Crack propagation on helicopter aluminum panel with bolted stringers

M. Giglio, A. Manes

Politecnico di Milano, Dipartimento di Meccanica, Via la Masa 34, 20158 Milano, Italy
andrea.manes@polimi.it tel. ++39-0223998213 fax. ++39-0223998202

ABSTRACT. *Aerospace structures need excellent structural efficiency and damage tolerant behavior to avoid critical failure in presence of small defect and repeated small loads typical of contingent loads. In order to verify the damage tolerant performance of a rear helicopter frame, a series of tests have been performed on panel specimens representative of the structure. In particular the central part of the specimens is representative of the real frame structure, while the extremity (in particular the constraint and the load application zones) are reinforced to avoid failures due to fatigue. A dedicated test equipment has been designed and built in order to apply the effective service load. An artificial damage has been created in each panel to start a crack, and a variable load with a fixed load ratio has been applied. During the tests the propagation of the crack has been acquired, from the starting of the crack at the two apexes of the artificial damage, until the progressive failure of the panel involve one or more stringers (failure of the specimen). In particular it has been monitored the passing through and the breaking of stringers. Moreover each specimen has been instrumented with several strain gauges to acquire a strain map along the specimen and during the crack propagation. The values have been compared with a detailed FEM model with good agreement. In particular for this work, a FEM submodel of the bolted joint, stringer and skin in the crack propagation path has been realized to obtain the crack parameter of a panel specimen.*

INTRODUCTION

Damage tolerance, flaw tolerance and fail safe are the most widely used approaches in the design of aerospace structures due to the fact that they make it possible to optimize the frame in terms of structural stiffness, strength and weight. In particular, it is important to analyze the damage tolerant behavior to avoid critical failure in presence of small defect and repeated loads as requested in FAR 29.571 [1].
Moreover with the aim to improve the performance of the structures new materials have been developed. Such materials, as the Al-Lithium alloy, are designed with the purpose to optimize stress/strain vs. weight. The advantages of Al-Li alloys over conventional aluminum alloys include relatively low densities, high elastic modulus, excellent fatigue and cryogenic strength, toughness properties, and superior fatigue crack growth resistance [2, 3]. The last property is a key factor for damage tolerant aircraft design.

However, it has been discovered also some disadvantages like acceleration of crack growth rates in presence of compressive overloads, mechanical properties with high anisotropic behavior and a very high crack growth rate for microstructurally short cracks which potentially allows for fast crack initiation. Moreover the cost of Al-Li alloys is typically three to five times that of the conventional aluminum alloys they are intended to replace. Thus it is important to verify the damage tolerant behavior of the component manufactured with a new material.
In particular the panel of this work is manufactured with a large amount of Al-Alloy 8090. These material has been developed as a replacement for some of the most long-serving of the commercial aluminum alloys, such as 2114 and 2024. Alloy 8090 has 10% lower density and 11% higher elastic modulus and its use is aimed at applications where damage tolerance and the lowest possible density are critical.
The construction of the panel is a typical aeronautic construction with skin and stringers. In particular an artificial damage has been created inside the skin and the propagation of the crack, due to a fatigue load, has been monitored.
Together with the experimental activity a numerical model has been developed with Finite Element Method to calculate the fracture mechanics parameter along the propagation.
Particular attention has been placed on the crack propagation during the passage through the bolted joint of the stringer. Like the most of aerospace structure, the joint between the parts of the panel are made with bolted joint. It is an easy and rapid way to assemble structures that are built of different materials and/or difficult to weld or glue. Moreover in the damage tolerance assessment, a bolted construction may assure a better damage tolerance behavior due to the slowing down of the crack in presence of discontinuity like stringer. The presence of stringer is very useful for damage tolerance behavior; the stress intensity factor K_I drops as the crack approaches to the stringer. Moreover the stringer, generally, does not break during the passage of the crack and this behavior has a sort of cohesive effect on the propagation [4]. Fatigue crack propagation in integrally stiffened panel shows in fact that stiffening element will always crack simultaneously with the skin with a little deceleration of crack growth. Otherwise the presence of a bolt hole through the crack path complicates the analysis of the propagation.
The specimen considered in this work is one of a series of specimens used for a wide test campaign that includes different position of the artificial crack and different load ratio.

