A LOCAL STRESS ANALYSIS OF THE EFFECT OF FIBRE ORIENTATION ON THE FATIGUE BEHAVIOUR OF A SHORT FIBRE REINFORCED POLYAMIDE

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Keywords: Short fibre, Fatigue, Fibre orientation, Modelling

ABSTRACT

In a previous work, the effect of fibre orientation on the fatigue behaviour of a short fibre reinforced polyamide was studied using specimens extracted at different orientations from injection moulded plates. The results were analysed in terms of the nominal stress, without taking into account the shell-core-shell inner structure typical of injection moulded plates. Using nominal stresses, a fatigue criterion derived from Tsai-Hill criterion was proposed. The skin-core-skin layered structure of the specimens used for the experimental tests was later investigated using micro computed tomography, which suggested further investigating the effect on the stress distribution of the variation through the thickness of the local fibre orientation structure. Finite element analysis of the specimens were conducted, taking into account the effect of fibre orientation by through process modelling, i.e. by simulating the injection moulding process and by defining local material's properties on the basis of simulated fibre orientation distributions. Simulated fibre orientation distributions were first validated by experimental analyses by the optical method. Then, local stress distributions were obtained. Results show that local fatigue strength values differ from those previously obtained based on nominal stresses.

1 INTRODUCTION

Fatigue of Short Fibre Reinforced Polymers (SFRPs) is a topic that has seen a growing interest, mainly due to the new perspectives for the employment of these materials as lightweight solutions for metal replacement, particularly in the automotive industry. Several factors affect the fatigue behaviour of SFRP. For a comprehensive review about these factors, see Ref. [1]. Among these factors, anisotropy, and related factors like layered micro-structure and fibre orientation, play a major role.

In order to take into account local anisotropy of SFRP components during their design phase, process simulation is nowadays usually performed using software packages allowing for estimating the fibre orientation distribution (FOD) over the whole part and across the thickness at every point. Based on FOD obtained by process simulation, linear and non-linear structural Finite Element (FE) analyses can be performed, allowing for the evaluation of stresses on a local scale using shell or solid finite elements. This approach is often defined a Through Process Modelling (TPM).

In this work we propose a review based on local stresses evaluated by TPM of the results of experiments already published in [2], which were previously interpreted on the basis of nominal stresses. In fact, a skin-core-skin layered structure of the specimens used for the experimental tests was first found by means of optical microscope analysis and later investigated more deeply using micro computed tomography [3]. This allowed for evaluating the differences in fibre orientation and degree of anisotropy through the thickness and suggested further investigating the effect of these features on the stress distribution inside the specimens.

Finite element analysis of the specimens were conducted, taking into account the effect of fibre orientation by TPM, i.e. by simulating the injection moulding process and by defining local material's properties on the basis of simulated fibre orientation distributions. Simulated fibre orientation distributions were first validated by experimental analyses by the optical method [4]. Then, local stress distributions were obtained and results showed local fatigue strength values different from those previously obtained based on nominal stresses.

2 EXPERIMENTAL AND THEORETICAL BACKGROUND

In a previous work [2], the influence of fibre orientation on the fatigue behaviour of a short fibre reinforced polyamide was studied by means of tests on dumbbell specimens. The specimens were extracted by water jet cutting from injection moulded plates at different orientations (0°, 30°, 60° and 90°) to the mould flow direction. These plates, 180 mm long, 120 mm wide and 3.2 mm thick, were made of polyamide 6 reinforced with 30 % by weight of short e-glass fiber (PA6 GF30).

The specimens were fatigue tested by subjecting them to sinusoidal cyclic loads with a stress ratio of 0.1 at a frequency of 4 Hz. Test were interrupted at specimen failure or at 10^6 cycles (run-out). The resulting s-n curves are reported in Fig. 1, together with a schematic representation of the position of the specimens used.

