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PREDICTION OF ELASTIC PROPERTIES OF SOME SHEET MOLDING COMPOUNDS

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Abstract: *This paper presents an original approach to compute the longitudinal tensile break stress of multiphase composite materials with short fibers as reinforcement. The model is seen as consisting of three phase compounds: resin, filler and fibers, model that is reduced to two phase compounds: substitute matrix and fibers. The upper and lower limits of the homogenized coefficients for a 27% fibers volume fraction Sheet Molding Compound (SMC) are computed. It is presented a comparison between the upper and lower limits of the homogenized elastic coefficients of a SMC material and the experimental data.*
Keywords: *multiphase materials, Sheet Molding Compounds, homogenization, homogenized coefficients*

1. INTRODUCTION

A typical Sheet Molding Compound (SMC) material is composed of the following chemical compounds: calcium carbonate; chopped glass fibers rovings; unsaturated polyester resin; low-shrink additive; styrene; different additives; pigmented paste; release agent; magnesium oxide paste; organic peroxide; inhibitors. The matrix (resin) system play a significant role within a SMC, acting as compounds binder and being “embedded material” for the reinforcement. To decrease the shrinkage during the cure of a SMC prepreg, filler (calcium carbonate) have to be added in order to improve the flow capabilities and the uniform fibers transport in the mold. For the materials that contain many compounds, an authentic, general method of dimensioning is hard to find. In a succession of hypotheses, some authors tried to describe the elastic properties of SMCs based on ply models and on material compounds. The glass fibers represent the basic element of SMC prepreg reinforcement. The quantity and rovings’ orientation determine, in a decisive manner, the subsequent profile of the SMC structure’s properties. There are different grades of SMC prepregs: R-SMC (with randomly oriented reinforcement), D-SMC (with unidirectional orientation of the chopped fibers), C-SMC (with unidirectional oriented continuous fibers) and a combination between R-SMC and C-SMC, known as C/R-SMC. The following informations are essential for the development of any model to describe the composite materials behaviour: the thermo-elastic properties of every single compound and the volume fraction concentration of each compound. Theoretical researches regarding the behaviour of heterogeneous materials lead to the elaboration of some homogenization methods that try to replace a heterogeneous material with a homogeneous one. The aim is to obtain a computing model which takes into account the microstructure or the local heterogeneity of a material. The homogenization theory is a computing method to study the differential operators’ convergence with periodic coefficients. This method is indicated in the study of media with periodic structure like SMCs. The matrix and fillers elastic coefficients are very different but periodical in spatial variables. This periodicity or frequency is suitable to apply the homogenization theory to the study of heterogeneous materials [1-11].

2. TENSILE BEHAVIOR MODEL FOR A SHEET MOLDING COMPOUND MATERIAL

A SMC material can be regarded as a system of three basic compounds: resin, filler and reinforcement (fibers). We can consider the resin–filler system as a distinct phase compound called substitute matrix, so a SMC can be regarded as a two phase compound material (fig. 1). This substitute matrix presents the virtual volume fractions

V_r' for resin and V_f' for filler. These virtual volume fractions are connected to the real volume fractions V_r and V_f, through the relations:

$$V_r' = \frac{V_r}{V_r + V_f}; \quad V_f' = \frac{V_f}{V_r + V_f}, \tag{1}$$

so that $V_r' + V_f' = 1$.

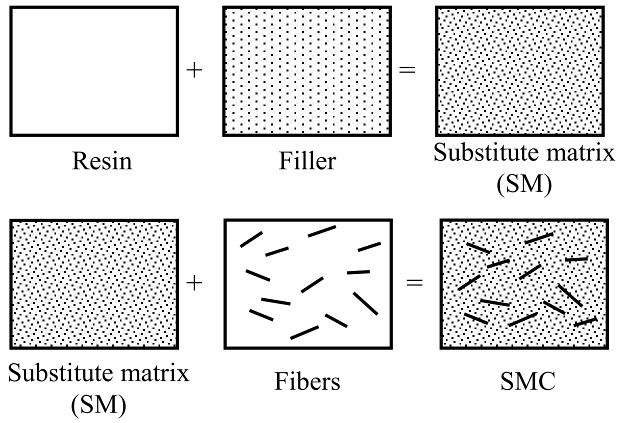

Figure 1: Schematic representation of resin-filler system

It is known that during the manufacturing process of a SMC, there is dependence between the production line speed and the fibers plane orientation on its advance direction. So, this material can be assumed to have the fibers oriented almost parallel to the production line of the SMC. Due to the longitudinal tensile loading, the SMC strain (ε_C) is identical with the substitute matrix strain (ε_{SM}) and fibers strain (ε_F), see fig. 2.

