Multiaxial fatigue behavior of short-fiber reinforced thermoplastic roof bars

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Abstract

The automotive industry needs to reduce the weight of vehicles for environmental and economical purposes. One expected way to reach this goal is to employ thermoplastic materials for the design of mechanical structures because of their high "fatigue strength / density" ratio compared to metallic materials.

Automotive components are exposed to repeated loadings with variable amplitude. As in-service failures must be avoided, fatigue characterization is necessary to optimize the design of thermoplastic parts. This allows designers simulating the fatigue behavior of components exposed to severe mechanical loadings.

The present study deals with a PBT+PET GF30 which is a mixture of polybutylene terephthalate and polyethylene terephthalate reinforced by 30% short glass fibers. Fatigue tests are carried out for different loading types (tension, torsion, pure shear) under two load ratios R = 0.1 and R = -1 and for three different fiber orientations. Based on these fatigue data, an energetic fatigue criterion is proposed. A Through Modeling Process finite element simulation using MoldFlow, Digimat and Abaqus is used to evaluate the local stress/strain fields. The results are in good correlation to strain measurements on the roof bar during the tests.

Key words

Short-fiber reinforced thermoplastic, roof bars, multiaxial fatigue criterion

Introduction

Thermoplastic roof bars are a good example to illustrate the benefits offered by such materials for the design of light and low cost structures. Short-fiber reinforced thermoplastics present a high resistance/density ratio and can replace aluminum alloys to reduce the weight and the cost of automotive components. This is in good agreement with the main objective of Renault which is to produce vehicles with low CO_2 emissions while ensuring a very competitive price.

As roof bars are considered as security components, the fatigue behavior has to be well understood to prevent in-service failures. In the past, the fatigue mechanisms have therefore been studied for polyamides by using various techniques [1-7]. However, on fiber reinforced PBT and PET there are only few studies available [8-11]. As Mandell [12] reports that fatigue mechanisms depend strongly on the fiber matrix interface system, one should also investigate PBT+PET GF30 in order to apply this material to car components. The authors have published on this topic in a separate communication [13].

Due to the fierce competition among car manufacturers and the reduction of development duration, simulations are more and more used to design mechanical structures. An accurate material database, a reliable fatigue criterion and a good description of the stress field are necessary to estimate the fatigue lifetime by finite element analysis.

Many fatigue criteria have been proposed in the past for continuous fiber reinforced composites [14] as well as for short-fiber reinforced thermoplastics [15-21]. The fatigue criterion should accord to the need of the engineer. While in preliminary studies simple criteria are suitable, the final dimensioning will require very accurate criteria. In this paper we will present both, one criterion which is based on static properties and which is easily identified and then a more complex model with a higher accuracy: an energetic criterion.

In the following, the short-fiber reinforced thermoplastic roof bar is presented. Then, a brief presentation of the material characterization is given. The different fatigue criteria are evaluated and finally the tests on the roof bars are discussed.

1 Automotive application: thermoplastic roof bars

1.1 Multiaxial loading

Typical spectrum loading due to imperfections of the road (bad pavement, noise) and driving maneuvers (cornering, lane change, braking) creates a multiaxial stress field in automotive parts as roof bars. This type of loading should be taken into account during the design phases to optimize structures regarding weight. On the figure 1, you can see the x, y and z direction in which roof bars are loaded. However, for the sake of simplicity, in this work we will take into account constant amplitude loading. This approach allows a safe dimensioning which will prevent any in service fatigue failures. Later on, the model will be extended to take into account spectrum loading in the aim of further weight reductions.

Figure 1: Multiaxial loading of the roof bar.

1.2 Material

The roof bars are manufactured by injection molding using a mixture of polybutylene terephthalate and polyethylene terephthalate, reinforced by short glass fibers at a mass ratio of 30% called PBT+PET GF30. Due to this process, the material has anisotropic properties which must be taken into account to describe the mechanical behavior of the structure.

