FATIGUE LIFE PREDICTION OF SHORT FIBER-REINFORCED THERMOPLASTICS

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Abstract
In order to predict the fatigue behavior of Short Fiber-Reinforced Thermoplastic (SFRT) parts, a large amount of experimental tests on specimens is generally required. It is known that the damage occurring in such materials, while cyclically loaded is a hierarchical process. Indeed, the composite degradation mainly develops at the matrix-level, driving the macro-properties decay up to the final failure of the component. The present work proposes a multiscale model that enables the prediction of lifetime duration of SFRTs, this implying a significant reduction of experiments for the material characterization. With the proposed criterion, a failure parameter derived from the stress distribution within the thermoplastic matrix is formulated. Nevertheless, the computation of the complete stress field within the composite requires the generation of equivalent microstructures, which frequently make use of complex algorithms. In this interest, an innovative approach based on the Pseudo-Grain methodology is hereby developed and validated in order to compute the cumulative stress distribution functions without relying on the generation of complex geometries. Eventually, the proposed micro-mechanical model has been validated with a bulk of experimental data, showing that the effect of fiber volume fraction and local fiber orientation onto the fatigue strength of SFRTs is well captured.

1. Introduction

In the last decades, short fiber-reinforced thermoplastics have gained an important role in the automotive industry. They have been mainly employed in the under-the-hood parts thanks to their low weight and good mechanical properties. On the other hand, the complexity of the material microstructure combined with multiaxial external loadings makes the formulation of failure criteria a difficult task. In particular, the fatigue strength of these materials is hereby considered.

In literature, different models for predicting the lifetime duration of SFRTs have been proposed. Kabir and al. [1] developed a fatigue criterion assuming no actual fiber orientation distributions. The authors distinguished between 0°- and 90°-oriented microstructures. Indeed, only unidirectional fibers were modeled with the proper fiber volume fraction. In order to predict the lifetime duration of the considered specimens, an approach based on a Weibull damage low was proposed by the authors in [1].

The effect of fiber orientation onto the fatigue strength of SFRTs was treated by Bernasconi et al. [2]. In [2] the authors presented SN-curves for the case of short glass fiber-reinforced polyamides. They highlighted that the fiber orientation is generally not constant in the through-the-thickness direction of injected plates. In fact, after performing microscopic analyses of transverse sections, the typical skincore effect can be observed, i.e. fibers result to be aligned better close to the plate upper and lower surfaces and approximately oriented transversally within the mid-thickness. In [2] a clear effect of the fiber anisotropy effect onto the fatigue curves has been observed and this effect has been found to be captured by normalizing the applied nominal stress by means of the material ultimate tensile strength.

In 2007 Sonsino and Moosbrugger [3] investigated the presence of notches in the case of a polyamide 66 filled with 35wt% of short glass fibers. In their work, the authors stated that no fiber anisotropy was considered while assigning the elastic properties to the equivalent models. Furthermore, in [3] the stress concentration obtained as a consequence of the notch effect was efficiently modeled by adopting two parallel approaches, i.e. based on the local maximum stress gradient and on the identification of critical volumes derived by a thresholding operation on the local stress distributions.

In [4] Klimkeit et al. proposed an extensive methodology for predicting the fatigue curves of dogbone and tubular specimens made of short fiber-reinforced PA66 and PBT+PET. Firstly, the information related to the FOT was carried out through process simulations. Secondly, mechanical properties were assigned to the models by means of two-steps homogenization schemes. Finally, the application of three different fatigue criteria was carried out (i.e. maximum principal stress, von Mises stress, strain energy density) yielding the most acceptable results through the energetic criterion. Furthermore, the authors remarked that the experimental cost related to the generation of sn-curves is now reduced and the effect of the stress multiaxiality on the fatigue strength of such materials can be predicted by generating only one experimental fatigue curve per material.

In 2011 Meneghetti and Quaresimin [5] developed an energetic approach to estimate the lifetime of a PA66-GF35 undergoing cyclic loads. The authors demonstrated how energy computed from the heat dissipation at the notch-tip could be adopted as a good parameter for the lifetime assessment.

