Short-Term Flexural Creep Behavior and Model Analysis of a Glass-Fiber-Reinforced Thermoplastic Composite Leaf Spring

C. Subramanian, S. Senthilvelan

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

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ABSTRACT: Present work investigated the short-term flexural creep performance of fiber reinforced thermoplastic injection molded leaf springs. Unreinforced polypropylene, 20 wt % short and 20 wt % long glass fiber reinforced polypropylene materials were injection-molded into constant thickness varying width mono leaf spring. Short-term flexural creep tests were performed on molded leaf springs at various stress levels with the aid of in-house developed fixture integrated with the servo-hydraulic fatigue machine. Spring rate reduction is reported as an index for the accumulated damage. Experimental creep performance of molded leaf springs for 2 h was utilized to predict the creep performance with the aid of four parameter HRZ model and compared with 24-h experimental creep data. Test results revealed that HRZ model is sufficient enough to predict short-time flexural creep performance of engineering products over wide range of stress. Test results also confirmed the suitability of long fiber reinforced thermoplastic material for creep application over other considered materials. J Appl Polym Sci 120: 3679–3686, 2011

Key words: thermoplastics; mechanical properties; creep; stiffness; injection molding

INTRODUCTION

Main motivation to utilize composite materials in automobile industries is to reduce fuel consumption. Replacement of steel leaf springs by composite leaf spring for the suspension application would contribute to the fuel economy and improved ride characteristics with the reduction of automobile unsprung weight. Adequate works have been carried out on the design, development, and performance of thermoset composite leaf springs in the past two decades.[1–7] Prior investigations[1–7] have identified thermoset composite material for leaf spring application, wherein majority of the works focused on the static and fatigue performance. However limited volume production capability of thermoset material recommends alternative material for leaf spring application. The desire to increase the volume of production has initiated the authors to attempt and identify thermoplastic composites for leaf spring applications. Development, static, and fatigue performance of thermoplastic leaf springs were reported elsewhere.[8,9] Creep performance evaluation is indispensable because of the time-dependent mechanical behavior of thermoplastic composite materials. Considering the need to predict the creep behavior of thermoplastic leaf springs, this work has been focused to understand the short-term flexural creep performance of the thermoplastic composite leaf springs. Various works have been carried out in the past pertaining to analytical and experimental methods for characterizing the creep behavior of thermoplastic composites.[10–16] Kim et al.[10] investigated the influence of fiber length in discontinuous glass fiber polypropylene and visualized the superior creep performance of long glass fiber reinforced material in comparison with short-fiber counterparts. Silverman[11] compared and investigated the flexural creep response of long and short glass fiber-reinforced thermoplastic material made of polycarbonate and polypropylene at various temperatures and reported the creep modulus reduction at elevated temperature for short fiber reinforced thermoplastic compared to long fiber reinforced thermoplastics. Findley and Khosla[12] experimentally evaluated the creep performance of polyethylene, polyvinyl chloride and polystyrene at various stress levels and compared with the results obtained from model based on Boltzman superposition principle. Hadid et al.[13] modified Findley's law and proposed a new model (HRZ) with four parameters and compared model performance with experimental results for unreinforced and reinforced polyamide materials. Banik et al.[14] experimentally evaluated the creep performance of unidirectional and cross ply polypropylene composites and compared the experimental results with Burger and Findley's power law

Correspondence to: S. Senthilvelan (ssvelan@iitg.ernet.in).

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model. Houshyar et al.[15] evaluated the effects of fiber concentration and temperature on the thermoplastic composite creep performance and the experimental results were compared with four parametric viscoelastic model. Liou and Tseng[16] used Findley's power law to estimate the creep compliance of carbon fiber nylon composites in hygrothermal condition.

Though adequate works have been reported on the creep performance modeling of fiber-reinforced thermoplastic composite, no attempts have been made to substantiate the usefulness of these models to predict the creep performance of an engineering part. Present work reported the influence of reinforced fiber length on the short-term creep performance of thermoplastic composite leaf springs for various stress levels at room temperature condition. Though leaf spring application demand creep performance evaluation in the range of 1000 h, present experimental work is limited to 24 h and the usefulness of HRZ model for the creep performance prediction of molded leaf spring is explored.

