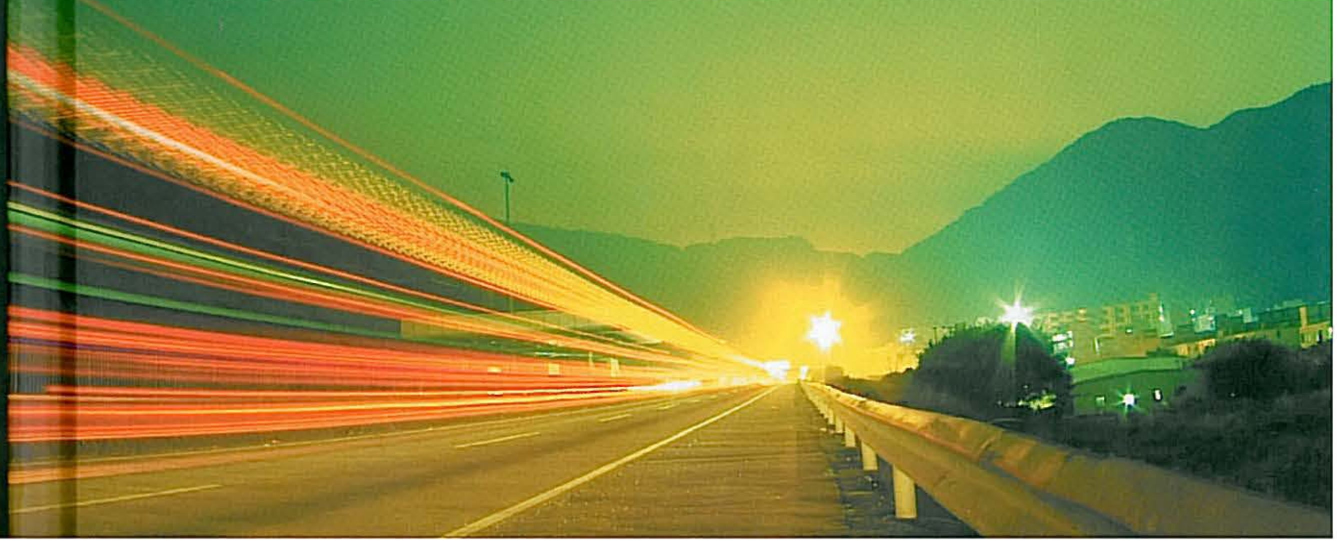
NEW ADVANCES IN VEHICULAR TECHNOLOGY AND AUTOMOTIVE ENGINEERING

Edited by João Paulo Carmo
João Eduardo Ribeiro



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Chapter 11

Structural Health Monitoring in Composite Automotive Elements

Hernani Lopes and João Ribeiro

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1. Introduction

The composite materials have demonstrated an improvement in some properties, like the weight, the durability, the corrosion resistance, and the sound and warmth insulation, relatively to the classical metallic materials. In addition, the low cost and flexibility of the structures manufacturing process with composite materials has motivated there growing in automotive engineering. With the advent of composite materials, lighter and with specific resistance higher than the metallic, the elements with lower responsibility in vehicles were gradually replaced by these new materials. Nowadays, the energetic crises, with the increase of oil prices, have forced the automotive industry to go further and creating a new generation of more efficient vehicles. One of the key elements in this strategy is to build new light weight vehicles, and the best option to achieve this goal is increasing the use of composite materials. This means that basic structural elements have to be constructed in composite materials. In these applications, the structural elements are highly demanded and work near of its mechanical strength limit, with high safety requirements. Also, these structures usually present a high strength/weight ratio. Accordingly, it requires a low tolerance to damage and therefore requires a tighter control of the integrity of the components by periodic inspections with non-destructive techniques. In those circumstances, a low tolerance to damage is required and, therefore, a tight control of the components integrity by periodic inspections with non-destructive techniques. Despite its higher strength / weight ratio, the composite elements are more sensitive to internal damages and present types of defects and/or damages are different than the metallic. The main damages in composite laminates are the interlaminar debonding, micro-cracks, micro-buckling and inclusions. These internal damages usually result from the manufacturing process and/or external stresses during service. The interlaminar unbound or delamination is the kind of invisible damage and, therefore, more severe and more common in structural components. Such damage appears essentially in laminated structures, like plate or shells with low curvature, and usually results in a substantial loss of structural performance by reducing its load capacity.

