A strain rate and temperature dependent criterion to describe the linear - non linear behaviour's transition of organic matrix composite materials in shear: Application to T700GC/M21

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A strain rate and temperature dependent criterion to describe the linear - non linear behaviour's transition of organic matrix composite materials in shear: Application to T700GC/M21

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Abstract

The organic matrix composites (OMC) are widely used in aeronautical industry. The mechanical behaviour of these materials is known to be strain rate and temperature dependent. Therefore it is necessary to take the influence of temperature and strain rate into account in the behaviour models. The mechanical behaviour of OMC can be split into two different parts: a first linear and a second non linear phasis. To predict the evolution of the mechanical behaviour, it is important to evaluate the transition between linear and non linear behaviour with respect to the influence of the strain rate and the temperature. For this purpose, different strain rate and temperature dependent failure criteria and yield stress criteria, available in the literature were considered. These criteria were compared to the experimental results obtained in previous works [1]. Finally a strain rate and temperature dependent criterion was proposed to describe more accurately this transition evolution.

Keywords: Polymer-matrix based composite, Transition stress, Strain rate dependency, Temperature dependency

1. Introduction

Nowadays, the aeronautical industry has to face new challenges, in particular to reduce the weight of the aircraft (for environmental and cost reasons). One of the solution to reach targeted weight reductions is to use carbon fibre based composite materials. These materials also allow to avoid corrosion, to manufacture complex parts and to optimize the mechanical

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properties according to the loads while weight is reduced with respect to aluminium or metallic structures. One important issue in the aeronautic transport industry is to improve safety (see Flightpath 2050, Challenge 4). The main difficulty concerning this question relies on the severe conditions to which the aircraft can be exposed, including a large range of impacts and strain rates, under various operational temperature conditions. To be able to cope with this difficulty, it is important to better understand the mechanical behaviour of composite materials for every conditions aircraft may face, with the aim to model it to reduce the safety margins. Indeed an accurate and efficient model would lead to perform numerous structural analysis representative from real conditions, from static to dynamic loadings and for various temperatures.

The material studied in the present paper is a carbon fibre reinforced plastic one (CFRP), and particularly a carbon/epoxy composite: the T700GC/M21 and particularly the laminate $[\pm 45°]_s$. The mechanical behaviour of CFRP is known to be strain rate dependent [2–5], especially with shear loading [4, 6, 7] and temperature dependent [2, 3, 8]. One important conclusion of these studies is that their mechanical shear behaviour can be decomposed into two different phasis: a first linear, a second non linear, followed by the final rupture of the material [4, 6, 9, 10]. In the literature, different models can be found to describe the mechanical behaviour of these materials [11–14]. These models differ by the method used to model the non linear behaviour, some of them use a non linear viscoelastic spectral method and a damage model [11, 12, 15], and others use a plasticity model and a damage model [13, 14, 16]. The linear behaviour of the T700GC/M21 material with respect to the influence of the temperature and the strain rate has already been studied by Berthe et al. [17, 18], who proposed a viscoelastic bi-spectral model to describe this linear behaviour. This behaviour once studied, the question arises of the transition between linear and non-linear behaviour. This transition can be evaluated in terms of stress σ_t or strain ε_t [1].

This works are focused on the shear transition between linear and non linear behaviour. The aim of the present works is to propose a strain rate and temperature dependent material model to describe the transition shear stress and strain (σ_t and ε_t) evolution laws for composite materials, such as T700GC/M21, based on the models available in the composites and polymers literature. For this purpose, an experimental investigation on the T700GC/M21 [±45] laminate for a large range of strain rates and temperatures using an hydraulic jack has been used [17, 18]. The σ_t and ε_t obtained in [1] were considered for modelling purposes. In a first step a strain rate dependent model is proposed. Then, the temperature dependence is added. The final model is compared to the experimental results.

