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# SOTA review of micro-scale fatigue damage mechanism models

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## Executive summary

This document reviews the last decade of research into composites fatigue, building on previous review papers which are also referenced.

The key factors in the review are:

- Micro-mechanisms of fatigue damage, and their representation by mechanistic or phenomenological models
- Macro behaviour of structures subjected to fatigue, and its representation by phenomenological or entirely empirical meso-level models
- Multi-scale frameworks, which seek to unify the length scales and provide a mechanistic underpinning to simplified models of behaviour at the meso-scale.

At the micro-scale, much published work focuses on generating reliable expressions to describe the accumulation of fatigue damage in each of various modes; particularly fibre breakage, fibre fatigue, interface debonding and matrix cracking. There are many formulations proposed, which do not typically fundamentally diverge from each other and none of which claim rigorous proof. Therefore, the selection of fatigue damage accumulation models for each failure mechanism is to some extent arbitrary. The relative importance of different mechanisms is clearly a strong function of the layup and loading of interest. In theory, once a robust micro-mechanical framework has been defined, it should be valid across a wide range of layups and loadings, but so far few authors have managed to justify the significant time and expense required to demonstrate this. This will be one of the key contributions of D-STANDART to the literature.

An active research topic of some note relates to the nature and importance of visco-elasticity and visco-plasticity in fatigue damage. D-STANDART has not been specifically designed to address this, but it is likely some significant insights will be provided particularly from our work on environmental effects.

At the meso-scale, three classes of models are assessed:

1. Papers which unify the S-N and Paris-Erdogan relationships. Both these relationships are entirely empirical, producing a set of approaches which are justified by their apparent performance rather than by the robustness of their theoretical background. Unfortunately, a round-robin benchmarking approach organised by the American Air Force Research Laboratory showed wide variation in the predictions of several models, particularly in terms of stiffness degradation for which predictions varied between >90% stiffness loss after  $2 \times 10^6$  cycles to none at all. Predictions for residual strength were rather better.
2. Papers which exploit AI-based methods. Similarly, AI-based methods can be viewed as empirical methods, unless they contain some constraint or regularisation which forces the model to respect known physical constraints. However, the process of constructing a valid phenomenological model of fatigue at the macro-scale essentially involves decomposition of the loading, layup and environmental state into an appropriately weighted set of fatigue damage accumulation functions. This is directly analogous the principle of convolution in training of neural networks and so therefore ANN-based models could be looked at as a form of phenomenological model; except that the

meso-scale model has "learned" the functions to represent the micro-scale mechanisms in its own way from training data, rather than being directly told what form to express them in. Owing to its clear potential to generate robust meso-level models from micro-scale training data, this is the approach proposed for D-STANDART.

3. Papers which unify the mechanical and thermal fatigue modelling. This is a relatively new class of techniques, which focus on the concept of entropy - disorder - as a concept which unifies both fatigue damage and heat. As a structure is damaged, the structural order which gives it its strength is degraded and its entropy increases. Similarly, as a structure heats up the atoms and molecules within it become more agitated and entropy increases at the molecular level. Many mechanisms of fatigue damage also generate heat - indeed the avoidance of this effect in high-frequency testing is a key objective for D-STANDART WP1. Therefore, there is an interesting avenue of research looking at unifying heat and damage through entropy. This is, however, outside the scope of D-STANDART.

In general, the strategy of D-STANDART to build a robust meso-scale modelling framework by allowing an AI model to "learn" how different micro-mechanisms combine to generate fatigue damage in arbitrary structures is strongly validated by the recent literature.

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## Glossary

Abbreviation	Meaning
AFRL	Air Force Research Laboratory
AI	Artificial Intelligence
CDM	Continuum Damage Mechanics
CFRP	Carbon fibre reinforced plastics
DTDP	Damage Tolerance Design Principles
EC	European Commission
FE	Finite element
FEM	Finite element method/model/modelling
FFE	Fracture Fatigue Entropy
FRP	Fibre reinforced plastics
GFRP	Glass fibre reinforced plastics
HaDEA	Health and Digital Executive Agency
KTF	Kinetic theory of fracture
LHS	Local Hydrostatic Stress
LMPS	Local Maximum Principal Stress
MCT	Multicontinuum theory
MMF	Micro-mechanics of failure
NN	Neural Networks
PDA	Progressive damage analysis
SOTA	State Of The Art
TTSP	Time-temperature superposition principle
UD	Unidirectional
UMAT	User Material

# 1. Introduction

Fibre Reinforced Plastic (FRP) composites have attractive mechanical and physical properties that are now extendedly utilised in aerospace, automotive, construction, marine and other technical applications over the decades worldwide. D-STANDART aims to reduce the time and effort required for the fatigue characterisation of large-scale composite structures. For these two strategies are followed: (1) the development of new test methods and (2) the employment of surrogate models trained on a combination of experimental and synthetic data.

This second point responds to the statement of Vassiloupoulos [1], who declares that "*most of the introduced models are usually capable of providing accurate fatigue predictions (limited mainly by their empirical character). However, for extrapolations to different scales (e.g. from the fiber/matrix characterisation to the lamina fatigue prediction, from the laminate to the laminate, or from the laminate to the structural component) multiscale modelling approaches should be adopted, such as those described in a series of articles in the special issue AFRL II*" schematically shown in Figure 1. That statement reflects the same challenge of D-STANDART, which is to (i) veer away from the limitation of the empirical character and (ii) upscale the process of modelling the fatigue behaviour.

The objective of the State-of-the-Art is to list and guide a reader through three levels of literature. The first level produced in this introduction is made of the review papers produced during the past ten years. These papers are listed in chronological order in Table 1. Upon exploring the abstract reproduced in the table, the reader is invited to read those reviews. These reviews report the broader research work carried out by several authors, either in modelling, testing, or combining both.

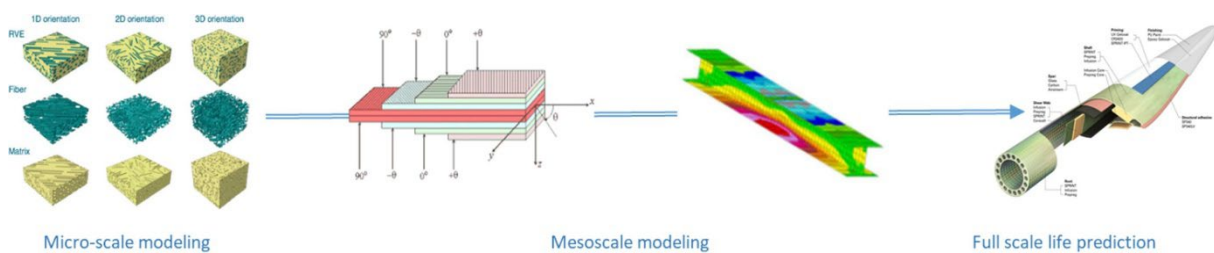


Figure 1 Multiscale modelling approach linking the micro scale to the full-scale modelling of engineering structures [1]

The second level is represented by a list of selected papers produced during the past ten years on the microscale modelling of fatigue. A summary gives a general overview of the paper and how that paper relates to the core objectives of the D-STANDART modelling effort. Finally, the third level is represented by a short list of selected papers focused on mesoscale modelling and considered the most relevant for the D-STANDART.

## 1.1. Review papers

Azinan et al. [2] produced the most up-to-date review about modelling the fatigue behaviour of composites. It produces valuable tables summarising damage mechanisms and fatigue models. Following the Duchene et al. work [3], the reader can appreciate how the damage from the microscale evolves up to the final failure. The damage mechanisms in composites are represented as a function of the lifetime, see Figure 2.

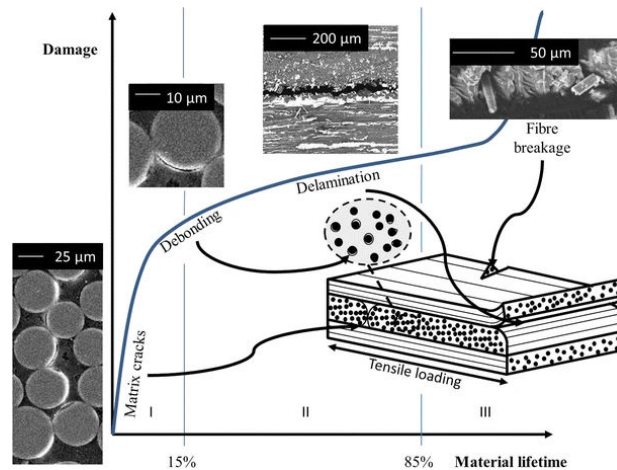


Figure 2 Evolution of damage in composite laminates during fatigue loading and related damage mechanisms [3]

Azinan reports that the mechanical degradation occurring in composite laminate materials, including stiffness and strength, can be analysed using three significant damage groups modelling:

- 1- the damage micromechanics
- 2- continuum damage mechanics (CDM), and
- 3- meso-mechanics.

The first one, the micro-mechanics, can be categorised further as follows:

- the self-consistent method,
- variational principles-based method,
- shear-lag method,
- stress transfer method,
- approximate elasticity theory solution method,
- analytical model method, and
- finite element method (FEM).

The damage mechanisms in composite laminates occurring under fatigue loading conditions are very difficult to describe since it usually involves various damages such as matrix cracking, delamination, fibre breakage and several others. These damage modes will reduce the three most important mechanical properties of laminated composite structural materials:

- 1- the residual strength,
- 2- residual stiffness, and
- 3- fatigue life.

Azinan produced useful tables summarising the fatigue models developed based on stiffness, strength and life. Figure 3 reports a table of the fatigue models based on the residual strength. Figure 4 reports the table summarising the fatigue models based on stiffness degradation. Finally, Figure 5 Part 1&2 reports the table of the fatigue models based on S-N curves.

Researcher	Summary of model	Test condition	Fatigue Test
Schaff & Davidson <sup>a</sup> [225, 226]	$R(n) = R_0 - f(R_0, S_p, R_s) n^v$ $f(R_0, S_p, R_s) = \frac{R_0 - S_p}{N^v}$ $R(n) = R_0 - (R_0 - S_p) \left(\frac{n}{N}\right)^v$ $P\left[\hat{R}(n) \leq S_p\right] = 1 - \exp\left[-\left(\frac{S_p}{R_0 - (R_0 - S_p) \left(\frac{n}{N}\right)^v}\right)^{B_f(n)}\right]$	glass/epoxy, graphite/epoxy	Tension-compression
Yang & Lui <sup>b</sup> [227]	$\frac{dR(n)}{dn} = -f(S, \omega, \varepsilon) / cR^{c-1}(n)$ $F_{R(0)}(x) = P[R(0) \leq x] = 1 - \exp[-(x/\beta)^\alpha]$ $N = [R^c(0) - S^c] / f(S)$ $F_N(n) = 1 - \exp\left\{-\left[\frac{n + [S^c/f(S)]^{\alpha/c}}{\beta^{\alpha/c} / f(S)}\right]^{\alpha/c}\right\}$	Stress ratio, = 0.1, graphite/epoxy [0, 90, ± 45] <sub>s</sub>	Tension-tension
Daniel & Charewicz <sup>c</sup> [229]	$\frac{f_s - \varepsilon}{1 - \varepsilon} = g\left(\frac{n}{N}\right)$ $\frac{dD}{dn} = -mD^{(m-1)} / m \frac{dg}{dn}$ $N_f = \int_{D_i}^{D_f} \frac{dn}{F\left(\frac{n}{N}, s, D\right)}$	Stress ratio = 0.1 AS4/3501-6 graphite/epoxy	Tension-tension
Whitworth <sup>d</sup> [231]	$S_R^y(n) = S_U^y - g(S) n$ $S_R^y = S_U^y - \left[S_U^y - S^y\right] \frac{n}{N}$ $S_R^y = S_U^y - J(S) n$ $J\left(S_U\right) = \frac{S_U^y - S^y}{\exp\left\{\frac{1}{n} \left[\left(\frac{c_1 - S}{S}\right)^{m/c_2} - 1\right]\right\} - 1}$ $F_{S_R}(z) = P[S_R \leq z] = P[S_U \leq y] = F_{S_U}(y)$ $J(y) = \frac{y^y - S^y}{\exp\left\{\frac{1}{n} \left[\left(\frac{c_1 y}{S}\right)^{m/c_2} - 1\right]\right\} - 1}$	Stress ratio = 0.1, [±35], T300/5280 graphite/epoxy	Tension-tension

<sup>a</sup> $R(n)$  = Weibull scale parameter for residual strength after  $n$  loading cycles,  $R_0$  = Weibull scale parameter for static strength,  $f(R_0, S_p, R_s)$  = rate of strength loss associated with cyclic loading,  $n$  = current number of cycles in a loading segment,  $v$  = strength degradation parameter,  $S_p$  = magnitude of the peak stress for a constant amplitude loading segment,  $N$  = Weibull scale parameter for constant amplitude fatigue life,  $\hat{R}(n)$  = residual strength distribution after  $n$  loading cycles,  $B_f(n)$  = Weibull shape parameter for residual strength after  $n$  loading cycles.

<sup>b</sup> $R(n)$  = residual strength,  $n$  = fatigue cycles,  $f$  = function,  $S$  = maximum stress,  $\omega$  = loading frequency,  $\varepsilon$  = stress ratio,  $c$  = constant,  $R(0)$  = ultimate strength,  $\alpha$  = shape parameter,  $\beta$  = scale parameter or characteristic strength,  $N$  = number of cycles to fatigue failure,  $S^c = R^c(0) - f(S)N$ .

