Improve Aircraft Structure Safety by Reinforcing the Critical Location Using Structural Health Monitoring

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TING DONG, ROQUE GIL SATO and NAM H. KIM

ABSTRACT

Fatigue remains the predominant mode of failure in the aviation industry, accounting for 55% of the incidents occurring. While the current industry practice relies on attaching a doubler on one side to address fatigue crack growth, the induced bending stress due to the neutral axis offset can be counterproductive and accelerate the crack growth rate. In this work, the fatigue crack growth of an airplane panel was examined for different configurations including one and two-sided doublers. With the aim of producing a reliable and simplified model capturing the fatigue crack growth mechanism. The results showed that while one-sided doublers reduce the operational lifetime by 38%, using a two-sided doubler, it increases by 86%. Analyzing the peak von-Mises stress across the different configurations, the one-sided doubler configuration had the highest stress due to bending, while the two-sided configuration mitigated and addressed this design problem. The work motivates further development in studying the application of two-sided doublers as a new industry standard to significantly extend the operational lifetime of an aircraft while reducing the operating costs of aviation companies.

INTRODUCTION

The general aerospace industry practice is that all structures and load-bearing elements need to be designed with the principles of damage tolerance. FAA introduced the concept of limit of viability (LOV) defined as the initiation of multisite and/or multi-elemental damage, which has become the industry definition of operational life for civil aviation [1]. The damage, i.e., cracks, will grow under conditions of cyclic loading, or under steady loading in hostile chemical environments. The growth can occur at stresses below the yield stress and is driven by the stress intensity factor which is dependent on a geometric/shape factor, stress and crack size. Once the crack reaches its critical size, failure occurs [2]. This process known as fatigue is based on the process where damage accumulates due to repetitive application of loads [3].

Fatigue is the most common failure mode in the aviation industry, accounting for 55% of the structural failures. Since 1920, fatigue failure accidents in aviation have been increasing at the average rate of 0.034% accounting for 2098 fatalities and 57 fatal incidents [4]. Some studies indicating that aerospace trends in design and operations require increased design stresses and operational flexibility for the purpose of increased performance, warns about the importance of studying fatigue in this context.

Depending on the structural characteristics of the affected piece, the crack damage can result in a catastrophic failure or repairs. In the industry, there are 2 main techniques to enhance the structural life of an aircraft structure: pre-stressing and repairs [5]. The pre-stressing techniques are a preventive method to retard the crack onset and growth by pre-stressing, preventing any catastrophic failure. The repair techniques allow the structure is able to carry the required load once it has already received in-service damage. The conventional repairing technique is the use of composite patch repair (often referred as doubler) [5, 6]. Bonded patches increase the cross-sectional area of the panel or skin to compensate for the increased load or reduced load carrying capacity due to the apparition of the crack [7]. This method avoids the economic barrier faced by companies of acquiring new aircraft by using effective and efficient repair methods [8].

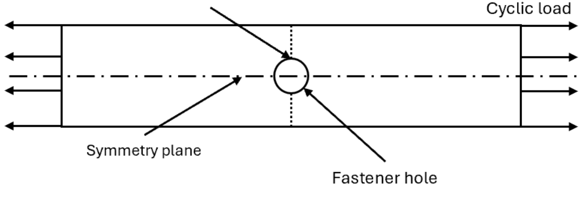
The current industry practice when using this conventional repairing technique is to use one-sided doublers which due to the neutral-axis offset, bending stresses are introduced. Among the recommendations from the FAA for acceptable practices for aircraft alterations on non-pressurized areas of civil aircraft of less gross weight than 12500 lbs., is that the doubler should have the equivalent thickness, material and strength as the existing skin, applied on one side. Looking at the available literature and practices, the bending stress implications arising from the neutral-axis offset are overlooked [1, 9].

Although some literature exists in terms of the stress intensity factor graph behavior for one-sided and two-sided doublers, there is no framework on the application of two-sided doublers available for engineers in charge of repairs [6]. Based on the current practices and literature, the objective of this work is to assess using Finite Element Analysis (FEA) methods the feasibility of current used one-sided doublers with bending stress, against the idea of using two-sided doubler without offsetting the neutral axis. Upon the analysis, this work aims to produce simplified model for the use and application of two-sided doublers to establish a new industry practice.

