DAMAGE INITIATION CRITERION OF CFRP UNDER VIBRATION FATIGUE TESTING: EXPERIMENTS AND MODEL VALIDATION

Fabrizio Magi[1], Dario Di Maio[2], Ibrahim Sever[3]

[1]Advanced Composites Centre for Innovation & Science, University of Bristol, UK
Email: Fabrizio.Magi@bristol.ac.uk
[2]Department of Mechanical Engineering, University of Bristol, Bristol, UK
Email: Dario.DiMaio@bristol.ac.uk
[3]Rolls-Royce plc, Derby, UK
Email: Ibrahim.Sever@rolls-royce.com

Keywords: Initiation, Fatigue, Resonance testing, VCCT, Failure criterion

Abstract

Fatigue failure of composites is an important aspect for characterizing the fatigue strength of components and structures. Despite the efforts in seeking a robust failure criterion, the failure definitions are often described as a percentage of stiffness degradation. Delaminations and microcracks are widely present in the specimen by the time the stiffness reduction reaches the aimed level. Therefore, a zero damage tolerance specification cannot be applied for designing composite components for fatigue. A testing campaign is carried out to study the damage development in a component with ply drop-offs undergoing vibration fatigue. This manuscript shows the evidence of a clean critical event in the fatigue life of the component, suggesting a novel failure criterion to be used for vibration fatigue testing. The critical event is captured from a sudden change in dynamic parameters of the structure. The exploitation of resonance conditions enables a very sensitive monitoring of the structural degradation of the specimen. The decrease in stiffness can still be measurable from the resonance frequency, but it is found to be too coarse for capturing the occurrence of the critical event during the vibration fatigue testing. To conclude, the dynamic VCCT is applied to a 2D model to validate the definition of initiation as the critical event.

1. Introduction

The definition of damage initiation is a discussed topics in fatigue behaviour of components. It is widely agreed that the nucleation of damage in a pristine component can be a large part of its total fatigue life, but unfortunately it is the most difficult part to understand and therefore predict. For this reason, even applying discretion, the crack initiation is always related to a subjective critical crack dimension [1, 2].

For composites, damage is identified by the complex status of the material rather than by a single crack. From the first studies of Reifsnider [3] it was clear that the damage development comprised a series of interacting phenomena, leading to continuous structural degradation and diffused damage. He proposed the definition of the Characteristic Damage State (CDS), which somehow aimed to replace the single crack in homogeneous materials. According to his sequence of damage development, the initiation should be defined as the first crack nucleation, well before the CDS is reached. However, the definition of initiation varies if considered at macroscopic level, where a crack nucleation may not affect the overall strength of component.

Excerpt from ISBN 978-3-00-053387-7

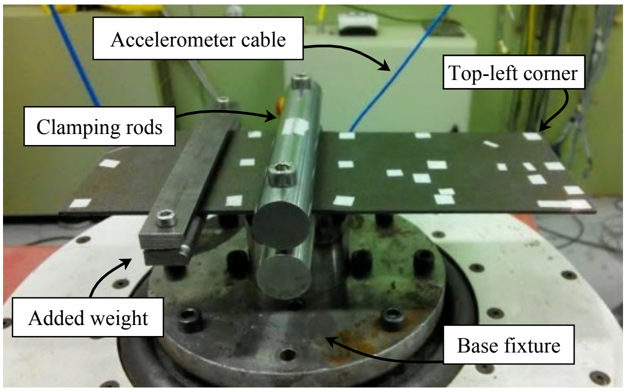

Figure 1. Rig setup.

A practical definition of initiation is the one given by Salkind [4] as “the time required to form a crack of detectable size”. Lomov et al. [5] considered the damage initiation as the occurrence of a crack that can be captured by an increase in the energy content of acoustic emissions. Quaresimin [6] set the limit to 0.3 mm for the crack to be considered detectable, justifying that small changes in the initial crack length have a small effect on the fatigue life. Sims [7] identified the need for a failure criterion based on loss of stiffness, as recommended by standard procedures [8], that could vary from 5% to 20%, depending on applications. May and Hallett [9] carried out an extensive testing campaign to build the S-N curves to initiation for mode I and mode II. In both cases they concluded that the damage initiation differed very little from the separation of the specimen in two pieces, therefore there was not room for subjectivity on the definition of failure.

