Modelling of Tensile Behaviour of Sheet Moulding Compounds

H. Teodorescu, S. Vlase, D. Cotoros, V. Munteanu and V. Guiman

***Abstract*— An original approach to compute the longitudinal tensile break stress of multiphase composite materials with short fibers reinforcement is presented. The most obvious mechanical model which reflects a multiphase composite material is a pre-impregnated material, known as prepreg. We may include in this class of prepregs, Sheet- and Bulk Moulding Compounds. 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 Sheet Moulding Compounds reinforced with discontinuous and almost parallel fibers, subjected to longitudinal tensile loads, presents a specific note by the existence of a shear mechanism between fibers and matrix. This shear mechanism transfers the tensile load through the fibers. The Young's moduli for the substitute matrix and for the entire composite are computed and a comparison between the theoretical approach and the experimental data is accomplished.**

***Index Terms*— Computing Model, Multiphase Composite Materials, Prepregs, Sheet Moulding Compounds.**

I. Introduction

The most obvious mechanical model which features a multiphase composite material is a pre-impregnated material, known as prepreg. In the wide range of prepregs there are the Sheet- and Bulk Moulding Compounds.

A Sheet Moulding Compound (SMC) is a pre-impregnated material, chemically thickened, manufactured as a continuous mat of chopped glass fibers, resin (known as matrix), filler and additives, from which blanks can be cut and placed into a press for hot press moulding. The result of this combination of chemical compounds is a heterogeneous, anisotropic composite material, reinforced with discontinuous reinforcement.

A typical SMC material is composed of the following chemical compounds: calcium carbonate (36.8% weight fraction); chopped glass fiber roving (30% weight fraction); unsaturated polyester resin (18.4% weight fraction); low-shrink additive (7.9% weight fraction); styrene (1.5% weight fraction); different additives (1.3% weight fraction); pigmented paste (1.3% weight fraction); release agent (1.2% weight fraction); magnesium oxide paste (1.1% weight fraction); organic peroxide (0.4% weight fraction); inhibitors (0.1% weight fraction). 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 following information are essential for the development of any model to describe the composite materials behaviour [1]: the thermo-elastic properties of every single compound and the volume fraction concentration of each compound.

II. The Longitudinal Tensile Behaviour Model of a SMC 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 the resin and $V_f^{'}$ for the filler. These virtual volume fractions are connected to the real volume fractions V_r and

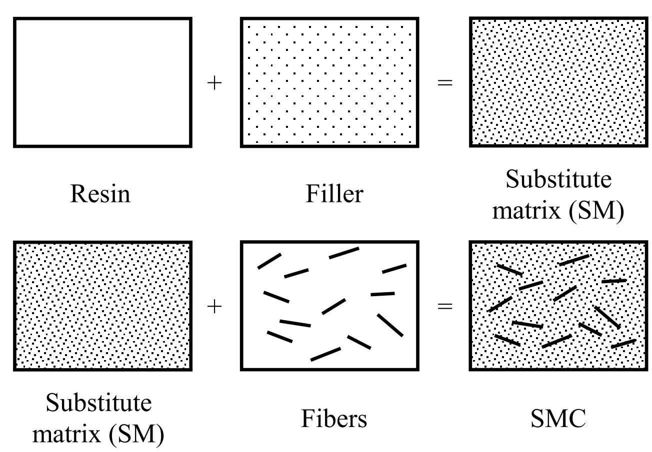

Fig.1

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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 $V_r^{'} + V_f^{'} = 1$.

It is known that during the manufacturing process of SMC, there is a 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. 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:

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

or:

$$\sigma_C \cdot A_C = \sigma_F \cdot A_F + \sigma_{SM} \cdot A_{SM},$$

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

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 $\frac{A_{SM}}{A_C} = V_{SM} = 1 - V_F$ is 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:

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

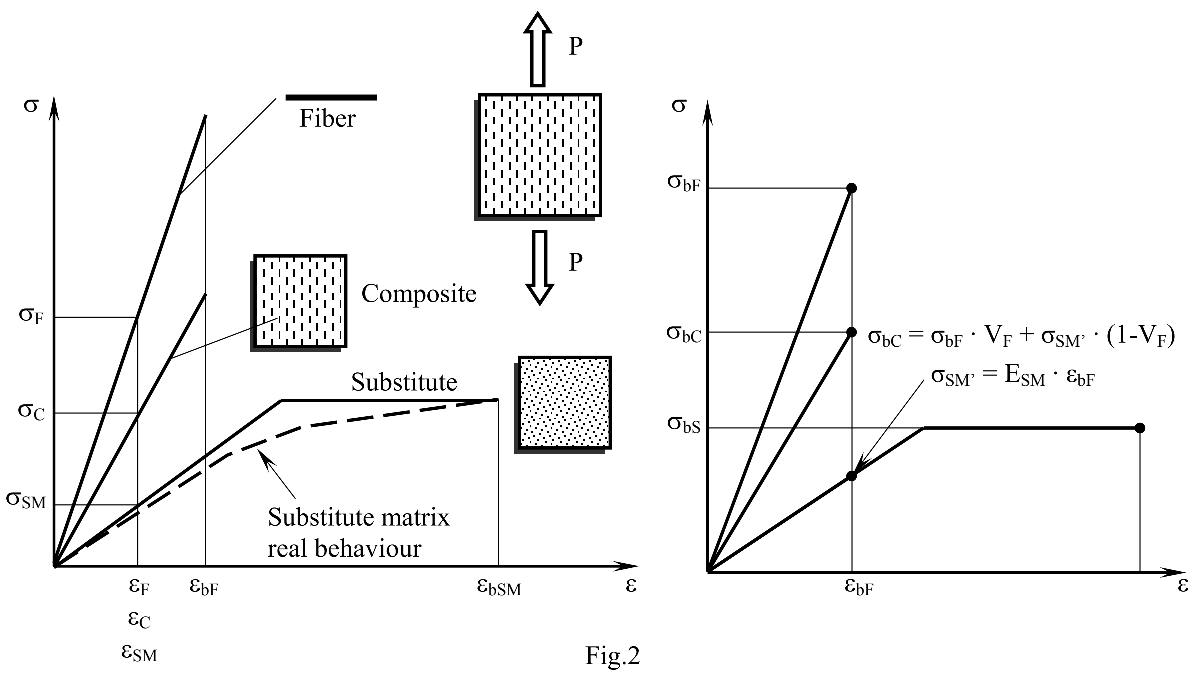

Fig.2

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

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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:

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

A SMC material reinforced with discontinuous almost parallel fibers, subjected to longitudinal tensile loads, presents a particularity by the existence of a shear mechanism between fibers and matrix, mechanism that transfer the tensile load to the fibers. Due to a difference between the substitute matrix longitudinal strain and the fibers strain, a shear stress along the fiber-substitute matrix interface occurs.

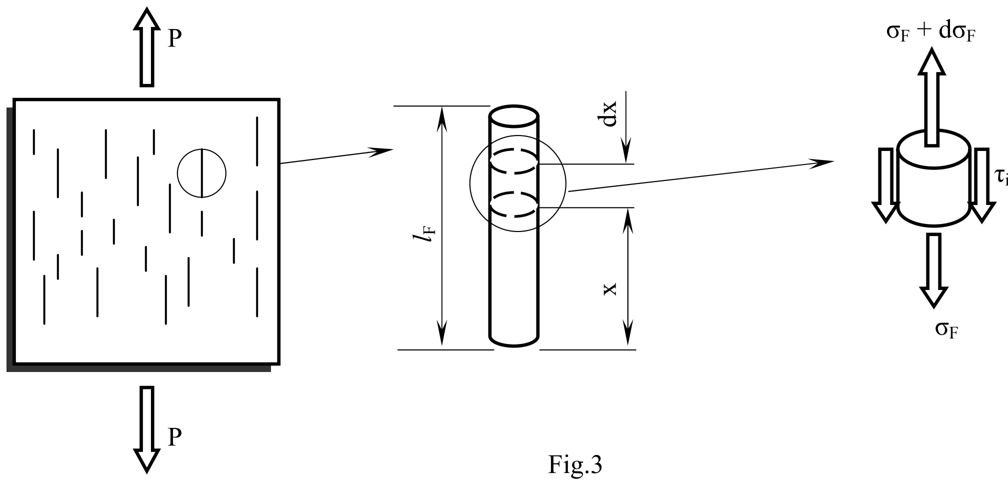

Fig.3

The normal stress distribution in a discontinuous fiber can be computed, considering an infinitely small portion dx at the distance x from one fiber end (fig. 3) [2]:

$$\left(\frac{\pi}{4} \cdot d_F^2\right) \cdot \left(\sigma_F + d\sigma_F\right) - \left(\frac{\pi}{4} \cdot d_F^2 \cdot \sigma_F\right) - \pi \cdot d_F \cdot dx \cdot \tau_i = 0 \quad (11)$$