In 2016 Krairi et al. [6] proposed a fatigue model for plain specimens, in which the fatigue strength of SFRTs is attributed to the presence of weak spots in the matrix phase, that obey a viscoelastic-viscoplastic-damage law. They applied this approach to the case of specimens that were extracted from plates at three different angles (0°, 45° and 90°) with respect to the injection direction, showing a good agreement between experimental and calculated data.

Once again, the present work proposes a method that aims at capturing the effect of local fiber orientation onto the fatigue strength of SFRTs. A fatigue failure parameter computed at the matrix level is hereby proposed, the identification of which lies in the computation of the matrix'von Mises stress distribution

2. Materials and experiments

In this section, the experimental data adopted for the model validation are presented. The attention is focused on a PA66-GF35 material, the fiber volume fraction of which is 19.7%. In this work, only plain specimens will be considered, i.e. dogbone-coupons extracted from injection-molded plates, the geometry of which is shown in figure 1.

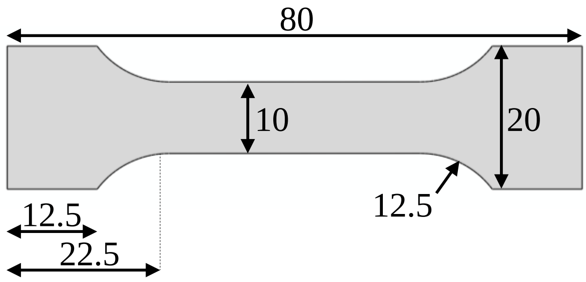

Figure 1. Specimen geometry [7]. The thickness is equal to 1mm.

The considered fatigue data were published by De Monte et al. in [7] and they are plotted in figure 2.

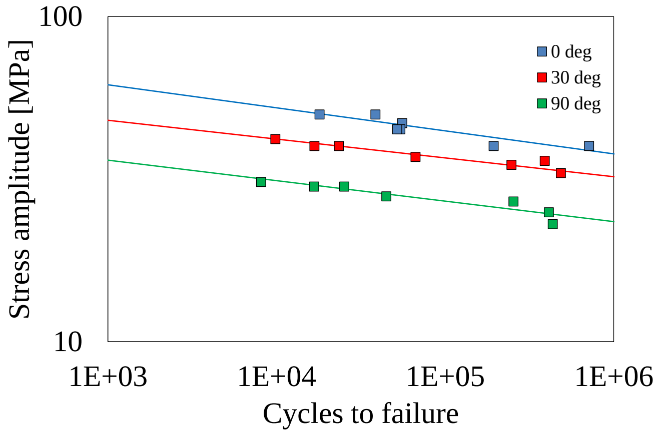

Figure 2. Fatigue data of the specimens shown in figure 1, for three different extraction angles θ [7].

Fatigue tests of figure 2 have been performed at room temperature (RT), in the dry-as-molded condition and with a load ratio equal to 0. By extracting the specimens along three different angles, the effect of the material anisotropy deriving from the local fiber orientation distribution can be observed. Indeed, the highest fatigue strength is encountered for 0°-extracted specimens, as it is expected, since fibers are mainly oriented along the main flow direction (MFD). Thus, the load bearing capability of the material is mainly attributed to fibers for the case of θ = 0° and this characteristic decreases while θ increases up to 90°.

3. Model development

In this section the fatigue multiscale model, which makes use of the matrix'stress distribution, is described. The constituents' properties are reported in table 1.

Matrix elastic modulus [GPa]	Matrix Poisson's ratio [-]	Fiber elastic modulus [GPa]	Fiber Poisson's ratio [-]
3.0	0.39	72.0	0.22

Table 1. Constituents' elastic properties.

3.1 Multiscale model description

As already mentioned above, a fatigue parameter based on the matrix stress distributions will be formulated according to a multiscale strategy. The procedure to reach the computation of the matrix fatigue failure parameter is the following:

- Generation and solution of a homogeneous layered model. The elastic properties of each layer can be computed by means its Fiber Orientation Tensors (FOT).
- Generation and solution of a heterogeneous model for each layer, which is characterized by the given FOT and undergoes periodic boundary conditions. Regarding the latters, the strain tensor computed from the macro-model are used as applied strain.
- Computation of the stress distribution for each micro-model and identification of the fatigue failure parameter.

