Mechanical Characterization of Sheet Moulding Composites for the Automotive Industry

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Abstract: The mechanical properties of Sheet Moulding Composite (SMC) have been analyzed by means of static and fatigue tests in tension. SMCs show a substantial in-plane anisotropy either in terms of stiffness or strength. Fatigue data were modeled adopting a fatigue model with two parameters, represented by the cyclic number and the mean stress. The statistical implementation of such model was based on the hypothesis that the monotonic tensile strength follows a two-parameter Weibull distribution. The model has the potential to be predictive indicating that the fatigue characterization of a given laminate can be achieved with a minimum number of experimental tests. The reliability of such procedure and its applicability limits are discussed in the light of the model parameters obtained for different glass fiber reinforced composites.

INTRODUCTION

SMC represents a mixture of the subsequent components: polymer resin, fiber reinforcement, inert fillers, pigments, catalysts, release agents, stabilizers, and thickeners exactly as other thermosets. SMC is a composite material that is being used in several industrial applications; thanks to its aesthetic and mechanical properties it can be employed in the manufacturing of many components in a wide range of industrial fields: building constructions, electrical/electronics, transportation, aerospace, chemical engineering, and the marine industry. The chopped glass fibers, that compose SMC, have a length ranging from 25 to 50 mm put in a thermosetting resin matrix system. SMC is normally manufactured in a conveyor belt where it is processed to form a sandwich structure containing the chopped fibers, resin matrix, and functional fillers, unlike fiber reinforced thermoplastics such as fiber reinforced PP composites. Then a shape, at a temperature of 140-170 °C, is used to press the SMC for 1-10 minutes depending on the thickness and sizes of the panels. In this paper we analyze the mechanical properties of SMC panels used as low cost structural components in the automotive industry [1, 2].

SMCs have emerged as suitable engineering materials due to their attributes that are competitive with existing engineering materials, especially metals. The low weight and low cost together with mechanical characteristics allow to reach cost-efficient performances in many weight-critical applications in spite of a product cost impediments compared with traditional materials. However, composites require higher sampling for their characterization compared to metals, being multiphase and anisotropic materials. In particular SMCs may show a substantial in-plane anisotropy due to the prevalent alignment of the fibers along the direction of the conveyor belt. Thus, similarly to other thermosetting resins-based composites, the inherent structural in-plane anisotropy of SMCs may induce distortions of parts both when the chemical shrinkage phenomena occur during cross-linking reactions and when non symmetrical cooling gives rise to substantial residual stress accumulation upon the components that are released from the mould. For this reason the mechanical characterization was carried out by taking specimens oriented at different angles in respect to the direction of the conveyor belt. The SMCs under study may undergo a severe temperature variations since the SMC components are located adjacent the engine compartment. This general aspect has been already highlighted showing that the fatigue behaviour of polymer based materials is influenced by its viscoelastic nature [3-10]. For instance, in [10] it was shown that conditioning a sample in the vicinity of Tg, resulted in a residual stresses relaxation, leads to higher fatigue life compared to the materials as manufactured. In all, SMCs are very complex materials resulting from compounding of resin, fibers, and fillers. In service, the residual material strength as well as the component reliability is the result of the accumulation of a diffuse damage having different origin and location, rather than the propagation of a single crack as in metals. Thus, the damage mechanisms occur at different dimensional scales while the possible in-plane anisotropy makes different microstructural specimens features, leading to a different mechanical response that requires the mechanical characterization to be carefully performed on statistical basis. Concerning the fatigue behaviour the definition of reliable allowables, in terms of structural strength, represents one of the most difficult goal during the design phase of a component made of polymer composite

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because it is affected by a large scatter in mechanical properties [11-18]. The SMCs under study may be exposed in service to hostile conditions, e.g. service temperature, Tg near glass transition, cyclic loadings, or aggressive environments [15-26]. In particular the viscoelastic behaviour of the polymer matrix and its long-term behaviour can be altered by the vicinity of the glass transition temperature of the polymer itself [27-37].

