RATE-DEPENDENT MECHANICAL BEHAVIOR OF CFRP LAMINATES UNDER COMPRESSION LOADING

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ABSTRACT

This work describes an attempt to characterize the rate-dependent non-linear behaviour of a polymeric composite material under monotonic compression loading in the range of 0.0001 to 400/s. A 3-parameter constitutive viscoplastic model [1,2] is used to describe the mechanical behaviour. This model was developed based on data for strain rate between 0.0001 and 0.07/s. In transverse direction the viscoplastic model was able to predict the high strain rate experiments conducted on a Split Hopkinson Pressure Bar.

1. INTRODUCTION

The influence of strain rate on compression properties of a CFRP is investigated and presented. This is part of a major research project aiming to study the mechanical behavior and failure of CFRP laminates under high strain rate. The increasing use of polymer matrix composite materials in many applications demands a characterization of their mechanical response under a range of strain rates from 10^{-3} to 10^{+3}/s. Several experimental studies have been performed with the goal of determining the effects of strain rate on the mechanical properties and response of polymer matrix composite systems at high strain rate conditions. A survey done by Gates [3] describes several analytical models to simulate the rate-dependent response of various types of polymer matrix composites. Later Gates and Sun [3] developed an elastic-viscoplastic model for an orthotropic material without tension/compression symmetry and Gates [4] used an extension of that model to describe an experimental methodology to generate material constants. Goldberg and Stouffer [5,6] presented an historical description of experimental development to study the strain rate effect on mechanical properties of polymer matrix composites, followed by constitutive modeling. These authors modified strain rate dependent inelastic constitutive models, used to model viscoplastic deformation of metals, to model non-linear viscoelastic deformation of polymers.

It is reasonably accepted that in the fiber direction, unidirectional fiber reinforced polymer matrix composites are insensitive to load level and time of load application, i.e. exhibit a linear behavior. Then again in all other directions polymer composites exhibit non-linear and time-dependent behavior, which also means a rate-dependent behavior. A quit simple methodology associated to a simple constitutive elastic-viscoplastic model was developed by Sun et al.[1-2]. This methodology was applied in the present work to study mechanical behavior of a composite laminate in the transverse direction with good success

In the present work the material system used was Texipreg® HS160 REM, comprising high strength carbon fiber and epoxy resin. The average thickness of cured laminates was 2.5 mm. Square samples with 8.5 mm side were cut using water jet from original laminates. The unidirectional coupon specimens were subjected to loading along the 30º, 45º, 75º and 90º directions.

2. THEORETICAL BACKGROUND

The 3-parameter viscoplastic model used in this work was first presented by Sun et at. [1,2]. This model was developed based on the one-parameter plastic model proposed by Chen and Sun [7]. This model was very successful in representing the non-linear behavior of fiber-reinforced polymeric composite materials. The requirements of orthotropic symmetry and assumption that in the fiber direction the material is linear elastic leaded to a very simple potential function for plane stress state

$$f = \frac{1}{2}\sigma_{22}^{2} + a_{66}\sigma_{12}^{2} \tag{1}$$

where a_{66} is an orthotropy coefficient and σ_{22} σ_{12} are the transverse and shear stresses, respectively. It is assumed that strain increments are so small that can be separated into elastic and plastic parts as

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} \tag{2}$$

The elastic part follows elastic strain/stress relations for the composite and the plastic strains are obtained from the potential function as

$$d\varepsilon_{ij} = d\lambda \frac{\partial f}{\partial \sigma_{ij}} \tag{3}$$

Defining the effective stress as

$$\bar{\sigma} = \sqrt{3f} = \sqrt{\frac{3}{2}\left(\sigma_{22}^{2} + a_{66}\sigma_{12}^{2}\right)} \tag{4}$$

and using the equivalence of plastic work rate [7], the effective plastic strain rate is obtained as

