scanning systems for SHM applications. CLoVER transducer (Composite Long-Range Variable-detection Emitting Radar)[24,25] was developed as an alternative concept for excitation of Lamb waves and for damage detection in SHM scenario. Qiu et al.[26] developed a Lamb wave and PZT network-based integrated multi-channel scanning system (PXI-ISS) for SHM applications. Experiments using this PXI-ISS were performed on a composite wing box of an unmanned aerial vehicle for assessing its functional integrity, especially the multi-channel frequency scanning and damage assessment function of the PXI-ISS. Recently, application of wireless smart sensors for full-scale SHM of complicated and large-scale structures has been attempted by various researchers. It includes development and application of high-sensitivity Wireless Smart Sensors Network (WSSN) for decentralized stochastic modal identification,[27,28] which involves combining the use of conventional wired high-sensitivity sensors with low-cost wireless smart sensors,[29] use of optimum number and location of sensors[30] etc.

3 Damage Detection Algorithms

Another key component in successful implementation of SHM strategy is damage detection algorithm. For processing signals or data captured by sensors, signal processing techniques in time and frequency domains are available. There are also techniques such as Short Time Fourier Transform (STFT), Wavelet Transform (WT), Bilinear time–frequency distribution function (Wigner-Ville Distribution (WVD)) and Modified Wigner distribution function etc. available for representation of the data in time-frequency domain.

Damage detection schemes based on Time-of-Flight (ToF),[31,32] amplitude in time and frequency domains and time-frequency domain,[33,34] wave velocity, energy etc. too have been proposed. Method for damage detection using sensor triangulation method combined with strain wave velocity with an optimization employing Genetic Algorithm (GA) was proposed and successfully validated on a composite plate.[35] Triangulation techniques based on Lamb waves when implemented on structures with complex shapes and discontinuities however, pose problems. Therefore, geodesic concept was used with triangulation technique to circumvent the problem.[36] Experimental validations on metal and composite plates were carried out.

Genetic Algorithm (GA) and Neural Network (NN) have also been explored for use in SHM applications. Reconstruction of effective material properties is also a part SHM. Single Transmitter and Multiple Receiver (STMR)[37] array patch was developed for both material characterization and health monitoring of anisotropic plates. Effective elastic moduli were predicted using GA from velocity measurements from different directions. Measurements from STMR were also used for imaging defects, if any, and reflections from edges. Su and Ye[38] established a Lamb wave based quantitative identification scheme for detection of delamination in CF/EP composite structures using Artificial NN. An Intelligent Signal Processing and Pattern Recognition (ISPPR) package was developed to perform the identification, in which a multi-layer artificial NN supervised by error Back Propagation (BP) was trained using spectrographic characteristics extracted from acquired Lamb wave signals. NN was used to predict location and size of transverse cracks in a composite beam by combining two damage features from Lamb waves (Time-of-Flight (ToF)) and amplitude ratio) and two from vibration (first and second natural frequencies).[6] Initially, NN was trained using numerically simulated data and the trained network was used for prediction of transverse crack. More details on use of NN and GA in SHM application can be found in.[39]

Artificial NN has been one of the most popular techniques for developing algorithms for strain based SHM. Artificial NN was used in strain based SHM to predict structural damage presence and extent in a GFRP T-joint[40] under tensile pull-loads. Numerical simulations using Finite Element Method (FEM) was conducted for various delamination sizes (30 mm, 60 mm and 90 mm) and locations in the structure. The simulation results were validated through experiments. Artificial Neural Network (ANN) was used to determine the extent of the damage. A real-time system was developed to detect the presence, location and extent of damage from the longitudinal strains obtained from a set of sensors placed on the surface of the structure. Gope et al.[41] developed an ANN based damage detection algorithm for health monitoring of five meter CFRP bridge using static strain data. Back propagation algorithm was trained using experimental strain data. The proposed algorithm could predict damage location and extent accurately from random test data. Kressel et al.[42] embedded FBG sensors for structural integrity of an Unmanned Aerial Vehicle. Data captured during flight was analyzed in time and frequency domains to identify any unusual behavior. FBG were also deployed for construction of mode shape and prediction of natural frequencies in SHM applications. Tyler et al.[43] used strain measured by FBG sensors for mode shape reconstruction and assess natural frequencies in wind turbine blades. The modal parameters were estimated using Frequency Domain Decomposition (FDD) method[44] and the Hilbert Transform Method (HTM) and demonstrated on a wind turbine model.

