Chair:
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DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

The aim of the course is the acquisition of the high level competence required to carry out innovative research and/or state of the art advanced applications in industries, public or private research centers, Universities or public and service companies in the area of aerospace engineering, including all the fields associated to it. The level of the course allows the graduates to compete in a European and international environment.
The course is three years long, requiring 180 credit points (ECTS), including possible study-abroad periods and internships in private or public institutions. The program and credits are divided in three main educational areas:

1. Main courses (30 credits), during the first year: courses examining fundamental subjects (problems, theories and methods) of the scientific research in the disciplinary areas involved;
2. Elective courses and training on specific themes (30 credits), gained in the second year: specific and personalized educational programs aimed at a more deep overall knowledge and to master the techniques adequate for the subsequent development of the doctoral thesis, plus seminars focused on specific and advanced methods;
3. Development of the Doctoral Thesis (120 credits): the thesis is developed within the Department or, in some cases, in other institutions, in close contact with the Department. The thesis is started immediately (20 credits in the first year), and developed in the second (40 credits) and third year (60 credits) of the doctoral program.

If the candidate has a background curriculum lacking some introductory knowledge required for the Doctorate, the Faculty will ask to recover such knowledge, with the assistance of the tutor. The same Faculty will verify afterward the overcoming of whatever was lacking during the annual meeting of admission to the second year of the course.
The course program related to point 1 does not follow a rigid scheme. So, besides widening the basic scientific culture of the candidate, it will take into consideration also the objectives and the core topics of the candidate's thesis. Again the program outlined at points 2 and 3 will try to consider general cultural requirements as well as what is deemed to be more specifically related to thesis subject, as agreed between the candidate and the Faculty. For the activities of type 2 and 3 a study period in a foreign country is allowed, even strongly suggested perhaps. Its duration should range from a few weeks up to one and a half years. The related activities should be carried out in well known and qualified scientific institutions (universities, research centers, etc.), and well contribute to the cultural and scientific achievements of the research.
Due to the amplitude and interdisciplinarity of the aerospace sector, the professional skills achievable will span a wide area and not cover just a specific topic. The educational goals will create high level specialists in the domains of: helicopters and rotary winged vehicles, fixed winged vehicles and space vehicles.
In this context, a more specific competence can be gained either in a single or in the integration of special subjects such as: dynamics and control, fluid mechanics, systems and equipment, flight mechanics, passive structural safety, intelligent and automated systems, structures and materials.
In this respect, some examples of professional skills achieved in the course of the past 24 years of doctoral program are here reported:

- expert in computational and/or experimental fluid mechanics, with capabilities to develop methods and models for both aerospace applications and generic vehicles;
- expert in active and passive control of the dynamics of aerospace structures, integrating global and subsystem design;
- expert in active and passive structural safety of vehicles, both aerospace and non-aerospace;
- expert in vibration and noise control, including modeling analysis, system design and implementation of specific subsystems;
- expert in the dynamics and control of aerospace vehicles and related operational missions;
- expert in integrated design of complex aerospace systems.

Since its foundation, 24 years ago, the doctoral course on Aerospace Engineering graduated more than 70 PhDs.

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AEROSERVOELASTIC MODELING AND CONTROL IN PRESENCE OF FREEPLAY

Sebastiano Fichera - Supervisor: **Prof. Sergio Ricci**

Abstract

Freeplay is one of the most important nonlinearities that affect the control surfaces of the aircrafts; it can induce flutter phenomena and limit the performances of the same airplane. To investigate the effect of control surface freeplay, an aeroelastic wind tunnel model of a T-tail was developed. A variable amplitude freeplay was introduced in the control chain by a specifically designed linkage. The numerical models were built, according to the modern aeroelastic approach, describing the dynamics of the tail by a state space system with a lumped nonlinearity.

Introduction

The research on nonlinear aeroelasticity and, in particular, on control surface freeplay, is motivated by the significant number of cases known in the literature of aircrafts that have experienced Limit Cycle Oscillations (LCO) caused by it. In fact, freeplay in the control chains may arise as consequence of many factors, including wear of the parts during the aircrafts life. In order to perform numerical and experimental investigations, a wind tunnel model of a T-tail equipped with the rudder and the control system was designed and manufactured.