2 Material characterization

In order to describe the mechanical behavior of the roof bars and to estimate as accurately as possible its fatigue lifetime, static and fatigue tests of the PBT+PET GF30 are carried out. On the one hand, tests are conducted on flat dog bone specimens milled out at three orientations regarding to the mold flow direction in order to address the anisotropy of the material. On the other hand, the influence of shear stresses on the fatigue behavior is identified on the basis of tests on tubular specimens exposed to tension, torsion and tension-torsion loading.

2.1 Specimens

End line gated plates are injected and flat dog bone specimens are milled out in the centre with an orientation angle α, figure 2.a. Three orientations are chosen 0°, 45° and 90°. Tubular specimens are directly injected, figure 2.b, and therefore always oriented at 0° to the mold flow direction.

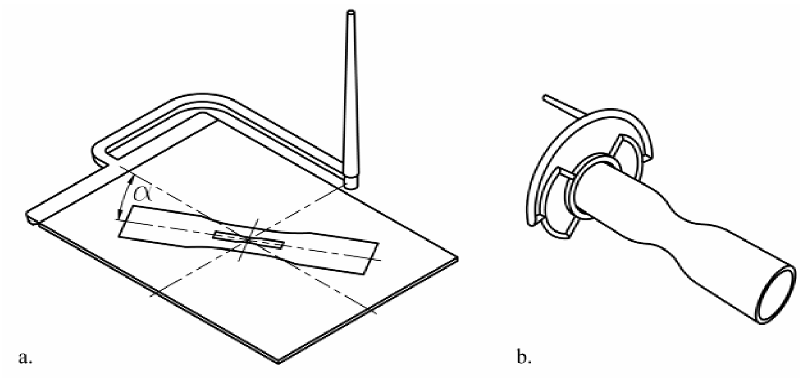


Figure 2: a. End line gated plate with dog bone specimens at orientation angle α. b. Tubular specimen.

The flat specimens are dog bone like specimens according to figure 3.a. while the geometry of the tubular specimens is presented in figure 3.b.

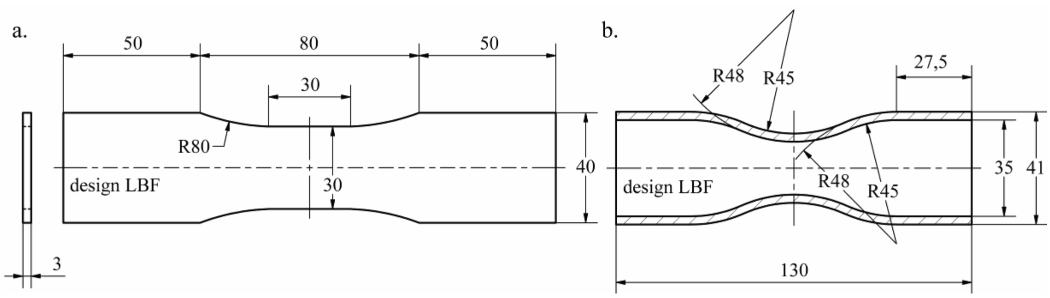


Figure 3: Geometry of a. the dog bone specimen and b. the tubular specimen.

2.2 Test results

Both, static and fatigue tests, are carried out on flat and tubular specimens. The fiber orientation influence is identified by means of tests on specimens milled out at 0°, 45° and 90° to the mold flow direction. The tubular specimens are exposed to tension, torsion and combined tension-torsion loading. All fatigue tests are carried out at two load ratios R = 0.1 and R = -1 which is the basis for the mean stress sensitivity characterization. Frequencies are chosen in order to prevent excessive hysteretic heating which reduces fatigue lifetimes. The maximum allowed heating was 4°C which did not reduce fatigue lifetimes according to a preliminary study. Resulting test frequencies were between 0.25 and 6 Hz. All tests are load controlled.

For each testing condition, the static behavior and the SN curve is identified. As an example, the test results for the longitudinal specimens milled out at 0° are presented in Figure 4.