or

$$\frac{d\sigma_F}{dx} = \frac{4\tau_i}{d_F}, \quad (12)$$

where: σ_F is the fiber longitudinal stress at the distance x from one of its end, d_F is the fiber diameter and τ_i represents the shear stress at the fiber-substitute matrix interface. Assuming τ_i constant, $\sigma_F = 0$ at the distance $x = 0$ and integrating (12), we get:

$$\sigma_F = \frac{4}{d_F} \cdot \int_0^x \tau_i \cdot dx = \frac{4\tau_i}{d_F} \cdot x. \quad (13)$$

The maximum fiber stress can be reached at a distance $x = \frac{l_T}{2}$ from both fiber ends, l_T being the load transfer length and represents the fiber minimum length in which fiber maximum stress is reached [2]:

$$\sigma_{\max F} = 2\tau_i \cdot \frac{l_T}{d_F}. \quad (14)$$

From (14) we may compute a critical fiber length for given d_F and τ_i:

$$l_{critical} = \frac{\sigma_{bF}}{2\tau_i} \cdot d_F. \quad (15)$$

Taking into account the normal stress distributions also near the fiber ends (for $x \langle \frac{l_T}{2}$) then a medium stress in fiber can be computed:

$$\underline{\sigma}_F = \frac{1}{l_F} \cdot \int_0^{l_F} \sigma_F \cdot dx, \quad (16)$$

or

$$\underline{\sigma}_F = \sigma_{\max F}\left(1 - \frac{l_T}{2 l_F}\right). \quad (17)$$

In the fiber length is greater than its critical length ($l_F > l_{critical}$), replacing $\sigma_{max\,F} = \sigma_{bF}$ and $l_T = l_{critical}$, the longitudinal break strength of a SMC material can be computed as follows:

$$\sigma_{bC} = \underline{\sigma}_{bF} \cdot V_F + \sigma_{SM'} \cdot (1 - V_F) = \sigma_{bF} \cdot \left(1 - \frac{l_{critical}}{2 l_F}\right) \cdot V_F + \sigma_{SM'} \cdot (1 - V_F). \quad (18)$$

III. RESULTS

Typical properties of the SMC compounds and the composite structural features are presented in table I.

Table I: Structural characteristics and typical properties of the SMC compounds

Property	Resin (Unsaturated Polyester)	Fiber (E-glass)	Filler ($CaCO_3$)
Elasticity	3.52	73	47.8

modulus E [GPa]			
Volume fraction [%]	61	18	21
Weight fraction [%]	41	27	32

According to (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 are presented in fig. 4.

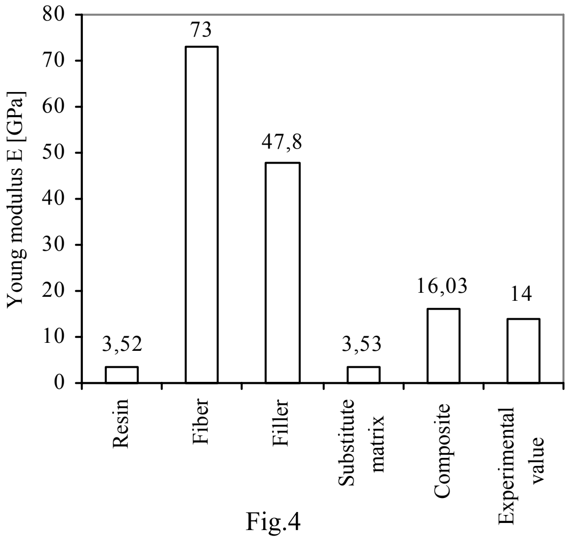

Fig.4

IV. CONCLUSIONS

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 the composite longitudinal break strength will be achieved.

In the case of using some fibers with greater lengths (e.g. l_F = 25,4 mm), the 10 times increase of the shear stress at the fiber-matrix interface, leads to an increase with only 3% of the composite longitudinal break strength. Two SMC composite materials with the same shear stress at the fiber-matrix interface (e.g. τ_i = 5 MPa) but with different fibers lengths, present different longitudinal break strength values, the composite with the fibers length l_F = 25,4 mm exhibit an increase with about 16% of this strength.

The computing model regarding the longitudinal tensile behaviour of multiphase composite materials like SMCs shows a very good agreement between the theoretical approach and experimental data.

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