2. About the transition between linear and non linear behaviour

To use the mechanical behaviour models [11–14, 16] it is important to define accurately the transition between the different phasis of the shear behaviour. To the authors knowledge, the value of the transition between linear and non-linear behaviour is usually characterised by inverse methods for a laminate [±45°]. In previous works [1], a direct method to evaluate accurately this transition using only experimental raw data was proposed. In these works, the authors obtained this transition for six different strain rates at ambient temperature and for three different strain rates at $-40°C$ and $-100°C$. This transition is hereafter referred as σ_t/ε_t. In [1], the strain rate and temperature dependencies of this transition were established. Therefore to take into account this transition in a behaviour model, it is necessary to have a model of this transition which includes temperature and strain rate dependencies.

A brief overview of the results obtained in [1] is presented in the sequel, more details can be found in the original paper. The studied material was a $[\pm 45]_s$ laminated composite made of four plies of M21 epoxy resin and T700GC carbon fibres which had been cured with a typical cure cycle. Tensile tests had been performed on a servo hydraulic jack for three different temperatures: $20°C$, $-40°C$, $-100°C$. At low temperatures, the temperature is controlled by a thermocouple. The regulation system used in the environmental chamber is a ”Microcor III” system. To obtain a uniform temperature in the tested specimen, before performing the test, a stabilisation time is applied (about 10 min). At ambient temperature six loading speeds between $8, 3.10^{-6} m/s$ and $2m/s$ were studied, for the two other temperatures three loading speeds were performed between $8, 3.10^{-4} m/s$ and $0, 5m/s$. For each material sample two strain gauges were glued on opposite faces of the specimens to measure the longitudinal and transverse strains. These tests were described in more details in [1, 18, 19]. For each test, the method described in [1] was applied and the transition between the linear and non linear behaviour, σ_t and ε_t, was characterized. The obtained results are plotted in Figure 1.

In Figure 1, one may notice that the σ_t and ε_t values increased with the increasing strain rate and with the decreasing temperature, so the influence of the temperature and of the strain rate had been demonstrated. The next step consists in trying to model the transition evolution criterion with respect to the strain rate and the temperature. This is the aim of the next paragraph.

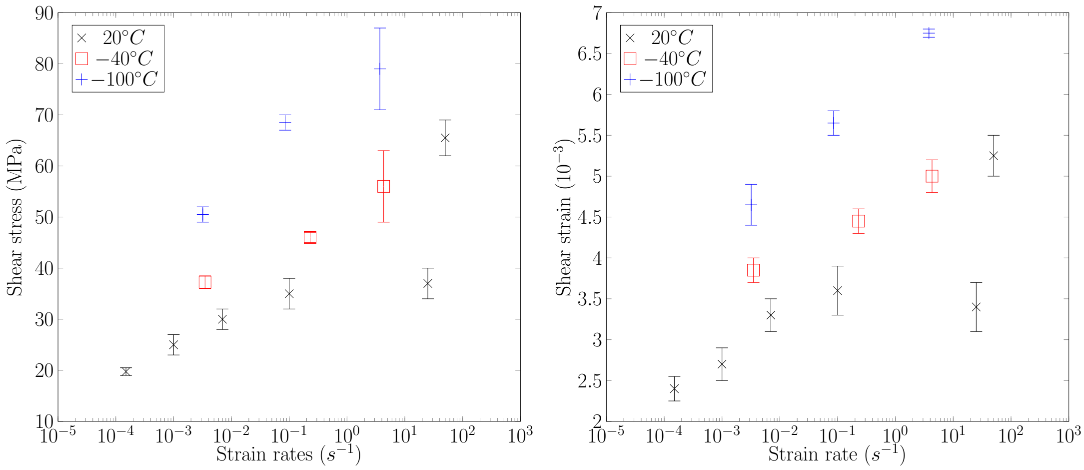

Figure 1: σ_t and ε_t at three different temperatures for $[\pm45°]_s$ T700GC/M21

3. The different strain rate and temperature dependent criteria of the literature

To the authors knowledge in the composites literature, no strain rate and temperature dependent criterion has been yet proposed. Classically the two dependencies were considered separately.

