Chapter 6
Mapping the Nonlinear Vibration Responses of Composite Aerospace Structures during Endurance and Qualification Testing

D. Di Maio, F. Oude Tanke, and J. van Tiggelen

Abstract While carbon fibre reinforced polymer composites are well-known for their high strength-to-weight ratio, their fatigue behaviour is difficult to predict. Fatigue of composites is generally considered one of the most challenging physical phenomena due to its multi-physics and stochastic behaviour. One of the most challenging aspects of exploring fatigue properties is the extensive time required for fatigue testing. To determine the fatigue life of a test specimen, the number of required load cycles ranges up to millions. The limitation of testing frequency is caused by the viscoelastic properties of the matrix material, which result in self-heating at high testing frequencies. The objectives of XCTE within the DSTANDART project are to increase the rate of mechanical testing by utilising the High Cycle Fatigue (HCF) testing technique and to understand how to measure, analyse, and decouple the thermo-mechanical forces under high rates of cyclic loading. Fatigue testing can be significantly accelerated when high-frequency testing methods are employed. This paper reports the technological advancement achieved through high-frequency testing on two aerospace components: a) a scaled turbine fan and b) a representative aero demonstrator. Both structures embed a typical design feature, ply termination, to change the thickness from the root to the aerofoil of the blade. Those terminations create resin pockets, which are known to be localised stress raisers leading to the onset of fatigue damage. The paper reports on high-frequency experiments conducted in two testing facilities. The first experiment was executed at the Rolls-Royce Mechanical Testing Operational Centre (MTOC) in Berlin (DE), the second experiment was conducted at the NLR testing facility in Marknesse (NL). High-frequency testing and analysis are now a key technology of the spin-off XCTE, which was born thanks to the D-STANDART European project.

Keywords Vibration fatigue · Nonlinear response · Composites

Introduction

Composite structures are known to exhibit complex fatigue behaviour due to their stacking sequence and embedded features, such as fibre discontinuity, waviness, resin pockets, and voids, among others. Therefore, any composite laminate requires mechanical testing to determine the material and fatigue properties. The latter properties can be very time-consuming when the number of excitation cycles is large, and the excitation frequency is set lower than five cycles/sec to avoid any self-heating caused by the viscoelastic properties of the resin in the composites. There are numerous research studies examining the environmental and self-heating temperature effects on fatigue life [1, 2, 3, 4, 5], which suggest a substantial reduction in residual life due to the coupling between mechanical and thermal loads during fatigue cycles. Clearly, temperature-dependent material properties are of no use for engineers who develop fatigue models, assuming a constant entropy behaviour during the development of fatigue damage. The temperature effect(s) are modelled via superposition principles by using test data generated using low excitation rates under different temperature conditions. The result is that a significant amount of time is invested in generating fatigue test data to feed fatigue damage models, even when any aerospace structure can naturally

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be subjected to oscillatory motions higher than five cycles/sec and environmental conditions (temperature and moisture). Within the D-STANDART project, the consortium partners investigate the effects of temperature and humidity, with one partner focusing on high-frequency testing under various environmental conditions. These tests clearly indicate how the loss of stiffness correlates with the increase in self-heating temperature in the cross-laminate made of IM7-8552. The research will be published after the ICCM event, so it is advisable to monitor the upcoming literature.

The high-frequency tests were developed and proven in several research studies [1, 2, 3, 4], which are briefly summarised in this paragraph. The composite sample is held by a specific fixture consisting of two rods that support the sample during the excitation of the first bending motion, allowing the structure to rotate at the clamping region. A ply-drop, or cut-ply, features the cross-ply laminate to generate a stress away from the clamping region. That stress raiser is typically placed a few tens of millimetres away from the clamp. The test is executed at a constant excitation frequency, corresponding to the pristine resonance frequency, during the fatigue test. The frequency response phase is measured by the ratio between the input stimulus (typically a base acceleration) and the output response, as measured by a laser Doppler vibrometer (LDV). The vibration amplitude is maintained constant during the fatigue test, thus achieving a displacement control test (noting that the velocity measured by the LDV is converted into displacement). The loss of stiffness as a function of the excitation cycles is measured by the frequency response phase rather than the change of the natural frequency of the test object. The phase is calculated from the inverse tangent of the ratio between the natural frequency and the drive frequency (constant). Consequently, a minimal natural frequency change is transformed into a significant phase deviation due to the tangent function. The temperature (measured by an IR camera) and vibration measurements are synchronised, with the temperature reading sampled every N elapsed cycles to avoid overloading the PC hard drive. The experiments are typically conducted inside an environmental chamber to control the ambient temperature, which scales up or down the effect of self-heating temperatures. The fatigue test data consist of frequency response phase, peak surface temperature (in the region of the ply-drop), and base acceleration versus excitation cycles. These plots will be presented in the following sections.