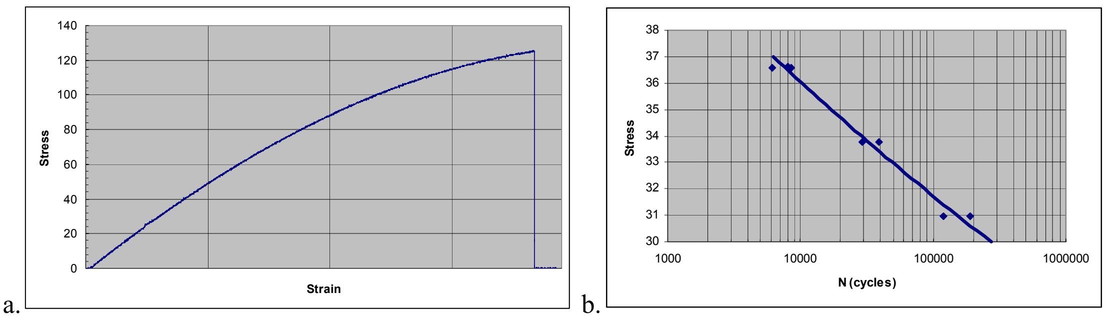


Figure 4: a. Static characterization and b. SN curve at R = 0.1.

3 Fatigue criteria

Two complementary approaches to evaluate the fatigue lifetime are presented in this section. Firstly, an estimation of the fatigue behavior on the basis of static test results is discussed. This method is used during very early phases of projects when no fatigue data is available. Secondly, a multiaxial fatigue criterion taking into account the fiber orientation as well as mean stress effects and multiaxial loading is presented. This allows evaluating the fatigue lifetime of components exposed to repeated loadings during validation phases of the design.

3.1 Fatigue behavior estimation on the basis of static properties

The described material database is used to interpolate the fatigue behavior on the basis of the static behavior of the material. With a representative number of test results, fatigue strength for a given lifetime and stress ratio correlates to the static strength as presented in figure 5. This kind of estimation is available for several stress ratio in order to take into account the mean stress influence.

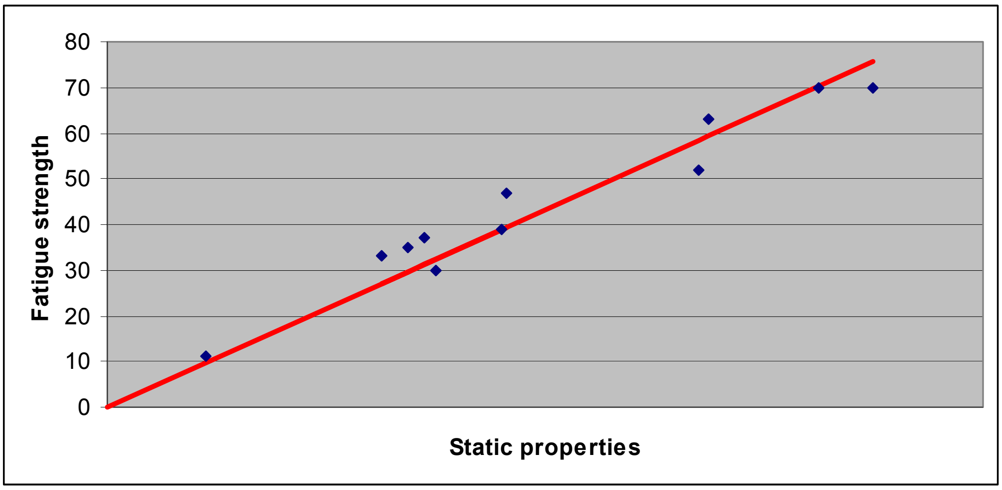


Figure 5: Fatigue strength estimated from static properties of short fiber reinforced thermoplastics

This simple law delivers rapidly the fatigue behavior of a new material to the designer with the only knowledge of the static strength which is in fact often given by the material supplier. The designers calculate the maximal principal stress on the component and compare it to the estimated fatigue strength to verify that no failure appears for a given number of cycles.

3.2 Multiaxial fatigue criterion

In the following, a multiaxial fatigue criterion is discussed. The criterion is applied on the stress tensor given by a finite element analysis and takes into account fiber orientation, mean stresses and multiaxial stress states.