3.1. Strain rate dependent criteria

There are at least three criteria in the composites literature, and in particular failure criteria, which are strain rate dependent [7, 20–22]. In their works, Daniel et al. [7, 20] proposed to model the influence of strain rate thanks to a linear logarithmic expression. A second criteria was proposed by Raimondo et al. [21]. These authors proposed to use the quadratic logarithm expression ($k = k_0 + k_1 * log(\dot{\varepsilon}) + k_2 * (log(\dot{\varepsilon}))^2$ with k_0, k_1, k_2 being constants) to model this dependency. However, after identification Raimondo et al. showed that for a carbon epoxy / composite the constant k_2 was equal to zero. Therefore the criterion proposed by Raimondo et al. [21] is similar to the one proposed by Daniel et al. [7, 20]. These two criteria were proposed considering only three strain rates. In the presented works six different strain rates are available. In the Figure 2, the values obtained thanks to a linear logaritm expression such as proposed by Daniel et al. [7, 20] and Raimondo et al. [21] are compared with the experimental transition shear stress obtained in 2. A linear logarithm expression seems not to be sufficient to describe the evolution of the transition shear stress with the strain rates if all strain rates are considered. Furthermore, a linear logarithm dependency implies an infinite transition stress or strain when the strain rate increases, which is assumed not to be physical.

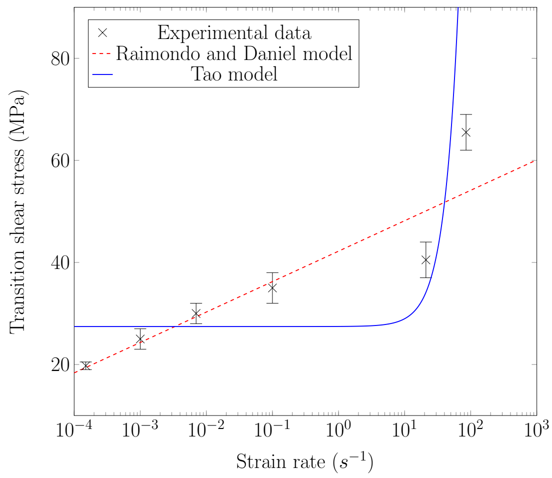

Figure 2: Comparison between experimental σ_t of the T700GC/M21 at ambient temperature and models of the literature

The third criterion available in the composites literature was proposed by Tao et al. [22]. This criterion is a polynomial criterion. Such as the two other criteria, this criteria was proposed considering three strain rates. Moreover this kind of criterion implies an infinite transition stress or strain for high strain rates, which is assumed not to be physical. This criterion was applied to the experimental shear stress. The achieved results are plotted in Figure 2. One may noticed that this model does not seem to be sufficient to describe the evolution of the transition shear stress with the strain rates.

The three different criteria proposed in the literature do not describe the evolution of the transition shear stress or strain with the strain rates.

3.2. Temperature dependent criteria

The composite literature regarding the influence of temperature on various criteria is sparse. One initial approach would be to consider the influence of residual strain ε^{th} due to the cure of the composite material. A common method to do so is to consider the thermal strain in the behaviour law [23]:

$$\underline{\sigma} = \underline{\underline{C}}^0 : (\underline{\varepsilon}^T - \underline{\varepsilon}^{th}) \tag{1}$$

$$\underline{\varepsilon}^{th} = (T - T_0) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{pmatrix} \tag{2}$$

Where $\underline{\underline{C}}^0$ is the initial elastic stiffness, $\underline{\varepsilon}^T$ the total strain tensor, T the test temperature and T_0

the stress free temperature. α_1 and α_2 are the thermal coefficients in the fibre direction and in the transverse direction.

