First International Conference on Damage Tolerance of Aircraft Structures
R. Benedictus, J. Schijve, R.C. Alderliesten, J.J. Homan (Eds.)

ADVANCES IN DAMAGE TOLERANT DESIGN AND ANALYSIS FOR EMBRAER JETS

Carlos E. Chaves*, Claudio J. F. Miscovich*, Francisco K. Arakaki*, Reinaldo S. Kolososki* and Waldir G. Gonçalves*

*Embraer – Empresa Brasileira de Aeronáutica S/A,
Av. Brigadeiro Faria Lima, 2170 – São José dos Campos – SP - Brazil
e-mail: carlos.chaves@embraer.com.br
Web page: www.embraer.com

Abstract. *This paper presents an overview of the advances in damage tolerance techniques applied to Embraer aircraft during the last two decades. Initially, a brief history showing the design evolution for the new families of Embraer jets will be presented, followed by a description of the current analysis methods and the most relevant tests that have been performed for verification of damage tolerance design and analysis. Some emphasis will be given to the Embraer 170 aircraft fuselage barrel fatigue test, its results and general conclusions. A further discussion will be presented with respect to damage tolerance applied to composite materials in primary structures and some advances in studies concerning novel techniques for monitoring the structure health.*

1 INTRODUCTION

During the beginning of the 21st century, the world economy is growing in a high pace, and nearly all continents are experiencing an increasing demand for commercial aircraft. On the other hand, many challenges must be overcome, such as the continuous search for lighter and increasingly high reliable structures, made with more efficient materials.

The damage tolerance (DT) philosophy for structural integrity was introduced in commercial aircraft design since the seventies, initially focusing metallic structures, and later extended to composite structures. Since then, it's been observed an increase in aircraft structures safety, that is by itself a proof of the effectivity of this approach.

Embraer has been studying and implementing the DT design since the 80's, by occasion of the Brasilia turboprop aircraft development. Since then, two important families of commercial jets with increasingly larger sizes have been developed, the 145 family and the 170/190 family. For each novel project, while the accumulated experience was incorporated, attention was given to changes in requirements and to accomplishment of special requirements applicable to larger aircraft. During the development and certification periods for all these aircraft, Embraer engineering performed detailed fatigue and DT analysis supported by extensive testing programs ranging from material test to full-scale structure fatigue tests.

With the belief that technology is a major driver for the success of future aircraft designs, recently new developments focusing new materials and manufacturing processes are being carried out. The amount of composite materials in the airplane structure is increasing and such materials are increasingly being incorporated to primary structures. Meanwhile, studies for metallic materials and structural solutions with higher efficiency (and therefore “competing” with the composite solutions) are also being carried out.

This paper presents a comprehensive overview of the advances in DT design for Embraer aircraft during the last two decades. Departing from a general description of the current criteria and analysis methods, subjects such as loading, materials and structural solutions will be discussed. The main tests carried out in order to corroborate analysis methods will also be described. While the material and sub-component tests, fuselage and wing component tests and full-scale fatigue tests that have been performed will be described in short, emphasis will be given to the Embraer 170/190 fuselage barrel fatigue test results and conclusions.

Additionally, two important subjects will be discussed in short: (a) first, some considerations for DT of composite primary structures and advances in design techniques, complemented by aspects such as the definition of allowable damages, damage scenarios, load enhancement factors, environmental factors and no-growth approach; (b) second, recent advances in studies with respect to techniques for monitoring the structure health *in situ*, allowing the development of more efficient structures with decreasing levels of redundancy. Such discussion aims to show that structural health monitoring technologies under study will require not only a very advanced technical “knowledge” of the structure stress behavior and crack propagation behavior but also the development of detection systems for airborne structures, as well as changes in future criteria for the aircraft certification.

2 EVOLUTION OF EMBRAER AIRCRAFT DESIGN

Embraer was founded in 1969 and later privatized in 1995. The first products developed by Embraer were turboprops for commercial and military applications. Today the company main products are commercial jets whose number of passengers ranges from 30 to 120. Other segments whose participation is increasing during the last years are defense products and mainly executive jets.

Among the commercial aircraft developed during these three decades, the first aircraft to incorporate the DT philosophy was the EMB120 Brasilia, a 30-seat turboprop with a pressurized fuselage. At that time, Embraer already had experience for development of full-scale fatigue tests, but many in-house tools for fatigue and DT analysis were then developed, with help of the advances in numerical analysis tools. At the end of its development, he EMB-120 was certified to comply with DT requirements, including one-bay and two-bay crack arrest capability. Further, coupon test campaigns started for main aircraft materials, whose results have been upgraded and used for subsequent designs.