<sup>c</sup> $f_r = F_r / F_0$  = normalized residual strength ( $F_r$  = residual strength after  $n$  cycles,  $F_0$  = mean static strength (used as a normalizing factor))  $s = \sigma_a / F_0$  = normalized applied cyclic stress ( $\sigma_a$  = applied cyclic stress),  $g(n/N)$  = function of normalized number of cycles ( $n$  = cycles of the residual strength,  $N$  = number of cycles to failure at stress),  $D$  = damage function,  $m$  = material parameter,  $N_f$  = number of cycles,  $D_i$  = initial value,  $D_f$  = final value.

<sup>d</sup> $y$  = constant,  $S_R(n) = S$  = residual strength after  $n$  cycles,  $g(s)$  = function of the maximum cyclic stress,  $S, S_U$  = ultimate strength,  $S$  = maximum applied stress,  $n = N$  = number of cycles to failure,  $h, m, c_1$ , and  $c_2$  = parameters.

Figure 3 Summary of mathematical models of the residual strength degradation model type [2]

Researcher	Summary of model	Test condition	Curve fitting parameter
Hwang and Han <sup>a</sup> [253]	$\frac{dF}{dn} = -Acnr^{c-1}$ $F(n, r) = \frac{\sigma_a}{\varepsilon(n)} = \sigma_a \frac{r}{\varepsilon(n)}$ $N = [B(1-r)]^{1/c}$	R = 0.0 glass/epoxy	A and C
Ye <sup>b</sup> [254]	$D = 1 - \frac{E}{E_0}, \frac{dE}{dN} = -E_0 C \left( \frac{\sigma_{max}^2}{1 - E/E_0} \right)^n$ $\frac{E}{E_0} = 1 - [NC(n+1)]^{1/(n+1)} \sigma_{max}^{2n/(n+1)}$	Short fiber composite	C
Whitworth <sup>c</sup> [241, 255]	$(I) \tilde{E}^a(N^*) = 1 - H [1 - \tilde{S}]^a N^*$ $(II) \frac{d\tilde{E}^*(n)}{dn} = \frac{-a}{(n+1) \tilde{E}^{*(n)m-1}}$ $\frac{S}{S_u} = c_1 \left[ \frac{E(N)}{E(0)} \right]^{c_2}$ $E(n) = E(0) \left( \frac{S}{c_1 S_u} \right)^{1/c_2} \left[ -h \ln(n+1) + \left( \frac{c_1 S_u}{S} \right)^{m/c_2} \right]^{1/m}$ $N = \exp \left\{ \frac{1}{h} \left[ \left( \frac{c_1 S_u}{S} \right)^{m/c_2} - 1 \right] \right\} - 1$	(I) [0/90/±45]s, R = 0.1, T300/5208 carbon/epoxy (II) [±35]2s, R = 0.1, AS4/3501-6 carbon/epoxy	(I) a, H (II) c1, c2, h, m
Yang et al. <sup>d</sup> [204]	<p>(I) Fiber dominant</p> $E(n) = E(0) [1 - Qn^0],$ $\frac{dE(n)}{dn} = -E(0)Qvn^{v-1}$ $Q = \alpha_1 + \alpha_2 v, v = \alpha_3 + BS$ <p>(II) Matrix dominant Replacing fatigue modulus F(n) Instead of elastic modulus E(n)</p>	(II) T300/5208 carbon/epoxy, [±45]s, R = 0.1, Stress level of 75%, 70%, 65%, and 55%	a1, a2, a3, B

<sup>a</sup> $F(n, r)$  and  $\varepsilon(n)$  are the fatigue modulus and resultant strain at  $n$ th loading cycle, respectively,  $\sigma_a$ : applied stress,  $r$  = ratio of applied stress ( $\sigma_a$ ), to the ultimate strength ( $\sigma_u$ ),  $B = F_0 / A$  and  $F_0$  = fatigue modulus at 0th cycle.

<sup>b</sup> $E$ , reduced modulus;  $E_0$ , initial modulus;  $N$ , number of cycles;  $r_{max}$ , fatigue stress level

<sup>c</sup>(I)  $E(N^*)$  = the residual modulus after  $n$  fatigue cycles, and  $E(0)$  = the initial modulus,  $N^* = n/N$  is the ratio of applied cycles to the fatigue life  $N$ . Parameters,  $a$ , and  $H$  are independent of the applied stress level and can be determined from experimental data.  $\tilde{E}^a(N^*) = E^a(N^*) / E(0)$ ,  $S = S / R(0)$ ,  $R(0)$  is ultimate static strength and  $\tilde{S}$  is the normalized applied stress range. (II) Where  $a$  and  $m$  are parameters depending on the applied stress, the constant  $h = a \cdot m$ ,  $E(N)$  is the failure stiffness,  $c_1$  and  $c_2$  are constants to be determined experimentally,  $S$  is the maximum applied stress and  $S_u$  is the ultimate strength.

<sup>d</sup> $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  are independent parameters of the applied stress level ( $S$ ), and  $B$  is a random variable with the lognormal distribution.

Figure 4 Mathematical models of the stiffness degradation model type [2]

Part 1

Researcher	Summary of model	Test condition	Fatigue test
Kawai et al. <sup>a</sup> [209]	$\frac{dD}{dN} = f(D, \Phi, R, N, p)$ $\frac{d\omega}{dN} = K\Phi^n \left(\frac{1}{1-\omega}\right)^k$ $N_f = \frac{1}{(k+1)K\Phi^n}$ $N_f = \frac{1}{(\sigma_{max})^n}$	R = 0.1, T800H/2500EP carbon/epoxy,	Tension-tension
Ellyin & El-Kadi <sup>b</sup> [210,211]	$\Delta W = S_{11} \Delta \sigma^2 / 1.62$ $\Delta W = \kappa N_f^2$ $\alpha = \alpha_0 + a\theta$ $\log \kappa = \log \kappa_0 + b\theta^p$	R = 0.1, glass/epoxy, boron/aluminium, graphite/epoxy	Tension-tension
Hashin & Rotem <sup>c</sup> [212]	<p>(I) Fiber failure mode:</p> $\sigma_A = \sigma \cos^2 \theta$ $\sigma_A^u = \sigma_A^t f_A(R, N, n)$ $\sigma^u = \begin{cases} \sigma_{(+)}^t(\theta) f_{(+)}(R, N, n, \theta) & \sigma > 0 \\ \sigma_{(-)}^t(\theta) f_{(-)}(R, N, n, \theta) & \sigma < 0 \end{cases}$ $f_A = f_A(R, N, n) = f(R, N, n, \theta) = f(R, N, n)$ <p>(II) Matrix failure mode:</p> $\left(\frac{\sigma_r}{\sigma_r^t}\right)^2 + \left(\frac{\tau}{\tau^u}\right)^2 = 1$ $\sigma_r^u = \begin{cases} \sigma_r^t(+)\ f_r(+)(R, N, n) & \sigma_r > 0 \\ \sigma_r^t(-)\ f_r(-)(R, N, n) & \sigma_r < 0 \end{cases}$ $\tau^u = \tau^t f_\tau(R, N, n) \text{ all } \tau$ $\left[\sigma^t(\theta) f(R, N, n, \theta)\right]^2 \left\{ \frac{\sin^4 \theta}{[\sigma_r^t f_r(R, N, n)]^2} + \frac{\sin^2 \theta \cos^2 \theta}{[\tau^t f_\tau(R, N, n)]^2} \right\} = 1$	R = 0.1, glass/epoxy	Tension-tension
Fawaz & Ellyin <sup>d</sup> [215]	$S_r = m_r \log(N) + b_r$ $m = f(a_1, a_2, \theta) g(R) m_r$ $b = f(a_1, a_2, \theta) b_r$ $S(a_1, a_2, \theta, R, N) = f(a_1, a_2, \theta) [g(R) m_r \log(N) + b_r]$	R = 0.5, carbon/epoxy, glass/epoxy, boron/aluminium	Tension-tension
Gathercol <sup>e</sup> et al. [216]	$F(\sigma, b, m) = 1 - \exp\left(-\left(\frac{\sigma - \sigma_0}{b}\right)^m\right)$ $\sigma_{max} = f(1+c)^2 / 4$ $f = f_0 - b \log N_f$ $\alpha = f(1-m)^u (c+m)^v$ $u = 0.474 + 0.28 \log N_f$ $\alpha = 1.06(1-m)^{1.51} (0.53+m)^{1.83}$	R = 0.5, 0.1, 10, -0.3, -0.6, -1.0, and -1.5, carbon/epoxy	Tension-tension, compression-compression, tension-compression
Adam et al. <sup>f</sup> [217]	$d = \left(\frac{n}{N}\right)^a$ $d = \sum \left[ A \left(\frac{n}{N_i}\right) + B \left(\frac{n}{N_i}\right)^2 \right]$ $d_1 = \left(\frac{n}{N}\right)_{a_1}^1$ $d_2 = \left(\frac{n}{N}\right)_2^{a_2} = \left[ (0 + \Delta_1)^{a_1/a_2} + \Delta_2 \right]^{a_2}$	R = 0.5, 0.1, 10, -0.3, -0.6, -1.0, and -1.5, carbon/epoxy	Tension-tension, compression-compression, tension-compression

part 2

Plumtree and Cheng <sup>9</sup> [218]	$P_N + P_s = \sigma^{\max} \Delta \varepsilon + \tau^{\max} \Delta \gamma$ $\Delta W^* = \Delta W_1^* + \Delta W_2^* = \sigma_{22}^{\max} \Delta \varepsilon_{22} + \tau_{12}^{\max} \Delta \gamma_{12} / 2$ $\tau_{12}^{\max} = \sigma_{22}^m + \Delta \sigma_{22} / 2$ $\tau_{12}^{\max} =  \tau_{12}^m + \Delta \tau_{12} / 2  \text{ or }  \tau_{12}^m - \Delta \tau_{12} / 2 $ $\lg \Delta W^* = 0.27 - 0.11 \lg(2N_f)$ $\sigma_{22} \varepsilon_{22} + \tau_{12} \gamma_{12} K = K''$	R = -1, 0 and 0.5, E-glass/epoxy	Tension-Torsion
Bond <sup>h</sup> [219]	$\log N = \phi - m \sigma_{\text{peak}}$ $\log N = \phi - m' \log \sigma_{\text{peak}}$ $\sigma_{\text{max}} = b \cdot \log N + c$ $b = K(R^*)^4 + L(R^*)^3 + M(R^*)^2 + N(R^*) + P$ $c = Q(R^*)^4 + T(R^*)^3 + U(R^*)^2 + V(R^*) + W$ $D = \sum (n_i / N_i)$ $D = \sum \{ A (n_i / N_i) + B (n_i / N_i)^C \}$	R = 0 and -1, E-glass/epoxy	Tension-tension, tension-compression, compression-tension, compression-compression
Xiao <sup>i</sup> [220]	$\sigma(T) = F[N, \alpha_T(T), b_T(T)]$ $\frac{dT}{dt} = \frac{q}{\rho c_p} - \frac{HA}{\rho c_p V} (T - T_0)$ $q = wf$ $w = C(1 - R)^2 \sigma (\sigma - \sigma_t)$ $\frac{T - T_0}{T_e - T_0} = 1 - \exp\left(-\frac{HA}{\rho c_p V} t\right)$ $p = b_T \left( p_0 + \frac{1 - p_0}{(1 + \alpha_T \tau N)^n} \right)$	R = 0.13, AS4/PEEK	Tension-tension
Xiao <sup>i</sup> [220]	$\sigma(T) = F[N, \alpha_T(T), b_T(T)]$ $\frac{dT}{dt} = \frac{q}{\rho c_p} - \frac{HA}{\rho c_p V} (T - T_0)$ $q = wf$ $w = C(1 - R)^2 \sigma (\sigma - \sigma_t)$ $\frac{T - T_0}{T_e - T_0} = 1 - \exp\left(-\frac{HA}{\rho c_p V} t\right)$ $p = b_T \left( p_0 + \frac{1 - p_0}{(1 + \alpha_T \tau N)^n} \right)$	R = 0.13, AS4/PEEK	Tension-tension