The complex scenario described so far requires a very expensive and lengthy test campaign. This manuscript has the aim to provide a preliminary mechanical characterization of the material under study as the basis for the exploration of the thermo-mechanical issues. The static strength data are modeled on the basis of a two parameters Weibull distribution while for the fatigue data a model widely used in literature for glass fiber reinforced composite was adopted [9-12, 14]. Under fixed loading conditions, the number of cycles at which fatigue failure occurs can be predicted by such model. It is assumed that the residual strength undergoes a continuous decay, following a power law, for their damage law.

EXPERIMENTAL

The material under study consists of a compound of polyester resin, chopped glass fibers, and calcium carbonate with a nominal wt/wt ratio of 40:30:30, respectively. It is used as a structural components, at a low cost, in the automotive industry. However resin, fiber, and filler contents were checked by means of standard method DIN-EN-ISO-11667. The results on five different samples showed that the percentage wt/wt of resin, fiberglass, and filler was 39:27:34, respectively. Samples were cut from sheets with nominal thickness t = 2.5 mm. The static tests were performed with a Zwick-Roell® Z010 dynamometer equipped with load cell of 10 kN. The deformations were measured with a Zwick extensometer with a gage length of 25 mm. The data were processed with the Test Expert software by Zwick-Roell®. The crosshead speed was 3 mm/min, according to ASTM D5083. The fatigue data in tension were performed at a frequency of 5 Hz on a Instron® 8100 hydraulic machine.

RESULTS AND DISCUSSION

In Fig. (**1**) the results of static tests are reported. The relevant parameters are reported in Table **1** and expressed in terms of elastic modulus E, apparent yield stress σ_y, maximum stress σ_{max}, ultimate stress σ_b, deformation at maximum stress $\varepsilon(\sigma_{max})$, deformation at break ε_b, together with the average values and the standard deviation.

From Fig. (**1**) it appears that the elastic modulus and the strength are correlated, confirming that fibers are not randomly oriented. To verify such hypothesis in Fig. (**2**) the nominal yield stress is reported as function of the elastic modulus. In the same figure the broken line represents the theoretical value of the elastic modulus corresponding to the lower bound (namely, when the fibers are oriented orthogonally to the applied load) and to the case of fibers with random distribution. The same approach is adopted in Fig. (**3**) where the cumulative distribution function of the elastic modulus is reported according to the Weibull equation; the general expression is:

$$F(X \le P) = 1 - \exp\left(\frac{P}{b}\right)^k \tag{1}$$

where P is the generic property under study b is its characteristic value and k is a measure of the distribution spreading.
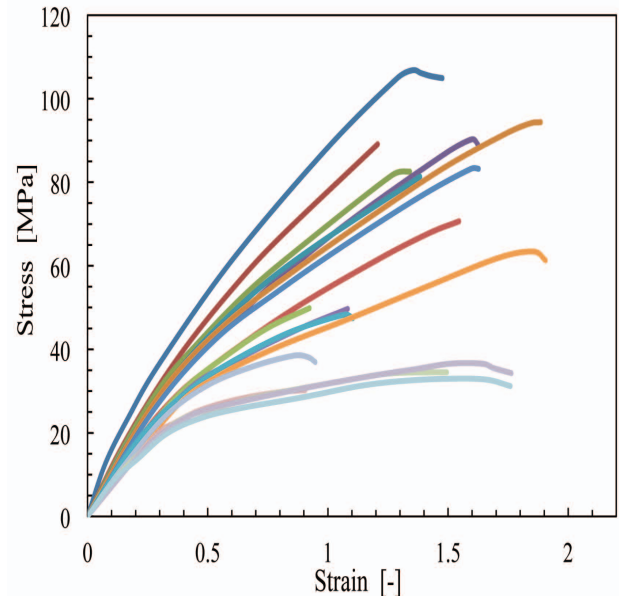

