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VIBRATION-BASED MODEL-DEPENDENT DAMAGE (DELAMINATION) IDENTIFICATION AND HEALTH MONITORING FOR COMPOSITE STRUCTURES — A REVIEW

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There are strong needs and requirements for on-line damage (delamination) detection and health-monitoring techniques on composite structures. Vibration-based model-dependent methods with piezoelectric sensor and actuator incorporated into composite structures offer a promising option to fulfil such requirements and needs. These methods utilize finite element analysis techniques, together with experimental results, to detect damage. They locate and estimate damage events by comparing dynamic responses between damaged and undamaged structures. According to the dynamic response parameters analyzed, these methods can be subdivided into modal analysis, frequency domain, time domain and impedance domain. Model-dependent methods are able to provide global and local damage information. They are cost-effective and are relatively easy to operate. However, there are still many challenges and obstacles before these methods can be implemented in practice.

1. INTRODUCTION

Due to their high specific stiffness and strength, composite materials are being used increasingly in many engineering applications. However, the mechanical properties of composite materials may degrade severely in the presence of damage. Failures of structures, particularly aircraft structures, often have tragic consequences. Therefore, damage detection, especially on-line, becomes a very important issue [1].

Composites are complex materials exhibiting distinct anisotropic properties. Common damage for composite materials are matrix cracking, fibre breakage, fibre–matrix debonding, and delamination between plies [2, 3]. Delamination, probably the most frequently occurring damage, appears as a debonding of adjoining plies in laminated composites. The causes of delamination such as imperfect bonding, crack in matrix materials, separation of adjoining piles, and broken fibres may originate during manufacturing. Alternatively, delamination may be induced during in-service loading, such as by foreign object impact or by fatigue [4].

Currently available non-destructive evaluation (NDE) methods are mostly non-model methods, i.e., either visual or localized experimental methods, such as acoustic or ultrasonic methods, magnetic field methods, radiographs, eddy-current methods and thermal field methods [5]. Accessing these techniques is time-consuming and costly. Some of them are also impractical in many cases such as in service aircraft testing, and space structure [6]. Almost all of these techniques require that the vicinity of the damage is known in advance and that the portion of the structure being inspected is readily accessible for human beings [5]. Subject to these limitations, these non-model (experimental) methods can provide only local information and no indication of the structural strength at a system level.

Shortcomings of currently available NDE methods indicate a requirement of damage inspection techniques that can give global information on the structure and they do not require direct human accessibility of the structure [5, 7]. This requirement has led to the development of model-based methods that examine changes in the vibration characteristics of the structure and also led to the development of smart structures/intelligent material systems.

Smart structures have the ability to detect damage on-line, and the capacity to locate the position of the damage, and to estimate its severity using sensor information. Smart structures, therefore, have the potential to achieve the ultimate objective in damage detection, i.e., predicting the remaining useful life of the structure. There are many researchers exploring various smart structures using different sensors.

This review focuses on the model-based delamination detection methods for composite structures using vibrations. After an overview of the categories of currently available model-based methods for damage detection, it describes the most commonly used structural modelling techniques for delamination and the effects of delamination on dynamic parameters. Then the review focuses on the application of vibration-based model-dependent damage detection methods in composite structures. Finally, this review is devoted to the development of this group of methods with incorporated piezoelectric sensors and actuators for on-line delamination detection for composite structures.

2. MODEL-BASED METHODOLOGIES

The model-based (MB) methods undertake analysis of structural models and are usually implemented by finite element analysis. Damage is simulated by modifying the models. Experimental data can then be compared with the analytical data to determine damage location and extent. The effectiveness of the whole group of MB techniques, however, is dependent on the accuracy of the structural model and these methods may have difficulties when applied to complex structures [7]. With the model, various response characteristics of the structure such as modal analysis, time response, frequency response and impedance response can be extracted and analyzed.

2.1. MODAL ANALYSIS METHODS

This group of methods utilize the information from all modal parameters (modal frequencies, mode shapes and modal damping ratio) or combinations of some of them to detect damage. The basic idea of these methods is that modal parameters are functions of the physical properties of the structure (mass, damping and stiffness). Therefore, changes in the physical properties, e.g., damage, will cause changes in the modal properties. Usually, damage will decrease mass and stiffness of the structure and increase damping ratio locally. Among the three structural property parameters, mass is less sensitive to damage while damping is most sensitive to damage. Because of its complex physical nature, proportional damping is often adapted in damage detection methods [8–10].

According to their different detection techniques, the modal analysis methods can be divided into the following major categories [9, 10]: modal shape changes methods [11, 12], modal shape curve methods [13, 14], sensitivity-based update methods [15, 16], eigenstructure assignment methods [17, 18], optimal matrix update methods [19, 20], changes in measured stiffness matrix methods [21, 22], frequency response function method [23, 24], and combined modal parameters method [25].

The majority of this group of methods uses the lower frequencies of the modal and can best describe the global behaviour of the structure. Therefore, they hold promise for global non-destructive inspection of a variety of structures, because surface measurements of a vibrating structure can provide information about the health of the internal members without costly (or impossible) dismantling of the structure [26]. Also, because of their global nature, these techniques allow the customization of measurement points. Another major advantage is that the modal information is cheap to obtain and easy to extract [9].

However, there are many limitations to this group of methods. Firstly, some of the modal-based methods can only detect particular forms of damage in their diagnostic schemes. Secondly, the methods usually use the undamaged structural modal parameters as the basline compared with the damage information. This will result in the need for a large data storage capacity for complex structures [8, 27]. But, a newly developed method, which tries to quantify damage without using a base line [27], may be a solution to this difficulty. Thirdly, they fail to detect small defects [8] in global features.

2.2. FREQUENCY DOMAIN

Damage may be detected only using frequency response of the structure. The foundation of this group of methods is that damage produces a decrease in structural stiffness, which, in turn, produces decreases in natural frequencies [28].

The location of the defect can be estimated from the degree of change in natural frequency, which in turn, depends on the position of the defect for a particular mode of vibration [29]. In other words, local or distributed changes in stiffness produce changes in natural frequencies, which affect each mode differently depending on the damage location [30]. This is because the damage event is a local phenomenon in most cases. Therefore, it was suggested [28] that monitoring local high-frequency modes of local area provide a better indication of damage for small damage. It was also pointed out that locating damage from changes in frequencies alone is impractical [28]. It was suggested that resonant frequency is a better indicator of defects than frequencies because it can change more significantly than frequencies do when properties change [28].

There are several other methods available in this frequency domain category such as the damage index method [31], the sensitivity analysis method, etc. [32, 33].

As only frequency information is required, these approaches can provide cost-effective structural assessment techniques. However, natural frequency changes alone may not be sufficient for a unique identification of the location of structural damage [32–34]. The current frequency domain methods are either using lower frequencies for providing global information of structures or using higher frequencies for providing local information of structures. None of these can provide sufficient information for the detection of both small and large defects.

2.3. TIME DOMAIN

Basically, all methods in this category are related because they use time history. These methods could be independent of modal information although they are usually combined with frequency domain methods. Damage is estimated using time histories of the input and vibration responses of the structure. Using time response over a long period while at the same time taking into account the information in several modes so that the damage evaluation is not dependent on any particular one, could be sensitive to any modes [8].

The big advantage of the methods in this group is that they can detect damage situations both globally and locally by changing the input frequencies [8, 35].