3.2 Macro-model

In order to compute the matrix stress distribution at the microscale, first, a macro-model needs to be solved and formulated to supply the proper boundary condition that must be applied to the heterogeneous micro-models. Such macro-model is hereby analytically defined and the following assumptions are done:

- The plain specimen can be identified as a stack of layers, the elastic properties of which can be analytically computed through two-step homogenization schemes [8], as it is shown in figure 3.a. The FOTs of each layer have been evaluated by means of process simulations carried out with the software MoldFlow®, as it is shown if figure 3.b.

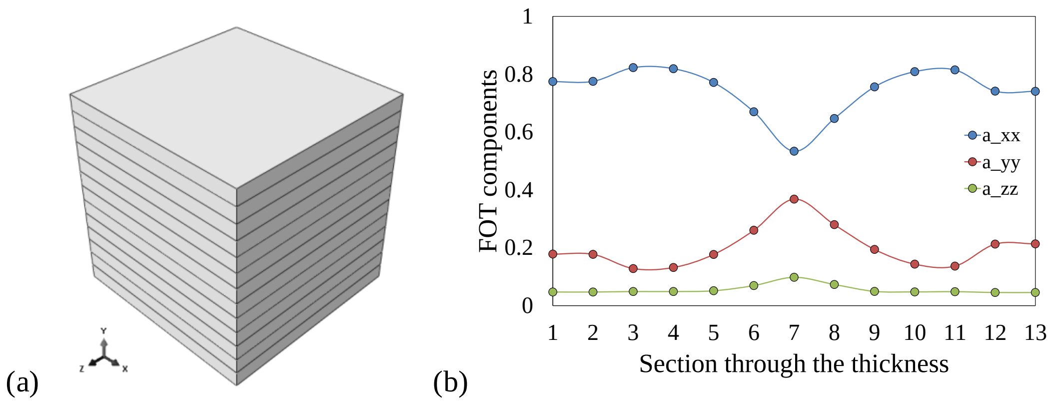

Figure 3. Homogeneous macro-model (a) and fiber FOT-components evaluated with MoldFlow® (b).

- The out-of-plain strain components (z-direction) are negligible because of the low grade of fiber orientation along the z-axis (this will be shown in the next paragraphs by means of process simulation):
- Since displacement-controlled periodic boundary conditions are assumed for the macro-model, the in-plane (xy) strain tensor is the same for each layer thanks to the compatibility equations. Therefore, it can be computed through the following equation:

$$\varepsilon^{layer}_{ij} = \langle \varepsilon \rangle_{ij} = \langle C \rangle_{ijkl}^{-1} \langle \sigma \rangle_{kl} \quad (1)$$

where ε^{layer}_{ij} denotes the strain tensor components of a generic layer and $\langle \varepsilon \rangle_{ij}$, $\langle C \rangle_{ijkl}$ and $\langle \sigma \rangle_{kl}$ respectively the average strain, average stiffness and average stress tensors of the whole model. Finally, $\langle C \rangle$ can be computed by averaging the stiffness tensors of all layers.

3.2 Micro-model

Once the macro-strain is computed, a micro-model can be generated and solved for each layer, according to the fiber orientation of each ply and by applying as boundary conditions the strain tensor component computed by means of Eq. 1.

In order to compute the matrix stress distribution of each layer, heterogeneous cells can be generated by means of the algorithm presented in [9] or, alternatively, the Pseudo-Grain technique reported in [10] can be adopted in order to avoid the solution of complex models with misaligned fibers.
Regarding the Pseudo-Grain method (figure 4) for the stress distributions' computation, the following procedure is formulated:

- Generation of unidirectional models oriented along discretized directions [8];
- Computation of the matrix Von Mises stress (σ_{VM}) distributions for each Pseudo-Grain;

- Computation of the fiber orientation probability function [8];
- Computation of the average of all Pseudo-Grains'stress distribution, weighted by the fiber orientation probability function, according to [8].

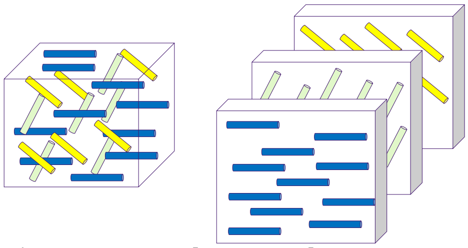

Figure 4. Pseudo-Grain discretization.