Fig. (1). Stress-strain curve at different sample orientation with respect to the conveyor belt direction. The crosshead speed is 3 mm/min and the extensometer gauge length is 25 mm.
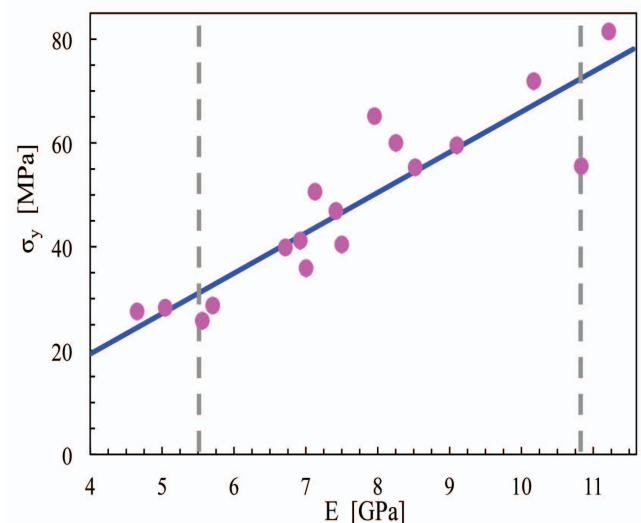

Fig. (2). The nominal yield stress σ_y, as function of the elastic modulus E. Symbols represent the experimental data. The continuous line is a linear regression between of data. The broken lines represent the lower bound modulus (left) and the modulus of randomly distributed fibers.

Figs. (**3**, **4**), where the distribution of σ_y is reported (please, notice that σ_y represents a substantial measure of the elastic limit) confirm that in most of the samples the elastic modulus is bounded between the lower bound and the value attained by the modulus in case of fibers randomly

Table 1. Summary of the results coming from stress-strain curves.

	E/GPa	σ_y/MPa	σ_{max}/MPa	$\varepsilon(\sigma_{max})$/%	σ_b/MPa	ε_b/MPa
	4.6	27.3	36.7	1.7	35.1	1.9
	5.0	28.0	34.9	1.6	33.7	1.6
	5.6	25.8	33.0	1.6	31.9	1.8
	5.7	28.5	30.3	0.9	30.1	1.0
	6.7	39.6	63.3	1.9	61.3	1.9
	6.9	41.0	49.6	1.1	49.6	1.1
	7.0	35.7	39.0	0.9	37.8	1.0
	7.1	50.4	70.5	1.6	69.1	1.6
	7.4	46.8	50.0	1.0	40.4	0.8
	7.5	40.3	48.6	1.1	45.6	1.1
	7.9	65.0	81.2	1.5	81.2	1.5
	8.2	59.8	94.3	1.9	94.3	1.9
	8.5	55.2	83.5	1.6	83.3	1.6
	9.1	59.4	90.0	1.6	89.1	1.6
	10.2	71.8	89.2	1.2	89.1	1.2
	10.8	55.5	82.5	1.4	82.5	1.4
	11.2	81.2	106.7	1.4	105.2	1.5
average	7.6	47.7	63.7	1.4	62.3	1.4
St. dev.	1.9	16.5	25.1	0.3	25.7	0.3

distributed. This is a clear manifestation of the in-plane anisotropy.
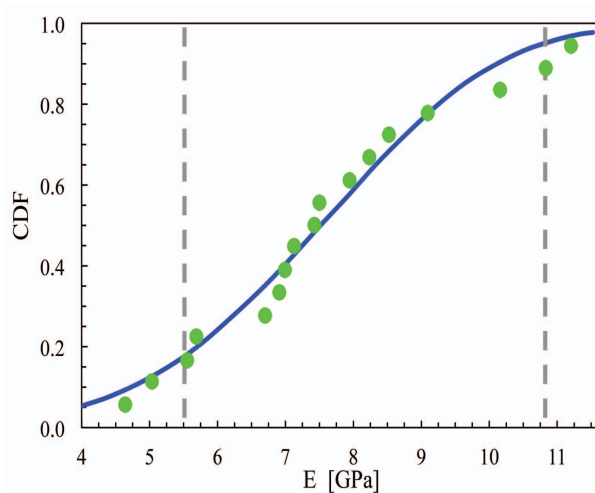

