A new hybrid fatigue modeling for short fiber reinforced composites

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ABSTRACT

It is well known that when composite materials are subjected to mechanical loading, several microscopic damage phenomena could take place and lead to progressive stiffness reduction. Indeed, many homogenization models into which it is possible to introduce these damage phenomena at the local scale have been proposed. These models have been validated to predict both quasi-static and dynamic mechanical response of composite structures. However, fatigue life prediction models adapted to Short Fiber Reinforced Composite materials (SFRC) still remain relatively poorly developed. In this study, it is proposed to adapt an existing micromechanical modeling approach to fatigue life prediction. The proposed methodology combines experimental analysis of monotonic and fatigue tests results to micromechanical modeling of a simple tensile test which integrates at the local scale fiber-matrix interface damage development. Coupling phenomenological description of the loss of stiffness evolution to the micromechanical prediction of the local damage density allows building a new hybrid and multi-scale method which is able to predict the SN curve for a SFRC material. In this paper, our approach is validated by accurate SN curves prediction for different working temperatures; 21°C and 80°C. Moreover, life prediction for specimens submitted to a thermo-mechanical fatigue loading including temperature variation is also found to give satisfactory results, as compared to those obtained experimentally.

1. INTRODUCTION

Due to their several advantages, short fiber reinforced composites (SFRC) have been chosen for many decades as a good replacement for metallic structures in different domains; automobile, aeronautic and many others applications. However, composites materials have a complicated behavior compared to homogeneous materials such as metals. In fact, many parameters can affect the fatigue properties of composites [1]; fiber length and fiber orientation distribution [2], the reinforcement structure [3], loading and environmental conditions like temperature [4], cycling frequency [5], stress ratio [6],...). For SFRC, damage starts very early and the size of damaged zones grows gradually with a loss of stiffness and strength [7]. The damage threshold and kinetic depend on the different loading conditions. There has been great effort to develop methods that can predict fatigue life of composites. These models can be classified into three main categories [1]: empirical, used generally for metals and based on S-N curves, phenomenological based on a macroscopic damage able to describe the residual strength or the residual stiffness and micromechanical models which are generally based on microscopic damage mechanisms.
In this study, we present a new hybrid model able to predict the fatigue life for SMC materials under different temperature conditions. This new model mixed the two previously defined approaches: phenomenological and micromechanical. This original approach consists in using an existing micromechanical model developed for a simple tensile test simulation [8]. Fiber-matrix interface damage, considered as the predominant mechanism in such type of materials submitted to quasi-static, dynamic or fatigue test [9, 10], is introduced in a Mori Tanaka approach through a local criterion which describes the evolution of micro-cracks density step by step during loading until

failure. This multi-scale damage model relates the relative stiffness E/E_0 to micro-cracks density for each calculation step. Consequently, a “state equation” relating the residual stiffness of the composite to a progressive micromechanical local damage parameter “d” can be established. This equation is then introduced into a phenomenological description of the loss in stiffness under fatigue loading coming from the analysis of experimental results. A critical value of the local damage parameter “d_c“ is also identified using inverse engineering and used in this hybrid approach in order to predict the fatigue life of the material for different amplitude and temperature.

2. Material, experimental methods and analysis

2.1 Material

The material used in this study is a polyester Sheet Molding Compound composite (SMC) with 28% of glass fibers and 37% of $CaCO_3$ weight contents. The considered glass fibers are presented in the form of bundles containing about 200 fibers. The material is obtained by thermo-compression under 60 Bars pressure and 165°C temperature. SMC plates used in this study have been obtained by placing the non-reticulated SMC flanks, before compression, in the middle of a rectangular mold (120×250 mm^2) in such a way that more than 80% of its surface is recovered. Due to the thermo-compression, no significant preferential fiber orientation is obtained. Figure 1 shows the microstructure of the obtained randomly oriented (RO) plate. One can notice different orientations of fibers grouped into bundles.

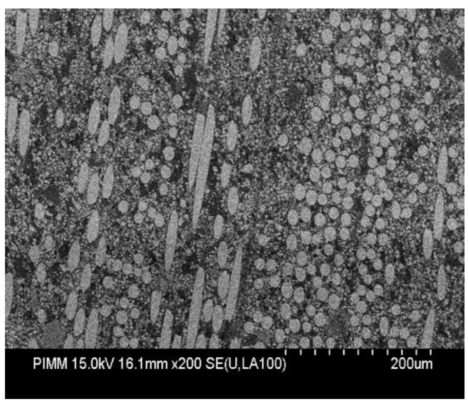


Figure 1: RO_Material

2.2 Experimental methods

2.2.1 Specimen geometry

All mechanical tests have been realized on a MTS 830 hydraulic machine. Figure 2 shows the selected specimen geometry.