<sup>a</sup>D = continuum fatigue damage, f = fatigue damage function,  $\omega$  = single scalar, K, k and n = material's constants,  $\Phi$  = fatigue strength parameter, R = stress ratio, N = number of fatigue cycles, p = history dependent parameter,  $\sigma_{\text{max}}^*$  = maximum non-dimensional effective stress,  $N_f$  = fatigue life.  
<sup>b</sup> $\Delta W$  = cyclic strain energy density, S = transformed compliances,  $\sigma^2$  = stress,  $N_f$  = number of cycles to failure,  $\kappa$  and  $\alpha$  = functions of the fiber's orientation angle, a, b and  $\beta$  = material's properties,  $\alpha_0$  and  $\kappa_0$  = values of  $\alpha$  and  $\kappa$  respectively at  $\theta = 0$ , where  $\theta$  = fibers orientation angle in degree.  
<sup>c</sup> $\sigma_A$  = static failure stress,  $\sigma_A^*$  = static failure stress in fiber's direction, A = constant variable,  $f_A$ ,  $f_T$ , and  $f_s$  = non-dimensional functions (material fatigue functions), R = stress ratio, N = number of cycles to failure, n = frequency of cycling.  
<sup>d</sup>S = applied stress, r = denotes parameters related to the reference line, N = number of cycles to failure, m and b = parameters (depends on materials properties and general loading conditions), f and g = non-dimensional function,  $\theta$  = angle the system makes with the principal directions of the material, R = stress ratio,  $\alpha_1$  = first biaxial ratio,  $\alpha_2$  = second biaxial ratio.  
<sup>e</sup>F = function,  $\sigma$  = stress, b = scale parameter, m = shape parameter,  $N_f$  = cycles to failure, f, u and v = adjustable parameters,  $\alpha$  = materials constant  
<sup>f</sup>d = damage parameter, n = number of cycles, N = cycles to failure,  $\alpha$  = materials constant,  $n_i$  = number of cycles per year within the tension range interval i,  $N_i$  = fraction of the life to failure,  $d_1$  = damage parameter in the first block,  $d_2$  = damage parameter in the second block,  $\Delta_1$  = first block,  $\Delta_2$  = second block.  
<sup>g</sup> $P_N$  = mean normal stress fatigue parameter,  $P_s$  = shear stress parameter,  $\sigma^{\max}$  = maximum stress,  $\Delta \varepsilon$  = tensile strain range,  $\tau^{\max}$  = maximum shear stress,  $\Delta \gamma$  = shear strain range,  $\Delta W^*$  = fatigue parameter,  $\sigma_{22}^{\max}$  = maximum normal stress,  $\tau_{12}^{\max}$  = maximum shear stress,  $\Delta \gamma_{12} / 2$  = shear deformation at the fiber/matrix interface,  $2N_f$  = number of reversals to failure,  $\tau_{12}$  = respective shear,  $\varepsilon_{22}$  = strain to the fiber (in-plane),  $\gamma_{12}$  = shear strain,  $\sigma_{22}$  = failure stress normal to the fiber (in-plane),  $K = G_{12}$  = modulus in the 1-2 plane.  
<sup>h</sup>N = median cycles to failure, m = mean,  $\sigma_{\text{peak}}$  = peak stress level,  $\sigma_{\text{max}}$  = maximum stress, b and c = values thus derived are fundamental elements of the subsequent life prediction model, R and R' = ratio range, K, L, M, N, Q, T, U, V, W = constitute the  $\sigma$ -N data set or life prediction model, D = annual cumulative fatigue damage ratio,  $n_i$  = number of cycles per year within the tension range interval i,  $N_i$  = number of cycles to failure at normalized tension range i, A, B and C = materials parameter.  
<sup>i</sup> $\sigma$  = stress, T = temperature, F = function, N = cycles to failure,  $\alpha_T$  and  $b_T$  = shifting factors, q = heat generation rate,  $\rho$  = density,  $c_p$  = specific heat, H = general heat transfer, A = surface area of the fatigue test specimen, V = volume of the fatigue test specimen,  $T_0$  = environment temperature, w = hysteresis loop, C = parameter, R = stress ratio of the fatigue test,  $\sigma_t$  = threshold stress,  $T_e$  = equilibrium temperature, p = normalized form,  $\tau$  = dimensionless parameter, n = exponent.

Figure 5 Fatigue models based on S-N curves [2]

Over the past ten years, several review papers were produced by various authors on fatigue behaviour of composites almost annually. Therefore, the material and structure communities exhaustively research and investigate the topic. As already said, this introduction lists these review papers in a table format. The year of publication, the first author's country, the journal and the abstracts are listed, respectively. Table 1 presents the list of the most recent review papers. The following sections will review papers on the micro and mesoscale models, which the reviews might not have captured.

However, before summarising the main points of the reviews, it is worth noting a couple of review papers on the modelling of concrete and braided composites. Although these are not within the topic of fibre-reinforced plastic of D-STANDART, the papers give some significant insights into how to model that composite material. Thilakarathna [4] reports that concrete is a heterogeneous material that poses significant challenges at the mesoscale level owing to the presence of several constituents such as aggregates. Table 1, in the paper, summarises the material models used by researchers for the consisting phases of the mesolevel. This review paper could be consulted to learn how the stochastic distribution of aggregates is treated from a modelling viewpoint. Wang [5] and Sevenois [6] report the developments in the modelling of braided composites; both highlight the importance, advantages and limitations of as-applied failure criteria and damage evolution laws for yarns and composite unit cells. In addition, their work provides a good reference for future research on FE simulations of braided composites.

Lee et al. [7] reviewed the existing metal and composite fatigue models. The review helps to put into context various types of models proposing the Unified Mechanics Theory from Basaran. A concluding remark of the paper can be summarised by saying that the authors consider entropy as damage or degradation criteria. Neither stress-strain nor force-displacement can be considered as such. On the one hand, the entropy approach appears to connect fatigue behaviour with temperature that results from loading rate, which is frequency-dependent. On the other hand however, assessing the hysteresis properties of large-scale structures in order to take advantage of this would be very challenging. Vassilopoulos [1] and Alam et al. [8] extensively review the fatigue of composites and models. Both reviews contribute to gaining good insights into the topic; both are highly recommended reading.

In particular, Vassilopoulos presents the historical chronology from early 1950 until recent years. Furthermore, Vassilopoulos concludes the review with a paragraph worth reporting verbatim, with key passages highlighted: "*It has been explicitly shown that the synergistic effects of load, environment, geometry, residual strength, time, and material microstructure should not be overlooked. A large number of fatigue life modeling/prediction theories have been introduced. Most of these fatigue theories are empirical; their implementation is strongly based on fatigue data. The behavior is simulated and empirical models are occasionally used for the prediction of the same material behavior under different loading conditions, .... Several of the theories that claim not to be empirical, are actually also empirical, for example fracture mechanics methods for delamination based on the measurement of the crack length are also empirical, since the final models are actually fitting equations that simulate the material behavior without having any physical meaning, and moreover, without modeling damage but rather the effects of it. The high demand for experimental evidence to support the development of data-based fatigue life modeling/prediction methodologies resulted in a significant amount of experimental data. Nevertheless, this urge to obtain experimental data led in some cases to questionable databases, if not to completely erroneous results...*" The last part of this

conclusion captures very well the necessity to deliver test data which should not be questionable, and better-quality test data should also help to calibrate the stiffness distribution with higher accuracy so far achieved. The same message is reported by Alam as follows and highlighting a crucial statement from the authors- conclusions: "*It is vital that greater research efforts are expended into understanding how strain is distributed at fibre-matrix interfaces during fatigue. There is currently a gap in our understanding on how strain fields actually evolve over a fatigue cycle at the micro and meso scales. This area is more easily tackled numerically, as it is difficult to map this reliably in fatigue given the current technologies available to us. As has been noted in the review, fatigue testing results tend to show considerable scatter. The lack of repeatability of CFRP in fatigue is a critical concern as it depreciates engineering confidence in the material.*"

D-STANDART deals with two material systems. One system is used in the aerospace industry, and one is used in the wind energy industry. Nine out of ten reviews of Table 1 are focussed on material systems for the aerospace industry, but Rubiella et al. [9] report the bulk of research carried out on fatigue in wind turbines, giving a good perspective on the fatigue behaviour of materials in that industry sector. It is relevant to report one of the statements from the conclusions: "*One major issue with fatigue-life models is their reliance on available S-N curve data and related CLD formulations. With each model seems to come a new formulation or fatigue life data interpretation methodology, which has resulted in significant discrepancy between seemingly similar models. As a result, a recurring point of criticism that arises to question such models is their inherent subjectivity, as it is rarely thoroughly clear why a particular set of data-fitting parameters or parameter values was chosen over another.*" The statement speaks for itself, and D-STANDART ought to develop homogenisation of the modelling and testing practices.

The last two review papers listed in the table are from Bak et al. [10] and Pascoe et al. [11]. Both still contain relevant information to be studied. The first paper reviews experimental methods, models and computational simulations of delamination from the onset to the propagation. The second one focuses primarily on the models to predict delamination growth.

Table 1 List of review papers with abstract from each

#	Year and Country	Authors, Title, Journal
1	2022 Malaysia	<i>Azinan, N., Halim Kadarman, A. and Sidhu, J.S.S.</i> <i>An overview of fatigue models for composite laminate materials.</i> Mechanics of Advanced Materials and Structures, 29(25), pp.4389-4411.
		<i>Composite laminate materials are used extensively in various applications particularly in aircraft structures. During operation, the aircraft's structure will experience mechanical responses due to environmental degradation or external damages. This mechanical loading may cause damages to further develop in the composite laminate materials. Thus, numerous attempts from previous researchers to develop theories to investigate the damage that appears in composite laminate materials under loading conditions. Therefore, this review paper presents an overview of theoretical models that have been used to investigate the effects on stiffness due to the damage mechanism in composite laminate materials under fatigue loading conditions specifically.</i>

2	2021 USA	<p><b>Lee, H.W. and Basaran, C.</b></p> <p><i>A review of damage, void evolution, and fatigue life prediction models.</i></p> <p>Metals, 11(4), p.609.</p>
<p><i>Degradation, damage evolution, and fatigue models in the literature for various engineering materials, mostly metals and composites, are reviewed. For empirical models established under the framework of Newtonian mechanics, Gurson–Tvergaard–Needleman (GTN) type model, Johnson–Cook (J-C) type damage model, microplasticity model, some other micro-mechanism-based damage models, and models using irreversible entropy as a metric with an empirical evolution function are thoroughly discussed. For Physics-based models, the development and applications of unified mechanics theory are reviewed.</i></p>		
3	2020 Australia	<p><b>Thilakarathna, P.S.M., Baduge, K.K., Mendis, P., Vimonsatit, V. and Lee, H.,.</b></p> <p><i>Mesoscale modelling of concrete—a review of geometry generation, placing algorithms, constitutive relations and applications.</i></p> <p>Engineering Fracture Mechanics, 231, p.106974.</p>
<p><i>Concrete can be considered as a heterogeneous material at mesoscale comprising of several constituents such as aggregates, mortar and Interfacial Transition Zone (ITZ). Mechanical behavior as well as the durability characteristics of concrete is highly dependent on the mesostructured of concrete and investigating the complex phenomena surrounding concrete at mesoscale considering the heterogeneity presents an important tool to understand these complex mechanisms. Presenting the state-of-the-art developments in mesoscale modelling of concrete considering different analysis methods such as continuum Finite Element Modelling (FEM), Lattice Element Method (LEM), Rigid Body Spring Method (RBSM), Discrete Element Method (DEM) and Lattice Discrete Particle Method (LDPM) is the focus of this review paper. Effective methods to generate the geometry of consisting phases in the mesoscale models including different particle shapes and placing algorithms, selecting suitable material constitutive relations for the consisting phases are discussed for these different methods of mesoscale modelling. Potential applications including fracture mechanics and strengths and weaknesses of each technique are highlighted with possible methods to overcome the challenges of mesoscale modelling of concrete.</i></p>		
4	2020 Switzerland	<p><b>Vassilopoulos, A.P.</b></p> <p><i>The history of fiber-reinforced polymer composite laminate fatigue.</i></p> <p>International Journal of Fatigue, 134, p.105512.</p>
<p><i>Investigations of the fatigue performance of composite materials have accompanied their introduction in several engineering domains since the 1950s. An abundance of publications have emerged dealing with the experimental investigation of the fatigue performance of composites under different loading and environmental conditions, as well as the development of theories for the modeling of the fatigue behavior and/or prediction of the fatigue life of the materials systems under consideration. This work aims to briefly review and present the history of fiber-reinforced polymer composite laminate fatigue investigations, dividing the last 70 years into three periods. The early 1950–1975 period, when the “new” materials and their behavior under (simple) fatigue loading patterns were discovered. The mature, 1975–2000 period, when more loading and material parameters were investigated and the basic theoretical background was established. And finally, the later period, in the new millennium, when more detailed experimental campaigns were performed</i></p>		

		<i>(assisted by developments in a multitude of engineering and scientific fields) and parameters that had previously been overlooked by researchers were taken into account.</i>
5	2019 UK	<b>Alam, P., Mamalis, D., Robert, C., Floreani, C. and Brádaigh, C.M.Ó.</b>  <i>The fatigue of carbon fibre reinforced plastics-A review.</i>  Composites Part B: Engineering, 166, pp.555-579.
		<i>Engineering structures are often subjected to the conditions of cyclic-loading, which onsets material fatigue, detrimentally affecting the service-life and damage tolerance of components and joints. Carbon fibre reinforced plastics (CFRP) are high-strength, low-weight composites that are gaining ubiquity in place of metals and glass fibre reinforced plastics (GFRP) not only due to their outstanding strength-to-weight properties, but also because carbon fibres are relatively inert to environmental degradation and thus show potential as corrosion resistant materials. The effects of cyclic loading on the fatigue of CFRP are detailed in several papers. As such, collating research on CFRP fatigue into a single document is a worthwhile exercise, as it will benefit the engineering readership interested in designing fatigue resistant structures and components using CFRP. This review article aims to provide the most relevant and up-to-date information on the fatigue of CFRP. The review focuses in particular on defining fatigue and the mechanics of cyclically-loaded composites, elucidating the fatigue response and fatigue properties of CFRP in different forms, discussing the importance of environmental factors on the fatigue performance and service-life, and summarising the different approaches taken to modelling fatigue in CFRP.</i>
6	2018 UK	<b>Rubiella, C., Hessabi, C.A. and Fallah, A.S.</b>  <i>State of the art in fatigue modelling of composite wind turbine blades.</i>  International Journal of Fatigue, 117, pp.230-245.
		<i>This paper provides a literature review of the most notable models relevant to the evaluation of the fatigue response of composite wind turbine blades. As wind turbines spread worldwide, ongoing research to maximise their lifetime – and particularly that of wind turbine blades – has increasingly popularised the use of composite materials, which boast attractive mechanical properties. The review first presents the wind turbine blade environment, before distributing fatigue models broadly between three categories: life-based failure criterion models, which are based on S-N curve formulations and constant-life diagrams to introduce failure criteria; residual property calculation models, which evaluate the gradual degradation of material properties; and progressive damage models, which model fatigue via the cycle-by-cycle growth of one or more damage parameters. These are then linked to current testing standards, databases, and experimental campaigns. Among the fatigue modelling approaches covered, progressive damage models appear to be the most promising tool, as they both quantify and qualify physical damage growth to a reasonable extent during fatigue. The lack of consensus and shortcomings of literature are also discussed, with abundant referencing.</i>
7	2017 Singapore	<b>Wang, C., Roy, A., Silberschmidt, V.V. and Chen, Z.,.</b>  <i>Modelling of damage evolution in braided composites: recent developments.</i>  Mechanics of Advanced Materials and Modern Processes, 3(1), pp.1-32.
		<i>Composites reinforced with woven or braided textiles exhibit high structural stability and excellent damage tolerance thanks to yarn interlacing. With their high stiffness-to-weight and strength-to-weight ratios, braided composites are attractive for aerospace and automotive components as well as sports protective equipment. In these potential applications, components are typically subjected</i>

