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Effect of fiber orientation and stress level on creep behavior of glass fiber reinforced epoxy composites

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Abstract

Glass fiber reinforced polymer (GFRP) composites, made of glass fiber and plastic, are widely used in structural applications because of their high strength and resistance to corrosion. But the orientation of the fibers and the level of stress have a major effect on their performance characteristics when subjected to constant stress. This paper experimentally investigates the flexural and flexural creep behavior of glass fiber-reinforced epoxy composites with varying fiber orientations. Composite laminates were made using the vacuum-assisted resin transfer molding (VARTM) process. The specimens with fiber orientations of 0°, 30°, 45°, and 60° were prepared and tested. Initially, static three-point bending tests were conducted to determine the ultimate flexural strength values. Creep tests were conducted at stress levels of 25%, 50%, and 75% of the maximum flexural strength for 120 minutes, based on these values. The results showed that the fiber orientation significantly affected both flexural strength and creep response. The specimens with a 0° fiber orientation showed the highest flexural strength as 133.1 ± 17.8 MPa and the lowest creep deformations which are 0.78 mm, 1.48 mm, and 2.69 mm for 25%, 50%, and 75% stress levels, respectively after two hours. On the contrary, the 45° fiber orientation showed the lowest strength as 63.2 ± 8.9 MPa and hence highest creep deformations which are 1.01 mm, 2.53 mm, and nearly 10 mm for 25%, 50%, and 75% stress levels, respectively. The 45° fiber-oriented sample was failed after nearly 2000 seconds which could not reach the two hours under 75% stress level. With an increase in the fiber orientation angle, the stiffness reduced and the displacement increased due to the dominance of matrix-dominated deformation mechanisms. As stress levels rose, the impact of fiber orientation intensified, leading to unstable creep behavior, especially in 45° specimens at a 75% stress level. The findings demonstrate that both fiber orientation and applied stress level must be considered in the design of GFRP components subjected to long-term loading conditions.

Keywords: *Glass fiber reinforced composite, flexural creep behavior, fiber orientation, three-point bending, VARTM.*

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Elyaf yönelimi ve gerilme seviyesinin cam elyaf takviyeli epoksi kompozitlerin sürünme davranışı üzerindeki etkisi

Öz

Cam elyafı takviyeli polimer kompozitler, cam elyafı ve polimerden oluşan yapıları sayesinde yüksek dayanım ve korozyona karşı dirençleri nedeniyle yapısal uygulamalarda yaygın olarak kullanılmaktadır. Ancak sabit gerilme altında kaldıklarında, elyafların yönelimi ve gerilme seviyesi performans özellikleri üzerinde büyük bir etkiye sahiptir. Bu çalışma, farklı elyaf yönelimlerine sahip cam elyafı takviyeli epoksi kompozitlerin eğilme ve eğilme yükü altında sürünme davranışını deneysel olarak incelemektedir. Kompozit yapılar vakum destekli reçine transfer kalıplama yöntemi kullanılarak üretilmiştir. 0°, 30°, 45° ve 60° elyaf yönelimlerine sahip numuneler hazırlanmış ve test edilmiştir. Öncelikle, nihai eğilme dayanımı değerlerini belirlemek amacıyla statik üç nokta eğme testleri gerçekleştirilmiştir. Bu değerlere dayanarak, maksimum eğilme dayanımının %25, %50 ve %75'i seviyelerinde 120 dakika süreyle sürünme testleri yapılmıştır. Sonuçlar, elyaf yöneliminin hem eğilme dayanımı hem de sürünme tepkisi üzerinde önemli bir etkiye sahip olduğunu göstermiştir. 0° elyaf yönelimine sahip numuneler 133,1 ± 17,8 MPa gerilme değeri ile en yüksek eğilme dayanımını ve iki saatlik sürünme yükü uygulanmasından sonra %25, %50 ve %75 gerilim seviyeleri için sırasıyla 0,78 mm, 1,48 mm ve 2,69 mm olan en düşük sürünme deformasyonları gözlemlenmiştir. Aksine, 45° lif yönelimi en düşük mukavemeti (63,2 ± 8,9 MPa) göstermiş ve dolayısıyla %25, %50 ve %75 gerilim seviyeleri için sırasıyla 1,01 mm, 2,53 mm ve yaklaşık 10 mm olan en yüksek sürünme deformasyonlarını sergilemiştir. 45° elyaf yönelimli numune, %75 gerilim seviyesinde yaklaşık 2000 saniye sonra kırılmıştır ve iki saatlik süreye ulaşamamıştır. Elyaf yönelim açısının artmasıyla birlikte, matris ağırlıklı deformasyon mekanizmalarının baskın hale gelmesi nedeniyle rijitlik azalmış ve yer değiştirme artmıştır. Gerilme seviyeleri arttıkça, elyaf yöneliminin etkisi daha belirgin hale gelmiş ve özellikle %75 gerilme seviyesinde 45° numunelerde kararsız sürünme davranışına yol açmıştır. Bulgular, uzun süreli yükleme koşullarına maruz kalan GFRP bileşenlerinin tasarımında hem elyaf yöneliminin hem de uygulanan gerilme seviyesinin dikkate alınması gerektiğini göstermektedir.