After the company privatization, the first product released was the ERJ-145 regional jet, a 50-seat twin jet with similar design when compared to EMB-120 (mainly concerning the fuselage cross section and forward fuselage characteristics), although with a higher flight ceiling and much more severe mission profiles. The ERJ-145 family of jets was designed to fully comply with FAA/EASA/RBHA* Part 25 DT requirements as well. Currently, there are

* FAA: Federal Aviation Administration, EASA: European Aviation Safety Agency, RBHA: Regulamentos Brasileiros de Homologação Aeronáutica.

about one thousand ERJ-135/140/145 aircraft in operation. The full-scale fatigue tests were completed in 2003.

Later the new 170/190 family of commercial aircraft from 70 to 120 seats was introduced. Embraer 170 first flight took place in 2002. Although all these aircraft are certified according to FAA/EASA/RBHA Part 25 requirements, comparing with the previous aircraft, some design and certification aspects of this new family of aircraft are worthy noting: (a) there was a significant increase in size and complexity of the airframe, and the structure *vs.* system integration required various specific analyses. To mention a simple example, many surface controls are based on fly-by-wire technology, such that specific investigations about the eventual influence of vibratory loads arising from actuators in the primary structure or in the actuator support fittings were required; (b) these aircraft were designed under risk partnership with other 16 aerospace companies, such that it became necessary to extend Embraer design criteria to many partners and (c) additional requirements were complied for many structural components, such as for example compliance of the aircraft structural integrity under sustained engine imbalance conditions.

There were significant improvements in the application of fatigue loads and in most of the fatigue and DT analysis methods during the 170/190 aircraft development. Some of these methods may be found in previous works[1], but will be briefly described along this text. Furthermore, new structural configurations were introduced, such as a non-circular fuselage cross-section (usually called a “double-bubble” section) and the use of shear joints for the lower wing-to-stub connection of the 190 aircraft. New materials were tested and applied, such as the 2524 aluminum alloy for the pressurized fuselage segments. All these advances were supported by an extensive validation test campaign whose main activities will be later described along these lines.

More recently, Embraer is focusing on the development of executive jets. The new Phenom 100/300 family of jets is under development and comprises the very light jet and light jet categories respectively. Although these jets will be certified under FAA/EASA /RBHA Part 23 requirements, which allow the aircraft manufacturer to choose among safe-life, fail-safe or DT approaches for certification, due to the company previous experience and reliance, it was decided to adopt the DT philosophy for certification of these aircraft. When compared to 170/190 family of jets, the Phenom jets are demanding less efforts for development, and their structure is being mostly designed in-house. However, one important issue to be mentioned here with respect Phenom 100/300 is a significant increase in application of composite parts for these aircraft. This subject will be later addressed in Section 4 of this document.

3 FATIGUE AND DAMAGE TOLERANCE EVALUATION

In this section, an outline of the fatigue and DT criteria and methods will be presented, departing from a brief discussion about the compliance of certification requirements. Later, a description of various tests referencing design of the aircraft described the previous section (with emphasis to 170/190) will be shown.

3.1 Certification Requirements and their Interpretation

Although structural requirements for fatigue and DT evaluation are defined by Aircraft Regulations in a couple of pages (whose information is complemented by means of Advisory Circulars), in practice there will be a massive amount of engineering work in order to comply with such requirements. The reasons for this may be related to the various ways that requirements can be interpreted, to the continuously evolving analysis methods, the large scatter of test data that has to be dealt, the relatively long duration before the full-scale fatigue test is completed and due to the characteristics of the work itself which is required to be implemented beyond the aircraft type design certification phase.

After several years of experience with the safe-life and fail-safe approaches, in order to establish a comprehensive safety aspect in an aircraft design, in the seventies the regulatory authorities decided to introduce requirements for DT evaluation of the structure. Such evaluation essentially intended to ensure that although a structure contains a certain amount of damage, it is still capable to withstand the specified loading (usually the limit load) until the damage is detected. Hence, it must be shown that there exists an ability to detect a probable damage before it grows to a critical size. Such evaluation includes determination of the possible location of damage initiation, the detectable crack size, and the subsequent damage propagation characteristics until critical conditions under typical loading spectra. It is also specifically required that the evaluation should be carried out by analysis supported by test evidence and available service experience of similar design. In fact, due to the known large scatter of the fatigue and DT data, obtaining test evidence to support the analysis becomes the interest not only to the certification authorities, but also to all engineers who are involved in the analysis. Test evidence can be obtained by performing test on several selected structural components. But obtaining test evidence from the full-scale fatigue test is deemed to be more representative. Nowadays it is considered mandatory for an aircraft manufacturer to perform a full-scale fatigue test for a newly designed aircraft.

