Vibration based damage inspection in composite structures- A critical review
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Abstract—The composite materials have certain distinct properties compared to other materials in respect of weight, durability, corrosion resistance, sound and warmth insulation. Further due to low cost and flexibility, it has registered substantial growth in automotive industry. In the present scenario, the increasing demand for higher strength to weight ratio of materials has increased. It requires a low tolerance to damage and requires a tighter control of the integrity of the components by periodic inspections using non-destructive techniques. It is more sensitive to internal defects and damages which differs from metallic. The damage occur during service due to operational loading, aging, chemical attack, mechanical vibration, changing of ambient conditions and shocks. Presently, automotive industries are highly focused in structural health monitoring, looking for the early damage detection. The risk of human lives loss is always associated with structural parts as its failure is unpredictable. Prognosis study of structural parts helps in predicting the remaining service life. The superior performance requirement of the materials has stimulated the development and improvement of experimental techniques used in structural health monitoring. The earlier damage identification helps to prevent structural failure and plan for its replacement well in advance.

Key words—Non-destructive techniques, Damage identification, prognosis, remaining service life, Structural health monitoring.

I. INTRODUCTION

Damage is defined as the changes in geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system’s performance. The main damages in composite materials are the inter-laminar de-bonding, micro-cracks, micro-buckling and inclusions. These internal damages usually originate from the manufacturing process and/or internal stresses during service. The inter-laminar unbound or de-lamination is the kind of invisible damage which is more severe and common in composite structural components. Such damage appears essentially in laminated structures and reduces its load carrying capacity.

These problems leads to variation in its mechanical characteristics and results in a substantial loss of structural performance, ultimately affect the static or dynamic response. It also affects load carrying capacity. In past, considerable research work has been carried out in the area of structural health monitoring (SHM). However, there is scope in detection of damages (discontinuities) likely to lead premature failure and effective planning for replacement of damaged elements.

Structural Health Monitoring is the process of implementing a damage detection strategy for engineering infrastructure. Increasing reliability and safety of technical systems for vehicles and machines is an effort of increasing importance for technical development. Safety means protection against damage due to misuse of instruments, overloading, unexpected events outside of human control, material defects, improper design and change of material properties due to aging fatigue or corrosion.

Non-destructive testing (NDT) is the process of inspecting, testing or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system. In other words, when the inspection or test is completed the part can still be used. In recent years, many new methods of NDT have been developed. However, all these tests have disadvantages, and there is no method which is universally accepted. A few of the common disadvantages in all NDT is piece wise inspection is not proper and in order to investigate the localized damages or measurements, nature of the damage, locate and quantify the damage will not be clearly understood [1]. There are four levels of damage assessment scale, where the information about the damage increases stepwise

Level 1: Structural integrity (Detect presence of damage).
Level 2: Damage localization (Detect presence and location of damage).
Level 3: Damage quantification (Detect presence, location and severity of damage) and
Level 4: Prognosis of remaining service life [9] (Detect presence, location, severity and consequences of damage).

II. LITERATURE SURVEY

R. D. Adams et al. [1] investigated the structural damage by the decrease in natural frequencies with the introduction of a single damage, by removing the equivalent to 1% of its cross-section. However, this methodology was insufficient to locate and quantify the damage severity, and also, shown the need for a more complete structural characterization.

W. H. Tsai et al. [2] considered the use of frequency response functions (FRF) as a solution for the detection of the structural integrity. The experimental measurement of FRFs in a laboratory bridge model, allowed the identification of a 3 mm cut in one of the tested bars. The analysis of the risk failure in trusses structures was investigated by using poles changes in the FRFs.

A. K. Pandey et al. [3] found in their work, the structural damage can be detected and located from disturbances in the matrix of flexibility. The identification of damage based on local maximum analysis, computed from the difference between the flexibility matrices of the original and damage structure. Sequences of five damage cases, created in two different locations of the beam, were located and gradual evolution of its severity identified.

M. Rucka et al. [4] presented the identification of singularities in the distribution of the signal components to detect the location of damages. This allows the position identification of the damage without the previous knowledge of the structure behavior or the use of mathematical models.

J. Y. Lai et al. [5] investigated the decrease of natural frequencies and increased damping for de-lamination detection in composite structures. The experimental results showed a higher sensitivity in variation of natural frequencies than in the modal damping, due to the low resolution and the instability of measurements.

M. A. Abdo et al. [6] were proposed the methodology for damage localization from the disturbances or discontinuities analysis of the modal rotation field. The numerical study performed with a finite element model of a plate with different boundary conditions, showed that the modal rotation field is more sensitive than the modal displacement field on the damage localization.

