BULETINUL Universității Petrol – Gaze din Ploiești	Vol. LX No. 2/2008	17 - 22	Seria Tehnică

Thermal Dilatation Anisotropy in Glass/Fibre Reinforced Polymer Composites

Gheorghe Ioniță, Adrian Catangiu, Dan Ungureanu

Universitatea Valahia din Târgoviște, B-dul Unirii, nr. 18, cod 130082, Romania
e-mail: danungureanu2002@yahoo.com

Abstract

The coefficients of thermal expansion, α, of uni-directional and bi-directional glass reinforced composites are reported for the temperature range 20-150°C. Composite thermal expansion is shown to be highly anisotropic. An analytical procedure to predict laminate coefficient of thermal expansion based on micromechanics lamination theory from the literature is also included. Finally, the experimental results have been compared with the values obtained by using the model. It is shown that calculated values of thermal expansion are in close agreement with those measured.

Introduction

For many application, a near-zero coefficient of thermal expansion is often highly desirable to obtain the thermal dimensional stability of a structure. The requirement of thermally stable structure has led to the selection of fibre-resin composite materials to achieve near-zero coefficient of thermal expansion. For carbon and Kevlar reinforced composite it is possible to obtain negative values but in case of glass reinforced composite these are positives and composite thermal expansion is highly anisotropic.

The coefficients of thermal expansions are strongly affected by the following factors:

- volume fraction of fibre;
- the lamina characteristics;
- stacking sequence;
- angle between measurement direction and the fibre direction.

The dependence coefficient of thermal expansion on fibre volume is illustrated in figure 1 for an unidirectional fibre reinforced composite.

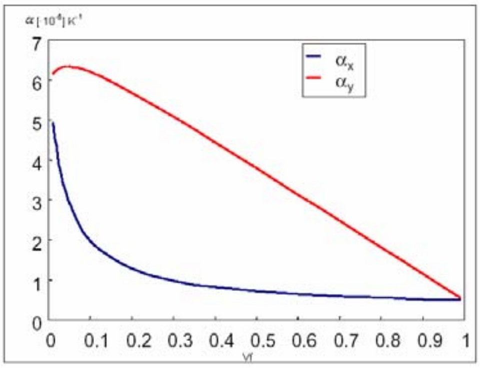

Fig. 1. Longitudinal and transversal coefficient of thermal expansion for a glass/epoxy composite [1]

As seen in figure 1, at approximately 50% fibre content, the longitudinal coefficient of thermal expansion is virtually unaffected by the change in laminate fibre content.

In return, lateral/transverse thermal coefficient of expansion is powerful induced by volume proportion of fibres.

Also, a great difference between the values of thermal coefficients of expansion lengthways the two directions has came out, which confirms marked anisotropy of thermal dilatation and influence of the fibres orientation on their coefficients.

In the case of stratifications from unidirectional lamina with the fibres oriented in diverse directions, the global thermal coefficient of expansion of material stratified is influenced by the contribution of each orientation.

Successful prediction of laminate thermal properties by the lamination theory is highly dependent on defining accurate mechanical and thermal properties of individual layers in a stratified composite material. In almost all cases this is accomplished by testing unidirectional laminates.

Mathematical modelling of thermal coefficient of expansion of a unidirectional varying with the volume proportion of fibres and the elastic characteristics of composite material are described by Schapery in [2] starting from the principle of the energy transformation induced by thermal expansion in the elastic energy and presented in most of specialty papers that deal with the characteristics of composite materials [3.4.5].

The total deformations induced in fibres and matrix are the result of strains σ_{fx}, σ_{mx} respectively and of the dimensional change due to the temperature difference. The x symbol infers the longitudinal direction of composite material (the fibres direction).

$$\varepsilon_{fx} = \frac{\sigma_{fx}}{E_f} + \alpha_f \Delta T \qquad \varepsilon_{mx} = \frac{\sigma_{mx}}{E_m} + \alpha_m \Delta T \quad , \tag{1}$$

where: ε_{fx} - longitudinal strain of fibre; ε_{mx} - longitudinal matrix strain; E_f - Young modulus of fibre; E_m - Young matrix modulus; α_f , α_m - coefficients of thermal expansion for fibre and matrix; ΔT - temperature variation.