Fig. (3). Cumulative distribution function for the elastic modulus. Symbols represent the experimental data, continuous line the Weibull fit with b = 8.22054 and k = 4.07054. Broken lines, as defined in Fig. (**2**).

Looking again at Fig. (**1**), one can recognize three main responses having low, medium, and high modulus, respectively. Accordingly, the statistical analysis for these three distinct behaviours is reported in Figs. (**5-8**) for the elastic modulus, the elastic limit, and the stress at break.
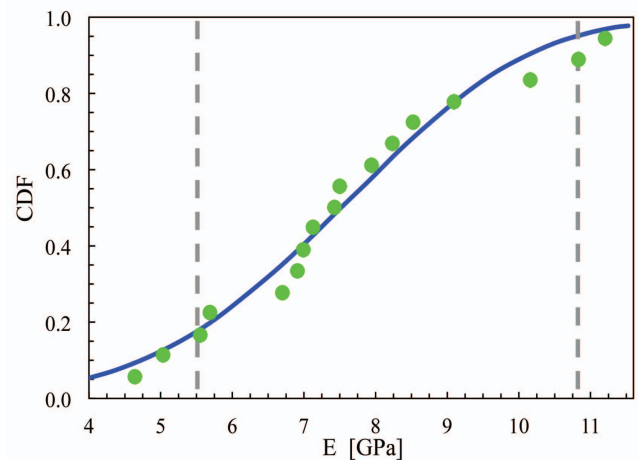

Fig. (4). Cumulative distribution function for the elastic limit, σ_y. Symbols: experimental data, the continuous line is the Weibull fit with b = 53.5554 and k = 2.72365.

The S-N cyclic fatigue data are reported in terms of the normalized maximum stress σ_{max}/σ_0, (σ_0 is the static material strength), the maximum cyclic stress, σ_{max}, or stress amplitude $\sigma_{max}-\sigma_{min}$, as a function of number of cycles to failure N. In this paper the value of the maximum stress is fixed with the cyclic load determined by the stress ratio
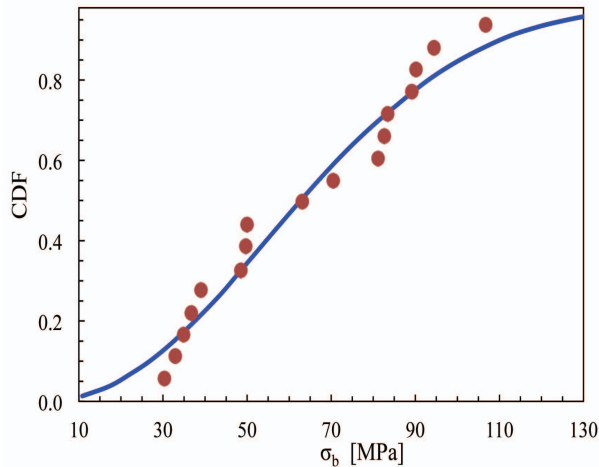
Fig. (5). Cumulative distribution function for the stress at break σ_b. Symbols: experimental data; continuous line: Weibull fit with $b = 73.5306$, $k = 2.16924$.
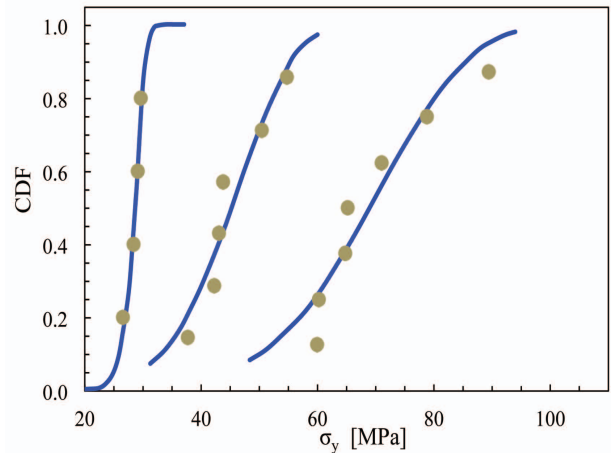