Anahtar kelimeler: *Cam elyaf takviyeli kompozit, sürünme davranışı, elyaf yönelimi, üç-nokta eğme, VARTM.*

1. Introduction

Fiber reinforced polymer (FRP) composites have been widely utilized across various engineering disciplines owing to their superb stiffness and strength-to-weight ratio. Among these, GFRP composites have achieved broad adoption in numerous industries due to their exceptional strength to weight ratio, corrosion resistance, and adaptability to diverse environmental conditions [1–5]. These materials find extensive application in the automotive, aerospace, and marine sectors, where friction and wear performance substantially affect component lifespan and operational efficiency. Moreover, GFRP composites provide highly versatile design possibilities, notable durability, and cost efficient manufacturing and assembly processes [6,7]. The analyzing of time-dependent mechanical properties of GFRP is essential to improve their durability not only for static loads but also for industrial applications. Creep behavior is an appropriate method to analyze the time-dependent properties under static loading [8,9].

Creep deformation refers to the gradual plastic deformation of materials over time under constant stress levels. It is a significant factor limiting the lifespan of components operating under continues loads for a period of time. The degree of creep deformation is influenced by intrinsic factors such as crystal structure, grain size, and defect concentration, as well as extrinsic factors such as load, temperature, and structural geometry like fiber orientation [10–12].

Sa et al. performed bending creep tests on pultrusion-produced GFRP material made of polyester and E-glass fiber on two different scales: (i) laminate and (ii) full-scale profile. The results confirm the significant effect of creep on GFRP profiles; small-scale specimens fractured even at load levels as low as 50% of the ultimate stress. Furthermore, the creep measured in both specimen types was quite significant after the first hours, even at an average load level of 30% [18]. In the study of Li et al., they investigated the flexural creep behavior of composite sandwich beams with GFRP surface layers and a balsa wood core. First, static three-point bending tests were performed on the beams, yielding an average ultimate load-carrying capacity of 6.08 kN. The results show that the creep behavior exhibits linear viscoelastic properties when the load level is below 40%, while creep failure occurs in all specimens at 60% and 80% load levels [19]. Gao et al. proposed a method for predicting the static and creep behavior of GFRP composites based on microscopic and macroscopic finite element (FE) analysis, as well as experimental tests. The relationship between static load and deflection, and the relationship between creep deflection, creep load, and creep time were obtained for GFRP laminates and laminations. The results demonstrate that the FE method effectively predicts the static and creep behavior of GFRP laminates [13]. Cheng et al. experimentally investigate the flexural creep behavior of a pultrusion tube made of GFRP and present the corresponding fit model and lifetime prediction equation. When the load level is below 45%, the creep behavior appears to be linear viscoelasticity. However, at a load level of 57.5%, the specimens underwent shear fracture, and at a load level of 70%, generalized flexural fracture occurred [14].

A great deal of work has been carried out in the area of creep behavior in GFRP composite materials. However, most of these works were carried out for specific configurations such as profiles or sandwich structures under numerical prediction methods. Very little has been carried out in the area of investigation of the flexural creep behavior of laminated GFRP composite materials under varying fiber orientations while subjected to similar conditions of loading. As it has been considered that one of the most important factors affecting anisotropic mechanical behavior in composite materials is the fiber orientation, it becomes necessary to have an idea about the influence of fiber orientation on creep behavior in GFRP composite materials for effectively designing these composite materials. In this paper, an experimental investigation has been carried out for investigating the flexural creep behavior under varying stress levels in woven glass fiber reinforced epoxy composite materials while subjected to varying fiber orientations. The static flexural tests along with creep tests provide an effective comparison of time-dependent flexural behavior in GFRP composite materials under varying fiber orientations.

2. Materials and methods

2.1. Materials

The plain-woven glass fiber fabric, with an areal density of 200 g/m², was sourced from Kompozitpazari (Turkey) for use as the reinforcing material. The epoxy resin was procured from Omnis Kompozit (Turkey). A Tekno Marin epoxy resin (ERA 4000-A) and a hardener (ERA 4000-B) were combined in a 2:1 weight ratio prior to impregnation of the glass fiber fabric layup. The composite laminates were produced at room temperature, with no post-curing treatment applied.

