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Article

Enhancements of Creep Compliance of Kevlar and Carbon Fi-Bars Reinforced Sika Epoxy Composites

Ali A. Battawi [1]*, Balsam H. Abed[2] and Ammar A.H. Al-Filfily[1],

[1] Engineering Technical College, Middle Technical University, Baghdad, Iraq [1]
[2] AL-Esraa University Technical Engineering College, Baghdad, Iraq [2]; balsam.college@yahoo.com
* Correspondence: ali-battawi@mtu.edu.iq; Tel.: (+9647801607235)

Abstract: Synthetic materials such as Carbon, Kevlar, and Glass fibers are extensively utilized in various industries due to their superior characteristics including high stiffness, great strength, low den-sity, and high wear resistance, these advantages contributed to making them widespread in ap-plications like; aerospace, automobile, civil and electronics. This research is carried out to enhance the creep compliance of epoxy composite material by considering two types of fibers as reinforcement. A composite material is produced by combining two fibers, Kevlar fiber mixed with sika epoxy resin, along with Carbon fiber also mixed with sika epoxy resin using a Hand-Layup process. Experiments and numerical modeling are examined to offer a comprehensive understanding creep behavior of epoxy composite material in different weight ratios. Burger and Prony models are used to represent stress relaxation and creep strain of Visco-elastic material. According to the results, sika epoxy resin reinforced with Kevlar and Carbon fibers exhibits enhancement in the mechanical properties compared with pure epoxy. The use of Kev-lar/Sika epoxy composite results in higher creep compliance and modulus of elasticity compared with Carbon/Sika epoxy composite.

Keywords: Composite material; Creep compliance; Burger model; Prony series; mechanical properties

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1. Introduction

Composite materials are widely used refer to their exceptional mechanical character-istics, including; impressive tensile strength, high strength-to-weight ratio, superior re-sistance to damage, and better stiffness [1]. Epoxy resin is a class of polymer thermo-set that exhibits remarkable adhesive abilities and mechanical toughness for a wide range of applications in industry. Their ability to be compatible with numerous reinforcement ma-terials allows for substantial design flexibility. This makes it beneficial in advanced epoxy-based composite materials used in industries such as aerospace, automotive, structural engineering, and electronics. Therefore, these composites provide superior performance and exceptional durability. thus, becoming an essential component in modern production [2,3].

Fiber-reinforced polymer composites are superior to traditional composites in terms of efficiency since fiber reinforcement gives the final product dimensional stability. These composites provide plenty of benefits, including flexibility, ease of installation, and an ex-tended life of service. There are numerous forms and types of fibers reachable, aramid fiber (Kevlar) is particularly remarkable due to its effect on strength, stiffness, and other essential characteristics [4–6].

Kevlar fiber is getting recognition for its excellent mechanical properties, compared with glass and carbon fiber it enhances impact resistance, and Kevlar exhibits a superior ability to withstand fracture and reduce impact load [7]. Several researchers have exam-ined fiber characteristics under creep behavior scenarios. Vasudevan et al. [8] investigate the influence of stacking sequences on the mechanical characteristics of Kevlar/glass fiber and carbon/glass fiber composite. Through their observation, they found that enforcement of this synthetic fiber into the fiber composites resulted in a 7.5% enhancement in absorp-tion energy. Sahu et al. [9] illustrated the effects of hybridization on the mechanical characteristics of Kevlar, glass, and carbon fibers hybrid composites via both experimental and numerical simulation. The finding shows a good correlation between the experiment and numerical results. Asit Behera et. al. [10] fabricated the effect of moisture on the