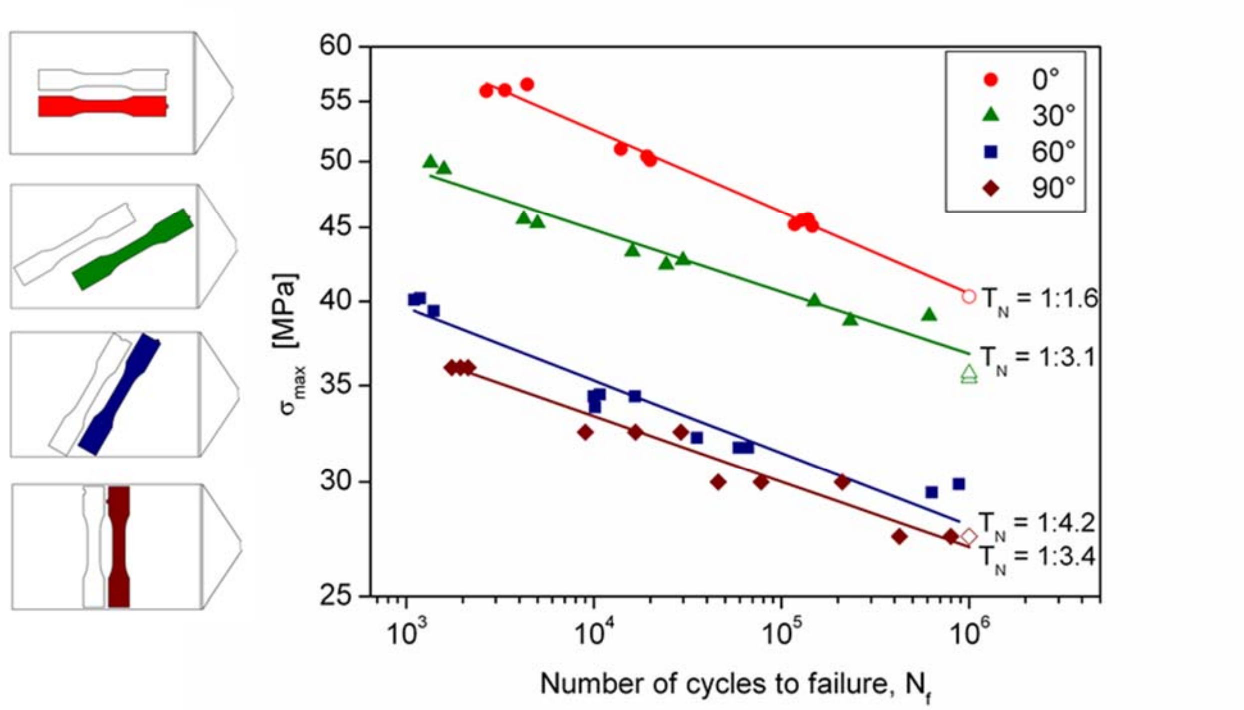

Figure 1. S-N curves for PA6 GF30 specimens with different fiber orientations based on the experimental results presented in [2].

Values of the average force (50% of probability of failure) which lead to failure at 10^6 cycles were extrapolated using a linear relationship to interpolate fatigue data. Fatigue strengths at 10^6 cycles were obtained on the basis of nominal stress values, i.e. by dividing the applied force by the specimen sectional area. These strength values displayed a relationship with the specimen's orientation angle which was found to be in agreement with a Tsai-Hill like relationship.

The specimens, as pointed out subsequently by micro-CT analysis [3], displayed the typical shell-core-shell layered structure frequently encountered in injection molded thin plates. However, this aspect was not taken into account in the analysis of data. Instead, nominal stress values were considered and a correction was proposed based on normalized fatigue life curves, i.e. by dividing fatigue strength values by the ultimate strength, as obtained using the same type of specimen.

3 FIBER ORIENTATION ANALYSIS

Injection molded plates made of the same material and belonging to the same batch of the ones used to obtain specimens for fatigue tests presented in [2] were available. Thus, new specimens were extracted at 0°, 30°, 60° and 90° to the longitudinal direction of the plate and exactly at the same location at which specimens used to perform fatigue tests where cut-out, i.e. the locations highlighted in Fig. 1.

In order to obtain fiber orientation data directly comparable with the results of numerical simulations of the injection molding process, these new specimens were analyzed by means of the optical method [4] for fiber orientation measurements. Local values of fiber orientations were measured over the entire area of the sections 1 and 2, whose position is shown in Fig.2.