4 Implementation of Damage Detection Methodology and SHM

Although principles behind SHM are known, implementation of real time fully automated SHM in a real structure is still a challenge to the community. There are many efforts to demonstrate SHM methodologies in laboratory level and scaled models. Tyler et al.[43] developed a FBG based distributed strain sensing system and demonstrated on a wind turbine model. FBG sensors were mounted over turbine blades. Strain data showed that the FBG sensor system can capture natural frequencies of blade, rotational frequencies, natural frequencies of the tower and coupling among three of them. Damage or ice accretion on one of the blades was simulated by adding lumped mass. FBG sensors could detect increase in power due to imbalance caused by the lumped mass, and also, the sensors could detect shift in natural frequencies. Damage detection in composite structures can also be carried out using either active or passive techniques. Staszewski et al.[45] demonstrated active and passive approaches for detection of impact damage on a composite structure. In the first approach, Lamb waves and a 3D laser vibrometer were used for detection of delamination and its severity. This approach requires sophisticated instrumentation but less signal processing. In the second approach, the impact location was identified using modified triangulation with GA optimization scheme. This approach does not require sophisticated instrumentation, but complex signal processing schemes are required. However, both the approaches can be combined for real time SHM applications. Numerical modeling using Finite Element Method (FEM) and Boundary Element Method (BEM) have been used in SHM applications.[46] Alaimo et al.[46] proposed a PZT based SHM to detect skin/stiffener debonding and delamination cracks in laminated composite structures. A dual reciprocity Boundary Element (BE) formulation for piezoelectricity was used to study SHM systems based on the piezoelectric dynamic strain sensing capability. The BE method was used to model a laminated structure as well as bonding between the host delaminated structure and piezoelectric sensor. Piezo patches as sensors for SHM were deployed on a representative structure with ply drop-offs to replicate fuselage flange-skin disbond. A damage index was proposed to look at the outputs of the piezosensors and it has been vindicated numerically as a good parameter for an ad hoc flange-skin SHM system. Sensors deployed for SHM applications can be used for detecting other modes of structural failure also. Kressel et al.[42] demonstrated a FBG based concept for tracking structural integrity of Nishant Unmanned Aerial Vehicle (UAV) during flight. Two tail booms of the UAV were embedded with FBG sensors. Using the sensors data, local buckling was identified at high touch-down impact. From analysis it was found that there was no permanent structural damage due to this. Attempts were made to use SHM sensors for material characterization also. Vishnuvardhan et al.[37] developed a STMR array for material characterization and SHM of composite plates. Using group velocities of S_0 mode in graphite-epoxy laminate, effective properties of the laminate were predicted using GA. They also demonstrated that the array can do imaging, which can be used for SHM applications.

SHM of stiffened panels becomes a challenge. This kind of structure causes attenuation and dispersion of Lamb waves. Hence, Lu et al.[45] initially studied Lamb wave attenuation and dispersion characteristics, before actually carrying out damage detection on a stiffened composite panel using surface bonded piezo patches. They employed inverse algorithm based on correlations between the Digital Damage Fingerprints (DDF) for detection of holes in the panel.

As a whole from the literature, it is observed that real time on-line SHM on a real structure is yet to be realized. As of now, many SHM schemes are confined only to laboratory level and scaled models.

5 Discussion and Conclusions

This paper presents a review of recent work on SHM, based on strain and Lamb waves. Since composites are more sensitive to defects, which may be surface or sub-surface, to evaluate structural performance and to avoid catastrophic failure, continuous health monitoring is essential. SHM is a multidisciplinary area which requires amalgamation of sensors, data acquisition, signal processing, algorithms, materials and mechanics. Thorough understanding of all these areas is important for successful implementation of any health monitoring scheme. Once an effective SHM methodology is deployed, it may be possible to avoid use of conventional NDE techniques for damage detection at a structure level. However, conventional NDE may still have to be used for component level damage detection. Since on-line and/or off-line health assessment of a structure is possible using SHM, down time, repair and finally maintenance cost of transportation of systems can be reduced. Moreover, scheduled maintenance can be converted to need based maintenance, thus cost, time and manpower can be saved.

