

EFFECT OF LOAD RATIO, TESTING FREQUENCY, TEMPERATURE, MOISTURE, NOTCH AND STACKING SEQUENCE ON THE FATIGUE RESISTANCE OF WOVEN CFRP LAMINATES

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ABSTRACT

A woven CFRP composite laminate has been thoroughly characterized under fatigue. Over 150 tests were performed in order to address the effect of sample geometry (Open Hole Tension, Open Hole Compression, Plain Compression, ...), testing frequency (5Hz, 30Hz) with and without cooling system, load ratio ($R=10$., $R=-1$., $R=0.1$), temperature (RT and 120°C), moisture intake (50% RH and 85+% RH at RT), notch (Open Hole Vs. Plain Specimen), stacking sequence (3 different stacking sequences) on the measured fatigue life of the specimens. This contribution presents the results of this experimental campaign, under the form of normalized SN curves and Constant Life Diagrams (CLD). An original method is proposed to build the CLD of the material by fitting the dependence of the parameters of the wear-out model proposed by Sendekyj [1] as functions of an appropriate bounded variable which is in objective relationship with the load ratio R .

INTRODUCTION

This contribution presents an exploratory experimental work carried out in the framework of the ECOM [2] and ICOGEN [3] regional collaborative projects.

The main objective of this research is to study the fatigue resistance¹ of a candidate material for manufacturing composite equipment for aircraft. Testing is performed in representative environmental and loading conditions. The fatigue testing results presented here are mainly SN curves and constant life diagrams (CLD)².

In order to limit the variability of the results, the study was carried out mainly on open hole specimens.

In a preliminary phase, the effect of the loading frequency on the fatigue life was estimated, along with an in-situ characterization of the stress and frequency dependent self-heating. The effect of the presence/absence of tabs on the failure mode and fatigue life was also examined.

Table 1 summarizes the tested conditions in terms of stress ratios and environment (OH yields for open hole specimen, P yields for plain specimen):

	$R = -1$	$R=10$	$R=0.1$
RT Dry	OH (3 lay-ups) P	OH	OH – long
RT Wet	OH	-	-
ETA (120°C) Dry	OH	-	-
Autogenous heating	RT Dry OH	-	-

Table 1.

As mentioned in table 1, the effect of the stacking sequence has also been estimated on open hole specimens at $R=-1$.

¹ In this document, the wording strength for an open hole specimen refers to the 'net section strength'.

² Detailed post-mortem failure modes analyses were performed on all the specimens. This information cannot be disclosed.

MATERIALS

The plates are manufactured using the RTM process with an aerospace grade highly cross-linked epoxy resin.

Three types of woven carbon fabrics are used: i) an unbalanced weave with F% ($F > 50$) of fibres in the warp direction and $(100-F)\%$ in the weft direction, ii) an unbalanced weave with $(100-F)\%$ of fibres in the warp direction and F% in the weft direction, iii) a balanced weave. The final fibre volume fraction, fabrics density and details, yarn characteristics, the nature of the fibre and resin cannot be disclosed.

The following lay-ups were tested: 1) L1: 11 plies : $[0_{100-F,2}, 45, 0_{F,2}, \overline{45}]_s$ with a nominal thickness of 3.63mm, 2) L2: 11 plies : $[0_{F,2}, 45, 0_{100-F,2}, \overline{45}]_s$ – actually orthogonal to L1, 3) L3: 15 plies : $[0_{100-F,3}, 45, 0_{F,3}, \overline{45}]_s$ with a nominal thickness of 5.0mm.

TEST SPECIMENS

Preamble: on the need for tabs

A preliminary coupled experimental and numerical study was carried out for stress ratios $R=-1$ and $R=0.1$ in order to assess the need for tabs in terms of correct load transfer to the specimen and valid failure modes. For open hole specimens, where sufficient stress concentration is present within the gauge length, tabbing was deemed unnecessary. For the plain specimen, tabbing could be avoided as a limited amount of non-valid failure modes were observed.