NUMERICAL MODELING OF FATIGUE CRACK GROWTH

Geometry Modeling

For the purpose of comparing the performance of one-sided doublers and two-sided doublers, the first step was to create an FEA model for a quarter of an airplane panel with a crack. Due to symmetry, a quarter panel was defined and then copied to represent half plate. It was assumed that the crack appeared in the radius of a fastener hole. Figure 1 shows the full model, the equivalent half and quarter representation of the full panel.



(a)

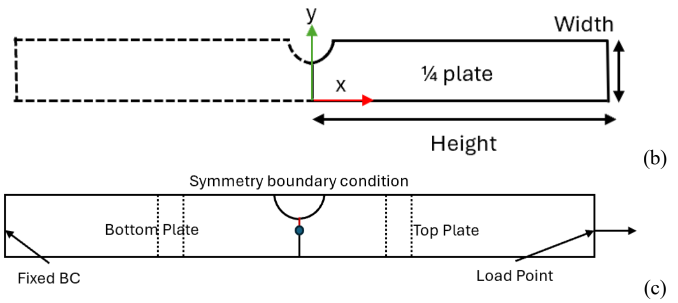


Figure 1. Symmetric quarter model of a plate with hole.

The radius of the fastener hole is 3 mm. The height and width of the quarter plate is 100 mm and 19.05 mm, respectively. The plate is made of Aluminum 6061 with thickness of 2.54 mm. It is more commonly used for light aircraft for the fuselage and wings which combine easy machinability, weldability while being strong [1, 10]. The properties of aluminum 6061 are shown in Table 1.

TABLE 1. Material properties of aluminum 6061.

Property	**Unit**
Young Modulus (E)	69.0 GPa
Poisson Ratio (υ)	0.33
Paris Law 'C'	5.88×10^{-11}
Paris Law 'm'	2.57
Fracture Toughness Mode I	33.5 MPa$\sqrt{m}$

Two quarter models are connected using a cohesive zone as shown in Figure 1(c). The contact surfaces are initially bonded until the blue point, such that the initial crack size becomes 1 mm. When a doubler is implemented, the doubler is bonded along the dashed lines in Figure 1(c).

Axial fatigue loads are applied as shown in Figure 1(c), to simulate Mode I fatigue crack growth. Cyclic load of maximum 13 kN and minimum 1.3 kN is applied using Direct Cyclic Analysis in Abaqus. Then, low-cycle fatigue using the Paris-Law relates the onset and rate of growth of fatigue crack to the relative fracture energy release rate.

Fracture Criterion

In this paper, fatigue crack growth is modeled using the modified Paris model, as shown in Figure 2. The onset of the fatigue crack growth is defined by ΔG being the relative fracture energy release rate when the structure is loaded at its minimum and maximum values. The initiation is dependent on some materials constants (c_1 and c_2), N as the number of cycles [11]:

$$f = \frac{N}{c_1 \Delta G^{c_2}} \tag{1}$$

The crack front does not propagate unless Eq. (1) is satisfied and $G_{\max}$ (cyclic energy release rate when structure loaded to its maximum) is greater than the threshold. Here it is assumed that this onset was satisfied automatically [11].

The linear regime of the Paris model is bounded by a lower and upper maximum energy release rate G_{thresh} and G_{pl}. For fatigue crack growth employing the Paris Law, the crack growth rate is based on the relative fracture energy release rate and only occurs if $G_{\text{thresh}} < G_{\max} < G_{\text{pl}}$, at a rate of [15]:

$$\frac{da}{dN} = c_3 \Delta G^{c_4} = C \Delta K^m \tag{2}$$

By comparing Eq. (2) with the traditional Paris model, the two constants can be determined as $c_4 = m/2$ and $c_3 = CE^{c_4}$.