In engineering there is broad interest in structural health monitoring, looking for the early damage detection. The risk of human lives loss resulting from structural unpredictable failure, as in the airplanes crashes, bridges or buildings, have motivated the investigation of the scientific community of the various branches of engineering. Similarly, the superior performance requirement of the materials has stimulated the development and improvement of experimental techniques with application in monitoring of the structural integrity. The earlier damage identification is intended to prevent structural failure and the programming the replacement of damaged element. The main technical inspection methods can be divided into global and localized methods (Alamos, 1996). The available inspection global techniques are based in the sound or ultrasound propagation, magnetic field variations, radiation inspection, electric current, the thermal emissivity and visual inspection techniques. All these techniques assume that the behavior of the material in the vicinity of the damage is known. In addition, a large majority of these techniques is intended exclusively for research of damage in metallic structures. Moreover, the detection of delamination from the change of the mechanical characteristics and the static or dynamic structural response has been extensively referred in the technical literature as preferable. The use of composites elements in the automotive market (Altenbach, 2004) is increasing and replacing the traditional ones, this trend shows the importance in the characterization of mechanical properties (Gibson, 2012) and health monitoring (Boller, 2009) during their time lives.

2. Damage inspection techniques

The development of global methods for damage detection in composite structures has been primarily motivated by applications to the aviation and aerospace industries (Lopes, 2011). In technical literature are presented different methodologies for damage characterization in composite materials. These are usually based in experimental measurements of located and /or global structure parameters. Generally, the damage identification methods can be classified into four levels of increased detection (Rytter, 1993): Level 1: Structural integrity; Level 2: Damage localization; Level 3: Damage quantification and Level 4: Prognosis of remaining service life. 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 actually experimental techniques don't allow the proper quantification damage in composite structures. Indeed, 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.

2.1. Structural integrity

The first work referenced in the literature addressing the damage detection in composites structures was made by Adams et al. (Adams, 1975). The proposed methodology is based on the principle of dynamic stiffness decreased and the damping increased due to the presence of structural damage. The change in stiffness, both local and global, leads to the decrease of natural vibration frequencies. As such, the non-uniform distribution of internal forces in each mode shape produced different variations into the natural frequencies. These changes are directly related to the location of the damage in structure. On the other hand, there is an increase in the structural damping caused by the growth of the vibratory energy dissipation in the region of damage (Peroni, 1991). The comparison of corresponding frequencies or damping ratio, before and after the structure is put to use, allow their integrity to be evaluated. The main advantage of using this technique is the simplicity of measuring dynamic structural properties, natural frequency and modal damping, which are global parameters and don't dependent on the measuring points, could be obtained by sparse measurements.

2.1.1. Methods based on natural frequencies and modal damping

The natural frequencies variation principle in one-dimensional structure was tested with introduction of a single damage, by removing the equivalent to 1% of its cross-section (Adams, 1978). The structural damage was successfully detected by the decrease of their natural frequencies. However, this methodology was insufficient to locate and quantify the damage severity, and also, shown the need for a more complete structural characterization. Similarly, experimental results on a bridge of a motorway had proven the effectiveness in detection of damage by a decrease in the natural vibration frequencies (Biswas, 1990). The same methodology was applied to offshore the structures monitoring (Loland, 1976; Vandiver, 1975). Subsequently, the decrease of natural frequencies and increased damping were investigated for delamination detection in composite structures (Lai, 1995). 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.

2.1.2. Methods based on frequency response functions

The use of frequency response functions (FRF) was considered by many other authors as a solution for the detection of the structural integrity (Tsai, 1988; Mannan, 1990; Samman, 1991; Biswas, 1994; Samman, 1994a; Samman, 1994b). 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 (Manning, 1994).

2.2. Damage localization

The methods dedicated to the damage localization are based on physical principle of the reduction local structural stiffness. Indirectly, they can be identified from the localization of disturbances or discontinuities in the experimental structural response, like the: displacement, rotation, bending moment or strain fields. Another approach is based on the analysis of the structural stiffness or flexibility changes, which are identified from experimental modal parameters.