The experimental technique introduced in the previous paragraph to characterise the fatigue behaviour is applied to two test structures made of composite materials. The first structure is a scaled turbine fan made of a composite material, the type of which and stacking sequence were unknown to the authors [2]. The second structure is an aero demonstrator developed in the D-STANDART consortium. The demonstrator is a quasi-isotropic stacking sequence made of IM7-8552 material. The two experiments were conducted in two different industrial testing facilities. This paper will present the experiments performed and the output generated by the fatigue tests.

Experimental set-up

This section describes the experimental set-up, which is common to both experiments, despite being executed in different years. The first experiment was conducted in Rolls-Royce MTOC in 2015, while the second experiment was conducted in NLR in 2025.

The experimental set-up is presented in Figure 1. The test structure is mounted on a slip table, which is connected to an electromagnetic shaker that exerts the excitation force. An accelerometer is attached to the slip table to measure the input base acceleration to the test structure. A strain gauge is mounted near the root of the test structure and is used for calibration between the input acceleration, output strain, and output displacement. The LDV and the IR camera are installed in front of the test structure. The XCTE sniper control panel is a custom-made software to control the sensors and exciter. The control panel can perform force or displacement control, depending on the test definition. Moreover, the frequency or phase lock loop at constant amplitude is yielded by a Proportional Integral Derivative (PID) control scheme.

The first task to accomplish is a frequency check before performing any High Cycle Fatigue with the High Frequency tests. The frequency check is a simple test where the excitation sweeps a frequency range to identify the resonances of the test structure. This step is essential to determine the first bending resonance for which a calibration step is required. In both experiments, the first mode of vibration was the target mode; however, any other fundamental mode can be tested similarly.

Once the frequency check is completed, the second task is to calibrate the base acceleration, the strain gauge, and the LDV laser output. This procedure ensures that a relationship is established between the three sensors, which typically exhibits nonlinearity due to large deformation. This calibration mustn't overload the structure; therefore, it is advisable to avoid large input forces.

At this point, the excitation frequency (resonance) and calibration are known; the final step is to set up the type of force or displacement control for the HCF test. Having decided the kind of control, the HCF can be started, and the frequency response phase is continuously tracked to monitor the loss of stiffness. At the same time, the sniper control panel measures and stores the output of the other sensors, but the strain gauge, whose wire has been cut, is not included.