2.2. Composite material production

A VARTM process was employed for the production of GFRP laminates [15]. A schematic depiction of VARTM process is presented in Figure 1. Initially, a release film was placed on the top of Teflon surface. Glass fiber fabrics, cut to 60 cm × 60 cm, were then stacked in ten layers over the release film. A peel ply and a porous flow mesh were positioned above the stacked fabrics to enhance the flow characteristics of the epoxy resin through the glass fiber web. After sealing the assembly with a vacuum bag and connecting the inlet and outlet lines, resin infusion was conducted under vacuum. Excess resin was collected in a resin trap to prevent contamination of the vacuum pump.

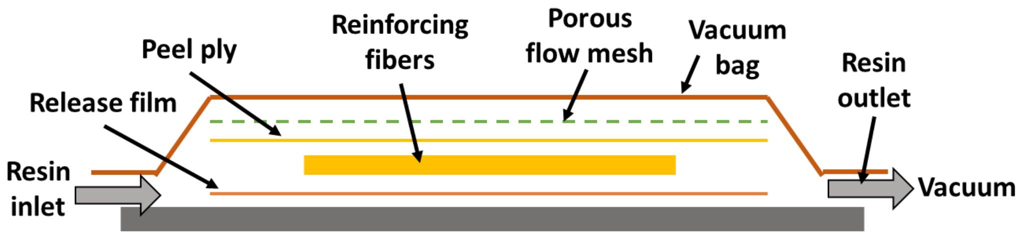

Figure 1. The schematic representation of VARTM process

Following the production of the flat composite sheet measuring 60 cm × 60 cm, the assembly was left to cure for 24 hours. The average thickness of the laminate was measured by caliper around 2.5 mm. Since the laminate was produced from a plain-woven fabric which has 0°-90° fiber directions, the test samples of 0°, 30°, 45°, and 60° fiber-oriented were cut by adjusting the angles from composite laminate.

2.3. Three-point bending test

Three-point bending tests were performed on GFRP composites with different orientations to calculate their stress values according to ASTM D790 standard. The three-point bending test was performed on an Instron 5982 static testing machine. The dimensions of the samples were 100 mm x 12.7 mm x 2.5 mm. The span length was kept 40 mm for all samples to get the 1:16 ratio with thickness. All tests were conducted under displacement control at a constant crosshead velocity of 1 mm/min. Three samples were tested from each experimental group, and average values were calculated.

2.4. Creep bending test

Creep bending tests were performed on GFRP composites with different orientations was performed on an Instron 5982 static testing machine. All tests were performed at room temperature with same dimensions of three-point bending test and with same test apparatus configuration. Three samples were tested from each experimental group, and average values were calculated. Creep bending experiments were conducted for 120 minutes (7200 s) at a loading rate of 5 N/s until the target load was attained, after which the load was held constant for the remainder of the test. A visual representation of the experimental system is shown in Figure 2. The sample codes for creep test results were labeled according to their fiber angles and stress levels. For instance, the 45-50 sample level shows the 45° fiber orientation and 50% stress level, and so on.

Figure 2. Creep bending test applied to GFRP composites

3. Results and discussion

3.1. Results of the flexural tests

In this study, the flexural creep behavior of glass fiber–reinforced composite specimens with different fiber orientations was investigated at various stress levels corresponding to 25%, 50%, and 75% of their ultimate flexural strength. For this purpose, static three-point bending tests were conducted on three specimens for each fiber orientation in order to determine the maximum load required to calculate the ultimate flexural stress (Equation 1). All tests were performed under displacement control at a constant crosshead speed of 1 mm/min. The maximum stress values were calculated using Equation (1), and the corresponding stress levels (25%, 50%, and 75% of the maximum stress) were subsequently defined for the creep tests. Flexural creep experiments were then carried out under these predefined load levels.

The results of the flexural tests are presented in Figure 3, while the stress values calculated using Equation (1), which were employed in the creep tests, are summarized in Table 1.

$$\sigma_{mean} = \frac{3}{2}\frac{PL}{bd^2} \tag{1}$$

In Equation (1), P represents the maximum load obtained from the flexural test, L denotes the specimen span length, b is the specimen width, and d corresponds to the specimen thickness.