It is thought the behaviour of composite material as being the one of a bulky body (the fibres deformation is equal to the matrix one):

$$\varepsilon_x = \varepsilon_{fx} = \varepsilon_{mx} \tag{2}$$

$$\sigma_{fx} \cdot V_f + \sigma_{mx} \cdot V_m = 0 \tag{3}$$

where V_f, V_m are the volume fraction of fibre and matrix in the composite

From the equality of deformation it results that:

$$\sigma_{mx} = \frac{(\alpha_f - \alpha_m)\Delta T}{\frac{1}{E_m} + \frac{V_m}{V_f}\frac{1}{E_f}} \tag{4}$$

Longitudinal strain became:

$$\varepsilon_{mx} = \varepsilon_{fx} = \left(\frac{\alpha_f E_f V_f + \alpha_m E_m V_m}{E_f V_f + E_m V_m} \right) \Delta T \tag{5}$$

and allows the inference of longitudinal thermal coefficient of expansion of lamina:

$$\alpha_l = \left(\frac{\alpha_f E_f V_f + \alpha_m E_m V_m}{E_f V_f + E_m V_m} \right) \tag{6}$$

For homogenizing of the linear thermal coefficient of expansion in transverse, it is thought that the transverse deformation of composite material is the sum of fibres deformation and of matrix weighted by their volume proportions (hypothesis of parallel system).

The y symbol means the direction perpendicularly to the fibres direction.

$$\varepsilon_y = \varepsilon_{fy} \cdot Vf + \varepsilon_{my} \cdot V_m \tag{7}$$

The transverse deformation is calculated starting from the longitudinal strains σ_{fx} and σ_{mx} as well as from the Poisson's numbers ν_{fx} and σ_{mx} of matrix fibres:

$$\varepsilon_y = \left(-\frac{\nu_m}{E_m}\sigma_{mx} + \alpha_m \Delta T \right) V_m + \left(-\frac{\nu_f}{E_f}\sigma_{fx} + \alpha_f \Delta T \right) V_f \tag{8}$$

$$\varepsilon_y = \left\{ \left(\alpha_f V_f + \alpha_m V_m \right) + \frac{\left(\nu_m E_f + \nu_f E_m \right)}{E_f V_f + E_m V_m} V_m V_f \left(\alpha_f - \alpha_m \right) \right\} \Delta T \tag{9}$$

$$\alpha_y = \alpha_f V_f + \alpha_m V_m + \frac{\left(\nu_m E_f - \nu_f E_m \right)}{\frac{E_m}{V_f} + \frac{E_f}{V_m}} \left(\alpha_f - \alpha_m \right) \tag{10}$$

Starting from the calculation relations presented previously, the thermal coefficients of expansion for two types of composite material that have in their constitution epoxy resin and E and R glass fibres have been calculated.

The elastic characteristics of constituent laminates of material stratified are taken over from the use book of semi impregnated materials [7].

Experimental

The measurement of the thermal coefficient of expansion of composite materials studied has been done using a SADAMEL dilatometer with the maximum heating temperature of 1500^0C (fig. 2). Measurements have comprised the temperature range 20-150^0C.

Fig. 2. Push-rod dilatometer

The dilatometer operates with linear variable differential transformers as a sensing element that is attached to a push-rod placed against an expanding sample in a furnace. Voltage is induced in the secondary winding of the transformer by the position of the axial core of the transducer. The signals in tension (proportional with thermal expansion and temperature) were recorded with a SEFRAM T2Y instrument.

The test bars have been sampled from two composite material plates made up of epoxy resin reinforced with 57% E glass, the one layered $[0/90]_s$ lengthways fibres (noted P10/90-0) and from a unidirectional with patterns formerly performed the transverse and longitudinal coefficients of thermal expansion.

Another test bar has been sampled uni-directionally from epoxy resin reinforced with 76.7% R glass fibres (noted T-0).

A test bar with fibres perpendicular oriented along the sampling direction can be carried out only if it initially we built a plate (raw material is roving).

It came out the stressed anisotropy of the material behaviour at the linear expansion. It also came out the high behaviour at the expansion of composite material reinforced with the R fibres due to the fact that the R fibres perform a lower coefficient of thermal expansion and the proportion of fibres longitudinally oriented is high.