2.4. IMPEDANCE DOMAIN

Damage is detected through measuring the changes of impedance in the structure. The basis of this technique is that each part of the structure contributes to the impedance of structure to some extent. Any variation in the structure integrity will generally result in changes in the impedance, i.e., the impedance will change with changes of the stiffness. This group of techniques models the defect as a spring and assumes that it is clamped around the edges of the defect. The spring stiffness is given by the stiffness of the layers above the detect. In the the absence of a defect, the spring stiffness is infinite. The damage detection process, therefore, becomes that of inspecting the change of stiffness and location of the spring within the structure. There are two groups of techniques in this domain. One is mechanical impedance, and the other is electrical impedance.

Mechanical impedance techniques are based on the measurement of the impedance, Z, at a point of a structure. The impedance is defined as $Z = F/v$, where F is the applied force input to the structure, and v is the resultant velocity of the structure at the same point [36, 37].

Similar to the mechanical impedance, electrical impedance techniques measure change of electrical impedance, which is defined as the ratio of the applied voltage to the resulting current, of the structure. The elastic admittance of the collocated sensor/actuator is assumed to be functionally equivalent to its mechanical impedance. This group of methods is capable of multi-location and real-time health monitoring [38, 39].

Impedance domain methods are particularly suitable for detecting planar defects such as delamination. The inspection is reliable except when the system impedance becomes spring-controlled and then the impedance only decreases with spring stiffness, i.e., the layer above the defect is thin and the base structure is relatively stiff [36, 37].

3. DELAMINATION MODELLING TECHNIQUES

Composite laminates can usually be modelled as beams or plates or shells for investigating the effects of delamination. Some common modelling techniques used in delamination detection are described below.

A constrained mode model was developed for beams with through-width delaminations parallel to the beam surface located arbitrarily in both the spanwise and thicknesswise direction [40]. In this technique, the beam is modelled as four separate component segments, each being analyzed as an Euler beam. Apart from the usual conditions of continuity of transverse displacements, slopes, bending moments and shear forces, two additional conditions were considered, i.e., the continuity of axial displacements and forces; see Figure 1. The solution for the beam as a whole is obtained in terms of the solutions of all the component Euler beams by satisfying the appropriate boundary conditions at the ends of the integral segments and the continuity conditions at the junctions between the integral and delamination regions.

A simplified model was presented based on the engineering beam theory [41]. The model assumes that delamination divides the beam into four regions: above, below and on either side of the delamination and extends over the entire width; see Figure 2. A Euler beam theory is applied to each region. In addition to general conditions of beam theory, two different assumptions are used. One is that the extensional and bending stiffnesses are uncoupled; the other is that the effect of the contact between the delaminated free surfaces is included, i.e., the sections above and below the delamination are constrained to vibrate together. It was concluded that the simplified analytical model was capable of predicting the stiffness degradation in composite laminates although bending/extensional coupling was not included in the model. This model is good for determining the natural frequencies of composite laminate. The characteristic equations have to be solved numerically.

A formulation of a composite beam was developed, based on Timoshenko beam theory and the Galerkin method, to analyze the delamination effect on natural frequency and vibration mode shape of composite laminated beam [42]. The same modelling technique of delamination was used as mentioned above. The coupling effect between longitudinal vibration and transverse bending motion was considered and the results showed that it affected the modes of vibration

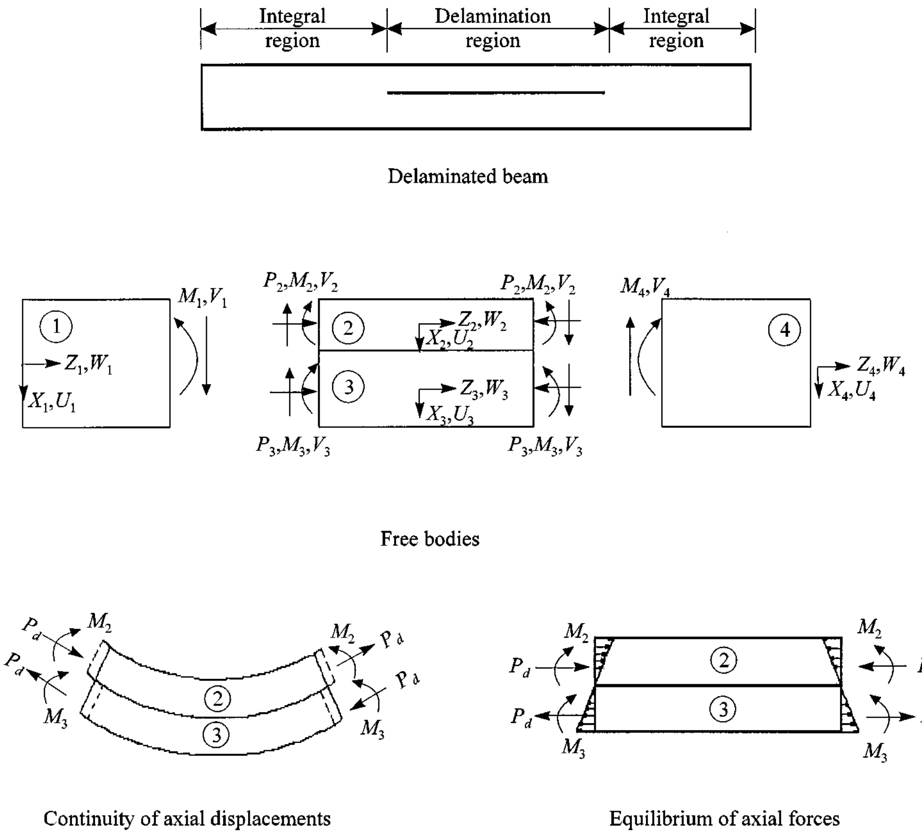

Figure 1. A constrained model of delamination [40].

significantly. This model can be extended to account for the effects of delaminations on the higher modes.

A finite element model using layer-wise theory was developed [43]. It is assumed that the same displacement distribution in the individual layers is capable of representing displacement discontinuity conditions at interfaces between layers. Delaminations are modelled by jump discontinuity conditions at the interfaces. At delaminated interfaces, the displacements on adjacent layers remain independent, allowing for separation and slope. The model can be used to study multiple delaminations through the thickness of the plate. The layer-wise linear approximation of displacements through the thickness and the use of Heaviside step functions to model delaminations prove to be an effective approach for an accurate analysis of local effects in laminated composite plates. However, the computational cost of the proposed analysis makes it unattractive for the prediction of global behaviour when compared with conventional theories. This modelling is further improved by higher order theory with enhanced strains to describe layer-wise displacements more accurately [44].