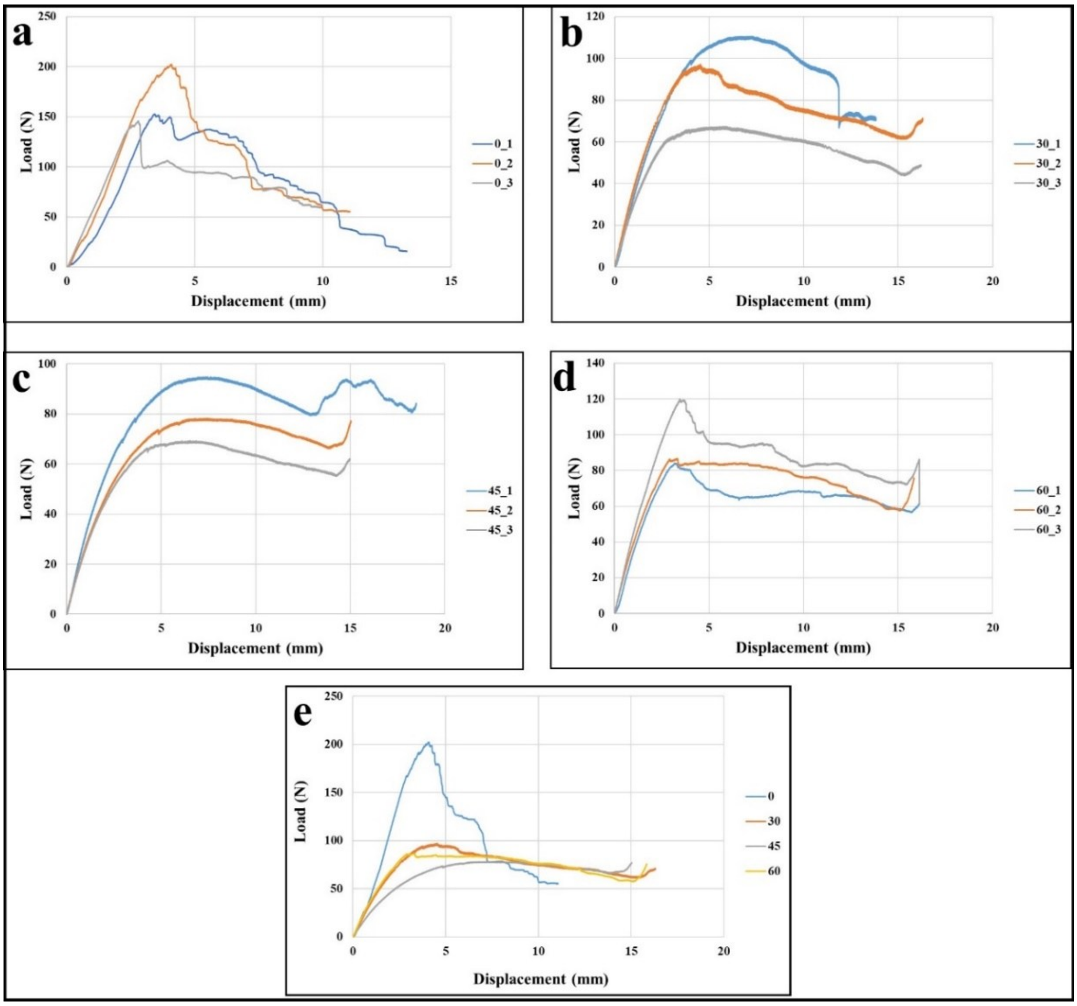

Figure 3. Load–displacement curves obtained from three-point bending tests for GFRP specimens with different fiber orientations: (a) 0°, (b) 30°, (c) 45°, (d) 60°, and (e) comparative response of all orientations

Figure 3 shows that fiber orientation significantly affects the flexural behavior of the composite specimens. All samples exhibit an initial linear elastic region followed by a peak load and subsequent load drop due to damage progression. The 0° specimens demonstrate the highest stiffness and maximum load, indicating efficient load transfer along the fiber direction, but show a more brittle post-peak response. As the fiber angle increases (30°, 45°, and 60°), both stiffness and maximum load decrease due to the increasing contribution of shear stresses and matrix-dominated behavior. The 45° and 60° oriented specimens display a more gradual load reduction, suggesting a relatively more ductile damage mechanism. Table 1 shows the applied loads for each stress levels to each fiber orientation configuration for creep tests. The sample width and thickness were measured by caliper; hence the creep load values are various for all orientation and stress levels.