To apply this method to the studied material, the viscoelastic bi-spectral model proposed by Berthe et al. [17, 18] is used as well as the results obtained in these works. The stress free temperature was taken from works of Huchette [24] and the thermal coefficient from works of Laurin [12] ($T_0 = 180°C$, $\alpha_1 = -1.10^{-6}/°C$ and $\alpha_2 = 26.10^{-6}/°C$). The stress tensor for each ply of the laminate were evaluated for four extreme configurations at ambient temperature for a quasi static test speed of $8,3.10^{-6}m/s$ and dynamic test speed of 2m/s, and at $-100°C$ for a quasi static test speed of $8,3.10^{-4}m/s$ and dynamic test speed of 0,5m/s. In this work, the linear behaviour is considered until the transition between linear and non-linear behaviour. Therefore the stress tensor was evaluated at the initial state of the test (for $\sigma_{11} = 0$) and for the transition state (for $\sigma_{11} = \sigma_{11_t}$ experimentally evaluated). All the stress values evaluated in the transverse direction (σ_{22}) were lower than the tensile transverse strength. This method does not seem to be adequate to describe the temperature dependency of the transition between linear and non-linear behaviour. Consequently, if a non linear behaviour is obtained, particularly at low temperature, the non linearity cannot be directly attributed to interfibre failure through a classical failure criterion.

The various criteria proposed in the composite literature appear not to be adequate to describe the evolution of the transition shear stress or strain with the strain rate and the temperature.

4. Modelling the T700GC/M21 σ_t and ε_t evolution laws

Regarding the different criteria of the literature, in a first step the strain rate dependency is considered.

4.1. Modelling of the effect of the strain rate on the T700GC/M21 σ_t and ε_t

The criteria proposed in the composite literature are not sufficient to describe the evolution of transition shear stress or strain. In their works Boumbimba et al. [25, 26], Wang et al. [27] and Raimondo et al. [21] have shown that the mechanical shear behaviour of a composite material was strongly dependent on the matrix behaviour. Therefore the polymers literature was also considered, and more particularly the epoxy resin studies about the influence of the strain rate on yield stress or failure criteria. Gerlach et al. [28] and Jordan et al. [29] proposed to model the yield stress of an epoxy resin with respect to $log(\dot{\varepsilon})$ by a bilinear criterion. But this solution also leads to an infinite yield stress or strain when the strain rate is infinite, which is assumed not to be physical. Therefore this solution was not studied. In their works Gerlach et al. [28] also proposed to model the influence of the strain rate on a strain failure criterion thanks to a model proposed by Goldberg [30]. The equation which was used was inspired from the Weibull distribution and can be summarized as:

$$\varepsilon_{fail} = \varepsilon_{ini} + \varepsilon_{diff} * (1 - \exp(c_2 * \dot{\varepsilon}^{c_3})) \quad (3)$$

Where ε_{ini} is the initial failure strain, ε_{diff} the difference between the failure strain in quasi-static and high rate experiments and c_2, c_3 the material constants.
This criterion is interesting because it leads to the saturation of the strain failure criterion for infinite strain rates. The criterion proposed by Gerlach et al. [28] was applied on the transition shear stress introduced in paragraph 2. The adapted equation of the Gerlach criterion is the following:

$$\sigma_t = \sigma_0 + \sigma_{diff} * (1 - \exp(c_2 * \dot{\varepsilon}^{c_3})) \quad (4)$$

As there was no available data at ambient temperature that reach the saturation value, an arbitrary value was taken which corresponds to the highest value obtained for all the tests including those at low temperature to obtain the σ_0 value. To identify the other parameters of the criterion, a least square optimization was done thanks to the PYTHON software. The obtained results are plotted in Figure 3.

One can notice that the Gerlach criterion seems to reach good agreement with the experimental data at high strain rates, but not at low strain rates. Indeed, in their works Gerlach et al. [28] identified their criterion for strain rates between $10^{-1}s^{-1}$ and $10^{3}s^{-1}$, therefore the range of strain rates used in Gerlach's works was less extensive than the one studied here. On the larger studied range of strain rates, many different mechanisms were involved. The strain rate dependent criterion proposed by Gerlach seems not to be sufficient to describe the evolution of the transition shear stress or strain with the strain rate. However, the Gerlach criterion is interesting because this model permit to obtain a saturation value of the stress when the strain rate increases. Moreover, this models seems to be in good agreement with experimental data at high strain rates. Therefore, it is proposed to adapt this model to describe the evolution of the transition shear stress or strain on the large range of strain rates studied.