Figures 3-5 present the expansion curves of the three test bars analysed, and table 1 centralizes the obtained data – the measurements characteristics made on composites of epoxy resin reinforced with the E and R glass fibres.

In the case of the tests done along the fibres direction, a coefficient of thermal expansion $4.6 \cdot 10^{-6}$ [K^{-1}] for the material reinforced with the R fibres has been obtained. This fact is also due to presence of resin into composite material (volume proportion of fibres 76.7%). Comparatively, a similar material made of epoxy resin reinforced with the R fibres from a unidirectional plate (it is not specified the fibres proportion) are performed from [7], the results of measurements done at ONERA Chantilon, that lent to the coefficient value of longitudinal linear expansion $4.7 \cdot 10^{-6}$ [K^{-1}], the transverse one $2.6 \cdot 10^{-5}$ [K^{-1}], respectively.

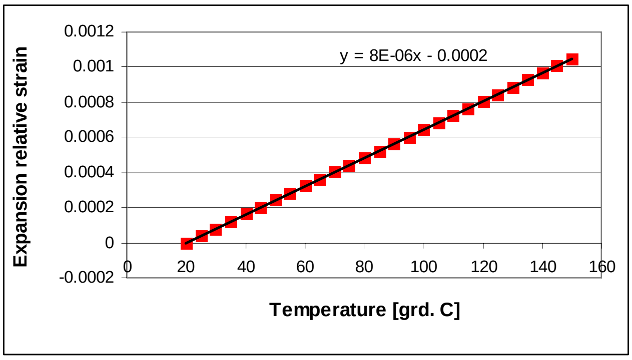

Fig. 3. Longitudinal coefficient of thermal expansion of a $[0/90]_s$ panel (57% vol. E fibre)

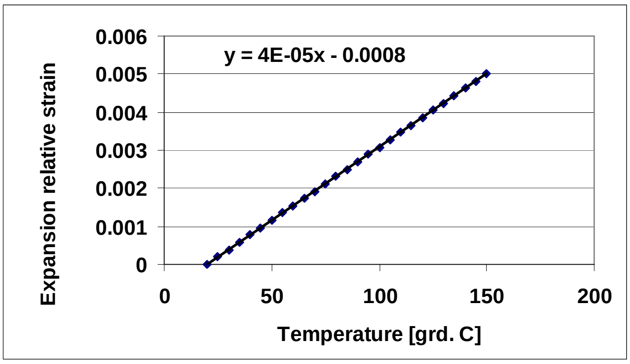

Fig. 4. Transversal coefficient of thermal expansion of an unidirectional panel (57% vol. E fibre)

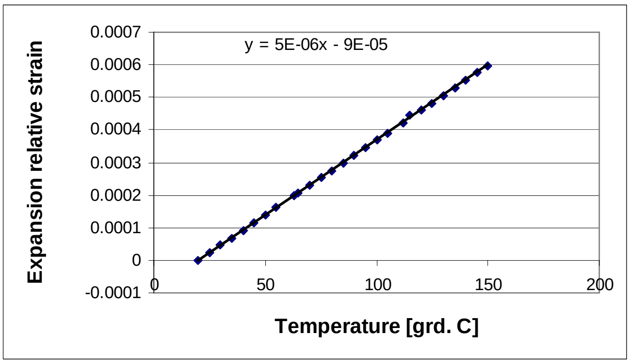

Fig. 5. Longitudinal coefficient of thermal expansion of an unidirectional (76,7% vol. R fiber)

Table 1. The coefficients of thermal expansion measured experimentally

Sample	**Fiber type**	**Fiber direction**	**Coefficient of thermal expansion[K^{-1}]**
Pl 0/90 -0	E	50% orientation 0^0 50% orientation 90^0	$8{,}06 \cdot 10^{-6}$
UD-90	E	orientation 90^0	$3{,}85 \cdot 10^{-5}$
T-0	R	orientation 0^0	$4{,}6 \cdot 10^{-6}$

In the case of the material sampled from composite with reinforcement from the F fibres, the difference between the value experimentally obtained by the producer $5.3 \cdot 10^{-6}$ [K^{-1}] (see table 2) is much greater (65%), due to on one hand of a total proportion of fibres in composite material smaller then in the case of the tubes (57% vol.), and on the other hand the fact that only half from the total proportion of fibres are longitudinally oriented as against the test bar axis.