2.2.1. Methods based on modal response

The extension to two-dimensional structures, plate geometry, of the methodology proposed by Adams et al. (Adams, 1975) was presented by Cawley (Cawley, 1979a; Cawley, 1979b; Cawley, 1980). As an alternative to experimental modal analysis, is proposed to apply the sensitivity method to the modes shapes to deduce the location of damage in plates (Cawley, 1979b). The effect produced by the damage into the modes shapes depends on the size and stress state of the damaged region. For the analyzed structures is observed that the stress varies along the plate thickness, being zero in middle plane. The sensitivity method was applied to a damage numerical model, where was consider stiffness and mass variation negligible in the damage elements. This analysis was used in localization of a sequence of damage introduced into a laminated composite plate (Cawley, 1979b). The procedure required a large computational effort to achieve a good agreement between the numerical model and the experimental measurements.

In the laminates structures, their dynamic characteristics are strongly dependent on the stack and orientation of the laminate layers (Saravanos, 1996). The experimental analysis performed in graphite/epoxy (T299/823) of a clamped-free beams which damage dimensions less than 10% of the beam's length, demonstrated that the global modal parameters, frequency and damping, were not sufficient to localize the damage and other local parameters should be also used (Saravanos, 1996).

The effect produced by damage in the fundamental modal vibration of a clamped-free beam was investigated by Yuen (Yuen, 1985). His numerical study shows the influence of the damage in the modal response. Its effect in the amplitude of the mode shapes was also analyzed by Chen (Chen, 1988). In this case, the distributions of the kinetic and potential energy were used as indicators to localize the damage.

The methodology for damage localization from the disturbances or discontinuities analysis of the modal rotation field was proposed by Abdo et al. (Abdo, 2002). The numerical study performed with a finite element model of a plate with different boundary conditions, show that the modal rotation field is more sensitive than the modal displacement field on the damage localization. This study also proved that was possible to localize damages up to 5% reduction of local stiffness using the perturbation analysis of the modal rotation field.

The sensitivity analysis of the FRF for damage localization in beams was presented and later improved by Lin (Lin, 1990; Lin, 1994). Recent results using experimental data demonstrated the good performance of this method (Maia, 2006).

2.2.2. Methods based on modal curvature

The modal curvature field analysis method was proposed by Pandey (Pandey, 1991). His method is based on the perturbation analysis of the model curvature field between undamaged and damage state. The curvatures are computed by applying the second-order central differences method to the modal displacements field. Contrary to the natural mode shapes, the perturbations in the modal curvature field are coincident with the damage region and its magnitude is proportional to its severity. A finite element model was used to calculate the natural mode shapes of a beam for clamped-free and simply supported boundary conditions. The damage was created by locally reducing the beam's flexural stiffness. The analysis shows that the change on curvature locates correctly the damage but not quantify its severity.

It was also shown that the parameters COMAC (Co-ordenate Modal Assurance Criteria) (Lienven, 1988) and MAC (Modal Assurance Criteria) (Wolff, 1989), calculated from modes shapes displacements, are effective only for identification of significant damages, and the smaller damage are masked by the superposition process. Likewise, the frequencies and deviations in the modal curvature field were used to estimate the location of deep cracks (Dimarogonas, 1996). According to the theory of elasticity for thin beams and plates bending, the deformation at the surface is proportional to its curvature (Timoshenko, 1959). The measurement of the modal deformation field was suggested to identify the damages position. The deformation field is a better indicator of damage location than the modal displacement field (Yao, 1992; Chen, 1994; Yan, 1996). Same conclusion was presented by Chang (Chang, 1993), who compared the sensitivity of the several modal parameters.

The formulation of the model of damage index is based on the modal curvature field information. The damage index correlates the curvature field before and after the introduction of damage at each of the structure segments (Stubbs, 1995). Its average deviation from the normal distribution of the damage index is used as an indicator to identify the most likely of damage region.