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mechanical characteristic of Kevlar fiber-reinforced epoxy composite. Using hand lay-up technique, by immersion in three different types of solutions. They revealed that compo-site-absorbed moisture decreases tensile and breaking strength significantly. Almeida Jr. et. al. [11] studied the creep characteristics of carbon fibers reinforced epoxy composite with different fiber orientations. By employing both [Findley's and Burger's models] to predict the creep behavior of carbon fibers reinforced epoxy composite, experimental data is then utilized to validate analytical results. Ali A. Battawi and Balsam H. Abed [12] examined the creep behavior of natural fibers (fish scales and chicken feathers) as a suitable reinforcement in polyester composite, with different weight fractions of natural fiber employing the hand lay-up method. In comparison with pure polyester, results reveal encouraging characteristics, as it increases creep strain to 74.2% and reduces creep stress to 40.71%. experimental, numerical, and theoretical results were compared with an average deviation of no more than 3.2%. Ali A. Battawi and Balsam H. Abed [13] explored the effects of adding two types of natural fiber sheep wool and horse hair as a reinforcement agent of polyester composite to improve mechanical properties in terms of creep behavior. ANSYS Mechanical APDL was implemented to verify experimental and theoretical results. Balsam H. Abed and Ali A. Battawi [14] studied the creep characteristics of polyester/polystyrene composites reinforced with a weight ratio of fish scales at constant load and temperature. The Maxwell technique was used to determine stress and modulus of elasticity from the (strain/time) curve, by employing curve fitting techniques. Creep characteristics, stress, and modulus of elasticity are studied experimentally. Balsam H. Abed et. al. [15] evaluated how immersion media affect the creep behavior of polyester compo-site material reinforced with fillers derived from chicken feathers. Creep samples were made by varying weight ratios and immersed in three separate mediums. The results show that composite samples show enhancing creep characteristics due to the immersions. Balsam H. Abed et. al. [16] investigated the creep behavior of epoxy composite with several weight ratios of Yttrium powder. The composite creep samples were subjected to five distinct loads at constant temperatures. Both numerical and experimental evaluations were conducted to assess creep behavior, Young's modulus, and stress of the composites. Yang et. al. [17] researched the creep behavior of epoxy composite tubes in flexural loading using an experimental analysis, creep test was conducted at various stress values from (45 – 75 %) of the flexural ultimate strength at constant temperature and time. The mechanical efficiency, deformation, and reliability of the tubes were evaluated using superposition techniques. Kaveh Rahmani et. al. [18] Examined the corrosion and creep characteristics of an epoxy-based composite material reinforced with Kevlar, carbon, and glass fibers. Results revealed that carbon fiber had the highest creep resistance in comparison with Kevlar and glass fibers, in contrast, Kevlar fiber exhibits the lowest corrosion risk among the three types of fibers. Madhu Bharadwaj et. al. [19] proposed a mathematical model to convert the Burger model into the Prony series by using the ANSYS program. Therefore, the model can depict the entire time-dependent creep behavior. A significant similarity between the data gathered experimentally and the data obtained via ANSYS software. The creep phenomenon in Visco-elastic material can be divided into three categories: (primary, secondary, and tertiary). Creep refers to the material elongation with time, usually occur-ring at high temperatures, while some materials exhibit creep at low temperatures or room temperature. In the primary stage, the material exposed high deformation which slowed down eventually. The creep curve is affected by the material, time, and load. While in the second stage, the material deformation is relatively constant. Finally, in the tertiary stage, a high rate of deformation will occur rapidly leading to material failure.

Most engineering practices focus on the primary and secondary stages, hence in practical applications high deformation seen in the tertiary stage was rarely experienced [20] Figure 1 shows the three stages of creep behavior.

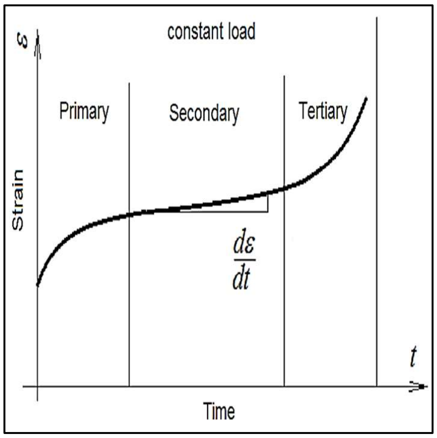

Figure 1. Stages of creep behavior [20].

2. Materials and Methods

2.1. Material

Aramid/Kevlar fiber used in this research Figure (2) has exceptional mechanical characteristics, such as high strength, high degree of stiffness, and resistance to heat, its weight is approximately 1/5 of steel wire weight, its modulus is (2-3) time of glass fiber or steel wire, also its strength (5-6) times compared to the latter. Additionally, it has impressive toughness twice that of steel wire. Notable, even at a temperature reach 560℃ Kevlar fiber sustains its structure integrity, without melting or decomposing. Further, it features strong insulation and aging abilities and a long lifetime.

Figure 2. Kevlar fiber.

Unidirectional woven Carbon fiber Figure (3) imported from Poland, comes in a roll with a length of 50m, width of 100mm, and thickness of 0.167 mm. exhibit specific me-chanical properties, including 4000N/mm2 tensile strength, 230,000 N/mm2 modulus of elasticity, 1.7% elongation to break and 1.82g/cm3 density.

Figure 3. Carbon fiber.

The epoxy resin used is Sikadur -31CF type manufactured in the Kingdom of Bahrain has the following characteristics: easy mix and use, very good adhesion, high resistance to chemicals, good wear resistance, and strong adhesive. Was used as a composite material to bind multiple layers of carbon and Kevlar fibers.

2.2. Preparation of Composite

Resin Sika epoxy is processed as a matrix and mixed with a curing agent named hardener with suitable proportions (3:2%). Samples were prepared as four different reinforcements of Kevlar and carbon fiber contents of 0,1,3 and 5 wt.% as well as pure sika epoxy samples using a conventional (hand layup) technique.