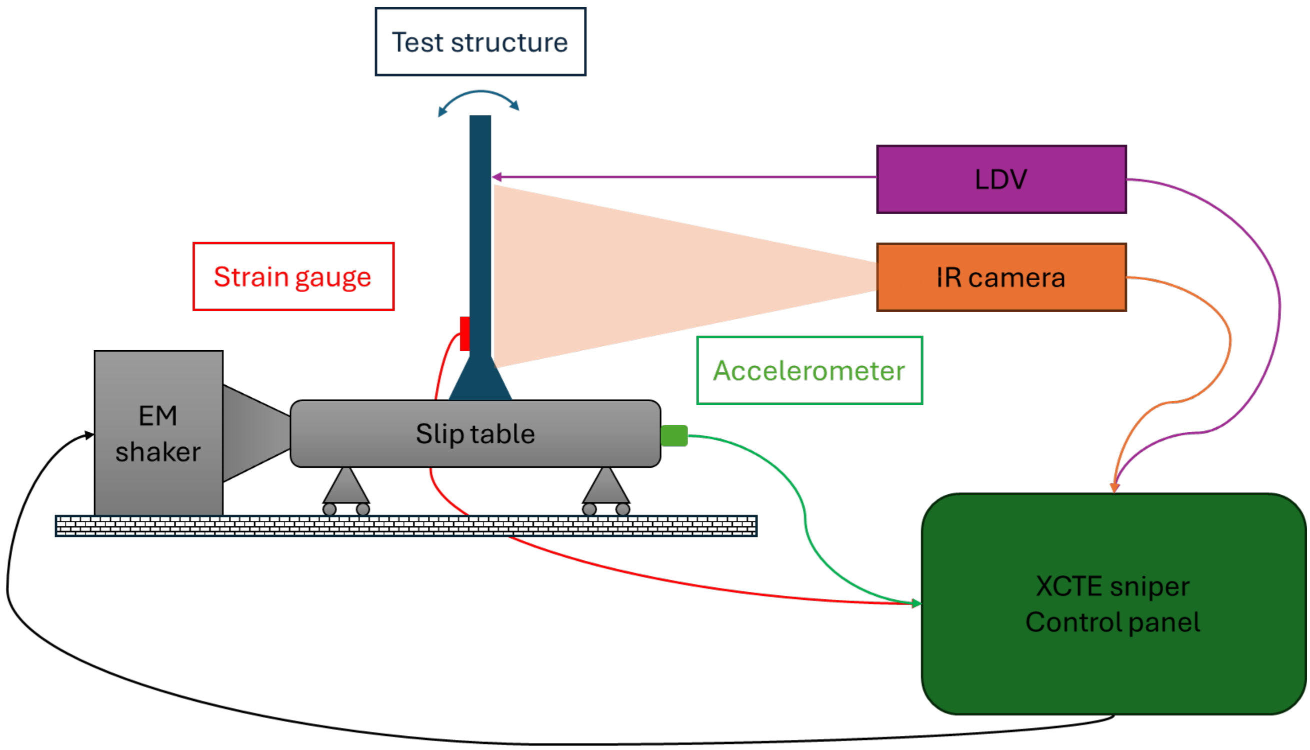


Fig. 1 Test set-up used for the two experiments

Figure 2 shows a close-up of the test set-up where the blade can be seen vibrating in its test fixture. Note that the test fixture was specifically designed to match the blade root. Figure 3 illustrates the complete measurement set-up, as schematically depicted in Figure 1.

Fig. 2 Close-up of the test set-up

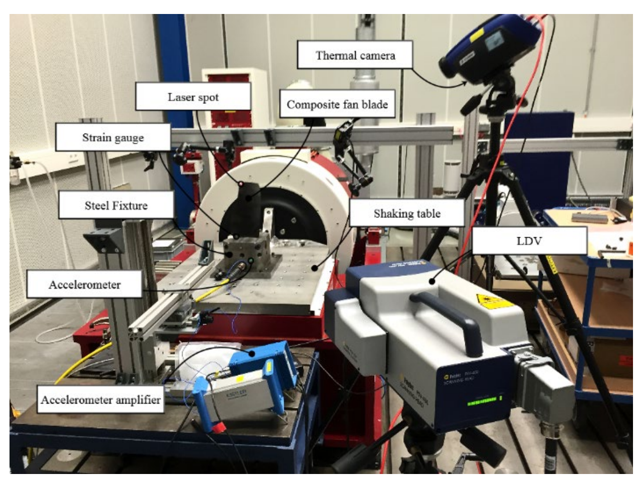


Fig. 3 Blade test set up

Although the two experiments were conducted in different years, the modus operandi remains the same. The set-up can be adapted to what the test facility can provide, as long as it can be realised as described in Figure 1. XCTE technology enables the set-up, performance, and analysis of fatigue test data in hours rather than days.

The following section presents the experimental test data and how the test data from the second experiment are used to evaluate a global master curve of fatigue onset damage growth. It is worth mentioning that the first experiment could be executed using only one fan blade; hence, it was a single shot that could not be missed. The second experiment could be executed using three aero demonstrators, which allowed verifying the repeatability of the results across the three test structures. The comparison between the first and second experiments is not presented in this paper. Figure 4 shows a close-up of the test structure, and Figure 5 shows the full test set-up.

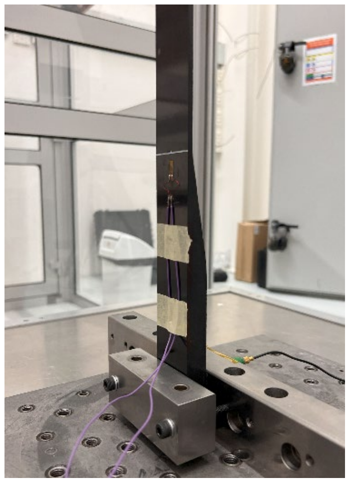


Fig. 4 Close-up of the test set-up with the strain gauge.

