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VISCOELASTIC ENERGY DISSIPATION OF DEPLOYABLE COMPOSITE STRUCTURES

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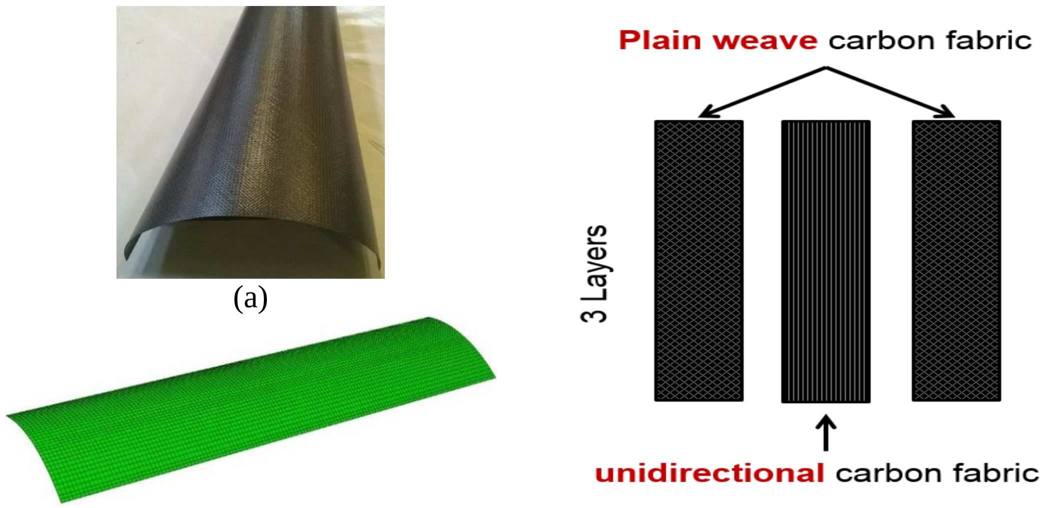
Summary: *Deployable aerospace structures made of fiber reinforced polymer (FRP) composites for space missions are of great interest to the aerospace community. The ability of folding and deploying these light weight composites without failure made them attractive materials for aerospace applications. A three-layer composite laminate tape spring made of (±45^o plain weave, 0^o unidirectional, and ±45^o plain weave) carbon fibers was recently suggested as an efficient deployment hinge. The rationale behind using the three-layer composite laminate is that during the stowage (i.e. storage) period, the first and third ±45^o plain weave lamina are subjected to pure shear stresses, and thus, their behavior will be dominated by the polymer matrix. Viscoelasticity of the polymer matrix can then be used to dissipate energy to control the deployment process. In this paper, time dependent implicit finite element analysis in ABAQUS is used to simulate the viscoelastic energy dissipation of a laminated composite tape spring. The challenge is related to modeling viscoelasticity of orthotropic materials. Most existing modeling techniques allow modeling viscoelasticity in isotropic but not orthotropic composite materials. We demonstrate the use of specifically designed user-defined material subroutine (UMAT) to model viscoelasticity of the composite tape spring. The suggested UMAT was first verified using stress-relaxation tension test data from literature. The verified FE model was then used to simulate viscoelastic energy dissipation in plain weave carbon fiber reinforced polymer (CFRP) lamina. The model prediction was validated experimentally. The proposed modeling approach can be extended to enable design of aerospace deployable composite structures for efficient deployment.*

1 INTRODUCTION

Fiber reinforced polymer (FRP) composites have been widely used in aerospace structures due to their high specific strength, specific stiffness, low cost, and flexibility in design. In addition, the ability of FRP composites to withstand relatively high strains without rupture made them attractive materials for deployable aerospace structures. In such structures, the FRP composite joint is stowed inside a compartment for a time period, launched to space, and is then depolyed in space to enable the use of accessories such as photovoltaic cells or mirrors. While the idea to replace the current metallic deployable aerospace structures with lightweight FRP alternatives is attractive, the process entails a considerbale challenge.