$$\dot{\bar{\varepsilon}}^{p} = \sqrt{\frac{2}{3}\left(\left(\dot{\varepsilon}_{22}^{p}\right)^{2} + \frac{1}{2a_{66}}\left(\dot{\gamma}_{12}^{p}\right)^{2}\right)} \tag{5}$$

where $\dot{\varepsilon}_{22}^{p}$ and $\dot{\gamma}_{12}^{p}$ are the transverse and shear plastic strain rate, respectively.
Under constant strain rate, the effective plastic strain can be related with uniaxial applied stress σ_x and plastic strain ε_x^p as

$$\bar{\sigma} = h(\theta)\sigma_x \tag{6}$$

$$\bar{\varepsilon}^{p} = \frac{\varepsilon_x^{p}}{h(\theta)} \tag{7}$$

where $h(\theta)$ is an off-axis parameter defined as

$$h(\theta) = \sqrt{\frac{3}{2}\left(\operatorname{sen}^4\theta + 2a_{66}\operatorname{sen}^2\theta\cos^2\theta\right)} \tag{8}$$

The reference master curve effective plastic strain/effective stress is obtained for the transverse direction, since for this direction $h(\theta)$ do not dependent on the orthotropy coefficient a_{66}. The coefficient a_{66} should be such that all curves obtained for all other directions collapse into a single master curve, i.e. the reference master curve. Therefore the viscoplastic model assumes that for each strain rate there is a unique master curve which can be represented by a power law as

$$\bar{\varepsilon}^p = A\left(\bar{\sigma}\right)^n \tag{9}$$

where n is a material constant and the parameter A is function of the effective plastic strain rate. Sun et al. [1,2] proposed the following relationship

$$A = \chi\left(\dot{\bar{\varepsilon}}^p\right)^m \tag{10}$$

where χ e m are material constants.
The off-axis material response for the unidirectional loading tests can be predicted using the following non-linear equation

$$\dot{\varepsilon}_x = \frac{\dot{\sigma}_x}{E_x} + \dot{\varepsilon}_x^p \tag{11}$$

where E_x is the apparent modulus of elasticity of the off-axis specimen which is obtained from the transformation equation

$$\frac{1}{E_x} = \frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\upsilon_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{1}{E_2}\sin^4\theta \tag{12}$$

where E_1, E_2, G_{12} and ν_{12} are the orthotropic elastic constants for the fiber composite. After algebraic manipulation of Equation (11) a convenient non-linear differential equation can be obtained, Sun and Thiruppukuzhi [2], using equations (6) and (7) and the expressions

$$\dot{\varepsilon}_x^p = \dot{\bar{\varepsilon}}^p h(\theta) \tag{13}$$

and from equations (9) and (10)

$$\dot{\bar{\varepsilon}}^p = \left(\frac{1}{\chi}\right)^{1/m}\left(\bar{\sigma}\right)^{-n/m}\left(\bar{\varepsilon}^p\right)^{1/m} \tag{14}$$

Finally the appropriate non-linear differential equation is obtained

$$\dot{\sigma}_x + \left(\frac{1}{\chi}\right)^{1/m} E_x\left[h(\theta)\right]^{1-n/m-1/m}\left(\sigma_x\right)^{-n/m}\left(\varepsilon_x{}^p\right)^{1/m} - E_x\dot{\varepsilon}_x = 0 \tag{15}$$