The aim of the article is to provide a more sensitive method for monitoring structural degradation and damage initiation by means of resonance vibration. Use of resonance vibration for fatigue testing and in-situ monitoring of damage is not new [10–13]. Since the first studies in the 50’s [14], the vibration fatigue testing method has become commonplace [11, 15], exploiting the resonance conditions to perform quick tests to a high degree of accuracy, even in the Very High Cycle Fatigue (VHCF) regime, up to the gigacycle [16].

In this manuscript, experiments are shown and described, and the framework is validated by a dynamic VCCT (Virtual Crack Closure Technique). Here, damage initiation is defined as a critical event that changes the rate of structural degradation for a given excitation level. In other words, an event that can abruptly change the distribution of internal forces within the component under fatigue loading conditions.

2. Changing the testing method

The testing setup adopted was presented in Ref. [17]. For ease of reading, it is summarised here. Figure 1 shows a steel fixture clamping the component and connected to the shaker head. In order to minimize friction and to avoid nonlinear boundary conditions, the fixture constrains the component along a line by means of two cylindrical rods. The component is a rectangular specimen 100 mm × 260 mm, made with 20 pre-preg plies of IM7/8552, 4 of which are interrupted plies 100 mm × 130 mm. The stacking sequence is $[0, 0_{drop}, 90_{drop}, (0, 90)_3, 0]_s$ and the ply-drop is 20 mm away from the clamp, in the middle of the specimen. The ply-drops are introduced to move the maximum stressed area away from the clamp, and to replicate a common feature of most of the composite components.

The test used to be run at the first bending mode, at constant vibration amplitude and constant resonance phase in order to keep the excitation on the peak of resonance. As a consequence, the more the component

Excerpt from ISBN 978-3-00-053387-7

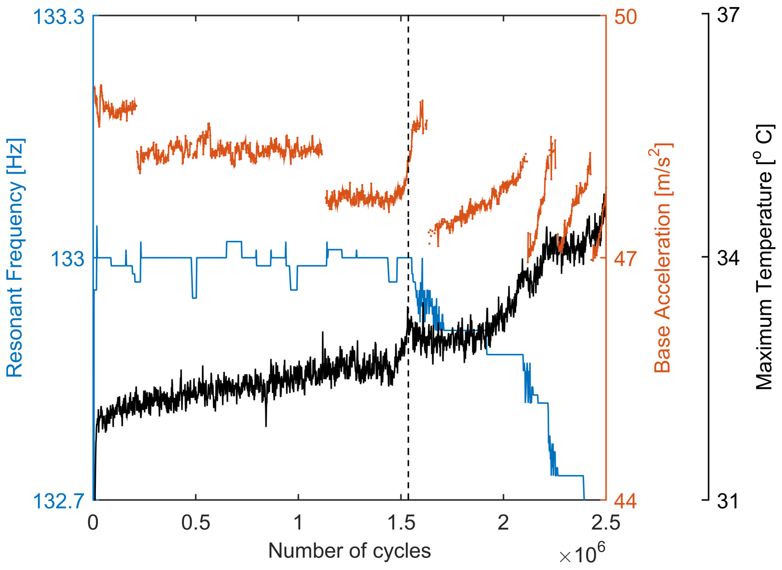

Figure 2. Experimental data of resonant frequency, base acceleration and maximum temperature of a single test run at constant vibration amplitude and resonant phase. The dotted line indicates the initiation of delamination captured by the thermal camera.

got damaged, the higher was the stiffness reduction and the resonant frequency reduction. The vibration was controlled by a LabView software which processed the feedback signals from a Laser Doppler Vibrometer (LDV) and an accelerometer.