		<p><i>to multi-directional static, impact and fatigue loadings. To enhance material analysis and design for such applications, understanding mechanical behaviour of braided composites and development of predictive capabilities becomes crucial. Significant progress has been made in recent years in development of new modelling techniques allowing elucidation of static and dynamic responses of braided composites. However, because of their unique interlacing geometric structure and complicated failure modes, prediction of damage initiation and its evolution in components is still a challenge. Therefore, a comprehensive literature analysis is presented in this work focused on a review of the state-of-the-art progressive damage analysis of braided composites with finite-element simulations. Recently models employed in the studies on mechanical behaviour, impact response and fatigue analyses of braided composites are presented systematically. This review highlights the importance, advantages and limitations of as-applied failure criteria and damage evolution laws for yarns and composite unit cells. In addition, this work provides a good reference for future research on FE simulations of braided composites.</i></p>
8	2015 Belgium	<p><b>Sevenoís, R.D.B. and Van Paepegem, W.,.</b></p> <p><i>Fatigue damage modeling techniques for textile composites: review and comparison with unidirectional composite modeling techniques.</i></p> <p>Applied mechanics reviews, 67(2).</p>
		<p><i>Composite structural parts have been successfully introduced in high performance industries. Nowadays, also lower performance, high volume production industries are looking for the application of composites in their products. Especially attractive are textile composites (woven, braided, etc.) because of their better drapability and higher resistance to out-of-plane and dynamic loads. Currently, however, extensive mechanical tests are needed to properly design a composite structure. This is a requirement the large volume industries typically do not have the resources nor the time for. Reducing the need for structural tests can only be done if reliable simulation techniques are available. Simulation techniques for fatigue loading are particularly interesting because products generally have to perform their function over a period of time. For the textile structural composites concerned in this paper, some notable modeling techniques have been developed over the past 15 years. These techniques are presented here and the state of the art is established together with insights for future development by comparing the state of the art with the modeling techniques for laminates from unidirectional (UD) laminae.</i></p>
9	2014 Denmark	<p><b>Bak, B.L., Sarrado, C., Turon, A. and Costa, J.,.</b></p> <p><i>Delamination under fatigue loads in composite laminates: a review on the observed phenomenology and computational methods.</i></p> <p>Applied Mechanics Reviews, 66(6).</p>
		<p><i>Advanced design methodologies enable lighter and more reliable composite structures or components. However, efforts to include fatigue delamination in the simulation of composites have not yet been consolidated. Besides that, there is a lack of a proper categorisation of the published methods in terms of their predictive capabilities and the principles they are based on. This paper reviews the available experimental observations, the phenomenological models, and the computational simulation methods for the three phases of delamination (initiation, onset, and propagation). It compiles a synthesis of the current state-of-the-art while identifying the unsolved problems and the areas where research is missing. It is concluded that there is a lack of knowledge, or there are unsolved problems, in all categories in the field, but particularly in the category of computational methods, which in turn prevents its inclusion in the structural design process.</i></p>

	<i>Suggested areas where short-term and midterm research should be focused to overcome the current situation are identified.</i>	
10	2013 The Netherlands	<p><b><i>Pascoe, J.A., Alderliesten, R.C. and Benedictus, R.</i></b></p> <p><i>Methods for the prediction of fatigue delamination growth in composites and adhesive bonds—a critical review.</i></p> <p>Engineering Fracture Mechanics, 112, pp.72-96.</p>
	<p><i>An overview is given of the development of methods for the prediction of fatigue driven delamination growth over the past 40 years. Four categories of methods are identified: stress/strain-based models, fracture mechanics-based models, cohesive-zone models, and models using the extended finite element method. It is highlighted that most models are phenomenological, based on the observed macro-scale behaviour of test specimens. It is suggested that a more physics-based approach, focusing on elucidating the mechanisms involved, is needed to come to a full understanding of the problem of delamination growth.</i></p>	

## 2. Microscale fatigue damage models

As observed in the D-STANDART proposal, one of the significant challenges of fatigue modelling is the upscaling process of modelling fatigue behaviour of composites from a micro- up to a macro-scale. Therefore, this section will start from the bottom scale, such as the microscale.

Cai et al. [12] 2018 issued a review paper claiming that the strength of unidirectional fibres under transverse tension is much smaller than that under longitudinal tension, mainly due to the lack of fibre strength in the transverse direction. Several fibre characteristics, such as fibre nature, fibre diameters, fibre volume fraction, fibre distribution, fibre array and fibre spacing, influence transverse tensile strength. The interfacial bond strength between fibre and matrix is often evaluated by measuring interfacial strength experimentally, applying elastic mechanics, or establishing a finite element micromechanics model to understand the influencing factors affecting the bonding strength. Voids and porosity in the matrix are critical imperfections in fibre-reinforced composite materials and harm the matrix properties. It is advised to read such a review paper as it helps to set the challenges of microscale modelling into the proper context, although it is not directly linked to the fatigue behaviour presented hereafter.

The following paragraphs summarise the most recent and significant papers identified over the past ten years, contributing to developing and implementing microscale fatigue models. The selected papers are reported in Table 2 from the newest to the oldest release. It appears clear that the development of a robust and comprehensive microscale fatigue model is a valuable research investigation. Ideally, the microlevel testing for extracting material and fatigue properties using a few fibres embedded in the matrix, primarily unidirectional fibres, requires inexpensive testing equipment and is thus accessible to many laboratories. However simple these tests may appear to be, the experiments are in reality not trivial, primarily due to the difficulties in achieving accurate instrumentation at such small scale. Therefore, samples are typically mesoscale coupons used to generate data modelled from the microscale level. The transition from the microscale model up to the mesoscale experimental data can lead to a degree of predictability of the fatigue behaviour. Unfortunately, such properties do not easily translate into behaviour observed at the macroscale or component level. The internal stress and strain calculated at the micro level do not scale up for various reasons, for instance, the change in fibre orientation or the propagation of defects during the manufacturing processes from one unidirectional lamina to a full-scale component.

One remark concerns the experimental test data generated by the paper's authors or gathered from the literature. Typically, the test data produced by paper's authors allow a better model calibration, leading to better prediction. In some cases, however, models tend to under- or over-predict the fatigue life. This is another element that D-STANDART will attempt to solve through a smarter standardisation of the test data.

The reader is offered a short summary of the proposed papers highlighting the cross-link with the D-STANDART main modelling objectives where possible. Such a summary is provided from the oldest to the newest papers.

Qian et al. [13] propose a multiscale numerical fatigue modelling methodology for the behaviour of unidirectional Glass Fibre Reinforced Polymer (GFRP) composites. The models

deal with fatigue load driven by axial tension–tension load. The valuable insight of this paper is the process of upscaling proposed by a methodology developed for linking the dominant fibre failure mechanism to composite fatigue properties. This study aims to provide composite fatigue predictions using only the fibres and matrix material properties. One significant remark is about the increase in the geometric size of the loaded material volume, which appears not to change the S–N slope significantly. Figure 6 shows the S–N curve, where the authors report a critical observation that the geometric scale of the composite structure does not significantly influence the  $C_1$  value of the composite materials. As a result, for better predicting the fatigue behaviour of the composite dog-bone specimens, the input fibre  $C_1$  value is calibrated by the experimental  $C_1$  value (-9.2) of the dog-bone specimens.

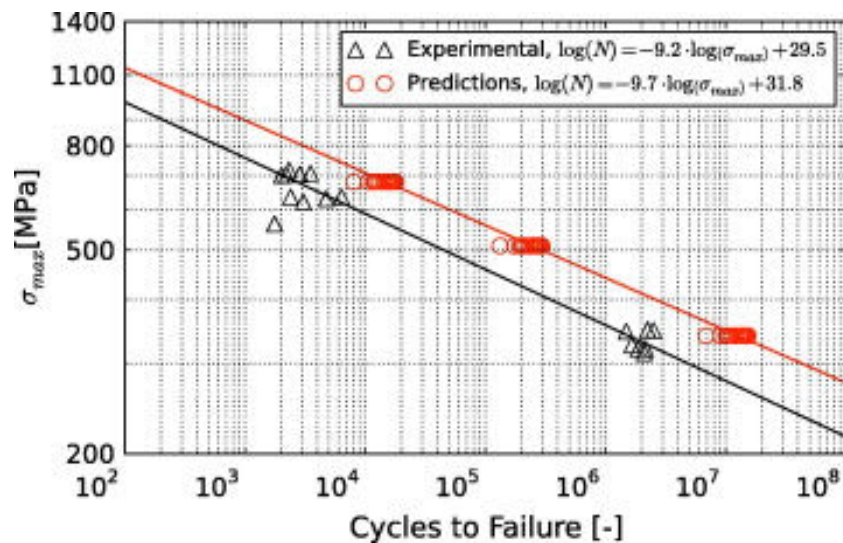


Figure 6 Experimental and predicted fatigue lives of the composite dog-bone Specimens [13].

Shokrieh et al. [14] report on a model based on the micromechanical and normalised stiffness degradation approaches. The paper focuses on the nanoparticle-filled fibrous composites. The main reason for reporting this paper is due to the new model developed in that research, which integrates two significant components: the micromechanical and the normalised stiffness degradation approaches. The proposed model can predict the final fatigue life of nanoparticle/fibrous polymeric composites under general fatigue loading conditions. The research assumes that the significant reason for the reduction in material properties of nanoparticle/ fibrous polymeric composites under general fatigue loading conditions is related to the reduction of fibres and matrix properties, while in cyclic load conditions, the mechanical properties of nanofillers are assumed to remain unchanged under different states of stresses.

Carraro et al. [15] present an investigation into the non-fibre-dominated (i.e. matrix-dominated or interface-dominated) fatigue behaviour of composite unidirectional laminae subjected to multiaxial loading. A new criterion is proposed.

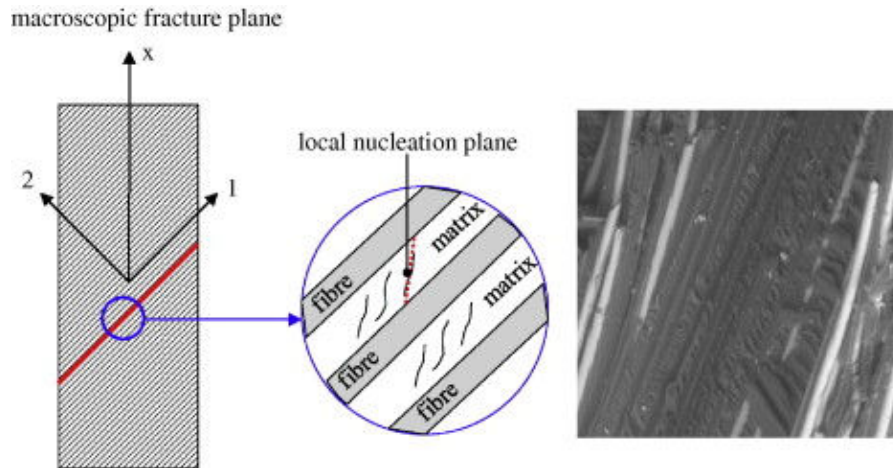


Figure 7 Concept of the local nucleation plane [15].

In this paper, the criterion is based on experimental observations of the damage modes occurring at the microscopic scale leading to the fatigue failure of a lamina. Two parameters have been identified from those observations as driving forces for the damage initiation, Local Hydrostatic Stress (LHS) and Local Maximum Principal Stress (LMPS), and these are calculated from the local stresses in the matrix obtained from Finite Element analyses of a fibre/matrix unit cell subjected to periodic boundary conditions. This paper also considers multiaxial loading as opposed to many other ones focussed on uniaxial load, either tensile, compressive loads or a combination of both. Finally, the paper from Min et al. [16] proposes a modelling approach to investigate fatigue damage in ceramic-based composites. Although the damage mechanisms differ, the paper might offer valuable insights into the modelling approach. Figure 8 and Figure 9 show the micro-mechanical model and the fibre array used for the investigation. Interestingly, the initial crack size is based on the idealised configuration of the fibre array, which in the physical model might not be the same due to intrinsic misalignment from manufacturing processes.

