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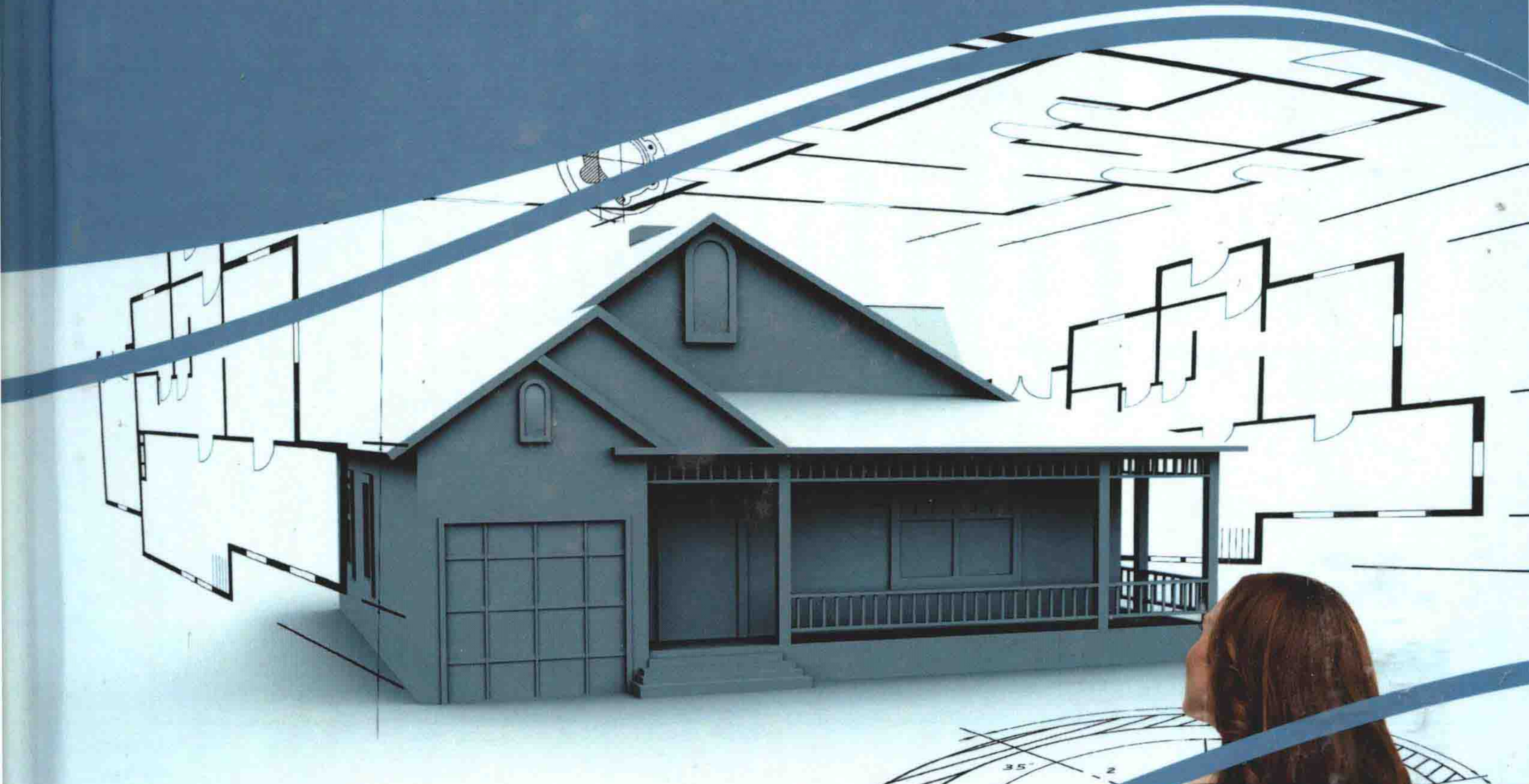
Emerging Design Solutions in Structural Health Monitoring Systems



Diego Alexander Tibaduiza Burgos, Luis Eduardo Mujica, and Jose Rodellar

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Preface

Structural Health Monitoring (SHM) consists of the acquisition and the analysis of data from a set of permanently installed sensors to determine the health of a structure in a non-destructive way. Since it is possible to assess the structure on demand or continuously, it is feasible to verify the integrity of the structure and determine whether a structure can work properly or whether it needs to be repaired or replaced, with the subsequent maintenance cost saving. In general, SHM includes different levels such as damage detection, damage localization, damage classification and prognosis of remaining lifetime. This book provides relevant theoretical frameworks and some of the latest research and developments in the SHM field. It is no focused specifically on data acquisition technologies neither strategies for signal processing or damage detection. It is focused as a whole system capable to monitor damages in structures. In addition, the book provides examples of applications and results using data-driven approaches in different areas such as civil, aerospace, mechanical engineering, among others.