Experimental rig

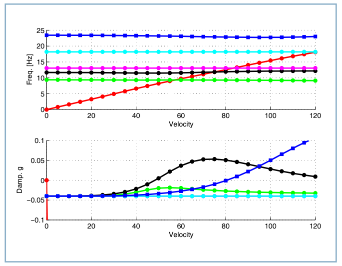
The T-tail unit considered in this work is the one of the X-DIA, an aeroelastic model representative of a nonconventional three surfaces regional jet (called Target Aircraft), intensively investigated in the last few years at the Department of Aerospace Science and Technology of Politecnico di Milano.

1. T-tail aeroelastically scaled wind tunnel model.

The model is composed by dynamically scaled aluminium alloy spars, which are inserted in a series of aerodynamic sectors made by styrofoam covered with a carbon fiber skins. In order to have a variable amplitude freeplay, a mechanism was introduced in the control chain between the actuator and the rudder; it is composed by a rigid linkage connected with the rudder and that ends with a pin that is slipped into a fork connected with the gear of the electric motor used to actuate the movable surface.

Numerical models

The T-tail State Space (SS) matrices are built using the structural Finite Element model and the aerodynamic DLM, both developed in MSC.Nastran. The SS model is a Reduced Order Model (ROM) with the basis made by the free surface rigid mode plus the significant elastic modes. The frequency domain aerodynamic matrix is transformed into a finite state space realization by using Roger's algorithm.



2. V-g V-f diagrams.

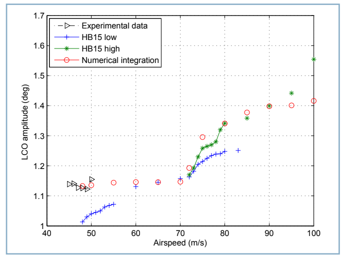
The linear aeroelastic behaviour of the model is shown in the numerical V-g/V-f flutter diagrams (see figure 2) computed with the free surface. The first (11.63 Hz) and the second (23.22 Hz) fin bending modes cross the zero damping line respectively at 47 m/s and 78 m/s.
The direct integrated (time marching) model was designed by assembling the structural and the aerodynamic state space systems. The nonlinearity was introduced as a lumped element in the feedback loop by using a penalty function approach. The model is time-varying velocity in order to be able to reproduce the effect of an increase (or decrease) of the free stream speed during the simulation.
An High Order Harmonic Balance (HOHB) was developed as well. The method approximates the response of a given nonlinear system, which is undergoing LCOs, with a Fourier series leading to a set of nonlinear algebraic equations that can be solved by an iterative method.
Once the numerical models were validated, an alternative control algorithm for vibration reduction was developed.

Experimental tests

Wind tunnel tests were conducted on the experimental rig in order to tune the FE model and to validate both the numerical models. The acquisition and control of the system was handled by an hard real time tool called R-TAI.

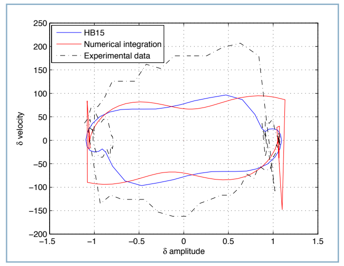
Results

The experimental results, as well as the numerical, show the typical trends for a nonlinear aeroelastic model.
Figure 3 shows the LCO amplitude trend increasing the airspeed. The HOHB, as the



3. LCO amplitude, NI - Experimental - HOHB comparison ±1°.

numerical integrated model and the experimental data, depicts two regions: the first is the consequence of the flutter of the first bending mode, while the second is a combination of the first and the second mode flutters.



4. LCO portraits at 50 m/s, NI - Experimental - HOHB comparison ±1°.

The portraits comparisons are shown in figure 4. It is possible to see a good agreement of the trends even if the HOHB is not completely able to catch the peaks due to the foldings of freeplay stiffness.

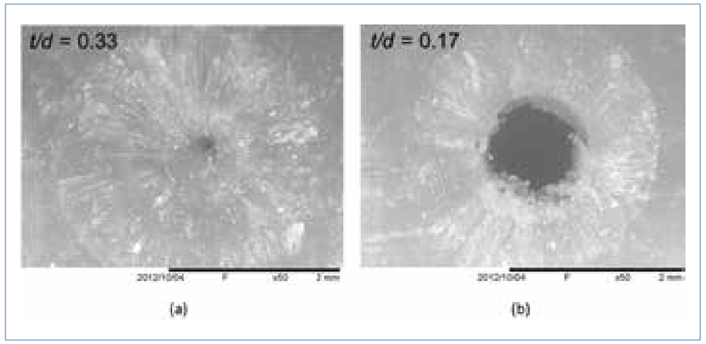
Conclusion

This work presented different methods for the study of nonlinear systems. The results of a numerical integrated model and an HOHB procedure are compared with experimental data for a T-tail in presence of freeplay nonlinearity in the rudder's control chain. The methods shown to be able to catch the correct solution for the nonlinear system.