3.2 Criteria Development

Besides the guidelines for compliance of certification requirements, in order to achieve the structure design objective it becomes mandatory for any aircraft manufacturer to develop internal criteria guidelines to support its own staff as well as for engineers working for partners that may be involved in the program development (that was the case of 170/190 development). Hence, during all recent Embraer developments, these criteria were set before any major fatigue and damage tolerance work was carried out. Based on these criteria the fatigue and damage tolerance tasks - such as preparation of method of analysis, determination of structure design features, load spectra development, fatigue and damage tolerance analysis and test planning - could be started.

3.3 Metallic Structures - Damage Tolerance Analysis Overview

The main items covered by the damage tolerant analysis methods for Embraer aircraft, according to related requirements, are: (a) stress intensity correction factor determination, (b) residual strength analysis and (c) crack propagation analysis. To accomplish this, in-house software, commercial software and a series of different sources have been used along the last twenty years. Some details about the analysis methods will be discussed in this section.

Load-Stress Transfer Functions: cyclic loads applied on structural components yield cyclic stresses to be used as input for the fatigue and damage tolerance analyses. Depending on the problem complexity, stress estimation for all cyclic loads may become very time-consuming and the process can be onerous or even unfeasible. A faster procedure is fitting an approximate function to a set of discrete stress-load data. This function, hereafter called a "Load-Stress Transfer Function" (LSTF), has experienced significant improvements in recent Embraer designs. It was verified that a multi-linear regression based on least square fittings result in good compromise criterion for the best-fit approximation. Such approach has been applied to the majority of components analyzed. Unit loads have been applied only to discrete points, such as engine pylons.

Once stresses are obtained, the cycles are extracted from the stress history and than counted. To accomplish this, a rainflow algorithm[2] was used. With this information available, the following steps were the fatigue evaluation and crack propagation analysis. The flowchart depicted in Figure 1 outlines the general method of analysis, where the so-called running loads represent results of many loading conditions to be used for static analysis.

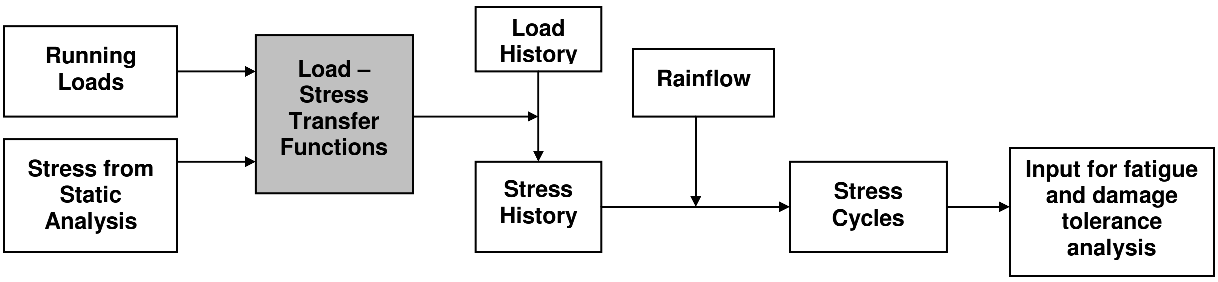

Figure 1: Overview of fatigue and DT analysis procedure

Stress Intensity Correction Factors: while some geometric configurations may be simplified to plane problems, allowing the use of more generic tools for analysis, in many occasions more sophisticated analysis methods become necessary in order to assure the correct representation of the problem. The main public domain sources used for the aircraft development are stress intensity factors handbooks[3,4] and more recently the Nasgro software database[5]. Many solutions available in Nasgro software are also extensively used for general cases (through cracks, surface cracks, corner cracks in plates), and for details and attachments (lugs, loaded pins, rows of rivets), except for cases when the influence of stiffeners must be taken into account. Geometry correction (β) factors for most of the built-in stiffened panel configurations are obtained by virtue of a set of in-house applications. For integrally stiffened panels, similar approaches and analysis tools are used. For specific cases, detailed finite element models corresponding to fuselage and wing panels have been developed.

