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ANALYSIS OF THE NON-LINEAR MECHANICAL RESPONSE IN SHEAR OF WOVEN FABRIC REINFORCED COMPOSITE (Glass/Polymer matrix) UNDER MONOTONIC LOADING

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Résumé

Cet article présente l'analyse de la réponse mécanique non-linéaire d'un stratifié constitué de 12 plis de tissus de fibres de verre E / résine époxyde testé en traction uniaxiale jusqu'à la rupture à vitesse de déplacement imposée constante.

La non-linéarité du comportement mécanique en cisaillement observée lors de l'essai de traction uniaxiale des échantillons orientés à 45 degrés testés **"essai à ± 45°"** est de nature **"plastique"**.

La loi de décroissance exponentielle proposée du module de cisaillement tangent est de nature plastique et se réfère à l'écoulement de la matrice. Elle exprime l'évolution du module tangent de cisaillement en fonction de l'état mécanique traduit par la déformation de cisaillement.

Mots clés *: Comportement non-linéaire, cisaillement, composites tissus, matrice polymère.*

Abstract

This paper considers the analysis of the non-linear mechanical response of a laminate constituted of 12 layers of glass fiber/ epoxy resin tested in uniaxial tension until the failure at constant imposed displacement rates.

The non linearity observed of mechanical behaviour in shear under uniaxial tension for the specimens oriented at 45° tested **"test at 45°"** has **"plastic"** nature.

The law exponentiel proposed for the tangent shear modulus has plastic nature and refers to the plastic flow of the matrix. This model precises the evolution of the tangent shear modulus depending on the mechanical state characterized by the shear strain.

Keywords: *Non-linear behaviour, shear, woven fabric composites, polymer matrix.*

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ملخص

يهدف هذا العمل إلى دراسة الخصائص الميكانيكية للقص و تحليلها ، الخاصة بالمادة المركبة ، المصنوعة من عدة طبقات (12 طبقة) نسيجية ، مكونة من ألياف زجاجية و رابط عضوي بلاستيكي.

لقد أظهرت النتائج التجريبية أن السلوك الميكانيكي الغير الخطي المتحصل عليه خلال تجربة الشد الأحادي المحور بسرعة إزاحة مفروضة ثابتة على العينات ذات الإتجاه 45 درجة بأنه لدن (بلاستيكي) و هذا معناه أنه مرتبط أساسا بخصائص طبيعة المادة.

إن الدالة الأسية التنازلية المقترحة لمعامل القص الخاصة بسلوك المادة المركبة الممتحنة تأخذ بعين الإعتبار مدى تأثير الرطوبة على الخصائص الميكانيكية للقص للمادة (قيمة أو نسبة التشوه للقص).

الكلمات المفتاحية: *السلوك الميكانيكي الغير الخطي ، القص ، المواد المركبة النسيجية ، الروابط العضوية.*

The non-linear behaviour of the FRP laminates, which is clearly visible, e.g., $[\pm\theta]_{ns}$, has already been the topic of numerous papers. Different hypothesis have been proposed by various authors in order to explain the lamina behaviour, usually in plane stress conditions. Hahn [1] and Han and Tsai [2] have first proposed a non-linear elastic approach. They show that a development of the complementary energy up to the fourth order in stress and the assumption of a linear behaviour along and transverse to the fibers lead to a shear stress dependent shear compliance of the lamina. Nevertheless, theoretical predictions and experimental data are in poor agreement and no discussion is made about the thermodynamical reversibility underlying the "elastic" concept.

Hiel, Cardon and Brinson [3] have focussed on the non-linear viscoelastic properties of the resin matrix composites, but they recognised a "definite accumulation of unrecoverable permanent strain" during experimental testing, and suggested a plastic yielding of the matrix, following Foye [4,5] who had under taken a FEM analysis of that yielding around the fibers. It is worth mentioning that this analysis shows important coupling effects between normal and shear stress within the lamina.

Sun and Chen [6] developed a one-parameter plasticity model and introduced an equivalent stress and an equivalent strain, which they link together by a power type flow rule. Experimental agreement is very good, but until now limited to the little range of strains permitted by the off-axis tensile tests they conducted.

Finally we will mention an early and relevant paper by Rotem and Hashin [7] who consider a non-linear relationship between shear modulus and shear stress in the lamina. They use that model to analyse the failure conditions in various $[\pm\theta]_{ns}$ laminates. More recently, Amijima and Adachi [8] derived the response of such laminates by an incremental calculation involving a variation of the tangent shear modulus of the lamina with respect to the shear stress. The relationship between those two quantities are numererically derived from experiments conducted on $[\pm 45]_{2s}$ specimens.