Specimen for testing at $R=-1$ and $R=10$

The option was chosen to go for a short gauge length specimen instead of a long specimen with anti-buckling devices. For the plain and holed specimens, a gauge length of 32mm X 32mm was selected, for a total specimen length of 132 mm, inspired by the AITM 1.0008 standard [5]. In holed specimen, a nominal hole diameter of 6.35mm is required. The specimen geometry is depicted in Figure 1.a.

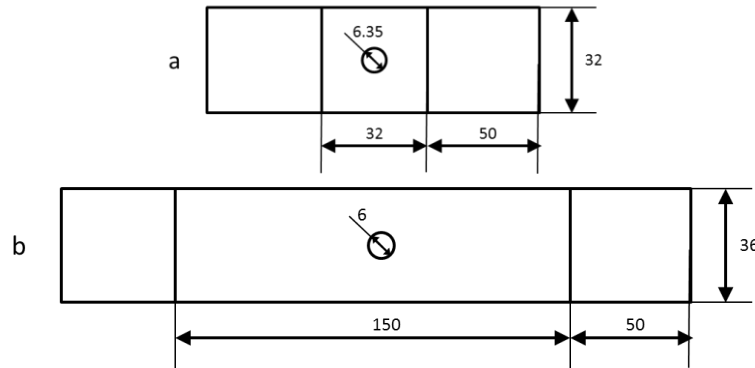


Figure 1. a) Open hole specimen used for $R=-1$ and $R=10$. The plain specimen has the same overall dimensions, the hole being absent (AITM1.0008 spec. A1 and B1). b) Open hole specimen used for $R=0.1$ (ASTM D5766).

Based on the static strength of the individual plies and a simple maximum stress failure criterion, calculations were made to verify that the material fails in compression before significant bending and buckling occur, both for open hole and plain specimens, and both for the pristine and significantly fatigued material. This was validated experimentally by static testing of both plain and open hole specimens: the bending percentage measured by back to back strain gauges was significantly below the requirements, confirming that bending and buckling were negligible.

Specimen geometry for testing at $R=0.1$

The selected specimen geometry was that of the standard ASTM D5766 [4], originally designed for open hole tensile strength testing of laminates. The specimen geometry is shown in Figure 1.b.

TEST SET-UPS

Room temperature / dry testing

The tests were performed in a conditioned room with controlled temperature (23°C +/-3°C) and relative humidity (50% +/-10%). The target temperature and relative humidity are selected according to ASTM D3479 [6].

The tests were performed on a hydraulic axial-torsion machine MTS 000337/002280 Type 319-25C with 250kN load cell and fatigue-rated surfalloy grips. A constant clamping pressure of 3000 Psi ~ 200 to 210 bars is used. Grip alignment was performed before the tests using a specific thick steel reference sample to set a constant grip angle (torsional mode) in order not to affect the axial loading mode.

The temperature on the specimen was measured and recorded during the test using a thermocouple bonded onto the sample surface between the hole edge and the specimen edge.

During cyclic loading, the sample can heat up due to intrinsic friction (viscous heating, internal friction between newly created surfaces e.g. micro-cracks, delamination), extrinsic friction (e.g. with the grips) or through the temperature increase of the hydraulic system itself, the heat being transferred to the sample by conduction. A temperature increase of about 10°C is generally admitted [7]. At low stress levels ($N > 10^6$), before the latest stages of fatigue damage evolution, the regime temperature indeed remains below 35°C, even at high testing frequencies. However, as the stress level increases and the number of cycles to failure decreases, the regime temperature can reach values as high as 40°C. Therefore it was deemed necessary to cool down the sample during testing in certain circumstances identified in section Test Results / Self-heating. The cooling system consists of RT air pulsed at a high flow rate on the two faces of the specimen, the air flow being focused on the hole interior for maximum cooling efficiency in the case of holed specimen.

Elevated temperature / dry testing

A climatic chamber type MTS 651.06E -04 1 (-129°C / +315°C) was used in combination with a special MTS extension rod with axial grips for high temperature testing (MTS 647.10A-321 (-129°C / +315°C)) as well as high temperature 'surfalloy', fatigue-rated, wedges type MTS647.10.