Fig. 5 DST aero demonstrator test set-up.

Experimental results

This section will present the experimental results obtained from the two experiments. It is worth explaining briefly hereafter why and what the objectives of the experiments were.

The first experiment of the composite blade had two objectives. The first objective was to prove that the fatigue behaviour observed from cross-ply laminate embedding ply drops [2, 3, 4] at the University of Bristol laboratory was not case-dependent. Hence, similar fatigue behaviours could be observed from scaled fan blades. The second objective was to demonstrate that such a fatigue behaviour could be reproduced and tested in an industrial testing facility.

The second experiment on the DST aero demonstrators also had two objectives. The first objective was to demonstrate that the first experiment on the fan blade was not a fortunate test case, but rather one that could be reproduced years later. The second objective was to evaluate a master curve based on the fatigue onset damage. The second goal was achieved due to the availability of three test structures and the novel testing technique used to obtain the master curve.

Calibration base acceleration, strain and displacement

Once the frequency check is executed to identify the target resonance, the calibration between the input base acceleration and the output strain and displacement responses is performed using a simple stepped sine test. The procedure consists of exciting under steady-state conditions a frequency near the resonance peak for multiple acceleration amplitude levels. The nought-to-peak of the vibration signals measured from each sensor is processed. Figure 6 shows the relationship between strain and displacement obtained from the fan blade calibration exercise. A linear relationship can be observed. However, a nonlinear behaviour might appear if the strain vs base acceleration or displacement vs base acceleration is plotted. Therefore, the calibration performed for the aero demonstrator retained the use of the three signals, rather than the two used for the fan blade.

Figure 7 shows the relationship between the input base acceleration and the output strain for the aero demonstrator. The calibration was performed up to 5 (g) to avoid overloading the test structure. However, it is visible that nonlinear behaviour, which is extrapolated up to 15 (g), where the fatigue behaviour is expected to develop. The nonlinear behaviour is expected because of the large deformation achieved under steady-state vibrations. It is essential to perform this experimental characterisation to avoid setting up incorrect vibration amplitudes during the HCF tests.

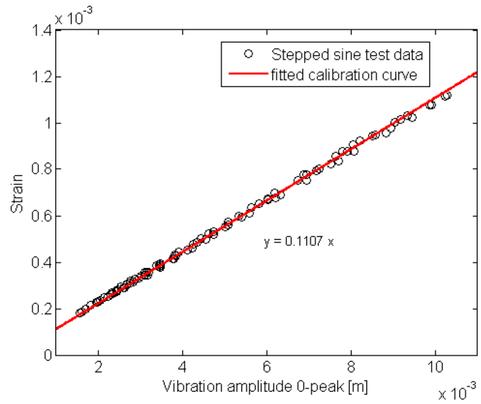


Fig. 6 Fan blade strain-displacement calibration.

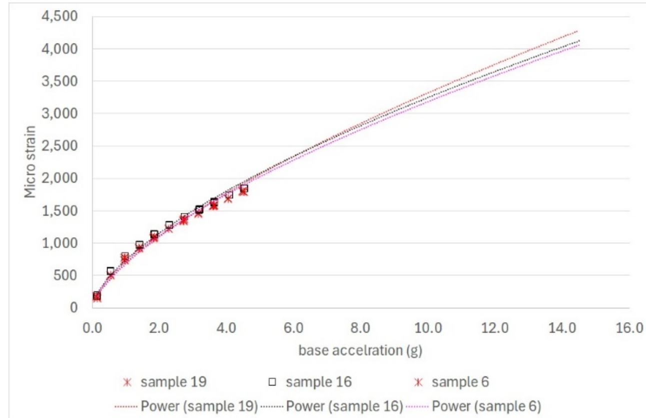


Fig. 7 Aero demonstrator strain - base acceleration calibration.

Test results

This section describes the HCF test data obtained from the fan blade and the aero demonstrator. The type of HCF test is displacement control, which involves using a single excitation frequency and vibrating the target point at a constant amplitude throughout the entire duration of the HCF trial. This procedure is also applied to the aero demonstrator, using a slightly different approach, which will be described later.