Fig. (6). Cumulative distribution of the elastic modulus. Symbols: experimental data; the continuous lines are the curve fitting with the Weibull distribution. The parameters of the distribution functions are (from left to the right): $b_1 = 28.0177$ and $k_1 = 21.2876$; $b_2 = 44.7353$ and $k_2 = 6.386$; $b_3 = 67.2306$ and $k_3 = 5.98318$.
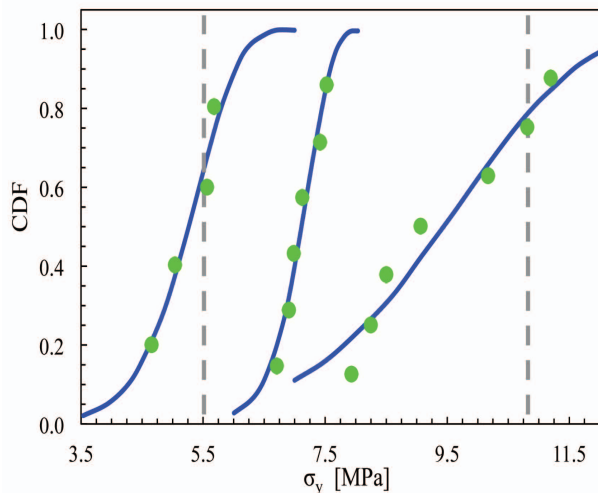
$R = \sigma_{min}/\sigma_{max} = 0.1$ (a loading condition commonly used for polymer composites) and then all the fatigue data are found for such fixed value. The maximum stress, σ_{max}, is chosen as a percentage of the characteristic strength $\sigma_{mean} = 53$ MPa. Cyclic loading was performed with a triangular waveform with the loading – unloading rate of 3 mm/min. Two loading conditions have been selected in terms of normalized maximum stress, namely $\sigma_{min}/\sigma_{max} = 0.8$ and $\sigma_{min}/\sigma_{max} = 0.7$. However, given σ_{max}, higher stress ratios, R, imply higher cycles to failure. Therefore to fit the experimental data we adopt a phenomenological analytic model appeared in literature that assumes R as the main variable [9-12, 14].

Furthermore, the concept of "strength–life equal rank assumption" is well established in polymer composites as it

Fig. (7). Cumulative distribution of the elastic limit σ_y. Symbols: experimental data; the continuous lines are the curve fitting with the Weibull distribution. The parameters of the distribution function are (from left to the right): $b_1 = 28.0177$ and $k_1 = 21.2876$; $b_2 = 44.7353$ and $k_2 = 6.386$; $b_3 = 67.2306$ and $k_3 = 5.98318$.
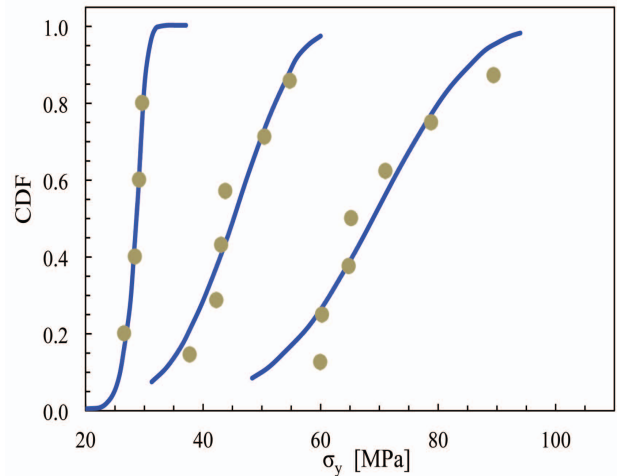