The challenge stems from the need to control energy storage and dissipation during the stowage/depolyment process. During the stowage process, the FRP joint will store a significant amount of strain energy. If the FRP composite is linear elastic, all of this stored energy will enact during deployment. It was observed that this deployment process takes place very abruptly such that most of the accessories attached to the FRP composite will be detached [1]. It was also well observed that the amount of stored energy is a function of the FRP composite behavior and whether it enables energy loss during stowage by means of viscoelasticity (i.e. creep and stress relaxation) or not [2]. To overcome this challenge a three-layer composite known as the tape spring (carpenter spring) was suggested [3].

The tape spring is a straight strip section of a cylindrical shell as shown in **Fig. 1 (a)**. Its moment–rotation behavior is linear elastic for small rotations and a constant moment for large rotations. Pollard and Murphey [4] suggested the FlexLam tape spring made of two (±45^o) plain weave external laminae and one unidirectional intermediate lamina to provide means of reducing the stored energy through viscoelasticity. In this tape spring, the first and third layer are made of plain weave carbon fiber lamina orientated at ±45^o with the longitudinal axis as shown in **Fig. 1(b)**. This arrangement allows these two layers to contribute to the tape spring viscoelasticity as their behavior is controlled by the matrix rather than the fibers (**Fig. 1(c)**). During stowage the two external layers are subjected to shear stresses. The middle layer is made of unidirectional carbon fiber lamina and is oriented at 0^o degrees to the longitudinal axis. Its response is governed by the fibers rather than matrix. The middle layer is responsible for restoring the tape spring position at deployment.



(b) (c)

Figure 1: The tape spring (a) rendering (b)example (c) carbon fiber laminae making tape spring

It is thus apparent that successful deployment of the tape spring requires designing composite material (fiber and matrix) such that the energy dissipation during stowage is controlled [5]. In other words, it is necessary to control the viscoelastic (i.e. stress relaxation) of the first and third composite lamina in the tape spring during the stowage time period. This requires careful selection/design of the matrix materials and the ability to simulate the viscoelastic behavior of the composite lamina and laminate. Parameters such as loading direction, type of polymer matrix, stress level, and environmental conditions, including moisture and temperature, affect viscoelasticity behavior of composite lamina. Daniali [6] examined creep of pultruded composites in flexure with two types of polymer matrix; polyester and vinylester. It was reported that the creep rate of polyester composites was almost twice that of the vinylester composites. Magid *et al*. [7] compared the flexure creep of the E-glass/polyurethane and E-glass epoxy composite systems. Although the two composites were similar in static behavior, their creep behaviors were significantly different. Loaded to 60% of their flexure strength, the polyurethane composite failed in a few hours while the epoxy composite survived for a few months. The effect of fiber orientation on creep compliance was also investigated by Gupta and Raghavan [8]. Plain weave carbon fabrics were tested in tensile creep with different fiber orientation. It was concluded that creep compliance increased with the increase in the angle of fiber orientation. This can be attributed to the increased role of the matrix as the angle of orientation increased. It was also shown that the stress level and the temperature had less effect on the on-axis creep test than off-axis creep. The time-temperature superposition principle (TTSP) was found useful to obtain master curves for different composites [8-10]. Furthermore, various tests were performed to investigate composite creep under tension [8-9], flexure [10], and compression [11]. Many of the above investigations proved that creep and stress relaxation of FRP composites are strongly governed by the polymer matrix rather than the fibers.

A considerable challenge in modeling viscoelasticity in composite laminates using the finite element model exists [12]. This is attributed to the fact that composite laminates are defined as an orthotropic material while models describing matrix viscoelasticity are typically isotropic. Combining these two types of material definitions in finite element modeling is challenging and requires special algorithms. In this paper a numerical model is developed for simulating viscoelastic behavior of laminated plain weave carbon fiber composites. A user-defined subroutine for ABAQUS, known as UMAT, is developed in order to implement viscoelastic material behavior of laminated composites. The developed subroutine is first verified using stress-relaxation tension tests of $\pm 45^{\circ}$ plain weave carbon fiber coupons and then is validated using experimental data.