BACKGROUND

Findley's power law model

Mechanical behavior of polymeric material under constant stress was developed by Findley and Khosla.[12] The general form of the power law equation is given as

$$\varepsilon(t) = \varepsilon_t' t^n \tag{1}$$

where $\varepsilon(t)$ is the time-dependent strain, ε_t' is power law coefficient which is stress- and temperature-dependent coefficient, n is the power law exponent, and t is the time after loading. Park and Balatinecz[17] used the above eq. (1) to investigate the flexural creep behavior of wood fiber reinforced polypropylene composites. Power law model is simple in approach and successfully predicted nonlinear viscoelastic creep behavior of thermoplastic composites over large range of stress[12–14,16] besides this model is also recommended by American Society of Civil Engineers (ASCE) for structural plastics design manual in the analysis of composite materials for long term structural behavior.[18]

HRZ model

Findley's power law was unsuccessful in accounting for the stress effect on the mechanical behavior of polymeric material. The two power law parameters in the Findley-Khosla model ε_t' and n are significantly influenced by the applied stress level. Karian[19] carried out flexural creep test on polypropylene short fiber composite and observed that creep strain is sensitive to stress level. Hadid et al.[13] modified the Findley's power law to incorporate time and stress dependence in the model where the power law coefficient (ε'_t) and power law exponent (n) were plotted with respect to stress level (σ). The best fitting curve proposed the relation between ε_t' and σ as

$$\varepsilon_t' = a.(\sigma)^b \tag{2}$$

Similarly the best fitting curve proposed between n and σ value takes the form

$$n = c.\,exp\,(e.\sigma) \tag{3}$$

Equations (2) and (3) are used in eq. (1) and strain at any particular time (t) can be calculated using the following HRZ equation

$$\varepsilon(t) = a.\sigma^b.t^{c.exp(e.\sigma)} \tag{4}$$

where a, b, c, e are the curve fitting parameters obtained from the regression analysis. Chevali et al.[20] used the four parameter HRZ model to fit the experimental data obtained from flexural creep investigation for nylon 6/6, polypropylene, and high-density polyethylene-based long fiber thermoplastic composites.

EXPERIMENTAL CREEP PERFORMANCE OF COMPOSITE LEAF SPRINGS

Leaf spring materials and manufacturing

In the current investigation, 20 wt % short glass fiber reinforced polypropylene (SFPP), 20 wt % long glass fiber reinforced polypropylene (LFPP) and unreinforced polypropylene (UFPP) obtained from Saint Gobain were used for injection molding the leaf springs. Chosen long fiber reinforced thermoplastic pellets were made by pultrusion process wherein fibers are well aligned within pellets unlike random orientations in the case of short fiber reinforced material. In general, lengths of the reinforced fibers in the short and long fiber reinforced pellets are 1 mm and 12.5 mm respectively.[21] Weight average fiber length of the reinforced fibers after injection molding for the chosen SFPP and LFPP materials are 0.440 and 1.251 mm respectively,[8] thereby aspect ratio is reduced to 44 and 125, respectively. The increase in fiber length of LFPP material accounts for more surface area of the fiber and provides good interfacial bonding strength with the matrix.[8] Similar aspect ratios were also reported in few works on long fiber reinforced thermoplastics.[22–24] The base resin of LFPP and SFPP materials were having same

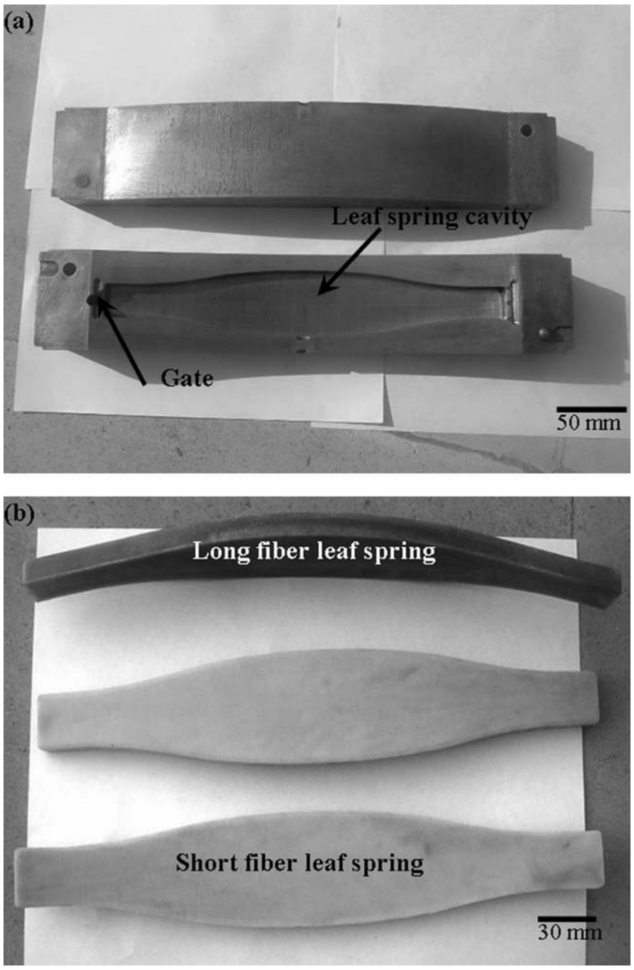

Figure 1 a. Developed die. b. Injection molded leaf springs.