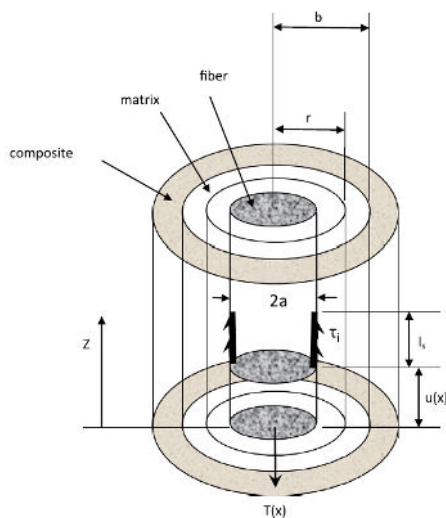


Figure 8 Three-phase shear-lag micromechanics model. [16]

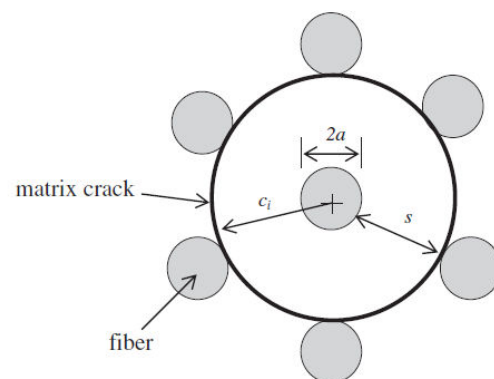


Figure 9 Hexagonal fiber array for initial matrix crack size calculation. [16]

Related to the open-hole exercise which will be undertaken in the validation process in D-STANDART, the paper of Li et al. [17] and [18] report on the application of the theory of micro-mechanics of failure (MMF) is extended to analyse the progressive fatigue failure and predict the strength for the bolted joint structures of carbon fibre reinforced polymer (CFRP) composites. Two main reasons to read this research output are 1) the investigation and implementation of the fatigue model on joints, with the main weakness represented by the open hole, and 2) the implementation of the User Define Material subroutine UMAT coded in Fortran. Figure 10 shows the S-N of the prediction against the experimental data. The scatter of the test data seems to be high.

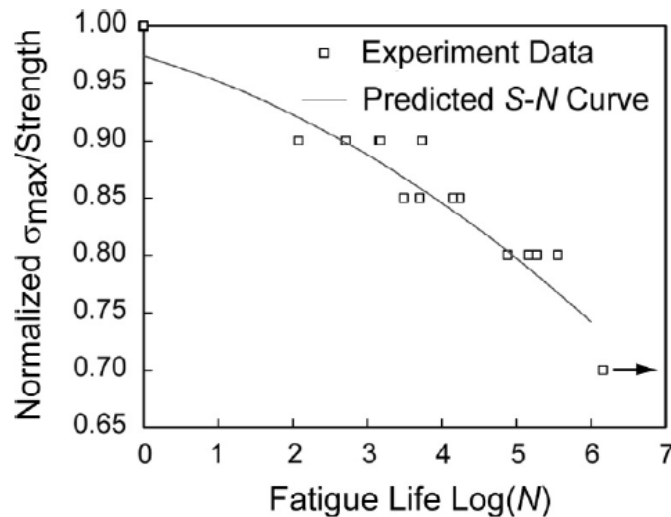


Figure 10 The S-N curves of the bolted joints structure. [18]

A couple of papers investigating the effects of self-heating and environmental temperature on composites' fatigue, and closely related to the work undertaken in D-STANDART, are the ones from Sayyidmousavi et al. [19] and [20]. These report a micromechanical approach adopted to study the role of viscoelasticity on the fatigue behaviour of polymer matrix composites. In particular, the study examines the interaction of fatigue and creep in angle ply carbon/epoxy at 25 and 114 °C. The fatigue failure criterion is expressed in terms of the fatigue failure functions of the constituent materials. The micromechanical model is also used to calculate these fatigue failure functions from the knowledge of the S-N diagrams of the composite material in longitudinal, transverse and shear loadings, thus eliminating the need for further experimentation.

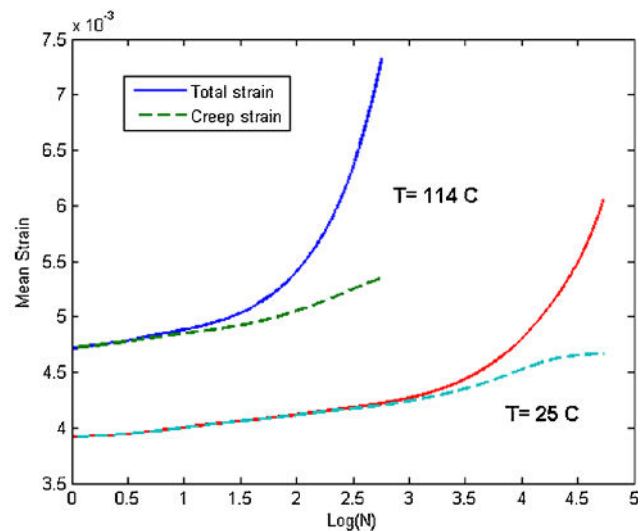


Figure 11 Contribution made by viscoelasticity to the total strain evolution at two different temperatures. [19]

Closely related to the temperature effects studied in the two previous paper, Wang et al. [21] proposes a micromechanics-based procedure to predict the long-term life of the cylindrical laminates under cyclic fatigue loading and high-temperature conditions. The method of integrating micromechanics of failure (MMF) with the time-temperature superposition principle (TTSP) method is interesting. In the paper, the time-temperature effect of the viscoelastic material is considered by the stiffness and fatigue master curves of the matrix, and the cyclic effect is handled by parameters such as the loading frequency and stress ratio.

Bridging micromechanical models have been used to observe the behaviour of unidirectional laminate composite under fatigue loading. Adibnazari et al. [22] use micromechanical models to study composite material's fatigue behaviour in this paper. The fatigue behaviour, stiffness degradation and strength degradation have been studied, and a driftnet model has been proposed for each. The work of Abdin et al. [23] and [24] on the Eshelby-based Mean-Field homogenisation is also worth mentioning, which is an effective method for modelling the mechanical response of short fibre reinforced composites. The primary motivation for reading this work is associated with the fatigue behaviour in the steered-fibre manufacturing process, where the curvature of the fibres might be linked to some possible detrimental fatigue behaviour of the material. Figure 12 shows the principal stress predictions for the FE and P-I models.

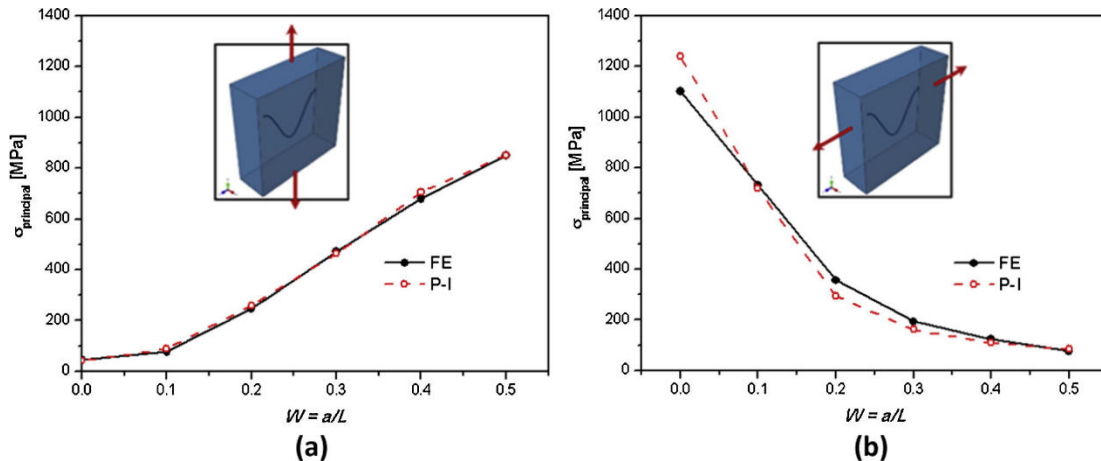


Figure 12 Comparison of the global maximum principal stress predictions vs principal of P-I model of the second test case (sinusoidal fiber) against full FE (a) transverse loading, (b) longitudinal loading. P-I model generated with 20 segments. [23]

Fazlali et al. [25] propose a damage progression in unidirectional (UD) composites in tension-tension fatigue, suggesting that it is vital to understanding fatigue in more complex laminates and loading conditions. These authors, as opposed to the work of Carraro, developed the UD fatigue model that considers fibre breaks, fibre-matrix debond growth, fibre fatigue, and interactions of these damage modes. The contribution of each mode of damage in fatigue is assessed, and those that dominate fatigue damage are identified. The predictions revealed that the densities of fibre breaks and clusters in fatigue loading are significantly higher than for quasi-static loading, which agrees with the experimental findings. The authors claim that *"compared to state-of-the-art micromechanical models, the presented model not only considers more fatigue damage mechanisms, but it also offers greater versatility, which enables the prediction of fiber break and cluster development as well as the full S-N diagram"*. Alvali et al. [26] present an analytical model to predict the fatigue life of unidirectional composites under longitudinal tension-tension. The matrix and fibre-matrix interface are represented through a cohesive constitutive law, and a Paris law is used to model fatigue due to interfacial cracks propagating from fibre-breaks. The strength of single-fibres is modelled by a Weibull distribution, which is scaled hierarchically through stochastic failure analysis of composite fibre-bundles, computing stochastic S-N curves of lab-scaled specimens.

Benedetti et al. [27] propose a paper on a grain-scale three-dimensional model to analyse fatigue intergranular degradation in polycrystalline materials. The authors claim that *"The distinguishing feature of the framework is that it is based on a boundary integral representation of the mechanical problem for the individual crystals, which allow to formulate the overall problem in terms of intergranular variables, i.e. displacement jumps and tractions, thus allowing (a) a particularly effective expression of the intergranular cohesive traction-separation laws, (b) a relative reduction in the number of DoFs with respect to volume discretisation methods (also when crystal plasticity is considered for the grains, ....and (c) a relative simplification in input data preparation."* Although it is out of the scope of D-STANDART, the three points listed by the authors, particularly point (b), can be a valuable lesson to learn.

Mohammadi et al. [28] propose a work that might interest the reader in deriving the constitutive laws. The constitutive law is derived at the level of fibre and matrix and extended

for a damaged lamina using the reformulation of Mori-Tanaka model. Moreover, it shows an interesting case of upscaling formulation and verification against test data.

One of the investigations in D-STANDART will be the effect of fibre orientation, and one aspect is the fibre-bridging effect on fatigue behaviour. Danesjoo et al. [29] state that fibre bridging significantly affects the behaviour of mixed mode I/II delamination. The paper reports the effects of fibre bridging and related micro mechanisms, where a novel micromechanical model called "mixed mode I/II micromechanical bridging model" is proposed based on the calculation of the delamination crack bridging zone energy absorption. Although the work does not investigate the fatigue behaviour, it presents the experimental work carried out with a Mixed-Mode Bending test fixture, shown in Figure 13.

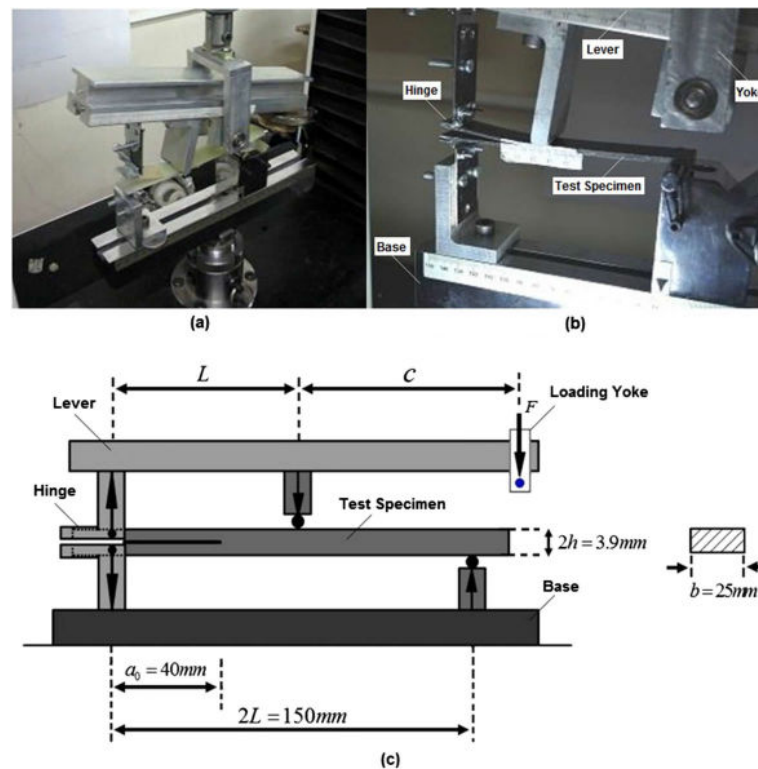


Figure 13 Test fixture [29]

The mesoscale modelling section discusses the Kinetic Theory of Fracture (KTF). However, Naderi et al. [30] present work on three-dimensional (3D) finite element analysis along with a damage model based on the kinetic theory of fracture (KTF), which are used to determine the onset of fatigue crack initiation in unidirectional carbon fibre reinforced composites. This paper presents a combination of micro- and macro-scale approaches combining Multi-continuum theory (MCT) and micromechanics analysis. The latter captures the stress field at the micro length scale level. Interestingly, the paper offers an excellent example of the formulation implementation by ABAQUS™ with user material (UMAT) subroutine.