A methodology for predicting and relating the natural frequencies, mode shapes and modal damping of composite beams with the delamination based on laminate

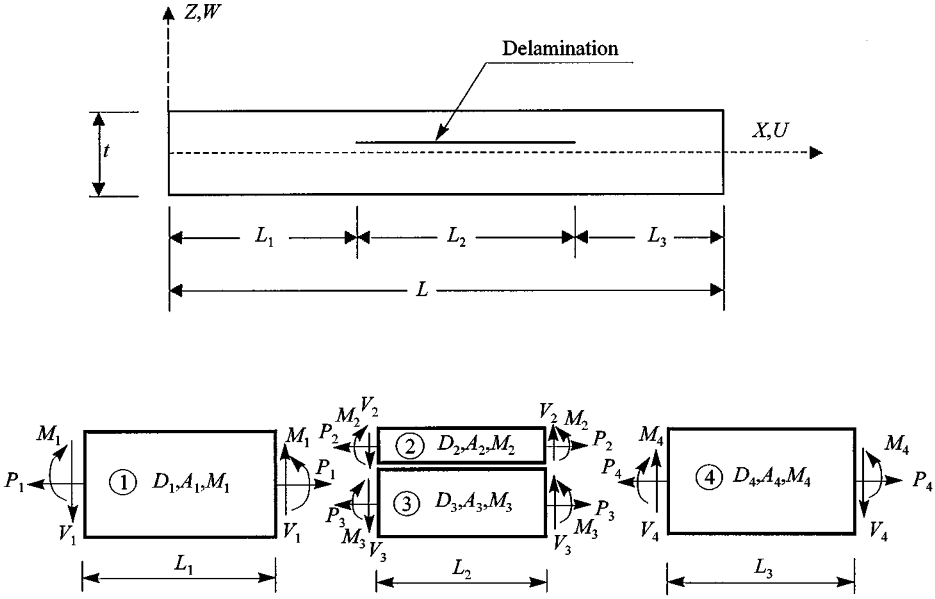

Figure 2. Simplified beam model of delamination [41].

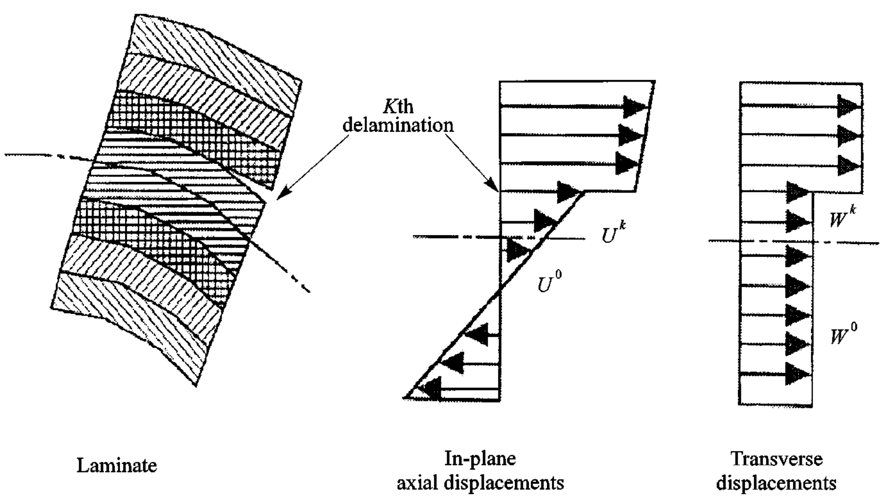

Figure 3. Effects of delaminations represented by kinematic assumptions of generalized laminate theory [45].

mechanics was developed [45]. The kinematic assumptions in this work allow for in-plane and out-of-plane relative motion between the delaminated sublaminates (Fig. 3). In this model, the induced discontinuity is treated as an additional degree of freedom. This model can handle delaminated laminates with single or multiple delamination. The merit of this model is that it considers the effect of damping.

A laminated shear deformable beam finite element model was developed originally for analyzing the growth of dynamic delamination [46]. The delaminated beam was modelled as two beams above and below the plane of delamination while spring element and rigid elements were used to connect the beams above and below the plane of delamination depending on the consideration of friction between the contact surfaces of sublaminates. Beam finite elements with nodes offset to the bottom and top are used to model the top and bottom sublaminates respectively. In the uncracked portion of the beam the nodes of top and bottom elements would be connected by rigid elements to ensure compatibility between the top and bottom sublaminates. The major advantage of this model is that it can be used to model any type of geometry and loading condition. This concept is further developed by dividing the delaminated part of the beam as three beam finite elements, which are connected at the tip of delamination by additional boundary conditions [47]. The advantage of this method is that it can be easily modified to accommodate different types of damage.

Currently, the theoretical basis for the majority of the analyses is the classical beam theory. However, there have been a few attempts to apply the Timoshenko beam theory to damage detection on composite structures.

4. EFFECT OF DELAMINATION ON THE DYNAMIC MODAL PARAMETERS

In general, delaminations decreases stiffness and increase damping of structure. These, in turn, decrease the frequencies and increase modal damping in delaminated structure. The existence of the "delamination modes" in composite beams has been proven theoretically and experimentally [48, 49] and it can be an important feature for delamination detection. For structural mass, the effects of delamination are usually very small and often can be neglected.

4.1. FREQUENCY

The effect of delamination on the natural frequencies of composite beam laminate structure depends on the size and location of the delamination. It has been found [41] that all first four modes are unaffected for very short delaminations. Among the first four modes, mode 1 (lowest frequency) is insensitive to the presence of normal-sized delamination while mode 4 is most sensitive (Figure 4). The effect of delamination position along the length of the beam on the first four frequencies is shown in Figure 5. It shows that the effect of delamination is much stronger in high shear regions than in high curvature regions. The study concludes that the extent of frequency degradation in a particular mode of vibration caused by a delamination depends on the size and location of the delamination in the structure. It is also found that local delaminations do not have a noticeable effect on the global mode shape of vibrations of composite beams [42]. It is pointed out that the delamination caused frequency shift and the maximum frequency shifts occurred in the modes where the wavelength was approximately of the same size as that of the debonding area [50].

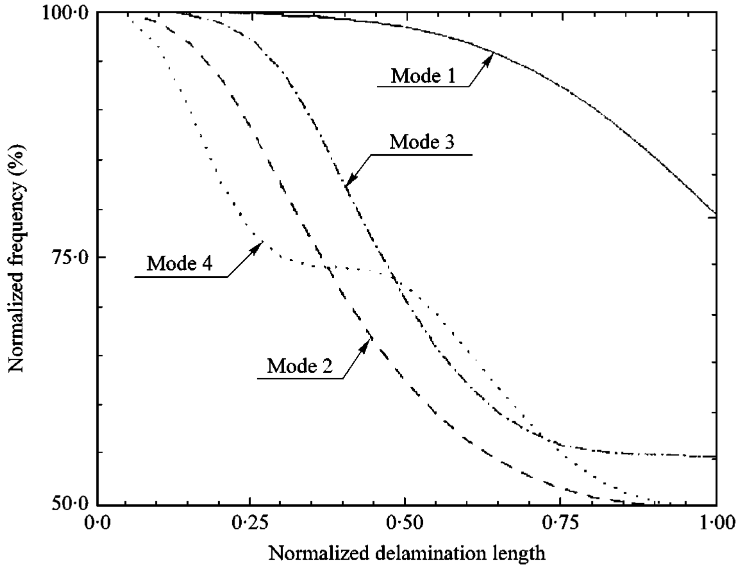

Figure 4. Effect of delamination length on frequencies [41].

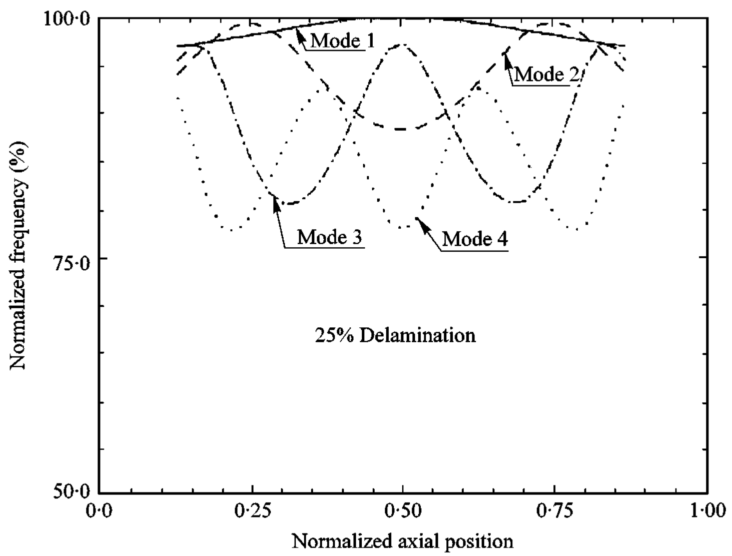

Figure 5. Effect of delamination axial position on natural frequencies [41].