The extension of the curvature method at all frequencies was proposed by Sampaio et al. (Sampaio, 1999). The changes in curvature of the frequency response functions (FRF), before and after the introduction the damage, are used to identify its location. The numerical simulations show that the method is most effective for the frequency band up to the first natural frequency or anti-resonance. Its comparison with the amplitude difference of the curvatures and the damage index method proved the superior performance of the method. The procedure was tested using experimental data measure from a concrete bridge, where was created four levels of damage in four different positions. Despite the greater effectiveness of the method, only the most severe case of damage was identified. Similar results were obtained with other methods.

Based on modal curvatures field analysis, Ratcliffe (Ratcliffe, 1997) developed a new procedure that doesn't require the previous knowledge of the structure behavior. The calculation of the modal curvature field is performed by applying the Laplacian operator to natural modes shapes. The localization of the damage is identified from the discontinuity or perturbation in the computed curvature field. Numerical simulations derived from finite element analysis allowed to identify the damage for the case of 10% thickness reduction in the section of a beam. In order to improve the sensibility of this technique, the authors presented a modified version of this method, which called the damage detection gapped smoothing method (Yoon, 2005). The difference between the smooth and the original modal curvatures profile is used, being smooth profile obtained by adjusting a third degree polynomial to the experimental data.

The application of this new technique to numerical modes shapes made possible the localization of damage up to 0.5% reduction of the beam thickness. It was also concluded that the effectiveness of the damage location is greatest for the fundamental mode shape and improves with increasing spatial resolution data. The experimental demonstration of the procedure was performed on a steel beam with a local damage, created by a cut along the cross section of the beam direction and with half thickness depth. For the first two natural modes was successfully identified the location of the damage. However, the low accuracy in the results led the authors to suggest the electrical strain gages to be used as an alternative technique for measuring the curvature. Direct measurement of the curvature of the natural modes of vibration of beams was proven to have superior performance in the localization of damages (Change, 1994).

The damage detection gapped smoothing method was applied to experimental mode shapes of a composite beam in order to locate delamination (Ratcliffe, 1998). The high sensitivity of this method was also demonstrated by localizing the damage in a steel beam, equivalent to 0.8% reduction in thickness (Ratcliffe, 2000). The application of hybrid techniques for the extraction of the smoothing curvature field, allowed the sensitivity improvement of this method (Yoon, 2001). The comparison between the experimental mode shapes and corresponded analytical ones, allows the localization of the damage (Yoon, 2001). Later, this method was applied to locate defects or delaminations in laminated composite plates (Yoon, 2005). In this case, the structural irregularity index, used to localized damage, derives from damage detection gapped smoothing method. The procedure can be applied to a response at any fixed frequency, but it is preferable to use the information from a frequency band. In this latter case, the structural irregularity index is analyzed statistically to serve as reference in the identification of damage position. The numerical simulations using the finite element method proved the effectiveness of this procedure. However, only the border of the damage position can be identified. This technique was tested on damage laminated plates. The methodology was unable to find the delaminations created artificially on the plates during manufacturing process by the introduction sheet of Teflon layer. The results show a superior performance of frequency band response method when compared with single modal response method, as result of canceling the measurement errors through the accumulative process.

2.2.3. Methods based on the dynamic measurement of stiffness or flexibility

As variant of the curvature method and having the change of local stiffness due to the damage, it was suggested the use new methodologies based on measurement of the structure dynamic stiffness (Yoon, 2005; Change, 1994). The differences in the structural stiffness matrix between undamage and damage cases is use to detect and locate cracks in structures [48]. Further, the method of the stiffness matrix error, defined by the difference of the stiffness matrix between the analytical/numerical model and experimental data, it was proposed to detect damage in the case of a large variation of stiffness (Park, 1988). For small variations, the same author proposed the use of a weight function by including others modal parameters. However, a large number of mode shapes are needed to increase the effectiveness of this method (Gysin, 1986). Indeed, in experimental modal analysis only the lowest frequency modes are measured. Furthermore, the analytical stiffness matrix should be representative of the experimental model. The combination of these two limitations will affect the precision of the method and conditions on its practical application. To overcome these limitations, it was proposed the differences flexibility method (Pandey, 1994; Pandey, 1995). This normalized model of the flexibility matrix was successfully tested for damages localization in underwater platforms (Rubin, 1983). The advantage of using the flexible matrix is in the accuracy of the estimating this matrix coefficients using a small number of mode shapes (Pandey, 1994). The flexibility matrix is defined as the inverse of the stiffness matrix. Thus, reduction in rigidity produce increased flexibility in the structure. Indeed, an approximation of the flexible matrix can be obtained from the experimental modal analysis.

