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DESCRIBING THE STRESS RELAXATION BEHAVIOR OF PREPREG USING A FRACTIONAL-ORDER VISCOELASTIC MODEL

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ABSTRACT

Pressure plays a crucial role in shaping composite materials during hot-stamp molding and hot diaphragm forming processes. The unique properties of prepreg result in distinctive viscoelastic behavior under compression, where stress relaxation is a prominent phenomenon. This research introduces a novel parallel fractional-order viscoelastic model, incorporating two Scott-Blair elements, to characterize the stress relaxation patterns in prepreg materials during compression. In contrast to traditional models, this approach takes into account the force history experienced by the prepreg, providing a more accurate representation of its mechanical response. The model's efficacy is compared with other established models, demonstrating its capability to capture intricate stress relaxation behaviors. Importantly, the model requires fewer parameters and offers improved physical interpretability, making it advantageous for simulating and predicting the compression behavior of prepreg materials in various manufacturing processes.

1 INTRODUCTION

Carbon fiber-reinforced plastic (CFRP) plays a crucial role in diverse manufacturing sectors, such as aerospace, automotive, and sports industries, owing to its exceptional strength-to-weight ratio and customizable properties[1]. Composite material formation involves applying external forces to shape carbon fibers and resin into specific configurations, utilizing techniques like automated lay-up, hot press molding, hot diaphragm molding, and liquid composite molding. Prepregs find extensive use in aircraft manufacturing due to their stable quality and high molding efficiency, particularly for complex components like frames or stringers[2].

During preforming, improper molding parameters, particularly pressure, can lead to defects like wrinkles and fiber bending, compromising mechanical performance and product service life[3, 4]. Pressure is a critical factor, driving prepreg deformation during preforming and influencing inter-layer slip resistance. Elevated interlayer slip resistance can result in defects in the final product, emphasizing the need for a thorough understanding of prepreg mechanical behavior during compression for process optimization and ensuring structural integrity[5, 6].

Unidirectional prepreg materials, comprising resin and fibers, exhibit intricate stress responses under compression, characterized by significant stress relaxation behaviors. While the generalized Maxwell viscoelastic model is widely used, its complexity and ambiguous physical interpretations due to numerous parameters limit its effectiveness. Some researchers have explored fractional derivatives for stress relaxation, demonstrating higher accuracy and superior predictive capability, particularly in the early stages of stress relaxation[7].

This paper introduces the Parallel Fractional-Order Viscoelastic (PFOV) model for capturing the stress relaxation behavior of unidirectional prepreg during compression. Stress relaxation experiments on unidirectional prepreg materials validate the model, showcasing its effectiveness with a reduced number of parameters compared to the Maxwell model. This research contributes to the understanding of stress relaxation in unidirectional prepreg materials and offers a practical model for accurate description and prediction in manufacturing processes.

2 EXPERIMENTAL AND METHOD

2.1 Experimental

The material used is M21C unidirectional prepreg with a single-layer thickness of 0.187mm. Prepreg specimens (150*100mm) were prepared, stacked, and compressed using a fixture on a universal testing machine (ETM204C). Compression distance was set at 0.2mm, and stress relaxation behavior was tested for 3600s. Experimental conditions ensured uniform pressure and temperature. The applied force during compression is shown in Figure 1, with ε_0 representing strain and t_0 representing time during the compression experiment.

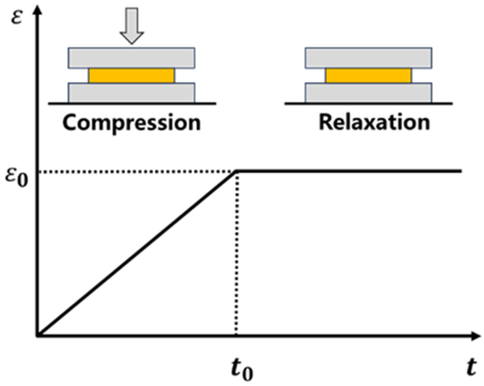

Figure 1 The force history of the prepreg during the experimental process.