4.2. DAMPING

For a variety of structures and loading conditions, damping is generally far more sensitive to delamination that stiffness is. This suggests that damping would be a better indicator of delamination damage especially in small and medium crack lengths. At small delamination sizes, changes in damping were caused primarily by changes in the viscoelastic laminate damping of the structure, while interfacial friction damping became important at large delamination cracks. Although it can be a better indicator, damping is a complex factor to be considered.

4.3. MODE SHAPE

Delamination causes irregularity of mode shape curves. The extent of the irregularity of the curve depends on the size and location of delamination [42, 51]. The bigger the delamination, the more irregular the mode shape curve. The closer to the surface of the structure the delamination, the more irregular the mode shape curve.

Overall, small delamination (less than 10% of beam span) may not be detectable by monitoring global modal characteristics of the beam. Therefore, other local parameters should be monitored [45].

Finally, the effect of delamination on the dynamic characteristics of structures is strongly dependent on the laminate configuration, and can be more profound in laminates with complex laminations [45].

5. DELAMINATION DETECTION

5.1. MODAL ANALYSIS

An experimental technique called gapped smoothing damage detection method was applied for locating a delamination in a composite beam [52]. The premise of the technique is that the curvature of an undamaged structure (no stiffness discontinuity) is smooth and continuous and the irregularity of the curvature could indicate the location of the damage for a homogeneous beam. The extent of the irregularity of the curvature is in positive relationship with the severity of damage. This relationship is significant for relatively large damage [51] as shown in Figure 6. For small damage, the irregularity in curvature is less pronounced. To capture reductions in stiffness as little as 1%, the gapped smoothing method has been developed and is used to extract small features from the curvature. This technique operates on the fundamental displacement eigenvector, which is converted to a curvature mode shape. Then, the gapped smoothing damage detection technique is applied to the curvature locally and yields a damage index that locates the delamination irrespective of its position along the beam or depth within the beam; see Figure 7. The method does not require an undamaged reference. The procedure operates solely on the measured mode shape obtained from the damaged structure. There is good agreement between numerical analysis results and experimental data. A big advantage of this method is that it can be applied to an existing structure where there is no prior knowledge of its state. Another advantage is that damage can be located in an efficient and cost-effective manner. However, when there are structural discontinuities, a baseline of undamaged structure has to be used.

Delamination detection for a composite structure using sensitivity analysis for dynamic modal parameters obtained experimentally was carried out [53]. The results show that delamination can be identified through four quantities: mode

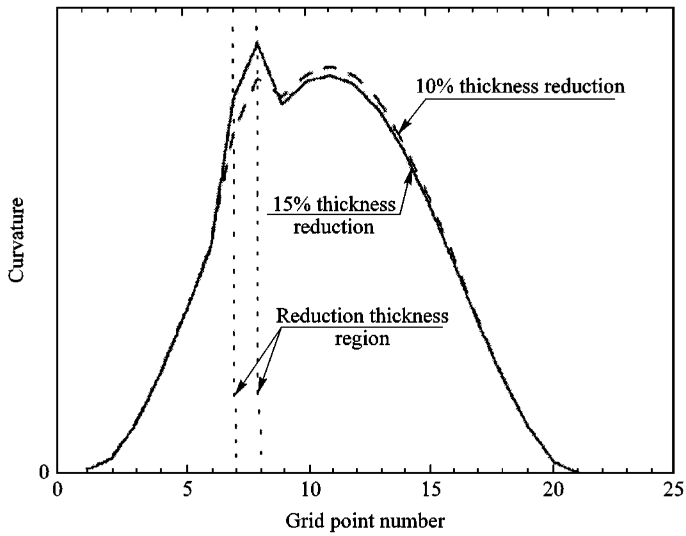

Figure 6. Effect of delamination on the fundamental mode curvature [52].

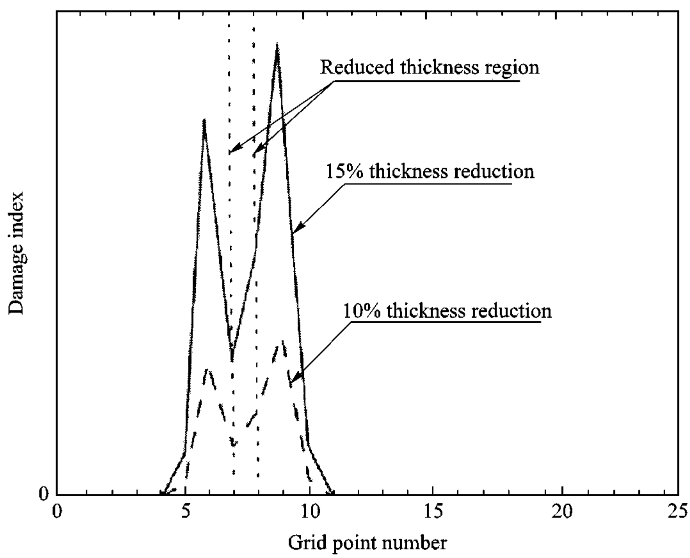

Figure 7. Damage index for the fundamental mode [52].

shapes, natural frequencies, damping ratios and delamination coefficients (defined as $D = \int_{\Omega}|\Delta\varphi|\,d\Omega / \int_{\Omega}|\varphi|\,d\Omega$, where φ is the mode shape of the structure, Ω is the area of the structure). Among the four factors, the delamination coefficients give a greater quantitative index of the delamination modes. The frequency changes and new extra modes called "delamination modes", which are caused by delamination and correspond to each different case of delamination as shown in Table 1, are also typical features in delaminated structure. Damping ratios of the new "delamination modes" are usually higher than their neighbouring original modes as shown in

Table 1

Effect of delamination on frequencies and damping ratios [53]

16-layer intact		6/10-layer through width delamination	
Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
57·340	1·020	54·886	0·731
170·966	1·179	162·587	1·514
		344·985†	1·135†
353·852	0·570	346·209	0·779
		555·691†	2·343†
574·061	1·319	557·884	1·317
		874·846†	3·510†
1018·230	1·992	885·361	1·685

† Caused by delamination modes.

Table 1. Mode shapes are different in delaminated structures. The research [53] also shows that the frequency information alone is not enough to provide a reliable prediction because the stiffness change due to the delamination is a complex combination of the transversal location, the longitudinal location, and the size of the delamination. The coupling between bending and stretching has also been proved to play an important role in stiffness of a delaminated structure.

5.2. FREQUENCY DOMAIN

A frequency-shift-based damage detection routine is applied to delamination detection for composite structures [31, 54]. The major assumption in this formulation is that the ratio of frequency changes for two modes is a function of the location of the damage only, if changes in stiffness are independent of frequency. The presence of delamination could be detected simply from changes in the natural frequencies without the need for any analysis. The position of delamination is located by this formulation combined with sensitivity analysis. The process of locating delamination starts with the ratio between frequency shifts for modes i and j, $\delta\omega_i/\delta\omega_j$. A grid of possible damage points is considered, and an error term is constructed that relates the measured frequency shifts to those predicted by a model based on local stiffness reduction. A number of mode pairs are considered for each possible damage grid location and the pair giving the lowest error indicates the location of the damage. The size of the frequency changes may also give useful information on the severity of the delamination. This method is also to locate low levels of damage accurately. However, successful location does require controlled temperatures and testing of the undamaged and damaged specimens in a short amount of time to prevent long-term frequency shift. Also, the formulation does not account for possible multiple-damage locations. Special consideration is given to the anisotropic behaviour of the composite materials.