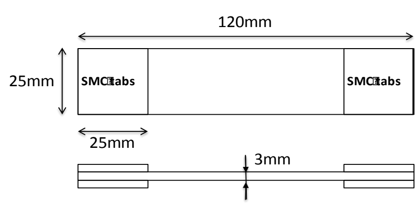


Figure 2: SMC specimen geometry

2.2.2 *Test configuration*

Several mechanical test procedures have been performed under two selected temperature, 21°C and 80°C:
- Tensile tests until failure
- Load - unload tests with progressive increasing maximum load at each reloading stage until failure
- Tension-tension fatigue stress controlled tests until failure at several applied maximum stress. The chosen stress-ratio and frequency were R=0.1 and f=10Hz.
- Tension-tension fatigue loading with variable temperature (figure 3).

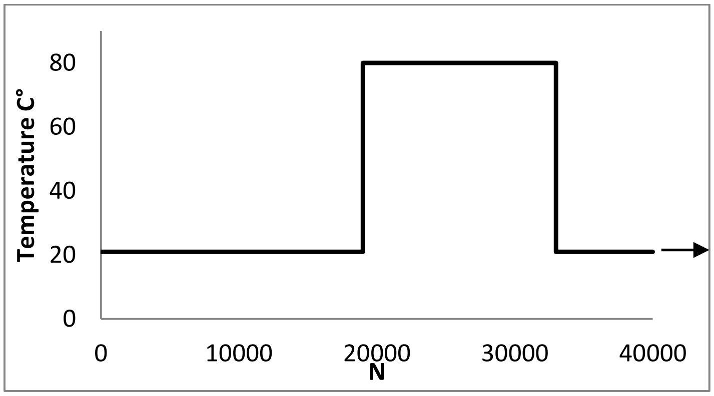


Figure 3: Example of a imposed temperature profile during fatigue.

2.3 *Experimental Analysis*

2.3.1 *Loss in stiffness in tensile loading*

As shown in figure 4, the evolution of the loss of stiffness obtained by loading-unloading tests can be approximated by a linear function. Thus, the evolution of the stiffness reduction during a tensile load, valuable from the damage threshold stress; σ_i^S, to failure, can be expressed as by:

$$\left(\frac{\mathrm{E}}{\mathrm{E}_0}\right) = 1 + \mathrm{a}_i\left(\sigma^{\mathrm{imp}} - \sigma_i^S\right) \quad (1)$$

The index, i, indicates the considered temperature. a_i defines the kinetics of the loss of stiffness under uniaxial load. $\sigma^{\mathrm{imp}}$is the imposed stress. Stress values are normalized by $\sigma_{21°C}^{\max}$, the average failure stress of samples at 21°C.

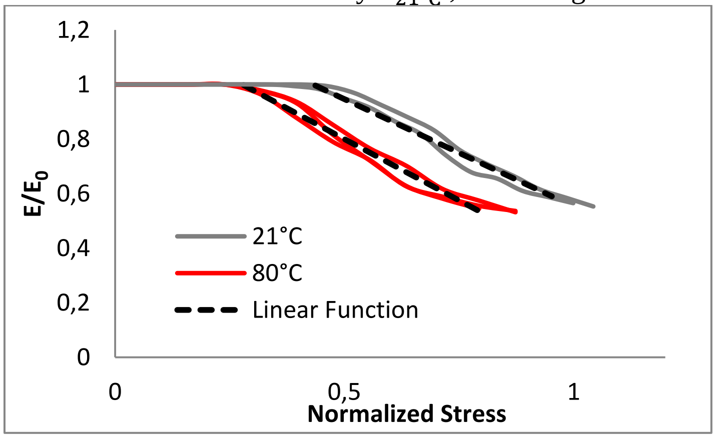


Figure 4: Loss of stiffness during tensile loading

2.3.2 Loss of stiffness during fatigue loading

Stiffness reduction during fatigue can easily be described by a power function as shown in figure 5:

$$\left(\frac{\mathrm{E}}{\mathrm{E}_1}\right)_{\mathrm{N}} = A_i\ \mathrm{N}^{B_i} \tag{2}$$