To create tensile and creep test samples, we used rubber molds, the reinforced Kevlar and carbon fiber were cut using a Stanly knife 5mm long and inserted in a longitudinal pattern by the specified weight ratios after the molds were entirely cleaned. next, epoxy resin was gradually poured over the fibers, to ensure sufficient hardening samples were left to cure for 48 hours. Afterward, placed in an oven set at 50 Celsius temperature for further hardening. Finally left for 7 days before the testing began. The blend must have a decent homogeneity to protect the particle from separating or settling, which could bring an uneven mixture and induce agglomeration following hardening.

2.3. Mechanical Testing

2.3.1. Tensile Test

Tensile strength test specimens were conducted in compliance with ASTM standard (D638) Figure 4. Tensile properties of the samples were assessed using a universal testing apparatus (Zwick /RoellZ100), which has a maximum load of up to 300KN Figure 5, by applying 5mm/min. of cross-head speed and occurred at room conditions. three different samples were examined in a tensile test, and their average values were considered and used as the final result. The mechanical property resulting from the test will used as an input data in numerical simulation.

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Figure 4. Tensile test machine.

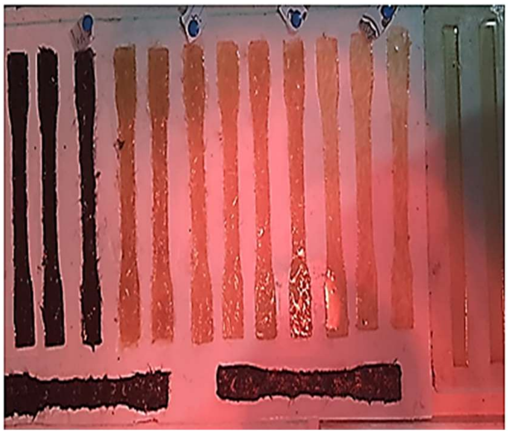
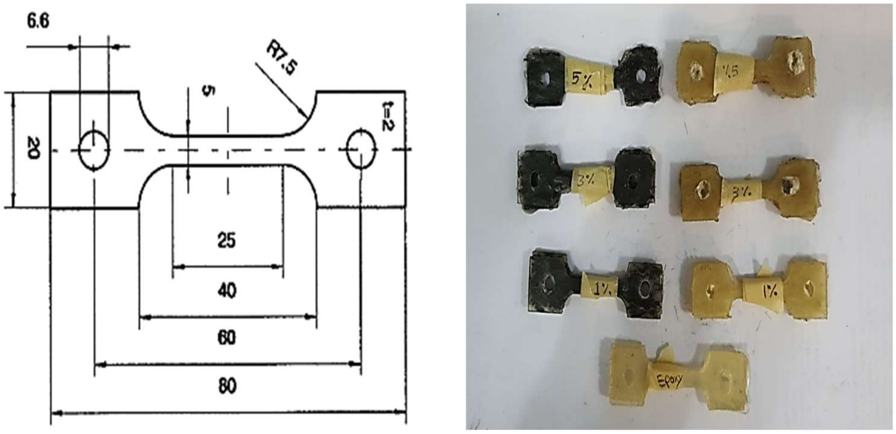


Figure 5. Tensile samples with different weight ratio of Kevlar and carbon fiber.

2.3.2. Creep Test

Creep testing was performed following (ASTM2990) standard [16] at a constant temperature of 27°C with applying a static load of 2N. strain rate of the samples was measured using a digital strain meter. The creep test was conducted utilizing creep test equipment (wp600) as depicted in Figure 6 (a and b). The data collected from the strain/force versus time were digitally stored, analyzed, and recorded on a personal computer. the specimen's dimensions are: 80mm in length, 20mm in width, and 2 mm in thickness as shown in Figure 6 (c), despite all specimens reinforced with different fillers, they share the same dimensions.



(**a**) (**b**)

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(**c**)

Figure 6. (a) Creep samples standard; (b) Creep samples of Kevlar/carbon fiber**;** (c) Creep test equipment (wp600)**.**

3. Constitutive Creep Equations

In essence, Visco-elastic models can used to describe the elastic and viscos of polymeric material. Hence the term (visco-elastic) demonstrates both elastic and viscos models. In the present study employed These models as a useful estimation for understanding the time-dependent behavior of polymers. To generate these models, simple linear component spring and dash-pot are combined in parallel or series layout Maxwell, Kelvin-Viogt and Burger models are mathematical models that combine the characteristics of spring and dash-pot to accurately reflect system behavior. Dash-pot viscosities and spring stiffnesses are model parameters, that can be determined through fitting procedures or experimental data. Maxwell model has an elastic spring (E_1) in parallel with vis-cos dash-pot (η_1), and the Kelvin-Viogt model, which features an elastic model (E_2), in parallel with vis-cos dash-pot (η_2) as shown in Figure 7. The fundamental equations for linear elastic and Viscos are presented in equations 1 and 2:

$$\varepsilon = \frac{\sigma}{E} \quad (1)$$

$$\acute{\varepsilon} = \frac{\sigma}{\eta} \quad (2)$$

Hence: σ: applied stress, ε: strain, ε´: strain rate, E: modulus of elasticity and η: Viscosity.

