Soutenance de thèse

Audrey BIGAND soutiendra sa thèse de doctorat préparée au sein de l'ICA et intitulée «*Evaluation de l'endommagement dans les structures composites en aéronautique généré par la contrainte foudre*»

Le 16 octobre 2020 à 9h30, Salle des thèses ISAE-SUPAERO

devant le jury composé de

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Résumé : L'utilisation des matériaux composites dans l'industrie aéronautique s'étant largement étendu, le dimensionnement de ces structures et de leur protection vis-à-vis de la foudre est devenu un enjeu majeur. Il est important de pouvoir développer des outils prédictifs permettant d'obtenir une conception de structure répondant aux critères de certification avec des temps et coûts de conception maitrisés. L'interaction de la foudre avec une structure composite est un phénomène multiphysique complexe, avec une difficulté ajoutée par la présence d'une protection métallique en surface et d'une couche de peinture. Dans ce contexte, cette étude a visé de développer la compréhension par rapport aux forces générées par la foudre et d'en évaluer ses conséquences quant à l'endommagement du composite. Dans cet objectif, le phénomène a d'abord été décomposé pour en étudier ses différentes parties et définir l'impact des interactions. Dans un premier temps, l'arc libre a été comparé au pied d'arc en interaction avec différents substrats permettant de définir un modèle de vaporisation de la protection foudre. Dans un second temps, la surpression générée par l'explosion de la protection en surface lors de la vaporisation a été évaluée pour définir des profils de pression spatio-temporels. Dans un troisième temps, une caractérisation mécanique de la peinture a été développée afin de quantifier son effet de confinement sur l'explosion de surface. A chaque étape, une théorie a été développée et analysée via des modèles numériques et des essais. Enfin, ces trois différentes briques ont été rassemblées dans un modèle mécanique simulant l'impact foudre sur une structure composite afin d'en prédire l'endommagement. De plus, une loi utilisateur a été développée pour appliquer ce chargement complexe ainsi qu'une loi d'endommagement. Ces modèles sont comparés aux résultats d'essai foudre en laboratoire afin d'en déterminer les limites de validité et leur capacité à prédire l'endommagement.

Mots-clés : Foudre, Composite, Aéronautique, Délaminage, Dynamique rapide non linéaire, Peinture

Summary: Aircraft manufacturers use more and more composite materials to design aerospace structures for weight and maintenance saving opportunities. But the low electrical conductivity of these structures makes them more fragile with lightning strikes. In order to ensure the safety of the flight and the operability of a commercial fleet, it is essential to limit the damage caused by a lightning strike. The conventional technique is based on the addition of a conductive protective film on the surface, often a metallic mesh that allows a better evacuation of the current. Despite this, the current ability of manufacturers to anticipate the performance of composite structures through appropriate models is limited. The use of tests first to refine a design and then to certify a new product remains the rule. The push for optimal designs forces the aeronautical world to develop an ability to predict damage, and to control the effect of the parameters involved. The goal is to be able to meet the needs of the designer without going through the expensive and time-consuming stage that an investigative testing campaign can represent. Several studies have been carried out to understand the phenomenon but also to try to model it. The phenomenology associated to damage as a direct effect of lightning strike can not be reduced to an electromagnetic problem. The multi-physical aspect of the

phenomenon (electrical, thermal and mechanical) and the multitude of parameters involved (carbon laminate, metal mesh, paint, resin, etc.) make the problem complex [1]. Several forces or constraints are to be considered: the shock wave associated with the arc, the Laplace forces and the Joule effect induced by the current flowing in the material, the thermal loading of the plasma but also the explosion of the protection confined by the paint layer [1]. The interaction of these surface phenomena with the composite structure to be protected is also poorly understood. Among the most developped thermoelectric models [2], the most advanced in multiphysical representation demonstrate that the mechanical component must be considered to correlate the physical damage of a composite panel with the multiple nature of the stresses induced by a lightning impact [3]. Initial work at the ICA laboratory shows that in some surface protection configurations the extent of damage induced in the composite structure can even be predicted with reasonable accuracy by a mechanical model alone in which the complexity of the surface phenomena is represented by a surface pressure deemed equivalent [4]. The work has also revealed the particular role of the paint already identified in previous works [5], and the fact that the interactions between surface phenomena and composite structure modify the final extent of delaminations and especially their distribution under protection . It is therefore essential to understand and model the interactions between surface phenomena and the composite structure. The difficulty of model development is partly related to the access of data during experimentation to validate the underlying assumptions. The lightning laboratories with the necessary instrumentation are few and the installation of tests is expensive. Indeed, the large and rapid dynamic, both thermal and mechanical, of the elements involved require a very specific individual characterization, difficult to access by conventional means. The project concerns the development of an ability to predict the damage induced by lightning stresses on monolithic composite structures. It is part of a national research project (EDIFISS: Effets Directs de la Foudre et Impact sur les Structures et les Systèmes) [6] launched in cooperation with industrial partners (Dassault, Airbus, Airbus Group Innovations, Airbus Helicopters, Aircelle & Herakles) and ONERA. It is complementary to work developed by ISAE-SUPAERO / ICA on the evaluation of damage generated in composite structures by equivalent mechanical shock [7]. It aims to improve the understanding of the role of protection design parameters on multiphysical surface phenomena and in particular on the exchanges and interactions between the electrothermal components on the one hand and the mechanical load on the other hand applied to the structure . The first step consists in choosing a set of contributing parameters among the known ones and then classifying them in order to define the need for basic electrical, thermal and mechanical characterizations. This work will, in the first place, be based on a detailed analysis of the bibliography and the results of existing test campaigns. Specific test protocols will be proposed, especially for paint whose effect is proven to be of the first order. The physical characteristics of the paints which contribute to the severity of the damage are not known. A preliminary study will define the experimental plan necessary to characterize the significant mechanical and thermal properties. At the end of this first part, a first list of parameters and relative weights on the distribution of damage will be established. In a second step, a more elaborate physical model will be developed using a strongly coupled computation code. This model will be based on two essential theoretical bricks: the first evaluating the induced stress at the foot of the arc and the second describing the physical mechanisms of damage resulting from this solicitation. The commercial numerical tools allowing to simulate a strong magneto-electro-thermo-mechanical coupling will be evaluated beforehand on the basis of qualitative and quantitative criteria which will be the subject of a specific study. Finally, a lightning test campaign on industrial panels will be conducted. Its objective will be to validate at the macroscopic level the hypotheses used for the physical models and to determine their limits. One of the key points of this project is the integration of an arc or arc foot model, whose interaction with the underlying structure during impact has a notable influence on the development of constraints. Taking into account the lightning arc implies the simulation of a fluid medium, with high thermal gradients, high radiation and electromagnetic properties close to that of a conductor [8-9]. This approach greatly expands the disciplinary field of this thesis, from the mechanics of structures to the magnetohydrodynamics of plasmas. The conclusion of this project will be the formulation of the complete theoretical framework, which is essential for the development of an industrial tool for design assistance, coupled with a precisely defined field of use, and prospects for evolution towards even more complex structures such as so-called "honeycomb" structures.

Keywords: Lightning, Composite, Aeronautics, Delamination, Transient non-linear Dynamics, Paint