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Modelling and analysis of crack turning on aeronautical structures

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Doctoral Thesis

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1 Introduction

New developments in airplane structures are directed to make aircraft safer, and also lighter, durable and more tolerant to damage compared to the existing riveted structures. This in turn should lead to the increase of the service intervals and the reduction of specific fuel consumption to make aircraft more economic and environmentally friendly. Coupled to reduce engineering and manufacturing costs, all these factors should make aircraft more affordable and faster to conceive.

To fulfil these demands, aircraft industries have distinguished three important activities.

a) The development of new materials. Specially, the development of new aluminium alloys with tailored properties and the qualification of composite materials, which are lighter than present structures and tolerant to damage.

b) The development of new manufacturing techniques. This field involves laser beam or friction stir welding, which permit a saving of weight and a reduction of manufacturing costs, eliminating the riveting process. On the other hand, the development of novel techniques to manufacture composite structures must be also developed or the available ones improved, because at present they are onerous and time consuming.

c) The introduction of computational methods. Testing before a commercial airplane reaches a full-scale validation is made up of thousands of coupon tests, hundreds of elements, joints and small panel tests, dozens of large panel and subcomponent tests, few wing-box and fuselage section tests and one or two full-scale airplane structure tests. These make testing costly and expensive. Thanks to the fast development of computer techniques and Finite/Boundary Element Method (*FEM/BEM*) on both linear and non-linear behaviour, some testing steps mentioned above could be substituted by means of simulation. This substitution decreases the costs of testing and simultaneously permits the evaluation of a whole set of new concepts and designs.

The introduction of new materials coupled with new manufacturing techniques as monolithic and welded structures, common integral structures, have been identified as a promising solution to meet the demands defined above, as they offer weight reduction, cost savings and they are more resistant to corrosion compared to differential structures, i.e. riveted structures. Furthermore, laser welding is considered as a backup technology, but also has the advantage of a higher weld velocity, though limited with regard to material type and weld quality in aluminium alloys.

An additional attractive benefit of integral structure is its automatic processing. This implies the elimination of the extremely expensive major assembly tools which are used nowadays in manufacturing environment [1]. However, in specific cases (for example residual strength in the presence of a long longitudinal crack, specially in the case of a broken stringer) the damage tolerance of integral structures is lower than that of differential structures [2]. When a skin crack crosses a fastened mechanical reinforcement, the crack does not directly damage the stiffening element, whereas when a skin crack crosses an integral reinforcement the crack grows simultaneously in both the skin and the stringer.

Nevertheless, in unstiffened cylinders, fuselage with adhesively bonded strengthening elements, reinforced cylinders, integrally stiffened fuselage structure with transverse cracks [2-7] and in cracked barrel tests under cyclic loading [8] a near *90°* crack turning on both ends of the crack, also called flapping, has been observed. Because it occurs frequently [9], the crack turning on such structures is identified as a promising feature to improve damage tolerance by deflecting and/or arresting the crack away from integral stiffeners, riveted tear straps or crack stoppers [3]. Thus, it has been found out that the event of crack turning on a barrel test increased the residual strength about *23%* compared to straight crack propagation [8, 9].

Integral structures are outstanding candidates to reduce manufacturing costs and kerosene consumptions since they are lighter and eliminate the riveting process. However, damage tolerance of integral structures is a critical issue; previous works have shown that it can be improved when crack turning takes place, so that the interval for inspections can be increased further enhancing the cost advantages of these structures. Unfortunately no systematic work has been carried out in commercial aerospace alloys to study in detail this issue. Based on the potential advantages of this phenomenon and keeping in line with the present targets of aircraft development research, this doctoral thesis has the objective to assess and predict crack turning under nearly *Mode I* situations on aeronautical structures selecting and modifying, if necessary, an existing *FE*-tool and delivering a reliable criterion.

The report of the dissertation is arranged in seven main chapters.

The second chapter deals with the state of the art. Primarily basic knowledge and principles on aeronautical structures are discussed together with fundamentals on fracture mechanics and simulation. This should provide the basis for the discussion of the crack turning studies and crack growth on fuselages.

The third chapter presents the tasks that have been identified to fulfil the outlined objectives.

The fourth chapter introduces the characterisation techniques, which are used in this study, and handles the materials, the experimental techniques and the tests used during this investigation.

The two following chapters expose the results of this work in detail. The fifth deals with the definition of the criteria used to select a code, describing briefly the screened tools able to compute fracture mechanics parameters and comparing some of them. Furthermore, it proves the reliability of the purchased and implemented tool by means of literature and experimental data. The sixth chapter presents the analyses, tests and simulations performed to reach a properly crack growth and turning assessment under near *Mode I* loading.

Finally, in the last chapter the achieved results and conclusions are summarised.