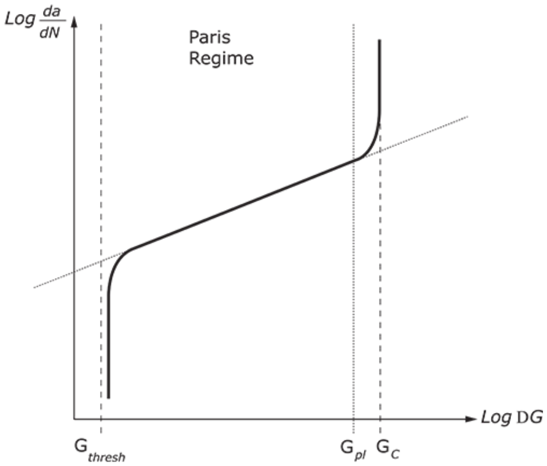


Figure 2. Fatigue crack growth model.

Fatigue Simulation without Doubler

First, fatigue crack growth simulation is performed without having a doubler. This simulation is used to calculate the baseline fatigue life. Once the results were available, by using the tool of path and selecting the bonded node set, it was possible to plot the crack growth against the cycles. Figure 3 shows a snapshot of low-cycle fatigue simulation at 765 cycles.

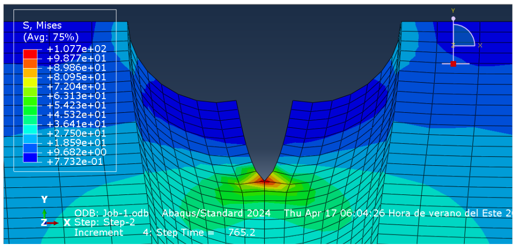


Figure 3. Fatigue crack growth simulation.

Figure 4 shows how the crack growth over cycles due fatigue without any doubler. Although the simulation was performed until failure, the results were only plotted until the crack grew to an unstable length. Having the initial crack size of 0.004 m, the crack grew to an unstable crack size of 9.62 mm after 29,780 cycles.

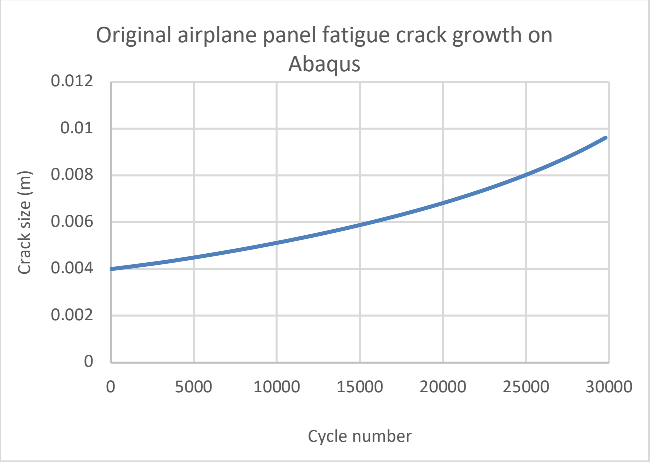


Figure 4. Fatigue crack growth without doubler.

Design of Doubler for Fatigue Life

Since the objective of this work is developing an easy and accessible model and framework that allows engineers to verify easily how the application of a double side doubler can enhance operational life, the development of a simple analytical model is essential. For that purpose, we use the Paris model to predict crack growth. Since the specimen is a finite size plate, the following stress intensity factor is used

$$K_I = \frac{P}{B\sqrt{W}} f\left(\frac{a}{W}\right) \tag{3}$$

where P is the load applied, B is the thickness, W is the width and $f(a/W)$ is a dimensionless function to account for the geometry, which is defined as

$$f\left(\frac{a}{W}\right) = \sqrt{\frac{\pi \cdot a}{4W} \sec\left(\frac{\pi \cdot a}{2W}\right)} \left[1 - 0.025 \cdot \left(\frac{a}{W}\right)^2 + 0.06\left(\frac{a}{W}\right)^4\right] \tag{4}$$

By considering the geometric factor, the model parameters c_3 and c_4 in Eq. (2) were estimated using least-square method between the analytical model in Eq. (2) and finite element simulation results in Figure 4. The fitted c_3 and c_4 values were 0.001 and 2.1128, respectively, producing, for a similar crack size, the results of 9.62 mm after 25,210 cycles.