The first test results presented are from the fan blade. As previously introduced, the expectation was to observe similar fatigue behaviour already observed with small coupons tested in a university laboratory. The results of the HCF test demonstrated that the experimental procedure was valid for both small coupons and scaled fan blades, thereby meeting the objectives. Figure 8 shows a plot that reproduces three curves: the frequency response phase, the base acceleration, and the surface peak temperature. It is essential to note the correlation between phase decay and the increase in acceleration. This

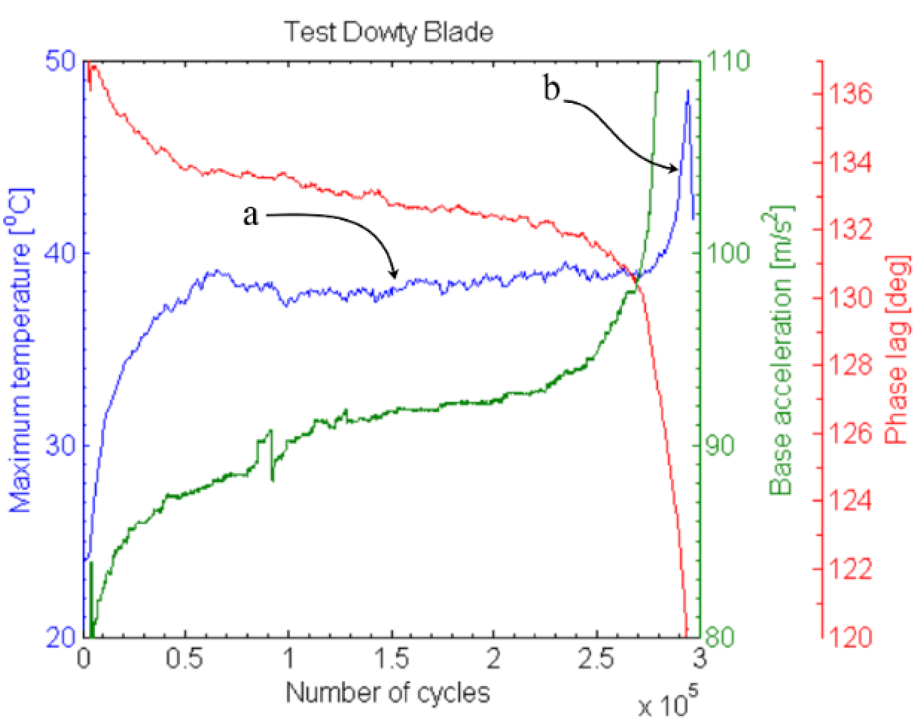


Fig. 8 Frequency response phase, base acceleration and surface temperatures of the fan blade.

behaviour occurs because the mechanical system loses stiffness due to fatigue, and thus, fatigue damage is initiated by the combined mechanical and thermal loads. Both the phase and the acceleration have a specular behaviour. At the same time, the surface peak temperature follows a trend similar to the acceleration towards the end when a temperature hot spot develops. Figure 9 shows two pictures from the IR camera at two different time instants, when the surface peak temperature reveals a stress concentration (point a) in Figure 8) and when the temperature hot spot is fully developed (point b) in Figure 8).

The main difference with the test carried out with the aero demonstrator was (i) to perform two HCF tests increasing the amplitudes every N number of cycles, instead of running a single amplitude, and (ii) to perform one HCF test at a higher amplitude than the previous two HCF tests. The latter goal was to demonstrate that one test structure was sufficient to extract a master curve capable of predicting the results of a different HCF test conducted using a new test structure.

Therefore, one aero demonstrator was tested at a very low amplitude of vibrations, which were incremented every 100,000 cycles. The test was interrupted every 100k cycles to perform nonlinear modal testing. The motivation of that modal test was to observe the change in the nonlinear dynamic response as a function of the increased fatigue behaviour. The modal test was conducted using the last HCF amplitude and was completed quickly to minimise excessive exposure to dynamic loads. At the end of each HCF test, the frequency response phase, acceleration and surface temperature were stored for analysis. These test sequences were executed for two of the three test structures; the last one was tested to HCF using a single amplitude, which was higher than the one set up for the other two demonstrators.