molecular weight with a melt flow index of 40 g/10 min. According to the material supplier's data, silane type coupling agent has been used for the manufacturing of SFPP and LFPP materials. Since both the investigated materials used the same type and amount of coupling agent, material behavior discussions were limited only to the reinforced fiber length. The best gate location was identified at the end of the part and a standard two-plate mold design is made with pin gates at the end for molding the leaf springs.[25] Developed injection molding dies and molded mono leaf springs are shown in Figure 1(a,b). Raw materials were initially preheated for 2 h at 353 K and during molding, screw speed of 50 rpm, and a low back pressure of 0.25 MPa were kept to retain the residual fiber length. Process parameters used for injection molding are listed in Table I. Because of the presence of reinforced fibers in LFPP and SFPP materials, temperature in the three zones was kept higher than unreinforced material. Detailed design of the chosen leaf spring with computer aided structural analysis at critical section is presented elsewhere.[25]

Experimental methodology

Creep performance of the molded leaf spring was evaluated with the aid of in-house developed fixture (Fig. 2) and suitably integrated with the servo hydraulic testing machine (Instron 8801). Rail way of linear guide (THK- E8-0620) was fixed to the lower platen of the servo hydraulic testing machine. Two retaining blocks were fastened over the sliding blocks of guide ways and leaf spring ends were positioned within the retaining blocks. When the load is applied at the center of the leaf spring through lower platen of the testing machine, leaf spring flattens. To accommodate the increase in length during deflection, leaf spring ends slides over the linear guide way rail. The upper platen of servo hydraulic test machine was fixed and connected to the load cell whereas the lower platen can be moved up and down either through load or displacement controlled servo hydraulic system. Test leaf springs were loaded up to 12 mm deflection (Camber) and released back as per the SAE standard (J 1528[26]). The load taken for this magnitude of deflection of test leaf spring is taken as P_{max}. Molded leaf springs are subjected to flexural creep test at 0.6, 0.8, 1.0, 1.2, and 1.4 times the P_{max} and the data are used to obtain parameters for the HRZ model. In addition molded leaf springs are also subjected to creep test for 24 h at 0.8 P_{max} and P_{max} to compare and validate the performance of HRZ model.

The crosshead speed during loading of the leaf spring was adjusted to reach the desired load level in a time of 5 s as suggested by ASTM D2990-95 standard.[27] Constant load was maintained and leaf spring deflection ($\delta(t)$) is continuously measured and recorded. Creep strain at instantaneous time $\varepsilon(t)$ is computed using the relation (5)[27] where δ (t) is

TABLE I
Injection Molding Parameters for Leaf Spring

Material	Zone-1 (°C)	Zone-2 (°C)	Zone-3 (°C)	Screw diameter (mm)	Injection speed (mm s^{-1})	Injection pressure (MPa)	Mold temperature (°C)
Unreinforced polypropylene	190	180	175	35	50	100	40
20 % glass fiber reinforced polypropylene	255	250	240	35	50	100	40

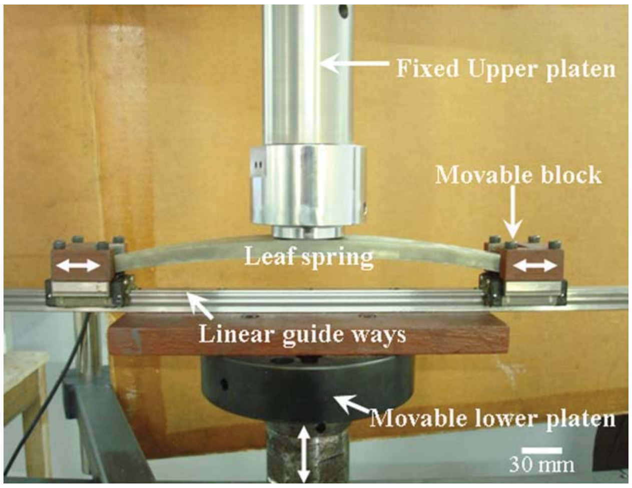

Figure 2 Experimental arrangement for the creep performance evaluation of the composite leaf spring. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the deflection at instantaneous time, d is the thickness and l the

$$\varepsilon(t) = \frac{6\delta(t).d}{l^2} \quad (5)$$

leaf spring length. From the measured creep strain, creep compliance ($J(t)$) in MPa^{-1} is computed using relation (6),[27]

$$J(t) = \frac{4wd^3\delta(t)}{Pl^3} \quad (6)$$

where w is the width of specimen and P is the applied load.