Once SHM scheme gives information on structural integrity, location and severity of damage at regular intervals of time, attempts may be made to use this data for prediction of residual life, residual strength, reduction in structural stiffness and survivability, and any other useful information. Moreover, continuous monitoring of structure's performance and integrity also helps in estimation of real time loads acting on the structure. This helps designers for accurate estimation of actual loads on a given structure. This is the other facet of implementation of real time SHM.

With advancement in sensors' technology, sensors with small footprint like PZT and FBGs are available for SHM applications. Attempts were made to use PZT sensors for Lamb wave based SHM applications. Majority of these attempts were on laboratory level models. PZTs can be either surface bonded or embedded as a SMART layer in a structure. Embedment process protects the sensor from any environmental effects and surface structural damages. If a structure having PZTs as sensors for SHM is operated in harsh environments (high and low temperatures and high or low moisture content when compared to ambient), propagation characteristics of ultrasonic waves will be affected. Moreover, PZTs are prone to EMI when deployed in a structure. These will finally influence efficacy of damage detection. Therefore, proper protection of piezoelectric sensors is essential.

In the recent past, FBGs have successfully been used for damage detection applications because of the versatility of the sensor. Since FBGs are sensitive to strain and temperature changes, temperature compensation during strain measurement should be incorporated. Sensing of strain using FBGs depends on directionality. FBG is more sensitive to strain if the strain is developed in the direction of fiber. To account for strain in other directions, FBG rosettes have been conceived and used for off-axis strain measurements. Size of FBG sensor is very important when embedded in a laminated composite structure. Presence of the sensor shouldn't act as a damage initiation point. Availability of high frequency and multi-channel interrogator for capturing high frequency ultrasonic Lamb waves is still an issue. Nevertheless, any sensor used for SHM applications should work reliably longer than life of the host structure.

SHM based on either strain or ultrasonic wave or vibration or impedance based techniques is sensitive to certain types of damages. There is no unique SHM technique, which can detect any type of damage. However, to enhance efficacy of detection of various types of damages, attempts can be made to marry at least two or more SHM techniques. This paves the way for development of Hybrid SHM techniques. Moreover, robust and rapid damage detection algorithms are required to be developed in synchronization with sensors' data for quick on-line damage identification.

Received 27 April 2015.