The test preparation methodology consists in

- pre-heating the chamber so that the grips and rods reach the required temperature
- installing the test sample in the chamber
- heating the chamber slightly above the target temperature of 120°C –e.g. 130°C- until the sample temperature (measured by a thermocouple) reaches effectively 120°C. A lag of 10°C between the chamber and sample temperatures can exist. The chamber target temperature is then set back to 120°C.
- starting the test.

Room temperature / wet testing

The specimens moisture intake was performed according to the standard ASTM D5229 [8].

The specimens were held at 70°C and relative humidity 85% in an oven with temperature and humidity control. The weight of one reference specimen was measured once a week with a 0.1mg accuracy until saturation was reached. About 110 days were necessary for acceptable saturation.

In order to maintain humidity saturation during the tests, the gauge length was 'packaged' in a plastic bag, and held in a sponge saturated with water at RT. The sponge saturation was verified periodically.

TEST RESULTS

Self-heating

Fatigue tests were performed on open hole specimens at R=-1 at different stress levels and at test frequencies of 5Hz and 30Hz. The specimens temperature was measured at the sample surface as explained here above.

A single test at R=-1 was performed with a second thermocouple positioned within the laminate, in order to estimate the efficiency of the implemented cooling system.

The conclusions are the following:

- high cycle fatigue testing at 30Hz ($N > 10^6$, $\frac{\sigma_a}{|\sigma_{OHC}|} < \sim 0.466$, where σ_a is the maximum cyclic stress) can be performed without the need for setting-up cooling systems. The threshold for cooling is set at $\frac{\sigma_a}{|\sigma_{OHC}|} = 0.525$.
- At large stresses and $f=5\text{Hz}$ or 30Hz , the implemented cooling system is needed and appears to be effective in the core. Therefore, it is decided to test the samples with the highest flow rate possible, accepting a slightly lower humidity percentage ($\sim 30\%$) due to drier air. Even though the temperature cannot be maintained below 26°C to remain in-line with ASTM D3479, the result will be considered for material evaluation. For instance, keeping a core temperature below 35°C can be considered sufficient.
- The grips have a temperature lower than the specimen itself, proving that the hydraulic machine does not heat up the specimen.

SN curve for open hole specimens - L1 material - RT / Dry conditions - R=-1

The SN curve normalized by the open hole compression strength for R=-1 at RT / Dry condition is shown in Figure 2. Four data sets are plotted: i) the static test results (Open Hole Compression Strength), ii) the fatigue test results at $f=5\text{Hz}$, iii) the fatigue tests results at $f=30\text{Hz}$ and iv) the run-out specimens.

The wear-out fatigue model proposed by Sendekyj [1] first identified based on static and fatigue resistance data at 5Hz is plotted in Figure 2.a, censoring the run-out specimens. The wear-out expression of the SN curve in this case writes

$$\sigma_a = \frac{|\sigma_{OHC}|}{(1-C+CN)^S} \quad (1)$$

where σ_a is the maximum applied cyclic stress, σ_{OHC} the open hole compression strength, N the number of cycles to failure, C and S are fitting parameters. In the iterative fitting procedure described in [1], fatigue data are first transformed to static data using expression (1), a Weibull distribution with shape and scale parameters is fitted to the set of static plus 'equivalent static' data using the maximum-likelihood method. The values of C and S are adjusted progressively in such a way as to maximize the shape parameter of the Weibull distribution. In this work, a gradient based optimizer was used to maximize the shape parameter. As shown in Figure 2.a, the SN curve flattens when approaching $N=1$, this is in line with other reported results on the fatigue of composite laminates.