3.2.1 Stress simulation

Different fatigue criteria have been evaluated. For all criteria, the stress distribution was firstly simulated by finite element analyses. Figure 6 presents the complete simulation chain which is divided into three blocks. Firstly, the geometry is modeled. Secondly, the stress/strain field is simulated by means of homogenization in order to take into account the microstructure heterogeneity. Finally, the respective fatigue criterion can be applied on the stress/strain tensors to evaluate the fatigue lifetime.

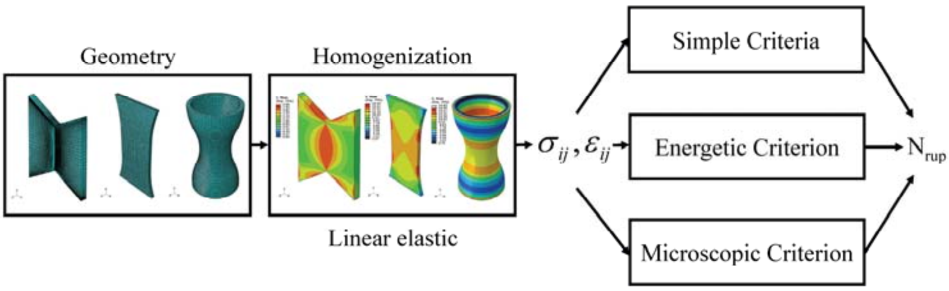


Figure 6: Simulation chain for fatigue lifetime evaluation.

The second block is detailed in Figure 7. Firstly, the fiber orientation is simulated by a Mold Flow simulation. Then, the mesh is optimized for the stress/strain simulation. The local material behavior is homogenized by Digimat and finally a coupled FEM simulation is carried out with Abaqus.

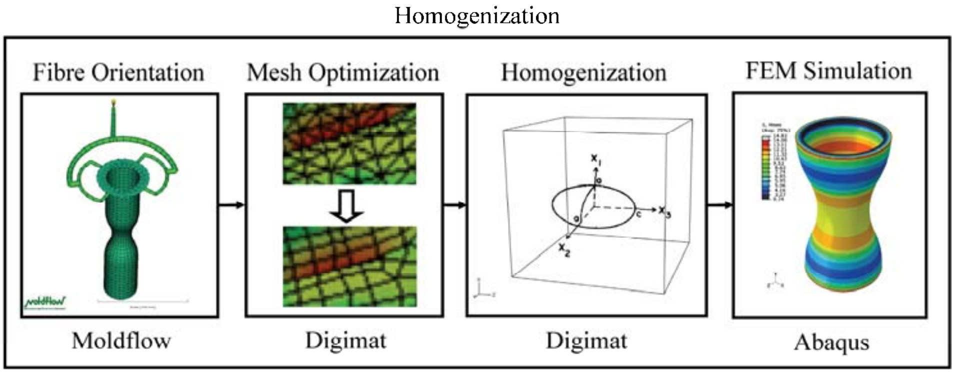


Figure 7: Stress simulation by homogenization.

In this paper, only the results for the energetic fatigue criterion are discussed.

3.2.2 Energy criterion

The fatigue lifetime evaluation is based on the work of Ellyin [22] see equation (3.1).

$$\Delta W = f \cdot \Delta W_e = f \cdot \frac{\varepsilon_{ij}\sigma_{ij}}{2} = f \cdot \kappa N^{\alpha} \qquad (3.1)$$

Where f is the function which takes into account mean stress effects. In this work the simple empiric function of Smith Watson and Topper is chosen [23], equation (3.2).

$$f = 1 + \frac{\sigma_m}{\sigma_a} \qquad (3.2)$$

The parameters κ and α are the two parameters of the Basquin relationship which are identified by one SN curve. Then the fatigue lifetimes can be evaluated and the result for all the fatigue tests mentioned before is given in Figure 8.