where

$$\varepsilon_x{}^p = \varepsilon_x - \frac{\sigma_x}{E_x} \quad (16)$$

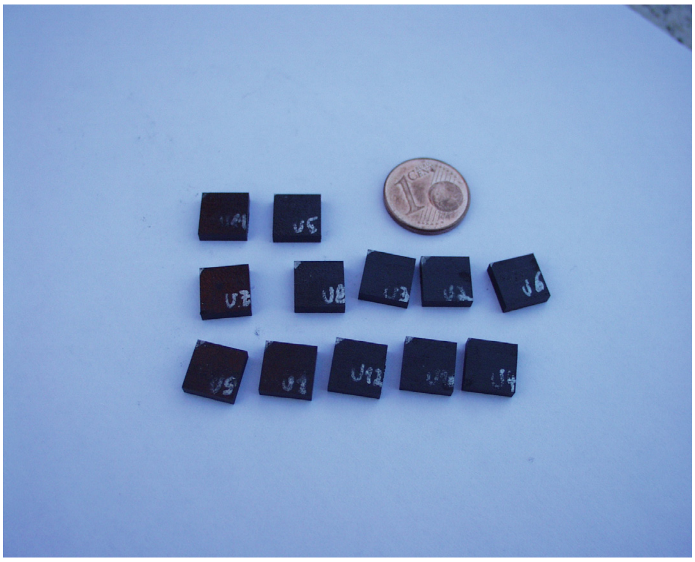
It is interesting to note that previous equation allows creep analysis. Let us consider the typical creep loading, with a constant load applied $\sigma_x = \sigma_0$ for $t \geq 0$, and $\varepsilon_x = \sigma_0 / E_x$ for t=0. Then solving equation (15) for this load condition, the following non-linear creep equation, power law of time, is obtained

$$\varepsilon_x = \frac{\sigma_0}{E_x} + \left[\frac{m-1}{m} \left(\frac{1}{\chi} \right)^{1/m} \left[h(\theta) \right]^{1-n/m-1/m} (\sigma_0)^{-n/m} \right]^{\frac{m}{m-1}} t^{\frac{m}{m-1}} \quad (17)$$

where t represents the time.

3. MATERIALS & SPECIMEN PREPARATION

The epoxy pre-preg system used in this work, Texipreg® HS160 REM manufactured by SEAL, is a modified epoxy REM reinforced with high strength carbon fiber in the form of unidirectional tape (0.125 mm thick). The laminates were produced on a 40-ton capacity SATIM hot plate press at 130°C under 1 bar pressure during 50 minutes and 3 bar pressure during more 60 min, which gives 110 min of dwell time. The average thickness of cured laminates was 2.5 mm and fiber content by volume, based on the fiber contents supplied by the pre-preg manufacturer, was $V_f \cong 0.6$. From the original manufactured laminates, square samples with 8.5 mm side were cut using water jet, displayed in Figure 1. Since some of the specimens would be tested in the Split Hopkinson Pressure Bar (SHPB), it was essential to obtain an accurate parallelism between the faces that would be in contact with the bars. A specific tool was designed to perform this task. The square specimens were then lapped using fine sandpaper (grit #600).



"**Fig. 1.** Experimental samples with 2.5x8.5x8.5 mm^3, compared with a coin of 1 cent of euro."

4. EXPERIMENTAL SET-UP

The low strain rate compression tests were carried out in an INSTRON conventional testing machine in displacement controlled mode with constant cross-head speed of 0.01, 1 and 100 mm/min.

The compression tests at high strain rate were performed with the Split Hopkinson Pressure Bar (SHPB). The particular setup used in the current study consists of striker, incident and transmission bars made of steel. The bars diameter is 12 mm. The striker bar is 1 m long, while the incident bar length is 2.5 m and the transmission bar 1.5 m. The specimen was sandwiched between the incident bar and the transmission bar. Lubricant grease was applied at the specimen surfaces in contact with the bars to reduce the effect of friction and to provide better contact. Equally, a small amount of lubricant grease was applied at the end of the striker bar to avoid high frequency phenomena in the signal acquired by the oscilloscope, consequence of heterogeneous contact. The full bridge with strain gage transducers A and B, used as signal monitors, were mounted at 1250 and 215 mm from the specimen, respectively. The striker bar was released at a pressure of 1 bar by a gas gun specially made for that proposes. The transient strain history is recorded from the strain gages A and B set up on the incident and transmission bars. A PICO CM001 signal conditioner adapter amplifies the gages output signal 10 times. The data is acquired using a LeCroy 9450A digital oscilloscope at a sampling rate of 1 MHz. A program named ADAVID® [6] imports the data from the oscilloscope data storage to the PC for posterior analysis.