TEST DESCRIPTION

The purpose of the test is to evaluate the behavior of the structural panels made in aluminum alloy 8090 with the presence of an artificial crack and to acquire the propagation of the crack in the panels subjected to fatigue loads. The test panels are geometrical representative of a helicopter rear fuselage structure, Figure 1.
The test specimen’s common and fundamental dimensions are listed in Table 1. The panels have been manufactured specifically for damage tolerance test and have been

reinforced in the boundary parts (load and constraint application) to avoid failure different from the one started from the artificial crack. The following materials manufacture the specimen components:

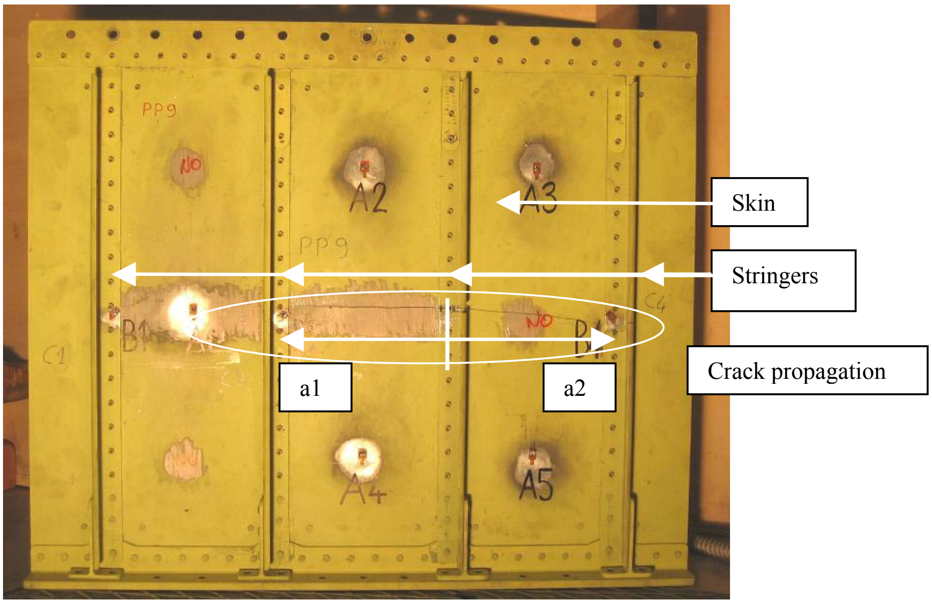

Figure 1. Specimen after the test with crack propagated and strain gauges

- aluminum alloy 8090 T81;
- aluminum alloy 2024 T3 (Alclad).

Al 8090 is used for stringers, skin and the angular connection between the stringers and the base (not under test). For the other components, generally used like reinforcement, Al 2024 has been used.

Table 1 - Common and fundamental dimension of the panel

Dimension	**Value or number**
Overall width	600 [mm]
Overall height	500 [mm]
Stringers	4

The specimens are connected in the top part with an hydraulic actuator by a stiff dedicated frame and constrained in the bottom with two plate fixed to a working plane, Figure 2.

A hydraulic actuator MOOG applies the loads; an internal load cell with 100 KN range controls the load.

The tests work in load control, using close loop instrumentation; a superior load limit of 105% of maximum applied load is set.

The specimen has been tested with a variable load (sine wave) with a load ratio R = 0.5. The maximum total applied load is 27469 N (2800 Kg) and is the net of the dead load (self weight, frame and grip loads).

Figure 2. The specimen installation

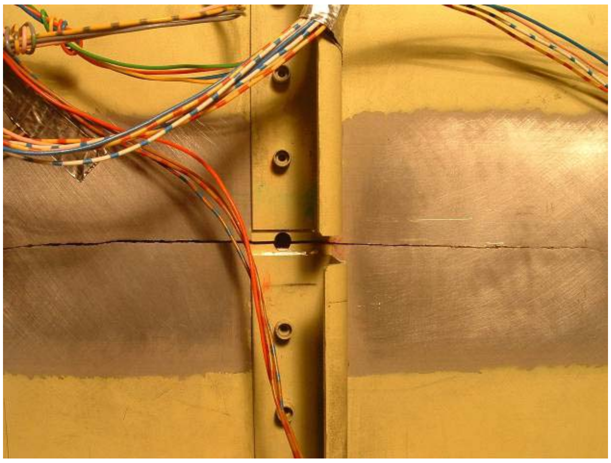

Figure 3. The artificial damage and the crack propagation

Specimen artificial crack and test procedure

An artificial damage has been created to nucleate a crack. The damage is a 16 mm through crack created with a very thin saws starting from a rivet hole, the extension of the crack (horizontal) is perpendicular to the load direction, Figure 3.

It is a side crack, on a central-side stringer; this crack has been made on the skin under the stringer, in correspondence of rivet hole, after the complete section of the stringer has been completely removed. So the crack involves directly the skin and a stringer above, whose load continuity transfer has been interrupted.