The book is addressed to students, engineers and researchers involved in the design and development of solutions for structural health monitoring systems. Besides, we expect that it will be a reference for understanding the importance of the field and also for encouraging new solutions in real applications.

Chapter 1 of the book is prepared as an introduction to Structural Health Monitoring (SHM), so that fundamental concepts and main levels of detection are described. Besides, a brief review of the main methodologies based on patter recognition is also presented. Chapter 2, named "Self-healing properties of conventional and fly ash cementitious mortar exposed to high temperature", demonstrates that heating at high temperature deteriorates the physical and mechanical properties of concrete with and without fly ash addition. Existence of partial micro cracks due to the thermal exposure is detected since the ultrasonic pulse velocity decreases. In addition, these micro cracks are confirmed by the decrease in the compressive strength and increase in apparent porosity or water absorption.

The next two, Chapters 3 and 4, named "New features for damage detection and their temperature stability" and "Wavelet transform modulus maxima decay lines: damage detection in varying operating conditions", respectively, are devoted to the first level of SHM, which might be considered by some researchers as the main and most important but also the easiest level. However, if the structure is subjected to variations in the environmental and/or operational normal conditions, the detection of any damage is a challenge since changes in the structural behavior due to these variations can mask patterns that indicate damages, or in opposite, they can wrongly suggest damages. The methodologies presented in these chapters use the response time series of vibrating structures and are based on Wavelet Transform (WT), complemented with Fuzzy Similarity measurements in the first case and decay lines in the second case. In the first of the two chapters, the vibration response is measured by means of piezo-ceramic transductors (PZT's). In the latter one, vibration signals are gathered by means of a high-speed camera. In both cases, structures have been subjected to variations in temperature in different ways.

The following chapters (5 to 9) are focused on the development of systems and strategies for damage detection, classification, localization and estimation of its severity. Chapter 5, entitled "Development of a system for detecting weld failures", presents a prototype of an electronic device capable to excite, efficiently, ultrasound transducers used for detecting weld failures at the junctions of metallic parts. This system can compete on the world market due to its easy implementation and small cost. To validate its efficacy, several kinds of defects on welds are tested (porosity, lack of penetration and lack of fusion) and the time of fly is analyzed comparing pristine specimens with the damaged ones. Chapter 6, "Structural damage assessment using an artificial immune system", proposes to use an artificial immune system to detect and classify damages in structures. The strategy employs data from a multiactuator piezoelectric system, which works in several actuation phases, and it is permanently attached to the surface of the structure under test. The advantage of using a multiactuator system lies in the analysis of the specimen across the surface covered by the network of transducers from different points of view. A known elastic wave is generated in one place of the structure and sensed in different locations, later on, the same wave is generated in other position and sensed in the rest of sensors. All the time series signals are organized and preprocessed by means of Principal Component Analysis (PCA) and finally used to define the antigens that are compared with antibodies by using some affinity function. Chapter 7, "Structure impact localization using emerging artificial intelligence algorithms", give an introduction of a novelty learning algorithm named Extreme Learning Machine (ELM) to locate impact damages in plate structures. The technique is compared with typical neural networks such as back-propagation neural network (BPNN) and least squares support vector machine (LSSVM) and illustrated through experimental studies. Results show that the introduction of the new technique decreases the training and testing execution time with comparable accuracy.