The structural damage can be detected and located from disturbances in the matrix of flexibility. Numerical and experimental results obtained in beams established the effectiveness of this methodology (Pandey, 1995). In this work, the damage was identified 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. However, for the case of multiple damages it was only possible to identify the location of the most dominant.

2.2.4. Methods based on wavelets transform

The methods based on natural modes shapes and its spatial derivatives prove its effectiveness using numerical data. However, the success of these techniques is affected by the noise present in experimental data (Gentile, 2003). A new research domain of structural damage is the application Wavelets transform to extract the signal spatial derivatives components. This has the advantage of identifying small changes or discontinuities in the signal, without the propagation of noise, such as in the common differentiation techniques.

The identification of singularities in the distribution of the signal components can be used to detect the location of damages. The study of the most appropriate technique for finding cracks in beams based on Wavelets signal processing was presented by Rucka and Wilde (Rucka, 2006). The proposed technique allows the position identification of the damage without the previous knowledge of the structure behavior or the use of mathematical models. Several damages with different degrees of severity were investigated based on the optical measurement of the beams bending profile. The damage is located by identifying the local maxima of the signal components for each profile (Rucka, 2006). The Gaussian and Coifet Wavelet functions show to be the most effective in localizing the slot, up to 27% section reduction of the beam thickness.

The comparison of differentiation process among Wavelets transform and several other differential operators, to calculate the curvature mode shape and sequent location of damage in beams, was presented by Messina (Messina, 2004). The differential operators integrate a low-pass filter to reduce the unwanted high frequency noise. This study reveals the perturbation on the low frequencies signal produced by the use of strong filter, which becomes clearer for higher order derivatives. The Fourier transform filter, the weighted least squares, Lanczos's differentiator filters and Gaussian Wavelets differentiator filter techniques were investigated to calculate the curvatures from the modal displacement field contaminated by Gaussian noise. For the computed curvatures field is observed similar results using all the techniques. However, the profile curvature obtained using the Gaussian Wavelet transform presents coarse result for the undamaged region. In this case, the curvature fields will present greater number of disturbances, making difficult the damage localization.

2.3. Quantification of the damage severity

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.

2.3.1. Methods based on the sensitivities of modal parameters

The sensitivities method of the modal parameters was used to localize and quantify the severity of damage in a discrete system with multiple degrees of freedom (Zhu, 2005). 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 mass-spring 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. A procedure defined in two steps was proposed to locate and quantify the severity of damages. First, the damage is located from the perturbations analysis of the modal curvature field. Next, the damage severity is estimate using a limited number of measured frequencies. The methodology was investigated by using the experimental analysis of different damage scenarios in a periodic model of a building with three degrees of freedom. The results are considered satisfactory for medium damage severity (13.12% - 26.74%). This 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.

2.3.2. Methods 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 an 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 by Lestari et al. (Lestari, 2005). The procedure is based on curvature difference between the original and damaged structure, measured directly using 31 piezoelectric sensors (polyvinylidenefluoride film) 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 debonding 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 estimative 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% and 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.