H. P. Zhu et al. [7] evaluated the effectiveness in the damage localization by comparing the sensitivity of the natural frequencies and the modal displacements, modal rotations and modal curvature fields. Finally, concluded the quantification of the damage severity increases with the number of natural frequencies used in the calculations. Deviations in the results are pointed to experimental measurement errors.

W. Lestari et al [8] presented the method for damage localization and quantify its severity on a sandwich beam, by measuring the curvature of the mode shapes using piezoelectric transducers. It is found that the difference between curvature (damage factor) and the sum of the differences between curvatures, allow identifying the approximate of the damage location.

A. Rytter [9] categorized the damage identifications into four performance levels Level 1: Structural integrity; Level 2: Damage localization; Level 3: Damage quantification and Level 4: Prognosis of remaining service life. According to the study, the first three levels of damage detection are related to methodologies directly supported in experimental measurements. Otherwise, a more complete characterization of damage requires the use of analytical and numerical time to estimate the remaining life, fourth level of damage characterization.

S. M. Lee [10] investigated the optical interferometry techniques as a non-destructive inspection of structures. These are the robust tools have proven to be very effective. Its advantages are undeniable compared to classical techniques for the inspection of composite materials.

Antti Huhtala et al. [11] worked on a structural model, a damage model and a measurement model and measured parameters for a given damage state. Finally, the method is experimentally verified to identify the damage on a steel cantilever beam. Though the presented method does not handle real-time data as such, it could still be used for almost real-time structural health monitoring.
K. Oruganti et al. [12] suggested that the constant health monitoring of composite structures is highly essential to prevent sudden failure. The paper highlights the utilization of Vibration based testing on Carbon/Epoxy composite beams for damage detection. The damage within the Carbon/Epoxy beams could be identified successfully by both the displacement mode shape analysis as well as curvature mode shape analysis.

Claus-Peter Fritzen [13] studied an overview on the current status of vibration-based methods for Structural Health Monitoring. It is found that the structural change due to a damage results in a more or less pronounced change of the dynamic behavior. By this different strategies can be deduced which depends on the type of measurement data (time/frequency domain) and the frequency spectrum.

D. Montalvao et al. [14] worked on latest advances in Structural Health Monitoring and Damage detection is reviewed, with an emphasis on composite structures. This class of materials currently has a wide range of engineering applications. The emergence of statistical pattern recognition techniques that allow a reduction in the number of sensors needed still requires considerable further effort.

Chaitanya et al. [15] discussed a systematic prognostic process, which can be implemented to automotive components. They applied the hybrid, data driven and knowledge based prognosis analysis to automotive suspension and battery system. Finally the Remaining Useful Life (RUL) of these components determined.

III. DAMAGE ASSESSMENT LEVELS

The damage assessments scales are categorized into four levels, where the information about the damage known stepwise: Level 1: Structural integrity (Detect presence of damage); Level 2: Damage localization (Detect presence and location of damage); Level 3: Damage quantification (Detect presence, location and severity of damage) and Level 4: Prognosis of remaining service life. (Detect presence, location, severity and consequences of damage) [9].

**Level 1: Structural integrity**

In this level, it is possible to get the information about the presence of damage in the structure. It can be achieved by monitoring certain mechanical properties of the structure over time. Those are strain energy, fundamental natural frequency, phase information, stiffness reduction. These are the some parameters which gives notice about the presence of damage. The most extensively used method to confirm the presence of damage is by monitoring the natural frequencies as the damage reduces the stiffness it induce changes in natural frequencies. By comparing base line fundamental frequency with fundamental frequency of the damage structure, one can confirm the presence of damage. As the dynamic stiffness decreases and the damping increases due to the presence of structural damage. The change in stiffness, both local and global, results in decrease of natural frequencies. [1]

**Level 2: Damage localization**

It increases the knowledge about the damage by determining the location(s) of single or multiple damage sites. The methods dedicated to the damage localization are based on physical principle of the reduction in local structural stiffness. Indirectly, they can be identified from the local disturbances or discontinuities. The experimental structural responses, such as displacement, rotation, bending moment or strain fields are the signs for the local disturbances. Another method is based on the analysis of the structural stiffness or flexibility changes, which are identified from experimental modal parameters.

**Level 3: Damage quantification**

It represents the quantification of the severity of the damage. Here, from the known input and measured output, it is necessary to determine the location of the defect and possibly its extent and orientation. The ultimate level of the damage characterization is the quantification of stiffness decrease and estimation of the damage real dimensions. The procedure requires a high accuracy in evaluating the structural response. The quantification stiffness in the damage region can be estimated from the local variation of the curvature or using mathematical models. With respect to area affected by the damage, this can be assessed by analyzing the contours of local disturbances, normally, requires the use of dedicate digital image processing techniques.
Level 4: Prognosis of remaining service life
Predicting Remaining Usef ul Life (RUL) of composite structure becomes currently an important aim by knowing the expensive failure which may occur suddenly. As the classical strategies of maintenance are not efficient and practical because they neglect the evolving product state and environment, the recent prognostic approaches try to fill this gap. This level shows to be important in ensuring high availability in minimum costs for industrial systems, like in aerospace, defence, petro-chemistry and automobiles.