The HCF test data stored from the first test structure were processed into a master curve based on the onset of fatigue damage. To achieve this, the frequency response phase curves were processed using a specific data analysis toolset to extract the loss of stiffness per unit cycle, described as $d\Phi/dN$, as a function of the input base acceleration. The same procedure was applied to the single frequency response phase curves obtained from the HCF test and plotted on the graph. Figure 10 shows the power law curve extracted from the aero demonstrator tested at several amplitudes, along with a single data point from the other test structure. The single data point (in blue) in Figure 10 lies not far off the power law curve.

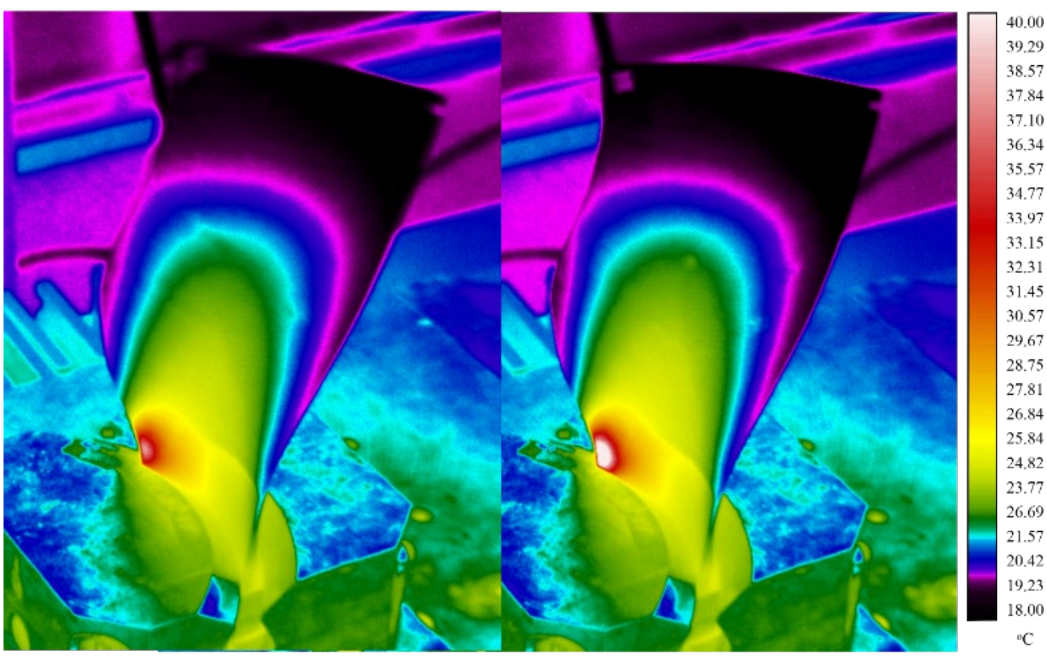


Fig. 9 Surface temperature profile in points a) and b) of Figure 8.

Finally, Figure 11 shows the infrared image of the test structure with a fully developed temperature hot spot caused by fatigue delamination.

Final remarks on the fatigue testing

There are many positive outcomes from this experimental campaign in NLR. The experimental procedure is repeatable and robust. Experiments conducted in two different environments and with two additional test structures indicate that the method for tracking loss of stiffness is valid regardless of geometry and material properties. Moreover, the experiments using the aero demonstrator show what was not possible with the fan blade. A single test structure can be used to evaluate a power law