E_1 represents the value of the residual stiffness after the first cycle. The later is always applied at quasi-static rate before fatigue loading in order to measure E_1 properly. Moreover, limitations inherent in the hydraulic system do not allow reaching the imposed effort before the 22th cycle. However, we noticed that this regulation stage do not add additional damage. So, we can assume that: $\left(\frac{\mathrm{E}}{\mathrm{E}_0}\right)_{\mathrm{N}=22} = \left(\frac{\mathrm{E}}{\mathrm{E}_0}\right)_{\mathrm{N}=1}$. Besides, $\left(\frac{\mathrm{E}}{\mathrm{E}_0}\right) = \left(\frac{\mathrm{E}}{\mathrm{E}_1}\right) * \left(\frac{\mathrm{E}_1}{\mathrm{E}_0}\right)$

The second term, $\left(\frac{\mathrm{E}_1}{\mathrm{E}_0}\right)$, defines the loss in stiffness after the first cycle whereas the first term, $\left(\frac{\mathrm{E}}{\mathrm{E}_1}\right)$, is related to the kinetics of loss of stiffness during fatigue through the parameter B_i.

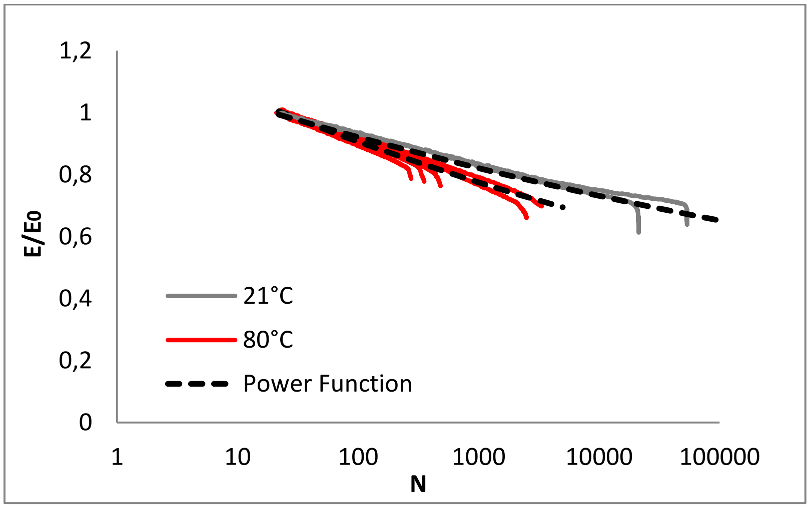


Figure 5: Loss of stiffness during fatigue loading

Finally, the evolution of the loss of stiffness during fatigue can be derived from the preceding expressions:

$$\left(\frac{\mathrm{E}}{\mathrm{E}_0}\right)_{\mathrm{N}} = \left(1 + \mathrm{a}_i\left(\sigma^{\mathrm{imp}} - \sigma_i^S\right)\right) * \left\lfloor\frac{\mathrm{N}}{22}\right\rfloor^{B_i} \tag{3}$$

2.3.3 Loss of stiffness during fatigue loading under variable temperature

Figure 6 shows the relative loss of stiffness for a RO materiel submitted to fatigue loading with variable temperature and a constant imposed maximum stress (0.4 of the $\boldsymbol{\sigma}_{21°\mathrm{C}}^{\boldsymbol{max}}$). The impose temperature profile was that of figure 3. The specimen broke after a total number of cycle of 36500 cycles during the third fatigue stage performed at ambient temperature.