SELF-HEALING IONOMER BASED SYSTEMS FOR AEROSPACE APPLICATIONS

Antonio Mattia Grande - Supervisor: **Luca Di Landro**

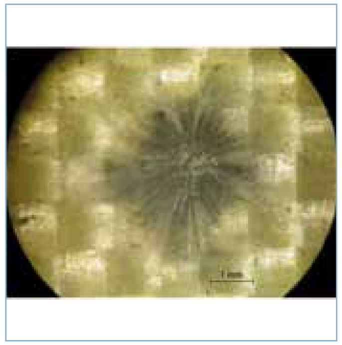
In recent years one of the most attractive topics in material science is the study of self-healing materials. Many researchers are working on this matter and different approaches have been developed to obtain new polymeric materials with self-healing ability.
Thermoplastic polymers as ethylene-co-methacrylic acid (EMAA) ionomers have shown a self-healing behaviour after high-energy impacts, however the exact relationship between the polymer physical properties and the repairing efficiency is still unclear.
In this research the self-healing feature exhibited by this particular class of polymers has been extensively studied and critical parameters for an efficient damage repair were identified. In particular, impact experiments were performed on sodium based EMAA ionomers at projectile velocity ranging from 180 m/s up to 4 km/s. After all experiments, the healing efficiency was evaluated by applying a pressure gradient. Hole closure was tested both by following vacuum decay and by checking for possible flow of a fluid droplet placed at the damage zone with the applied pressure difference. A morphology analysis of the impact zones was also made observing all samples by scanning electron



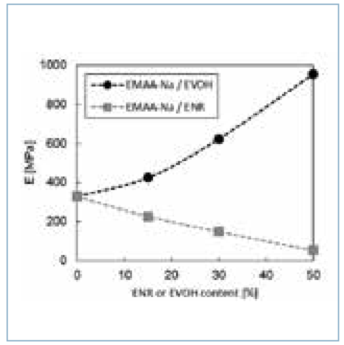
1. SEM micrographs of EMAA projectile entry side in a repaired sample (a) and unrepaired sample (b), tested at low impact velocity (180 m/s).

microscope (SEM) both in the bullet entrance and exit sides. The results showed a different behaviour of the materials subjected to impacts at different rates. At low bullet speed, a full melting process does not seems to take place; however, SEM analysis revealed small melted zones in the impact site. Furthermore, the self-healing behaviour was detected up to a specific sample thickness/ projectile diameter ratio (t/d), as shown in Figure 1. Similar results were obtained in tests at mid bullet speed (400 m/s); in this case an extension of the melted zone was also observed. Conversely, in hypervelocity tests, a completely different morphology of the damaged areas was detected. Melting of the material in the impact zones occurred still maintaining in some condition an effective self-healing behaviour. The promising self-healing response even after hypervelocity impact tests suggests to consider the use of ionomers in multilayer systems for aerospace applications.

Furthermore, series of physical experiments aimed to the understanding of the correlation between polymer structure/ properties and self-healing behaviour were carried out.
In order to get information about the relevance of thermal effects due to viscoplastic dissipation, tensile tests were performed at different strain rates/temperatures and observed with an infrared camera in order to assess the variation of temperature during stretching. Even though strain rates employed in tensile tests were consistently lower than those experienced by the