In this paper, we will present an empirical plastic model which has been derived from an experimental work involving tensile tests on glass fiber fabric/epoxy resin $[\pm 45]_{3s}$ samples. We propose a behaviour for the lamina seen as an homogeneous anisotropic material. Although no assumption is made on the damage processes involved, it is demonstrated that the occurring non-linearities cannot be explained only by the viscoelastic properties of the resin.

MATERIAL AND MECHANICAL TEST

The material used was a laminate constituted of 12 layers of glass fiber/epoxy resin in one sequence $[\pm 45]_{3s}$. The $[\pm 45]_{3s}$ laminate was tested in off-axis configuration. Each sample (200 mm by 30 mm by 3,2 mm) was equiped with aluminum end-tabs and three-directional rosettes. All the samples were carefully conditioned : after prior total drying, the samples were exposed to various moist environments. A periodic weighing allowed to ensure that a physical equilibrium had been reached before testing. The test itself was performed in a temperature and moisture controlled environmental chamber. Both conditioning and testing were carried on at 60°C, value chosen to enhance matrix influence on the material behaviour. The test was a tensile loading up to failure at constant imposed displacement rates.

VISCOELASTIC HYPOTHESIS

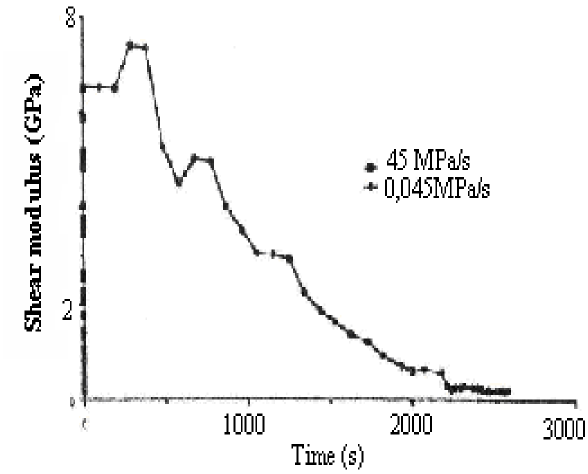
In the framework of linear viscoelasticity, i.e., assuming the linear superposition at time (t) of the mechanical responses to stress, the time-dependent stress-strain relationship.

In the case of a linear viscoelastic behaviour in shear only, the tangent shear modulus is given in terms of the shear creep function by:

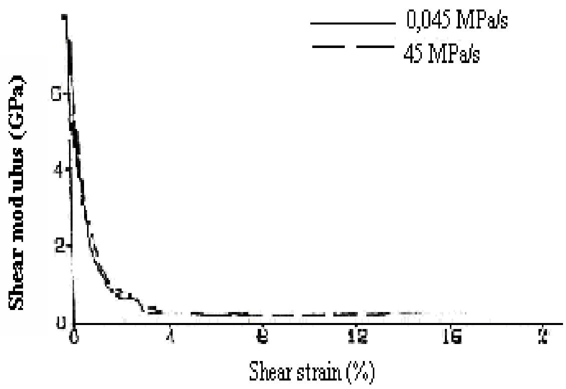
$$G(t) = [1/J_G(t)] \quad (1)$$

So, under the hypothesis of a linear viscoelastic behaviour, and in the case of a tensile loading at constant rate, the shear modulus evolution wih respect to time is rate- independent, as stated by (1).

In order to check the viscoelastic hypothesis validity, two tests were conducted on glass fiber fabric/epoxy resin $[\pm 45]_{3s}$ samples, with respective rates of 0.045 Mpa. S^{-1} and 45 Mpa.S^{-1}. Plots of the obtained shear moduli versus time are presented in Figure 1 and versus shear strain in Figure 2. It clearly turns out from Figure 1, where the two curves should have been identical (but experimental scatter), that ***viscoelasticity cannot be responsible*** for the non-linearities observed in the shear stress-shear strain response of those laminates. About Figure 2, it must be said that no definite conclusion can be driven from the fact that the initial values are the same for the two curves.



<u>Figure 1:</u> Evolution of the quasi-static shear modulus of a $[\pm 45]_{3s}$ specimen versus time for two different axial stress speeds : 0.045 Mpa. S^{-1} and 45 Mpa.S^{-1}.



<u>Figure 2:</u> Evolution of the quasi-static shear modulus of a $[\pm 45]_{3s}$ specimen versus shear strain for two different axial stress speeds : 0.045 Mpa. S^{-1} and 45 Mpa.S^{-1}.

Although time does not seem to be the most relevant parameter, from Figure 2 it appears that a representation versus the total shear strain is meaningful. Viscous effects are nevertheless clearly visible in Figure 2, but appear as a rate sensitivity traducing in a multiplying factor on the overall range.