Chapter 8, "Case based reasoning for stiffness changes detection in structures: Numerical validation by using finite element models", presents an expert monitoring system to detect, locate and quantify stiffness variations. The methodology is based on pattern recognition and artificial intelligence techniques that emulate knowledge based on human reasoning. As previous chapters, this strategy uses time-series dynamic responses of the structure. They are preprocessed by means of Wavelet Transform and Principal Component Analysis (PCA). The knowledge of the expert is organized and retrieved following a reasoning based on cases (CBR) supported by self-organizing maps (SOM). To evaluate the accuracy, dynamical responses of the structures to different damage scenarios were simulated and collected by solving its finite element model. Chapter 9, "Systematic statistical approach to structural damage diagnosis", also presents a methodology for detecting, locating and estimating damages in structures. In this case, uncertainties such as physical variability, measurement uncertainty and model errors that affect structural damage diagnosis are considered. A statistical approach is used to identify these sources of uncertainty, quantify their combined effect on diagnosis, and thereby, provide an estimate of the confidence in the results of diagnosis. Damage detection was based on statistical hypothesis testing. While the classical hypothesis testing procedure calculated the uncertainty in detection based on the significance level of testing, the Bayesian hypothesis testing procedure calculated the likelihood of "no damage" scenario to "damage" scenario, thereby providing a robust Bayesian metric to assess the confidence in detection. The uncertainty in localization was quantified using heuristic measures in the classical statistics-based approach while the Bayesian method directly quantified the probability that a given damage parameter is faulty. The uncertainty in damage quantification was expressed in statistical confidence intervals in the classical statistics-based approach while the Bayesian method gives the entire probability distribution of the damage parameter.

The next three chapters (10 to 12) concern to the last level in SHM (Damage Prognosis), which includes the quantification of the damage to determine the useful lifetime remaining for the structure and the conditions to continue operating, The chapter "Nonlinear ultrasonics for early damage detection" suggests that nonlinear mechanical properties may be a key factor to quantify changes in an incipient state. It gives an introduction of the fundamentals of nonlinear ultrasonics, focusing primarily on classical and non-classical hysteretic nonlinearities. Next, nonlinear ultrasonic techniques of the main interest for industrial applications are described. An explanation of nonlinear evidences in metals and composites are also included, because of their relevance in industries with high security standards. Right after, the need for computational modeling to solve the inverse problem for evaluation is addressed; acquired data and theoretical models can be integrated strengthening the evaluation process to allow the solution of cases with weak damage signatures. Finally, the Bayesian inverse problem is explained as the suitable link to prognosis tools. Chapter 11, entitled "Fatigue crack growth analysis and damage prognosis in structure", presents a methodology for modeling crack growth in structures with complicated geometry and multi-axial variable amplitude loading conditions. During cycle-by-cycle integration of the crack growth law, a Gaussian process surrogate model is used to replace the expensive finite element analysis, thereby significantly improving computational effort. The effect of different types of uncertainty on crack growth prediction is investigated. Three different types of modeling errors – crack growth model error, discretization error and surrogate model error – are included in the analysis. The different types of uncertainty are incorporated into the framework for calibration and crack growth prediction, and their combined effect on crack growth prediction is computed. Finally, damage prognosis is achieved by predicting the probability distribution of crack size as a function of number of load cycles. This methodology is useful for design of structural components and systems where the focus is to maximize life expectancy and minimize cost through efficient and accurate reliability analysis. Straightaway, Chapter 12, "Prognostics design for structural health management", details a physics-based modeling approach whereby the behavior of the damaged components is encapsulated via mathematical equations that describe the characteristics of the components as it experiences increasing degrees of degradation. Mathematical rigorous techniques are used to extrapolate the remaining life to a failure threshold. Additionally, Bayesian state estimation is used to compute the probability distribution of the system states by accounting the different sources of uncertainty with making predictions.

Finally, the chapter entitled "An implementation of a complete methodology for wind energy structures health monitoring" is addressed to show a complete methodology for SHM damage detection solution in a particular application, wind energy plants. Several methodologies are proposed for the typical entire process of SHM. Starting with sensor placement (the best possible sensor locations are found), selecting the more representative data, classifying the different environmental and operational conditions and, applying a damage detection methodology, including sensor fault detection. The damage detection methodology is based on Stochastic Subspace Identification (SSI). This identification applies Null-Space analysis of the Hankel matrix, which is able to detect changes in the dynamic response of the structure.

In general, the solutions presented in this book for damage detection, localization and classification are based on data models instead on analytical models. In some cases, due to the lacking of well-equipped laboratory facilities, or to the novelty of the methodology, data are generated and collected by means of detailed physical modeling, typically of the Finite Element type. In other cases, real although not realistic structures are used to generate the data. Original signals are usually preprocessed with the help of Wavelet Transform (WT), Principal Component Analysis (PCA), among others. On the contrary, solutions focused on damage prognosis need the help of an analytical/physical/mathematical model to predict the behavior of the damage and to schedule maintenance. Regarding to examples presented through the book, the reader can find satisfactory results using simulated data as: three degree of freedom mass, spring and damper system, metallic frames, pipeline and, two-radius hollow cylinder; experimental data from simple structures as: cantilever beams, metallic plates, metallic welded specimens; and even more complexes structures as: composite plates, skin panel of the torsion box of the wing provided by stringers and ribs, a wind energy tower model and, graphite-epoxy composite.