2.2 Model Approach

The stress relaxation behavior of materials is commonly described using the Generalized Maxwell model. This model comprises an elastic unit and multiple Maxwell units connected in parallel. The expression for the Generalized Maxwell unit can be articulated using a Prony series:

$$(t) = E_0\varepsilon_0 + \sum_{i=1}^{n} E_i\varepsilon_0 \mathrm{e}^{-\frac{t-t_0}{\tau_i}} \tag{1}$$

But the Generalized Maxwell model's numerous parameters and ambiguous interpretations pose data processing challenges. Thus, the Scott-Blair fractional viscoelastic model is employed for clearer elucidation of relaxation behavior[8]:

$$\sigma(t) = c_\beta \frac{d^\beta \varepsilon(t)}{dt^\beta} \tag{2}$$

Here, β ($0 \leqslant \beta \leqslant 1$) signifies the fractional derivative order, indicating material viscoelasticity. c_β is the viscoelastic coefficient denoting material deformation resistance. Smaller β values imply behavior closer to an elastic solid, while larger β values indicate Newtonian fluid characteristics. For β = 0, Eq.2 represents a linear elastic model with c_β as the elastic modulus. For β = 1, Eq.2 represents a Newtonian fluid with c_β as the viscosity coefficient.

Despite the Scott-Blair model's concise depiction of viscoelastic behavior with fewer parameters, it inadequately captures the significant stress drop in the relaxation of unidirectional prepreg. This study employs a Parallel Fractional-Order Viscoelastic model (PFOV model), comprising parallel Scott-Blair elements, expressed as follows:

$$\sigma(t) = \sum_{i=1}^{n} c_{\beta_n} \frac{d^{\beta_n}\varepsilon(t)}{dt^{\beta_n}} \tag{3}$$

For an individual Scott-Blair element, employing the Caputo fractional derivative calculus definition provides:

$$\sigma(t) = \frac{c_\beta}{\Gamma(1-\beta)} \int_0^t (t-\tau)^{-\beta} \dot{\varepsilon}(\tau) d\tau \tag{4}$$

Here, $\Gamma(\cdot)$ represents the Euler gamma function. In the experiment illustrated in Figure 1, the prepreg undergoes compression initially, followed by stress relaxation behavior, leading to its strain evolution:

$$\varepsilon(t) = \begin{cases} \varepsilon_0 \dfrac{t}{t_0} & 0 \le t < t_0 \\ \varepsilon_0 & t > t_0 \end{cases} \tag{5}$$

By substituting Eq.5 into Eq.6, the stress expression for the Scott-Blair model during the stress relaxation phase in this experiment can be derived as follows[9]:

$$\sigma(t) = \frac{c_\beta \varepsilon_0}{\Gamma(2-\beta) t_0} \left[t^{1-\beta} - (t-t_0)^{1-\beta} \right] \tag{6}$$

So, the Parallel Fractional-Order Viscoelastic (PFOV) model with two parallel Scott-Blair elements is:

$$\sigma(t) = \sum_{i=1}^{2} \frac{c_{\beta_n} \varepsilon_0}{\Gamma(2-\beta_n) t_0} \left[t^{1-\beta_n} - (t-t_0)^{1-\beta_n} \right] \tag{7}$$

3 RESULTS AND DISCUSSION

Figure 2 displays fitting results for stress relaxation in a typical prepreg using the Scott-Blair model, PFOV model, and Maxwell model expressed with second and third-order Prony series. The graph indicates a sudden stress drop in the prepreg's initial relaxation stages, gradually diminishing over time. It's evident that a single Scott-Blair or a Maxwell element (second-order Prony series) cannot precisely capture the rapid initial stress drop observed in the relaxation experiment.

错误!未找到引用源。 illustrates the stress reduction ratio obtained from the fitting results of different models. The calculation formula for the reduction ratio is as follows:

$$Reduction\ ratio = \frac{\sigma(t)}{\sigma_{t_0}} \times 100\% \tag{8}$$

Where, $\sigma(t)$ denotes the compressive stress on the prepreg measured at a given moment, and σ_{t_0} is the compressive stress on the prepreg measured at the initiation of the experiment.

From the observations in Figure 3, it is evident that both the PFOV model and the Maxwell model, expressed with a third-order Prony series, closely align with the experimental stress reduction rate results. This alignment indicates the accurate representation of the stress relaxation behavior of the prepreg by these two models. In contrast, significant deviations from the actual situation are observed for the Scott-Blair model and the Maxwell model expressed with a second-order Prony series. These models fail to precisely capture the abrupt initial drop in prepreg stress. Consequently, in subsequent experiments, the PFOV model and the Maxwell model, expressed with a third-order Prony series, are selected for fitting the stress relaxation behavior of the prepreg, ensuring improved accuracy and reliability.