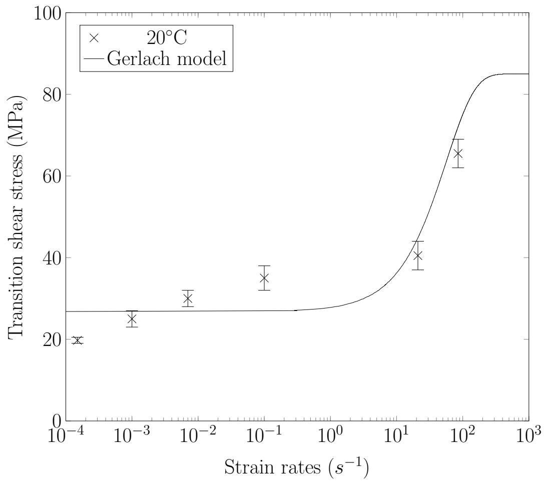

Figure 3: Application of the Gerlach criterion to the σ_t limit at ambient temperature for T700GC/M21

To adapt the previous model the polymer literature is considered. In their works Jordan et al. [29] proposed to use a bi-sigmoidal criterion to describe the evolution of the elastic modulus of the epoxy resin with the temperature. In this last works the authors used the Decompose / Shift / Reconstruct method defined in [31, 32] to decompose the elastic modulus according to the mechanisms involved. According to the works of Jordan et al. [29] each sigmoid represents distinct mechanisms related to transition temperature, the β transition for the sigmoid at low temperature and the α transition for the sigmoid at moderate temperatures. The α and β mechanisms are phenomena resulting from the blocking of macromolecules mobilities. The α relaxation is called the main relaxation and is usually related to the glass transition [33]. The β relaxation occurs for temperature lower than the glass transition. This β relaxation is related to the molecular mobility of main chain and side groups [32], and in particular for epoxy resin to the relaxation of glyceryl or diphenlypropane groups [34]. Using the time-temperature equivalence, this bi-sigmoidal shape should also be found when the evolution of the elastic modulus with the strain rates was studied.

Regarding the modelling of the yield stress, some authors [35–37] have shown that two rheological mechanisms are necessary to completely describe the evolution of the yield stress. Consequently, many models have been developed [31, 32, 38–40] in the form of an expression bi component: a component to describe the α mechanisms and another component to describe the β mechanisms. A similar method is used in the works of Berthe et al. [17, 18] to describe the evolution of the linear behaviour with the strain rate. In their works Berthe et al. [18, 19]

proposed to used a bi-spectral model to describe the different mechanisms involved from quasi-static to dynamic loadings. The viscoelastic spectral law used in [17, 18] decompose the viscous strain in elementary viscous mechanisms associated to a relaxation time. A bi-spectral model is introduced to take into account the influence of strain rate on the linear behaviour: one spectre to the quasi-static mechanisms and a second spectre to the dynamic mechanisms.
Assuming that a parallel can be done between the literature and the presented works, it is proposed to model the evolution of σ_t with the strain rate thanks to a bi-sigmodal criterion, hence it is proposed to superpose two Goldberg's type functions, following the equation:

$$\sigma_t = \sigma_0 + \sigma_{diff_1} * \exp(c_1 * \dot{\varepsilon}) + \sigma_{diff_2} * \exp(c_2 * \dot{\varepsilon}) \tag{5}$$

Since there was no available data at ambient temperature that reach the saturation value, an arbitrary value was taken which corresponds to the highest value obtained for all the tests including those at low temperature to obtain the σ_0 value. On the equation 5, four parameters are necessary to describe the evolution of the transition stress with strain rate. To identify the proposed criterion parameters a least square optimization was done using PYTHON on every obtained stress transition and not on a mean value. In the Figure 4, the experimental transition shear stress values are compared with the transition shear stress obtained with the proposed criterion.