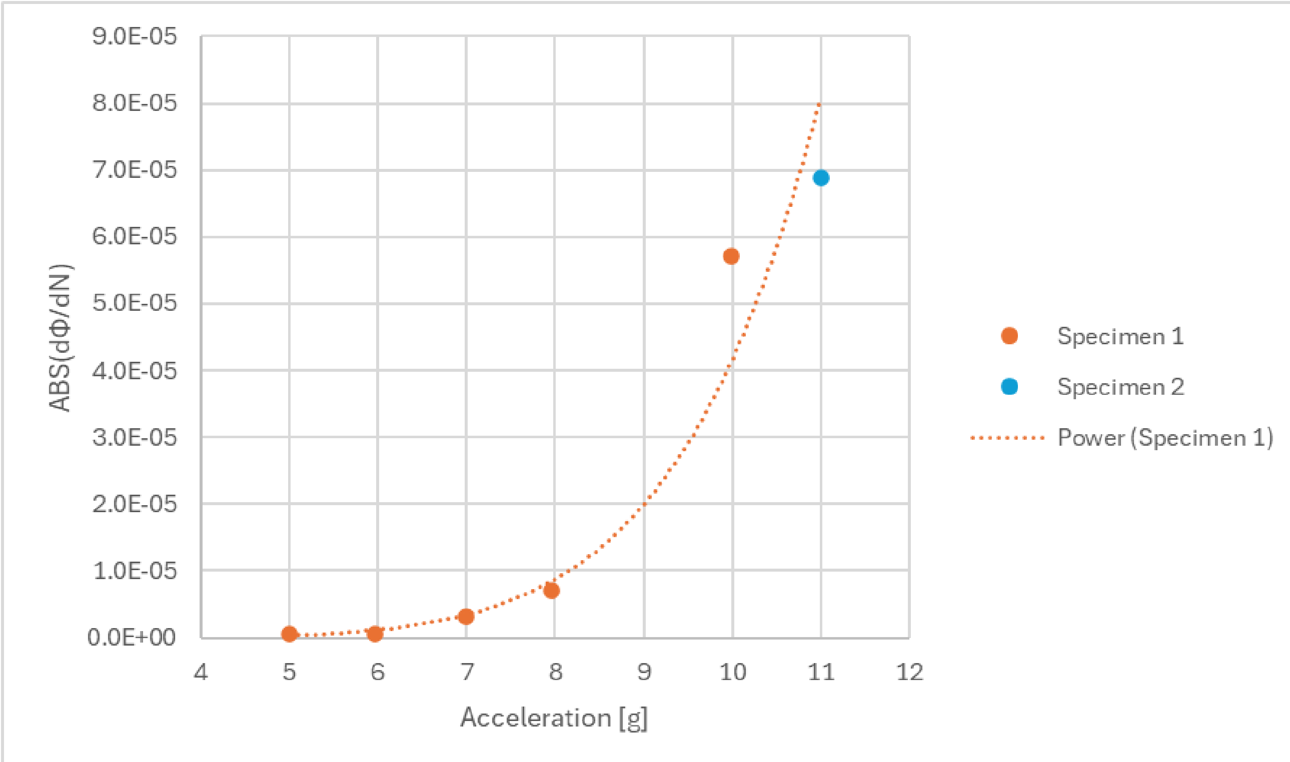


Fig. 10 Surface temperature profile in points a) and b) of Figure 8.

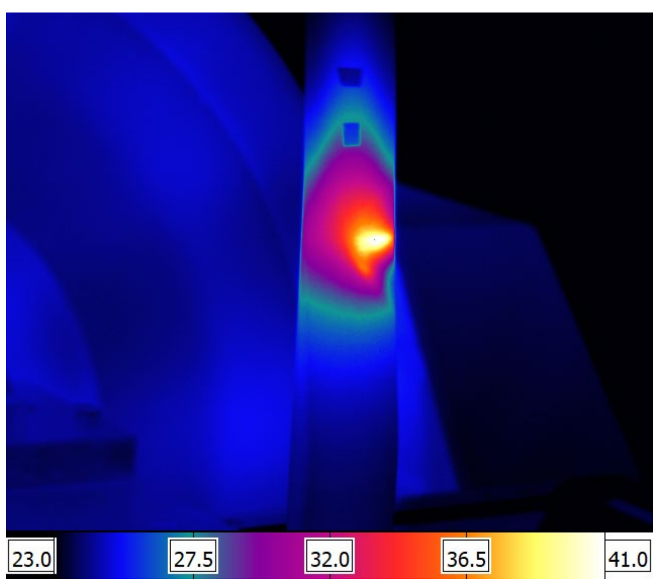
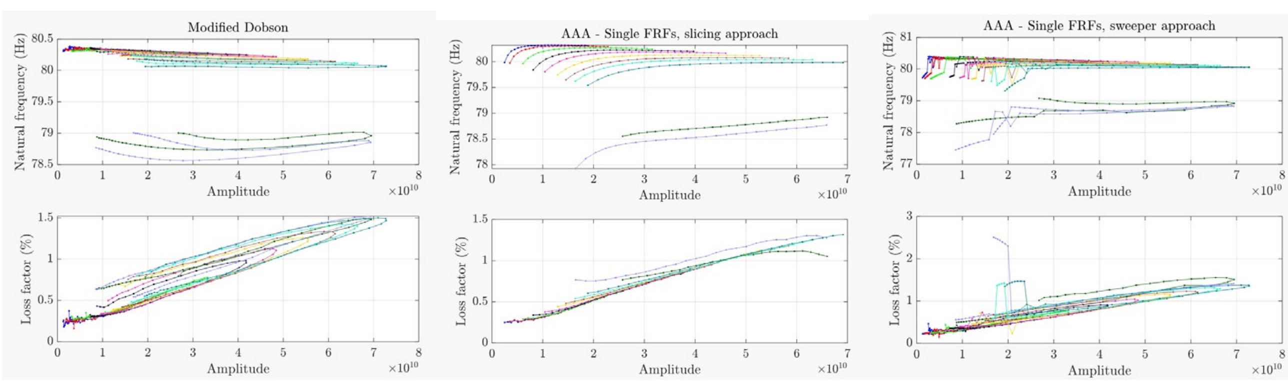