2 VISCOELASTIC BEHAVIOR OF LAMINATED COMPOSITES

The effective viscoelastic response of a woven composite lamina consisting of elastic carbon fibers embedded in a viscoelastic epoxy matrix depends on factors such as the matrix relaxation moduli and weave geometry. In order to model viscoelastic behavior of a composite lamina made of a polymer matrix with bidirectional fibers, the *rule-of-mixtures* models [13] are used. The lamina-level elastic properties such as E_1, E_2, and G_{12} are expressed as functions of matrix and fiber properties as demonstrated by Eqs. (1)-(3).

$$E_1 = E_{1f}V_f + \ddot{E}_m\left(1 - V_f\right) \tag{1}$$

$$E_2 = \frac{\ddot{E}_m E_{2f}}{\left(1 - V_f\right)E_{2f} + V_f\ddot{E}_m} \tag{2}$$

$$G_{12} = \frac{\ddot{G}_m G_f}{(1 - V_f)G_f + V_f \ddot{G}_m} \tag{3}$$

$$G_f = \frac{E_{1f}}{2(1 + \nu_f)} \tag{4}$$

Where E_{1f} = E_{2f} =E_f is the modulus of the fiber, V_f is the fiber volume fraction, and G_f is the shear modulus of the fiber. In these equations $\ddot{E}_m$and $\ddot{G}_m$ are the time-dependent elastic and the shear modulus considering stress relaxation. For the present study, the Poission's ratio, ν_{12} is assumed to be constant and is given by Eq. (5) following the *rule-of-mixtures*:

$$\nu_{12} = (1 - V_f)\nu_m + V_f \nu_f \tag{5}$$

For time-dependent stress analysis, it is necessary to know the viscoelastic properties of the materials at any time instance. The material properties described in Eqs. (1)-(5) are provided by the material manufacturers. Creep or stress-relaxation of the matrix shall be determined experimentally is typically described by what is known as a Prony series [14]. The Prony series for relaxation bulk modulus $\ddot{E}_m(t)$ is described by:

$$\ddot{E}_m(t) = E_{m0}\left(1 - \sum_{k=1}^{1} k_k (1 - e^{-\frac{t}{\tau_k}})\right) \tag{6}$$

In Eq. (6) k_k and τ_k are Prony series coefficients, N are the number of series terms, and E_{m0} is the initial static modulus. The corresponding relaxation shear modulus may be found as:

$$\ddot{G}_m(t) = \frac{\ddot{E}_m}{2(1 + \nu_m)} \tag{7}$$

where ν_m is assumed to be constant. The stiffness matrix for two dimensional composite lamina may be given as:

$$\boldsymbol{K} = \begin{bmatrix} \frac{E_1^2}{E_1 - E_2\nu_{12}^2} & \frac{E_1E_2\nu_{12}}{E_1 - E_2\nu_{12}^2} & 0 \\ \frac{E_1E_2\nu_{12}}{E_1 - E_2\nu_{12}^2} & \frac{E_1E_2\nu_{12}}{E_1 - E_2\nu_{12}^2} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \tag{8}$$

The objective of developing the UMAT subroutine is to provide to the finite element solver in ABAQUS [15] an updated lamina stiffness matrix at each time instance such that the time-dependent viscoelastic behavior of the lamina is considered. Assuming the model implementation is strictly two-dimensional, the state of stress at the material principal coordinate system at a time instance is found following Hooke's Law:

$$\sigma_{11} = \varepsilon_{11}\frac{E_1^2}{E_1 - E_2\nu_{12}^2} + \varepsilon_{22}\frac{E_1E_2\nu_{12}}{E_1 - E_2\nu_{12}^2} \tag{9}$$