Crack Growth Analysis: for most of the principal structural elements the crack propagation analysis is performed with in-house applications or with Nasgro software. Figure 2 is a simplified flowchart showing the input information that is necessary to run the crack propagation analysis, as well as the general process that is performed to obtain the residual strength and the crack propagation curves. The necessary input information is the material crack propagation (da/dN – ΔK) curve, load spectrum data converted to stress values by means of a load-stress transfer function (LSTF), stress intensity correction factors (SICF) and limit stress.

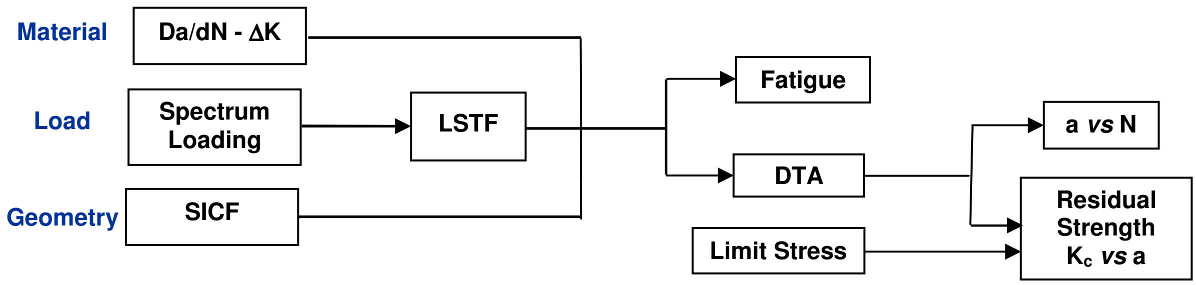

Figure 2: Overview of fatigue and DT analysis procedure

Residual Strength Analysis The residual strength analysis of cracked components is performed according to net section yield and fracture mechanics criteria. Verification of net section yield and crack instability is usually carried out with information supplied by in-house damage tolerance design software, Nasgro software and sources available from the literature. For the net section yielding in particular, many results are obtained by artificially introducing cracks in the finite element models and running the analysis for the cracked configuration. Most of the material fracture toughness information is supplied from Embraer materials database.

3.4 Metallic Structures - Tests for Validation of Analysis Methods

An increasing number of fatigue and DT development tests have been performed on a series of typical structural configurations for Embraer aircraft. The main purpose of such tests is to obtain advanced information on the structural behavior under fatigue loading and to perform analysis-test correlation in order to validate many of the methods of analysis. Although not formally presented by means of a "test pyramid"[6], Embraer aircraft development tests, when complemented by certification tests, obey a natural hierarchy departing from coupon tests until the full-scale fatigue test.

Table 1 shows a summary of the main Embraer 170/190 fatigue tests, their purpose, the number of specimens used and some remarks regarding each test, such as the application of certain test results for the aircraft certification. Landing gear certification tests, although performed under safe-life requirements, were not included in this table. The full-scale fatigue tests are underway, and the 170 test specimen, which will cycle for three design lives, has already completed its first life. Among the tests presented, the fuselage barrel fatigue test will be described with some level of detail in next section.

Name	Specimen Description	Number of Specimens	Purpose / Remarks
Coupon Fatigue Tests	Standard Specimens (ASTM E-466)	Thousands	New materials + results added to available database
Coupon Fracture Toughness Tests	Standard Specimens (ASTM E-399/561)	Hundreds	New materials + results added to available database
Coupon Crack Propagation Tests	Standard Specimens (ASTM E-647)	Hundreds	New materials + results added to available database
Fuselage Lap Joints and Butt Joints	Custom Specimens	13 Configurations / 9-20 Specimens per Configuration Total 185 Specimens	Applied for Certification
190 Wing – Stub Shear Joints	Custom Specimens	2 Configurations / Total 22 Specimens	Validation of Analysis Methods
Fuselage Structure Residual Strength & Crack Propagation	Large Built-in Flat Panel (Custom Specimens)	3	Validation of Analysis Methods
Wing Structure Residual Strength & Crack Propagation	Large Integrally Stiffened Flat Panel (Custom Specimen)	1	Validation of Analysis Methods
Fuselage Cross Beam to Machined Frame Joint Fatigue Test	Aircraft Actual Assembly Structure	1	Verification of Influence of PAX Loads
Fuselage Barrel Fatigue Test	Fuselage Assembly + Experimental Configurations	1	Fatigue, Propagation, Residual Strength and Repair Analysis
Horizontal Stabilizer Fatigue Test	Aircraft Sub-Structure	2	Certification Test
Full-Scale Fatigue Test	Aircraft Structure (except Horizontal Stabilizers)	2	Certification Test