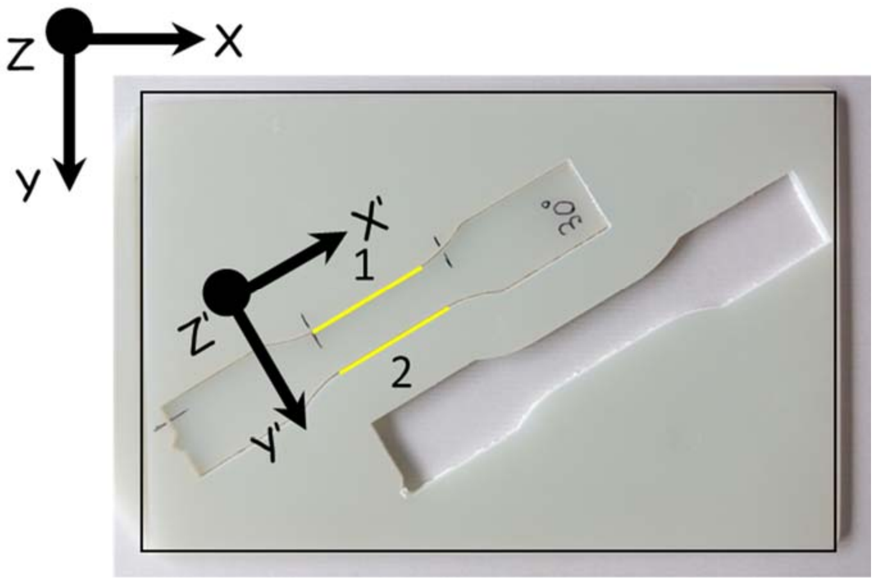

Figure 2. Position of the scanned surfaces and the reference frame used for the evaluation of the FO tensor components.

The analysis based on the optical method allows for evaluating the orientation of each single fiber in terms of angles θ_x, θ_y and θ_z formed by the fiber's axis with the X',Y' and Z axes respectively. From the orientation of each fiber, the components of the fiber orientation tensor a_{xx}, a_{yy}, and a_{zz} were evaluated.

The injection molding of the plates was simulated using Autodesk Moldflow MPI 2015 by means of a FE model shown in Fig.3. The plate was modelled using a midplane approach. In order to capture the variation of FO through the thickness, the maximum allowable number of 20 layers was selected. The main parameters of the simulation are reported in Table 1. Four models were built for each orientation of the specimen, with a partition representing the specimen, which was subsequently used to extract and map FO onto the structural models of the specimens, as described later.

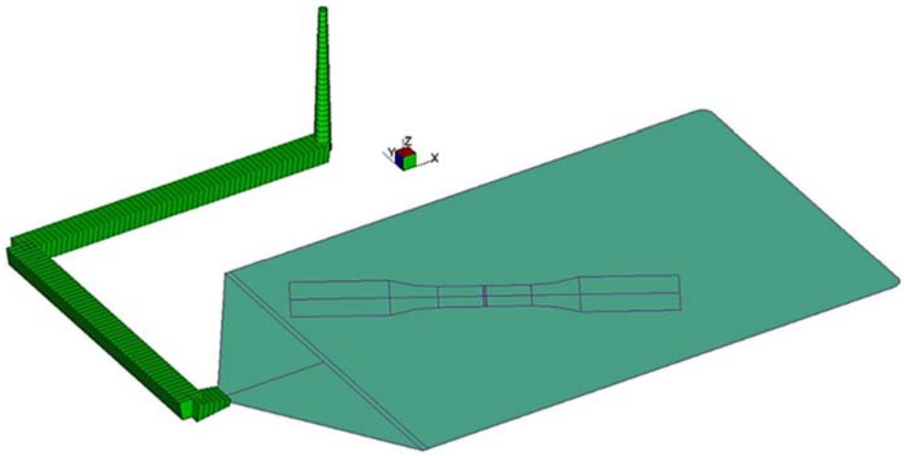

Figure 3. Model of the plate used for injection molding simulations.

In order to model FO evolution during injection, two models are available: Folgar-Tucker (F-T) and Reduced Strain Closure (RSC). The parameters employed for the F-T and RSC models, reported in Table 2, were chosen by a trial and error approach so that the best agreement with measured and simulated FO could be obtained.

Injection time [s]	1.0
Hold pressure [MPa]	45.0
Hold time [s]	6.0
Cooling time [s]	16.0
Mould temeperature [°C]	90.0
Melt polymer temperature [°C]	275.0

Table 1. Parameters used for injection molding process simulations.

Folgar-Tucker	**RSC**
$C_I = 0.0155$	$k = 0.4$
$D_z = 0.17$	$C_I = 0.01$

Table 2. Values of the parameters of the FT and RSC models.