In the presented work, one substantial modification to the described testing method is made to enhance the critical event, avoiding a controller action. In Figure 2, which shows data of a coupon tested with that methodology, the critical event is captured by the temperature rise around 1.5 M cycles. The temperature increase resulting from the delamination onset was about 0.5°C, a relatively small value compared to the sensitivity of the thermal camera and the signal to noise ratio. Nevertheless, focussing on the acceleration curve, a very steep change in slope can be observed at the same number of cycle. For that test, the Phase Lock Loop (PLL) was controlling the excitation frequency, causing drop-offs both in frequency and acceleration traces. By excluding these drop-offs, the acceleration profile would have a smooth trend that changes abruptly as soon as the delamination onset. The same profile was observed for other tests as shown in Figure3.

3. The critical event

In the light of these observations, a new testing campaign was carried out at constant frequency and constant vibration amplitude. The excitation frequency was chosen to be at the right hand side of the transmissibility response in order to have a decrease in the transmissibility factor for an increase of structural degradation.

A clean critical event was observed in the fatigue of the components as an abrupt change of dynamic parameters, such as base acceleration and resonant phase. In Figure 4 critical events are depicted by steep changes in the resonant phase. For all the cases, that step-change occurred at the moment of the sharp increase in temperature. By plotting the strain versus time to failure (or number of cycles) one obtains the S-N curve shown in Figure 5.

Excerpt from ISBN 978-3-00-053387-7

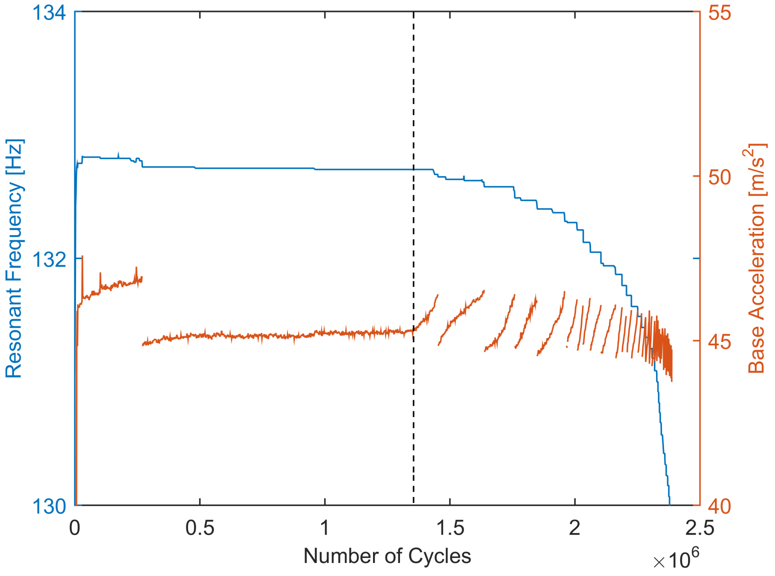

Figure 3. Experimental data of resonant frequency and base acceleration of a single test run at constant vibration amplitude and resonant phase. The dotted line indicates the initiation of delamination captured by the thermal camera. It can be seen that the drop in frequency starts after the initiation of delamination.

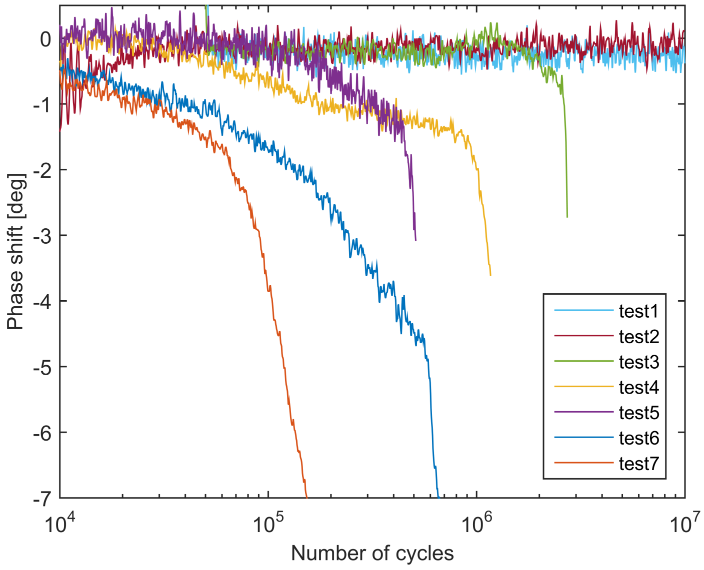

Figure 4. Experimental data at different increasing severities. T1 refers to the lowest severity and T7 refers to the highest severity.