References

1. W.J. Staszewski, C. Boller and G.R. Tomlinson, health monitoring of aerospace structures: Smart sensor technologies and signal processing, John Wiley & Sons, UK, (2004).
2. Z. Su and L. Ye, Identification of damage using Lamb waves, Springer publications, Germany, (2009).
3. A. Raghavan and C.E.S. Cesnik, Review of Guided-Wave Structural Health Monitoring, *Shock Vib. Digest*, **39**(2), 91–114 (2007).
4. H. Sohn, C.R. Farrar, F.M. Hemez, D.D. Shunk, D.W. Stinemates and B.R. Nadler, A Review of structural health monitoring literature, 1996–2001, *Los Alamos National Laboratory Report*, LA-13976-MS, (2003).
5. S.W. Doebling, C.R. Farrar, M.B. Prime and D.W. Shevitz, Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review, *Los Alamos National Laboratory Report*, LA-13070-MS, (1996).
6. C. Ramadas, K. Balasubramaniam, M. Joshi and C.V. Krishnamurthy, Detection of transverse cracks in a composite beam using combined features of Lamb wave and vibration techniques in ANN environment, *International Journal on Smart Sensing and Intelligent Systems*, **1**(4), 970–984 (2008).
7. M. Lin, X. Qing, A. Kumar and S. Beard, SMART Layer and SMART Suitcase for Structural Health Monitoring Applications, *Proc. of SPIE,* 4332 (2001).
8. V. Giurgiutiu, Tuned Lamb wave excitation and detection with piezoelectric wafer active sensors for structural health monitoring, *Journal of Intelligent Material Systems and Structures*, **16**, 291–305 (2005).
9. Sungwon Ha and Fu-Kuo Chang, Adhesive interface layer effects in PZT-induced Lamb wave propagation, *Smart Material and Structures*, **19**, doi:10.1088/0964-1726/19/2/025006 (2010).
10. R.S.C. Monkhouse, P. Wilcox and P. Cawley, Flexible interdigital PVDF transducers for the generation of Lamb waves in structures, *Ultrasonics*, **35**, 489–498 (1997).
11. R.S.C. Monkhouse, P. Wilcox, M.J.S. Lowe, R.P. Dalton and P. Cawley, The rapid monitoring of structures using interdigital Lamb wave transducers, *Smart Materials and Structures,* **9**, 304–309 (2000).
12. http://www.acellent.com.
13. R.M. Crane and J. Gagorik, Fiber optics for a damage assessment system for fiber reinforced plastic composite structure, *Quant NDE*, **28**, 1419–1430 (1984).
14. K.S. Kim, Y. Ismail and G.S. Spring, Measurement of strain and temperature with embedded instrinsicFabry-Perot optical fiber sensors, *Composite Materials*, **27**, 1663–1677 (1993).
15. S.M. Melle, K. Liu and K. Measures, Strain sensing using a fiber optical bragg grating, *Spieproc.*, 1588, 255–263 (1991).
16. P.D. Foote, Fiber bragg grating strain sensors for aerospace smart structures, *Spieproc.*, 2361, 290–293 (1994).
17. G. Zhou and L.M. Sim, Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors: Review, *Smart Materials and Structures*, **11**, 925–939 (2002).
18. M. Majumder, T. Gangopadhyay, A.K. Chakraborty, K. Dasgupta and D.K. Bhattacharya, Fibre Bragg gratings in structural health monitoring—Present status and applications, Sensors and Actuators A: *Physical*, **1**(147), 150–164 (2008).
19. H. Shiuh-Chuan and T. Chang-Yu, Strain measurement of fiber optic sensor surface bonding on host material, *Trans. Nonferrous Met. Soc. China*, **19**, s143–s149 (2009).
20. K.T. Lau, L.M. Yuan, L. Zhou, J. Wu and C.H. Woo, Strain monitoring in FRP laminates and concrete beams using FBG sensors, *Composite Structures*, **51**, 9–20 (2001).
21. Bin Lin and Victor Giurgiutiu, Development of optical equipment for ultrasonic guided wave structural health monitoring, Smart Sensor Phenomena, Technology, Networks, and Systems Integration 2014, edited by Wolfgang Ecke, Kara J. Peters, Norbert G. Meyendorf, E. Theodoros, Matikas, *Proc. of SPIE* Vol. 9062, 90620R (2014).
22. D.C. Betz, G. Thursby, B. Culshaw, W.J. Staszewski, Acousto-ultrasonic sensing using fiber Bragg gratings, *Smart Materials and Structures*, **12**, 122–128 (2003).
23. D.C. Betz, G. Thursby, B. Culshaw and W.J. Staszewski, Structural damage location with fiber Bragg grating rosettes and Lamb waves, *Structural Health Monitoring: An International Journal*, **6**(4), 299–308 (2007).
24. K.I. Salas and C.E.S. Cesnik, Guided wave excitation by a CLoVER transducer for structural health monitoring: Theory and experiments, *Smart Materials and Structures*, **18**, 075005 (2009).
25. K.I. Salas and C.E.S. Cesnik, Guided wave structural health monitoring using CLoVER transducers in composite, *Smart Materials and Structures*, **19**, 015014 (2009).
26. L. Qiu, S. Yuan, Q. Wang, Y. Sun and W. Yang, Design and Experiment of PZT Network-based Structural Health Monitoring Scanning System, *Chinese Journal of Aeronautics*, **22**, 505–512 (2009).
27. H. Jo, S. Sim, T. Nagayama and B. Spencer, Jr., Development and application of high-sensitivity wireless smart sensors for decentralized stochastic modal identification, *J. Eng. Mech.*, **138**(6), 683–694 (2012).
28. C. Liu, J. Teng, H. Zhang, X. He and Y. Guo, Dynamic monitoring of an experimental cable-stayed bridge model using wireless sensor network, *Earth and Space*, 1118–1127 (2012).
29. S. Dorvash, S. Pakzad and C. Naito, In-Service vibration monitoring of a tall building structure using wireless sensor networks, *Structures Congress*, 2826–2838 (2014).
30. M. Chang and S. Pakzad, Optimal sensor placement for modal identification of bridge systems considering number of sensing nodes, *J. Bridge Eng.*, **19**(6), 04014019 (2014).