RESULTS AND DISCUSSION

Creep performance of thermoplastic composite leaf spring

In the service conditions suspension leaf springs were subjected to constant stress as the chassis weight is taken by the suspension system. Besides, leaf springs were also subjected to various stress levels due to the different prevailing payload conditions. Thus creep response investigation of the molded leaf spring under various stress levels is of practical importance.

Creep performance evaluation was carried out at various loading levels corresponding to the value of P_{max}. P_{max} for unreinforced polypropylene leaf spring (UFLS), 20 wt % short glass fiber reinforced polypropylene leaf spring (SFLS), and 20 wt % long glass fiber reinforced polypropylene leaf spring (LFLS) are 110*N*, 190*N*, and 490*N* respectively, for a deflection of 12 mm (camber) obtained from the static test.[8] The induced leaf spring bending stress (S_{max}) was computed using eq. (7) for the tested load levels. Rajendran and Vijayarangan[28] made use of similar equation for designing the mono composite leaf spring for depicting the leaf spring bending stress estimation

$$S_{max} = \frac{3Pl}{2wd^2} \quad (7)$$

where P is the applied load, l is effective length of the spring, w is the width at the center, and d is the beam thickness at center. The stress level corresponding to P_{max} for UFLS, SFLS, and LFLS were 8.25, 14.25, and 36.75 MPa, respectively. It is to be noted that the stress value corresponding to P_{max} is well below the yield stress value of the leaf spring material.[21] Figure 3 shows the 24-h creep response of the chosen test leaf springs. A raise in creep compliance was observed with the time period for all the leaf springs. The time-compliance data at 100 s for P_{max} reveals that LFLS, SFLS, and UFLS exhibited creep compliance of 4.0E-04 MPa^{-1}, 8.0E-04 MPa^{-1}, and 1.6E-03 MPa^{-1} respectively. Subsequent to the preliminary rapid increase in creep compliance, the rate of creep compliance decreases. The compliance at the end of 24 h-test reveals that LFLS, SFLS, and UFLS showed an increase in creep compliance of 20.87, 51.62, and 65.20%, respectively. Three trails were conducted for calculating creep compliance for all the molded leaf springs and deviations for LFLS, SFLS, and UFLS were found to be 3.5, 4.2, and 2.5%, respectively. Improved creep resistance behavior of LFLS is due to the improved load transfer from the matrix to the reinforced fibers and the matrix constriction to deformation. Chevali et al.[20] also observed a similar behavior with the increase in loading of glass fiber reinforcement in the nylon composites. Since creep compliance

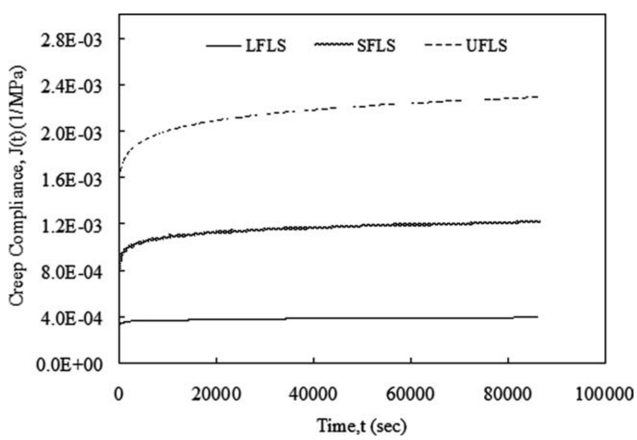

Figure 3 Experimental creep performance of molded test leaf springs at P_{max}.