Table 1: Summary of tests related to fatigue and DT for Embraer 170/190

3.5 Embraer 170 Fuselage Barrel Fatigue Test

The 170 fuselage barrel test article has a constant section of seven frame-bays long with dummy steel pressure bulkheads closing the barrel at both ends. The skin section at the steel pressure bulkhead interface to the test article is reinforced. Test set-up with a vertical position of the barrel was selected (see Figure 3). The test article was mounted on a rig and the top steel pressure bulkhead weight was compensated during the test.

The main objective of the barrel test was to verify the application of fuselage “double-bubble” cross-section design and the use of new damage tolerant material Al-2524-T3 in the ERJ-170 fuselage skin. The test article also contained ERJ-170 fuselage typical design features such as longitudinal and circumferential skin splices, floor cross-beam to machined-frame joints, machined-frame to sheet-frame joints, window cut-out, and shear clip connections. To reveal potential fatigue critical areas, the barrel test article was tested for four times or the equivalent design service life or 320,000 cycles.

Strain gages and displacement transducers were installed at different locations of the test article. Measurement at various loading fractions were carried out to assess the test performance and to verify whether good analysis-test correlation existed. Daily walk around and scheduled detail inspections for verification of possible cracks and occurrence of other types of damages in the test article were performed to determine safety for test continuation. Damages found during inspections were monitored and recorded. Damages considered to be critical were repaired before test continuation. A finite element model was created for the barrel and stress analysis was performed. The analysis results were then compared to the strain gage and displacement transducer measurement results. In general, the analysis results showed more conservative when compared to test results.

After the fatigue test was completed, and with a few non-significant damages reported, the test program continued with crack growth and tests during 80,000 pressurization cycles or an equivalent of 1 design life. This crack propagation period was divided in two phases (40,000 cycles each), namely Phase I and II. For each phase, prior to the test execution new strain gages and artificial damages were introduced at different locations of the test article. The damages were selected based on the consideration that they would represent typical crack growth scenarios and were located sufficiently away from each other such that the influence due to its individual presence would not create significant load path changes in the surrounding area. For Phase I, 12 damages were artificially introduced, while for Phase II, with the knowledge from previous crack growth results some cracks that showed propagation were kept while other cracks were artificially extended and some primary members were failed in order to simulate crack propagation for secondary members (such as cracks growing through the skin, departing from a broken stiffener). Figure 4 shows an outline of the induced damages applied during Phase I.

All crack scenarios were compared with previous predictions. While some cracks showed nearly no evolution (showing that analysis predictions were eventually overly conservative), some scenarios such as skin cracks departing from the middle of a bay, skin through cracks departing from a broken frame and corner cracks departing from a window cutout allowed a good correlation with analysis methods.

Regarding analysis methods for skin cracks and when bulging effects were significant, nonlinear analysis and application of the MCCI approach[7,8] showed a quite good agreement, while for corner cracks the β values obtained from Nasgro program showed high confidence.