The fourth level of characterization of the damage require the information from three previous levels, this explains why there aren’t any numerical model capable to predict the remaining life of such components.

IV. DAMAGE ASSESSMENT METHODS

The various vibration techniques are followed in assessing the damage levels (stages)
Assessment of Level 1: Structural integrity
1. Method based on Natural Frequency
The variation of natural frequencies in one-dimensional structure was tested with single damage, by removing 1% of its cross-section. The structural damage was successfully detected by the decrease in natural frequencies. However, this methodology was insufficient to locate and quantify the damage severity, and also, shown the need for more complete structural characterization. The physically tangible relation between stiffness and mass changes and natural frequency changes, coupled with ease of measurement of the natural frequencies. The observation that changes in structural properties cause changes in vibration frequencies was the drive for using modal methods for damage identification. Multiple frequency shifts can provide spatial information about structural damage because change in the structure at different locations will cause different combinations of changes in the modal frequencies. However, there are often an insufficient number of frequencies with significant enough changes to determine the location of the damage uniquely [4].

2. The Forward Problem
The forward problem usually falls into the category of Level 1 damage identification consists of calculating frequency shifts from a known type of damage. Typically, the damage is modelled mathematically and then the measured frequencies are compared to the predicted frequencies to determine the damage. Silva and Gomes (1994) presented the method for solving the damage-detection problem. The technique requires an analytical model for the frequency shifts as a function of crack length and position. The program searches over combinations of crack location and length and selects the combination that minimizes the function. At least two modes are required for this method, and better results are usually obtained by including more modes [4].

3. Method based on Frequency Response Functions (FRF)
The use of frequency response functions (FRF) was considered by many researchers as a solution for the detection of the structural integrity. The experimental measurement of FRFs in a laboratory bridge model, allowed the identification of a 3 mm cut in one of the tested bars Mannan (1990). The analysis of the risk failure in trusses structures was investigated by using poles changes in the FRFs.

Assessment of Level 2: Damage localization
1. Method based on the Inverse Problem
This method consists of calculating the damage parameters, e.g., crack length and/or location, from the frequency shifts. Adams (1978) examines a method whereby damage in a structure that can be represented as one-dimensional case and it can be identified from changes in resonant frequencies associated with two modes. In particular, they looked at axial vibration modes. The method is based on the relationship between the receptance function on either side of the damage, \( \beta \) and \( \gamma \) respectively, and the stiffness of a spring representing the damage \( k \). It is also observed in the literature that necessity to correct frequency measurements for the changes in temperature, which is another possible source of error when frequency changes are used to locate the damage [4].

2. Method based on Mode Shape
West (1984) presents the first systematic use of mode shape information for the location of structural damage without the use of a prior FEM. The author uses the modal assurance criteria to determine the level of correlation
between modes from the test of an undamaged body and the modes from the test after it has been exposed to acoustic loading. The mode shapes are partitioned using various schemes, and the change in model assurance criteria across the different partitioning techniques is used to localize the structural damage. The decrease of natural frequencies and increased damping were investigated for delamination detection in composite structures. The experimental results show a higher sensitivity in variation of natural frequencies than in the modal damping, due to the low resolution and the instability of measurements [5].

3. Method based on Modal Strain Energy
When a particular vibration mode stores a large amount of strain energy in a particular structural load path, the frequency and mode shape are highly sensitive to changes in that load path. Thus, changes in modal strain energy might be also considered as logical choice of indicator of the damage location. The literature has generally concentrated on 1-D strain methods, though these are applicable to 2-D and 3-D structures, which are decomposable into beam-like elements.

4. Method based on Dynamically Measured Flexibility Matrix
Another class of damage identification methods uses the dynamically measured flexibility matrix to estimate changes in the static behavior of the structure. Because the flexibility matrix is defined as the inverse of the static stiffness matrix. Thus, each column of the flexibility matrix represents the displacement pattern associated with a unit force applied at the associated DOF [7].

Assessment of Level 3: Damage quantification
1. Method based on the sensitivities of modal parameters
The modal parameters were used to localize and quantify the severity of damage in a discrete system with multiple degrees of freedom. The sensitivity of the natural frequencies and the modal displacements, modal rotations and modal curvature fields were compared in order to evaluate the effectiveness in the damage localization. The numerical simulations of a spring-mass model with 10 degrees of freedom showed that the modal curvature field is the more sensitive to the damage, while the modal rotation is a better indicator of its position. The following two steps were proposed to locate and quantify the severity of damages. First, the damage is located from the perturbations analysis of the modal curvature field. Second, the damage severity is estimated using a limited number of measured frequencies. The author concluded that the quantification of the damage severity increases with the number of natural frequencies used in the calculations. Deviations in the results are pointed to experimental measurement errors [7].