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Introduction

Structural Health Monitoring (SHM) defines a well-known engineering area whose main issue is the verification of the state or the health of structures in order to ensure proper performance using non-destructive tests, involving sensors permanently attached to the structure and computational algorithms. SHM brings different benefits such as: knowledge about the structural behavior under different loads and different environmental changes, knowledge on the current state in order to verify the integrity of the structure and determine whether a structure can work properly or whether it needs maintenance or replacing, with the corresponding maintenance cost saving. Basically, the use of SHM can be extended to any system with structures, this means, a wide range of applications in engineering areas such as civil, aerospace, aeronautics, mechanical and others.

As an example, it is possible to mention aeronautics, where the currently daily passengers flow, merchandise and operations in airports in a global scale suggest increasing the safety in the daily operations in all the elements involved. According to the International Civil Aviation Organization (ICAO), in 2012 the total world volume of scheduled commercial flights began to edge over 31 million per year (ICAO, 2013) and still increasing. However, despite this trend, the global accident rate (accidents per million departures) has changed compared with the year 2011, when it was of 4.2, decreasing in 2012 up to 3.2. This result implies an improving safety and the implementation of best solutions for monitoring. To ensure safety, the ICAO promotes the systematic implementation of Standards and Recommended Practices (SARPs) for the aviation safety through the following activities:

- Policy and standardization initiatives;
- Safety monitoring;
- Safety analysis;
- Regional safety;
- Implementing programs to address safety issues.

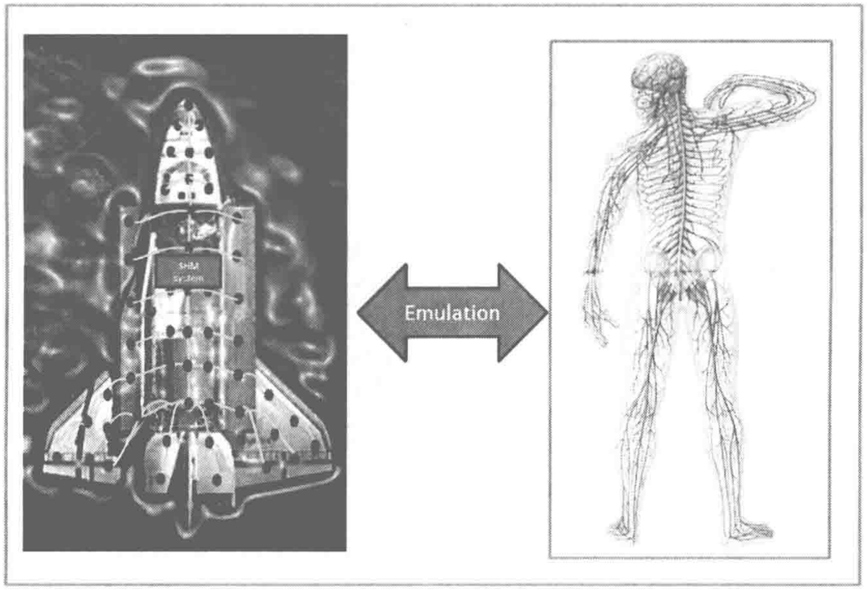
At airports level, Safety Management Systems (SMS) are defined in order to contribute to the airports to detect and correct safety problems before they result in aircraft accidents or incidents (FAA, Federal aviation administration, 2012; International Civil Aviation Organization, 2013). These management systems are very important because the risk and the probability of an accident are present in the daily tasks. In addition, there is an increment in this factor due to the higher number of operations, which are significant and still rising. As example, in Spain airports during 2011, the total number of passengers was 204.373.288 and the number of merchandise transportation was 671.722.190 according to AENA ("Aeropuertos Españoles y Navegación Aérea") (AENA, 2012). These quantities associated with the value of what is transported daily, provide important reasons for increasing the safety in airport operations and in the involved elements (airplanes, helicopters, etc.). In a low level, each flight company requires to ensure the reliability of its aircrafts during the different phases of the flight (pre-flight, departure and climb, route, cruise, descent and landing). To do that, the company needs to guarantee the proper performance of their aircraft structures, navigation systems, communication systems, among other elements. According to (FAA, Aircraft inspections, 2012): "when an aircraft is being designed and produced, the aviation authority, the manufacturer, and selected industry participants form groups called Maintenance Steering Groups (MSG) and industry steering committees (ISC). These groups, through numerous meetings determine the frequency and scope of aircraft inspections to be performed. This information is provided to another group called the Maintenance Review Board (MRB) which will issue their final recommendations to the manufacturer on how an aircraft should be maintained". In general, the inspection of any civil aircraft is determined by operation type. The aircraft must also be maintained in an airworthy condition (referred to as continued airworthiness) between those required inspections (Bureau, 2015). Additionally, a preflight inspection is conducted before each flight in ramp, which consists of checking the aircraft by visual examinations and operational tests to detect defects and maladjustments (Navyaviation, 2012). Many times these inspections have revealed faults and damages in the structures. Recently, for instance some small cracks were discovered in the world's biggest passenger aircraft (Airbus A380) during a routine inspection. To correct this possible problem 20 aircrafts were inspected and according to the vice-president of AIRBUS (Tom Williams): "This is not a fatigue problem, but a problem during the manufacturing process" (Staff, 2012). Unfortunately, failures of this type have traditionally been detected during routine inspection periods and normally with the use of various non-destructive techniques, but in the case of visual inspections, it is sometimes impossible to detect small structural damages (for instance between each flight). In this sense, Structural Health Monitoring (SHM) has appeared as a solution to provide tools for early structural damage detection using non-destructive techniques and algorithms.