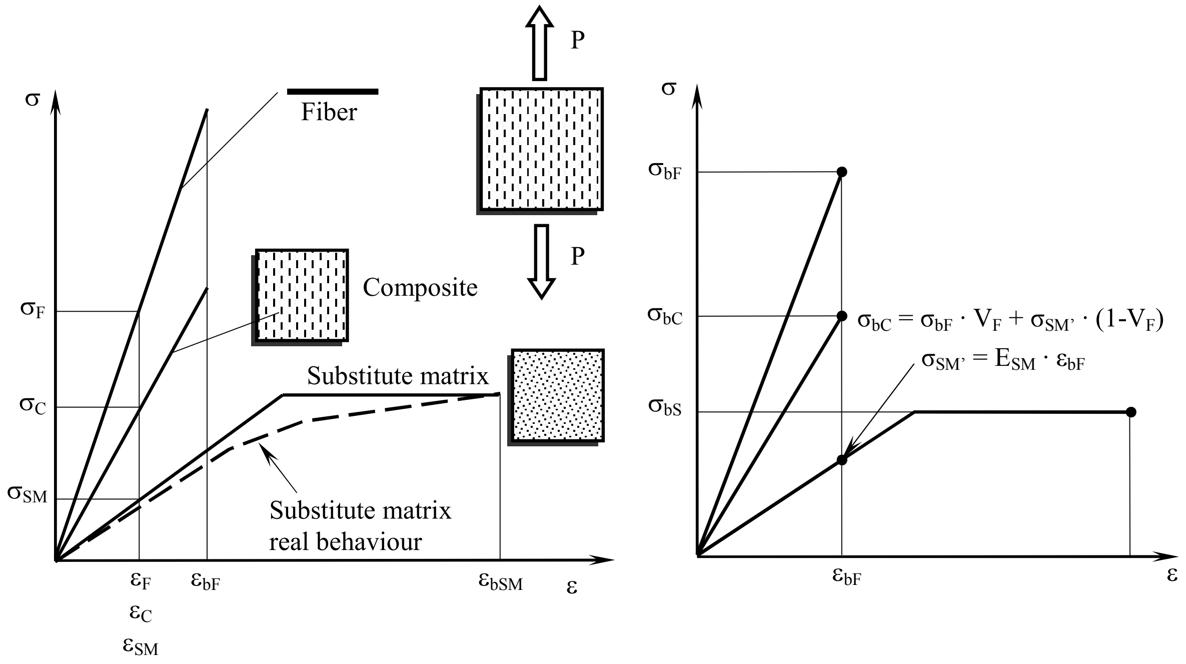

Figure 2: Schematic representation of stress-strain behaviour of a SMC material

Assuming the fact that both fibers and substitute matrix present an elastic linear behaviour, the respective longitudinal stresses are:

$$\sigma_F = E_F \cdot \varepsilon_F = E_F \cdot \varepsilon_C, \tag{2}$$

$$\sigma_{SM} = E_{SM} \cdot \varepsilon_{SM} = E_{SM} \cdot \varepsilon_C. \tag{3}$$

