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Numerical Simulation of Fatigue Crack Growth in Straight Lugs Equipped with Efficient Structural Health Monitoring

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Abstract

This paper addresses the influence of the efficient Structural Health Monitoring system (eSHM) on the fatigue life of straight lug components. The eSHM system is a mechanical fatigue crack detection system developed at the Vrije Universiteit Brussel (VUB). It consists in integrating pressurized capillaries into the to-be-monitored component, so that when a fatigue crack breaches the capillary network, a leak flow is created, and the pressure equilibration between the capillary and the open atmosphere is detected by a pressure sensor. The system is therefore aimed for additively manufactured structures. In this paper, one considered the example of straight lugs, quite common in aeronautical structures and well documented in the literature, to assess whether fitting the lug with the eSHM would significantly influence the fatigue crack growth behavior. Therefore, comparisons are made between lugs not equipped with the eSHM and lugs with integrated capillaries, both with identical initial defect. The aim is to determine whether the capillaries have a significant influence on the number of cycles to failure. The evaluation of this influence will be done by numerical computations using the eXtended Finite Elements Method (XFEM). In particular, the computations will be done on the Morfeo software developed by Cenaero. Conclusions from this research will serve as basis for sound implementation of the crack detection system on industrial components. Indeed, the system has to offer a quick detection of the propagating fatigue crack (by being placed as close as possible to the most probable initiation region) while not affecting the component’s life (the capillary should not initiate a defect nor reduce the crack growth life of the lug).

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Keywords: efficient structural health monitoring (eSHM); fatigue crack growth; XFEM; straight lug

1. Introduction

It is a very well known fact for all scientists active in domains related to fatigue of materials that fatigue failures are particularly insidious, in the sense that they occur with little warning, or even no warning at all, that rupture is imminent. This point is sadly enough well illustrated by the occurrence frequency of unexpected fatigue failures on
components where the propagating crack remained undetected, and which lead to possibly dramatic consequences. Aircraft industry has proven that propagating fatigue crack can lead to the crash or emergency landing of an airplane, the Comet aircraft’s in the years 1950 or the Aloha Airlines flight 243 in 1988 being the most famous examples. The latter two examples might however give the impression that fatigue failures in aircrafts in operation were a concern in the past, but is now resolved. One should note that this is a faulty impression, as fatigue failures still occur nowadays. To the purpose of illustration, one should not dig very far in the history of aircraft accidents involving passenger fatalities in the United States to find the trace of a deadly fatigue crack. Indeed, the third most recent deadly crash took place on the 19th of December 2005, and concerned a Chalks Ocean Airway’s Grumman G-73T that ditched into the water due to an in-flight wing/fuselage separation, which had been triggered by a fatigue crack in the wing structure (NTSB AAR0704 [2007]). Thanks to a very comprehensive study performed by the National Bureau of Standards (now, NIST) on 230 failed aircraft components, one can estimate that about 60% of all failures of aeronautical components are due to fatigue (see also Manson and Halford [2006]). Aviation is thus highly concerned, still today, by the consequences of undetected fatigue cracks, and other industries are concerned as well. Another famous - and tragic! - example is the accident of an ICE German high speed train near the village of Eschede on the 5th of June 1998. The train derailed while driving at 250 km/h, leading to 100 deaths and more than 100 injured passengers. After investigations, it was found that the derailment was due to the rupture of one wheel, which had been provoked by a propagating fatigue crack (detailed information can be found in Esslinger et al. [2004]). All this illustrates very well the need for new approaches to deal with the detection of propagating fatigue cracks in structural components, and Structural Health Monitoring is precisely one of the alternatives, thought to be very promising.

Formally, Structural Health Monitoring (SHM) can be defined as the process of acquiring an analyzing the data from on-board sensors to evaluate the health of a structure (De Baere et al. [2014]). Up to now, research around SHM has primarily focused on vibration-based damage identification systems (Farrar and Worden [2007]). However, the advent of the additive manufacturing technology and inherent smart metals concepts lead the researchers of the VUB to consider another implementation of the SHM philosophy, which lead to the now patented efficient Structural Health Monitoring, or eSHM system (De Baere et al. [2014], Strantz et al. [2015]). The system consists in integrating pressurized capillaries (the capillaries are thus internal channels) into the to-be-monitored component, so that when a fatigue crack breaches the capillary network, a leak flow is created, and the pressure equilibration between the capillary and the open atmosphere is detected by a pressure sensor. Figure 1 illustrates the working principle on a four point bending test sample equipped with an under-pressurized sinusoidal capillary: the pressure is normally 0.5bar in the capillary, but as soon as the propagating fatigue crack reaches it (clearly seen on the micro-XCT image), air from the open atmosphere enters the capillary, and internal capillary pressure rises sharply. The system presents the intrinsic advantage of robustness (since the capillaries are integrated in the component, there are no concerns of surface contamination by oil or dirt; only one sensor is necessary to inspect the entire component; etc.), but it remains to be proven that the integration of capillaries inside the real life component does not affect the component’s quality of fulfilling its function with all related specifications. Previous researches have already shown that the presence of the capillaries had no influence on the crack initiation behavior of the component, provided it was located at an
adequate distance from possible original initiation site (Hinderdael et al. [2017]). This works now deals with the crack propagation behavior of a component equipped with the eSHM system. The objective will hence be to assess, by numerical fatigue crack growth simulations, whether the capillaries significantly reduce the fatigue crack growth life of the component or not. In particular, capillaries of different diameters and with different initial capillary pressures will be examined.