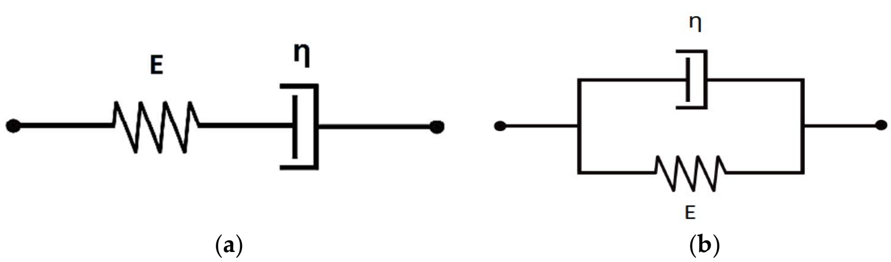

Figure 7. [21] (a) Maxwell model; (b) Kelvin-Viogt model.

These constants represent the required Burgers model. It intends to model the behavior of creep with constant initial stress (σ_0), by combining these two models, by considering initial, primary, and secondary creep strain with acceptable accuracy as illustrated in Figure 8 shows the schematic representation of Burger's model. Generally, the fundamental equation of Visco-elastic material is presented in the differential equation form below:

$$\sigma+(\eta_1/E_1+ \eta_1/E_2+ \eta_2/E_2)\ \dot{\sigma}+ \eta_1\eta_2/E_1E_2\ \ddot{\sigma} = \eta_1\ \acute{\varepsilon} + \eta_1\eta_2/E_2\ \ddot{\varepsilon} \quad (3)$$

To determine material constants (E_1, E_2, η_1, η_2) experimental data may use in the linear viscoelasticity:

$$\sigma(t)= \varepsilon_o/A\ [(q_1-q_2\ r_1)\ e^{(-r_1 t)} – (q_1-q_2\ r_2)\ e^{(-r_2 t)}] \quad (4)$$

where:

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$r_1 = (P_1\text{-}A)/2P_2$, $r_2 = (P_1+A)/2P_2$, $A = \sqrt{(P_1+4P_2)}$, $P_1=(\eta_1/E_1+\eta_1/E_2+\eta_2/E_2)$, $P_2=\eta_1\eta_2/E_1E_2$, $q_1=\eta_1$, $q_2=\eta_1\eta_2/E_2$
stress relaxation equation can be presented as:

$$E(t)= (\sigma(t)/\varepsilon_o = 1/A\ [(q_1\text{-}q_2\, r_1)\, e\text{\^{}}(-r_1t) - (q_1\text{-}q_2\, r_2)\, e\text{\^{}}(-r_2t)] \qquad (5)$$

where r_1, r_2, P_1, P_2, A, q_1, q_2 are material constants, this fundamental equation of linear stress (4), strain (5), derivate with time $\dot{\sigma}$, $\ddot{\sigma}$, $\dot{\varepsilon}$, $\ddot{\varepsilon}$

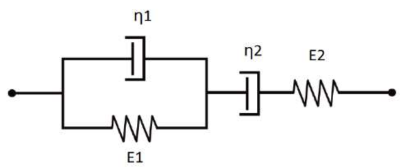

Figure 8. Burger model [21].

Maxwell and Kelvin-Viogt models are appropriate for theoretical and qualitative assessment, but they frequently struggled to depict accurately the physical behavior of actual material, to improve the realism of these materials, additional springs and dash-pots need to be combined to raise the number of elements involved.

The Burger model shown in Figure 8 is the simplest linear model that accurately describes the behavior of time-dependent Visco-elastic materials. This model combined Maxwell and Kelvin-Viogt models in series. The fundamental equation could be derived by investigating the strain responses under applied load, which represented in equation (6).

$$\varepsilon(t)= \sigma_0/E_1+ \sigma_0/\eta_1 t+ \sigma_0/E_2(1\text{-}e\_\eta 2\text{\^{}}(-E_2t)) \qquad (6)$$

(σ_o) initial stress, $\varepsilon(t)$ creep strain with time (t), Experimental data from creep test in linear Visco-elasticity can apply to calculate materials constants (E_1, E_2, η_1, η_2).

Table 1. Constant values of Burgers model.