Another frequency domain system identification technique that has been used to detect and characterize the existence and location of cracks and other damages for various composite structures is presented [55]. The results presented indicate that the size of damage is proportional to changes in the magnitudes of system parameters. Damage location could easily be identified by investigating the elements in mass ratio or flexibility matrix. It has been noted that the mass ratio matrix is more sensitive to damage in the structure than the flexibility matrix.

5.3. OTHER METHOD

An anti-optimization strategy in conjunction with system identification was used to detect delamination on a composite beam [56]. Anti-optimization is a method for maximizing difference of responses between delaminated and intact structural models. By using this method, the delaminations can be detected by maximizing the difference in frequency and spatial distribution of excitations between the delaminated and intact beams under harmonic excitation. To measure this difference in responses, the ratios of strain energies, external works, and surface strains were used. A finite element model for a delaminated composite, based on a layer-wise laminated plate theory, is used in conjunction with a step function to simulate delaminations. The first step of delamination detection is seeking the optimal excitation load distribution, which maximizes the difference in harmonic response between intact and delaminated beams. Once the optimal excitation that maximizes the response ratio between delaminated and undelaminated beam has been obtained, this excitation is used to detect the location of delamination as force input in a residual force calculation. The delamination location is assumed to be the region where the derivative of residual force is high (Figure 8). When there is more than one peak in the residual force responses, the candidate whose eigenvector makes the smallest angle with the measured eigenvector is considered to be the actual location of delamination. The size of delamination can be estimated by comparing the eigenvalue of the candidate with an experimentally achieved eigenvalue. This anti-optimization method can detect cases of multi-delamination at various locations and sizes. Another advantage of this method is that it reduces the amount of data required to detect the damage by using system identification processes. This method has been validated both numerically and experimentally.

6. ON-LINE DELAMINATION DETECTION

Among with the continuous competing requirements of improving the weight, interdisciplinary performance, and reliability of composite components, the development of real-time non-destructive “health-monitoring” techniques based on the dynamic characteristics of the composite structures is receiving growing attention. Among them, the techniques of detect delaminations by monitoring changes in the dynamic characteristics or in the dynamic response of the structure

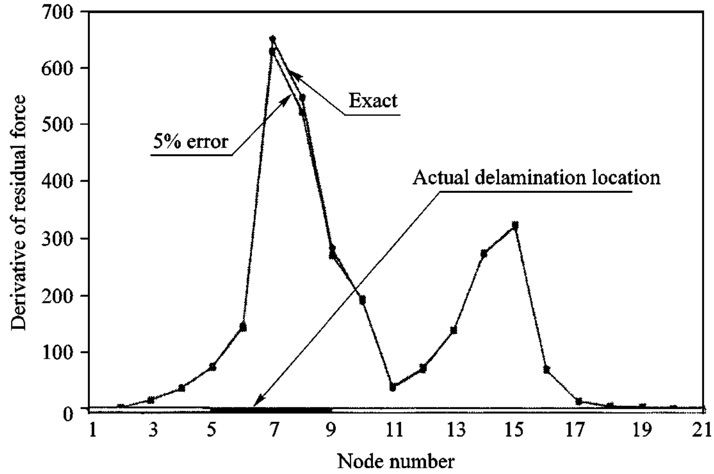

Figure 8. Indication of delamination position from theory calculation [56].

seem to be attractive and promising. To implement the on-line monitoring techniques, an essential condition is making the structure smart or the material intelligent. This is the new generation of composite materials or structures, often called "intelligent material or smart structure".

6.1. SMART STRUCTURE

A smart structure/intelligent material system contains a network of sensors and actuators, real-time control capabilities, computational capabilities and a host structural material. The structure/system can inspect the health conditions of the structure automatically and continuously by itself. The actuator induces actuation into the structure, such as vibration through strain or displacement. The sensors recognize and measure the signal, such as the resultant vibrational response. Information from the sensors is acquired by the control/processor unit. The goals of developing smart structures in damage detection is that the structure/systems could, through the damage identification process, be able to detect damage as it is incurred by the structure, determine the location and extent of the damage, predict if and when catastrophic failure of the structure will occur, and alert the operator as to how the performance of the structure is affected so that appropriate steps can be taken to remedy the situation [57, 58].

6.2. APPLICATION OF PIEZOELECTRIC MATERIALS

There are a number of sensors and actuators available for use in smart materials, and systems. Commonly used ones are piezoelectric materials, electro-rheological fluids, shape-memory materials, magnetostrictive materials, electrostrictive materials and thermal materials. Among them, piezoelectric materials offer a number of advantages. Piezoelectric materials can generate a charge in response to mechanical stimulus, or alternatively provide a mechanical strain when an electric field is applied across them. Because of these characteristics, piezoelectric materials can be easily used for both actuation and sensing, also referred to as collocated actuator–sensor. Utilizing the same material for both actuation and sensing not only reduces the number of sensors and actuators, but also reduces the electrical wiring and associated hardware. Piezoelectric materials are low in cost and can generate high voltage with a low current. Piezoelectric materials can be in the form of crystals, ceramics or polymers. These materials exhibit excellent mechanical strength, have low acoustic impedance, a flat response over a wide frequency range, and a broad dynamic response. Due to their low mechanical impedance, a number of piezoelectric films/patches can be distributed along the structure with only minor effects on the structure's mechanical properties. The films/patches can be readily cut and shaped to conform to the structure under consideration. They are especially good for incorporating into composites, usually attached to or embedded into a structure, and thus are the ideal materials to constitute an "active" methodology for structure damage monitoring and on-line health monitoring. It is important to note that there is an optimum size and an optimum placement or arrangement of piezoelectric sensors to give maximum sensitivity for the various damage cases and load conditions [59–62].

6.3. ON-LINE HEALTH MONITORING WITH PIEZOELECTRIC TRANSDUCER

The group of on-line delamination detection techniques is used to monitor changes in the dynamic characteristics or in the dynamic response of a structure. The group of techniques usually uses algorithm for finite element model update or test-analysis correlation. Most of these works begin with measured dynamic response and modal parameters to find the differences between the undamaged and damaged system. There have been a few attempts at on-line delamination detection using piezoelectric sensors and actuators. Most of them are combined with AI-based techniques such as neural network. The following will describe some recent research work using on-line damage detection concepts.