Figure 3: Overview of 170 fuselage barrel fatigue test specimen

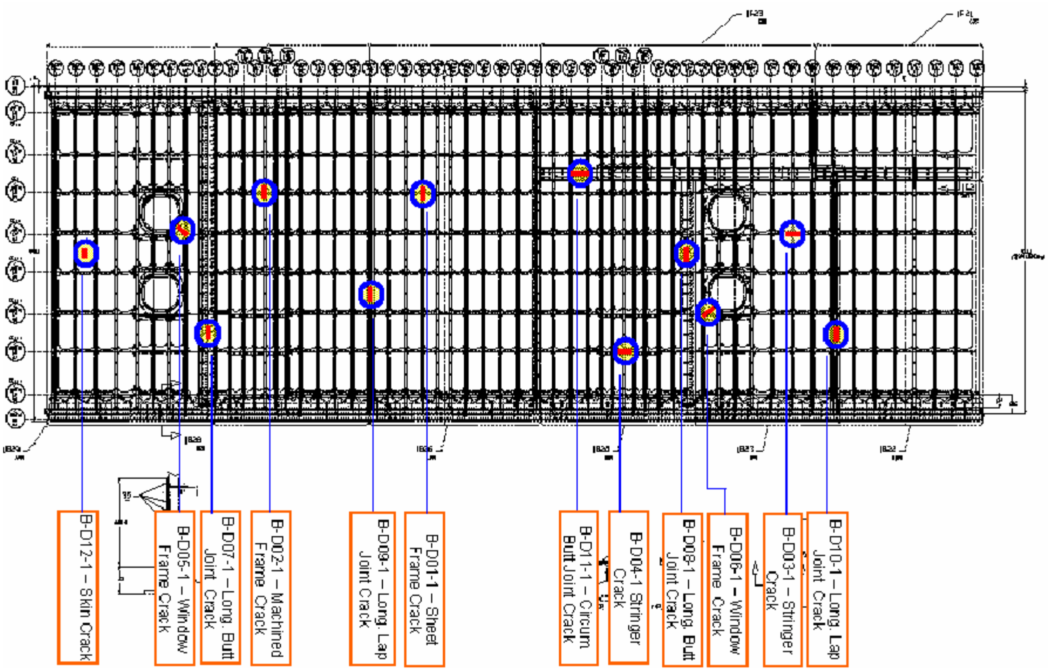

Figure 4 – Outline of induced damages for Phase I

4 ADVANCES IN DAMAGE TOLERANCE FOR COMPOSITE STRUCTURES

4.1 A brief history of composites application in Embraer aircraft

The application of composite materials at Embraer dates from 1970, with the EMB-110 Bandeirante aircraft development, where only non-structural components, fairings in hand wet lay-up process, were made with FRP (Fiber Reinforced Plastics). Structural composite technology was later introduced in 1982 with EMB-120 Brasilia aircraft, with fairings, leading edges and flaps. The beginning of integrated structures, next step in the middle of the eigthies, was introduced by the MD-11 Composite Outboard Flap program, that required significant investments for new installations and equipment. Structural bonding was introduced with AMX, a military aircraft and aluminum and fiber-glass/nomex core was introduced in the wing tip for 777 aircraft in the same year.

Structural composite parts became more integrated and complex in subsequent programs. In the nineties, ERJ 145 aircraft with ailerons, spoilers, flaps, tabs and shrouds. S-92A Sykorsky helicopter with integrated box structure for fuel. The great changes in terms of component integration took place with the project of ALX-314 rudder. Regarding the designs of the present decade, Embraer 170/190 rudder and elevator were made with integrated composites. For Embraer Phenom family of executive jets the vertical tail is being included with a design totally integrated, and a thermoplastic application. An outline of Embraer composite material evolution is shown in Figure 5.

4.2 Composite Static, Fatigue and Damage Tolerance Analysis

A particular component of the structure may be subjected to many different types of material degradation, processability and variability effects (environmental and cyclic loading) which must be accounted for to ensure the structural integrity of the component, and many different types of damage (namely, fatigue, corrosion, and accidental) which must be detected and repaired before it becomes catastrophic[9]. This is accomplished by: (a) adhering to proven static, fatigue, and damage tolerance analysis methods which have been test validated; (b) ensuring a basis for fabricating reproducible and reliable structures, and (c) prescribing inspections that will detect any damage before it becomes critical.

Composite material components with allowable damages in the critical regions must sustain ultimate loads for 3 seconds, when the occurrences of failures such as delaminations, disbonds and excessive deflections must be verified. The size of the damages before tests shall be verified after the limit and ultimate loading tests in order to match the so-called “non-growth” concept of damage. Fatigue and DT evaluations for composite structures can be based on fatigue (Safe-Life) or DT (Residual Strength) substantiation approaches. For Embraer composite structural components, the fatigue approach is usually adopted because analytical damage growth methods are considered not yet reliable. For the fatigue approach, substantiation should be accomplished by component fatigue tests or by analysis supported by test evidence which accounts for the effects of the anticipated environment extremes.