Constant values of Burgers model for epoxy reinforced Kevlar							
Additives %	P_1 min	P_2 Min^2	q_1 Mpa. min	q_2 $Mpa.min^2$	A Min^2	r_1	r_2
0	330.3054	271.4549	36630.0366	36683.1002	328.6577	0.0030	1.2137
1	803.0154	1016.5172	105263.157	206609.1898	800.4796	0.0012	0.7887
3	354.0365	598.5443	79051.3833	184735.9090	350.6389	0.0028	0.5886
5	203.7521	258.5752	104112.441	184696.5895	201.1980	0.0049	0.7830
Constant values of Burgers model for epoxy reinforced Carbon							
1	625.456	422.264	7502.944	6246.478	420.260	0.2429	1.2382
3	1898.479	1192.898	58993.569	38480.515	1190.896	0.2965	1.2949
5	921.341	1029.704	45997.102	64356.514	1027.702	0.0516	0.9464

4. Finite Element Modeling

Because of the intricacy of a mathematical model, few Visco-elasticity problems have a proven analytical solution. Nevertheless, the implementation of numerical simulation and digital technology has had an important effect on this field of study. Finite element analysis is one of the numerical techniques created to face the difficulties of structure analysis consisting of both linear and non-linear Visco-elastic material. Such methods are carried out through specialist application programs made for this purpose such as ANSYS software [22].

Many commercial finite element approaches like ANSYS and ABAQUS do not incorporate the Burger model into their software. However, a more general Visco-elastic model named the Prony series that can be used to represent a wide range of materials. The burgers model may be implemented into this finite element software by modifying the constants of the Prony series appropriately. This process is described in this section, in which the Burgers model is imitated by modifying the Prony series. Literature [19] indicates that a specific approach can be used to transform

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Burger parameters into Prony coefficients (τ_1, τ_2, g_1, g_2). As a result, the material constant must be presented in ANSYS as follows:

$$\tau_1=1/\beta,\ \tau_2=1/\alpha,\ g_1=1/(\alpha-\beta)\ \{Gk/\eta k-\beta\},\ g_2=1/(\alpha-\beta)\ \{\alpha-Gk/\eta k\} \quad (7)$$

where: $\alpha, \beta = (P_1 \pm \sqrt{([P_1] ^2-2P_2)})/2P_2$

Burger model parameters and Prony series coefficients used in the ANSYS program for different weight ratios of Kevlar and carbon fiber are presented in Table 2.

Table 2. Constant values of PRONY SERIES.

Constant values of PRONY SERIES for epoxy reinforced Kevlar								
Additive %	**β 1/sec**	**p_1 sec2**	**τ_1 sec**	**g_1 N/mm**	**α 1/sec**	**p_2 sec2**	**τ_2 sec**	**g_2 N/mm**
0	5.1098E-05	19617.1253	19570.0164	1.801	0.0212	921922.4436	47.1089	8.888
1	2.0782E-05	48193.6442	48117.5351	2.710	0.0131	3662182.7608	76.1091	4.952
3	4.7303E-05	21242.1908	21140.2640	4.115	0.0098	2154759.642	101.926	11.028
5	8.2314E-05	12225.1288	12148.5045	9.523	0.0130	930870.8113	76.6243	24.691
Constant values of PRONY SERIES for epoxy reinforced Carbon								
1	1.7494E-05	57248.7134	57160.9726	1.975	0.0113	5015351.5541	87.7408	8.1300
3	3.1619E-06	316324.895	316256.9103	4.301	0.0147	21500570.718	67.9845	16.606
5	1.8059E-05	55439.2245	55371.803	8.333	0.0148	3733197.7323	67.4205	33.167

In this study, the commercial finite element software ANSYS 15.0 was used to confirm the numerical solution. Plane 182 2D solid structure element with four nodes and two degrees of freedom commonly used in the ANSYS program, was performed to model a finite element analysis of the creep test sample utilized in this simulation. AutoCAD software was used to create a Two-dimensional creep sample, then exported to ANSYS to simulate the behavior of creep for an epoxy composite sample reinforced with two types of filler in different weight ratios. Figure 9 depicts a two-dimension finite elements design of a creep test sample.

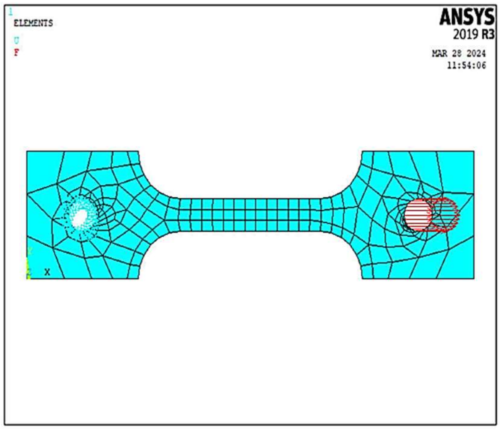

Figure 9. Finite elements design of creep test sample.