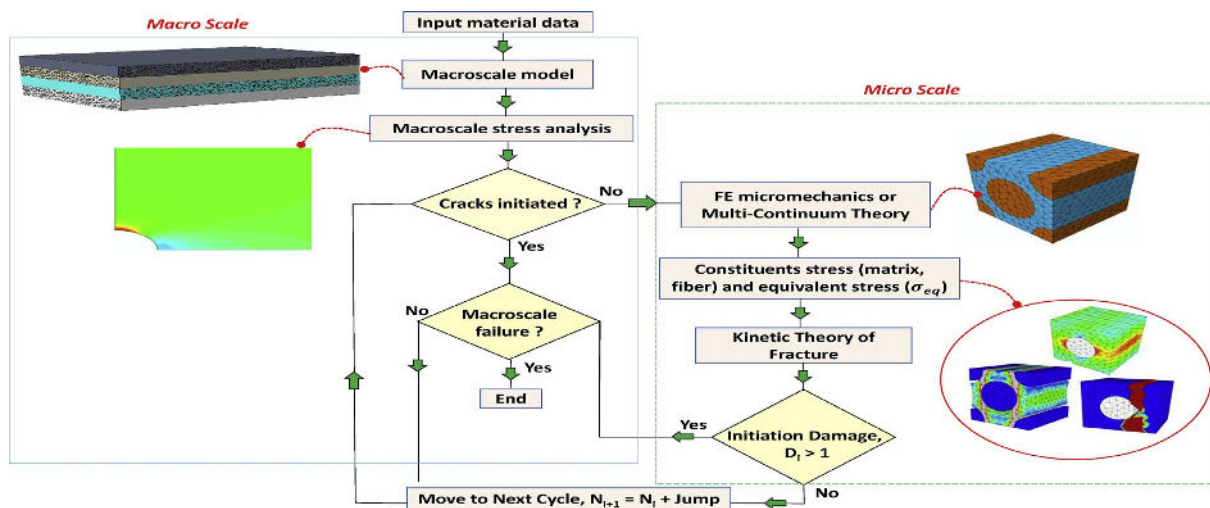


Figure 14 Current fatigue numerical flow chart. [30]

Section 5.5 presents results obtained with the IM7/8552. The paper suggests that KTF-based fatigue damage initiation life predictions are in reasonable agreement within the range of test data with some slight under/overestimation. The authors stress that a crucial motivator for incorporating the KTF in the proposed analysis is the fact that only a minimal set of material parameters are required while, at the same time, it can encapsulate the direct effect of temperature, creep and loading frequency. Alongside this paper, Kordkheili et al. [31] propose a multiscale progressive micro-mechanical fatigue model. What is interesting about this paper is the use of the Kinetic Theory of Fracture proposed by Baker-Jarvis. The multiscale approach is demonstrated against the open-hole test case relevant to one of the D-STANDART validation test cases. The KTF formulation is highly appealing when high-frequency tests combine the effect of temperature and loading frequency, making such formulation more comprehensive (*quasi-static + dynamics*) than the others enlisted so far.

The last two papers reported in this document have relevance in terms of the probabilistic modelling of D-STANDART. Laveuve et al. [32] and Davidson et al. [33] produced two valuable investigations. The latter reports that a novel micromechanics approach is utilised in this study to predict stiffness degradation due to fatigue. The micromechanics model includes micro and mesoscale misalignment and explicit modelling of fibre and matrix. The fatigue model utilises in-situ matrix fatigue degradation curves obtained from coupon-level experiments and implemented using a user subroutine in the FE. What is relevant in this paper is that the authors claim that by knowing only the matrix degradation behaviour, it is possible to describe both stiffness degradation and the S-N curve of a fibre-reinforced composite. Figure 15 shows the damage evolution, while Figure 16 shows the S-N curve produced by the microscale model.

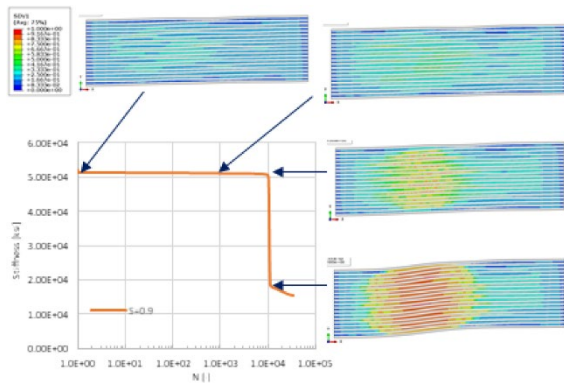


Figure 15 Evolution of damage index with number of cycles for  $S = 0.9$ . [33]

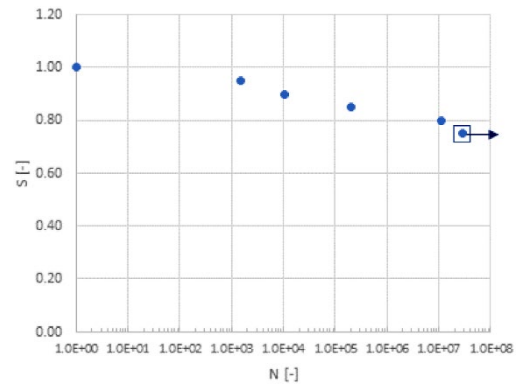


Figure 16 S-N data obtained from micromechanics simulation. [33]

Much more interesting is the first paper from Laveuve, who approach the micromechanical modelling of fatigue with stochastic methods. A Monte-Carlo algorithm generates random arrangements of unidirectional carbon fibres embedded in a polymer matrix. Figure 18 shows a flow diagram of the algorithm. The cross sections of these geometries are tessellated using Voronoi-cells and Delaunay-triangles to create potential crack paths and meshed using finite volume elements. The material behaviour is then statistically analysed for samples of random fibre arrangements containing different numbers of fibres. The results show that the effective properties' scatter depends on the size of the composite material volume considered. Even more importantly, the fibre arrangements show a prominent statistical size effect on the fatigue life to crack initiation.

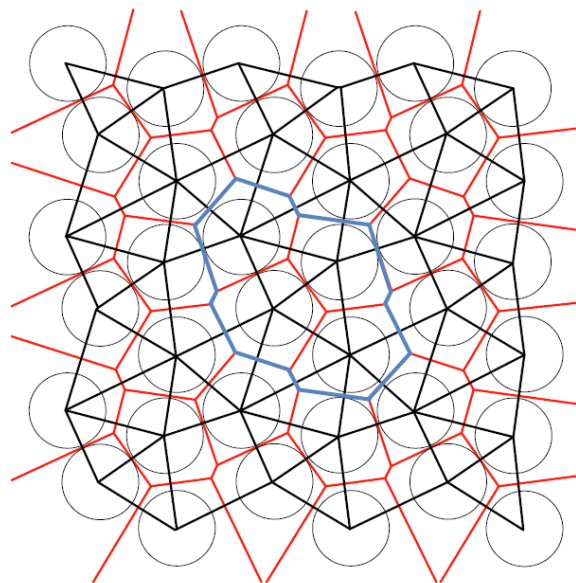


Figure 17 Random periodic arrangement of four fibres temporarily multiplied to all sides for Voronoi (red) and Delaunay (black) tessellation; blue: Voronoi boundary of the arrangement; Delaunay-edges are omitted, if they do not intersect orthogonal Voronoi-edges. [32]

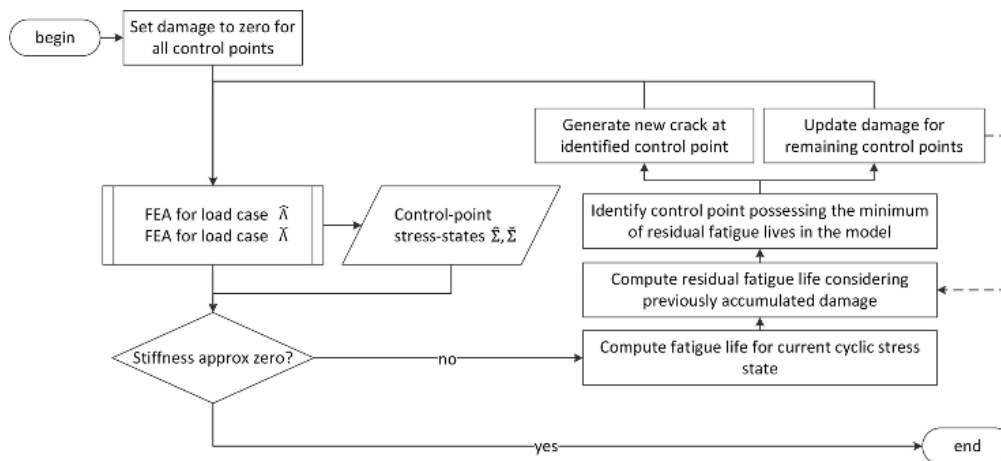


Figure 18 Progressive failure algorithm for FE-models containing random fiber arrangements. [32]

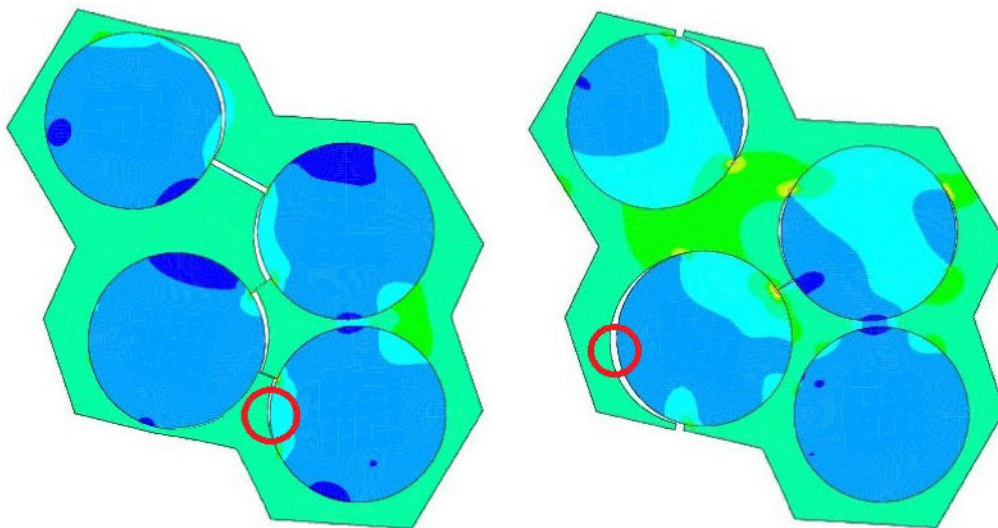


Figure 19 Model containing four fibers after generation of ten cracks; left: under cyclic strain level  $\epsilon_1 = 0.001$ , right: under cyclic strain level  $\epsilon_2 = 0.002$ ; red circles: location of first crack. [32]

Sørensen et al. [34] developed a theoretical model for predicting a fatigue limit of unidirectional fibre composites subjected to cyclically varying tensile loads in the fibre direction. Their claim is "The fatigue limit is defined from the condition that failure of one fibre does not lead to progressive failure of the neighbouring fibres. The model describes the fibre/matrix interface in terms of fracture energy and frictional sliding shear stress. Fatigue damage in the form of cyclic debond crack growth and a decrease in the frictional sliding shear stress along the fibre matrix interface is considered. Describing the fibre strength variation in terms of Weibull distribution, an equation for the fatigue limit is developed." Figure 20 show the approach for estimation of the maximum stress.

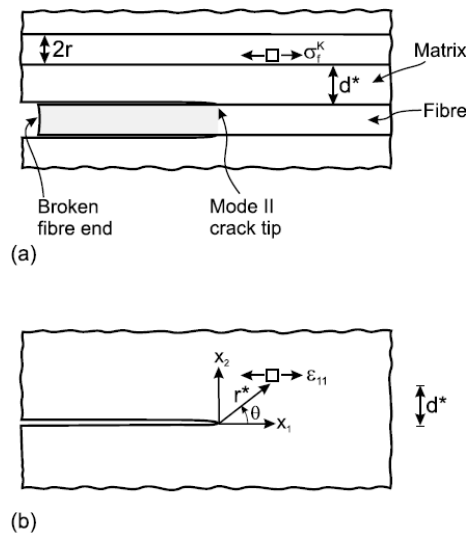


Figure 20 Approach for estimation of maximum stress induced in neighbouring fibres due to the debond crack tip stress field of a broken and debonded fibre (a), and the associated plane problem of a homogenous material (b).

[34]

Finally, Bojja et al. [36] present a paper about an investigation, where the stiffness degradation behaviour of a glass-fibre epoxy silica-nano-particle composite (GFRP nanocomposite) under a two-step block load sequence was predicted from micro-mechanics based models.

As a concluding remark, the reading of research papers highlights an incorrect assumption which commonly arises when a model is generated for carrying out fatigue analysis, particularly when finite element analysis is used. It appears that researchers consider the mass and stiffness distribution adequately calibrated once simulated strains are matched with experimental ones for given bending tests. Unfortunately, an accurate estimation of the specimen bending stiffness does not necessarily mean that the stiffness distribution, the  $[K]$  matrix, of the simulated specimen is correct. The bending stiffness alone does not provide enough information to identify a unique  $[K]$  matrix. That stiffness and mass distributions are only correct when all eigenfrequencies of the test specimen are matched to the simulated one. Lavueve [13] assumes that the fibre alignment cannot be idealised, but it is subjected to a random distribution. This randomness leads to a non-uniform distribution of stiffness at the mesoscale, and in terms of eigenfrequencies, a model might predict those incorrectly. Ultimately, stress calculations will be intrinsically inaccurate whatever model is used for the fatigue analysis, considering that fatigue leads to a much more complex stress redistribution.