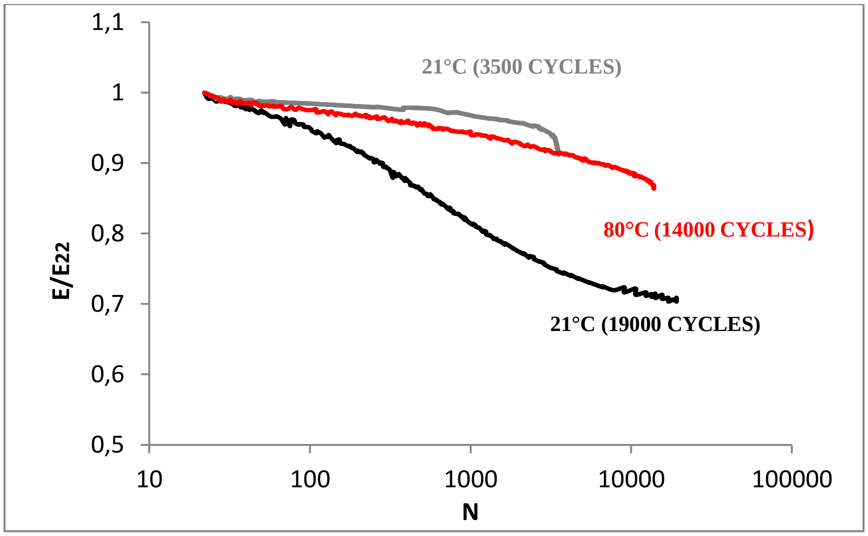


Figure 6: The loss of stiffness under a thermo mechanical loading

3. Hybrid Model

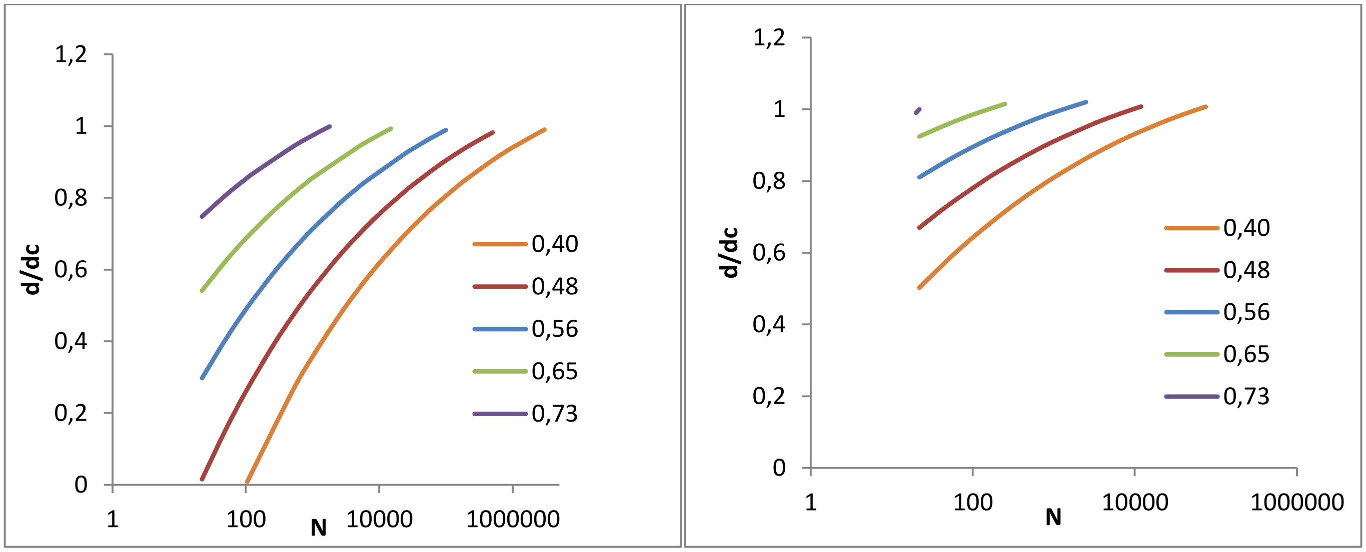
We propose a hybrid methodology which combines micromechanical and phenomenological approach. The originality of this model stand in the facility to integrate the outputs of a simple micromechanical damage model validated for a monotonic quasi-static tensile loading into a phenomenological formulation of the fatigue loss of stiffness. The mainly assumption made here is that there is an intrinsic relationship, "a state equation", between the local damage and the macroscopic loss of stiffness. We consider that this relationship is still valuable under fatigue loading. The generated state equation is then given by the following equation:

$$(\frac{d}{d_c})_i = \alpha_i \left[\left(\frac{E}{E_0}\right)\right]^2 + \beta_i \left[\left(\frac{E}{E_0}\right)\right] + \gamma_i \tag{4}$$

α_i, β_i and γ_i are micromechanical parameters depending on temperature and identified on the basis of tensile modelling using reverse engineering. Combining equation (3) to equation (4) a state equation under fatigue loading emerges:

$$(\frac{d}{d_c})_i = \alpha_i \left[(1 + a_i(\sigma^{imp} - \sigma_i^S)) \left\lfloor\frac{N}{22}\right\rfloor^{B_i}\right]^2 + \beta_i \left[(1 + a_i(\sigma^{imp} - \sigma_i^S)) \left\lfloor\frac{N}{22}\right\rfloor^{B_i}\right] + \gamma_i \tag{5}$$

This expression allows plotting the evolution of the local damage ratio d/d_c under fatigue for several values of the applied stress versus the number of cycle (see Figure 7). Finally, this hybrid methodology allows converting the evolution of the phenomenological macroscopic loss of stiffness to the evolution of a local damage indicator under fatigue.