5. Results and Discussion

Sika epoxy composite conducted to mechanical test prior to and after adding fiber reinforcement to assess the effects addition of fibers on the mechanical characteristics of the materials.

5.1. Creep Strain

Figures (10 and 11) present the behavior of creep strain as a function of time for both Sika epoxy-reinforced Kevlar fiber and Sika epoxy-reinforced carbon fiber in three different weight fractions compared with pure sika epoxy between experimental, theoretical, and numerical studies. the pure Sika epoxy composite exhibits a high creep strain value in comparison with the one reinforced with the fiber. With increasing the percentage of Kevlar and carbon fiber creep strain tends to decrease gradually. the lowest creep strain value obtained with Kevlar fiber at 3% weight fraction, the rate of creep strain was reduced by half compared with pure sika epoxy, while for carbon fiber creep strain was reduced to 44% at 1% weight fraction.

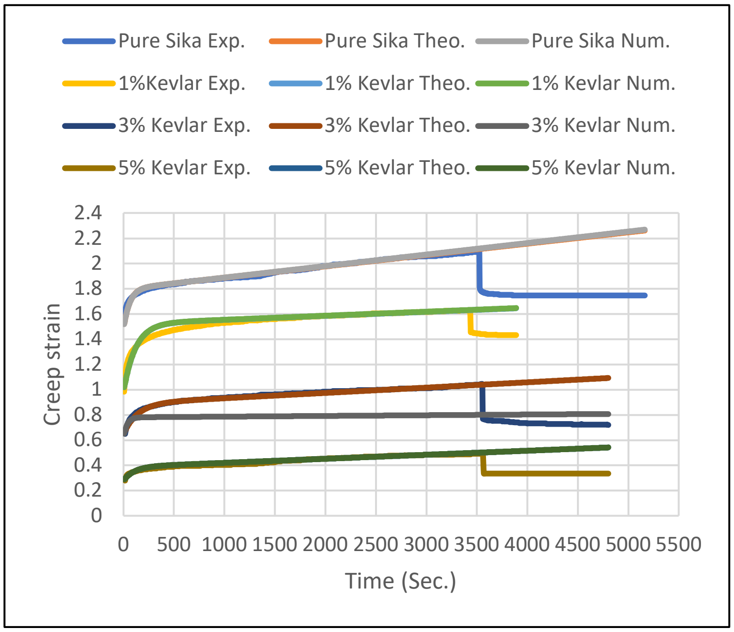

Figure 10. A comparative of creep strain between exp. Theo. And num. result for Kevlar fiber.

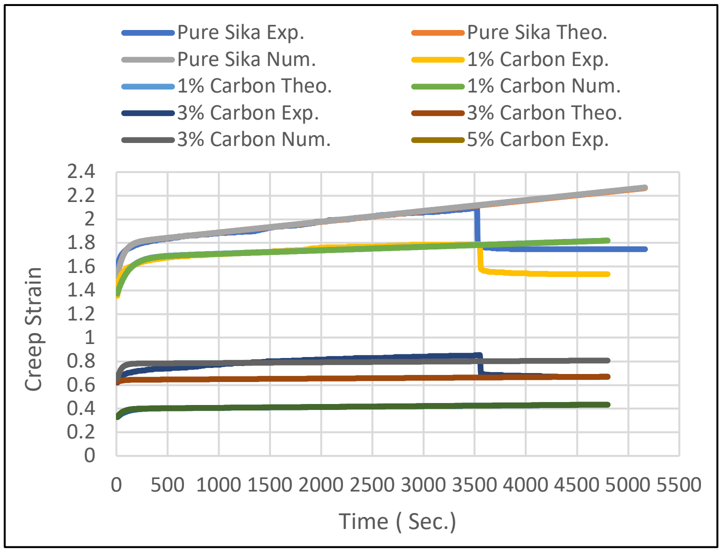

Figure 11. A comparative of creep strain between exp. Theo. And num. result for carbon fiber.

The experimental results indicate that pure sika epoxy has a creep strain (0.0148) but when Kevlar fiber was added at weight fractions (1%, 3%, and 5%) this value dropped gradually to (0.00984, 0.00648, and 0.0028). and adding carbon fiber to sika epoxy creep strain was reduced to (0.01352, 0.0062, and 0.0032) compared with pure sika epoxy.

5.2. Creep Stress

Figures (12, and 13) show the discrepancy of creep compliance, defined by the proportion between stress and versus time by applying a static load of 2N at constant temperature (27c⁰). the stresses steadily decrease with an increase in the weight fraction of Kevlar and carbon fibers. Yet, the sika epoxy composite containing a 3% weight fraction of Kevlar fiber has the highest percentage compared with carbon fiber and pure epoxy. Hence, can withstand more stress up to 15% compared with sika epoxy, while carbon fiber can handle only 8%.