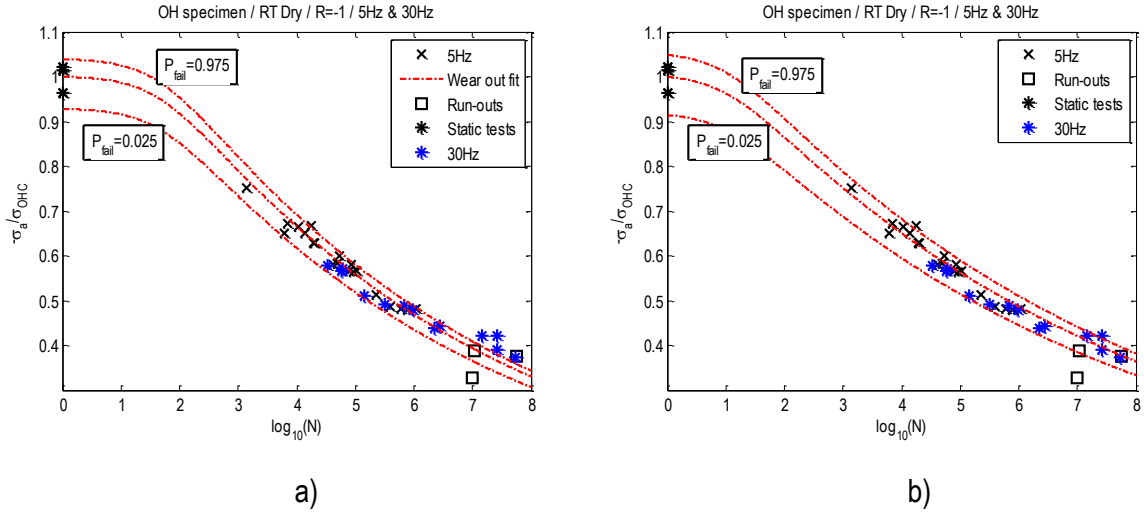


Figure 2. Normalized fatigue and static test results for open hole specimens of the L1 material in RT Dry conditions, at $R=-1$, for $f=5\text{Hz}$ and 30Hz . Also shown in a) the wear-out model identified using the 5Hz results, b) the wear-out model identified using the 5 and 30Hz results.

Figure 2.b shows the fit obtained when taking into account the fatigue data obtained at 5Hz and 30Hz. The 5Hz and 30Hz points somehow overlap below 10^7 cycles, hence the 30Hz fatigue test results are within the 95% confidence interval of the 5Hz fit in this range, suggesting that there is no effect of the test frequency on the fatigue resistance. Indeed, a Wilcoxon rank sum test performed on the sets of equivalent static strengths (below 10^7 cycles) at 5Hz and 30Hz leads to failure to reject the null hypothesis that the medians of the distribution are equal. Beyond 10^7 cycles, the 30Hz points fall outside the 95% confidence interval of the 5Hz-only fit, however there is no experimental point of comparison at 5Hz in this zone. This suggests that the results obtained at 5Hz and 30Hz should both be used in order to achieve a wear-out model fit that flattens adequately beyond 10^6 cycles. More data are needed to characterize the shape of the SN curve at very low stresses (10^8 cycles target).

SN curve for plain specimens - L1 material - RT / Dry conditions - $R=-1$

A limited number of plain specimens were tested under fatigue at $R=-1$. After conducting a rapid screening of the static compressive strength and browsing the stress levels to build a preliminary SN curve, 5 fatigue tests were conducted targeting a fatigue life of 10^5 cycles. All the fatigue tests were performed at 5Hz. The experimental results and wear-out model fit with 95% confidence interval are illustrated in Figure 3.

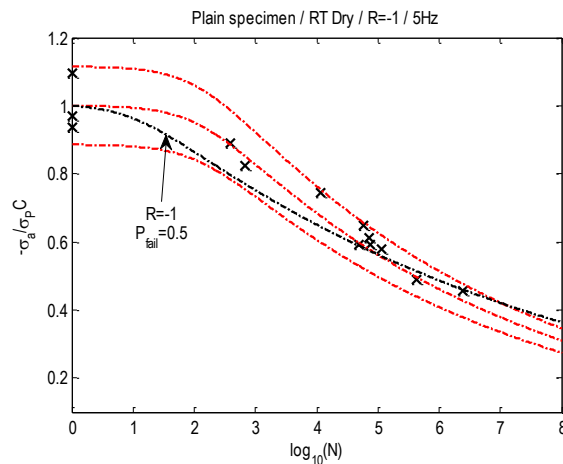


Figure 3. Normalized fatigue and static test results for plain specimens (L1 material, RT Dry, $R=-1$, $f=5\text{Hz}$). Also shown: wear-out model fits for plain (+ bounds of the 95% confidence interval), and holed specimens (black).