5. RESULTS & DISCUSSION

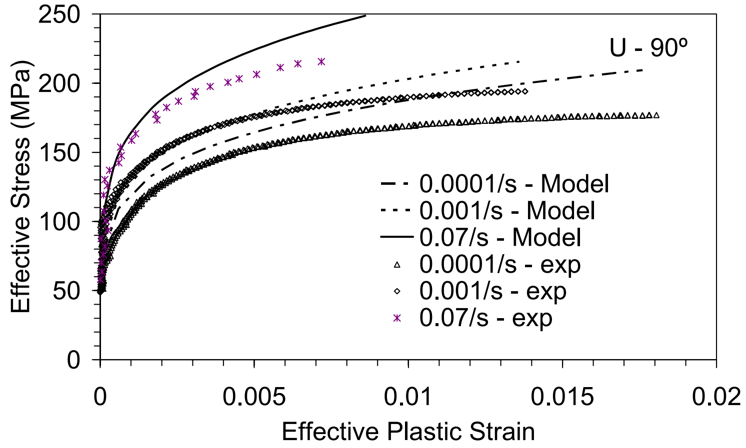
An analysis of strain rate dependent mechanical behavior of unidirectional laminates was performed. In Figures 2, 3, 4 and 5 the effective stress-effective plastic strain rate is plotted for three strain rates, 0.0001, 0.001 and 0.07/s, for each off-axis specimen. In this study, it was used the viscoplastic model proposed by Sun et al.[1,2], previously described. This model is very simple to use and in this case the master effective stress – effective plastic strain was represented as follows.

$$\bar{\varepsilon}^{p} = A\left(\bar{\sigma}\right)^{5.20} \tag{18}$$

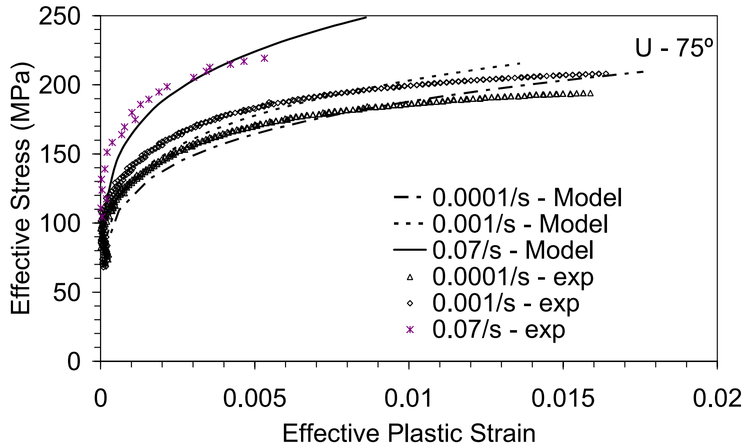
where the parameter A is function of the effective plastic strain rate. Assuming that A is a power law function of effective plastic strain, it was obtained the following relationship

$$A = 1.310\times10^{-15}\left(\dot{\bar{\varepsilon}}^{p}\right)^{-0.2740} \tag{19}$$