2. Optical image of EMAA-Na/aramid fabric multilayer system after high-energy impact.



3. Evolution of tensile modulus in the prepared ionomer binary blends.

material during bullet impact a remarkable temperature increase was observed, which suggests a strong interdependence between thermal/mechanical behaviour and healing capacity.
In view of an extension of the property ranges required in different potential applications, new polymeric systems have been prepared and tested under different impact conditions. In particular multilayer systems incorporating one or more self-healing layers and polymeric blends, both based on a sodium ethylene-co-methacrylic acid ionomer, were designed.
The self-healing behaviour of the various ionomer based multilayer systems was investigated and four different configurations were manufactured and tested coupling the ionomer with an aramid fabric, a carbon foam, a carbon fibre reinforced composite or a polymeric honeycomb.
Regarding blends, a semi-crystalline poly(vinyl alcohol-co-ethylene) polymer (EVOH) or an epoxidized natural rubber (ENR) were chosen as secondary component for the sodium based EMAA blends. The addition of a second component to an ionomer base deeply change its physical and mechanical properties, thus providing materials with selectable performances over a wide range (Figure 3). After impact test, all the samples show at least partial reduction of the punctured surface but, interestingly, all EMAA-Na/ ENR blends exhibited complete healing; EMAA-30/EVOH blends up to 30% EVOH also showed an efficient self-healing behaviour.

These new results underline how ionomer based materials may find employment in multifunctional structures for space applications to heal high velocity impact damage, indeed, the design of a space structure must take into account the high probability of impact with micrometeoroids or space debris during the operational life of the space system. This opportunity could highly increase the reliability of future spacecrafts allowing a longer duration of mission for deep space exploration and a safer environment for astronauts against pressure leakage.

DESIGN, SIMULATION, MANAGEMENT AND CONTROL OF A COOPERATIVE DISTRIBUTED EARTH-OBSERVATION SATELLITE SYSTEM

Riccardo Lombardi - Supervisor: **Prof. Michèle Lavagna**

The research presented in this thesis explores the potential of, and develops a framework for, the application of fractionated satellite systems to science-dedicated Earth observation missions.
The label fractioned satellite highlights the physical distribution of the functionalities of the spacecraft (e.g. power generation, telecommunication, etc.) over a cluster of orbiting elements.
The resultant distributed system can be seen as a free-flying payload supported by free-flying service modules. In general, the paradigm shift towards using a multiple-satellite cluster has been fuelled by the perceived advantages of increased robustness, greater flexibility, and in order to accomplish the large-scale geometries imposed by specific science objectives.
There are many ways to implement the fractionation; by interpreting literally the idea, it is possible to de-couple entirely the subsystems using different modules thus creating a completely heterogeneous system. Nonetheless a complete functional decomposition with the current technology not only is impractical, it is physically impossible.
Every module must be able to provide by itself to basic functionality like power distribution or thermal control as well as structural integrity, thus the most logic configuration is a combination of shared resources and module-owned properties.
Apart from design issue, operation phase poses a new class of challenges by itself: the introduction of the fractionated approach requires a new methodology to control and coordinate the spacecraft system efforts in order to guarantee that remote resources will be gathered and distributed according to the satellites needs; furthermore the proposed concept has been thought to be scalable to large systems, possibly involving tenth of different elements.
The operational costs of monitoring and commanding a large fleet of close-orbiting satellites is likely to be unreasonable unless the on-board software is sufficiently autonomous, robust, and re-configurable.
As no satellites with fractioned architecture actually exist, frameworks tailored to address this unique concept have to be developed and, in order to compare the performances of the fractionated system with the equivalent monolithic satellite, objective quantities have to be evaluated, as the total cost including development and research, ground support, construction, integration and launch.
For the design phase, several topics have been investigated, ranging from automated satellite design, analysis and evaluation of distributed resources and optimisation techniques.
The first step has been the creation and validation of a monolithic-satellite aimed design tool able to assemble science-dedicated LEO satellite with a reasonable degree of confidence given informations about payload, mission and additional constraints like specific launchers or ground stations.
Fundamental requirements for the tool are the capacities to estimate satellites' power and mass budgets, part list and reliability.
Then the capacity to handle fractioned resources has been introduced by requirements and hardware modifications; considered shared resources are power generation and transfer by means of lasers, distributed communication and data processing and remote attitude determination.
Finally a particle based optimisation method has been used to evaluate whose combination of number of satellites, shared resources and mission requirements, could exhibit highest fitness values.
The optimisation algorithm highlighted that only distributed communication and data handling could, in some cases, allow for a cost reduction whereas the reduced efficiency of the present day wireless energy transmission methods penalises this approach.
Analogously the shared attitude determination is not attractive due its complex implementation without significant performances improvement.
The operation phase is aimed at simulate the behaviour of the satellite during its orbit; due to the particular features introduced by the fractionation, it has been modelled to consider the additional effects introduced by fractionation, mainly the fact that resources and users are not necessarily co-located within the same satellite thus a strategy to enable and control the remote access to means must be provided.
The capacity to replicate a single spacecraft has been the first step; included elements in the simulation framework are orbit and attitude evolution including effects due to disturbances and controls, power subsystem, with evaluations of generated, consumed and available power; communication subsystems, including long and short range connections; thermal subsystem, able to evaluate the satellite components temperature and to control them using heaters; propulsion subsystem; attitude control system with simplified actuator models whose used power and propellant affect power and propulsion systems respectively; GNC.
Considerable attention has been given to subsystems mutual influences, identified through a priory analysis.
Additional features to account for multiple satellite simulations have been included, as a cooperation model for communication, relative attitude and position evaluation and the upgrade of GNC algorithm to manage several spacecraft.
In particular a game theory based schema has been used to coordinate satellites efforts and share autonomously the communication resources.
Optimisation and simulated operation phase highlighted possible advantages and drawbacks of the fractionated concept: unlike the remote power transfer and attitude determination, shared communications and data handling could allow a cost reduction and performances improvement.
However the already commissioned data relay systems could achieve similar objectives thus reducing the need for on-purpose communication modules and making the traditional configuration, with a certain