Figure 3. also shows a comparison of the wear-out model fits for plain and open hole specimens. The flattening seems more important compared with open hole specimens, essentially between $N=1$ and $N=100$. After that, the decrease of fatigue strength goes faster for the plain specimens and the curves cross at $N=10^5$. When normalized by the corresponding static strength, the SN curves of open hole and plain specimens look thus rather different which makes it difficult but not impossible to transfer results from one configuration to the other.

Additional tests are planned to better characterize the SN curve of plain specimens at moderate stresses, notably also to better estimate variability. Tests at lower stresses targeting fatigue lives beyond 10^7 cycles would also be necessary.

SN curves for open hole specimens - L1 material - RT / Wet & ETA / Dry conditions - $R=-1$

The fatigue resistance data obtained at RT / RH = 85+% and 120°C / Dry normalized by the corresponding open hole static strength are plotted in Figure 4 along with the wear-out model fit (and 95% confidence interval) for RT / Dry at $R=-1$.

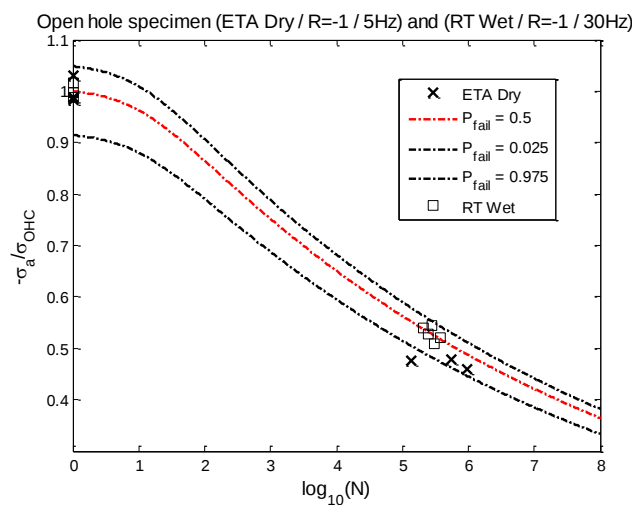


Figure 4. Normalized fatigue and static test results for the L1 material in ETA Dry and RT Wet conditions, at $R=-1$. Also shown: the wear-out model and corresponding bounds of the 95% confidence interval for the L1 material identified in RT Dry conditions.

A very limited number of fatigue data were generated in order to check rapidly that the fatigue data points normalized by the corresponding average static strength for ETA Dry and RT Wet fall within the 95% confidence interval of the wear-out model fit of the RT dry condition. Hence, different authors report that the SN curve in other environmental conditions can be obtained by scaling the RT Dry SN curve using the ratio of the corresponding static strengths. The results plotted in Figure 4. suggest that it is a reasonable hypothesis - which would obviously require more test data at different stress ratio in order to be validated. More ETA Dry tests are indeed planned for further assessment.

It is worth noticing that the strength knock-down due to moisture intake was lower than previously experienced by the authors.

SN curves for open hole specimens – L2 and L3 materials - RT / Dry conditions - $R=-1$

RT Dry fatigue tests have been performed at 5Hz and 30Hz on the L2 material, which is actually the L1 material rotated by 90° , i.e. the proportion of the plies remains unchanged. The normalized fatigue data points and wear-out model fit are plotted in Figure 5 along with the wear-out model fit for the L1 material. The L2 material normalized fatigue data points mainly lie below the 95% lower bound of the L1 material. Hence the flattening of the normalized SN curve is almost non-existent for the L2 material.