Table 2 Table reporting the most up-to-date paper on microscale fatigue models

#	Year	Authors, Title, Journal
10	2022	Davidson, P. and Waas, A.M., 2022. A micromechanics-driven model for compressive fatigue of fiber-reinforced composites. <i>Journal of Reinforced Plastics and Composites</i> , 41(17-18), pp.661-669.
11	2021	Fazlali, B., Lomov, S.V. and Swolfs, Y., 2021. Fiber break model for tension-tension fatigue of unidirectional composites. <i>Composites Part B: Engineering</i> , 220, p.108970.
12	2020	Sharma, A. and Daggumati, S., 2020. Computational micromechanical modeling of transverse tensile damage behavior in unidirectional glass fiber-reinforced plastic

		composite plies: Ductile versus brittle fracture mechanics approach. <i>International Journal of Damage Mechanics</i> , 29(6), pp.943-964.
13	2019	Laveuve, D.M. and Büter, A., 2019. Modeling fatigue life of composite laminates: A statistical micro-mechanics approach. <i>International Journal of Fatigue</i> , 128, p.105201.
14	2019	Sørensen, B.F. and Goutianos, S., 2019. Micromechanical model for prediction of the fatigue limit for unidirectional fibre composites. <i>Mechanics of Materials</i> , 131, pp.169-187.
15	2019	Naderi, M., Michopoulos, J., Iyyer, N., Goel, K. and Phan, N., 2019. Multiscale analysis of fatigue crack initiation life for unidirectional composite laminates. <i>Composite Structures</i> , 213, pp.271-283.
16	2018	Daneshjoo, Z., Shokrieh, M.M. and Fakoor, M., 2018. A micromechanical model for prediction of mixed mode I/II delamination of laminated composites considering fiber bridging effects. <i>Theoretical and Applied Fracture Mechanics</i> , 94, pp.46-56.
17	2018	Alves, M. and Pimenta, S., 2018. A computationally-efficient micromechanical model for the fatigue life of unidirectional composites under tension-tension loading. <i>International Journal of Fatigue</i> , 116, pp.677-690.
18	2018	Mohammadi, B. and Fazlali, B., 2018. Off-axis fatigue behaviour of unidirectional laminates based on a microscale fatigue damage model under different stress ratios. <i>International Journal of Fatigue</i> , 106, pp.11-23.
19	2018	Cai, R. and Jin, T., 2018. The effect of microstructure of unidirectional fibre-reinforced composites on mechanical properties under transverse loading: A review. <i>Journal of Reinforced Plastics and Composites</i> , 37(22), pp.1360-1377.
20	2018	Benedetti, I. and Gulizzi, V., 2018. A grain-scale model for high-cycle fatigue degradation in polycrystalline materials. <i>International Journal of Fatigue</i> , 116, pp.90-105.
21	2017	Hosseini Kordkheili, S.A., Toozandehjani, H. and Soltani, Z., 2017. A progressive multiscale fatigue model for life prediction of laminated composites. <i>Journal of Composite Materials</i> , 51(20), pp.2949-2960.
22	2016	Abdin, Y., Jain, A., Verpoest, I. and Lomov, S.V., 2016. Mean-field based micro-mechanical modelling of short wavy fiber reinforced composites. <i>Composites Part A: Applied Science and Manufacturing</i> , 91, pp.472-483.
23	2016	Wang, L., Wang, B., Wei, S., Hong, Y. and Zheng, C., 2016. Prediction of long-term fatigue life of CFRP composite hydrogen storage vessel based on micromechanics of failure. <i>Composites Part B: Engineering</i> , 97, pp.274-281.
24	2016	Bojja, R., Anil Chandra, A.R., Jagannathan, N. and Manjunatha, C.M., 2016. Micromechanics modeling and prediction of stiffness degradation behavior of a fiber reinforced polymer nanocomposite under block amplitude fatigue loads. <i>Transactions of the Indian Institute of Metals</i> , 69, pp.403-407.
25	2015	Sayyidmousavi, A., Bougherara, H. and Fawaz, Z., 2015. The role of viscoelasticity on the fatigue of angle-ply polymer matrix composites at high and room temperatures-a micromechanical approach. <i>Applied Composite Materials</i> , 22, pp.307-321.
26	2015	Adibnazari, S., Farsadi, M., Koochi, A. and Khorashadizadeh, S.N., 2015. New approach for fatigue life prediction of composite plates using micromechanical bridging model. <i>Journal of Composite Materials</i> , 49(3), pp.309-319.
27	2015	Li, W., Cai, H., Li, C., Wang, K. and Fang, L., 2015. Micro-mechanics of failure for fatigue strength prediction of bolted joint structures of carbon fiber reinforced polymer composite. <i>Composite Structures</i> , 124, pp.345-356.
28	2015	Abdin, Y., Lomov, S.V. and Jain, A., 2015. Mean-field based fatigue damage modeling of composites reinforced with short straight and wavy fibers. In 20th International Conference on Composite Materials (ICCM-20).

29	2015	Sayidmousavi, A., Bougherara, H. and Fawaz, Z., 2015. A multiscale approach for fatigue life prediction of polymer matrix composite laminates. <i>Journal of Reinforced Plastics and Composites</i> , 34(13), pp.1099-1109.
30	2015	Cai, H. and Li, W., FATIGUE STRENGTH PREDICTION OF BOLTED JOINT STRUCTURES OF CARBON FIBRE REINFORCED POLYMER COMPOSITE BASED ON THE MICROMECHANICS.
31	2014	Min, J.B., Xue, D. and Shi, Y., 2014. Micromechanics modeling for fatigue damage analysis designed for fabric reinforced ceramic matrix composites. <i>Composite Structures</i> , 111, pp.213-223.
32	2014	Carraro, P.A. and Quaresimin, M., 2014. A damage based model for crack initiation in unidirectional composites under multiaxial cyclic loading. <i>Composites Science and Technology</i> , 99, pp.154-163.
33	2013	Shokrieh, M.M. and Esmkhani, M., 2013. Fatigue life prediction of nanoparticle/fibrous polymeric composites based on the micromechanical and normalised stiffness degradation approaches. <i>Journal of Materials Science</i> , 48, pp.1027-1034.
34	2013	Qian, C., Westphal, T. and Nijssen, R.P.L., 2013. Micro-mechanical fatigue modelling of unidirectional glass fibre reinforced polymer composites. <i>Computational materials science</i> , 69, pp.62-72.

### 3. Mesoscale fatigue damage models

The last section of this State-of-the-Art document proposes a short selection of papers believed to be valuable to D-STANDART work packages involved in testing and analysing fatigue behaviour. Therefore, it is not meant to be as extensive as the review papers in Chapter 1 and the microscale papers in Chapter 2. The selection of the papers followed these criteria:

- (i) papers which unify the S-N and Paris-Erdogan relationship models,
- (ii) papers which exploit Ai-based methods for the fatigue modelling and
- (iii) papers which unify the mechanical and thermal fatigue modelling, such as fatigue and self-heating.

Engelstad et al. [37] in 2017, issued a paper that compares modelling techniques of progressive damage analysis methods across seven research groups. Engelstad reports that *"During the last 10–15 years, many composites researchers have concentrated on the development of progressive damage analysis (PDA), implemented in the latest finite element analysis software. To evaluate the state of the art in this area, an Air Force Research Laboratory (AFRL) program entitled "Damage Tolerance Design Principles (DTDP)" was conducted from 2014 to 2015 to evaluate existing technologies in composite damage progression modeling and prediction, and evaluate them for application to future damage growth analysis needs."* Therefore, the groups were challenged to make blind predictions of the behaviour of nine different composite materials in different stacking layouts, in static and tension-tension fatigue tests and for different loading cycles. Their models considered both in-house codes as well as commercial software. Figure 21 reports the table containing the team members and the PDA used.

Team members	PDA method
Vanderbilt University	Eigendeforination-based Reduced Order Homogenization (EHM)
University of Dayton Research Institute (UDRI)	B-Spline Analysis Method with Mesh Independent Cracking (BSAM with MIC)
Global Engineering and Materials (GEM)	Discrete Crack Network (DCN)
NASA Glenn/University of Michigan (UM)	Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC)
Multiscale Design Systems (MDS)	Multiscale Design System for Linking Continuum Scales (MDS-C) (now part of Altair)
AutoDesk/LM Aero	Helius PFA (formerly ASCA)
AlphaSTAR	GENOA

PDA: progressive damage analysis.

Figure 21 Analysis teams and their codes for fatigue predictions. [37]

The paper is a derivation of the special issue produced in the same journal and should be consulted because of the wealth of information delivered by the authors. The plot, reproduced in Figure 22 as an example, indicates the challenge faced by the teams. Given a confidence bound of 90-95%, the authors report the following statement: *"Figure 4 displays the stiffness degradation up to 2000K cycles and the residual stress–strain plots after 300K cycles for the seven blind predictions as well as the experimental average for the [0/45/90/-45]<sub>2S</sub> layup. For stiffness degradation in Figure 4(a), it can be seen that half of the codes overpredicted the stiffness while the other half underpredicted the stiffness as a function of cycles. The residual OHT and OHC results shown in Figure 4(b) and (c) indicate that the seven analysis codes generally agreed with the experimental averages for both stiffness and strength for this layup after 300K cycles."*

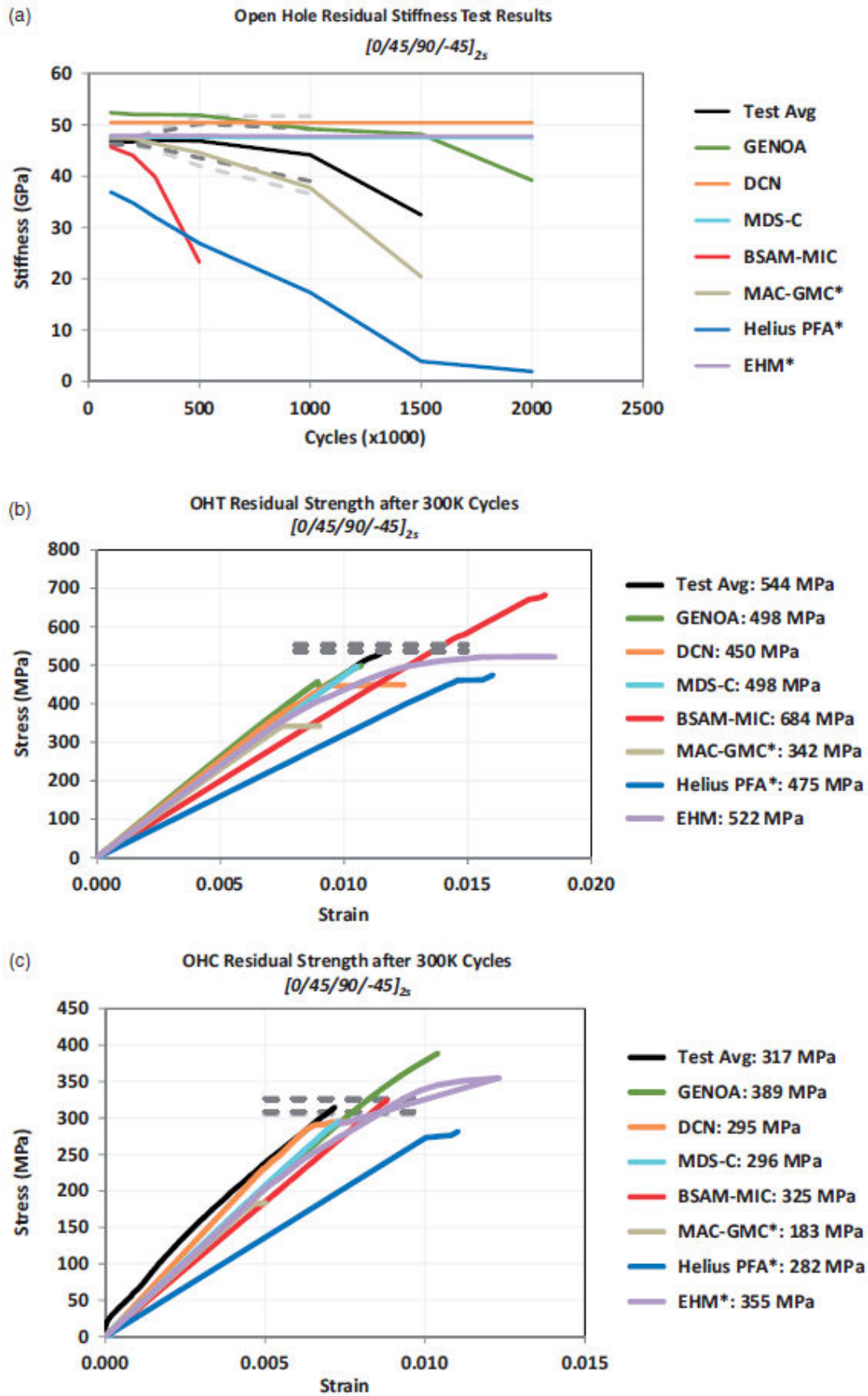


Figure 22 Blind prediction plots for open-hole (a) residual stiffness, (b) residual tension strength, and (c) residual compression strength for  $[0/45/90/-45]_{2s}$  layup. [37]

Their blind models were calibrated, after experiments, for better longitudinal and compression moduli. After calibration, they achieved an overall stiffness error of 18%, across teams, samples and length of tests after an initial 42%. These two numbers are very indicative of what the D-STANDART consortium is intended to achieve. An error of 42% indicates that our safety factors are very conservative because of the inaccuracy of the predictions. It means more material to use despite the loss of sustainability. After calibration, the error is still relatively large (18%). That calibration is a process that, during production, is not always possible. This gives a useful indication of the prediction accuracy that can be achieved with the current state-of-the-art models, and therefore indicates an informal success criterion for the D-STANDART approach.