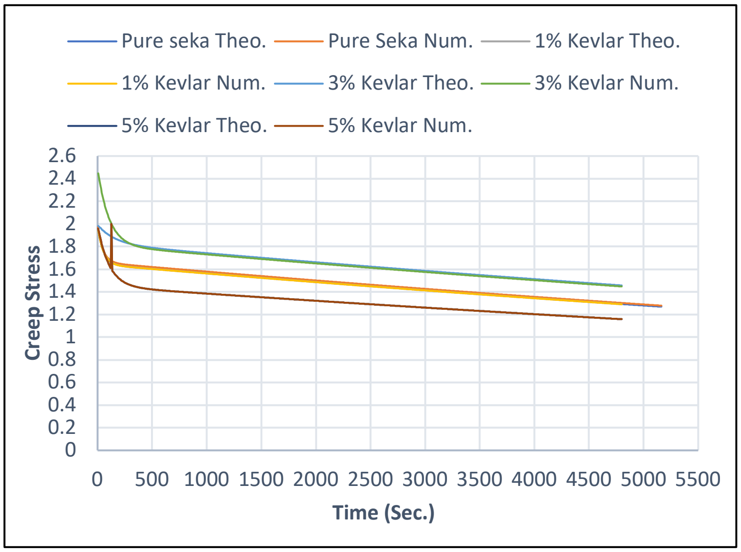

Figure 12. A comparative of creep stress between exp. Theo. And num. result for Kevlar fiber.

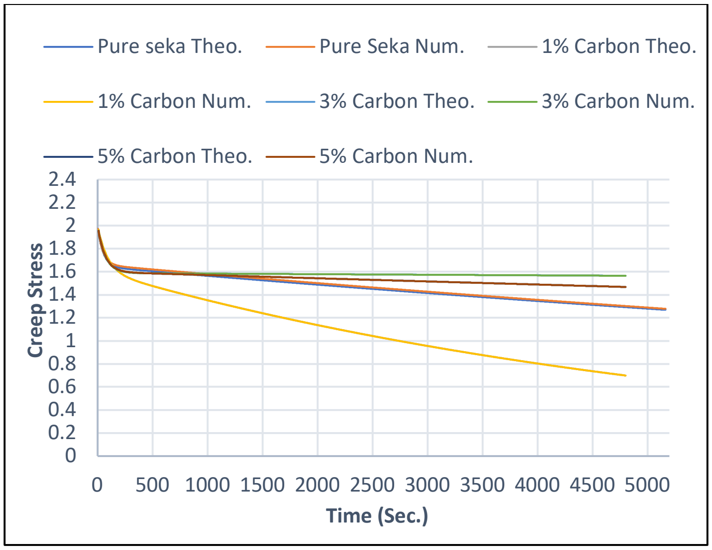

Figure 13. A comparative of creep stress between exp. Theo. And num. result for carbon fiber.

Three compliant master curves that were nearly coincidental depicted convergence of experimental, theoretical, and numerical results and showed a relatively small percentage of error.

Fiber absorbs a large amount of load, enhancing composite materials' creep strength. For instance, a composite with 3% Kevlar fiber has lower creep stress than 1% Kevlar fiber, as a result, the levels of stress are reduced.

The finite element result (Ansys 15.0) utilized Prony series equations to illustrate the Burger model. Creep strain and creep stress for a specimen with 2N load and 27Co temperature were analyzed Figure 14 shows creep behavior for maximum and minimum values. Also, it discovered that numerical simulation results of creep strain satisfy experimental data.