The tensile force applied to the entire composite is taken over by both fibers and substitute matrix [12]:

$$P = P_F + P_{SM} \tag{4}$$
or:

$$\sigma_C \cdot A_C = \sigma_F \cdot A_F + \sigma_{SM} \cdot A_{SM}, \quad \sigma_C = \sigma_F \cdot \frac{A_F}{A_C} + \sigma_{SM} \cdot \frac{A_{SM}}{A_C}, \tag{5}$$

where σ_C is the medium tensile stress in the composite, A_F is the net area of the fibers transverse surface, A_{SM} represents the net area of the substitute matrix transverse surface and $A_C = A_F + A_{SM}$. The ratio: $\frac{A_F}{A_C} = V_F$ is the fibers volume fraction and $\frac{A_{SM}}{A_C} = V_{SM} = 1 - V_F$ represents the substitute matrix volume fraction, so that (5) becomes:

$$\sigma_C = \sigma_F \cdot V_F + \sigma_{SM} \cdot (1 - V_F). \tag{6}$$

Taking into account (2) and (3) and dividing both terms of (6) through ε_C, the longitudinal elasticity modulus for the composite is:

$$E_C = E_F \cdot V_F + E_{SM} \cdot (1 - V_F). \tag{7}$$

Equation (7) shows that the value of the longitudinal elasticity modulus of the composite is situated between the values of the fibers and substitute matrix longitudinal elasticity moduli. In general, the fibers break strain is lower than the matrix break strain, so assuming that all fibers present the same strength, their break lead inevitable to the composite break. According to equation (6), the break strength at longitudinal tensile loads of a SMC material, is:

$$\sigma_{bC} = \sigma_{bF} \cdot V_F + \sigma_{SM'} \cdot (1 - V_F), \tag{8}$$

where σ_{bF} is the fibers break strength and $\sigma_{SM'}$ represents the substitute matrix stress at the moment when its strain reaches the fibers break strain ($\varepsilon_{SM} = \varepsilon_{bF}$). Assuming that the stress-strain behaviour of the substitute matrix is linear at the fibers break strain, (8) becomes:

$$\sigma_{bC} = \sigma_{bF} \cdot V_F + E_{SM} \cdot \varepsilon_{bF} \cdot (1 - V_F). \tag{9}$$

The estimation of the substitute matrix longitudinal elasticity modulus in case of a heterogeneous material like SMC, obtained by mixing some materials with well defined properties, depends both on the basic elastic properties of the isotropic compounds and the volume fraction of each compound. If we note down E_r the basic elastic property of the resin, E_f the basic elastic property of the filler, V_r the resin volume fraction and V_f the filler volume fraction, the substitute matrix longitudinal elasticity modulus can be estimated computing the harmonic media of the basic elastic properties of the isotropic compounds, as follows:

$$E_{SM} = \frac{2}{\frac{1}{E_r \cdot V_r} + \frac{1}{E_f \cdot V_f}}. \tag{10}$$

3. ELASTIC PROPERTIES OF SMC-R27 COMPOSITE MATERIAL

In the case of a SMC composite material which behaves macroscopically as a homogeneous elastic environment, is important the knowledge of the elastic coefficients. Unfortunately, a precise calculus of the homogenized coefficients can be achieved only in two cases: the one-dimensional case and the case in which the matrix- and inclusion coefficients are functions of only one variable. For a SMC material is preferable to estimate these homogenized coefficients between an upper and a lower limit. Since the fibers volume fraction of common SMCs is 27%, to lighten the calculus, an ellipsoidal inclusion of area 0.27 situated in a square of side 1 is considered. The plane problem will be considered and the homogenized coefficients will be 1 in matrix and 10 in the ellipsoidal inclusion. In fig. 3 the structure's periodicity cell of a SMC composite material is presented, where the fibers bundle is seen as an ellipsoidal inclusion. Let us consider the function $f(x_1, x_2) = 10$ in inclusion and 1 in matrix. To determine the upper and the lower limit of the homogenized coefficients, first the arithmetic mean as a function of x_2-axis followed by the harmonic mean as a function of x_1-axis must be computed. The lower limit is obtained computing first the harmonic mean as a function of x_1-axis and then the arithmetic mean as a function of x_2-axis. If we denote $\varphi(x_1)$ the arithmetic mean against x_2-axis of the function $f(x_1, x_2)$, it follows:

$$\varphi(x_1) = \int_{-0,5}^{0,5} f(x_1, x_2)\,dx_2 = 1, \; for \quad x_1 \in (-0{,}5;\ -0{,}45) \cup (0{,}45;\ 0{,}5), \tag{11}$$

$$\varphi(x_1) = \int_{-0,5}^{0,5} f(x_1, x_2)dx_2 = 1 + 9,45\sqrt{0,2025 - x_1^2}, \; for \quad x_1 \in (-0,45; \quad 0,45). \tag{12}$$