Having briefly described the outcome of the Engelstad's paper, one expert outside the materials and structures community can observe that experimental tests and data results did not go through any verification process. Actually, quantifying the data scatter seems sufficient to achieve a degree of confidence. In Structural Dynamics, the verification of test results, as mode shapes (eigenvectors), is achieved by verifying the orthogonality conditions. It means that test data can be projected onto itself to verify whether the parameters identified are unique or biased by an unknown source, such as an incorrect measurement setup. This observation is the rationale for selecting two authors who have contributed greatly to the materials community and which can be exploited further within the D-STANDART consortium.

### 3.1. Papers which unify the S-N and Paris-Erdogan relationship models

Allegri, first in [38], and Dávila, as soon as after in [39] and [40], delivered research work focused on the Cohesive Zone formulation.

Davila in NASA reports [40] the following statement: "*...The finite element analyses performed demonstrate that the cohesive fatigue accumulation function provides a link between the S-N diagram that describes crack initiation, and the Paris law that characterises the rate of crack propagation. However, when the model was proposed, it was not known whether the form of the damage accumulation function associated with a desired S-N diagram is unique and, if not, if the link between S-N and the Paris law is unique and independent of the fatigue function selected...*".

Allegri reported just earlier that: "*....It is also shown that the Paris-Erdogan law for fatigue crack growth can be directly obtained from engineering S-N curves via the linear traction displacement model introduced here. The Paris-Erdogan propagation regime is attained when the crack propagation rate is much smaller than the length of the process zone. The exponent of the Paris-Erdogan law is equal to half the inverse of that characterising the material S-N curve. The main advantage of the cohesive zone model introduced here is that it does not require neither ad-hoc additional parameters nor calibration constant to obtain the Paris-Erdogan law from material S-N data. It is also proved that the cohesive zone length in fatigue depends on the exponent of the S-N curve and it is always shorter than its static counterpart....*".

No matter who of them achieved this understanding earlier, the good news is the link between the S-N curve and the Paris-Erdogan relationship. In essence, test data from two tests are characterised by the same slope assuming that the damage modes or their ratio are the same. Figure 23 shows how the S-N and the Paris-Erdogan relate to each other. There is a wealth of test data and simulation in both cited authors. As introduced earlier, this paper's relevance is to establish a cross-correlation between two independent tests as it was done for Structural

Dynamics. Although this is still a hypothesis, it is fair to assume that two sample run under the same condition with the same mode-mixity should deliver the same slope of damage accumulation. Allegri demonstrated the hypothesis by analytical formulation with the aid of numerical analysis for a non-linear Fredholm integral equation of the second kind. Davila proposed a Finite Element workflow which is reported in Figure 24.

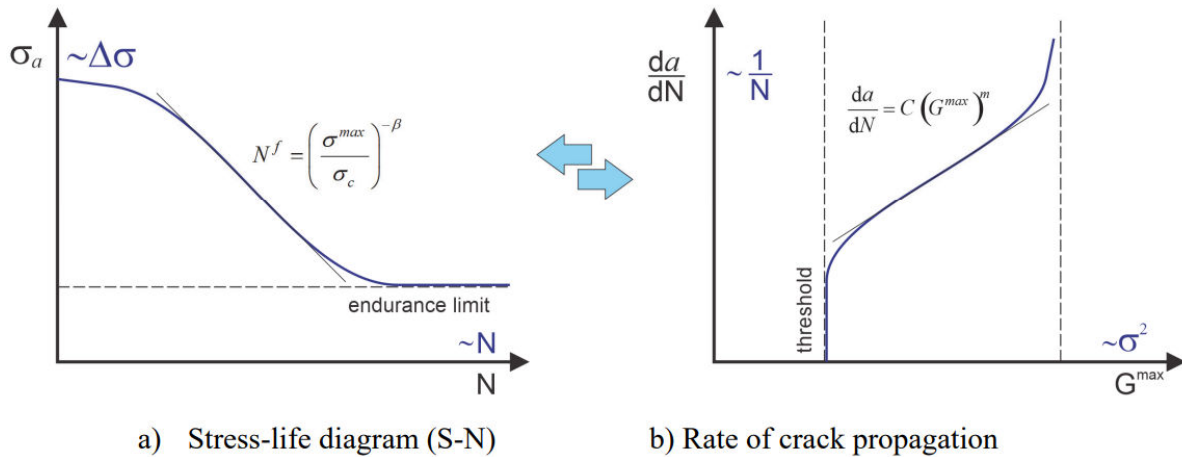


Figure 23 Relationship between the S-N curve (left) and the Paris law (right). [40]

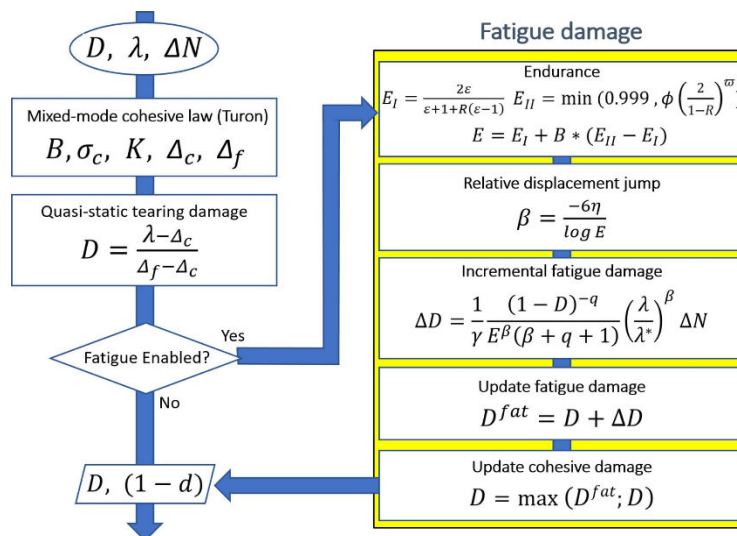


Figure 24 Flowchart of CF22 cohesive fatigue user subroutine. [39]

### 3.2. Papers which exploit AI-based methods for the fatigue modelling

If, on the one hand, the above relationships might lead to unique cohesive zone formulation, on the other end, one needs to deal with the stochastic nature of the fatigue behaviour. As anticipated earlier, the heterogeneity of the material requires a bold approach to the modelling which ought to include the stochastic behaviour of the fatigue life. The ambition of D-STANDART is to develop a surrogate fatigue model, and to do that, probabilistic models are required to generate synthetic data for training the AI and use experimental data to verify the AI simulation capabilities. Allegri attempted this framework [41], 2018, presents a mathematical formulation of a power-law kind for mixed modes I and II fatigue delamination growth was

provided and tested for unidirectional composites (assuming constant temperature and small delamination cracks compared to the characteristic length of the samples). A self-similar formulation, which implies that the found expression works at different geometrical scales, was found and expressed in non-dimensional terms. The law is characterised by three terms: fatigue, a static fracture and a brittleness parameter. The self-similarity is of the first type, which means that the found expression is bounded (it does not diverge when one of the three terms diverges, for example, at the threshold or fracture). A Neural Network (NN), as shown in Figure 25 is used to predict the behaviour of samples from the training dataset. To do this, the author mapped previously published experimental data into the three characteristic parameters and linked them to the output, a function of  $da/dN$  (as shown in Figure 26), through a single hidden layer. Interestingly, he imposed physic-based knowledge into the limits of the internal weight coefficients of the hidden layer. The results from the NN are compared against a modified Hartman-Schijve model for different mode-mixities (pure Mode I, II and values in between) and stress ratios, with comparable or better results in some cases in favour of the proposed approach.

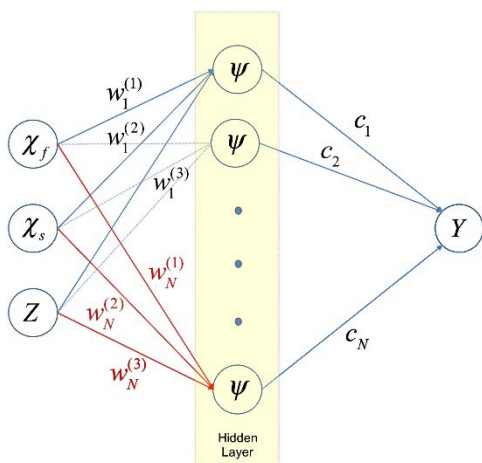


Figure 25 Architecture of SHLNN for FDG description. [41]

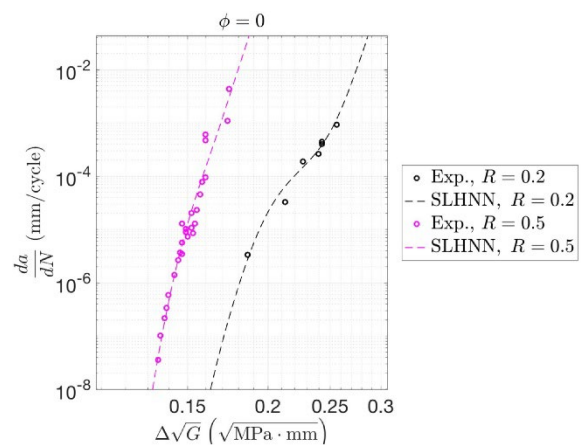


Figure 26 Mode I FDG data for T800H/#3631; SHLNN output in dashed lines. [41]

### 3.3. Papers which unify the mechanical and thermal fatigue modelling, such as fatigue and self-heating.

This final section reports a few papers which align with the two objectives of the D-STANDART, such as (i) evaluating/modelling the fatigue temperature dependence of composites (self-heating) and (ii) modelling composite fatigue. It was found that Entropy is an indicator used for characterising the accumulation of heat and of fatigue damage. Naderi et al. worked on several pieces of research, both focused on the fatigue of metals [42] and [43], and more recently, on the fatigue of composites [30]. Naderi postulated that '*the thermodynamic entropy of metals undergoing repeated cyclic load reaching the point of fracture is a constant, independent of geometry, load and frequency*'. To find a mathematical expression of the value of the Fracture Fatigue Entropy (FFE), the accumulated entropy generation until the moment of fracture, they developed the theory from the First and Second Laws of Thermodynamics, applied to continuum mechanics. First, they reached an expression for the entropy generation rate, which they progressively simplified in the paper by assuming small deformations, neglecting thermoelastic coupling effects and ignoring internal heat conduction. Although the

work of Naderi is not directly linked to the D-STANDART material selection, the formulation based on Entropy might help model some of the composites' thermal behaviour. As a matter of example, Figure 27 and Figure 28 show the temperature characteristics of an Aluminium alloy and the IM7/8552 under fatigue, respectively. The two material systems have a rather remarkable similarity in terms of their surface heat response.

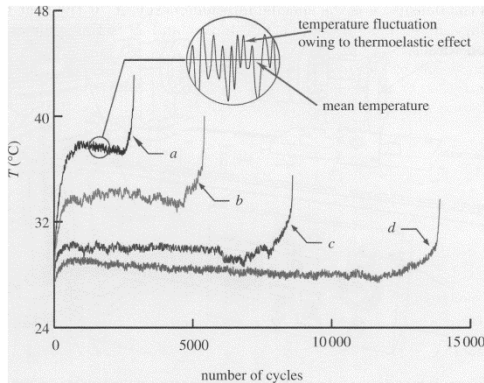


Figure 27 Evolution of temperature in the bending fatigue of an AL specimen at 10Hz at different displacement amplitude. [42]

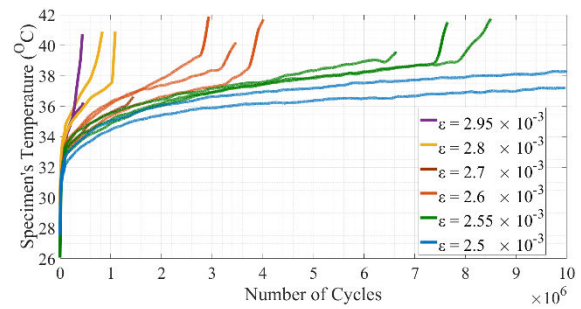


Figure 28 Surface temperature measured at different strain load during vibration tests

## 4. Conclusions and Outlook

This document reports three chapters, the first providing a general overview reproduced by many review papers on the fatigue of composites. It is clear from the most significant statements reproduced that D-STANDART targets to correct objectives in modelling and testing.

All reviews highlighted that fatigue models are inaccurate, require extensive calibrations and often only work on a limited number of test cases. Furthermore, the experiments provide test data biased by large scatter despite the test protocols implemented. It was noticed that the only way to verify the quality of the test data is to quantify the scatter, but no other experimental formulation allows reading one test result across the other to ensure the consistency of the experimental datum. Hence, the work of Allegri and Davila assumes a critical relevance in the D-STANDART context because S-N curve slopes could be correlated to Paris one, thus creating one of the first verification processes in the experimental technique.

The document aimed to review the microscale fatigue models of the past ten years. There is a consistent bulk of literature, even though the community assumes that the microscale fatigue models suffer from the upscaling process.

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