The test consists in acquiring the propagation of the crack, from its starting at the two apexes of the artificial damage until the progressive failure of the panel skin involve one or more stringers (passing and/or breaking of the other stringers), Figure 4. Moreover in this figure the crack propagation of the two apexes have been presented separately, a1 and a2, Figure 1.

In the first part of the propagation the crack length has been measured by replication of the cracked panel surface with very thin acetate paper and measuring the extension of the crack apex with an optical magnifier and a micrometer. When the crack growth and the dimension become near 100 mm a data eye relieve with graph paper has been choosing.

It is interesting to notice in Figure 4 the propagation of the crack on the two apexes: a1 is the apex that involves the bolted joint, Figure 5. The stop of the crack propagation at about 150 mm is just for the bolted joint passing through.

Comparing the propagation of the two apexes it could be noted that the behavior of the crack near the hole is very complex due to the presence of the hole and of the stringer. As reported in [5], a fatigue crack approaching a hole present a higher stress intensity factor K_I that leads to an accelerated crack growth. This behavior, with the increase crack size as soon as the hole has become part of the total defect should balances the arrest period inside the hole. Moreover the presence of the stringer above the hole (constrained to the skin with the upper and lower rivets) induces the slope of crack length vs. the cycles to decrease. The other apex of the crack passed through two rivets holes and so it is not stopped.

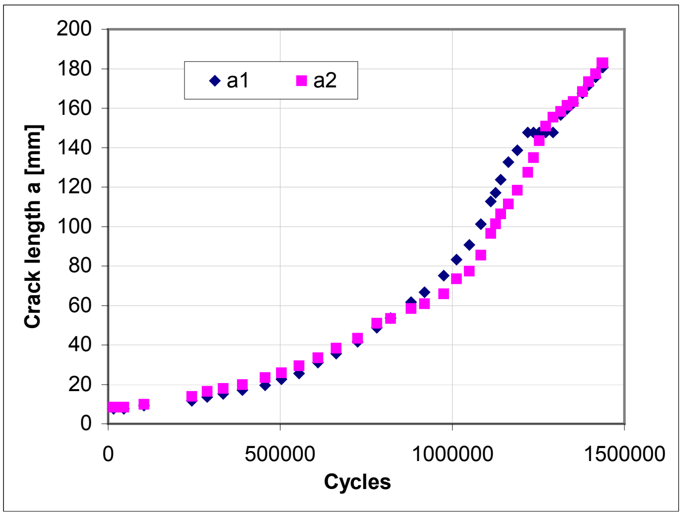

Figure 4. The crack propagation on the two apexs

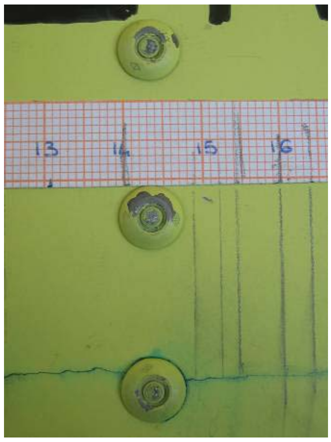

Figure 5. The crack path near the rivet hole

The panel has been also instrumented with strain gauges to compare the experimental strain with the strain from the FE model. Strain gauges have been placed on stringers, at the same height of the artificial crack, and on skin in perpendicular and parallel direction. The skin has been also instrumented by strain gauges in the bay between the stringers; the strain gauges direction is parallel to stringer axis.
Using all the data from the whole panels series, taken after approximately 10% of the life of the specimen to improve the stability of the data, all the FEM strains lie in the 97.7 % confidence band of the experimental strains.

THE FE MODELS

Two FE models have been developed with the aim to investigate the crack parameters during the propagation of the artificial crack. A global model of the whole panel and a submodel of the skin, stringer and bolted joint involved in the crack path have been developed using MSC PATRAN 2005 preprocessor and analyzed with the finite element code ABAQUS/Standard, version 6.5.

Both the models have been realized with shell elements, due to the very low thickness of the components of the panels. The reinforcements in the global model have been modeled superimposing shell layers. Also in the global model, the connection between the stringers and the skin, obtained with rivets in the real panel, has been modeled with tie contact (same DOF for the node connected) due to the large number of rivet used to joint the parts. However this simplification gives good results in terms of strain gauges validation and fracture mechanics parameter if ulterior stringers are not involved, or completely broken together with the skin, during the crack propagation. The submodel instead comprises a part of stringer and skin with an extension that includes 3 rivet holes, centered on the cracked one. The holes are modeled empty but with two series of displacement constraint (a group for the skin and a group for the stringer, for each hole) joining surface of the holes with the axis of the rivets. The rivets are modeled like simple beams, connecting the displacement constraint, without preload. The contact between the shell elements of the skin and of the stringer has been modeled with a simple contact without friction only to avoid compenetration.
The principal characteristics of two FE models are reported in Table 2.