This criterion seems to be in agreement with the σ_t experimental transition stress at ambient temperature, and describes pretty well the evolution of the transition shear stress on a large range of strain rates, from quasi-static to dynamic loadings. By analogy, the same work could be done to model the evolution of ε_t with the strain rate.

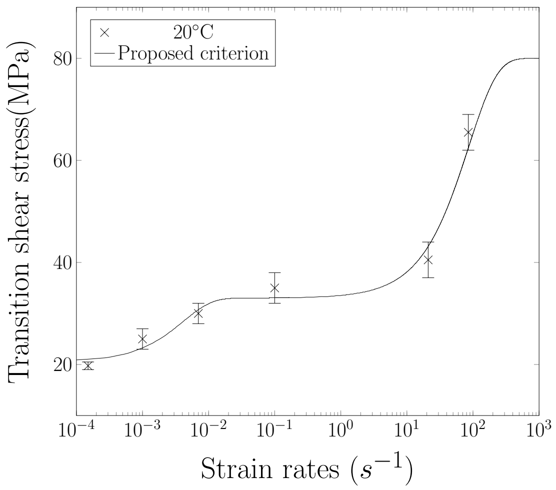

Figure 4: Application of the proposed criterion with the strain rates dependence to the σ_t limit at ambient temperature for T700GC/M21

σ_0(MPa)	σ_{diff_1}(MPa)	c_1	σ_{diff_2}(MPa)	c_2
80	-13.5	-181	-45.7	-110

Table 1: Value of the parameters obtained with the optimization method

The proposed bi-sigmoidal model well describes the evolution of the σ_t transition according to the strain rate and the mechanisms involved, but in previous works [1] the evolution of the σ_t transition stress with the temperature was also pointed out. Therefore, it is now considered to take the temperature dependency into account in the transition stress evolution law. This is the aim of the next paragraph.

4.2. Modelling of the effect of the temperature on the T700GC/M21 σ_t and ε_t

The influence of temperature on various criteria in composite literature is sparse, as shown in section 3. Therefore, to model the influence of temperature on the transition, the polymers literature has been considered to select possible solutions and particularly some works done by Richeton et al. [39, 40]. In these works, the authors proposed a strain rate and temperature dependent criterion for the yield stress for different polymers: PMMA, PC, etc. This criterion described the evolution of the yield stress under a wide range of temperature (-40°C to 180°C). Richeton's model can be summarized by the following equation (6):

$$\sigma_{yield} = \sigma_i(0) - m * T + \frac{2 * k * T}{V} \sinh^{-1}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0 * \exp\left(-\frac{\Delta H_\beta}{k*T}\right)}\right) \quad (6)$$

Where $\sigma_i(0)$ is the internal stress at 0°K. This parameter relies on the story of the material and the process used such as injection moulding, infusion or RTM. m is a material constant, k the Boltzmann constant, V an arbitrary activation volume, $\dot{\varepsilon}_0$ the constant pre-exponential strain rate and ΔH_β the β activation energy. This model is a new formulation of the model proposed by Fotheringham and Cheery [41, 42] . The adaptation proposed by Richeton et al. is based on the principle of the strain / rate temperature superposition principle of the yield stress described by Bauwens-Crowet et al. [35–37]. Richeton et al. also proposed to extend the model to describe the evolution of the yield stress above the glass transition.

The criterion proposed by Richeton et al. [39] is based on the physico-chemical properties of the resin material, and the model coefficients are expressed as functions of the activation energy of transition and the Boltzmann constant. For the material studied in these works some of these parameters are not directly available and are difficult to evaluate, such as the activation energy. To evaluate this parameter, a method has been proposed by Matadi Boumbimba et al. [26].