31. S. Seth and S. Kessler, Mark Spearing and Constantinos Soutis, Damage detection in composite materials using Lamb wave methods, *Smart Material and Structures*, **11**(2), doi:10.1088/0964-1726/11/2/310 (2002).
32. C. Ramadas, P. Janardhan, K. Balasubramaniam, M. Joshi and C.V. Krishnamurthy, Delamination size detection using time of flight of anti-symmetric and mode converted Ao mode of guided Lamb waves, *Intelligent Material Systems and Structures*, **21**(6), 817–825 (2010).
33. F. Aymerich and S. Meili, Ultrasonic evaluation of matrix damage in impacted composite laminates, *Composites Part B: Engineering*, **33**(1), 1–6 (2000).
34. A.P. Christophe, G. Sébastien, L. Klas and D. Christophe, Damage assessment in composites by Lamb waves and wavelet coefficients, *Smart Material and Structures*, **12**(3), doi:10.1088/0964-1726/12/3/310 (2003).
35. P.T. Coverley and W.J. Staszewski, Impact damage location in composite structures using optimized sensor triangulation procedure, *Smart Material and Structures*, **12**(5), doi: 10.1088/0964-1726/12/5/017 (2003).
36. R. Gangadharan, M.R. Bhat, C.R.L. Murthy and S. Gopalakrishnan, A geodesic-based triangulation technique for damage location in metallic and composite plates, *Smart Material and Structures*, **19**(11), 115010 (2010).
37. J. Vishnuvardhan, M. Ajith, C.V. Krishnamurthy and K. Balasubramaniam, Structural health monitoring of anisotropic plates using ultrasonic guided wave STMR array patches, *NDT&E International*, **42**, 193–198 (2009).
38. Z. Su and L. Ye, Lamb wave-based quantitative identification of delamination in CF/EP composite structures using artificial neural algorithm, *Composite Structures*, **66**, 627–637 (2004).
39. R. Jha and S.K. Barai, ‘Neural Networks and Genetic Algorithms in Structural Health Monitoring’, in ‘Intelligent Materials and Structural Health Monitoring: Materials, Devices, and Analysis’, S. Nayak and J. Agrawal (Eds.), John Wiley and Sons (2012).
40. A. Kesavan, M. Deivasigamani, S. John and I. Herszberg, Damage detection in T-joint composite structures, *Composite Structures*, **75**, 313–320 (2006).
41. J.K. Gope, N.G. Singh, M. Joshi, I. Khan and M. Pawar, Damage detection of carbon composite bridge using static strain and artificial neural network, ISAMPE National Conference on Composites—INCCOM 10, November 18–19, R&DE(E), Pune, (2011).
42. I. Kressel, A. Handelman, Y. Botsev, J. Balter, P. Guedj, N. Gorbatov, M. Tur, A.C.R. Pillai, M.H. Prasad, N. Gupta, A.M. Joseph and R. Sundaram, Evaluation of Flight Data from an Airworthy Structural Health Monitoring System Integrally Embedded in an Unmanned Air Vehicle, 6th European Workshop on Structural Health Monitoring.
43. J.A. Tyler, A. Ajit, M. Pier, G. Chiara and C. Giuliano, Development of a FBG based distributed strain sensor system for wind turbine structural health monitoring, *Smart Materials and Structures*, **22**, 075027, doi:10.1088/0964-1726/22/7/075027 (2013).
44. R. Brincker, L. Zhang and P. Andersen, Modal identification of output-only system using frequency domain decomposition, *Smart Materials and Structures*, **10**, 441 (2001).
45. W.J. Staszewski, S. Mahzan and R. Traynor, Health monitoring of aerospace composite structures—Active and passive approach, *Composites Science and Technology*, **69**, 1678–1685 (2009).
46. A. Alaimo, A. Milazzo and C. Orlando, Numerical analysis of a piezoelectric structural health monitoring system for composite flange-skin delamination detection, *Composite Structures*, **100**, 343–355 (2013).
47. Y. Lu, L. Ye, D. Wang and Z. Zhong, Time-domain analyses and correlations of Lamb wave signals for damage detection in a composite panel of multiple stiffeners, *Composite Materials*, **43**(26), 3211–3230 (2009).

Ramadas is currently with the Composites Research Centre of Research and Development Establishment (Engineers), DRDO, Pune. Graduated in Mechanical Engineering, Ramadas has his Ph.D in Machine Design from Indian Institute of Technology Madras, Chennai. His areas of interests include stress waves in solids, mechanics of laminated composites, continuum mechanics, non-destructive evaluation using ultrasonics and structural health monitoring.