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A statistical treatment of the loss of stiffness during cyclic loading for short fiber reinforced injection molded composites

Atul Jain [a, b, *], Wim Van Paepegem [c], Ignaas Verpoest [b], Stepan V. Lomov [b]

[a] Siemens Industry Software NV, Interleuvenlaan 68, B-3001, Leuven, Belgium
[b] Department of Materials Engineering, KU Leuven, Belgium
[c] Department of Material Science and Engineering, Ghent University, Belgium

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ABSTRACT

Injection molded short fiber reinforced composites (SFRC) have different local fiber orientation distribution (FOD) at every point. SN curves of short fiber reinforced composites are known to depend on the fiber orientation distribution. Such materials also suffer from continuous loss of stiffness during cyclic loading. It is not known whether the loss of stiffness is different for SFRC with different FOD.

A statistical analysis of the loss of stiffness curves is presented in this paper. Tension-tension fatigue experiments are performed and loss of stiffness is collected for every data point in the SN curve. A systematic method for comparing the loss of stiffness is developed. It is concluded that the difference in loss of stiffness curves for coupons of SFRC with different FOD is not statistically significant.

1. Introduction

Increasingly composites are being looked at as possible replacements for metals in automobiles. This is due to the rising awareness and regulations towards reducing CO_2 emissions. Short fiber reinforced composites (SFRC) have reasonable specific properties and are easy to manufacture on a large scale which makes them cost effective. Thus, they are ideal candidates for deployment in various industries like automotive etc. Optimum deployment of SFRC necessities that the fatigue behavior must be completely understood and simulated.

SFRC composites are usually made by the injection molding process, this process leads to different fiber orientation distribution (FOD) at every point in the part. It is known and has been experimentally confirmed that the SN curve depends on the fiber orientation distribution (FOD) of the SFRC [1–4]. Like most other polymer composite materials, SFRC are also known to suffer loss of stiffness when subjected to cyclic loading. There is a large amount of experimental evidence which confirms the loss of stiffness during cyclic loading particularly tension-tension fatigue [2,5–9].

There is very little known about the dependence of the loss of stiffness to the FOD of SFRC material. Based on a qualitative observation, De Monte et al. [2] remarked that the loss of stiffness depended on the applied load and fiber length distribution but was independent of the orientation of the coupons, but an statistical proof of the same was not provided. Klimkeit et al. [9] observed greater loss of stiffness in the coupons with fibers in the loading direction as opposed to coupons with fiber in the transverse to loading direction. It is hard to make qualitative judgements about loss of stiffness curves since like all fatigue based quantities there is some inherent scatter and uncertainty. Two coupons having the same fiber content, length and orientation distribution; when subject to the same cyclic load may have different number of cycles to failure. Even if the number of cycles to failure are the same (or similar), the loss of stiffness could follow a different trend. Thus a thorough statistical treatment of the loss of stiffness is necessary to relieve the confusion.

Statistical methods to access variance in fatigue data have been tried for metals and welds [10,11]. Proper use of statistics can provide insights about composite fatigue. For example, Marshall et al. [12] using simple student test based statistics were able to prove that the scatter in his fatigue data of glass fiber UD composites was due to change in failure mode.

Apart from helping gaining further insight about the fatigue mechanisms in SFRC and dependence on the FOD the study of loss of stiffness and its dependence on FOD could be important for many

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[*] Corresponding author. Current address: M.C. Gill Composites Center, University of Southern California, United States.
E-mail address: atuljain@usc.edu (A. Jain).

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reasons, a couple of them are highlighted here.

Recently, a hybrid multi-scale approach to derive the local SN curves was developed by Jain et al. [13–15]. Using a combination of the Mori-Tanaka formulation [16] and an algorithm for treating fiber matrix debonding [17], this method predicts the local SN curve with only one SN curve as input. The approach was named the Master SN curve approach, in short the MSNC approach. A major assumption of this formulation was that the damage propagation and subsequent loss of stiffness is the same for SFRC with different FOD. A statistical treatment of the loss of stiffness will confirm whether or not this assumption is true as it is suggested by good predictions reported in Ref. [13].

Also, during a SN curve based component level (high cycle) fatigue simulation of SFRC, each element in the RVE has a known FOD which is calculated using manufacturing simulation tools. Each element is treated as different material whose stiffness is typically calculated by mean field homogenization techniques [18], for example the Mori-Tanaka method [19]. The SN curve of every element is calculated either by interpolation or by other mechanics based methods for example the Master SN curve approach. The local loads are calculated using FE software by applying suitable boundary conditions and the reduced lifetime is derived from the local loads and the local SN curves. Apart from reduced lifetime, the composites also suffer from loss of stiffness which leads to stress redistribution and must be accounted for during fatigue simulation. A typical method is to reduce the stiffness of the elements and rerun the FE calculations after certain number of cycles [20]. If the loss of stiffness is the same for all FOD, this will simplify the calculations significantly as the loss of stiffness curve can be experimentally derived for one coupon with a certain FOD and the same loss of stiffness relation can be used for all the RVE. If the loss of stiffness is different for SFRC with different FOD then either additional tests have to be performed and/or relation between the FOD and loss of stiffness curves must be developed.