In a general way, it is possible to compare a SHM system with the human nervous system as in Figure 1. In both cases a sensor network is connected to a central system, which allows apply excitation signals and measure the responses from the sensors distributed along the structure. Additionally there is a system for processing the data, which defines the state or the health of the structure.

In SHM different classes exist for damage diagnosis (Rytter, 1993) in a general way, which can be grouped in four levels (Figure 2). The first level corresponds to the damage detection. In this level it is important to know whether there is any change in the structure and if this change is due to damage. In the second level, after detecting damage, using proper techniques, the position of the damage can be determined. The third level considers the definition of the type of damage and its size. Finally, in the level 4, the remaining lifetime is determined. Recently, an extra level is considered in order to include the capability of auto-healing in smart structures (Inman & Grisso, 2007).

Most common applications in SHM are concentrated in the first three levels and there are many applications using different techniques. The majority of these implementations include the use of Non-Destructive inspections by means of sensors attached to the structure. These experimental setups normally require knowing the structure in order to define which sensors can be used and their distributions in the structure. The variety of sensors and configurations for data acquisition is quite broad as will be shown in the literature review.

Figure 1. Analogy of a SHM system and the human nervous system



In aeronautic and astronautic areas, it is very common the use of aluminium and composite materials for building the structures (Ye, Lu, Su, & Meng, 2005). Since some years ago (probably since the first introduction into commercial use in 1944 as fuselage skin for Vultee BT-15 trainer plane (Hoskin & Baker, 1986; Ye, Lu, Su, & Meng, 2005), the trend in the design of the structures has been directed towards the use of composite materials because the advantages compared with traditional materials as the aluminum allowing the weight-saving among others benefits. There are many examples useful to show the diversity of the materials currently used in military and commercial applications among, others.