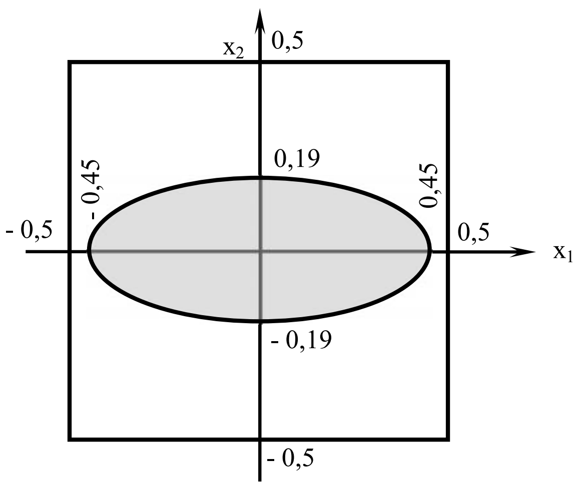

Figure 3: Structure's periodicity cell of a SMC material with 27% fibers volume fraction

The upper limit is obtained computing the harmonic mean of the function $\varphi(x_1)$:

$$a^+ = \frac{1}{\int_{-0,5}^{0,5} \frac{1}{\varphi(x_1)}dx_1} = \frac{1}{\int_{-0,5}^{-0,45} dx_1 + \int_{-0,45}^{0,45} \frac{dx_1}{1+9,45\sqrt{0,2025-x_1^2}} + \int_{0,45}^{0,5} dx_1}. \tag{13}$$

To compute the lower limit, we consider $\psi(x_2)$ the harmonic mean of the function $f(x_1, x_2)$ against x_1:

$$\psi(x_2) = \frac{1}{\int_{-0,5}^{0,5} \frac{1}{f(x_1, x_2)}dx_1} = 1, \; for \quad x_2 \in (-0,5; \quad -0,19) \cup (0,19; \quad 0,5), \tag{14}$$

$$\psi(x_2) = \frac{1}{\int_{-0,5}^{0,5} \frac{1}{f(x_1, x_2)}dx_1} = \frac{1}{1-3,42\sqrt{0,0361-x_2^2}}, \; for \quad x_2 \in (-0,19; \quad 0,19). \tag{15}$$

The lower limit will be given by the arithmetic mean of the function $\psi(x_2)$:

$$a_- = \int_{-0,5}^{0,5} \psi(x_2)dx_2 = \int_{-0,5}^{-0,19} dx_2 + \int_{-0,19}^{0,19} \frac{dx_2}{1-3,42\sqrt{0,0361-x_2^2}} + \int_{0,19}^{0,5} dx_2. \tag{16}$$

Since the ellipsoidal inclusion of the SMC structure may vary angular against the axes' centre, the upper and lower limits of the homogenized coefficients will vary as a function of the intersection points coordinates of the ellipses, with the axes x_1 and x_2 of the periodicity cell.

4. RESULTS

Typical elasticity properties of the SMC isotropic compounds and the composite structural features are: E_M=3.52 GPa; E_F=73 GPa; E_f=47.8 GPa; G_M=1.38 GPa; G_F=27.8 GPa; G_f=18.1 GPa; φ_M=30%; φ_F=27%; φ_f=43%. According to equations (10) and (7), the longitudinal elasticity moduli E_{SM} (for the substitute matrix) and E_C (for the entire composite) can be computed. A comparison between these moduli and experimental data is presented in fig. 4. In practice, due to technical reasons, the fraction of each isotropic compound is expressed as percent of weight, so that the dependence between volume- and weight fraction can be determined:

$$\varphi = \frac{1}{1+\frac{1-\psi}{\psi} \cdot \frac{\rho_F}{\rho_{SM}}}, \tag{17}$$

where φ and ψ are the volume respective the weight fraction, ρ_F as well as ρ_{SM} are the fibers- respective the substitute matrix density. From fig. 4, it can be noticed that the Young modulus for the entire composite is closer to the experimental value unlike the Young modulus for the substitute matrix. This means that the rule of mixture used in equation (7) give better results than the inverse rule of mixture presented in equation (10), in which the basic elastic property of the filler and the filler volume fraction can be replaced with fibers Young modulus and fibers volume fraction, appropriate for a good comparison.