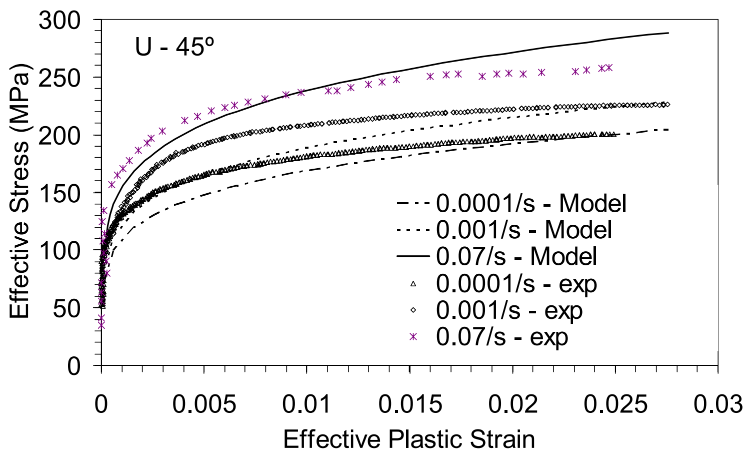
It was found that the orthotropic parameter a_{66} remain the constant (a_{66}=2.6) for the three strain rates, 0.0001, 0.001 and 0.07/s. In Figures 2, 3, 4 and 5 it is possible to verify the model ability to reproduce experimental data. It should be noted that the indicated strain rates are nominal values. Depending on fiber orientation real strain rates presented small deviations form nominal values. For numerical evaluation of the viscoplastic model, real strain rates were used instead of nominal values. Although some discrepancies are clearly observed between the model and experimental results, the evolution of the plastic strain, function of strain rate, was capture satisfactorily for all tested orientations.



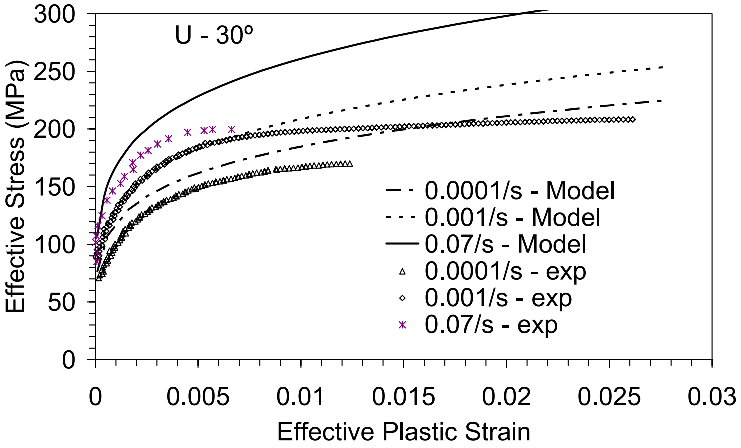
“**Fig. 2.** Comparison of effective stress/effective plastic strain curves and model fitting for transverse loading.”



“**Fig. 3.** Comparison of effective stress/effective plastic strain curves and model fitting for the 75º off-axis specimen.”



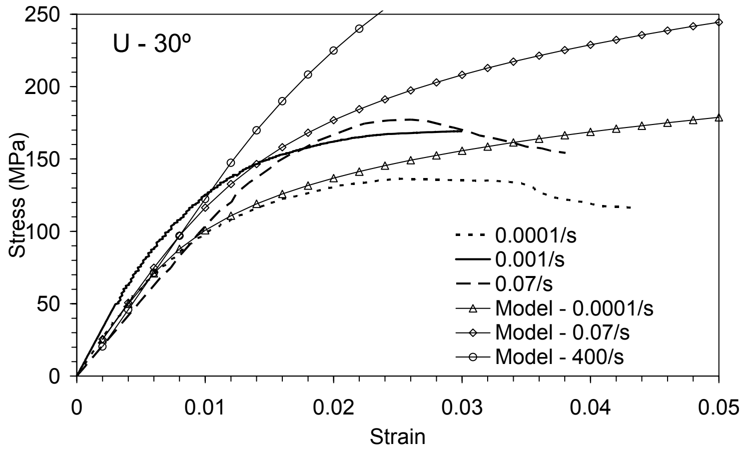
“**Fig. 4.** Comparison of effective stress/effective plastic strain curves and model fitting for the 45º off-axis specimen.”