$$\sigma_{22} = \varepsilon_{11}\frac{E_1E_2\nu_{12}}{E_1 - E_2\nu_{12}^2} + \varepsilon_{22}\frac{E_1E_2}{E_1 - E_2\nu_{12}^2} \tag{10}$$

$$\tau_{12} = \gamma_{12}G_{12} \tag{11}$$

3 NUMERICAL METHODS

To simulate time-dependent behavior of a composite tape spring, the above *rule-of-mixtures* equations shall be implemented. While ABAQUS incorporates a composite module that includes the *rule-of-mixtures*, it would not allow time-dependent calculation under the composite module. The reason for that is composite laminae are defined as an orthotropic material in which an elastic matrix needs to be defined as an isotropic material [15]. To overcome this challenge, a user material subroutine (UMAT) shall be developed.

3.1 Viscoelasticity modeling using a UMAT Subroutine

The UMAT subroutine is programmed in FORTRAN to define the viscoelastic behavior of a lamina by implementing Eqs. (1)-(5) in a step-by-step in-time format. UMAT allows ABAQUS/Standard to implement general constitutive equations by the user. The subroutine UMAT may be used when none of the existing material models included in the ABAQUS material library accurately represents the behavior of the material to be modeled. The UMAT interfaces make it possible to define any (proprietary) constitutive model of arbitrary complexity to be combined with any type of structural element in ABAQUS. The overview of the model implementation in UMAT is shown in **Fig. 2**.

The inidividual properties of the fiber and the matrix are given as input in the material manager of the ABAQUS main solver. The UMAT subroutine then imports these material data from the ABAQUS main solver for further analysis to obatin the new state of stress. Using the *DSTRAN* utility subroutine, UMAT imports the strain components and the strain rates at each increment. The element stiffness matrix as described by Eq. (8) is provided to the ABAQUS main solver at each time instance by the UMAT subroutine.

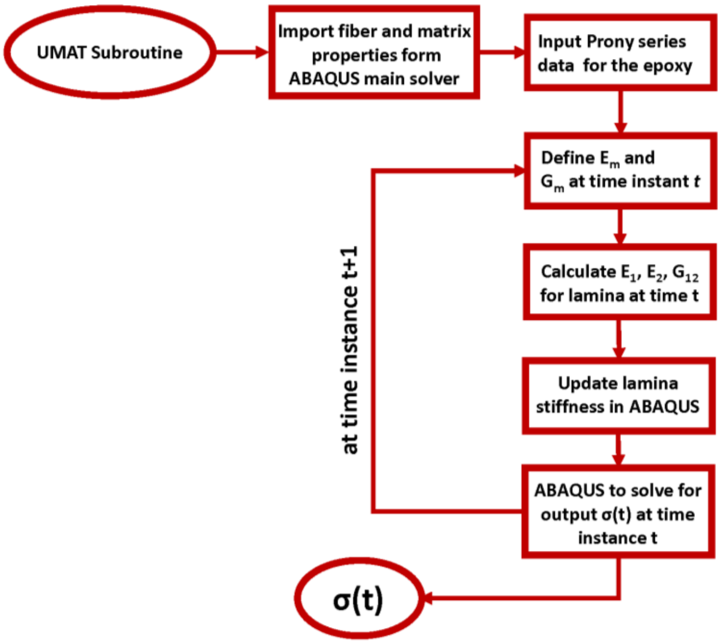


Figure 2: Overview of model implementation in UMAT subroutine in ABAQUS/Implicit.

3.2 Numerical Model Verification and Validation

To verify our proposed numerical model, we examined the model's ability to simulate the creep behavior of glass fiber lamina experimentally tested by Haj-Ali and Muliana [16]. In this work unidirectional fiber specimens are modeled at a 45^o off-axis under applied displacement. The elastic properties for glass and epoxy are given in Table 1. The Prony series of the used epoxy are reported in Table 2. **Fig. 3** shows the geometry of the specimen, which has a length of 152.4 mm, a width of 25.4 mm, and a thickness of 0.45 mm. The axial creep response over a time period of 1200 seconds as reported by Haj-Ali and Muliana [16] and as predicted by our proposed subroutine under ABAQUS are shown in **Fig. 4**. It is apparent that the proposed modeling approach is capable of simulating creep behavior of FRP composites in a very reasonable fashion.