The results of the FO measurements and the comparison with the simulated FO results, obtained with the FT and the RSC model, are shown in Fig. 4 for the a_{xx} FO tensor components. Values of the simulated FO tensor were extracted from the entire gauge section of the specimens, which coincided in length with the 1 and 2 sections used for the experimental analysis, and then averaged through the *X'* and *Z* directions to obtain the variation through the thickness of values averaged in a manner consistent with that of experimental data.

It appears that the RSC model provided a better agreement with experimental data, particularly in the case of 0° and 90°. In any case, both FT and RSC models have been retained in the following step, and the final choice has been made considering the agreement with stiffness values obtained in structural simulations.

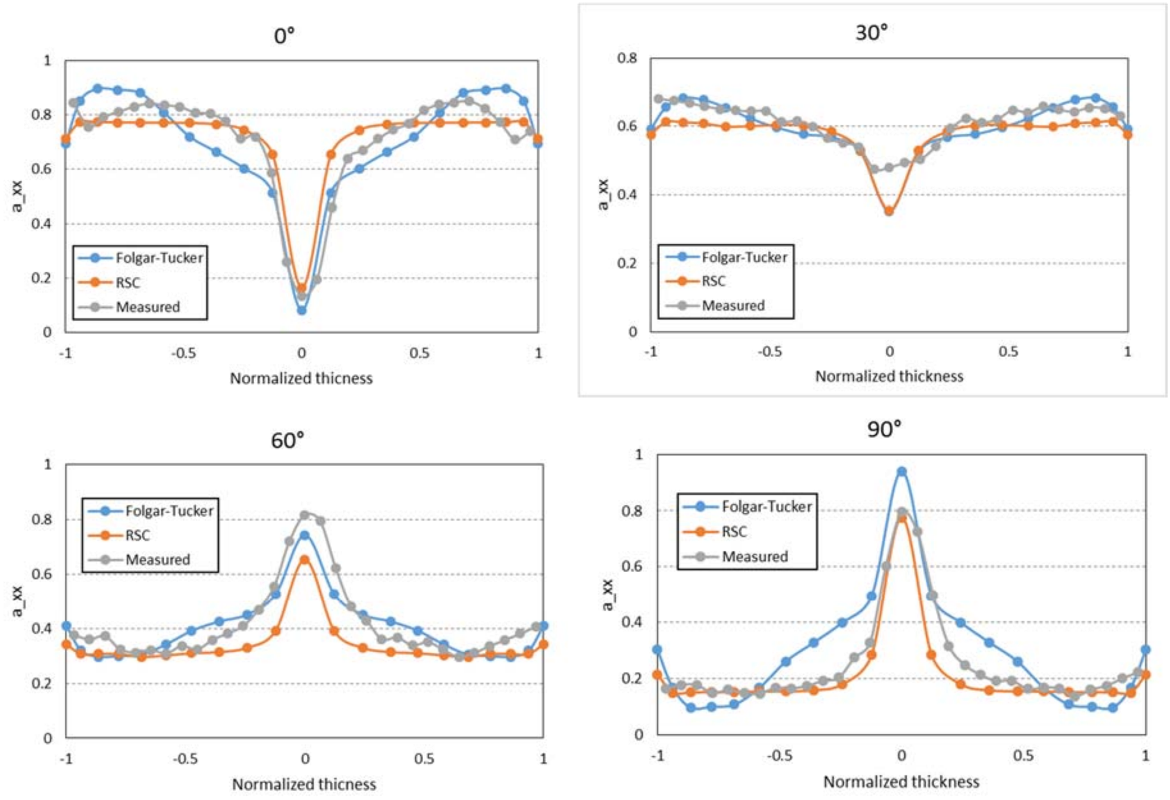

Figure 4. Comparison of values of a_{xx} obtained by simulation, using FT and RSC models, with values of a_{xx} obtained experimentally

4 STRUCTURAL ANALYSIS

Test specimens showed, both in micro-CT analyses and optical measurements, a layered structure that should make the specimen behave like composite laminates, with non-uniform stress distribution through their thickness. On the basis of the numerically determined fiber orientation tensor fields, structural analyses have been conducted by means of Finite Element Method (FEM) in order to determine local stress values to be used for fatigue data analysis, capturing the effect of the layer structure of the specimens.

