Identification of accelerated wet-ageing cycles

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1 Introduction

The increasing use of polymer-matrix composites in aircraft structural parts calls for a better knowledge of the long-term properties in cyclic hygro-thermal conditions. For example, the new A380 aircraft is composed of composite structural parts that are more than 20 mm thick. In such cases, wet-ageing, partially characterized as a through-the-thickness water concentration profile, evolves over several decades. Wet-ageing is, typically, so slow that characterization experiments based on direct reproduction of the hygro-thermal cycles are not possible within the development time of the aircraft. The identification of cycles leading to comparable through-the-thickness water concentrations in shorter times has been proposed using a Fickian water diffusion model in [7, 8].

This article presents a rigorous methodology and software development for the identification of accelerated wet-ageing cycles. Depending on the formulation, identification time and water concentration profiles are treated either as objective functions or as constraints. The results of the different identifications exhibit the trade-offs that exist between water profile accuracy and experiment time. The numerical implementation is performed in the LAMKIT© software ([3]), which is an object oriented platform for the analysis and optimization of composite laminates ([4]). An application is given for a thick and humid laminate.

2 Accelerated wet-ageing problem formulation

Let $c(t, z)$ be an available through-the-thickness water diffusion model, where t is the time and z the thickness location. In this case, it is the one-dimensional multi-material Fickian model included in LAMKIT ([2]). The accelerated wet-ageing inverse problem determines thermal and hygral external conditions, $T(t)$ and $H(t)$, such that two criteria, t_{final} and J_c, are properly controlled : t_{final} stands for the total conditioning time and J_c is the average Euclidean distance between the target water profile and the water profile at time t_{final}.

Thermal and hygral cycles are parameterized as nt plateaus of value T_i or H_i, respectively, starting at t_{i-1} and finishing at t_i. nc cycles are then repeated. The identification variables are summed up in the x array,

$$x \in \{(t_1 - t_0), \ldots, (t_{nt} - t_{nt-1}),\ T_1 \ldots T_{nt},\ H_1 \ldots H_{nt},\ nc\}\ . \tag{1}$$

Now that the accelerated ageing variables and criteria are defined, two constrained mono-objective optimization problems are solved[1] :

$$(P_t) \qquad \begin{cases} \min_x t_{final} \\ \text{such that } J_c \leq J_c^{lim} \\ \text{and } x^{min} \leq x \leq x^{max} \end{cases}$$

$$(P_J) \qquad \begin{cases} \min_x J_c \\ \text{such that } t_{final} \leq t_{final}^{lim} \\ \text{and } x^{min} \leq x \leq x^{max} \end{cases}$$

(P_t) minimizes the conditioning time such that the water profile is not too distant from the target, and vice versa with (P_J).

3 Application

A 20 mm thick graphite-epoxy structure is considered where the saturation mass and the coefficient of water diffusion are

$$M_s = 0.001 H^{1.5}\ , \tag{2}$$
$$D = 6.10^{-6} \exp(-2500/T)\ . \tag{3}$$

The target concentration profile (symbol + in Figure 1) is humid (about 0.75% of the mass). A first (P_t) identification is performed where the maximum distance between the water profiles is $J_c^{lim} = 0.02\ \%$. The six continuous and bounded variables ($nt = 2$) are $0 \leq T_1, T_2 \leq 100\ °C$, $0 \leq H_1, H_2 \leq 100\ \%$, $0 \leq (t_1 - t_0), (t_2 - t_1) \leq 200\ h$. The number of cycles is fixed at $nc = 5$. The problem is solved using the Globalized and Bounded Nelder-Mead algorithm [5]. A trivial solution is obtained where all variables hit their upper-bounds (maximum times, temperatures and humidities). The total conditionning time is $2 \times 200 \times 5 = 2000\ h \approx 83$ days. Despite the very fast diffusion conditions created by this tuning, the specimen center is not humid enough (see Figure 1). Clearly, a longer conditionning is necessary.