Figure 2. Levels in SHM

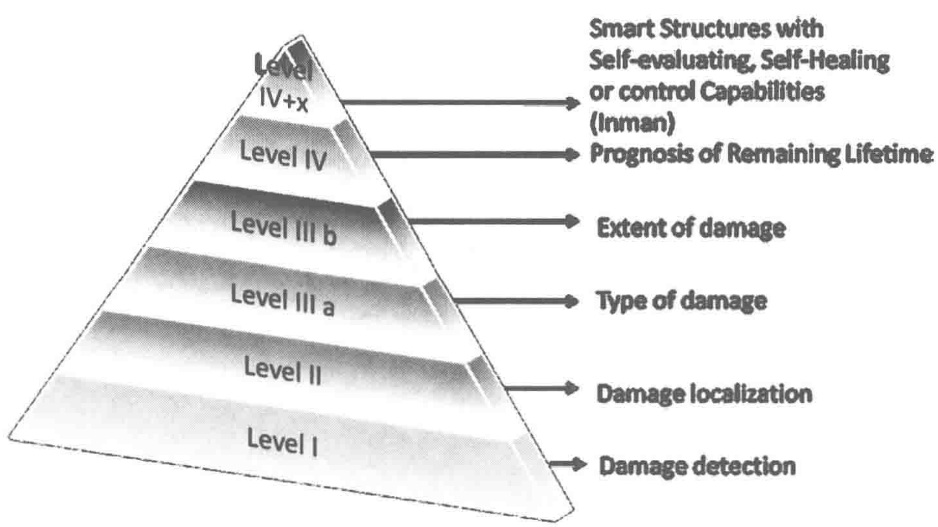


Figure 3a. Fighter aircraft F-18 E/F: F/A-18F Super Hornet
(Daily, 2012).

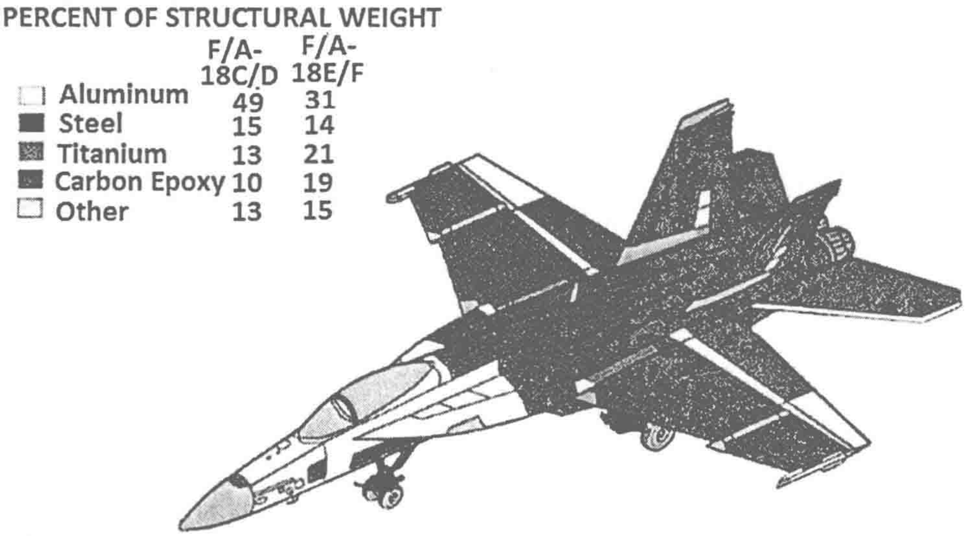
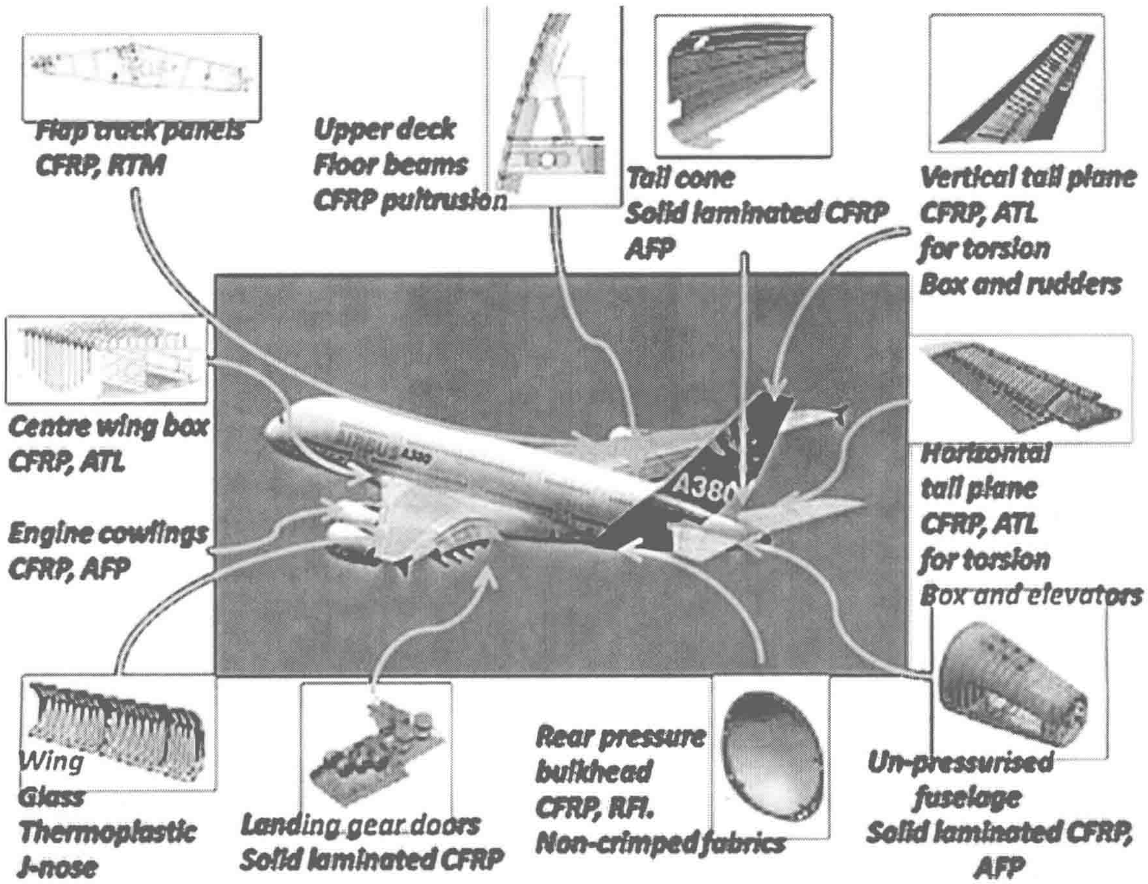