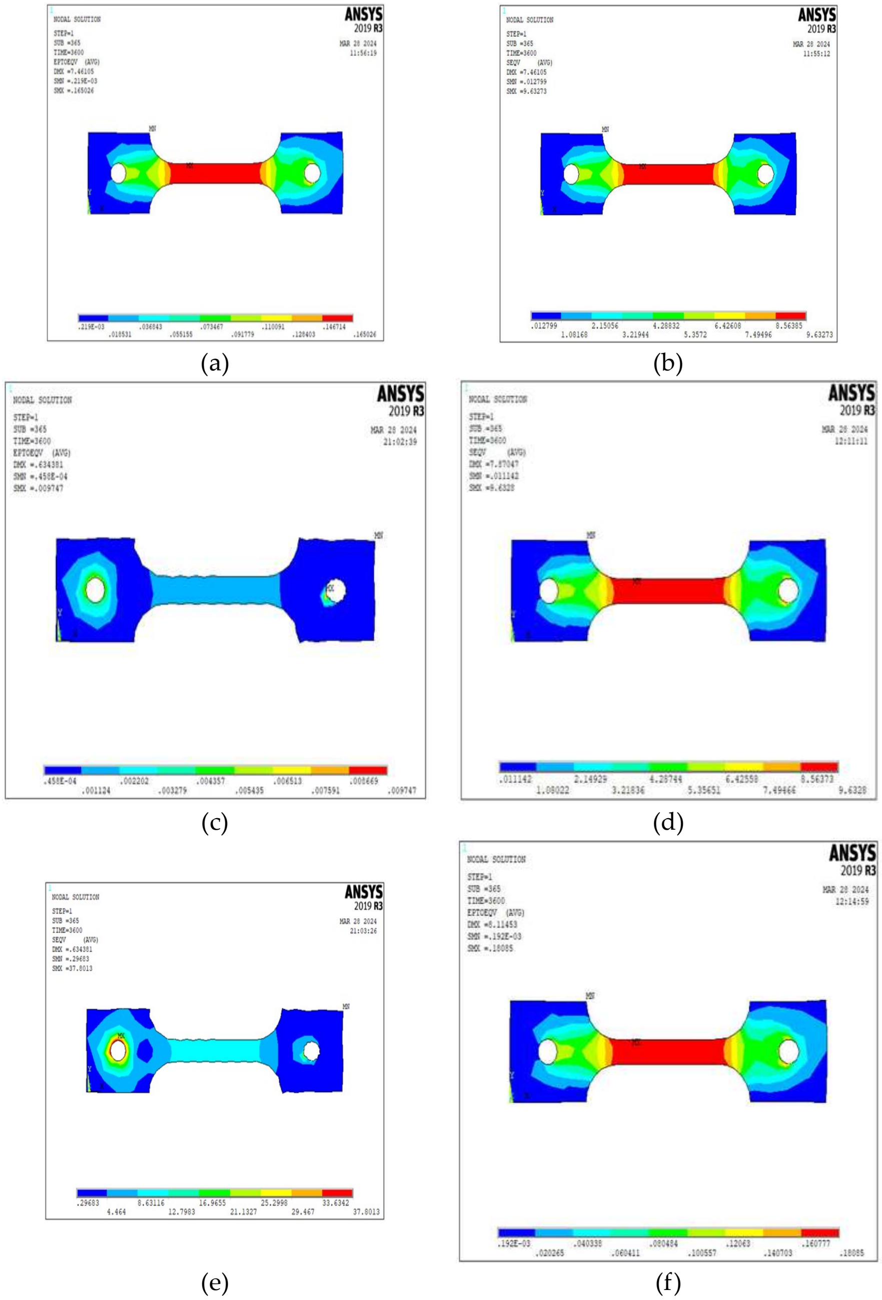

Figure 14. Numerical simulation results of creep strain and stress for epoxy reinforced with Kevlar and carbon fiber (a) creep strain for pure epoxy, (b) creep stress for pure epoxy, (c) creep strain for 3%Kev lar fiber, (d) creep strain for 1% carbon fiber, (e) creep stress for 3% Kevlar fiber and (f) creep stress for 3% carbon fiber.

6. Conclusions

In this study, the creep behavior of sika epoxy composite reinforced with carbon fiber and Kevlar fiber was investigated. The result of the creep test revealed that improved creep compliance correlated with high weight fraction, this suggests that weight percentage is essential for determining the mechanical characteristics of the materials. Fiber type is cruel, Kevlar fiber possesses the lowest creep strain and low-stress level than carbon fibers. Hence Kevlar fibers are stronger and have greater resistance to creep. Consequently, it's strongly recommended. The results proved that the theoretical results obtained using the Burger method fit closely with the Prony series utilized in numerical simulation ANSYS 15.0 program results both had potential for accurate prediction of experimental findings.

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The significant improvement of mechanical characteristics, especially creep strength, by the inclusion of carbon and Kevlar fibers with weight fractions up to 5%, offers an important chance for incorporating these material composites in the arrangement of mechanical applications. Especially for lightweight components. This could permit it to be utilized as an alternative to iron or metal parts.

Conceptualization: A.A.H., A.A.B. and B.H,A.; methodology, A.A.B. and B.H.A. ; software, A.A.H. and B.H.A.; Preparation of composite, B.H,A.; theoretical analysis, B.H.A. and A.A.H.; investigation, A.A.H. and B.H,A.; resources, A.A.B.; data curation, B.H.A. and A.A.B.; writing—original draft preparation, A.A.H. and A.A.B. ; writing—review and editing, A.A.B.; visualization, A.A.H. and B.H.A.; supervision, A.A.H.; project administration, B.H.A.; funding acquisition, A.A.H., A.A.B. and B.H,A. All authors have read and agreed to the published version of the manuscript.

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