	E, GPa	ν
Glass Fiber	72.40	0.22
Epoxy Matrix	4.30	0.31

Table 1: Elastic properties for glass fiber and epoxy matrix

k	Value	τ	Value
k_1	$1.0668 \, x \, 10^{-4}$	τ_1	1
k_2	$4.7753 \, x \, 10^{-5}$	τ_2	10
k_3	$4.5779 \, x \, 10^{-5}$	τ_3	100
k_4	$3.5024 \, x \, 10^{-5}$	τ_4	1000
k_5	$1.2708 \, x \, 10^{-4}$	τ_5	10000
k_6	$8.0192 \, x \, 10^{-5}$	τ_6	100000

Table 2: Calibration Prony series coefficients for the epoxy matrix from Ref. [16]

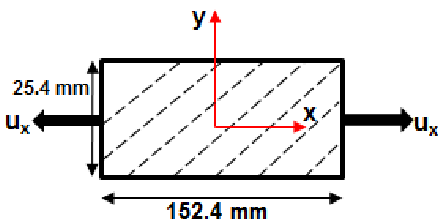


Figure 3: Off-axis unidirectional tension specimen from Ref. [16]

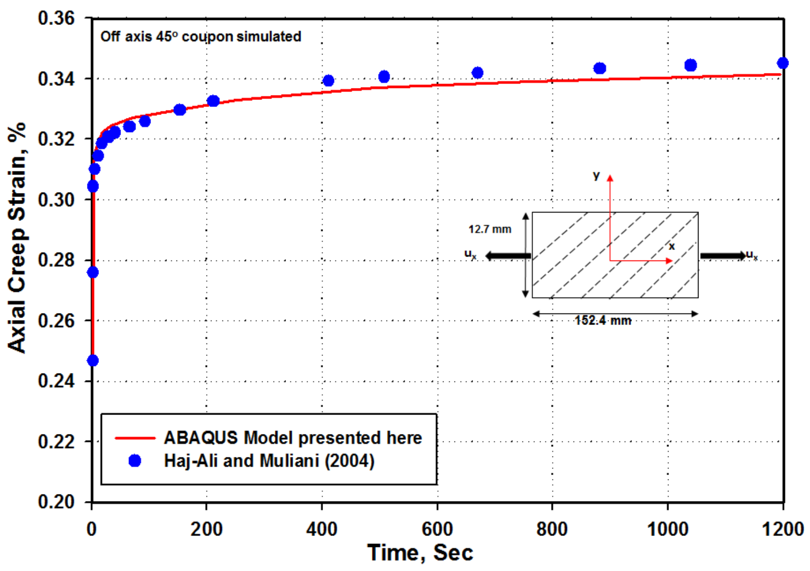


Figure 4:Experimental versus modeled axial creep strain for 45° off-axis coupon.

The finite element model using the proposed UMAT was then validated against experimental data for the plain weave lamina used to produced the tape spring. The properties of the plain weave lamina fiber and matrix are provided in Table 3 and Table 4. The ±45° plain weave lamina with the off-axis loading are shown schematically in **Fig. 5.**

	E, GPa	**ν**
IM7 GP-6k plain weave carbon fabric (each direction)	229	0.239
GP-6k Epoxy Matrix	3.3	0.35

Table 3: Elastic properties for carbon fiber and matrix used for numerical simulation.

k	Value	τ	Value
k_1	$5.0361 \, x \, 10^{-2}$	τ_1	10
k_2	$5.0011 \, x \, 10^{-3}$	τ_2	1000
k_3	$8.6650 \, x \, 10^{-3}$	τ_3	10000
k_4	$3.5024 \, x \, 10^{-5}$	τ_4	1000000
k_5	$1.2708 \, x \, 10^{-4}$	τ_5	10000000