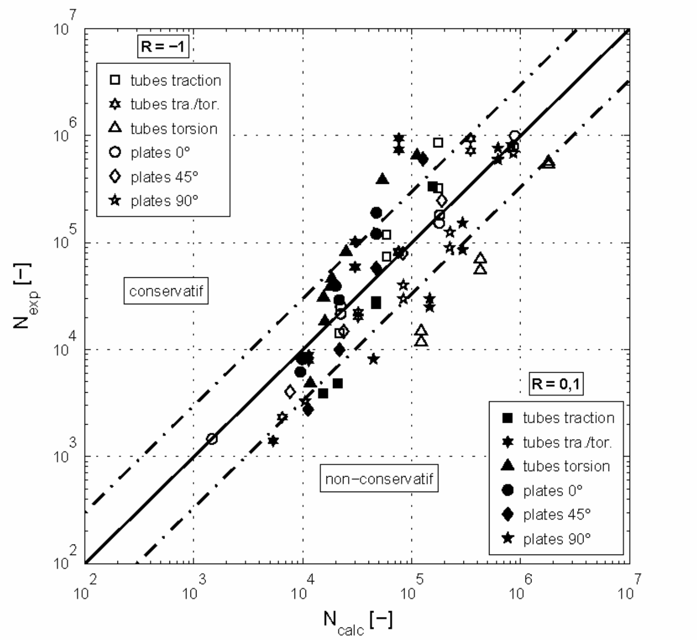


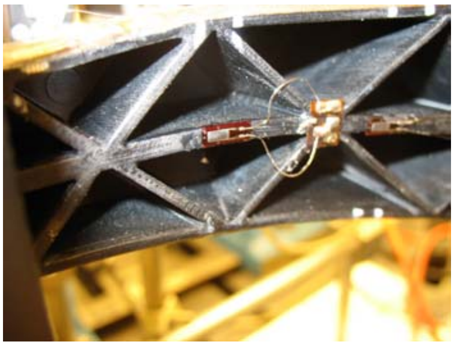
Figure 8: Experimental lifetimes over evaluated lifetimes.

4 Application on thermoplastic roof bars

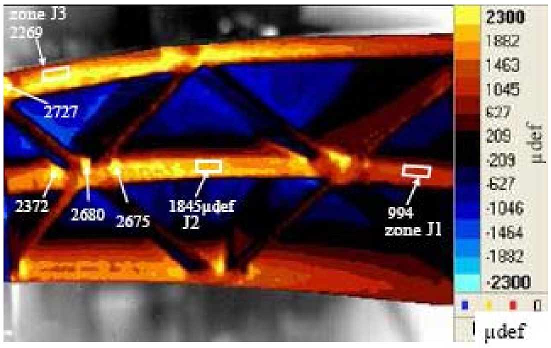
The two methods presented can be used for the design of thermoplastic roof bars. In this section, the first results obtained on the structure are presented.

4.1 Correlation of the finite element simulation and strain measurements

A finite element model as described before in Figure 7 is created for the thermoplastic roof bar. The local fiber orientation states are simulated by Mold Flow. The mesh is optimized and then the material behavior is homogenized by the Mori Tanaka approach with Digimat. The stress/strain field can then be simulated with Abaqus. In order to evaluate the accuracy of this simulation, the simulated strain field is verified by strain measurements on the roof bar exposed to a static load. Figure 9.a. presents the strain gages used for local strain measurements while Figure 9.b. shows the strain measurement by Infrared thermography.



a.



b.

Figure 9: Measurements on the roof bar a. by strain gages and b. by thermography.

The simulation is in good agreement with the strain measurements. Therefore, the simulation chain for the roof bar is validated up to the second block.

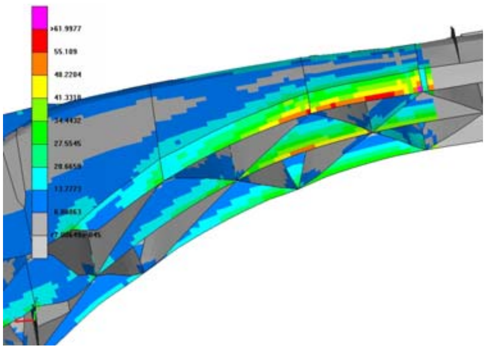


Figure 10: Results of the finite element analysis on the thermoplastic roof bar.

4.2 Fatigue tests

Before using the fatigue criterion for variable amplitude loading as observed under real service conditions, the method will be validated for constant amplitude loading. A fatigue test is set up on a fatigue bench according to Figure 11.