As an example, the validation of the proposed approach is reported in figure 5, in the case of a unit load rotated by 0°, 45° and 90° around the z-axis and diag(FOT)=[0.7, 0.2, 0.1].

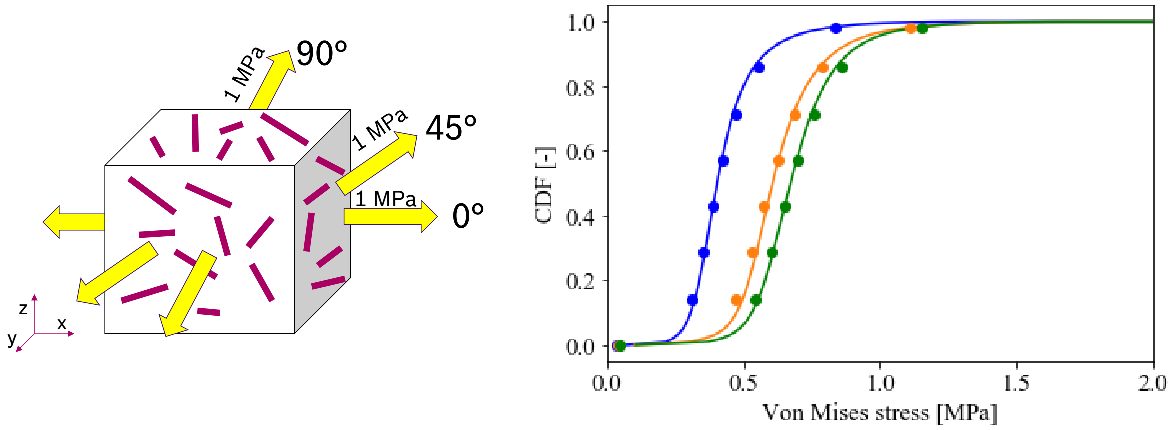

Figure 5. Schematic representation of a cell with misaligned fibers and comparison between the matrix cumulative density functions (CDF) from an actual microstructure (dots) and from the Pseudo-Grain approach (lines).

3.3 Fatigue failure parameter computation

In this paragraph, a failure criterion based on the von Mises stress is presented. As observed in [11], the damage occurring at the matrix level during fatigue loadings can be identified in the region around fiber tips and walls, i.e. the critical volume is related to the highly stressed matrix regions corresponding to the stress distribution tails, as it is shown in figure 6.

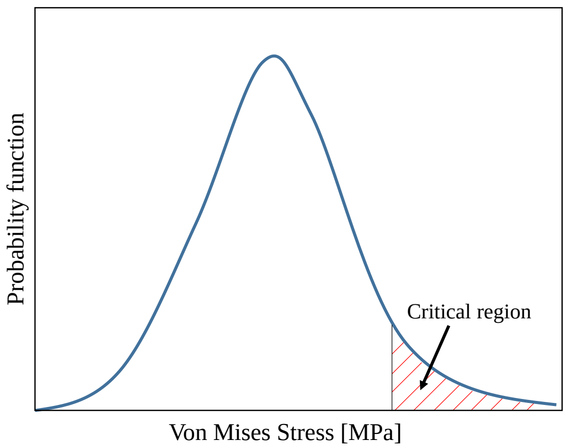

Figure 6. Schematic representation of the von Mises stress probability function within the matrix.

4. Results and discussion

In order to validate the proposed model, the fatigue data reported in figure 2 have been employed. The red region highlighted in figure 6 can be identified by setting a high stress threshold of the corresponding cumulative distribution function. According to [12] a 90% value is herein chosen. The mean value of the Von Mises stress within the critical region of figure 6 can be computed and that of the most critical layer is used as fatigue failure parameter. It is now possible to plot all fatigue data in terms of the aforementioned fatigue failure parameter (figure 7).