1. Fractioned Satellite Concept (image courtesy of DARPA)

margin, the optimal solution when costs are used to evaluate the performances.
A comparison of different configurations to achieve extended design life also resulted that convectional approach takes advantage from the limited increase in launch and operation costs whereas fractioned satellites not only have to exploit multiple launchers but their construction cost is significantly influenced by research and development expenses.
Further studies will address the development of an increased accuracy cost model influenced by failure probability and the improvement of design and simulation frameworks.

MODEL ORDER REDUCTION FOR COMPUTATIONAL AEROSERVOELASTICITY

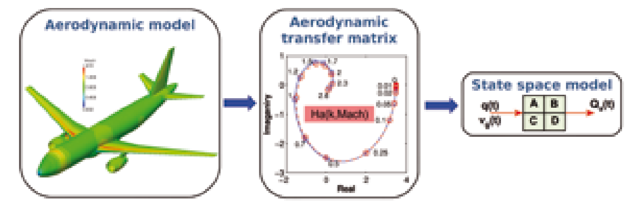
Matteo Ripepi - Supervisor: **Paolo Mantegazza**

The thesis presents a few approaches to reduced order models within the framework of computational aeroservoelasticity. The advent and development of high-performance computing is requiring, more and more, procedures and techniques aimed at reducing the computational effort of high-fidelity high-dimensional computational fluid dynamic based aeroelastic systems, in order to afford accurate and fast evaluation of the load databases essential for aircraft design. The adoption of reduced order modeling techniques represents a promising approach to achieve this goal. The generation of low-dimensional models preserving the main behavior and the features of the original problem may be realized in many ways.

In the thesis, the model order reduction of the aerodynamic subsystem, aimed at obtaining accurate aerodynamic generalized forces, is addressed through the use of both identification techniques as well as projection methods. Linearized aerodynamic models are at first considered, both in a state-space form or through their transfer matrix representation. A Petrov-Galërkin approach is developed where the linearized aerodynamic subsystem is projected onto left/right Schur subspaces. Global reduced bases are obtained from an eigenanalysis of the state space matrices of the system. The method proposes a Schur-based formulation, completely decoupling the low and fast subspaces of the system spectrum. This allows an efficient residualization of the fast dynamic, contributing to more accurate reduced order models. The drawback of the eigenbased model reduction for an aerodynamic subsystem is that the dominant spectrum becomes more and more rich as the computational grid is refined. Therefore a proper selection of the aerodynamic modes must be devised in order to avoid retaining in the subspace many worthless eigenvectors which would make the reduced model larger than necessary. Hence, instead of focusing on the dominant state dynamics, the proposed method try to complements the low frequency Schur subspace by further mapping the input-output behavior, which is the key parameter to be captured by the reduced model. This is achieved through a dominant pole criterion plus, the controllability and observability, thus selecting the global modes which are likely to contribute more to the input-output relation of the aerodynamic model.