Figure 4A illustrates the relaxation behavior for samples with different layer counts, specifically 5, 10, and 15 layers. Figure 4B-D presents the fitting results of stress relaxation in the prepreg using two different models: the Maxwell model with third-order Prony series and the PFOV model. Table 1 presents the parameters for the fitting results of stress relaxation curves using the Maxwell model with third-order Prony series. These fits consistently exhibit a coefficient of determination (R^2) is 0.99. Table 2 provides the specific parameters for the fitting results of stress relaxation curves using the PFOV model. The R^2 for these fits consistently is 0.99. The fitting results demonstrate that both the Maxwell model and the PFOV model effectively capture the stress relaxation behavior of the prepreg. However, the description of stress relaxation behavior using a Maxwell model expressed with a third-order Prony series involves 7 parameters, whereas the PFOV model requires only 4 parameters.

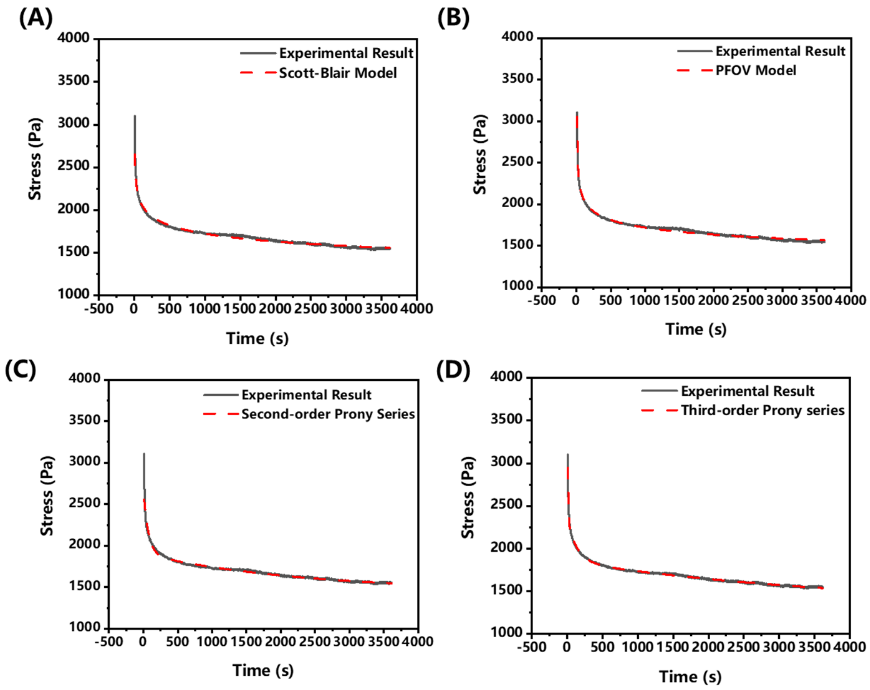

Figure 2 The fitting results of different models:(A) Scott-Blair model; (B) PFOV model; (C) Maxwell model expressed with a third-order Prony series; (D) Maxwell model expressed with a third-order Prony series