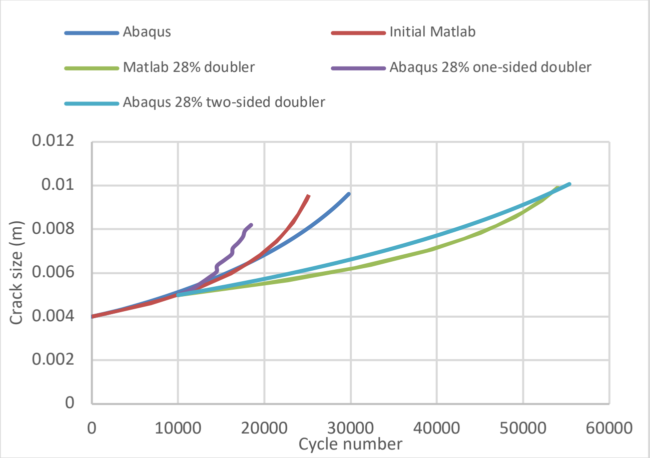


Figure 5. Comparison of life cycles after adding doubler.

Using the fitted analytical model, the thickness of doubler is designed such that the repaired plate can have a life of 55,000 cycles. The analytical model predicted that the thickness of doubler should be 28% of the original plate. Two possible designs of doubler are considered. In the first design, the doubler is installed on one-side of the plate, which is the current practice in the industry. In the second design, two half-thickness doublers are implemented on both sides of the plate. Figure 5 and Table 2 compare the life cycle of plate with or without doubler using analytical and FEA simulations. It is surprising to note that FEA simulation of one-side doubler yields a shorter life cycle than the original plate. This happens because the one-sided doubler caused unexpected bending deformation, which causes stress concentration on the plate and accelerates crack growth. On the other hand, two-sided double yields a similar result to the analytical model because the analytical model does not consider bending effect.

TABLE 2. Comparison of life cycles using different models.

Model	Cycles	Crack Size (m)
FEA Initial	29780	0.009618
Analytical Initial	25210	0.009619
Analytical 28% Doubler	54270	0.010012
FEA 28% one-sided Doubler	18460	0.008198
FEA 28% two-sided Doubler	55360	0.010070

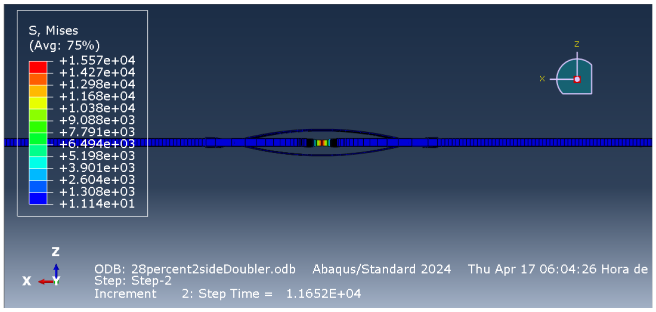


Figure 6. Symmetry of simulation results when two-sided doubler is implemented.

CONCLUSION

The results from this work showed that the industry standard and practice of employing one-sided doublers can compromise fatigue performance as the crack grows at a faster rate due to the introduction of bending stress. Through the validation using the FEA simulation, it was possible to create a simplified analytical model that captures the critical crack lengths with results that, although remain quite accurate with the simulation physics, are conservative with a 18.12% difference with the panel without the doublers and 1.97% for the two-sided doublers. The simulation showed that one-sided doublers reduce the operational lifetime by 38.01% compared to if the doubler was not repaired, while two-sided doublers improved the operational lifetime by 85.90%. These results are in accordance with the fact that using a one-sided doubler, it offsets the neutral axis introducing bending stress which was consistent with having the greatest von Mises stress while the two-sided doubler, by maintaining the neutrality, registered the lowest Von Mises stress.

Although there were some sources of uncertainty including the doubler bonding setup, the Paris model parameters or the c_3 and c_4 non-linear least squares tuning, with the results obtained, the theme should be further researched to shift a current industry practice towards a safer one. Future work in this topic includes producing a model that accounts for the use of newly developed adhesive bonding processes and obtain Paris model parameters for the purpose of an airplane panel.

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