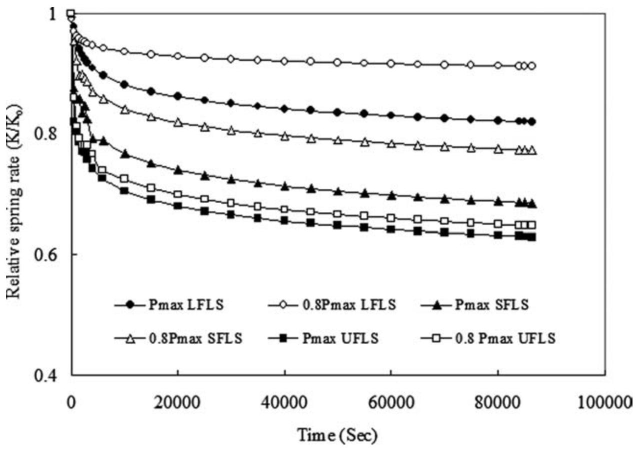

Figure 4 Spring rate performance of molded test leaf springs.

increase is associated with the spring rate reduction, further quantification of spring rate is of practical importance to the suspension application.

Spring rate of thermoplastic composite leaf spring

Spring rate of a vehicle suspension system is decided by the sprung mass (mass of the body and other component supported by the suspension). If the spring rate is very high (excessively rigid springs) than required, then springs do not absorb shock and vibration thereby all the vibrations are transmitted to the vehicle. If the spring rate is very low (excessively flexible springs) than required, then springs deflect drastically which contributes to the poor isolation of the vehicle from the road against the vibrations. Hence for the good suspension system, appropriate spring rate is required and to be retained during operation. Creep behavior of molded leaf spring results in spring rate reduction with the progression of time. Spring rate (K_s) was computed using the following relation

$$K_s = \frac{P}{\delta(t)} \tag{8}$$

where P is the constant load and $\delta(t)$ is the deflection at instantaneous time. To investigate the creep damage on the test leaf spring, relative spring rate [ratio of instantaneous spring rate (K) to the initial spring rate (K_o)] was measured and plotted as a performance index. The relative spring rate of test leaf springs at various time intervals were computed and Figure 4 shows the relative spring rate of test leaf springs at two different loads (0.8 $P_{\max}$ and $P_{\max}$) for a time period of 24 h. At the loading level of $0.8P_{\max,}$ initial spring rate (at the end of 30 s) of LFLS, SFLS, and UFLS are 39.8, 15.5, and 9.17 N mm^{-1}, respectively, and after 24 h it dropped to 36.2, 11.9, and 5.9 N mm^{-1}. Because of the increase in reinforced fiber length, spring rate retention is more pronounced in LFLS and better isolation of shocks from the vibration can be achieved. Because of the substantial time requirement for the creep