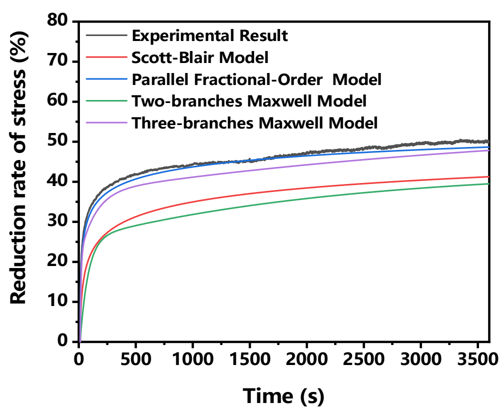

Figure 3 The reduction ratio of different models

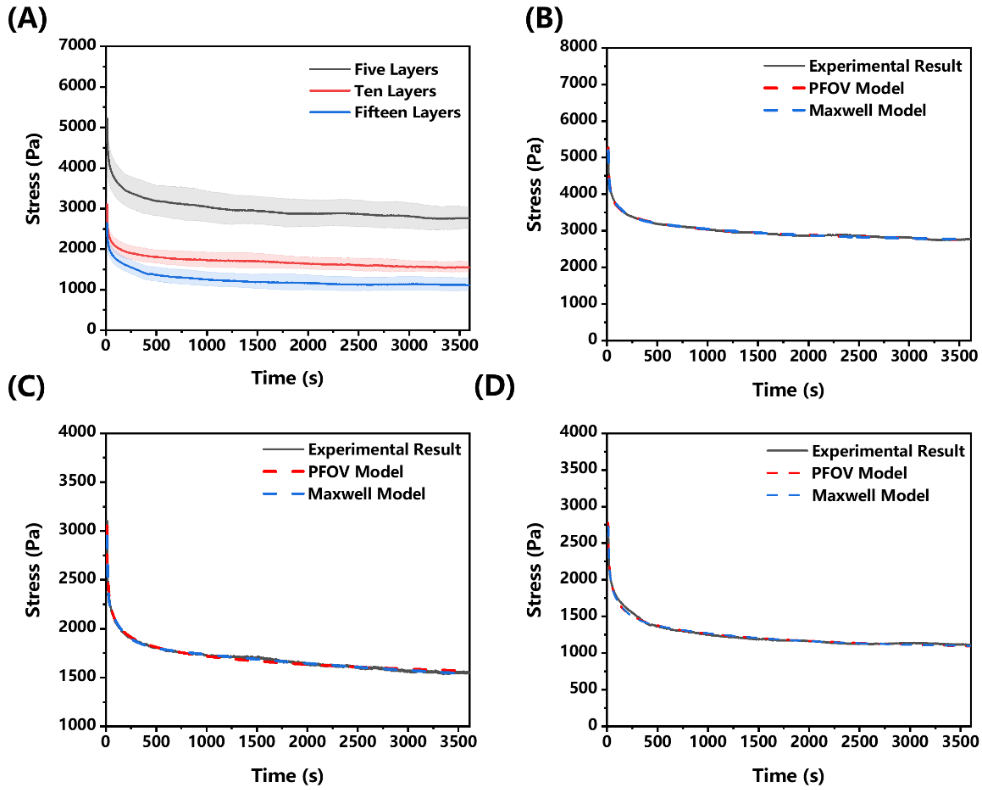

Figure 4 (A) Relaxation curves of samples at different number of prepreg layers (Shaded areas indicate measurement errors); (B) The theoretical fitting for the stress in the relaxation phase of prepreg with five layers; (C) The theoretical fitting for the stress in the relaxation phase of prepreg with ten layers; (D) The theoretical fitting for the stress in the relaxation phase of prepreg with fifteen layers

Table 1 The parameters of the maxwell model for different number of layers.

Number of layers	5	10	15
τ_1/s	8.13	5.52	10.84
τ_2/s	122.92	99.36	121.21
τ_3/s	1391.46	1204.24	1271.93
E_0/Pa	12943.63	14119.91	15343.08
E_1/Pa	5212.13	6324.519	10044.32
E_2/Pa	3418.24	3567.43	7419.53
E_3/Pa	3192.07	3574.05	6109.03
ε_0	0.21	0.11	0.07
t_0/s	12	12	12
R^2	0.99	0.99	0.99

Table 2 The parameters of the PFOV model for different number of layers.

Number of layers	5	10	15
β_1	0.05	0.07	0.12
β_2	0.30	0.57	0.62
$c_{\beta_1}/Pa \cdot s^{\beta}$	13278.99	26189.44	44719.67
$c_{\beta_2}/Pa \cdot s^{\beta}$	19553.60	16677.37	21737.57
t_0/s	12	12	12
ε_0	0.21	0.11	0.07
R^2	0.99	0.99	0.99

4 Conclusion

In summary, this study introduced a parallel fractional-order viscoelastic (PFOV) model with two Scott-Blair elements, investigating stress relaxation in unidirectional prepreg materials under compression. Results showed superior performance for the PFOV model ($R^2 = 0.99$). The study explored layer count effects on model parameters. PFOV, requiring fewer parameters than Maxwell, accurately represents viscoelastic behavior, making it well-suited for predicting compression behavior in manufacturing processes.

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