Figure 3b. Fighter aircraft F-18 E/F: schematic diagram with the percentage of structural weight
(Baker, 2004).

Figure 4. Utility of composite structures on A380: monolithic CFRP and thermoplastics
(Ye, Lu, Su, & Meng, 2005).



For instance, in the U.S. Navy, the F-18 E/F fighter has 31% of aluminium of the total weight, while the carbon epoxy has the 19% as can be seen in the Figure 3. Other example can be found in the AIRBUS A380, which is one of the biggest commercial aircraft. Although the use of composite materials has increased, the aluminum is still widely used (Figures 4 and 5).

The SHM systems are currently in a development stage and the majority of the applications are available in a research level, especially in the aeronautic and astronautic areas. To perform the inspection of the structures in the majority of applications, the structure is isolated and the monitoring is performed under special conditions. In areas as aeronautical and aerospace it is really important to evaluate the health of the structures in normal operational conditions when the element is integrated into the system (aircraft, helicopters, satellites, space shuttle, among others). This reason has motivated the development of new methodologies. An additional motivation is the reduction in the cost of maintenance to avoid that the aircraft goes out of operation for periodical maintenance and to increase the safety in the normal operation of the structures.

Other examples about the need of SHM systems can be found in civil engineering. This area presents big interest since large infrastructures imply big quantity of humans that use daily these civil developments. One example in this area can be found in the building called SPACE in Medellin-Colombia, where a bad design and the lack of effective state inspection, resulted in loss of life and the destruction of one of its buildings (Figure 6).

Figure 5. Utility of composite structures on A380: materials distributions (weight breakdown)
(Ye, Lu, Su, & Meng, 2005).