Fig. (8). Cumulative distribution of the stress at break σ_b. Symbols: experimental data; the continuous lines are the curve fitting with the Weibull distribution. The parameters of the distribution function are (from left to the right): $b_1 = 35.1212$, $k_1 = 10.5269$; $b_2 = 58.5418$, $k_2 = 3.78681$; $b_3 = 91.258$, $k_3 = 12.0063$.

reflects the fact that the dispersion of fatigue data is a mirror image of the dispersion of static strength data, provided a statistical ensemble of static and dynamic data are available.

The phenomenological model under study was used in different fiberglass reinforced composites with thermoplastic or thermosetting matrices. The model has the potential to be implemented statistically and assumes the following form [10]

$$\frac{\sigma_{max}}{\sigma_{mean}} = \left[\alpha\left(N^\beta - 1\right)(1 - R) + 1\right]^{-1} \tag{2}$$

where α and β are the model parameters, N is the number of cycles to failure, and R has been already defined. Finally, an

interesting form of the model is taken into account as it allows recovering the statistical strength of virgin samples subjected to fatigue loads.

$$\sigma_0 = \sigma_{0N} = \sigma_{max}\left[\alpha\left(N^\beta - 1\right)(1 - R) + 1\right] \qquad (3)$$

In Equation 3, from the fatigue data taken at different maximum stress can be deduced the distribution of the static strength, σ_{0N}, of the virgin material.

In Fig. (**9**) the fatigue data are reported. The data are obtained fixing the maximum stress to the mean strength ratio, $\sigma_{max}/\sigma_{0mean}$, where σ_{0mean} is the mean static strength obtained describing the static strength data with a two parameters Weibulll distribution. Then, given the loading ratio $R = \sigma_{min}/\sigma_{max}$, the stress amplitude $\Delta\sigma = \sigma_{max} - \sigma_{min}$ is fixed. In order to accelerate the response in fatigue two levels of maximum stress were adopted, such that $(\sigma_{max}/\sigma_{0mean}) = 0.8$ and 0.6. The experimental data are then elaborated by a best fitting procedure to obtain the parameters of Equation 2. To summarize, in Table **2** are reported the model parameters for the SMCs under study together with those found in literature on different fiberglass composites.