2.3.3. Methods based on full-field measurement of displacement or rotation field by interferometric techniques

The optical interferometry techniques have been widely investigated in the last four decades, robust tools and have proven to be very effective in non-destructive inspection of structures (Lee, 1991; Sirohi, 1993; Hung, 1997a; Hung, 1999; Hung, 1998; Sirohi, 1999; Gomes, 2000; Santos, 2004)). Its advantages are undeniable compared to classical techniques for the inspection of composite materials (Lee, 1991). The ESPI (Electronic Speckle Pattern Interferometry) and Shear (Shearography) techniques are two examples currently used for nondestructive inspection of composite structures. These are full-field techniques for measuring the information on a surface and allow easily locating disturbance in structural response. The ESPI technique measures the absolute value of the displacements of the surface, including the rigid body. The principle of the Shear technique was first demonstrated by Leendertz and Butters (Leendertz, 1973) through the construction of the Michelson optical interferometer. The Shear technique is only sensitive to the object displacements gradient, which can assumed, for the case of small displacements, as a good approximation to the surface rotation field (Kreis, 2005). Due to their properties and insensitivity to rigid body movement, this technique is often used for the localization of delaminations in composite structures. Comparative analysis of the measurements quality between the ESPI and Shear techniques for internal damage identification was studied by several authors (Hung, 1997; Gomes, 2000). In ESPI technique, the fringes produced by rigid body motion makes difficult its interpretation and may mask the presence of damage. Consequently, the Shear technique is more suitable for damage localization. In this case, the internal damage is reveal by appearing two juxtaposed lobes of concentric fringes representative of local disturbance.

Contrary to ESPI technique, the Shear measures directly the surface rotation field and eliminates the need of the numerical differentiation. Another major advantage is the simplification of the optical setup, which allow the use of low coherence length Lasers. Also, the optical setup can be built in a very compact form, giving a greater stability to the measurements and isolation to external disturbances (Gomes, 2000). In addition to the damage localization in composite structures, several other applications can be found in the literature including: the static and dynamic measurement of the rotation field and the measurement of surface residual stress. (Santos, 2004; Kreis, 2005; Hung, 1978; Lùkberg, 1997; Hung, 1997b; Devesa, 2002; Pedrini, 1997).

The damage identification using shearography technique is based on comparison of two states of the object deformation. The type of excitation will depend on the type of defect and the material used. The success of such techniques will be influence by several factors: the material properties, type of defect and method of excitation. The thermal, the vacuum or transient excitations are most effective techniques to the reveal the inter-layer defects (Hung, 1997a; Gomes, 2000; Santos, 2004; Ambu, 2006). However, the best choice is typically defined by a heuristic process in which the previous experience influences the selection of the excitation method. The analysis of the fringes obtained by ESPI techniques was used to investigate damages in laminated thin plates (Ambu, 2006). Damage was induced by the impact of metallic spheres with different masses. The thermal excitation with infrared lamp was used and the plate out-of-plane displacement field was measured. The damage size and position were estimated from the raw fringes analysis, using digital image processing techniques. The results revealed that the ESPI technique is less sensitive to damage in relation to the holographic techniques. Both of these optical techniques can identify well the damage location. However, the comparison with ultrasound (C-scan) measurements reveals that the interferometric techniques are inadequate to located damages with depths greater than 0.7 mm. The introduction of the phase calculation methods on the classic interferometric techniques permit to improve the spatial resolution of the measurements. The phase map and the corresponding raw fringes, measured with the ESPI technique, were used to locate and quantify delaminations in a fiberglass reinforced polyester plates (Richardson 1998). The damages created by impact were analyzed by C-Scan and by sectioning the matrix. Both methods were used as reference for the analysis of other techniques. The results show a good correlation between optical techniques and reference techniques.

The propagation elastic waves in plates and pipes using holographic interferometry techniques were proposed by several authors (Aprahamian, 1971; Fallstrom, 1989a; Fallstrom, 1989b; Olofsson, 1994; Olofsson, 1996; Fallstrom, 1996; Fallstrom, 1998). A double pulse Laser technique is used to measure the displacements in isotropic plates (Aprahamian, 1971; Olofsson, 1994), anisotropic plates (Fallstrom, 1989a; Fallstrom, 1989b; Olofsson, 1994; Fallstrom, 1996; Fallstrom, 1998) and anisotropic tubes (Olofsson, 1994; Olofsson, 1996). The holographic interferometry and the flexural waves propagation were also used to investigate the debonding in the interface areas of ceramic-metal plate (Conrad, 2001). The quality of the bond between the two materials influences the wave propagation of transients bending waves. These are produced by a piezoelectric exciter mounted near of plate's surface. Distinct damage models were introduced into three plates, simulating the interface discontinuities and cracks in the ceramic plate. A YAG pulse Laser with double cavity was used to generate two pulses with adjustable intervals between 1 and 80 μs. The two interferometric pulses were recorded on a holographic plate by changing the angle of incidence. Afterword, the interferograms were reconstructed and the phase map is extracted by using the phase-shift technique. The damages located by identifying perturbations in the phase map of the wave propagation. However, the complexity of fringes distribution observed in the phase map doesn't permit the interpretation of the damaged area.