Linear elastic FE analyses of the four specimens have been performed using Abaqus 6.13. In order to take into account the effect of the FO upon elasticity of the SGFR polymer used, it was necessary to use numerical tools allowing for:

- Mapping the local FO values obtained by process simulation onto the structural mesh
- Evaluating the local values of the stiffness matrix, assuming that each element behaves like a composite laminate, with each lamina having the properties of an orthotropic material, whose elastic constants are related to the FO orientation tensor components

To perform these two tasks, the Digimat software package by e-Xtream engineering and its plug-ins for Abaqus have been used, allowing for conducting a structural analysis coupled with process simulation results. The first task was performed using the available mapping tool, which transferred FO data to the structural mesh. Linear 4 node shell elements were used. The second task required the choice of a suitable homogenization scheme. Both the Mori-Tanaka and Double Inclusion homogenization schemes available in the Digimat package were used for comparison purposes each applied in combination with either the FT or the RSC models. The FE models were loaded and constrained to simulate the experimental test conditions.

The specimen stiffness was evaluated using the four combinations of homogenization and fiber interaction schemes, resulting into the apparent longitudinal elastic modulus values that were compared with experimental values measured in quasi-static tests. The best agreement between experimental test results and numerical test results was found using the RSC model together with the Mori-Tanaka approach. Thus, these results have been used subsequently to analyze fatigue data in terms of local stresses.

5 LOCAL STRESS AND FATIGUE ANALYSIS

In order to evaluate the possibility to apply a local stress approach to fatigue strength assessment of SGFRP, the fatigue test results presented in [2] have been considered. For each specimen type, the value of the average force which lead to failure at 10^6 load cycles was obtained interpolating fatigue data by a linear relationship in a bi-logarithmic scale. Fatigue strength at high number of cycles has been considered so that as, to a first approximation, the material behavior can be assumed linear elastic as in numerical simulations.

The stress fields induced by these loads in specimens with different fiber orientations, i.e. 0°, 30°, 60° and 90°, have been obtained by means of the structural analysis previously described. As a consequence of the shell-core-shell microstructure of the specimens, the stress state, that is quite homogeneous in the gauge area of specimens, varies through thickness following the shell-core-shell structure.

Evaluating the stress tensor components expressed in a material reference frame, i.e. in a reference frame with the axes coincident with the principal directions of the fiber orientation tensor, the normal stress acting on a plane perpendicular to the first principal direction of the fiber orientation tensor was always predominant over the other stress components, that were nearly negligible respect to this one. As shown in Fig. 5, apart from the case of 30° in which similar values were found in the shell and in the core, the values of the normal stress aligned with fibers varied significantly going from the core to the shell layers in all the specimens.

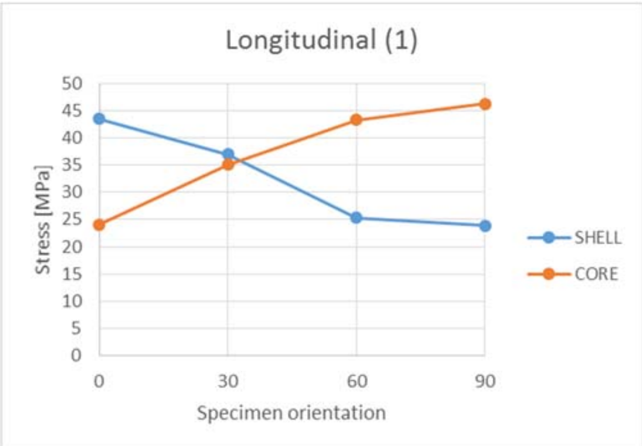

Figure 5. Normal stress acting in the core and in the shell layers on a plane perpendicular to the first principal direction of the fiber orientation tensor.

In the case of 0° specimen the maximum stress was found in the shell layer, while for 60° and 90° the maximum was in the core and its magnitude was very close to the one acting in the shell layer of the 0° specimen. In the case of the 30° specimen, equal stresses were found in both the shell and the core layer of magnitude lower than the maximum stresses acting in the highly stressed layer of the 0°, 60° and 90° specimens. Based on these observations, a maximum stress criterion based on local stresses seems to be more appropriate for explaining the behavior of 0°, 60° and 90° specimens, while the behavior of the 30° specimens seems to indicate the need of a different criterion.