Differently, identification methods are more suitable whenever the aerodynamic subsystem is available through its transfer matrices, related to structural motions and gusts, thus requiring the identification of an asymptotically stable finite state aerodynamic subsystem. To such an aim the thesis develops an improved rational matrix approximation, combining three nonlinear least squares identification techniques with a system reduction based on a double dynamic residualization, which maintains an accurate fitting up to relatively high frequencies. It significantly improves a previous matrix fraction description formulation through: the adoption of a more appropriate performance index, the avoidance of a tweaked iterated weighting to ensure the identification of a stable model, the obtainment of either lower order models for an assigned precision or a better fitting for a given order, and the omission of a costly final constrained nonlinear optimization.

An alternative gust formulation is also proposed which approximates the gust profile traveling towards the aircraft using a series of disturbance velocity shape functions fixed in space, named gust modes. The approach, reconstructing generalized gust forces through these special structural motion like modes, makes it possible to determine a gust response even without the usual gust penetration model. In the time domain an impulse response is then obtained from each of the gust modes, so recovering the aerodynamic load response using a convolution technique. The traveling contribution of the gust running towards the aerodynamic model, as well as the true gust shape profile, is devolved to generalized coordinates calculated as a post-processing through a least squares interpolation of the gust profile. The approach avoids building an aerodynamic reduced model for each different gust profile case considered in the loads database, thus reducing the overall number of gust simulations required in the gust loads analysis process. The procedure has proved its effectiveness in carrying out aerodynamic transfer matrices obtained from low fidelity models (e.g. Theodorsen theory, strip theory, double-lattice method), as well as reconstructing loads responses of high-fidelity aerodynamic models, based on Euler equation, for complete aircraft cases of industrial relevance.



1. Identification procedure

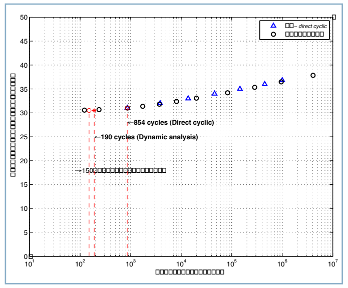
In order to include nonlinear effects, necessary to better predict important aeroelastic and aerodynamic phenomena (e.g. limit cycle oscillations), reduction techniques for nonlinear systems have been also developed. A method identifying a nonlinear state-space model approximating the behavior of nonlinear aeroelastic systems from input-output time histories training signals is proposed. The procedure carries out a linear state space using the matrix fraction description, which is then extended with polynomials nonlinear terms in the state and the input, whose unknown coefficient matrices are obtained through a least-squares fitting.

Alternatively, within projection based framework, a recently developed model reduction approach for the efficient and fast solution of nonlinear finite-element based dynamical systems is exploited for nonlinear aeroelastic systems. Such a model reduction relies on a Galërkin projection of the high-dimensional dynamical system onto a set of Proper Orthogonal Decomposition modes, followed by an hyper-reduction carried out with a weighted evaluation of the nonlinear terms onto a subset of the finite elements. The weights, taking into account for the contribution of the discarded elements, are precomputed using a non-negative least-squares problem minimizing the discrepancy between the nonlinear term and its approximation onto the elements subset. This hyper-reduction step enables an online evaluation of the reduced-order model that does not scale with the large dimension of the original problem. Afterwards a parametric reduced order model is obtained using a global reduced basis carried out by considering reduced bases computed after simulating the system on a set of parameters.

DAMAGE TOLERANCE OF COMPOSITE STIFFENED STRUCTURES UNDER POST-BUCKLING CONDITIONS

Duo Zou - Supervisor: **Prof. Chiara Bisagni**

Composite stiffened panels have been extensively used in primary aerospace applications over the past decades, due to their high specific strength and stiffness to weight ratios. In spite of their apparent superiority to metals, such as the possibilities to integrate parts and reduce the number of fasteners, the susceptibility of composite stiffened structures to interface delamination has been proven to be critical. Delamination is one of the most important mechanisms of damage in laminated fiber-reinforced composites because their interlaminar strengths are relatively weak. In stiffened aeronautical structures, the main cause of the delamination is usually introduced by foreign object impacts or compressive loading. Under the latter condition, the buckling of the skin and stiffener exhibits opposite buckling mode shapes, and so that the delamination occurs in the interface. Moreover, most of the in-service structures are under cyclic loading, the delamination can appear when the post-buckling has been reached thousands of times. It is therefore important to investigate the onset of the critical delamination under single static loading and develop methods to characterize the onset and propagation of the delamination under cyclic loading.