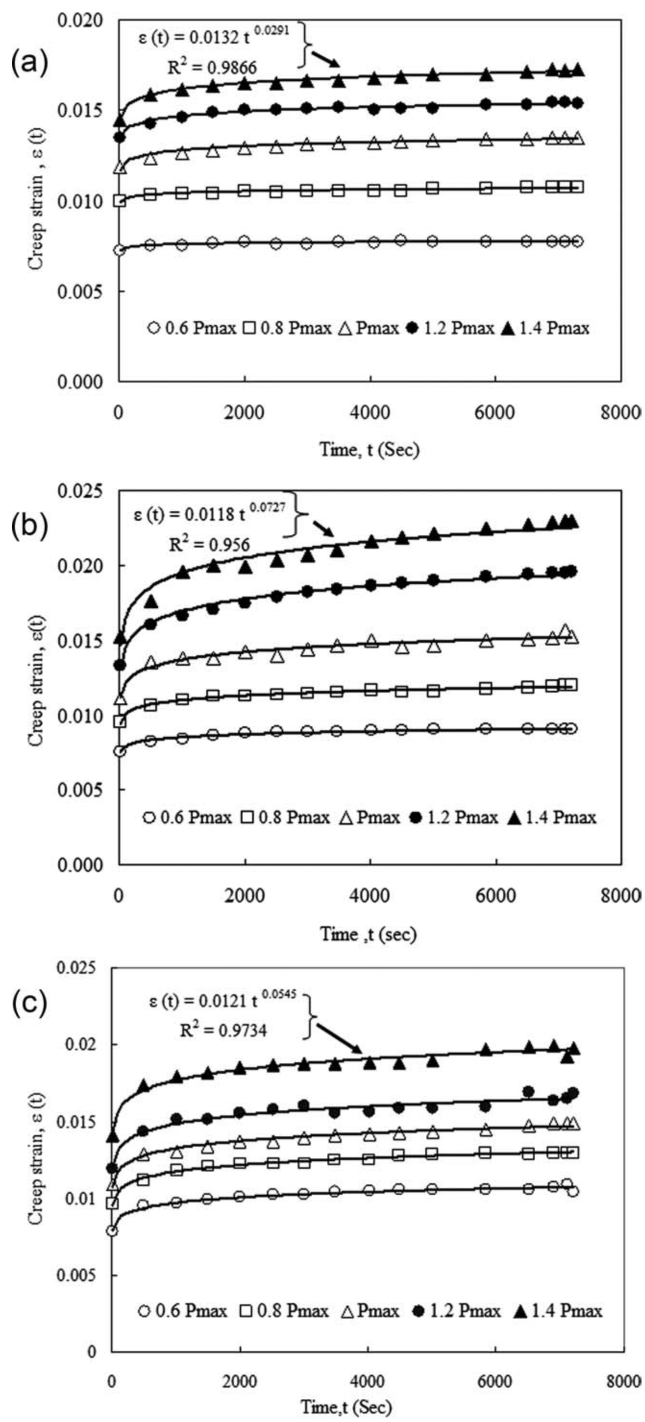

Figure 5 a. Short term experimental creep performance of long fiber reinforced polypropylene leaf springs. b. Short term experimental creep performance of short fiber reinforced polypropylene leaf springs. c. Short term experimental creep performance of unreinforced polypropylene leaf springs.

TABLE II
Power Law Parameters for Leaf Springs

Material	Constants	Load (P)				
		$0.6P_{max}$	$0.8P_{max}$	P_{max}	$1.2P_{max}$	$1.4P_{max}$
Long glass	Power law coefficient (ε_t')	0.007	0.009	0.010	0.012	0.013
fiber reinforced	Power law exponent (n)	0.011	0.012	0.023	0.023	0.029
leaf springs	Correlation index (R^2)	0.878	0.921	0.947	0.971	0.986
Short glass	Power law coefficient (ε_t')	0.006	0.008	0.009	0.010	0.011
fiber reinforced	Power law exponent (n)	0.032	0.039	0.052	0.067	0.072
leaf springs	Correlation index (R^2)	0.974	0.983	0.965	0.985	0.956
Unreinforced	Power law coefficient (ε_t')	0.006	0.008	0.009	0.010	0.012
leaf springs	Power law exponent (n)	0.051	0.052	0.052	0.053	0.054
	Correlation index (R^2)	0.978	0.989	0.984	0.954	0.973

investigation, an empirical model is made use of in the subsequent section to predict the leaf spring performance for a specific period of time.

Empirical model for predicting short term creep behavior

The creep performance of molded leaf springs was experimentally investigated for 2-h duration in the load range varying from 0.6 P_{max} to 1.4 P_{max} and the test results are shown in Figure 5(a–c). Power law function is fitted using eq. (1) for each and every stress levels thereby power law coefficient (ε_t'), power law exponent (n), and correlation index (R^2) are determined and plotted in Table II.

The correlation index, R^2 indicates that power law function provides a good approximation to the visco elastic behavior at every stress levels. It is vivid from Figure 5(a–c) that the power law coefficient (ε_t') and power law exponent (n) are dependent on the stress level and increases with the increase in stress level. Since the power law coefficient (ε_t') and power law exponent (n) are sensitive to the stress level, a methodology adopted by Hadid et al.[13] was used to establish the dependence of power law coefficient (ε_t') (Fig. 6) and power law exponent (n) (Fig. 7) on applied stress level.

Figure 6 shows the best fitting curve using eq. (2) and depicts the influence of applied stress (σ) on power law coefficient (ε_t') for the test leaf springs. The constant curve fitting parameters [a, b from eq. (2)] are also shown in Figure 6. In general the constant parameters a and b are dependent on glass transition temperature, degree of crystallinity, and fiber orientation in the composite.[20] These parameters represent the instantaneous strain normally visualized during the initial period of load application. Figure 7 shows the best fitting curve using eq. (3) and elucidates the influence of applied stress (σ) on power law exponent (n) for the test leaf springs. The constant curve fitting parameters [c, e from eq. (3)] are also shown in Figure 7. The constant parameters c and e are dependent on the time period of testing and relaxation mechanisms involved for the composite.[20] These parameters represent the viscous response visualized during the secondary creep