As concerns the behaviour at the expansion of plate material on the transverse direction the one of fibres it is seen a meaningful influence of the matrix properties. The coefficient of linear thermal expansion along the direction of fibres (even if this orientation belongs only to a half from the total proportion) is almost four times smaller than the transverse one of thermal expansion. The value obtained for the transverse one of thermal expansion as against fibres, 3.85·10-5[K-1] is rough three times smaller than the one characteristic to unreinforced resin, 11 10-5 K-1 [8].

With the data supplied by the producer of glass fibres Saint Gobain Ventrotex [9] and the one of preimpregnated [8] listed in table 2, the transverse and longitudinal coefficients of thermal expansion have been calculated according to patterns formerly performed.

Table 2. Thermo-elastic characteristics of glass fibre and epoxy resin [8],[9]

Property	**Fibre direction**	**Value**
Coefficient of thermal expansion (R fibre) [K^{-1}]	longitudinal	$4 \cdot 10^{-6}$
Coefficient of thermal expansion (E fibre) [K^{-1}]	longitudinal	$5.3 \cdot 10^{-6}$
Coefficient of thermal expansion (epoxy) [K^{-1}]		$11 \cdot 10^{-5}$
Elastic modulus (R fibre)[GPa]	longitudinal	86
Elastic modulus (E fibre)[GPa]	longitudinal	72
Elastic modulus (epoxy resin)[GPa]		3.2

Due to un-knowledge of the Poisson's number neither for the glass fibres nor for the epoxy resin, the calculations have been done with the average value 0.28 supplied in [8] for an unidirectional epoxy glass composite material.

The transverse and longitudinal coefficients of thermal expansion for composite material from epoxy resin reinforced with the E and R fibres calculated according to the relations (6) and (10) with data listed in table 2 are included in table 3.

Table 3. The coefficients of thermal expansion calculated by model

Fiber type	**Fiber direction**	**Coefficient of thermal expansion[K^{-1}]**
E	longitudinal	$8,69 \cdot 10^{-6}$
E	transversal	$3,86 \cdot 10^{-5}$
R	longitudinal	$5.18 \cdot 10^{-6}$
R	transversal	$2.21 \cdot 10^{-5}$

It is shown that calculated values of thermal expansion are in close agreement with those measured.

References

1. http://www.mdi.espci.fr/~chateau/COURS/Composites/cont_residuells/cont_res.pdf
2. Schapery R.A. – Thermal expansion Coefficients of Composite Materials Based on Energy Principles, *Journal of Composite Materials*, vol. 2, p.380, 1968.
3. Jones, R.M. – *Mechanics of Composite Materials*. Taylor & Francis, Philadelphia, 1999.
4. Gay, D. – *Materiaux composites*, Hermes, Paris, 1997.
5. Berthelot J. M. – *Materiaux composites, Comportement mecanique et analyse des structures*. Ed. Masson, 1992.
6. Hadăr A. – *Structuri din compozite stratificate.* Ed. Academiei Române, Ed. AGIR, 2002.
7. Lazuardi D. – *Une approche du role des contraintes internes liees de l'elaboration sur le comportement des composites stratifies*, Ph.D. thesis nr.701. Université de Franche Comté, 1998.
8. *Prepreg technology.* Hexcel Corporation, January 2004.
9. http://www.vetrotextextiles.com/pdf/E_R_and_D_glass_properties.pdf

Anizotropia dilatării termice a compozitelor polimerice armate cu fibre de sticlă

Rezumat

Coeficienții de dilatare termică ai compozitelor unidirecționale şi bidirecționale armate cu fibre de sticlă au fost măsurați pentru domeniul de temperatură 20-150 ^{0}C. S-a remarcat anizotropia accentuată a dilatării termice a compozitului. Lucrarea cuprinde şi procedura analitică de estimare a coeficientului de dilatare termică, bazat pe teoria micromecanică, prezentată în literatura de specialitate. Valorile experimentale obținute au fost comparate cu cele calculate şi s-a constatat o bună concordanță între aestea.