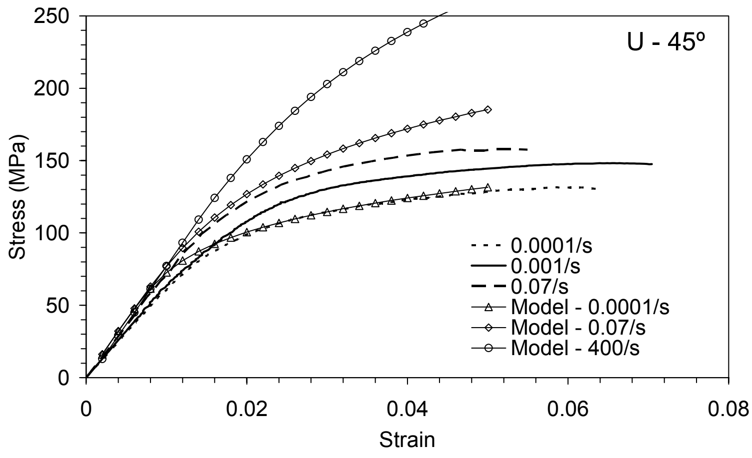
"**Fig. 5.** Comparison of effective stress/effective plastic strain curves and model fitting for the 30º off-axis specimen."

Now, it is possible to reconstruct the stress-strain curves for the off-axis orientations by integration of the non-linear differential equation (15). This equation describes the off-axis material response for the uniaxial compression (or tension) tests. The Figures 6, 7, 8 and 9 exhibit model predictions in comparison with experimental results at various strain rates. For all directions, except 75º off axis, the model and experimental results are in good agreement. Further, in the case of 75º off axis, the discrepancy between model and experimental results is only verified in the case of the lower strain rate.

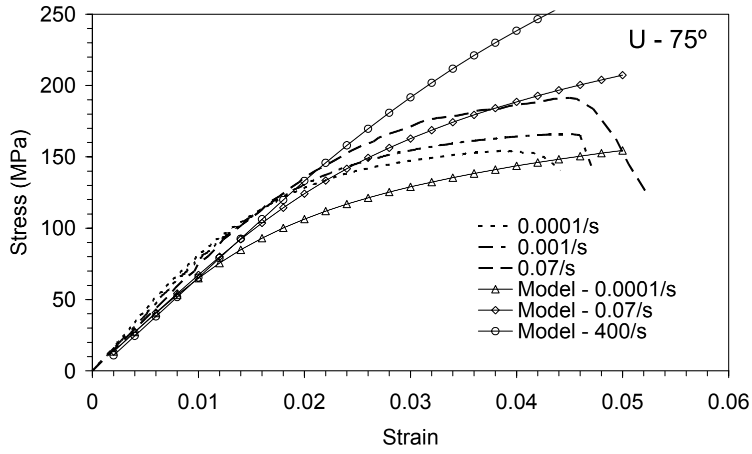
The development of viscoplastic model was based on low strain rates 0.0001, 0.001 and 0.07/s. The experimental tests for high strain rates 400/s were conducted on a Split Hopkinson Pressure Bar (SHPB) located at the Optical Lab of INEGI. At this moment there are only results for transverse direction. Still, in this direction the viscoplastic model proved to be valid for high strain rates, as it is depicted in Figure 9.



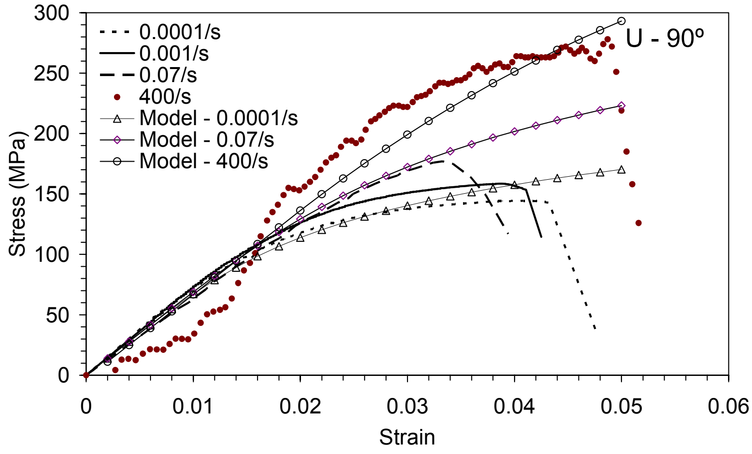
"**Fig. 6.** Comparison of experimental and theoretical stress-strain curves for different strain rates for the 30º off-axis specimen."