The previously described stress distributions obtained by numerical simulations suggested to perform SEM analyses of the fracture surfaces of the fatigue tested specimens in order to find a correlation between damage appearance and stress levels in different locations along specimen thickness. In the SEM analyses performed, due to the skin-core-skin microstructure and the different orientation of fibres respect to the longitudinal axis of the specimens, which is coincident with the loading direction, different fatigue damage patterns were observed on fracture surfaces of specimens with different fibre orientations, as shown in Fig. 6.

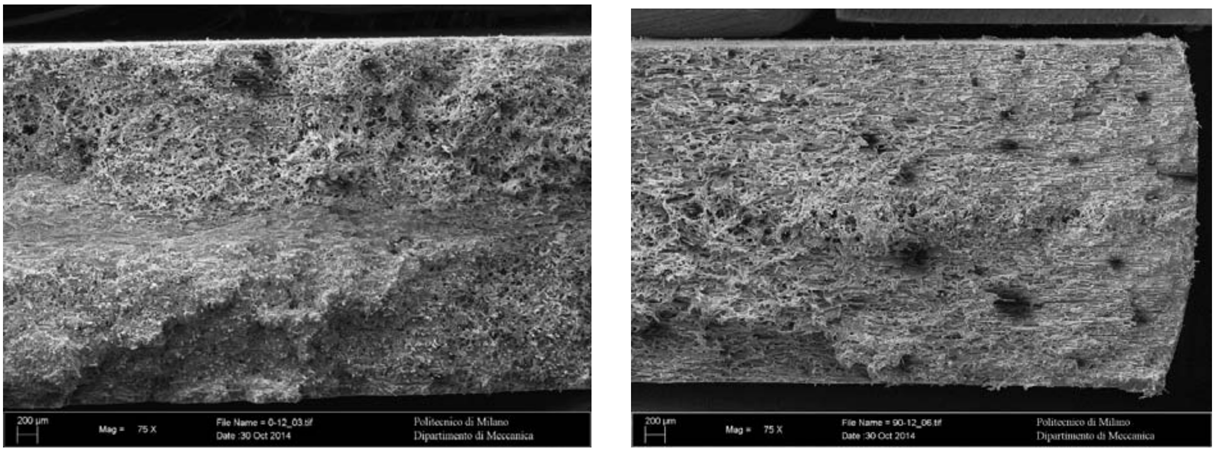

Figure 6. SEM images of the fracture surfaces of specimens at 0°, on the left, and at 90°, on the right.

For specimens with fibres aligned in the loading direction (0° specimens), the skin layer showed a micro-ductile damage, typical of the initiation and propagation phases, while in the core the appearance of the damage was typical of final rupture phase, i.e. it was micro-brittle. On the contrary, for specimens with fibres aligned transversally to the loading direction (90° specimens), a micro-ductile area, with a pronounced ductile aspect in the central part, was found in the core and a micro-brittle damage was visible on the remaining section, allowing to argue that fatigue damage initiated and propagated from the core. On specimen with fibre aligned at 60° the damage pattern was more complex, but a micro-ductile damage with a more pronounced ductile aspect was visible in the core area and large micro-brittle areas have been found in the shell layer. For 30° specimens a micro-ductile damage was diffused on the whole fracture surface.

6 CONCLUSIONS

The paper presents a TPM of off-axis tests performed on specimens extracted at different orientations from an injection moulded plate made of a Short Glass Fibre Reinforced Polyamide (PA6 GF30). The two main steps of the TPM, i.e. fibre orientation analysis and structural analysis, have been validated by means of experimental data. The results of this simulation process have been used for reanalysing previously obtained fatigue data on the basis of a local stress analysis. The following conclusions can be drawn:

- a TPM approach is necessary to capture, as an effect of the different fibre alignment directions of the specimens, the variation through specimen thickness of local stress levels present due to their typical shell-core-shell microstructure;
- in order to obtain accurate results, calibration with experimental data is of paramount importance in a TPM approach, both in fibre orientation analysis and in the structural simulation phase;
- a correlation between local stress levels through specimen thickness and the location of fatigue damage initiation can be found: in the case of 0°, 60° and 90° specimens the correlation through a local maximum stress criterions seems possible, while for 30° specimens the complexity of both the pattern of fatigue damage and local stress distributions makes this correlation more difficult.

- a local stress analysis, made possible by a TPM approach, coupled with the use of a suitable fatigue criterion seems to be promising for the definition of local fatigue strengths of SGFRPs.

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