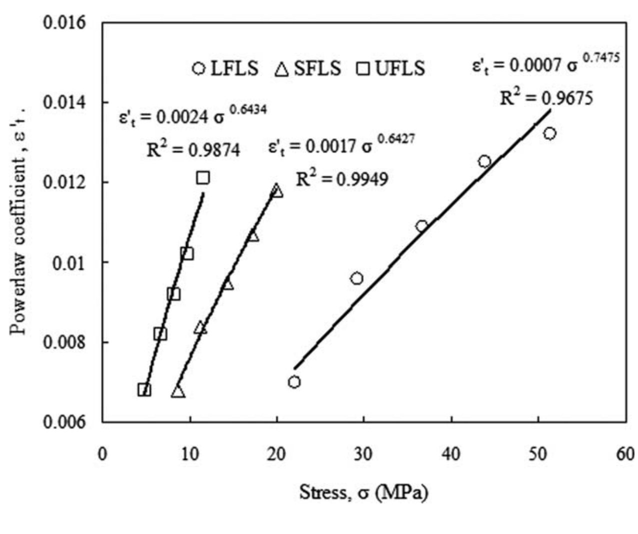

Figure 6 Variation of power law coefficients over leaf spring stress.

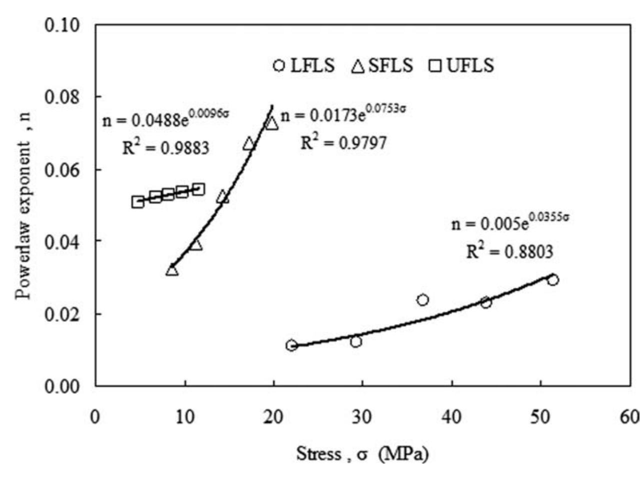

Figure 7 Variation of power law exponent over leaf spring stress.

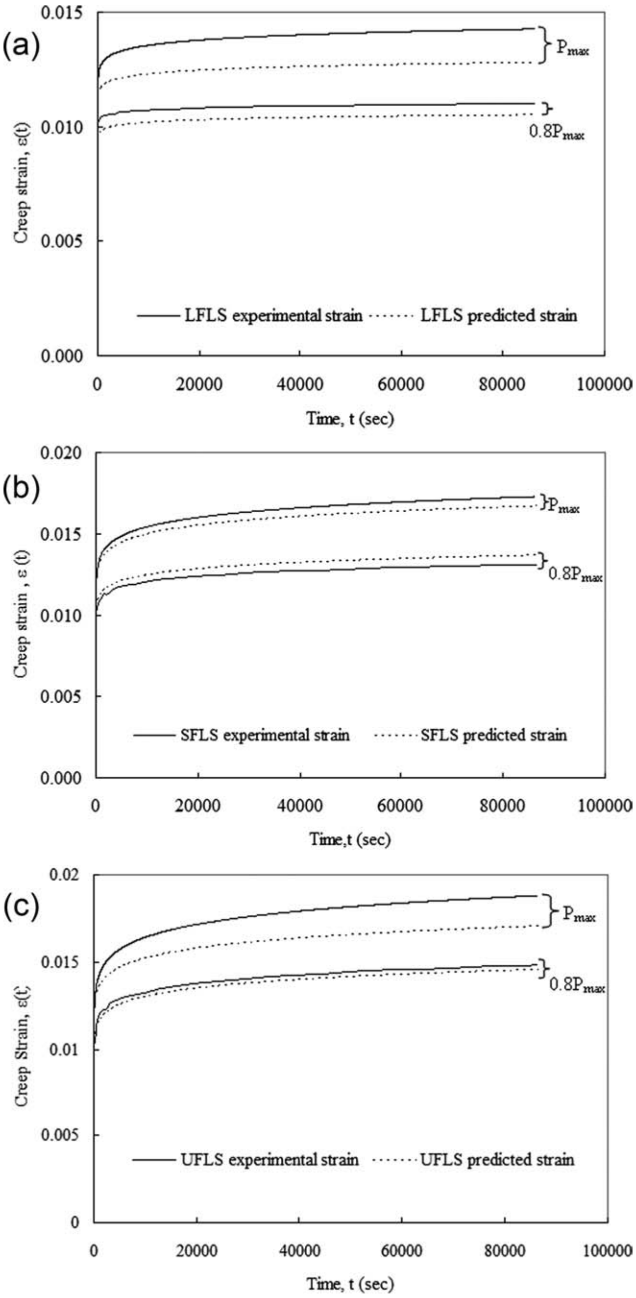

Figure 8 a. Experimental and predicted creep performance of long fiber reinforced polypropylene leaf spring. b. Experimental and predicted creep performance of short fiber reinforced polypropylene leaf spring. c. Experimental and predicted performance of unreinforced polypropylene leaf springs.