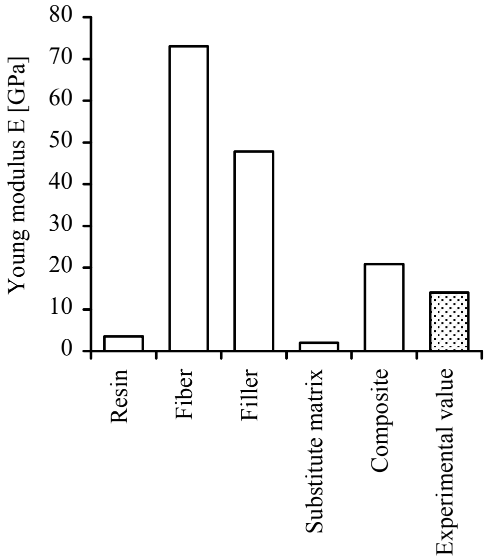

Figure 4: Young's moduli E_{SM} and E_C for a 27% fibers volume fraction SMC material

The material's coefficients estimation depends both on the basic elasticity properties of the isotropic compounds and the volume fraction of each compound. If we write P_M, the basic elasticity property of the matrix, P_F and P_f the basic elasticity property of the fibers respective of the filler, φ_M the matrix volume fraction, φ_F and φ_f the fibers- respective the filler volume fraction, then the upper limit of the homogenized coefficients can be estimated computing the arithmetic mean of these basic elasticity properties taking into account the volume fractions of the compounds:

$$A^{+} = \frac{P_M \cdot \varphi_M + P_F \cdot \varphi_F + P_f \cdot \varphi_f}{3}. \tag{18}$$

The lower limit of the homogenized elastic coefficients can be estimated computing the harmonic mean of the basic elasticity properties of the isotropic compounds:

$$A\_ = \frac{3}{\frac{1}{P_M \cdot \varphi_M} + \frac{1}{P_F \cdot \varphi_F} + \frac{1}{P_f \cdot \varphi_f}}, \tag{19}$$

where P and A can be the Young modulus respective the shear modulus. Fig. 5 shows the Young's moduli of the isotropic SMC compounds as well as the upper and lower limits of the homogenized elastic coefficients.

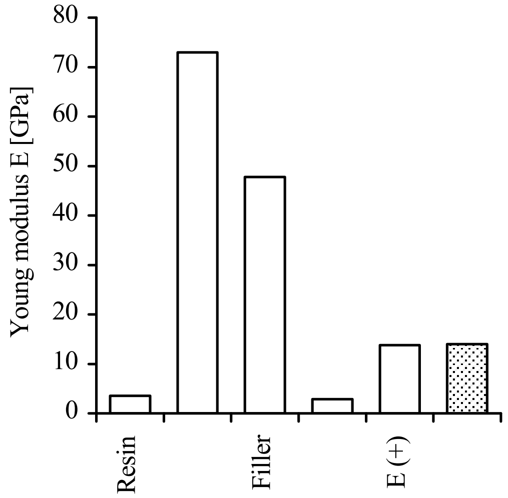

Figure 5: Young's moduli of the SMC compounds and the upper/lower limits of the homogenized coefficients

5. CONCLUSION

For the same fibers length (e.g. l_F = 4.75 mm) but with a shear stress 10 times greater at the fiber-matrix interface, it results an increase with 18% of the longitudinal break strength of the composite. Therefore, improving the bond between fibers and matrix by using a technology that increases the fibers adhesion to matrix, an increase of composite longitudinal break strength will be achieved. The computing model regarding the longitudinal tensile behaviour of multiphase composite materials like SMCs shows that the composite's Young modulus computed by help of rule of mixture is closer to experimental data than the inverse rule of mixture.

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