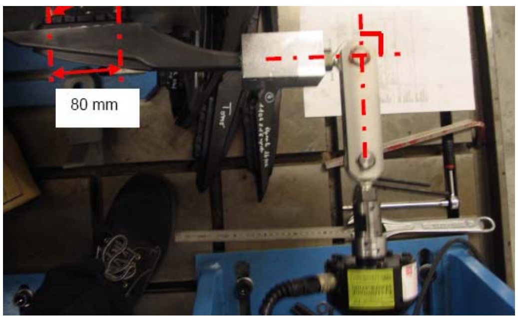
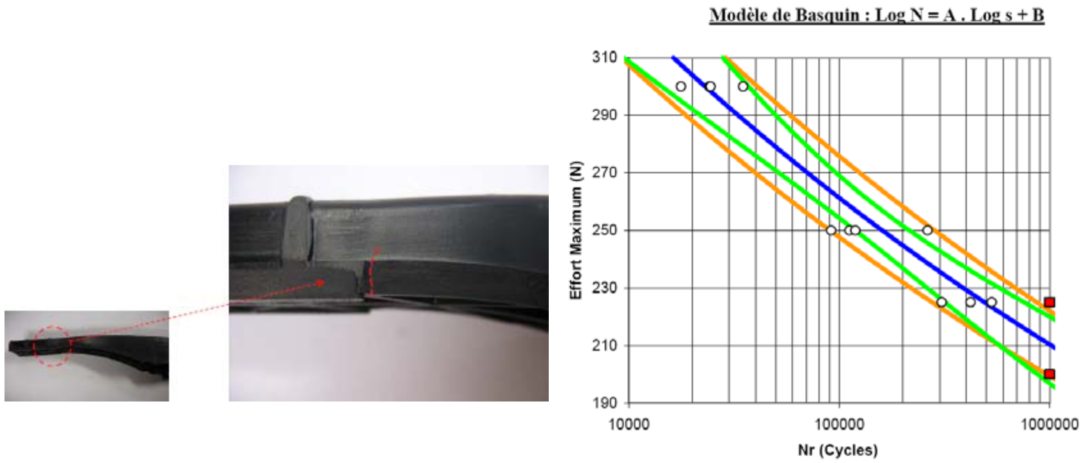


Figure 11: Roof bar tested on the fatigue bench.

Tests are carried out for the two load ratios R = 0.1 and R = -1. The tests are stopped when a crack appears on the roof bar figure 10.a. The location of the crack corresponds to the hot spot detected by the FE simulation. Fatigue tests are carried out for four load levels and a statistical analysis is done on the results figure 10.b. with ESOPE software provided by N'Code.



a. b.

Figure 12: a. Fatigue crack detected on the roof bar and b. Wöhler curve.

The fatigue criterion will be used to evaluate the fatigue lifetime for the roof bar. Therefore, the fatigue lifetime evaluation tool is now under further development.

5 Conclusion

In this paper, a method used to design short-fiber reinforced thermoplastic components is presented. The application is a roof bar which is exposed to multiaxial fatigue during service life.

To evaluate the fatigue behavior, static and fatigue tests are carried out on specimens in tension, torsion and combined tension-torsion. Two load ratios are applied in order to take into account the mean stress effect. As the material has anisotropic properties, tests are also conducted for three different fiber orientations.

Two fatigue criteria are presented. During early phases of projects, the fatigue strength can be estimated by a simple relationship based on the static properties. In order to evaluate the fatigue lifetime in a more accurate way, the use of a more sophisticated criterion is recommended. In this paper we present an energetic fatigue criterion which yields good results with only one SN curve for identification. The fiber orientation, the mean stress effect and multiaxial stress states are well described. Nevertheless, the improvement of the results of this model is still under investigation.

The stress/strain field of the roof bar is modeled by a Through Modeling Process using Moldflow/Digimat/Abaqus simulation. The results are in good agreement with strain gage and thermoelasticity measurements. Fatigue tests are carried out on the roof bars for the two load ratios. The fatigue lifetime evaluation tool is under further development in order to validate the fatigue criterion on the structure.

6 References

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