(a) **(b)**

Figure 7: Evolution of d/dc for several normalized applied stress: **(a)** T 21°C and **(b)** T 80°C

Fatigue life prediction supposed to set d/dc=1. Thus, the resolution of this equation gives the following solution:

$$\mathrm{G} = \frac{-\beta_i \pm \sqrt{{\beta_i}^2 - 4\alpha_i(\gamma_i - 1)}}{2\alpha_i} \tag{6}$$

and to the expression of the number of cycle to failure, $\mathrm{N_R}$:

$$\mathrm{N_R} = 22 * \left[\frac{\mathrm{G}}{((1 + a_i(\sigma^{\mathrm{imp}} - \sigma_i^S))}\right]^{\frac{1}{B_i}} \tag{7}$$

S-N curves plotted for two different temperature conditions (21°C and 80°C) are compared with experimental data and are in good agreement (figure 8). In fact, local damage is indirectly taken into account though the micromechanical parameters, α, β and γ. The initial damage is conditioned by the parameter a_i and σ_i^S and the kinetics of damage are influenced by the parameter B_i. These parameters are identified separately for different temperature conditions (indicated by the i index). Prediction of Wöhler curve is illustrated in the following figure. Good agreements justify the efficiency of this approach.

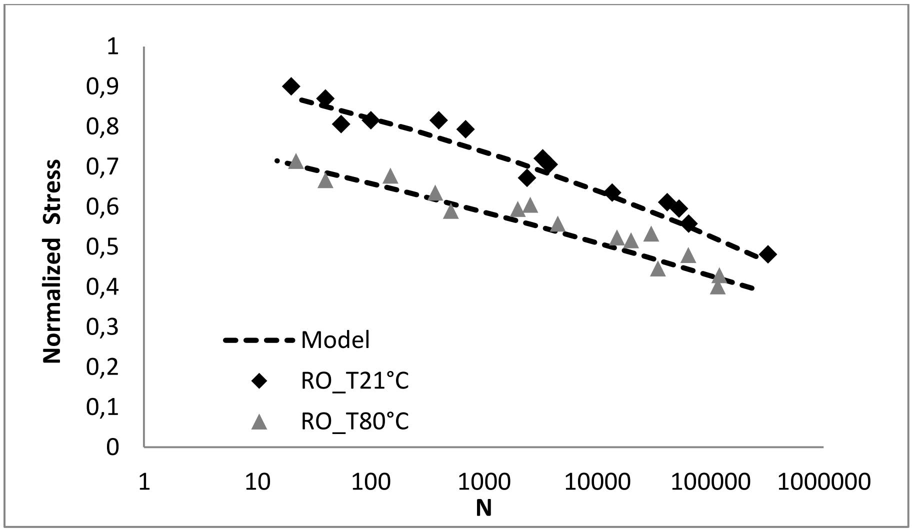


Figure 8: Wohler curves prediction

4. Thermo mechanical fatigue life modeling

The cumulative damage state was calculated by the new model in the case of the temperature profile of figure 3 and for an applied maximum stress 0.4 of the $\boldsymbol{\sigma}_{21°C}^{max}$ (figure 9). Damage accumulation is calculated and cumulated stage after stage through the calculation of the evolution of the local damage ratio from equation 5. The cumulative evolution of d/dc is represented on the following figure. Discontinuities are observed at the temperature changes. Indeed, for each temperature stage, the local damage kinetic is also determined by the phenomenological parameters, a_i, σ_i^S and B_i which are temperature dependent. These results indicate that damage occur and grow rapidly at the firsts cycles. The failure happened when d/dc reach 1, after approximately 37000 Cycles. This is in good agreement with the experimental result.