Table 2 - Characteristics of the FE model

FEM Model	**Number of elements**	**Average element dimension [mm]**	**Minimum element dimension [mm]**
Global	11372	7.125	3.75
Sub Model	18603	0.7804	0.06083

The connection between the panel and the hydraulic actuator in the global model is fully modeled to preserve the sliding block constraint set of the real equipment. The lower t between the panel and the connection plate is modeled with beam elements that simulate the bolted joint of the lower part of the panel with the constraint plate. In Figure 6 a von Mises stress map of the global model with crack propagated is presented.

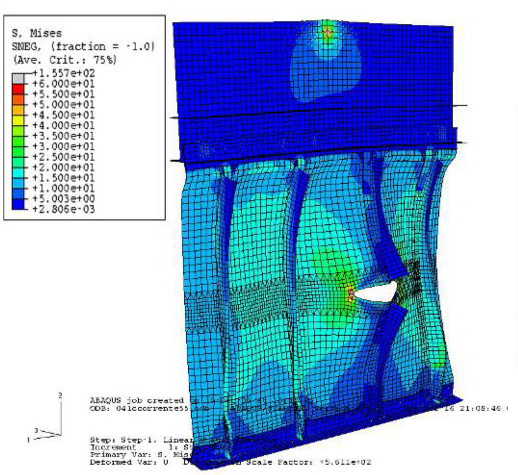

Figure 6 – Mises stress in the damaged panel, crack length 262 mm, for 10000 N load (magnification factor: 561)

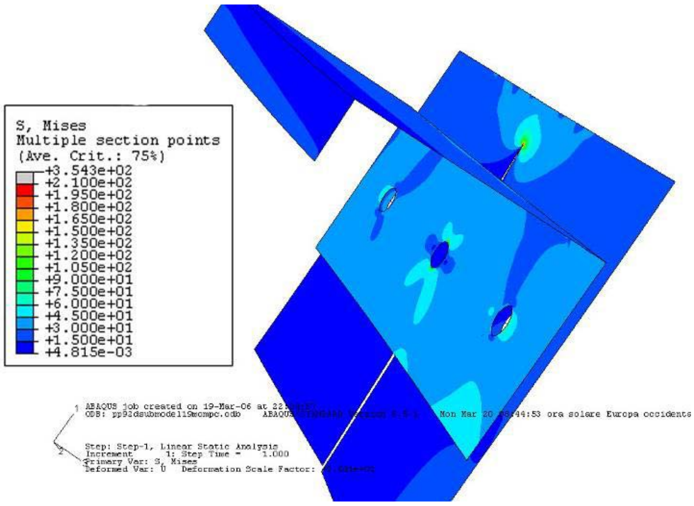

Figure 7 – Mises stress in the damaged panel, submodel, crack 346.5 mm, for 10000 N load (magnification factor: 26)

In particular, on the global model the crack has been symmetrically propagated through the panel for 230 mm (2a), that is in proximity of the stringer. This is similar to the behavior of the crack during the test. The last part of the propagation, on the global model and on the submodel, has been analyzed using, step by step, the crack position acquired by the test (not symmetrically due to the presence of the bolted hole) to reproduce with accuracy the real state of stress at the two apexes. Also on the submodel the crack propagation has been modeled by experimental steps. In Figure 7 the von Mises stress map of the submodel with crack propagated is presented.

Stress intensity factor K_I calculation

The FEM models have been used to obtain the fracture mechanics parameter during the crack propagation. Several models with different crack lengths have been modeled by which it is possible to obtain the K_I value and its trend along the crack path using an opportune submodel with a mesh dedicated with the quarter point modification of the nodes in the elements at the apexes of the crack. Near the rivet hole the submodel of the skin and the stringer has been used to obtain the K_I value simply using the refined mesh of the model. In the present analysis the K_I expression has been determined from the J-integral calculation, such option has been directly executed by the FEM program. In particular, the linear elastic fracture mechanics concepts have been used after verify the fundamental hypothesis (nominal stress far from the yielding stress / reduced plastic zone) The stress intensity factor K_I values obtained from FEM have been subsequently considered together with the experimental da/dN values, at the same crack length *a*. In particular the experimental data have been elaborated using the secant method presented in ASTM E647-00 [6].