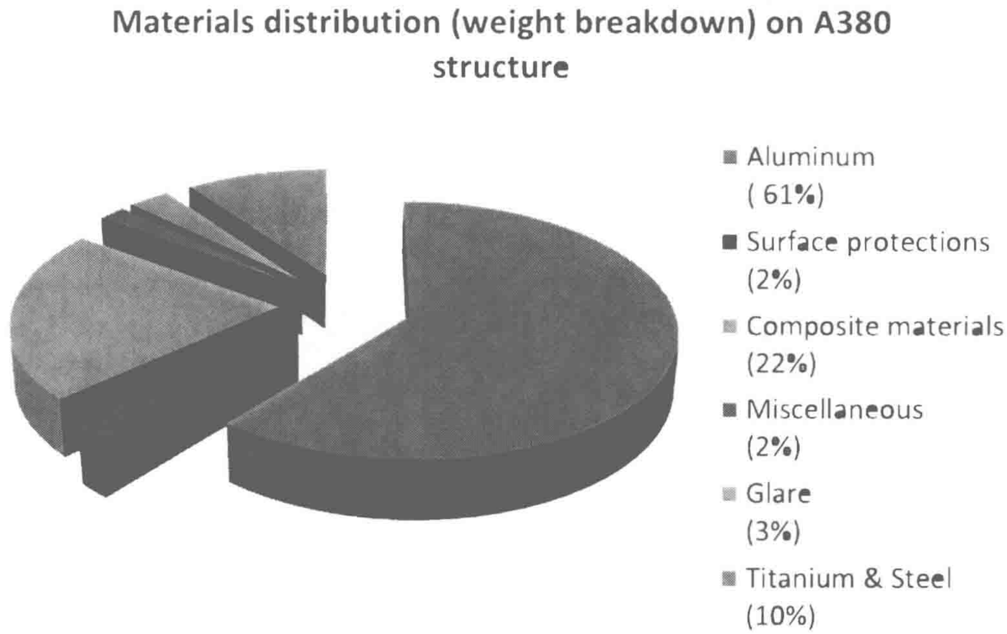


Figure 6. Building Space, Medellín-Colombia
(Tiempo, 2014).

A BRIEF REVIEW OF STRUCTURAL HEALTH MONITORING AS A PATTERN RECOGNITION APPROACH

The problem of structural monitoring can be tackled from different points of view. Some authors have built mathematical and numerical models based on physical laws to describe the characteristics of the structure. In this kind of approaches, a high-fidelity model of the structure is required to perform a reliable damage identification. On the other hand, other authors use techniques based on data gathered by experiments or by numerical simulations. These approaches usually require a statistical model representation of the system to perform the structural state analysis (Worden & Manson, 2007). In this case, the system does not use physically based models and the problem of damage identification can be approached as a pattern recognition application, where some features of the collected signals are used as reference pattern. In general, it exploits the fact that the vibrational response of a structure is deferent when it is healthy or damaged. In this way, if some defect exists in the structure, its vibrational response will change and these changes can be analyzed.

Several reviews have been carried out in Structural Health Monitoring (SHM). Among them, Chang, Flatau, and Liu (2003) presented a review of SHM for civil infrastructures. Fritzen (2005) presented an overview of the developments of vibration based methods in the year 2005, also in 2006, Lynch and Loh (2006) presented a summary review of wireless sensors and sensor networks. Farrar and Worden (2007) performed a brief historical review of SHM technology development. The same year, Brownjohn (2007) presented a review of SHM applications to various forms of civil infrastructure, including a discussion about the damage diagnosis procedure in terms of instrumentation, data acquisition, communication systems and data mining. The next year, Chiang, Lee, and Shin (2008) presented a review focused in damage detection methods for a wind turbine system. In 2010, Mujica, Rodellar, and Vehi (2010) performed a review of impact damage detection in structures using strain data, which included sensors, specimens and impact sources used for developing and testing strategies. Recently, in 2011, Fan and Qiao (2011) presented a review and comparative study of vibration-based damage identification methods. The review included methods based on modal parameters, natural frequencies, mode shapes as well as curvature/strain mode and shape-based methods. These reviews have proved that the interest in the development of algorithms and methodologies in SHM has been growing. As result of this interest, SHM has been applied in different areas, which include applications in civil, aeronautics and astronautics structures. Many works has been reported for more than three decades (Chang, Flatau, & Liu, 2003) with promising results, for instance, tests in bridges (Azevedo, et al., 1996; Lee, Kim, Yun, Yi, & Shim, 2002; Riveros, 2007; Kawano, Mikami, & Katsuki, 2010; Panetsos, Ntotsios, Papadimitriou, Papadioti, & Dakoulas, 2010), buildings (Garziera, Amabili, & Collini, 2007; Serino & Spizzuoco, 2010), wind turbine blades (Park, Taylor, Farinholt, & Farrar, 2010), and other structures (Law & Sohn, 2000; Mujica et al., 2005; Sohn, Farrar, Hunter, & Worden, 2001; Jaques, Adams, Doyle, & Reynolds, 2010).

The next subsections give a brief overview of the SHM levels in order to show from a general point of view the wide range of methods and applications developed in SHM.

Brief Review of the Structural Health Monitoring Levels

As it was mentioned, SHM includes different levels starting by the detection of the damage and following with the localization, classification, identification and the prognosis of damages (prediction) (Worden & Manson, 2007).