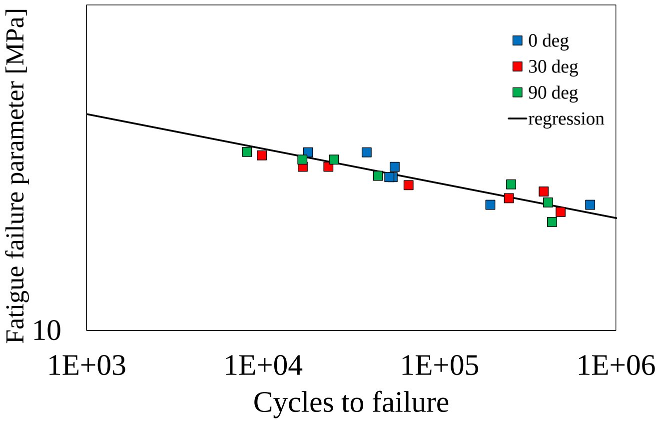

Figure 7. Fatigue data expressed in terms of fatigue failure parameter.

Data reported in figure 7 are now characterized by a low scatter band, demonstrating the efficacy of the proposed approach.

Since the presented method is based on the formulation of a failure parameter defined at the micro-scale (matrix), the developed fatigue model can be applied to specimens with different materials, enabling to capture the effect of fiber volume fraction onto the fatigue life.

5. Conclusion

In the present paper an innovative multiscale model has been proposed, that takes into account the elastic stress distribution to which the matrix phase is subjected. The generation and solution of complex microstructure is still a difficult task and, therefore, the Pseudo-Grain methodology has been adopted in order to analytically compute the stress distribution. Once these distributions are available, the fatigue failure parameter can be identified for the most critical layer by computing the mean value of the von Mises stress within matrix regions identified by the stress distribution tails.

References

[1] M. R. Kabir, W. Lutz, K. Zhu and S. Schmauder, "Fatigue modeling of short fiber reinforced composites with ductile matrix under cyclic loading," *Comput. Mater. Sci.,* vol. 36, p. 361–366, 2006.

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

[3] C. M. Sonsino and E. Moosbrugger, "Fatigue deisgn of highly loaded short-glass-fibre reinforced polyamide parts in engine compartments," *International Journal of Fatigue,* vol. 30, pp. 1279-1288, 2008.

[4] B. Klimkeit, Y. Nadot, S. Castagnet, C. Nadot-Martin, C. Dumas, S. Bergamo, C. M. Sonsino and A. Büter, "Multiaxial fatigue life assessment for reinforced polymers," *Int. J. Fatigue,* vol. 33, p. 766–780, 2011.

[5] G. Meneghetti and M. Quaresimin, "Fatigue strength assessment of a short fiber composite based on the specific heat dissipation," *Composites: Part B,* vol. 42, pp. 217-225, 2011.

[6] S. Kari, H. Berger and U. Gabbert, "Numerical evaluation of effective material properties of randomly distributed short cylindrical fibre composites," *Comput. Mater. Sci.,* vol. 39, p. 198–204, 2007.

[7] M. De Monte, E. Moosbrugger and M. Quaresimin, "Influence of temperature and thickness on the off-axis behaviour of short glass fibre reinforced polyamide 6.6 - cyclic loading," *Comp. Part A,* vol. 41, pp. 1368-1379, 2010.

[8] O. Pierard, C. Friebel and I. Doghri, "Mean-field homogenization of multi-phase thermo-elastic composites: a general framework and its validation," *Compos. Sci. Technol.,* vol. 64, p. 1587–1603, 2004.

[9] M. Schneider, "The sequential addition and migration method to generate representative volume elements for the homogenization of short fiber reinforced plastics," *Comput. Mech,* vol. 59, p. 247–263, 2017.

[10] E. Belmonte, M. De Monte, T. Riedel and M. Quaresimin, "Local microstructure and stress distributions at the crack initiation site in a short fiber reinforced polyamide un-der fatigue loading," *Polym. Test.,* vol. 250–259, p. 250–259, 2016.

[11] E. Belmonte, "Multi-scale modeling of the fatigue behavior for short fiber reinforced thermoplastics," *PhD Thesis,* 2016.

[12] R. Pietrogrande, P. A. Carraro, M. De Monte and M. Quaresimin, "A novel Pseudo-Grain approach for the estimation of the elastic stress distributions within the matrix of Short Fiber-Reinforced Polymers".*Composite: Part B,* article in press.