Fig. 11 Infrared picture of specimen 1 with developed temperature hot spot.

function that describes the loss of stiffness per unit excitation cycle as a function of the input load. In this example, the base acceleration was used instead of the strain load; however, the calibration curve allows the references to be interchangeable. Ultimately, the XCTE team had 60 hours to perform the HCF tests with three aero demonstrators in NLR. Despite the self-heating condition, which affected the residual life, the results showed that the fatigue behaviour of the aero demonstrator is a matter of hours rather than days. Finally, any analyst can commission such an experimental test to verify if the design choice delivers the expected durability or not.

Mapping nonlinearity during fatigue testing

One of the experimental tasks conducted during the vibration fatigue experiment was to map the nonlinear behaviour of the aero demonstrator blade. As explained earlier, the fatigue test was executed using incremental excitation steps. Hence, one modal test at the level of the fatigue test amplitude was initiated before the fatigue test began. One Frequency Response Function was measured for each excitation step. The observation of the nonlinear behaviour of the test article aimed to map the change in structural dynamic properties during fatigue damage. Figure 12 illustrates three different analysis techniques used to derive both the natural frequency and the damping loss factor at varying levels. The identification techniques used were the modified-Dobson and the AAA methods. Two of these identification methods were executed using the sweeper approach [6], while the other used the slicing approach. Each colour in the plots identifies the processed FRF at the excitation level of the fatigue test. The variation in dynamic properties is identified over the amplitude of vibration in the FRF. One observation concerns the natural frequencies, which indicate a softening behaviour as fatigue damage occurs. A sudden change is visible in the frequency plot, indicating that a major stiffness change occurred due to the onset of fatigue damage. The other observation is about the damping loss factor curves. The change in damping is continuous, and the plots do not exhibit sudden variations, unlike the natural frequencies. Hence, the damping is continuously increasing over the fatigue excitation steps. This behaviour seems to indicate that (i) the composite material is changing its loss modulus and (ii) the contact friction is increased as a function of the excitation force. Unfortunately, it is not possible to discriminate between the two damping behaviours in the presented tests.



(a) Modified-Dobson (b) AAA Equal amplitude (c) Sweping method

Fig. 12 Natural frequency and damping loss factor estimations as a function of the vibration amplitude.

Conclusions

This short paper presents some new developments in the area of accelerated fatigue testing developed by XCTE, as part of the D-STANDART EU Horizon project. The testing technology proved to be robust and adaptable to different laboratory environments. Two test cases were presented in the paper; one was an experiment on a composite fan blade conducted in 2015 at a facility in Berlin, and the other was a more recent experiment on an aero demonstrator. The first experiment shows the type of testing set-up and test data generated during an HCF test. The second experiment shows how the HCF test data can be converted into a power law describing the loss of stiffness as a function of the input base acceleration. The scientific value is auspicious because one test structure is sufficient to evaluate a power law describing the fatigue behaviour. The scientific impact will enable engineers to utilise XCTE testing technology to probe structures and assess the most robust design. Moreover, the effectiveness of the proposed HCF tests is demonstrated by their time-saving and potentially cost-saving benefits. The second experiment was conducted over a 60-hour time frame, which is considerably shorter than the standard mechanical tests executed at low excitation cycle rates. Hence, engineers will be able to probe their design optimisations in a very short time. The time savings will enable optimal optimisation towards the standard route of validation and verification.

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