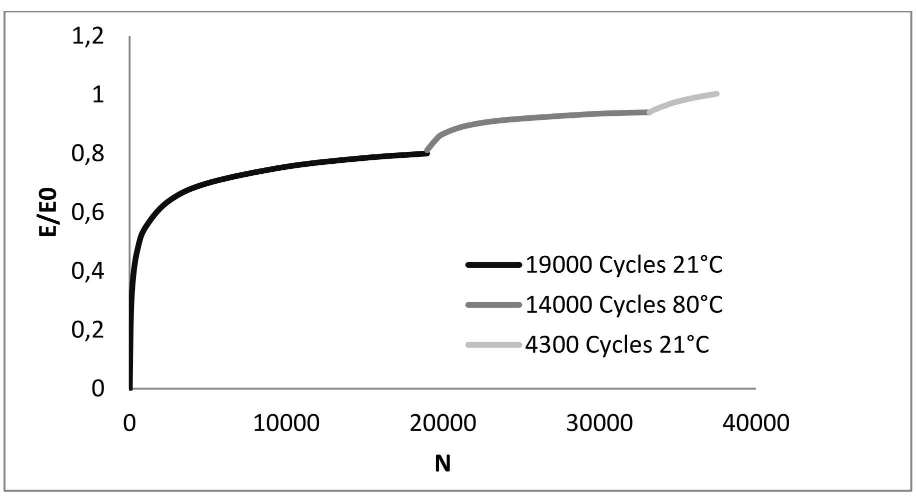


Figure 9: Evolution of d/dc for 0.4 of $\boldsymbol{\sigma}_{21°C}^{max}$

5. Conclusion

An accurate hybrid model has been developed to predict fatigue life of SMC composite materials. It corresponds to a stiffness based phenomenological approach coupled with a micromechanical damage model taking into account local fiber-matrix interfacial failure development. A state equation relating a local damage ratio to the applied stress, the number of cycle, micromechanical parameters and stiffness reduction parameters has been derived. One parameter set has been identified for two temperature conditions. S-N curves at 21°C and 80°C have been predicted and have been found to be in good agreement with experimental data. Moreover, the approach allows modelling the evolution of the local damage ratio under fatigue loading with variable temperature. One can conclude that, although pragmatic, the proposed new hybrid model has shown a strong potential and a high level of relevance for SFRC fatigue life prediction. In the near future, the model will be introduced into a finite element analysis and adapted for fatigue design of SMC structural components.

6. References

[1] Degrieck, J. and Van Paepegem, W. “Fatigue Damage Modelling of Fibre-Reinforced Composite Materials: Review”. *Applied Mechanics Reviews*, 54(4), 279-300. 2001.

[2] Bernasconi A, Davoli P, Basile A, Filippi A.” Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6”. *Int J Fatigue* 2007; 29:199–208.

[3] W. Roundi and al. / “Experimental and numerical investigation of the effects of stacking sequence and stress ratio on fatigue damage of glass/epoxy composites”. *Composites Part B* 109 (2017) 64-71.

[4] Bellenger V, Tcharkhtchi A and Castaing P. “Thermal and mechanical fatigue of a PA66/glass fibers composite material”. *International Journal of Fatigue*. 2006; 28(10): 1348-52.

[5] R. Khan, R. Alderliesten, S. Badshah, R. Benedictus. “Effect of stress ratio or mean stress on fatigue delamination growth in composites”. *critical review Compos Struct*, 124 (2015), pp. 214–227.

[6] M. Eftekhari, A. Fatemi . “On the strengthening effect of increasing cycling frequency on fatigue behavior of some polymers and their composites: Experiments and modeling”. *International Journal of Fatigue* 87 (2016) 153–166.

[7] E. Belmonte and al. / “Damage mechanisms in a short glass fiber reinforced polyamide under fatigue loading”. *International Journal of Fatigue* 94 (2017) 145–157 .

[8] Jendli Z, Meraghni F, Fitoussi J, Baptiste D. “Multi-scales modelling of dynamic behaviour for discontinuous fibre SMC composites” *Composites. Science and Technology* 69 (2009) 97–103.

[9] Tamboura S., Sidhom H., Baptiste D, “Evaluation de la tenue en fatigue du composite SMC R42”. *Matériaux et Techniques*, N° 3-4, p3.-11, 2001.

[10] Jendli Z, Meraghni F, Fitoussi J, Baptiste D. “Micromechanical analysis of strain rate effect on damage evolution in sheet molding compound composites”. *Compos Part A*: Appl Sci Manufact 2004;35: 779–85.