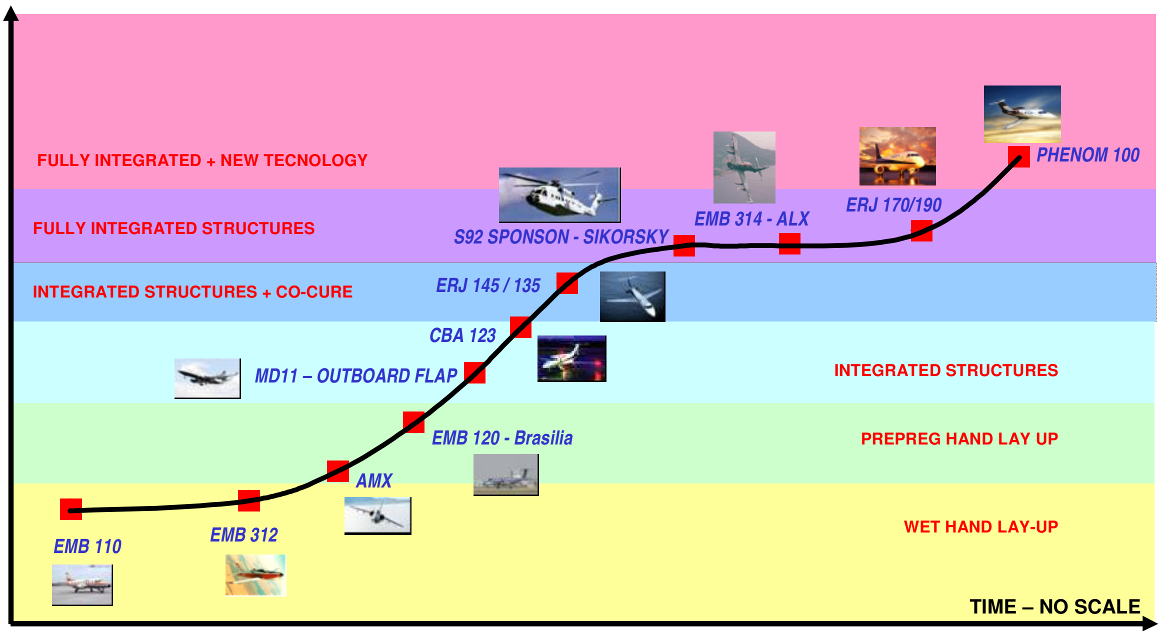

Figure 5 – Evolution of composite applications in Embraer aircraft

The nature and extent of tests on complete structures, components or subcomponents, will depend upon applicable previous design and structural tests, and service experience with similar structures.

Fatigue analysis must demonstrate that the composite material component, subcomponent or coupon can withstand through two lives without failures, while the DT analysis must demonstrate that the composite material component or subcomponent or coupon can withstand two lives, without damage growth and failures.

Fatigue "load enhancement factors" (taking into account the material processability and variability dispersions) must be applied into the fatigue loads. When considering the effects of material processability and variability factor or load enhancement factors on the repeated load behavior of composite structures, a factor related to loading is preferred to a factor related to life. Usually a load enhancement factor of 1.15 is applied to enable two lifetimes during test in order to represent one service lifetime with a B-Basis relationship based on variability in flaw growth[10].

Environmental effects should be investigated with respect to fatigue and DT. The fatigue and DT tests may be performed with an "environment degradation factor" unless the components or subcomponents are set in climate chambers to simulate the adverse moisture absorption and temperature conditions.

The composite materials structures are susceptible to two basic types of damage that can be grouped by their occurrence: manufacturing damages or in-service damages. Manufacturing damages, such as delaminations, scratches, disbonding, nicks, etc, must always be considered. The type and number of such damages may be induced in the specimen at discretion of the manufacturer in order to comply with the worst scenarios, with the most severe combination of damages from the different sources. A preliminary survey on impact damages must be performed prior to the certification campaign in order to provide sufficient results to allow a proper selection of the most critical energy levels and locations. It is recommended to induce at least barely visible impact damages at each one of the critical regions in order to substantiate structural integrity in the presence of undetectable damages.

Non-visible damages might occur early in the aircraft's life and remain undetected during subsequent service inspections. Thus, unless detection is ensured by more discriminating inspection procedures, the damage or defect must be assumed to be present for the entire life of the aircraft. Hence, non-visible or barely visible damages specimens should be cycled at least two airplane lives and afterward should generate a residual strength equal or higher than the ultimate load. Further, visible damaged specimens should be cycled during at least two intervals of inspection of the component and afterward should present a residual strength level equal to or higher than limit loads specified.

After fatigue tests are performed, damaged regions should be inspected to check the "no-growth concept", which encompasses the area and depth, including delaminations around it.

Allowable damages incorporated in the MRB (Material Review Boarding) may be defined, proposed and tested statically up to ultimate load and DT tested when intervals inspections and a final procedure to repair are established. The type of damage and the type of inspection (ultra-sound, tap test, x-ray, etc) must be defined.

When applicable, all damages may be simultaneously proposed and substantiated in the DT and residual strength tests and/or analysis.