In the works presented, it is proposed to draw on the same general philosophy of the Richeton's model to build a temperature dependent model. To this end, the general structure of the equation was considered and particularly the temperature dependent terms. By analogy, the previous terms σ_{diff_1} and σ_{diff_2} are replaced by temperature dependent terms ($\frac{2*T}{b}$ and $\frac{2T}{e}$). Moreover c_2 and c_3 are replaced by $(\frac{c}{T})^d$ and $(\frac{f}{T})^g$ in order to represent the $\exp(-\frac{\Delta H_\beta}{k*T})$ term . The σ_0 term could also be modified in $\sigma_0 * T$ but in the case presented here there is no information available about the temperature dependence of the highest transition stress, therefore the value of σ_0 was kept.

Finally the third criterion including the strain rate and temperature dependencies was described by (7):

$$\sigma_t = \sigma_0 - \frac{2 * T}{b} * \exp\left(-(\frac{c}{T})^d * \dot{\varepsilon}\right) - \frac{2 * T}{e} * \exp\left(-(\frac{f}{T})^g * \dot{\varepsilon}\right) \quad (7)$$

To identify the parameter of the proposed criterion, it is chosen to consider that g=d, indeed there is not enough available data to identify the g parameter. As previously, the saturation value σ_0 corresponds to the highest value of the transition shear stress for all tests including those at low temperature. On the equation 7, one may notice that only one parameter is added in comparison with the criterion strain rate dependent to take into account the temperature dependency. The parameters of this criterion were identified performing a least square optimization thanks to PYTHON software. The optimization was performed on all shear stress transitions obtained for each test and not on a mean value for each strain rates. The obtained parameters are summarized in Table 2 and the optimization result is plotted in Figure 5.

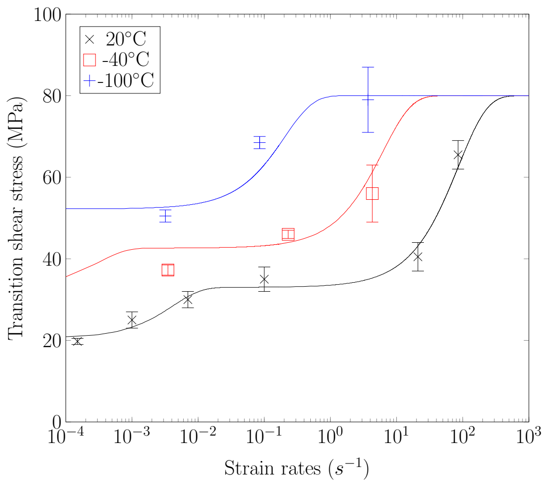

Figure 5: Application of the proposed criterion with the strain rate and temperature dependencies to the σ_t transition at three temperatures for T700GC/M21

a(MPa)	b(K.MPa^{-1})	c(K)	d	e(K.MPa^{-1})	f(K)
80	47	473	11.5	12.5	199

Table 2: Value of the parameters obtained with the optimization method

As a preliminary conclusion the proposed criterion seems to be in good agreement with the experimental data, and appears to be representative enough to describe all the phenomenology involved in the σ_t evolution law according to the strain rate and temperature. The same works can be done to obtain an evolution law in terms of transition shear strain and the same conclusions can be done.

5. Conclusion

In previous works [1], the σ_t and ε_t, the transition shear stress or strain of the T700GC/M21 carbon/epoxy composite material, had been experimentally evaluated for six strain rates at ambient temperature and for three strain rates at $-40°C$ and $-100°C$. The influence of the strain rate and the temperature on these transitions has also been studied.

In the present work, a strain rate and temperature dependent criterion has been formulated to describe the transition shear stress or strain evolution law of the T700GC/M21 material. This criterion is only based on six parameters, and can take into account both the strain rate and the temperature dependencies. The proposed criterion allows to describe all the phenomenology involved in the evolution law of this shear stress or strain transition on a large range of strain rates and temperatures. This evolution law could be used in a behaviour law to describe the global behaviour of CFRP material. The proposed criterion is complex and includes six parameters but this criterion could be simplify to be used in a structural analysis.

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