2. Numerical framework

2.1. Geometry and load case

In the context of this research, it has been decided to study the influence of the capillaries on the crack propagation behavior within a lug type component. Indeed, the eSHM system has originally been designed for the aerospace industry, where lug type connections are frequently used thanks to their simplicity and ease of mounting/dismounting. Moreover, it is also very well known that lugs are very sensitive components in terms of fatigue life, as crack initiation due to fretting and corrosion is very likely to take place (Schijve et al. [1979]). In addition, the existing literature around fatigue crack growth in lugs is quite abundant, enabling the authors to take advantage of a strong and reliable reference point to start conducting the study. Amongst the existing literature, it has been decided to work on a geometry similar to the straight lug studied by Boljanovic and Maksimovic [2014]. The in-plane dimensions of the lug are depicted in Figure 2. The lug thickness is 12.7mm. Capillaries of circular cross-section will be integrated around the hole of the studied lug. The edge-to-edge distance between the bottom of the capillary and the lug hole surface, named “a” in the eSHM terminology, will in all case remain 3mm, but different capillary diameters will be analyzed, namely 0.5mm, 1mm, 2mm and 4mm. To serve as reference, a simulation will also be run on a lug without integrated capillary. A through-the-thickness crack, with a crack size of 0.635mm, and located on the top part of the lug hole will be assumed as initial defect. This was done both to be in accordance with the work of Boljanovic and Maksimovic [2014] and also because this type of defect is, together with quarter elliptical corner cracks, the most fore-coming type of defects on lugs (Boljanovic and Maksimovic [2014]). Even if the objective here is rather make a comparison between two situations (lugs equipped or not with the eSHM system) rather than obtaining a reliable estimate of crack growth life, one should note that “artificial cracks” will always grow in practice at a faster rate than “natural cracks” (initiated by fretting corrosion for example; see also Schijve et al. [1979]). Therefore, estimations of fatigue crack growth life based on numerical models will always be conservative with respect to reality.

The same load case will be applied to the different configurations (different capillary diameters and initial capillary pressures): translations on the straight-end of the lug will be blocked, while an axial constant amplitude cyclic loading of 45000N (maximum value; \( R = 0.1 \)) will be applied to the lug hole, to be consistent with the studies of Boljanovic and Maksimovic [2014] (this force has however been converted in our study into an equivalent uniform pressure applied on half of the lug hole surface).
2.2. Material

The eSHM system is undoubtedly aimed at fully or partly additively manufactured structures, as the capillaries need to be integrated in the monitored components, which is barely impossible without resorting to the additive manufacturing technology. However, the influence that additive manufacturing has on material properties, and especially on fatigue properties, is still subject to intensive research and is depending of many parameters, such as process used, process parameters and post-treatment applied if any (Leuders et al. [2013], Reschetnik et al. [2016]). Nevertheless, as here above mentioned, the goal of this work is to establish a comparison between lugs with and without capillaries, and not obtaining an estimate of what the crack growth life of such a component should actually be. Therefore, the same material properties are enforced to all the models that have been used. These properties are actually those of conventional aluminum: a Young’s modulus of 71700MPa and a Poisson ratio of 0.33. For what concerns crack growth properties, a Paris law has been used in the simulations, with a Paris exponent of 3.06 and a Paris coefficient of $1.2029 \cdot 10^{-11}$ (propagation rate expressed in $\frac{mm}{cycle}$), in accordance with the material properties used by Boljanovic and Maksimovic [2014].

2.3. Mesh

Figure 3 illustrates the type of mesh that was used for the simulations. It consists of all linear tetrahedrons, and depending on the capillary geometry, there are in total between 468000 and 470000 elements in the mesh. It was obtained after several refinement steps, ensuring the use of a converged mesh. In particular, the mesh was highly refined in the crack region, as can be seen on the right of Figure 3, to ensure for converged stress intensity factors. All the meshes used in this study were generated using the open source pre- and post-processor “Gmsh”, developed by Geuzaine and Remacle [2009].