Repairs can be introduced in the specimen for static and fatigue and DT analysis. Two types of repairs can be provided: cosmetic repairs and structural repairs. It must be demonstrated that the structure with repairs in the most critical locations can withstand the static test and the fatigue test including environment cyclic degradation factor and the material processability and variability factor when new materials are used in the repairs.

5 STRUCTURAL HEALTH MONITORING

Structural Health Monitoring (SHM) is a sensing network that assesses the aircraft structural integrity and automatically detects damages in the structure. Once installed, the SHM system works monitoring the structure flight-by-flight and detecting damages automatically without human interference (areas of difficult access can be monitored without disassembly). With SHM application, damages are detected as soon as damage grows beyond the detection threshold, what means more time for repairing before it becomes critical.

Improving Structural Efficiency using SHM: aircraft weight plays a major role on aircraft costs and in the direct operational costs since it has impact from the manufacturing to operation. Due to this fact it is understandable the current effort to increase the structural efficiency and decrease the structural weight.

Nowadays several aeronautical structures are designed under the DT philosophy, where the structure is designed to behave as multi-load path or single-load path with slow crack propagation. One of the major benefits of applying SHM in early stages of development is to change this scenario. With application of SHM at early development phase the design philosophy can be changed enabling to improve structural efficiency, decreasing the weight and the level of complexity of the structure. Other benefits related to SHM application are: increasing of time for inspection intervals, improvement of aircraft availability and scheduled repairs (due to earlier damage detection).

In metallic structures the SHM system can be applied to reduce high redundancy and to monitor locations where damage tolerance scenarios are severe, eliminating the necessity to consider the primary element failed with propagation on the secondary element. In composite structures the SHM can be applied to detect smaller damages than current visual inspections what will lead to less severe analyses scenarios and consequently to weight saving.

Certification Issues: the following issues regarding SHM and certification must be considered: (a) how to prove to certification authorities that SHM systems are reliable as traditional methods of inspection, (b) aspects of installation, operation and maintenance of SHM systems, (c) compliance with FAA FAR §25.1309 requirements (also referring to AC 25.1309-1A and AC 20-115B), (d) the ability to fly with known cracks, as smaller damages are prematurely detected, (e) verification of the necessity to apply ultimate loads with damages on composites, once all damages are readily detected by the system.

Furthermore, the aircraft manufacturer will face many challenges, such as: (a) to ensure that SHM system is reliable along all aircraft life and (b) tasks to be performed after damage detection (damage monitoring, repairing), to say the least.

6 CONCLUDING REMARKS

This work presented an overview of Embraer advances in DT analysis and design during these years. While most of the analysis methods and tests described are applicable to metallic structures, there have been many advances regarding composite materials technologies. Issues about composites were here described focusing the main tasks nedded in order to comply with all requirements for certification. The SHM technology is also being investigated and was briefly discussed, but many questions about the applications of this technology in actual aircraft design and their impact mainly in future certification requirements still remain.

REFERENCES

[1] Gonçalves, W., Pramono, A., Chaves, C.E., Embraer New Family of Jets – Meeting the Current Fatigue and Damage Tolerance Requirements, 21st ICAF Symposium, June 2003, Lucerne, Switzerland.

[2] Downing, S.D., Socie, D.F., “Simple Rainflow Counting Algorithms, International Journal of Fracture, January, 1982.

[3] Rook, D.P., Cartwright, D.J., “Compendium of Stress Intensity Factors”, 1976.

[4] Tada, H. “The Stress Analysis of Cracks Handbook”, 1973.

[5] NASGRO Crack Propagation Analysis Software, NASA Johnson Space Center and Southwest Research Institute, 2002.

[6] Schmidt, H-J, Schmidt-Brandecker, B. Aerostruc Fatigue and Damage Tolerance Course, 2006.

[7] Rahman, A., Bakuckas, J.G., Tan, P.W., Bigelow, C.A., "Bulging Effects of Longitudinal Cracks in Repairs", ASIP 2001, December, 2001, Williamsburg-VA.

[8] Viz, M.J., Potyondi, D.O., Zehnder, A.T., International Journal of Fracture, Vol. 72, pp. 21-38, 1995.

[9] Arakaki, F. K. Composite Static, Fatigue and Damage Tolerance Structural Design Criteria, Embraer Internal Report, 2003.

[10] MIL-HDBK-17-3F – Polymer Matrix Composites Material Usage, Design, and Analysis – Department of Defense Handbook - Volume 3 of 5 – 2002.