[1] A third problem associated to the multi-objective formulation

$$(P_{tJ}) \quad \begin{cases} \min_x t_{final} \\ \text{and } \min_x J_c \\ \text{such that } x^{min} \leq x \leq x^{max} \end{cases}$$

can be solved using LAMKIT but, for concision, it will not be discussed here.

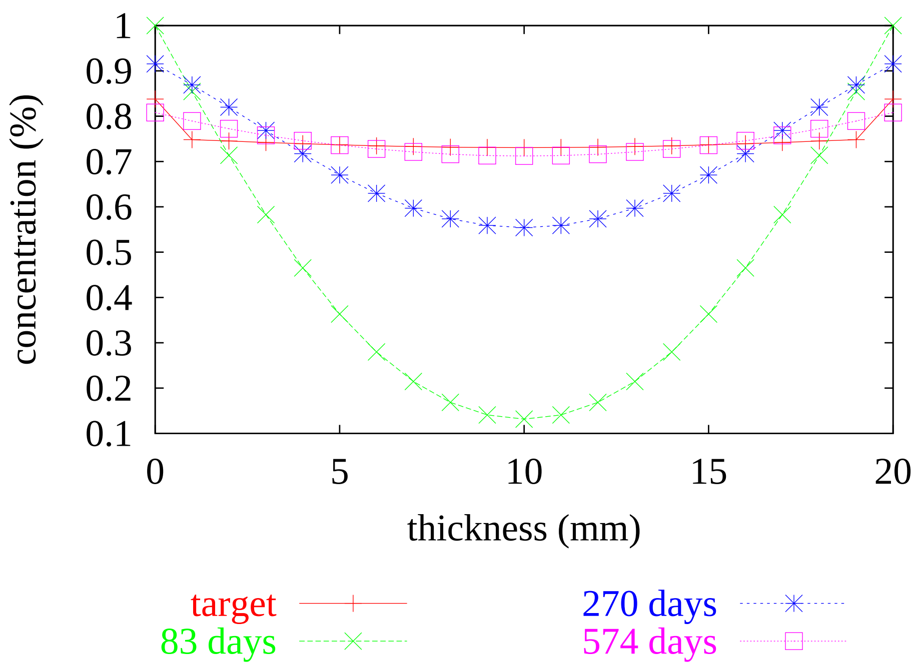

Figure 1: Comparison between a target water profile and three accelerated ageings of various t_{final}.

The (P_t) identification is therefore repeated but the largest possible experiment time is increased by the following changes : $nc = 20$ cycles are made and $0 \leq (t_1 - t_0), (t_2 - t_1) \leq 400\ h$. The solution is $t_1 = 383.\ h$, $t_2 = 688.\ h$, $T_1 = 100.\ °C$, $T_2 = 100.°C$, $H_1 = 85.\ \%$, $H_2 = 87.\ \%$, which has $t_{final} = 13776\ h = 574$ days and $J_c = 0.0207$. The corresponding water concentration profile is plotted in Figure 1. This solution is not satisfactory because the conditionning remains too long.

In order to better understand what is feasible in terms of concentration profile resemblance within a realistic time, a (P_J) identification is carried out. The maximum conditionning time is set to $t_{final}^{lim} = 270$ days. The discrete variable “number of cycles”, nc, is added to the identification variables x. Because there are both continuous and discrete variables, an evolutionary algorithm ([1, 3, 4]) that handles mixed variables is used for solving the optimization problem. The solution is $nc = 10$, $t_1 = 375.\ h$, $t_2 = 649.\ h$, $T_1 = 97.\ °C$, $T_2 = 97.°C$, $H_1 = 98.\ \%$, $H_2 = 94.\ \%$, which has $t_{final} = 270$ days and $J_c = 0.112$. The associated concentration profile is plotted in Figure 1.

4 Concluding remark

The careful identification problem formulation and programming performed for the LAMKIT project has been applied to the acceleration of wet-ageing. Similar work is underway to accelerate inelastic strains setting ([6]).

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