obviously. However the adopted theory [10] allows to recover such values directly from fatigue data, provided that α and β are reliable parameters. Thus, in principle, the distribution of the static strength coming from fatigue data, σ_{0N}, should superpose to the distribution of static strength data. In both cases a two parameters Weibull distribution can be adopted. The results of this procedure are illustrated in Fig. (**10**) and can be summarized as follows: the mean strength of the σ_{0N} distribution coming from dynamic tests is $\sigma_{0Nmean} = 57$ MPa while the static strength counterpart was $\sigma_{0mean} = 53$ MPa. Instead, the shape factors differ much more (see the numerical values of mean strength and shape factor of Table **2**), and this is a sign of the limited number of fatigue tests under study. To this end, we argue that the optimum number of fatigue tests to obtain reliable α and β parameters of Equation 2 is strictly linked to the shape factor of the Weibull distribution of the static strength. In fact, the superposition of static strength distribution, σ_0, to the strength distribution coming out from fatigue data, σ_{0N}, is readily obtained on materials showing narrower distribution of the static strength as shown in [10, 11, 14]. Nonetheless, the approach appears as a promising guideline to study the thermo-mechanical behaviour of SMCs, when deeper statistical analysis is needed.
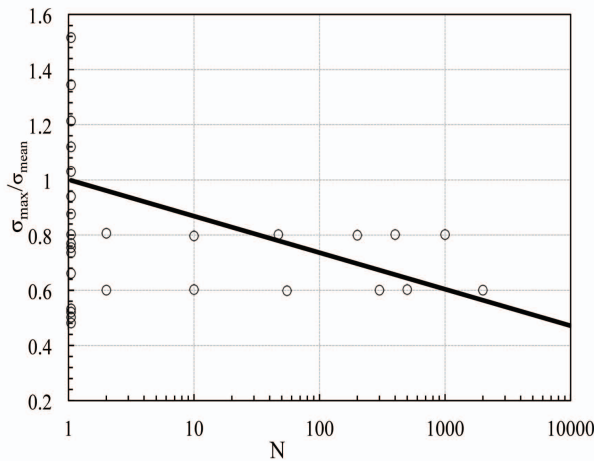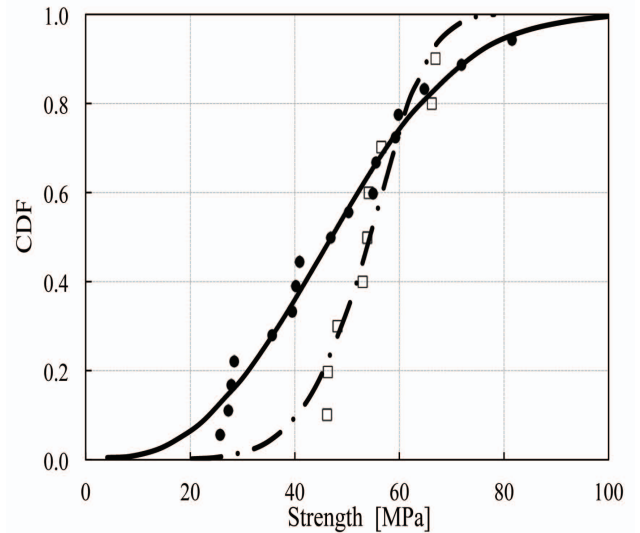

Fig. (9). The normalized maximum stress as function of cycle to rupture. The symbols represent the experimental data; continuous line: best fitting according to Equation 2.

Furthermore, using Equation 3 one can recover the static strength of samples tested in fatigue. This procedure is a way to test the reliability of the model parameters. The strength, σ_{0N}, of the virgin samples tested in fatigue are unknown,

Fig. (10). Statistical distribution of static strength σ_0 (filled symbol) and the calculated (according to Equation 3) monotonic strength, σ_{0N}, for SMC under study.

Table 2.   Comparison of fatigue and Weibull model parameters for different fiberglass reinforced composites.

Material	v_f	σ_R(MPa)	α	β	γ(MPa)	δ
TSC	0.35	290	0.353	0.150	298	20.31
SMC	0.22$_{(nom)}$	53	0.250	0.168	53.55	2.72
TPC	0.20	185	0.224	0.194	195	11.93
TPP	0.16	146	0.135	0.236	154	10.34

v_f: Volume fraction of glass fibers; σ_R:Average static strength; α, β: fatigue model parameters; γ: shape parameter of Weibull distribution of static strength; δ= mean value of Weibull distribution of static strength.
TSC= ThermoSetting Continuous fibers; SMC=Sheet Moulding Composite; TPC = ThermoPlastic Continuous fibers; TPP=ThermoPlastic Particulate-short fibers.

CONCLUSION

SMCs are very complex materials showing a substantial anisotropy due to the preferential orientation of chopped fibers along the conveyor belt. The selection of their properties at the design stage is not easy when a deep mechanical characterization is not considered. The fatigue behaviour of such materials is in line with the trend showed by other materials, namely it depends substantially on the volume fraction of fibers.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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