3. Crack growth in lugs equipped or not with the eSHM system

In this section, an analysis of the crack propagation behavior is performed on lugs equipped with integrated capillaries, and compared with standard lugs. All the crack propagation computations presented below have been performed with Morfeo software developed by Cenaero (Wyart [2007], Moës et al. [1999]). The input mesh and the load case have been presented in the previous section. In the software, the propagation is driven by a user defined crack propagation step $\Delta a$. The software then computes the corresponding $\Delta N$, number cycles required to propagate the crack by $\Delta a$. It has to be noted that $\Delta a$ has to be set to a value ensuring that the propagation path of the crack is properly computed, and that the time integration yielding the $\Delta N$ is correctly evaluated. The crack position in the mesh is marked by referring to level sets (Duflot [2007]), which are at each step updated based on propagation length and direction.

The capillary diameter is thought to have an important influence on the crack propagation behavior, as it modifies the cross-section through which the crack propagates. Moreover, as mentioned in the introduction, the capillaries should be under- or over-pressurized with respect to the open atmosphere for the system to work properly. In particular, for aerospace application, the capillaries are more likely to be set to an absolute pressure significantly higher than one
bar (“over-pressurization”), as putting them to an absolute pressure of less than one bar (0.5bar absolute were typically used in the experimental investigations, see Hinderdael et al. [2017]) would result in under-pressurization at ground level, where the open atmosphere is at an absolute pressure of approximately one bar, but not at high altitudes anymore. Therefore, the influence of the presence of the capillary will be assessed in function of two parameters: the capillary diameter and the capillary internal pressure.

3.1. Influence on crack propagation, depending on capillary diameter

Crack growth curves have been computed for different capillary diameters, namely 0.5mm, 1mm, 2mm and 4mm. For all these simulations, the capillaries are set to an absolute pressure of 2bar. The crack growth curves (crack length vs. cycles) are presented in Figure 4. The crack growth lives, considered to be the number of cycles required to propagate the crack from \( a_0 \) till \( a_c \), critical crack length at which the maximum stress intensity factor reaches the fracture toughness of aluminum (here, taken as 917MPa \( \sqrt{m/m} \)), are presented in Table 1. From the results, it can be seen that only large capillaries (4mm is about the third of the lug thickness) have a significant influence on the crack growth behavior, as the crack accelerates in the region of the capillary due to the locally reduced section (the crack resumes to its “normal propagation speed” after having passed the capillary). Conversely, small capillaries (0.5mm, 1mm) have almost no influence on the crack growth. Up to now, capillaries having a diameter of 2mm have been used in experimental investigations (see Strantz et al. [2015], Hinderdael et al. [2017]). The present result shows clearly the interest of working with even smaller capillaries, which is actually the direction the research around eSHM was aiming for (hence the name “capillaries”, implicitly referring to very small diameters) due to a reduced influence on crack initiation. It is worth noting that the manufacturing of components with embedded ultra-small capillaries (0.25 - 0.5mm diameter) will be rendered possible thanks to the research around hybrid manufacturing (additive manufacturing in combination with micro-milling). Post-processing also reveals that the capillary diameter has no influence on the propagation path followed by the crack.

3.2. Influence on crack propagation, depending on capillary internal pressure

A similar study has been conducted, this time with the capillary internal pressure as parameter (all the capillaries having then 2mm as diameter, since, as here above mentioned, this has been up to now the “standard value” in experimental works). The objective is then to determine whether the over-pressurization of the capillary, required for proper functioning of the eSHM system (see above), would lead to some crack retardation or not, and should it be so, to
which extent. To that purpose, simulations were run keeping the same geometry, but where the internal pressure inside the capillary was changed. Four different over-pressures have been tested (absolute pressure in the capillary is given): 1.5 bar, 2 bar, 2.5 bar and 3 bar. The crack growth lives, in function of the capillary internal pressures, are presented in table 2, while the crack growth curves are depicted in figure 5. From the results, it is clear that over-pressurization of the capillaries has strictly no effect on the propagation. Indeed, the application of these low pressure loads on the capillary surface barely influence the stress field, thus implying no modification to the crack growth behavior.

4. Conclusion

The results of these numerical studies have shown that the introduction of small capillaries (0.5mm to 1mm diameter) around the hole of a straight lug type component do not influence significantly the crack growth behavior of the component. Moreover, it has also been shown that over-pressurization of the capillaries up to pressures of 3 bar also do not affect the crack growth behavior. This opens the door to possible applications of the eSHM system on actual components, as its effectiveness in detecting fatigue cracks has been demonstrated previously, and as it has been shown here that it does not affect the fatigue life of the monitored component.

References