2. Method based on the measurement of modal curvatures fields
The effectiveness of the methods based on the modal curvature field is determined by the quality measurements imposed. Typically, the modal curvature is obtained through the application numerical differentiation techniques to experimental modal displacement field. As a result, the high frequency experimental noise is amplified and propagates through this process and has a strong impact on the final quality of the results. Alternatively, the direct measurement of the curvature has the advantage of avoiding the numerical differentiation of the data with consequent improvement in the efficacy of the methods.

The method for damage localization and quantify its severity on a sandwich beam, by measuring the curvature of the mode shapes using piezoelectric transducers was presented. The procedure is based on curvature difference between the original and damaged structure, measured directly using 31 piezoelectric sensors glued and equally spaced on the structure surface. The natural frequencies and modal curvature field of a clamped-free sandwich beam with a local damage caused artificially: the first – by removing the nucleus (to simulate the delamination between the core and the skins) and, second – by crushing the lower interface core / skin (to simulate the crushing of the core). The difference between curvature (damage factor) and the sum of the differences between curvatures, allow identifying the approximate of the damage location. The results also show that the crushing produces greater reduction in structural stiffness than separation between core and skin. The estimation of the damage region stiffness variation was obtained from the difference of first six modal curvature fields. It was observed a local stiffness reduction for the delamination damage between 30% to 60% and for the crushing damage of 40% to 90%. The disparity in some of the values is justified by errors associated to the measurement of curvature field [8].
Assessment of Level 4: Prognosis of remaining service life

Prognosis is viewed as an add-on capability to diagnosis that assesses the current health of the system and predicts its remaining useful life based on sensed features that capture the gradual degradation in the operation of the machine condition or components.

Prognosis have mainly evolved upon three major paradigms
i) Model based approach
ii) Data driven based approach and
iii) Knowledge based approach

1. Model based approach

It uses a mathematical representation of the system and thus incorporates a physical understanding of the system into the monitoring scheme. These models are statistical estimation techniques based on residuals generated using observers (Kalman filters, reduced order unknown input observers, interacting multiple models, particle filters) and parity relations (dynamic consistency checks among measured variables) to track the component degradation.

This prognostic process estimate the remaining useful life (RUL) involves
a) Developing a system model from first principles or identify it from it.
b) Collecting system performance data by simulating or running the system under various operating conditions including environmental.
c) Relating system parameters / features to deterioration
d) Estimating systems parameters from data via output error method
e) Tracking the degradation measures via interacting multiple modes (corresponding to usage mode) and
f) Forecasting the remaining useful life (along with a confidence estimate)

2. Data driven based approach

This approach is suitable when system models are not available, but instead system monitoring data is available. Here, failure prognosis involves forecasting of system degradation and time to failure based on state awareness gleaned from monitored data. Neural network and statistical classification methods are illustrative of this approach [15].

3. Knowledge based approach

It uses graphical models such as petri nets, multi signal flow graphs and Bayesian network (BNS) for system monitoring and troubleshooting. This approach is especially well-suited for prognosis of coupled system where the prognostic test outcomes (from a model based or data driven approach) can be used to isolate the root cause to replaceable components. Multi signal models are preferred because they can be applied to large scale systems with thousands of failure modes and tests, and can conclude failure probabilities and unreliable tests as part of the inherence process in a way that is computationally more efficient than BNS.

The first three levels of damage detection are related to methodologies directly supported in experimental measurements. Otherwise, a more complete characterization of damage requires the use of analytical and numerical time to estimate the remaining life, fourth level of damage characterization. The experimental techniques don’t allow the proper quantification damage in composite structures. The fourth level of characterization of the damage requires the information from three previous levels [15].

V. CONCLUSION

In this study, the damage inspection and structural health monitoring is emphasized by vibration techniques. Specially, the damage detection in composite structures by vibration techniques is quite simple; a great care is taken while analyzing experimentally any of the composite structures. Numbers of measuring points are studied thoroughly before fixing. The sensors will provide the required information about the vibration parameters. Most of the vibration methods results in accuracy of damage configurations and a few have certain limitations. Some of vibration methods need analytical model of the structures being tested. However, there is wide scope for damage inspection in the areas of automotive structural parts which are in service. The last step in damage inspection is prognosis analysis. The prognosis analysis can be done by predicting the failure of any composite structures by the thorough knowledge of present status of the structure.
REFERENCES


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