We have dealt up to now with linear viscoelasticity, but it has been shown (Truesdell and Noll [9]) that any non-linear functional relating the stress history to the strain history could be expanded in a series of multiple order integrals, whose first term corresponds to linear viscoelasticity. In other words, any non-linear viscoelastic behaviour reduces to the linear one when the considered strains tend to zero. This fact has not only been theoretically demonstrated but experimentally assessed on the more tractable model usually referred to as the "Schapery model", where the different non-linearizing functions collapse to unity at low strains or stress (Brouwer [10]). As a consequence, the two curves in Figure 1 should have a common tangent near the origin. So, although viscoelastic effects are obviously present in the material response, viscoelasticity whether linear or not is unable to explain the gross non-linear response of polymer-based composites submitted to tests where the shear behaviour plays an important role.

MODELING

From the preceding study, it follows that it is reasonable to modelize the lamina (glass fiber fabric/epoxy resin) behaviour by a definite shear modulus-shear strain relationship. We will propose here the following exponential law:

$$\frac{G_6 - G_1}{G_{06} - G_1} = \exp\left(-\frac{\gamma_6}{\gamma_{06}}\right) \qquad (2)$$

The asymptotic value G_1 of expression (2) is not easy to immediately determine on experimental plots, due to its very nature. However, it can be assumed to fall within the range 0.1-0.2 GPa and will be determined with more sensitivity by fitting the computed laminate response to the experimental curves, as the sequel will show. Nevertheless, choosing any value in the range 0.1-0.2 GPa does not have a great influence on the values of G_{06} and γ_{06} obtained in plotting ln $(G_6 - G_1)$ versus γ_6. We will admit that the agreement is acceptable in first approximation between the proposed model and the experimental data. Table 1 summarizes of G_{06}, G_1 and γ_{06} derived from tests on $[\pm 45]_{3s}$ for various humidities.

Table 1: Results of the principal parameters of the model proposed.

Humidity	G_1	G_{06}	γ_{06}
0% RH	0,080	6,080	0,620
60% RH	0,180	5,550	0,550
90% RH	0,200	3,490	0,430

From the data in Table 1, two main features can be pointed out:

* The different methods used to determine the shear modulus correspond to different mechanical states of the laminae, and the evolution of the shear modulus governed by the value of γ_{06} depends on that mechanical state.

* Humidity both reduces the initial shear modulus, especially beyond 60% (the decrease from dry to 96% RH samples is 43%, and activates its decrease, with γ_{06} varying from 31% for $[\pm 45]_{3s}$). Thus, environmental conditions prove to have a prominent influence on the mechanical behaviour of epoxy-based composites.

The comparison between experimental and computed stress-strain responses of $[\pm 45]_{3s}$ are shown in Figure 3, where there is a good fit for all moisture contents.

CONCLUSION

Experimental results from laminate constituted of 12 layers of glass fiber/epoxy resin in one sequence $[\pm 45]_{3s}$ tensile tests have been presented. It was shown that viscoelasticity could not explain the non-linear behaviour observed. An expression was then proposed to modelize the lamina plastic response, consisting mainly in an experimental decrease of its shear modulus with increasing shear strain. Moisture effects are easily quantified in this approach and turn out to be of severe importance.

The model is a useful tool to investigate the evolution of the plane state of stress in the lamina.

The outcoming facts are that there is no threshold in the non-linear behaviour, and that matrix cracking and delamination do not seem to modify significantly the evolution of the tangent modulus of the layers.

We think that this evolution is inherent both to the composite nature of the material, and to its elaboration (curing), leading to an highly inhomogeneous state of stress, which may cause some early local plastic flows.

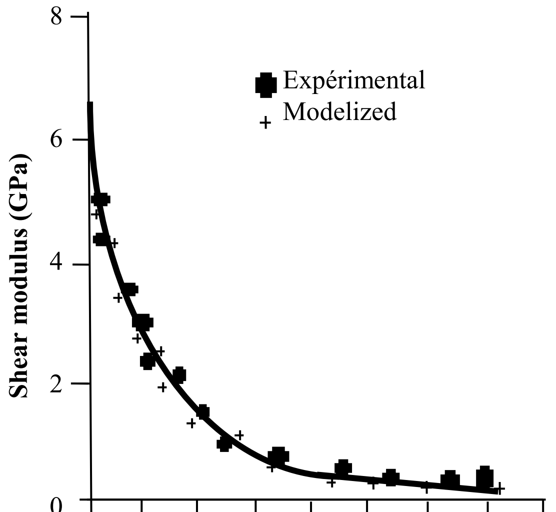


Figure 3: Comparison between experimental and modelized responses for $[\pm 45]_{3s}$ specimen.

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