Excerpt from ISBN 978-3-00-053387-7

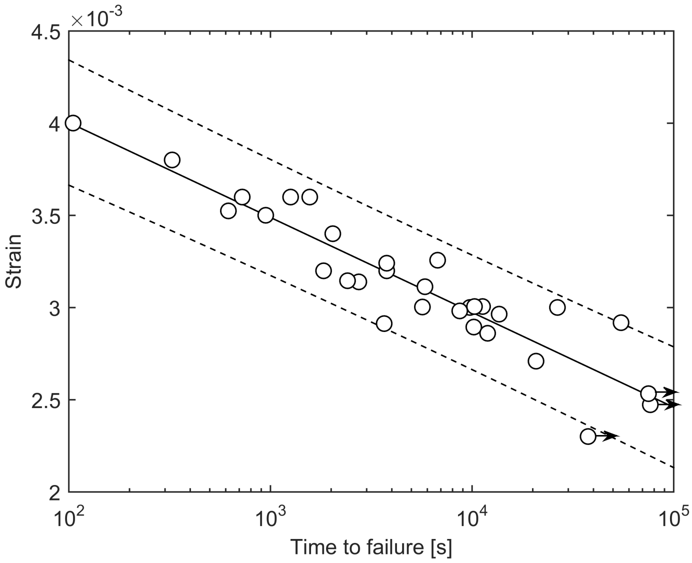

Figure 5. SN curve by means of strains up to the critical event.

4. FE analysis

In order to verify the possibility of simulating the critical event with an FE model, a dynamic VCCT is carried out in a 2D analysis, using ABAQUS. It is demonstrated, assuming the overall structural degradation as a consequence of a single and well-defined crack, that the increase in ERR drives a fast delamination after a certain number of cycle of stable propagation.

The 2D model is built and meshed starting from a micrograph, in order to have a high fidelity representation of the component cross section. The specimen is an assembly of three parts, bonded together by tie constrains but in the areas affected by delamination. These three areas represent the transverse crack, the crack in the thick section and the one in the thin section, as shown in Figure 6.

For the pristine case the nodes that the tree parts have in common are connected by massless spring elements. In a dynamic simulation this approach allows to extract the forces at the nodes without considering the inertial effects.

The transverse crack is extremely fast due to the weak interface and the high stress concentration, hence it can be considered already open in the pristine case. Therefore the crack tips to be propagated are two, one in the thick section and one in the thin section, at the interface between the outer ply and the second ply (Figure 7). Other possible directions are neglected considering the experimental outcomes, where, in all the cases, the delamination occurred between the first two plies.

Spring elements are removed one by one, both to the thick section and to the thin section, according to the Paris' law using the rules of mixture as follows:

$$\frac{da}{dN} = C_m \left(\frac{\Delta G_I}{G_{Ic}} + \frac{\Delta G_{II}}{G_{IIc}} \right)^{n_m} \tag{1}$$

where C_m and n_m are calculated from C_I, C_{II}, n_I and n_{II} (Table 1) and considering the mode mixity as

Excerpt from ISBN 978-3-00-053387-7

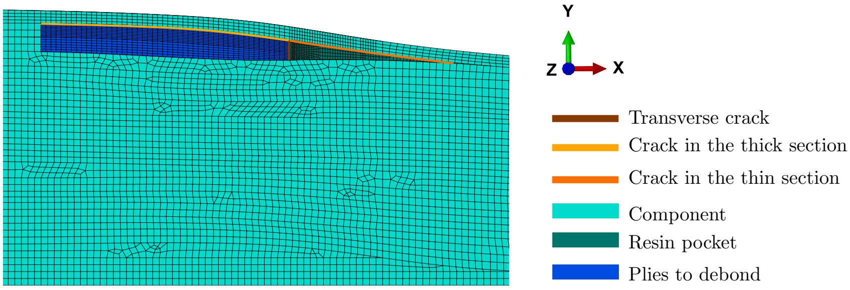

Figure 6. Zoom of the side of 2D model showing the three parts and the interfaces where the crack is propagated: the transverse crack is opened from bottom to top, the crack in the thick section from right to left and the crack in the thin section from left to right.