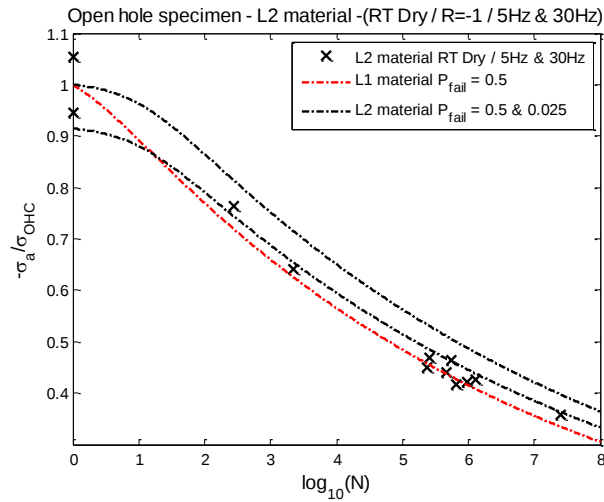


Figure 5. Fatigue and static test results for the L2 material in RT Dry conditions, at $R=-1$, for $f=5\text{Hz}$ and 30Hz . Also shown: the fitted wear-out model (probability of failure of 50%). For the sake of comparison, the wear-out model identified at $R=-1$ for the L1 material is also plotted at probabilities of failure of 50% and 2.5% (lower bound of the 95% confidence interval).

A twofold tentative explanation of the difference is the following:

- at $R=-1$, failure under fatigue loading occurs in compression, it is driven by delamination at the hole edge along the $45/0_{100-F}$ and $45/0_F$ interfaces. At a threshold delaminated area, local bending/buckling of the load carrying 0_F plies and 'brooming' towards the specimen exterior are triggered. These local bending/buckling and consequent 'brooming' phenomena of the load carrying plies should be delayed in the case of the L1 material due to the constraining role of the surrounding plies.
- Although the fibre volume fraction in the longitudinal direction of the load carrying plies remains the same in the L1 and L2 materials, there can be slight differences in the yarn waviness and the weave micro-architecture between the warp and weft directions. These directions are usually known to bring – sometimes very – slightly different mechanical properties.

This case shows that simple ply degradation models are by essence not suited to predict the fatigue strength knock-down when delamination dominates or triggers the final failure. Both ply degradation and interfacial crack initiation and propagation models should be combined.

RT Dry fatigue tests have been performed at 5Hz and 30Hz on the L3 material. In this case, the proportion of load carrying plies increases by 10%. The fatigue data points and wear-out model fit are plotted in Figure 6 along with the wear-out model fit for the L1 material. Note that the run-out specimens are censored in the fitting procedure.

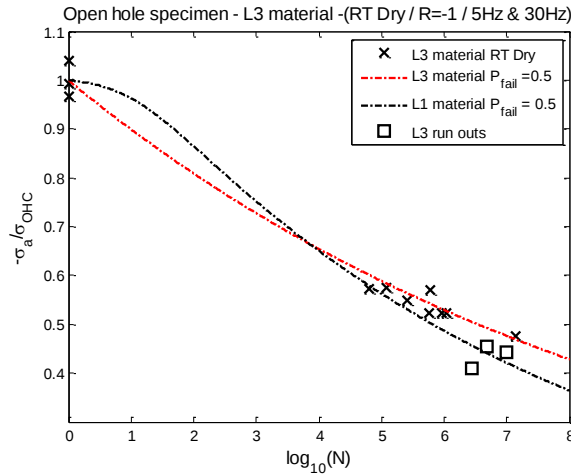


Figure 6. Fatigue and static test results for the L3 material in RT Dry conditions, at R=-1, for f=5Hz and 30Hz. Also shown: the fitted wear-out model (probability of failure of 50%). For the sake of comparison, the wear-out model identified at R=-1 for the L1 material is also plotted.

Figure 6. shows almost no curve flattening in the wear-out model fit. The normalized SN curves for the L1 and L3 materials cross around 10^5 cycles, above which the L3 material looks less sensitive to fatigue loading (the literature generally reports that a larger proportion of 0° load carrying plies leads to reduced SN curve slope). Indeed, while the average open hole compression strengths surprisingly differ by less than 1%, the fatigue resistance of the L3 material is higher, at least at low stress levels. Possible explanations are that

- the delamination propagates at a lower rate and/or
- the threshold delaminated area triggering local bending/buckling and subsequent 'brooming' must be larger, leading to a slightly delayed final failure.