CRACK PROPAGATION OF THE MATERIAL AND COMPARISON

For the comparison, the crack propagation behavior of the material, represented with the NASGRO relationship obtained from tests on 8090-T 81 (sheet; thickness 0.6-4 mm, orientation L-T; mat. Specific. EM201; HT specific. EM 101), is considered. Crack growth rate calculations in NASGRO 4.11 [7] use a relationship called the NASGRO equation. Thus it is possible to compare the FEM /experimental values with the material data, Figure 8. The agreement is very encouraging also in the passage of the rivet hole and, of course, of the stringer. It is important to remark the contemporary presence of the two parts (hole and stringer) because they have opposite effect on the crack propagation. However the submodel is able to describe with good accuracy the crack parameter along the crack path also in presence of complex path of the stresses.

CONCLUSIONS

The propagation of a crack on a structural stiffened panel used in aerospace construction has been analyzed. In particular the passage of the crack through a rivet hole, connecting the skin with a stringer, has been considered. FE models of the whole panel specimen, with a submodel of the rivet hole passing through, have been constructed to investigate numerically the crack parameter.

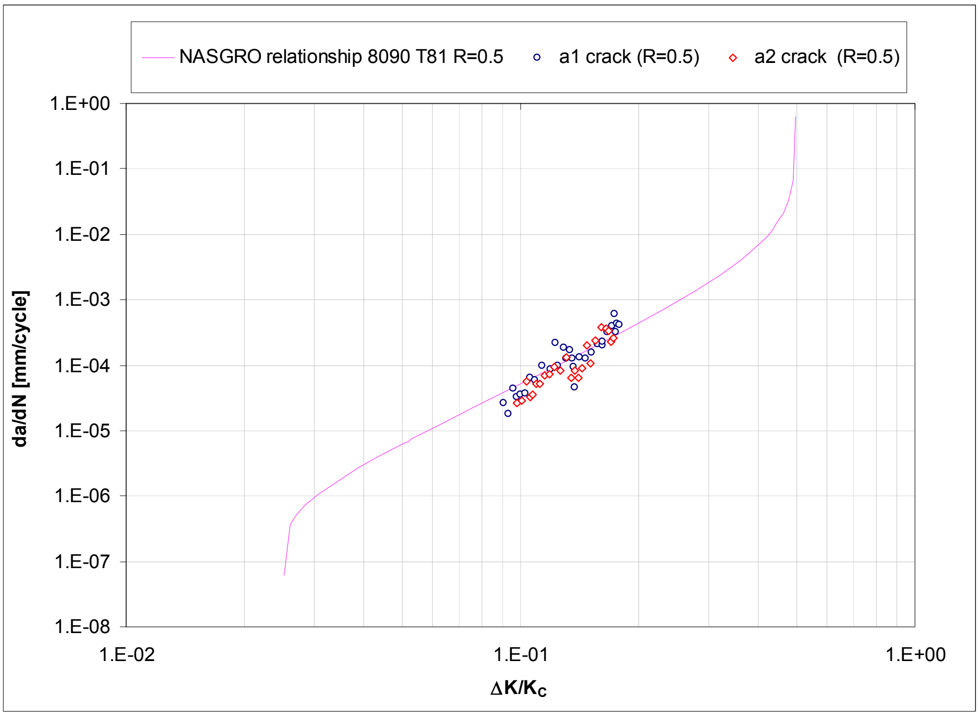

Figure 8 – Comparison between the experimental FEM data with the behavior of the material

From the research results, it is possible to state that:

- The fully numerical method for the structural design of the component give valid advice for the crack propagation and thus for the damage tolerance assessment of the panel.
- With a relative opportune safety factor is possible to use the material data, together with a detailed FEM model, to predict the crack propagation on the structural panels.

REFERENCES

1. Federal Aviation Administration, “Part 29- Transport Category Rotorcraft”, USA, 1991
2. Jata, K. V., Starke, E. A. (1986) *J. Metal Trans.* 17A, 1011
3. Venkateswara, K. T., Ritchie, R. O., (1988) *J. Metal Trans.* 19A, 563
4. Broek, D., “Elementary Engineering Fracture Mechanics”, Kluwer 1986
5. Slingeland V.O., Broek, D., “ Fatigue crack approaching circular holes” Delft Univ. Report, 1973
6. ASTM E647-05 “Standard test method for measurement of fatigue crack growth rates”, USA 2005
7. NASGRO 4.11, “Fracture Mechanics and Fatigue Crack Growth Analysis Software”, Reference Manual, NASA Johnson Space Center 2004