Table 4: Prony series coefficients used in simulation

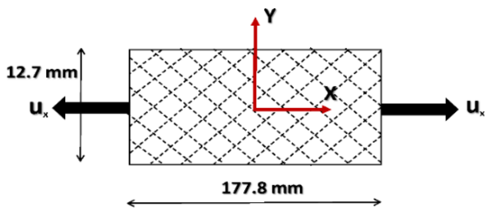


Figure 5: Off-axis plain weave tape spring carbon fiber lamina simulated

4 EXPERIMENTAL METHODS

Patz IM7 GP-6k plain weave carbon fiber fabric preimpregnated with GP2-61-2 resin was used to fabricate two-layer plates cured in a Stahl's Hotronix heat press. The curing process consisted of one hour at 49°C under 0.138 MPa followed by 3 hours at 177°C under 0.552 MPa. The plate was cut into coupons that were 177.8 mm long and 12.7 mm wide with the fibers running at ±45° to the loading direction. Static off-axis tension tests were performed in accordance with ASTM D 3518/D 3518M-94 using an MTS Bionix servo-hydraulic machine as shown in **Fig. 6.** The displacement control was set at a crosshead rate of 1 mm/minute. The specimens were equipped with an extensometer to measure axial strain during testing. In addition to an extensometer for measuring axial strain, axial strain gauges were also used to ensure accuracy. The force *F*, axial displacement δ, and axial strain γ, were recorded during testing. Shear stress τ was calculated as:

$$\tau = \frac{F}{2A} \tag{12}$$

where *A* is the cross-sectional area of the specimen. The shear modulus G_{12} was calculated as:

$$G_{12} = \frac{\tau}{\gamma} \tag{13}$$

Once an axial displacement of 3 mm was reach, the crosshead displacement was stopped and the specimen was held in place for 30 minutes. The stress-relxation test was conducted at a maximum strain of 1.5% representing 60-70% of the ultimate strain of the carbon fiber lamina as determined from static off-axis tension tests to failure.

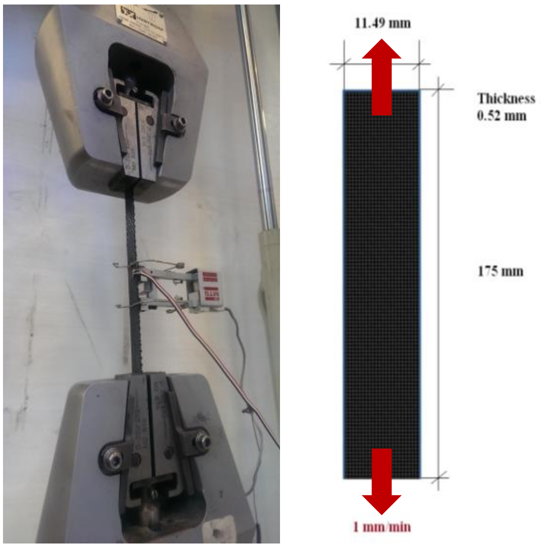


Figure 6:Set-up for off-axis static tension and stress relaxation test of plain weave CFRP lamina.

5 RESULTS AND DISCUSSIONS

Fig. 7 shows the stress-relaxation response of the plain weave composite lamina as predicted by the proposed numerical model versus the experimentally measured stress-relaxation. It is apparent that the numerical model can simulate the stress-relaxation/viscoelasticity of the carbon fiber lamina very well and is in good agreement with the experimental data. Extracting the energy dissipation due to stress-relaxation, as shown in **Fig. 8**, it is apparent that stress-relaxation can dampen the composite lamina and allow energy dissipation which is essential to controlling the deployment process of the tape spring.