The sandwich panels removed from the wing of an airplane model were used to investigate the damage, created by low-speed impact (Ruzek, 2006). The skin made of carbon fiber and core honeycomb, suffered several low energy impacts (10J - 40J). The Shear and C-scan techniques were used for non-destructive inspection of the panels and with the purpose of visually comparing the results. Based on the measurements acquired with Shear technique were possible to identify very well the damage location and size. By contrast, the C-Scan technique, due to their operating principle has proved to be less suitable for such structures. In addition to be more time consuming, presents difficulties in dealing with the multiple discontinuities in the material, rupture / indentations in the skin and distortion of the honeycomb core produced by the impact.

The application of ESPI and Shear techniques to the analysis of debondings in the interface region of thin coatings was investigated by Gomes et al. (Gomes, 2000). The thermal excitation was used to reveal the damage position and its size. The phase maps present similar results for both techniques. However, a superior fringe contrast was observed in the measurements with Shear technique. A technical review of Shear technique and its several applications to composite materials was presented by Hung et al. (Hung, 1999). The measurement of residual stresses, strain field and damage localization are some of the mentioned applications using this technique.

A modified version of the Mach-Zehnder optical interferometer was developed by Pedrini et al. (Pedrini, 1996) for measuring the modal rotation field in plates. The two images created by the interferometer are sheared and rotated before being combined, in order to later compute the phase map. A double pulse Ruby Laser was used to record modal rotation field of a circular plate. The same technique was then used in localizing damages in a sandwich plate with Nomex core and fiberglass skins (Santos, 2004). The two damages were artificially created by removing 2.5 cm diameter of skin and 1 cm diameter of core. An impact hammer with electromagnetic drive was used to produce transient excitation of the structure. The time plate response was recorded for posterior damage localization. The smallest damage was located based on fringes concentration analysis. However, larger damages produce a higher number of fringes, becoming difficulty to distinguish them form fringes produce by the natural vibration of the structure. These and other difficulties have led other authors to develop alternative procedures for nondestructive inspection of damage. The high speed measurements using phase shift technique was considered in order to reduce phase errors and improve the quality of the data (Davila, 2003). The procedure is based on the technical implementation of the temporal phase and the application of phase unwrapping algorithm for recording in time the structure dynamic response.

The combination of ultrasound excitation technique with pulsed interferometric technique for investigating internal damages in the plates was developed by Cernadas et al. (Cernadas, 2001). The ultrasonic elastic waves (Lamb waves) can penetrate deep into the material to reveal the surface damages. These are detected through the use of high resolution optical techniques. The measurement by real-time holography has already been used to identify minor cuts and holes in plates (Schroeder, 1996). The ESPI technique and pulsed Laser method can be used to measure freeze in time the bending wave propagation (Mast, 2001). However, the high speed and small amplitude of the ultrasonic elastic waves requires a good insulation of exterior disturbances. The use of the ESPI technique with double pulse laser has been suggested to solve the stability problems in the measurement (Cernadas, 2001). A piezoelectric transducer coupled to the plate surface is used to generate surface acoustic waves, Rayleigh waves that propagate along the structure surface. These waves can also be generated remotely by strong Laser pulses. However, to generate this Rayleigh waves with amplitude in the measurement range of the ESPI technique, requires the application of high energy on the surface and its protection to prevent being damage. In this study, two types of damage were introduced into an aluminum plate. A blind hole and cross section cut were generated artificially in the plate. The sequence of two images, separated by 1.5 μs, was used to measure the plate displacement field caused by a propagation chain of the Rayleigh waves, introduced through the fourth Laser pulses. Through the disturbances fringes analysis was possible to identify the damages. The introduction of the phase calculation into the displacement measurement allows improving the quality of the results (Cristina, 2003). This new methodology was used to measure the real and imaginary components of the displacement field generated by the propagation of Rayleigh waves. Based on these two components was possible identified damage the position and size of damage, even in the situation of poor quality fringes.

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