“**Fig. 7.** Comparison of experimental and theoretical stress-strain curves for different strain rates for the 45º off-axis specimen.”



“**Fig. 8.** Comparison of experimental and theoretical stress-strain curves for different strain rates for the 75º off-axis specimen.”



“**Fig. 9.** Comparison of experimental and theoretical stress-strain curves for different strain rates for the transverse loading.”

The 3-parameter viscoplastic model was proposed by Sun and Thiruppukuzhi [1,2] applied and verified for GFRP composite materials. In this work the very same model was applied to a CFRP. The first results indicate that the model possesses a good capability to represent the strain rate dependent mechanical behaviour of a CFRP composite material, over a wide range of strain rates i.e. from 0.0001 to 400/s. Therefore the 3-parameter viscoplastic model appears to be applicable to CFRP composite materials with good success.

6. CONCLUSIONS

Studies were carried out on 26 quasi-isotropic and unidirectional laminates under compression loading. The setup used were one conventional mechanical testing machine (INSTRON) for strain rates between 0.0001 and 0.07/s and one Split Hopkinson Pressure Bar for strain rates of about 400/s. The material system used was Texipreg® HS160 REM, comprising high strength carbon fiber and epoxy resin. Square coupons with $8.5x8.5x2.5mm^3$ were used for tests. The unidirectional coupon specimens were subjected to loading along the 30º, 45º, 75º and 90º directions.

An attempt is made to characterize the rate-dependent non-linear behaviour of a polymeric composite material under monotonic compression loading. A 3-parameter constitutive viscoplastic model proposed by Sun and Thiruppukuzhi [1,2] was used to describe the mechanical behaviour. This model was developed based on data for strain rate between 0.0001 and 0.07/s. In transverse direction the viscoplastic model was able to predict the high strain rate experiments conducted on a Split Hopkinson Pressure Bar. Consequently, this 3-parameter viscoplastic model was able to describe the strain rate dependent mechanical behaviour of Texipreg® HS160 REM composite material, under compression, with good accuracy.

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References

1. **Tsai J.** and **Sun C.T.** "Constitutive model for high strain rate response of polymeric composites", *Composites Science and Technology*, **62** (2002), 1289-1297.
2. **Thiruppukuzhi S.V.** and **Sun C.T.,** "Models for the strain-rate-dependent behavior of polymer composites", *Composites Science and Technology*,. **61** (2001), 1-12.
3. **Gates T.S.**, "Rate Dependent Constitutive Models for Fiber Reinforced Polymer Composites", NASA TM 102665, NASA Langley Research Center, May (1990).
4. **Gates T.S.** and **Sun C.T.**, "An Elastic/Viscoplastic Constitutive Model for Fiber Reinforced Thermoplastic Composites", AIAA Journal **29**/3 (1991), 457-463.
5. **Goldberg R.K.** and **Stouffer D.C.**, "High Strain Rate Deformation Modeling of a Polymer Matrix Composite: Part I- Matrix Constitutive Equations", NASA TM 206969, NASA Lewis Research Center, August (1998).
6. **Goldberg R.K.** and **Stouffer D.C.**, "Strain rate dependent analysis of a polymer matrix composite utilizing a micromechanics approach", *J. Composite Materials* **36**/7 (2002), 73-793.
7. **Sun C.T.** and **Chen J.L.**, "A simple flow rule for characterizing nonlinear behavior of fiber composites", *J. of Composite Materials*, **23** (1989), 1009–20.
8. **Gary G.** and **Klepaczko**, "A Computer Program for the Analysis of SHPB Test", Paris / METZ:1998