However this explanation does not help interpreting the fact that the normalized SN curves should apparently cross. Anyway, more experimental data at higher stress levels are needed to obtain a more representative wear-out model fit. New fatigue tests are planned; these tests will be periodically interrupted and analyzed by micro-computed X-ray tomography to analyze in-situ the kinetics of damage evolution during fatigue loading. These results will help building failure scenarios for different lay-ups.

SN curves for open hole specimens – L1 material - RT / Dry conditions - R=10 & R=0.1 & Constant Limit Diagram (CLD)

RT Dry fatigue tests at 5Hz and 30Hz for R=0.1 and R=10 have been performed on open hole specimens made of the L1 material. The fatigue data normalized by the appropriate static strength (the open hole compression strength at R=10 and the open hole tensile strength at R=0.1) and the resulting identified wear-out model fits are shown in Figure 7.

Figure 7. also shows a comparison of the fitted normalized SN curves for the three load ratios. As expected, fully reversed loading is the most severe: a limited amount of delamination starting from the hole edge is necessary to trigger instabilities and failure in compression and this threshold delaminated area is reached faster when R=-1 than when R=10 due to a higher alternate stress. In tension-tension fatigue (R=0.1), a huge amount of delamination occurs before fibre breakage in tension becomes the dominant final failure mode. Therefore, the normalized SN curve at R=0.1 is even more flat than the two others.

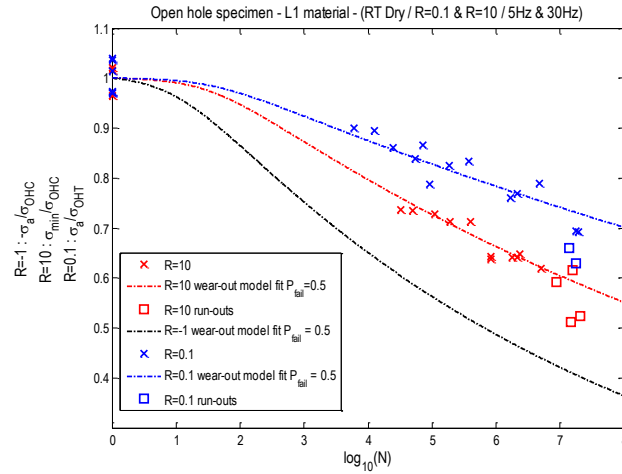


Figure 7. Normalized SN curves predicted by the wear-out model at R=-1, 0.1,10.

Assuming that the wear-out model fitting parameters are zero when the alternating stress is zero, five pairs of (C,S) are available to model mathematically their dependence on the load ratio R. To do so, it is easier to perform a change of variable and study the dependence of C and S on the term $\alpha = \cos\left(\arctan\left(\frac{1-R}{1+R}\right)\right)$ which is bounded between -1 and 1. Actually this term is the cosine of the angle made by the bisectors characterized by R in the Haigh 'space' (alternate stress Vs. mean stress). Figure 8 shows that C-driving the SN curve flattening close to N=1- is symmetric around 0, while S-driving the slope of the SN curve- is not. A 4th degree polynomial fit is used here to fit both C and S.

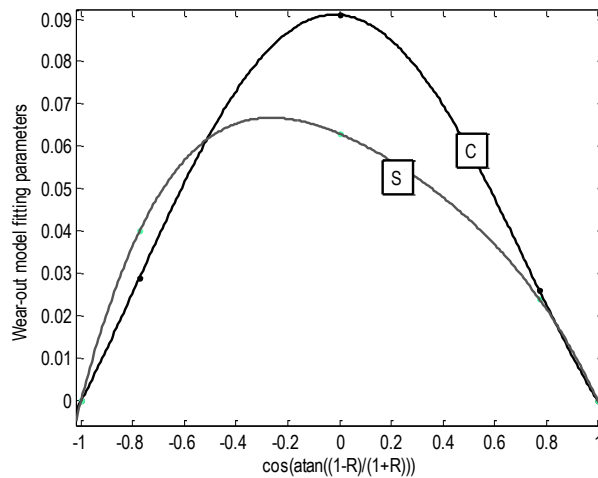


Figure 8. Polynomial fit of the wear-out model parameters C and S the abscissa in the graph is the cosine of the angle made by the bisectors characterized by R in the Haigh diagram (alternate stress Vs. mean stress).