process. Equation (4) is used to predict creep performance of molded leaf spring and compared with the 24-h experimental data as shown in Figure 8(a–c). The deviation between the predicted creep strain and experimental creep are shown in Table III. It is found that HRZ model predicted well with the experimental creep performance of the chosen thermoplastic composite leaf springs. Furthermore it was observed that at a loading level of $0.8P_{max}$ the error between experimental and predicted creep strain is less than loading level at P_{max}. Similar observations were visualized by Hadid et al.[13] where the error between experimental and predicted values were high at higher stresses.

Influence of material crystallinity on power law coefficient

Prior investigation with HRZ model for predicting the creep behavior of thermoplastic materials is limited.[13,20] Hadid et al.[13] have not attempted to correlate parameters with any of the material behavior. Chevali et al.[20] reported that the power law coefficient depends upon on material characteristics which include degree of crystallinity, glass transition temperature, and fiber orientation, however no specific correlations with any behavior was attempted. In the present investigation, the evaluated power law coefficient (ε_t') of UFLS, SFLS, and LFLS corresponding to 11.55, 19.95, and 22.05 MPa stress are 0.012, 0.011, and 0.007 respectively, (Table II). The crystallite size of investigated leaf spring materials; unreinforced, short glass fiber reinforced, and long glass fiber reinforced polypropylene are 100.330, 118.615, and 146.784 Å, respectively. Detailed methodology and mechanisms were reported elsewhere.[8] From the crystallite size and power law coefficient, it is confirmed that increase in crystallinity reduces the power law coefficient. To confirm this correlation further, experimental creep data of Banik et al.[14] is also considered. Banik et al.[14] experimentally evaluated the creep performance of unidirectional polypropylene composites and crossply laminates at various loads and temperatures and compared with an empirical model. In the present investigation, experimental creep response of Banik et al.[14] is extracted and analyzed using data capturing software Windig 2.5 where the creep test was conducted at 30°C for an applied stress of 10 MPa. The extracted creep data results were found to be fit with the power law function. The evaluated power law coefficient of

TABLE III
Comparison of HRZ Model Predicted Strain and Experimental Strain

Material	Loading level	Experimental creep strain	HRZ predicted creep strain	Deviation (%)
Long glass fiber reinforced leaf springs	P_{max}	0.0141	0.0123	14.2
	$0.8\ P_{max}$	0.0112	0.0102	9.09
Short glass fiber reinforced leaf springs	P_{max}	0.0171	0.0168	5.88
	$0.8\ P_{max}$	0.0136	0.0131	3.67
Unreinforced leaf springs	P_{max}	0.0188	0.0170	9.57
	$0.8\ P_{max}$	0.0148	0.0145	2.02

crossply laminates and unidirectional composites are found to be 0.1831 and 0.0729, respectively. Banik et al.[14] measured and reported the crystallinity of crossply laminates and unidirectional composites as 49.5 and 51.0%, respectively. Thus it is confirmed that increase in material crystallinity reduced the power law coefficient.

CONCLUSIONS

Discontinuous fiber reinforced thermoplastic composite leaf springs were injection molded and investigated for its short term flexural creep performance. Because of the extensive time requirement for the creep performance evaluation, HRZ model was used in this work. Creep performance of the molded leaf springs were experimentally evaluated for 2 h and short term creep performance (24 h) was predicted with the aid of HRZ model over wide range of stress. The predicted performance was compared with 24-h experimental results and found to be satisfactory. From the present investigation, HRZ model was found to be useful in predicting the short-term creep performance of viscoelastic engineering products. Experimental results confirmed the suitability of long fiber reinforced thermoplastics for engineering applications against creep. HRZ model parameters were also utilized to correlate investigated material characteristics.

NOMENCLATURE

a, b, c, e	curve fitting parameters
d	thickness of leaf spring
l	length of leaf spring
n	power law exponent
P	load
t	time period
S_{max}	leaf spring bending stress
w	width of the leaf spring
K_s	spring rate
σ	applied stress level
J(t)	creep compliance
δ(t)	deflection at instantaneous time
$\varepsilon(t)$	time dependent strain
ε_t'	power law coefficient

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