A recently proposed on-line damage diagnostic technique was successfully applied for predicting delamination with piezoelectric sensors and actuators attached to the top and bottom of a beam and validated by experimental works [63–65]. The results are shown in Figure 9. This diagnostic scheme is a search-based technique with an iterative damage identification algorithm combined with a wave response and a frequency domain method. This damage identification technique includes three components, a structural model, a response comparator and a damage selector. The structural model combined the constrained mode of Mujumdar *et al.* [40] with the electromechanical effect of piezoelectric material for predicting the output voltages from the sensors when a delaminated beam was excited by the actuators. The presence of damage is simply indicated by the difference between the damaged and undamaged structure. To locate the damage, the structural model is run repeatedly to predict the changes in responses due to

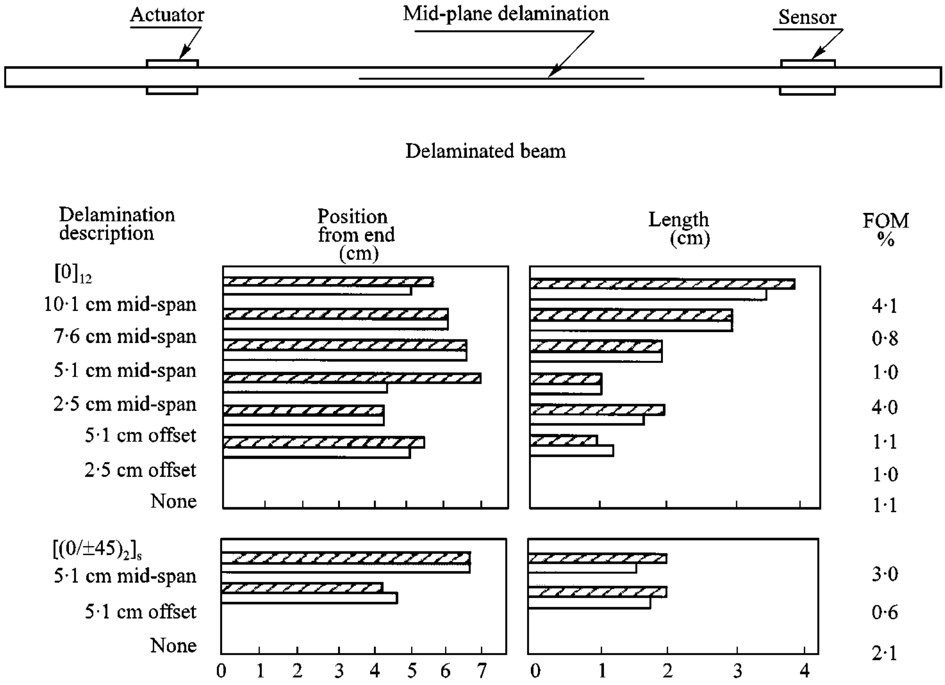

Figure 9. Comparison between actual and predicted delamination length and location [65]; ▨, actual length; □ calculated length.

different possible delaminations. During these runs, delamination sizes and locations are selected randomly by the damage selector over the entire feasible space, and the predicted results are compared with the measured ones continuously. To estimate the extent of the damage, the response comparator quantifies the agreement between measured and calculated responses using a weighted quadratic objective function. The best estimate of the damage occurs when the responses are matched and the objective function is minimized. However, this method needs to be improved to be able to detect small size delaminations and other types of damage in composite structures. The structural model was also applied to detect impact delamination [66] and further for self-monitoring of the manufacturing process and self-diagnosising of service-induced damage [67].

An electromechanical structural model combined with neural network was used to conduct on-line delamination detection on composite structures with embedded piezoelectric sensors and actuators [68]. The structural model was an extension of the Tracy and Pardoen modelling of delamination [41] by including unsymmetrical laminates and effects of embedded piezoceramic patches. This model was validated by both experimental and numerical work. A good match was found in the case of mode shape verification. Detecting the presence of damage still called for a conventional technique. Two methods are used to locate the damage position and determine type and size of damages. The first compared numerical with experimental frequency results. The second used a back-propagation neural network, which is trained by the frequencies of the first five modes obtained from dynamic modal analysis data. It was pointed out that the embedded actuator patches, in addition to acting as excitors, have the potential to redistribute strain for damage mitigation.

Another Artificial Intelligent-(AI) based damage detection technique was proposed [69]. This technique, as mentioned above, combined modal analysis with neural network. The delamination is modelled by the structural model of the Mujumdar and Suryanarayan [40] without considering the effect of lead zirconate titanate (PZT) patches. The presence and location of delamination were identified by comparing theoretical and experimental results. The size of delamination was estimated by neural network. It was found that the third and fourth modal frequencies were better indicators of delamination detection. The efficiency of this method was demonstrated experimentally.

A neural network method in conjunction with system identification technique [70], which can identify various damage cases, was applied for on-line damage detection in composite structures. The method contains two parts: training and recognition. In the training part, various types of damage modes are designed as the patterns and organized into pattern classes according to the location and the severity of the damage. Then system identifications are used to extract the transfer functions as the features of the structural systems. The multi-layer perception (MLP) was trained by the transfer functions. The MLP serves as a nearest-neighbourhood classifier. In the pattern recognition part, an unforseen damage in a structure is classified within the closet class in the training set and the damage in the structure is identified as that of the class.

There are many other valuable studies using neural networks to detect delamination in composite structures, such as an experimental study [71] for a composite/aluminium beam to identify the severity and presence of a delamination according to the frequency response data obtained from bonded piezoelectric actuators/sensors. This experimental work also investigated the effectiveness of different configuration of network. Another example is the dynamic learning rate steepest descent method [72]. This method can improve learning convergence speed significantly without increasing the computational effort, the memory cost, the algorithm simplicity, and the computational locality in the standard layered error back-propagating training algorithm.

7. DISCUSSION AND CONCLUSION

Vibration-based model-dependent methods combined with modal analysis provide global as well as local information on structural health condition and do not require direct human accessibility to the structure. The methods are cost-effective and easy to operate, and has the potential for on-line damage detection with appropriate structural modelling.

Vibration-based model-dependent methods utilize finite element analysis techniques together with experimental results to detect damage. The structural model is critical when using this group of methods. Accuracy of the model affects the effectiveness of the method. Various response characteristics of the structure such as time responses, frequency responses and impedance responses, can be extracted and analyzed with the model.

Modal analysis methods are based on the concept that modal parameters are functions of physical properties, and thus changes in the physical property, such as a damage, will cause changes in the modal parameters. The most important task in detecting damage with these methods is to find the particular modes which best describe the individual damage event. Because of the global nature of the methods, health conditions of the internal members of a structure can be obtained without incuring high cost (or impossible) for dismantling of the structure. Therefore, the methods can be applied to a variety of structures such as infrastructures, aerospace structures, and are especially useful for large structures. Given their global nature, these techniques allow the customization of measurement points. Another major advantage is that modal information is cheap to obtain and easy to extract. Nevertheless, many limitation exist when using this group of methods. Firstly, application of some of the modal-based methods is limited since they can only detect particular forms of damage in their diagnostic schemes. Secondly, these methods usually use undamaged structural modal parameters as the benchmark when compared with the damage information. This will result in the need for a large data storage capacity for complex structures. Thirdly, they fail to detect small defects in global feature.

Frequency domain methods use only frequency information for damage detection. These approaches can provide cost-effective structural assessment techniques. However, natural frequency changes alone may not be sufficient for a unique identification of the local of structural damage. Current frequency domain methods are either using lower frequencies for providing global information of structures or higher frequencies for providing local information of structures. None of them can provide sufficient information for detection of both small and large defects.

Time domain methods use time history and are usually combined with frequency domain methods for damage detection. One major advantage of these methods is that they can detect damage events both globally and locally by changing the input frequencies.

Impedance domain methods detect damage from variations in impedance of the structure. Impedance domain methods are particularly suitable for detecting planer defects such as delamination. The inspection is usually reliable except when the system impedance becomes spring-controlled and thus the impedance only decreases with spring stiffness.