Starting from the SN curves at different load ratios, there are many procedures / expressions to model a CLD [9]. The approach followed here is slightly different: hence, the wear-out model fitting parameters being known for any load ratio R, they are used to build a complete CLD. Contrary to the rest of the document, the CLD shown in Figure 9 does not present normalized stress values but absolute stress values; however these values cannot be disclosed. The absolute stress values or real SN curves that must be used to build the diagram are obtained by multiplying the normalized SN curve by an appropriate static strength (compressive or tensile). In this contribution, the normalized SN curve if multiplied by the open hole tensile strength only when $0 \leq R \leq 1$. Indeed, one can consider that final failure will always occur in compression as long as there is a compressive load in the fatigue cycle.

Abrupt switching from one static strength reference to the other at $R=0$ leads to a strong discontinuity in the CLD. Whether this discontinuity has any physical meaning / existence cannot be decided based on the available results. Fatigue tests should be performed at other well positioned R -values to validate the obtained shape. Such discontinuities have however been reported for quasi-isotropic lay-ups of carbon–epoxy UD plies by Vassilopoulos et al. in [10].

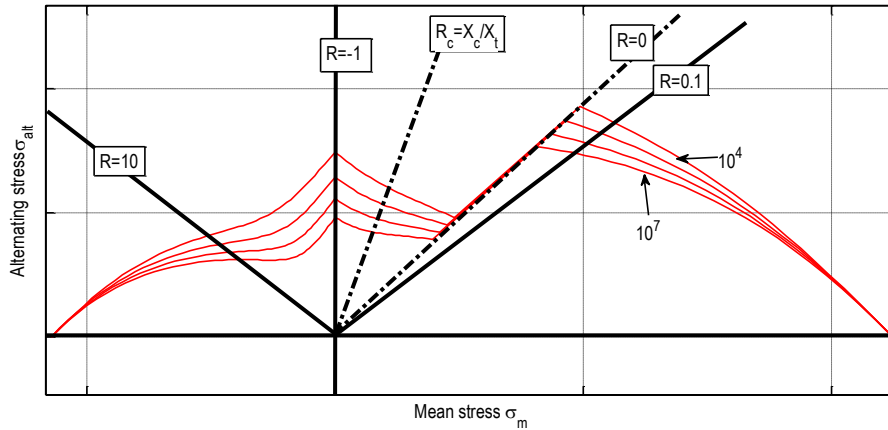


Figure 9. Constant life diagram built using the wear-out model with R -dependent C and S parameters.

CONCLUSION

The experiments allowed for drawing the following conclusions:

- the selected specimens are suited to perform fatigue testing at different load ratios, and an anti-buckling device is avoided under compressive loads. Tabbing is not necessary: acceptable failure modes (according to the standards) are observed within the gauge length.
- Specimen cooling is not necessary for very low or high cycle fatigue. However for moderate stresses (e.g. targeting 10^5 cycles), cooling is necessary.
- Provided sufficient specimen cooling, testing frequency has apparently no effect on the RT fatigue resistance.
- The SN curves at high temperature and high moisture intake can be approximately obtained by scaling the RT Dry curve by the ratio of corresponding static strengths.
- For the epoxy resin considered in this study, and based on a very limited number of tests, it seems that the moisture intake does not have a significant effect on the fatigue resistance at room temperature.
- The SN curve for plain specimens cannot readily be obtained by scaling the SN curve of holed specimens, however the obtained normalized SN curves are very close.
- As expected, the slope of the SN curve is directly related with the fraction of fibres in the longitudinal direction.
- Depending on the load ratio, different damage and failure scenarios are observed, the major difference coming from the amount of delamination at failure.

An original method was proposed to derive the CLD of the material based on a wear-out model fit of the SN curves.

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