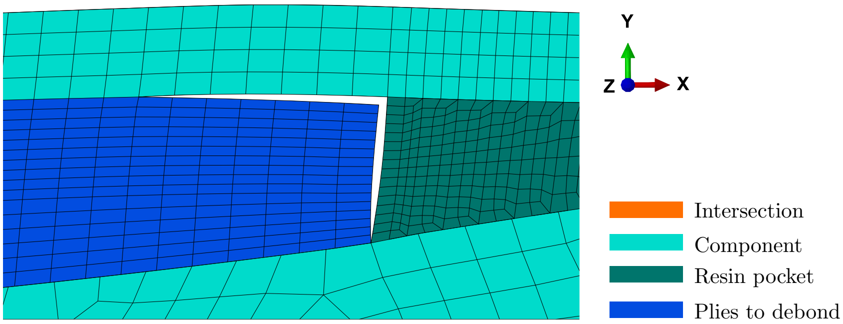

Figure 7. Details of 2D model around the ply-drop. Image shows the local mode shape that is used for the calculation of the SERR, while the crack is propagating only towards the thick section.

weight factor:

$$C_m = \frac{G_I}{G_T} C_I + \frac{G_{II}}{G_T} C_{II} \tag{2}$$

$$n_m = \frac{G_I}{G_T} n_I + \frac{G_{II}}{G_T} n_{II} \tag{3}$$

The final results is shown in Figure 8. Despite a very small change in resonance frequency, the structure undergoes a sharp change in phase response.

5. Conclusions

Data from fatigue testing campaign are analysed and a new method for carrying out vibration fatigue testing is described. The first conclusion concerns the cost-effectiveness of the presented method. Assuming that the critical event is acceptable as the failure criterion, the testing time is reduced. It would be not necessary to wait until the resonant frequency change reaches a 10% reduction to define a component as failed.

Further to that, critical events are well detectable in a vibration fatigue testing. These events are points of discontinuity in the slope of some dynamic parameters (e.g. base acceleration, phase). It is shown that critical events divide the fatigue life of the component in two parts, each of those governed by a different ratio of change of the dynamic parameters. Therefore one can consider the critical event as the failure

Excerpt from ISBN 978-3-00-053387-7

Table 1. Fracture mechanics properties for IM7/8552.

G_{Ic} (N/m)	C_I (m/cycle)	n_I	G_{IIc} (N/m)	C_{II} (m/cycle)	n_{II}
208 [18]	6.51e-6 [18]	5.29 [18]	1334 [18]	6.69e-5 [19]	9.6 [19]

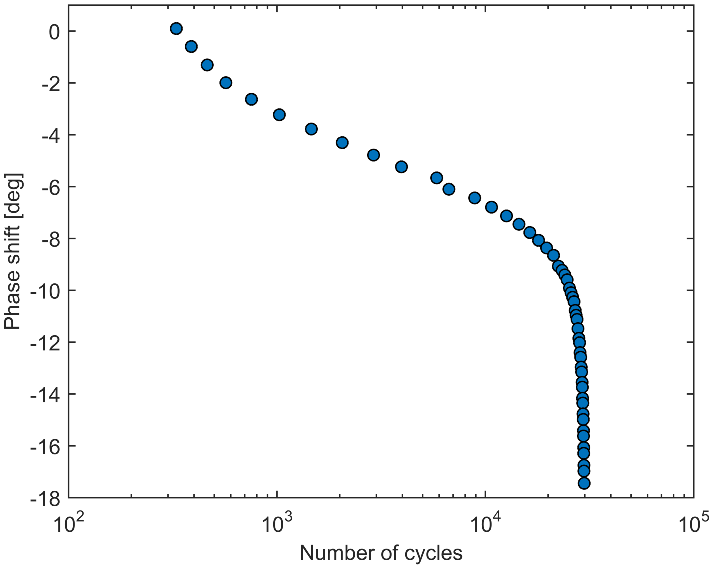

Figure 8. Phase change in the response of 2D model with a crack propagated by means of VCCT.

criterion since it marks a well defined change in the structural degradation rate. Up to that point there are not obvious structural consequences for the tested component.