1. Predicted number of cycles to fatigue delamination onset.

The research presented in this dissertation expands the work on static and fatigue delamination of composite laminates from 2-dimensional unidirectional shells to 3-dimensional stiffened panels. The damage tolerance behavior of conventional stiffened panel is investigated based on the fracture mechanics and structural analyses carried out with finite element program ABAQUS. Two different approaches to simulate delamination between the skin and stiffener are discussed. The first approach implements VCCT (virtual crack closure technique) in the finite element shell model as pre-defined bonded region where the crack initiates. The second method considers the cohesive zone modelling in the interface, for which there is no need to know the crack initiation locations.

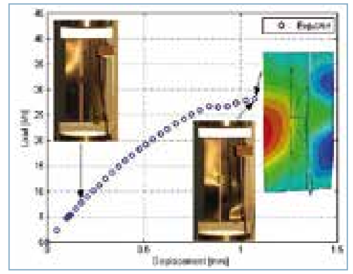
Two benchmark examples were studied and compared with experimental results taken from literature, showing the capability of the combination of fracture mechanics and damage mechanics to capture the delamination propagation under static and fatigue loading. Good agreements were obtained in the load-shortening curve, maximal load and number of cycles versus the crack lengths. Particularly, the number of cycles to delamination onset was calculated based on the power law relationship between the number of cycles and the maximal energy release rate, where the energy release rates were obtained directly from VCCT analysis in one single cycle. Apart from the single cycle simulation, the direct cyclic analysis was able to capture the structural response when the loading is repeated under low cycle fatigue. The predicted number of cycles was slightly larger than the one obtained from VCCT analysis, and the comparison curve is shown in Figure 1. An advantage of this analysis is to avoid the high computational cost by using cycle jump strategy. It has been noticed that the direct cyclic analysis assumes geometrically linear behavior.

Moreover, the post-buckling strength reserving capability and crack growth characteristic of two types of the stiffened panels with different configurations subjected to distributed compressive load is also examined with respect to the material, dimension, geometry, layups and stiffener shapes. Firstly, a single L-stiffened structure was proposed to investigate the structural response, especially the damage tolerance behavior under cyclic loading. Secondly, a T-stiffened subcomponent, supposed to be double L-stiffener, was carried out to study further how the delamination propagated under static and fatigue loading.

The specimens were manufactured and tested for the experimental characterization of static and fatigue delamination under compression. The most important observations resulted from the aid of experimental results and their correlation to the finite element models are described as follows. Experimental results show that delamination propagation appears in the post-buckling regime. Generally, the fatigue delamination propagated in an unstable way and is potentially the most detrimental for structural stability, while the free-edge delamination in the stiffener web affected strongly the load-carrying capacity of the structure. The predicted results from complex subcomponents consisting of panels with L stringer were compared to the experimental data (as shown in Figure 2).

Particularly, it was found that the Abaqus VCCT algorithm and cohesive approach properly predict crack propagation onset even under post-buckling deformations, which results in a valuable tool for a preliminary design in terms of ultimate load and damage types. The direct cyclic fatigue algorithm was found to be unsuitable for fatigue analyses of panels which present nonlinear displacements and are under mixed-mode loading. However, the idea of using the Abaqus VCCT for calculations of the energy release rate components provided detailed information about the mode mixity.

Contrary to unidirectional DCB under pure fracture mode I, it is established that the fatigue delamination crack of stiffened structures was under mixed-mode fracture type. Hence the fatigue parameters under mixed-mode fracture are required to define the power law between the crack length and the number of cycles. Since the energy release rate components are not uniform along the delamination crack tip, it has been noticed that the direct cyclic analysis



2. Experimental and numerical comparison - structural performance of the L-stiffened specimen.

has experienced considerable difficulty in finding the correct mode mixity to achieve a reliable solution for delamination crack propagation. The Paris fatigue law is a function of the mode mixity and only a single law at one time can be specified, hence it will be not possible to describe the fatigue propagation rate for all mode mixities. The additional limitation related to accounting for variable fracture mode mixities prevents further the technique from being extended to structural problems with complex geometrical configurations. Therefore, the detailed procedure provided in this thesis which currently supports just linear analyses, will be useful for other researchers to use this approach appropriately with linear behavior and a constant crack propagation mode shape.