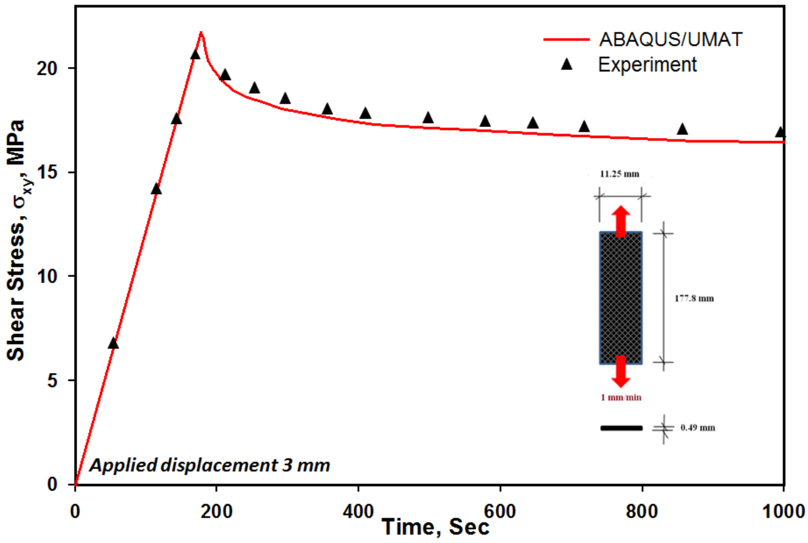


Figure 7: Stress-relaxation for $\pm 45^o$ plain weave lamina under off-axis tension.

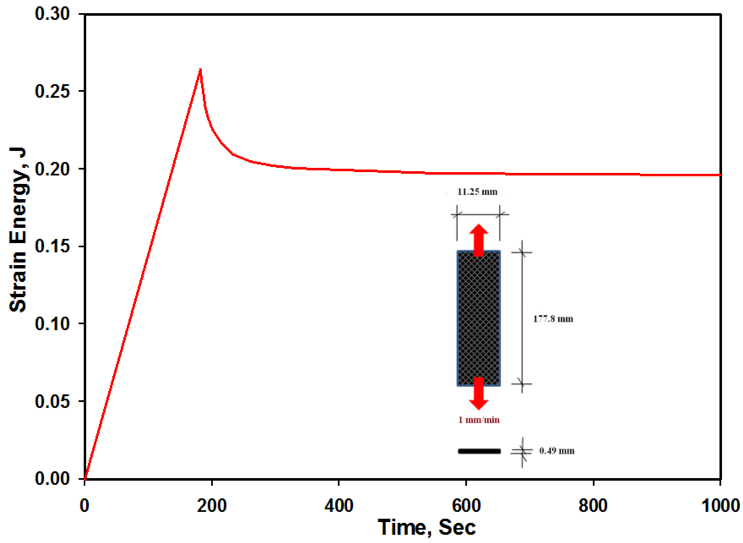


Figure 8:Energy loss in plain weave carbon fiber lamina during stress-relaxation.

The following step will be to incorporate this lamina behavior in modeling the composite laminate used to make the tape spring. We will then examine the effect of altering the polymer matrix on the lamina viscoelasticity and on the energy dissipation of the tape spring during stowage time. Further research is underway to identify the optimal matrix material to achieve enough energy dissipation such that a controlled deployment is accomplished.

6 CONCLUSIONS

A numerical model for simulating viscoelastic behavior of the plain weave lamina in the deployable FRP tape spring has been developed using a user subroutine for ABAQUS. The user subroutine is based on the *rule-of-mixtures* at the lamina level. The nonlinear viscoelastic response for the matrix can be calibrated using a creep test of the matrix represented by a Prony series. The proposed numerical model was verified successfully against published data from the literature for creep of glass fiber lamina under off-axis tension. The model was then validated against a stress-relaxation test of a plain weave IM7 carbon fiber lamina similar to that used in making the tape spring. The model proved capable of predicting the viscoelastic behavior of FRP composites with good accuracy. The developed subroutine can be further used to simulate the behavior of the tape spring during a stowage time period.

7 ACKNOWLDEGMENT

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