Because of the increasing requirements to ensure the safe operation of structures, especially aerospace structures and aircraft, on-line damage detection and health monitoring have received growing attention and is one of the major directions for future research. On-line damage detection has the advantages of identifying damage as soon as it is initiated, monitoring continuously the structure's health condition without affecting the operation of the structure, and possibly rectifying the damage by migrating stresses. To implement on-line damage detection techniques, piezoelectric material is ideal for acting as sensor and actuator. This is due to its advantages over other materials in terms of easy incorporation into any shape of surface and minor effects on the host structural mechanical properties. With piezoelectric actuator and sensor, the structure can be vibrated in any frequency, either low or high, in any location, and the response information can be extracted continuously.

There are many challenges in the development of on-line damage detection techniques. Typical ones are the ability to identify minor damages and the ability to differentiate the type of damages on composite structures. So far the modal-based methods are limited in this regard. Analytical methods of predicting changes in modal parameters or response characteristics become dubious with complex structures. Another challenge is signal extraction for on-line damage detection. The difficulties lie in the ability to separate changes in vibration signature due to damage from changes, normal usage, or changes in boundary conditions. Laboratory experiments are often conducted under tightly controlled repeatable conditions to ensure that the changes are only due to the self-created damage. Therefore, to develop practical and capable on-line damage detection methods, a large amount of work awaits to be explored.

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REFERENCES

1. T. G. Gerardi 1990 *Journal of Intelligent Material System and Structure* **1**, 375–385. Health monitory aircraft.
2. S. W. Tasi and H. T. Hahn 1980 *Introduction to Composite Materials*. Westport, Connecticut: Technic Publishing Company.
3. G. Z. Voyiadjis 1993 *Damage in Composite Materials*. Amsterdam, New York: Elsevier.
4. J. E. Masters 1992 *Damage Detection in Composite Materials*. Philadelphia, PA: ASTM.
5. S. W. Debling, C. R. Farrar, M. B. Prime and D. W. Shevitz 1995 *Report LA*-13070-*MS*, *Los Alamos*, *NM*, Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review.
6. Z. Chaudhry and C. A. Rogers 1994 *Proceedings of the* 48*th Meeting of the Mechanical Failures Prevention Group*, *Wakefield*, *MA*, *U.S.A.* 13–19. Smart structures: on-line health monitoring concepts and challenges.
7. P. M. Tappet, T. D. Snyder and H. H. Robertshaw 1995 *Proceedings of SPIE — The International Society for Optical Engineering Smart Structures and Materials*: *Smart Sensing*, *Processing*, *and Insturumentation* **2443**, 286–294. Attacking the damage identification problem.
8. H. T. Banks, D. J. Inman, D. J. Lwo and Y. Wang 1996 *Journal of Sound and Vibration* **191**, 859–880. An experimentally validated damage detection theory in smart structure.
9. D. C. Zimmerman and S. W. Smith 1992 *Intelligent Structural Systems* (H. S. Tzou and G. L. Anderson, editors), 403–452. Dordrecht: Kluwer Academic Publishers. Model refinement and damage location for intelligent structures.

10. R. D. Adams, P. C. Cawley, J. Pye and B. J. Stone 1978 *Journal of Mechanical Engineering Science* **20**, 93–100. A vibrational technique for non-destructively assessing the integrity of structures.
11. H. F. Lam, J. M. Ko and C. W. Wang 1995 *Proceedings of the* 13*th International Modal Analysis Conference*, 1499–1505. Detection of damage location based on sensitivity analysis.
12. J. H. Kim, H. S. Jeon and C. W. Lee 1992 *Proceedings of* 10*th International Modal Analysis Conference*, 536–540. Application of the modal assurance criteria for detecting and locating structural faults.
13. O. S. Salawu and C. Williams 1994 *Proceedings of the* 12*th International Modal Analysis Conference*, 933–939. Damage location using vibration mode shapes.
14. J. Chance, G. R. Tomlinson and K. Worden 1994 *Proceedings of the* 12*th International Modal Analysis Conference*, 778–785. A simplified approach to the numerical and experimental modeling of the dynamics of a cracked beam.
15. M. J. Schulz, P. F. Pai and A. S. Abdelnaser 1996 *Proceedings of the* 14*th International Modal Analysis Conference*, 105–111. Frequency response function assignment technique for structural damage identification.
16. T. W. Lim 1995 *Journal of Guidance, Control, and Dynamics* **18**, 411–418. Structural damage detection using constrained eigenstructure assignment.
17. M. Sanayei and O. Onipede 1991 *AIAA Journal* **29**, 1174–1179. Damage assessment of structures using static test data.
18. M. Sanayei, O. Onipede and S. R. Babu 1992 *AIAA Journal* **30**, 2299–2309. Selection of noisy measurement locations for error reduction in static parameter identification.
19. S. W. Doebling 1996 *Proceedings of the AIAA/ASME/AHS Adaptive Structures Forum*, 360–370. Damage detection and modal refinement using elemental stiffness perturbations with connectivity.
20. D. C. Zimmerman and M. Kaouk 1994 *Journal of Vibration and Acoustics* **116**, 222–230. Structural damage detection using a minimum rank update theory.
21. L. D. Peterson, K. F. Alvin S. W. Doebling and K. C. Park 1993 *Proceedings of* 34*th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 1518–1528. Damage detection using experimentally measured mass and stiffness matrices.
22. O. S. Salawu and C. Williams 1993 *Proceedings of the* 11*th International Modal Analysis Conference*, 254–260. Structural damage detection using experimental modal analysis — a comparison of some methods.
23. Z. Wang, R. M. Lin and M. K. Lim 1997 *Computer Methods in Applied Mechanics and Engineering* **147**, 187–197. Structural damage detection using measured FRF data.
24. S. K. Thyagarajan M. J. Schulz and P. F. Pai 1998 *Journal of Sound and Vibration* **210**, 162–170. Detecting structural damage using frequency response functions.
25. H. F. Lan, J. M. Ko and C. W. Wong 1998 *Journal of Sound and Vibration* **210**, 91–115. Localization of damaged structural connections based on experimental modal and sensitivity analysis.
26. G. James, R. Mayes, T. Carne, and G. Reese 1994 *Adaptive Structures and Composite Materials*: *Analysis and Application*, ASME. New York: Vol. AD-**45**/MD-**54**, 371–380. Damage detection and health monitoring of operational structures.
27. N. Stubbs and J. T. Kim 1996 *AIAA Journal* **34**, 1644–1649. Damage localization in structures without baseline modal parameters.
28. O. S. Salawu 1997 *Engineering Structures* **19**, 718–723. Detection of structural damage through changes in frequency: a review.
29. A. Rytter and P. H. Kirkegaard 1994 *Proceedings of the* 12*th International Modal Analysis Conference*, *Hawaii*, 1602–1608. Vibrational-based inspection of a steel mast.
30. A. J. M. A. Gomes and J. M. M. E. Silva 1991 *Proceedings of the* 8*th International Modal Analysis Conference*, *FL U.S.A.* 1108–1115. On the use of modal analysis for crack identification.