A physical justification of the assumption is that for SFRCs with different FOD (and FLD) but same constituents (fiber and matrix), the extent of damage (which is quantified by a loss of stiffness) needed to propagate and cause failure after same number of cycles should be similar. The expected damage events happening at the micro-level are expected to be similar, provided the FOD of the material is sufficiently random.

In this paper, a sufficiently large number of fatigue experiments are performed on SFRC with different FOD, the loss of stiffness curves are experimentally derived for each data point and a systematic method for the comparison of loss of stiffness is developed. For the scope of this paper only tension-tension fatigue tests are considered, but the method developed in this paper can be used for comparison of loss of stiffness curves at different applied load ratios as well.

Section 2 of this paper describes the experiments; the data extraction and analysis is elaborated in Section 3. The experimental results are presented in Section 4, the statistical study is presented in Section 5. The conclusions are summarized in Section 6.

2. Experiments

Polybutylene terephthalate (PBT) reinforced with 0.5 wt fraction of glass fiber (equivalent volume fraction is 0.35) compound was injection molded to plates having dimensions 170 × 170 × 2 mm. The thickness of the plates are chosen to be as thin in order to ensure uniform FOD (with negligible core layer) through the thickness of the coupon based on the advice of Vincent et al. [21]. Coupons were machined from the plates in three directions, inclined at angles $\varphi = 0$, 45 and 90 with respect to the prevailing flow direction (Fig. 1). For the rest of the paper, they are referred to as 0, 45 and 90-degree coupon respectively. Three coupons were machined from each plate for the 0 and 90-degree coupon, while only one coupon per plate was machined for the 45-degree coupon.

The plate used for injection molding has been designed so that the variation of the orientation is negligible in the areas where the coupons were machined. Also, the coupons are machined in such a way that the gauge length region of the horizontal, vertical and 45-degree coupon are all from the same square region in the center of the plate. This ensures that the variation of FOD (if any) within three horizontal coupons machined from the same plate will be the same as the variation of the FOD in the gauge length of one vertical coupon or the 45 −degree coupon (Fig. 2). Thus, we are confident that there could be only minimal variability in the static and fatigue properties of the three coupons machined from different locations in the same plate (owing to some small variations in FOD). Also, the variability in the properties (for three coupons from same plate) if any, is the same as inevitable variance in local stiffness across the gauge length of a single coupon. This slight variation of properties for different coupons (and different regions in the same coupon) could add to scatter in the static and fatigue properties. This strategy of deriving several coupons from a single plate has been previously reported in literature [4] [22], [23]. Overall, it must be kept in mind that the confirmation of similar FOD for coupons machined from same plates but different locations is actually an assumption which is supported by simulation and other indirect observations. A direct FOD measurement through experimental means has not been reported. Instead, manufacturing simulation has been performed. For the analysis presented in this paper, this was seen as sufficient. Exact values of the FOD are not needed, we simply want to study of variance of loss of stiffness for coupons with different FOD and not perform any specific analysis which requires the exact values of the FOD as input. Thus, confirmation that the 0, 45 and 90-degree coupons had sufficiently different FOD was enough.

Manufacturing simulation was performed on the plates by the commercial software SIGMASOFT [24]. The simulations are based on the Advani-Folgar [25] equation. The simulation was performed with the following process parameter set (the same as the one used for the injection molding process):

Melt temperature: 290 °C
Mold Temperature: 85 °C
Holding pressure: 700 bar
Holding pressure time: 3.5 s
Filling time: 0.86 s
Cooling time: 53.5 s

There were 10 elements through the thickness of the plate. This number is confirmed based on a sensitivity analysis. No improvement or change was seen in the predicted FOD if the mesh is refined. The predicted variation of the FOD through the thickness was studied in the regions where coupons were machined. Simulation confirms that the variation of FOD in the region is minimal (less than 1% difference). The variation of the FOD through the thickness in two regions of the plate from where the coupons were machined has been given in Fig. 3a, b. The simulations suggested the absence of “skin-core” distribution of orientation, this finding is consistent with the reported FOD for thin plates by De Monte et al. [26] who reported no variation of both experimental and simulated FOD through the thickness for thin plates of 1 mm and Vincent et al. [21] who used 2 mm plates. Also, a qualitative inspection of the fractured samples confirms the absence of the skin-core effect. We however, do believe that the FOD will not be as uniform as the simulation suggests, there can be some minor variation between the different layers, which the simulation cannot capture.