One last remark on the presented work is that the described critical event occurs while the resonant frequency change is less than 0.5%, or in other words the bending stiffness reduction is about 1%.

Acknowledgments

The authors would like to acknowledge the support of Rolls-Royce plc for the support of this research through the Composites University Technology Centre (UTC) at the University of Bristol, UK.

References

[1] B. Bhattacharya. Continuum damage mechanics analysis of fatigue crack initiation. *International Journal of Fatigue*, 20(9):631–639, 1998.

[2] M. D. Sangid. The physics of fatigue crack initiation. *International Journal of Fatigue*, 57:58–72, 2013.

[3] K. Reifsnider. Fatigue behavior of composite materials. *International Journal of Fracture*, Vol. 16(6):563–583, 1980.

[4] M. J. Salkind. Fatigue of composites. *Composite Materials Testing and Design (2nd Conf), ASTM STP 497, American Society for Testing and Materials*, pages 143–169, 1972.

[5] S. V. Lomov et al. Experimental methodology of study of damage initiation and development in

Excerpt from ISBN 978-3-00-053387-7

textile composites in uniaxial tensile test. *Composites Science and Technology*, 68(12):2340–2349, 2008.

[6] M. Quaresimin and M. Ricotta. Fatigue behaviour and damage evolution of single lap bonded joints in composite material. *Composites Science and Technology*, 66(2):176–187, 2006.

[7] G. D. Sims. Fatigue test methods, problems and standards. In Brian Harris, editor, *Fatigue in Composites*, chapter 2, pages 36–62. Whoodhead Publishing Limited, 2003.

[8] ISO 13003 - Fibre reinforced plastics - Determination of fatigue properties under cyclic loading conditions, 2003.

[9] M. May and S. R. Hallett. A combined model for initiation and propagation of damage under fatigue loading for cohesive interface elements. *Composites Part A: Applied Science and Manufacturing*, 41(12):1787–1796, 2010.

[10] D. Di Maio and F. Magi. Development of testing methods for endurance trials of composites components. *Journal of Composite Materials*, 49(24):2977–2991, 2015.

[11] O. KováÅík et al. Resonance bending fatigue testing with simultaneous damping measurement and its application on layered coatings. *International Journal of Fatigue*, 2015.

[12] S. Han et al. Vibration fatigue analysis for multi-point spot-welded joints based on frequency response changes due to fatigue damage accumulation. *International Journal of Fatigue*, 48:170–177, 2013.

[13] P. Lorenzino and A. Navarro. The variation of resonance frequency in fatigue tests as a tool for in-situ identification of crack initiation and propagation, and for the determination of cracked areas. *International Journal of Fatigue*, Aug 2014.

[14] B. Lazan et al. Dynamic testing of materials and structures with a new resonance-vibration exciter and controller. Technical report, Wright Air Development Center, Ohio, 1952.

[15] M. Traupe, J. Hug, and H. Zenner. Variable Amplitude Loading on a Resonance Test Facility. *Journal of ASTM international*, 1(10):1–14, 2004.

[16] Daniel Backe, Frank Balle, and Dietmar Eifler. Fatigue testing of CFRP in the Very High Cycle Fatigue (VHCF) regime at ultrasonic frequencies. *Composites Science and Technology*, 106:93–99, jan 2015.

[17] F. Magi, D. Di Maio, and I. Sever. Development of a testing method for vibration fatigue at resonance. In *20th International Conference on Composite Materials*, Copenhagen, July 2015.

[18] Peter Hansen and Rod Martin. DCB, 4ENF and MMB characterisation of S2/8552 ans IM7/8552. Technical Report September, Materials engineering research laboratory LTD, 1999.

[19] Lf Kawashita, Mi Jones, R.S. Trask, S.R. Hallett, and M.R. Wisnom. Static and fatigue delamination from discontinuous plies - experimental and numerical investigations. In *Proceedings of the International Conference on Composite Materials - ICCM 17*, pages 1–17, 2009.

Excerpt from ISBN 978-3-00-053387-7