31. P. Cawley and R. D. Adams 1979 *Journal of Strain Analysis* **4**, 49–57. The location of defects in structure from measurements of natural frequencies.
32. D. Sanders, Y. I. Kim and R. N. Stubbs 1992 *Experimental Mechanics* **32**, 240–251. Non-destructive evaluation of damage in composite structures using modal parameters.
33. R. Ceravolo and A. D. Stefano 1995 *The International Journal of Analytical and Experimental Modal Analysis* **10**, 176. Damage location in structure through a connectivistic use of FEM modal analyses.
34. L. Balis Crema and F. Mastroddi 1995 *Proceedings of the International Modal Analysis Conference*, 1322–1330. Frequency-domain based approaches for damage detection and localisation in aeronautical structure.
35. S. Thwaites and N. H. Clark 1998 *Australian Acoustical Society Conference*, Vol. **26**, 5–8. Non-destructive testing of composites using long waves.
36. P. Cawley 1984 *Journal of NDT International* **17**, 59–65. The impedance method of non-destructive inspection.
37. B. S. Wong, T. C. Guan and L. M. King 1993 *British Journal of NDT* **35**, 3–9. Mechanical impedance inspection of composite structures.
38. F. P. Sun, Z. Chaudhry, C. A. Rogers and M. Majmundar 1995 *Proceedings of SPIE — The International Society for Optical Engineering Smart Structures and Materials: Smart Sensing, Processing, and Instrumentation* Vol. **1443**, 236–243. Atomated real-time structure health monitoring via signature pattern recognition.
39. Z. Chaudhry, T. Joseph, F. Sun and C. Rogers 1995 *Proceedings of SPIE — The International Society for Optical Engineering Smart Structures and Materials Smart Sensing, Processing, and Instrumentation*, Vol. **2443**, 268–276. Local-area health monitoring of aircraft via peizoelectric actuator/sensor patches.
40. P. M. Majumdar and S. Suryanarayan 1988 *Journal of Sound and Vibration* **125**, 441–461. Flexural vibrations of beams with delaminations.
41. J. J. Tracy and G. C. Pardoen 1989 *Journal of Composite Mateials* **23**, 1200–1215. Effect of delamination on the natural frequencies of composite laminates.
42. M. H. H. Shen and J. E. Grady 1992 *AIAA Journal* **30**, 1361–1370. Free vibration of delaminated beams.
43. E. J. Barbero and J. N. Reddy 1991 *International Journal of Solids and Structure* **28**, 373–388. Modelling of delamination in composite laminates using a layerwise plate theory.
44. C. M. Dakshina Moorthy and J. N. Reddy 1998 *International Journal of Numerical Mathematical and Engineering* **43**, 755–779. Modelling of laminates using a layerwise element and enhanced strains.
45. D. A. Saravanos and D. A. Hopkins 1996 *Journal of Sound and Vibration* **195**, 977–993. Effects of delaminations on the damped dynamic characteristic of composite laminates: analysis and experiments.
46. B. V. Sankar 1991 *Computers and Structures* **38**, 239–246. A finite element for modelling delaminations in composite beams.
47. M. Krawczuk, W. Ostachowics and A. Zak 1997 *Computational Mechanics* **20**, 79–83. Dynamic of cracked composite material structures.
48. S. Hanagud and H. Luo 1994 *SEM Spring Conference on Experimental Mechanics, Baltimore, MD*. Modal analysis of a delaminated beam.
49. G. L. Nagesh Babu and S. Hanagud 1990 *Proceedings of the* 31*st AIAA/ASME/ASCE/AHS/ASC SDM Conference, Part* 4, 2417–2426. Delaminations in smart composite structures: a parametric study on vibrations.
50. A. Paolozzi and I. Peroni 1990 *Journal of Reinforced Plastics and Composites* **9**, 369–389. Detection of debonding damage in a composite plate through natural frequency variations.
51. A. K. Pandey, M. Biswas and M. M. Samman 1991 *Journal of Sound and Vibration* **145**, 321–332. Damage detection form changes in curvature mode shapes.
52. C. P. Ratcliffe and W. J. Bagaria 1998 *AIAA Journal* **36**, 1074–1077. Vibration technique for locating delamination in a composite plates.

53. H. Luo and S. Hanagud 1995 *Proceddings of AIAA/ASME/ASCE/AHS Structures, Structural Dynamics & Materials Conference* Vols. **10–13**, 129–139. Delamination detection using dynamic characteristics of composite plates.
54. P. Cawley and R. D. Adams 1979 *Journal of Composite Materials* **13**, 161–175. A vibration techniques for non-destructive testing of fibre composite structures.
55. W. H. Tasi and J. C. S. Yang 1988 *Journal of Engineering Materials and Technology* **110**, 134–139. Non-destructive evaluation of composite structures using system identification technique.
56. J. Lee, R. T. Haftka, O. H. Griffin Jr, L. T. Watson and M. D. Sensmeier 1994 *Structural Optimization* **8**, 93–100. Detecting delaminations in a composite beam using anti-optimization.
57. M. V. Gandhi and B. S. Thompson 1992 *Smart Materials and Structure*. London: Chapman & Hall.
58. B. Culshaw 1996 *Smart Structures and Materials*. Boston: Artech House.
59. S. C. Gales, W. K. Chiu and J. J. Paul 1993 *Journal of Intelligent Material Systems and Structures* **4**, 330–336. Use of piezoelectric films in detecting and monitoring damage in composites.
60. S. Egusa and N. Iwasawa 1996 *Smart Materials Structures* **7**, 438–445. Piezolectric paints os one approach to smart sturctural materials with health-monitoring capabilites.
61. X. H. Jian, H. S. Tzou, C. J. Lissenden, and L. S. Penn *Journal of Composite Materials* **31**, 345–359. Damage detection by piezoelectric patches in a free vibration method.
62. C. S. Galea, W. K. Chiu and J. J. Paul 1993 *Journal of Intelligent Material System and Structure* **4**, 683–639. Use of piezoelectric films in detecting and monitoring damage in composites.
63. C. H. Keilers, Jr. and F.-K. Chang 1993 *Proceedings of SPIE—The International Society for Optical Engineering Smart Structures and Intelligent System* Vol. **1917**, 1009–1015. Damage detection and diagnosis of composites using bull-in piezoceramics.
64. C. H. Keilers Jr., and F.-K. Chang 1995 *Journal of Intelligent Materials Systems and Structures* **6**, 649–663. Identifying delamination in composite beams using built-in piezolectrics: Part I—experiments and analysis.
65. C. H. Keilers Jr., and F.-K. Chang 1995 *Journal of Intelligent Material Systems and Structures* **6**, 664–672. Identifying delamination in composite beams using built-in piezolectrics: Part II—an identification method.
66. K. Choi, C. H. Keilers, Jr., and F.-.K. Chang 1994 *Proceedings of the AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* Vols. **18–20**, 118–124. Impact damage detection in composite structures using distributed piezoceramics.
67. B. S. Shen, M. Tracy, Y.-S. Roh and F.-K. Chang 1996 *Proceedings of the AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 390–397. Built-in piezoelectrics for processing and health monitoring of composite structures.
68. A. S. Islam and K. C. Cralg 1994 *Smart Materials and Structures* **3**, 318–328. Damage detection in composite structures using piezoelectric materials.
69. A. C. Okafor, K. Chandrashekhara and Y. P. Jiang *Smart Materials and Structure* **5**, 338–347. Delamination prediction in composite structures with built-in piezoelectric devices using modal analysis and neutral network.
70. J. Rhim and S. W. Lee 1995 *Computational Mechanics* **16**, 437–443. A neural network approach for damage detection and identification of structures.
71. Z. Chaudhry and A. J. Ganino 1994 *Journal of Intelligent Material Systems and Structures* **5**, 585–589. Damage detection using neural networks: an initial experimental study on debonded beams.
72. H. Luo and S. Hanagud 1997 *AIAA Journal* **35**, 1522–1527. Dynamic learning rate neural network training and composite structural damage detection.