Table 1. Flexural test results and creep loads for each stress levels

Properties	0°	30°	45°	60°
σ_{mean} (MPa)	133.1 ± 17.8	74.4 ± 14.3	63.2 ± 8.9	74.6 ±11.4
P_{25} (N)	44	26	19	20
P_{50} (N)	79	52	40	40
P_{75} (N)	117	78	60	71

σ_{mean}: *Max. average stress in flexural test; P_{25}: denotes the load corresponding to 25% of the average maximum flexural stress; P_{50}: denotes the load corresponding to 50% of the average maximum flexural stress; P_{75}: denotes the load corresponding to 75% of the average maximum flexural stress.*

3.2. Flexural creep test results

In this study, flexural creep tests were performed on GFRP specimens with different fiber orientations under the load levels given in Table 1, corresponding to 25%, 50%, and 75% of the maximum flexural stress. The creep experiments were conducted for 120 minutes at a loading rate of 5 N/s until the target load was reached and then maintained constant throughout the test duration. The load–displacement curves obtained from the creep tests are presented in Figure 4, while the displacement–time curves are shown in Figure 5.

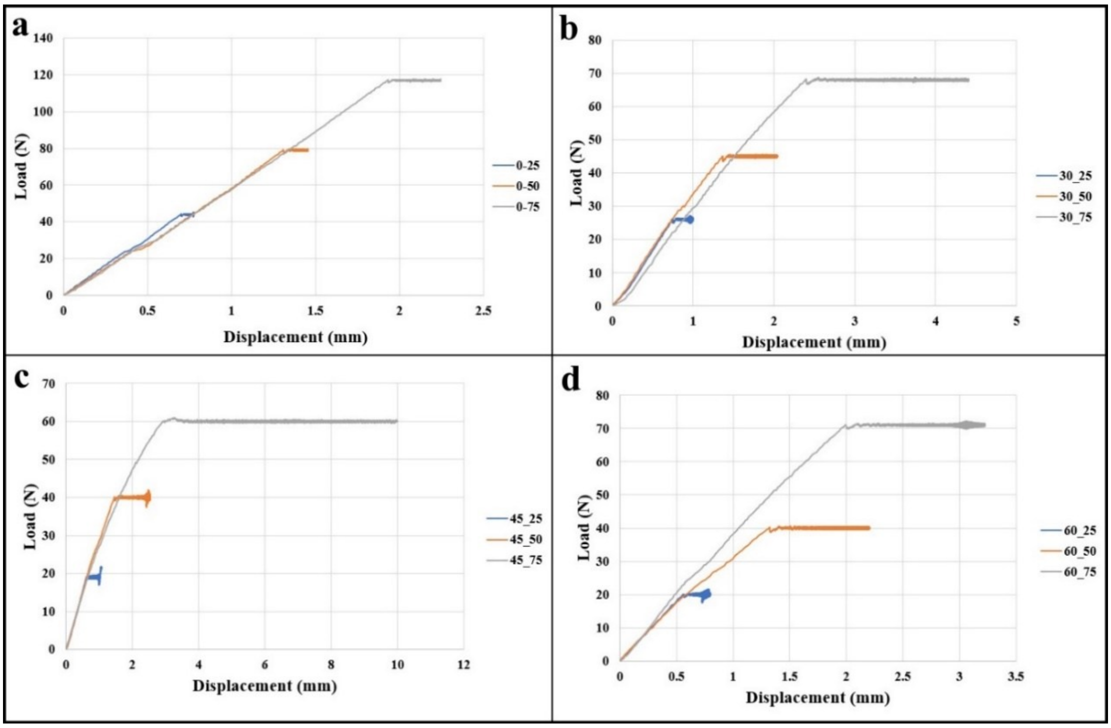

Figure 4. Load–displacement curves obtained from flexural creep tests of GFRP specimens with different fiber orientation angles: (a) 0° orientation at 25%, 50%, and 75% load levels; (b) 30° orientation at 25%, 50%, and 75% load levels; (c) 45° orientation at 25%, 50%, and 75% load levels; (d) 60° orientation at 25%, 50%, and 75% load levels

The load–displacement curves show an initial linear elastic region for all specimens, representing their flexural stiffness. After reaching the target load levels (25%, 50%, and 75%), a plateau region is observed, indicating that the load was kept constant during the creep test. Higher load levels result in greater displacement, confirming the stress-dependent nature of creep deformation.

Fiber orientation significantly affects the mechanical response. The 0° specimens exhibit the highest stiffness and lowest displacement due to efficient load transfer along the fiber direction. As the fiber angle increases (30°, 45°, and 60°), stiffness decreases and displacement increases, indicating a greater contribution of shear stresses and matrix-dominated behavior. Overall, increasing the fiber orientation angle reduces flexural stiffness while enhancing deformation capacity. The study conducted by Wang et al. [16] showed the similar trend for the change of stiffness with increasing fiber orientation.

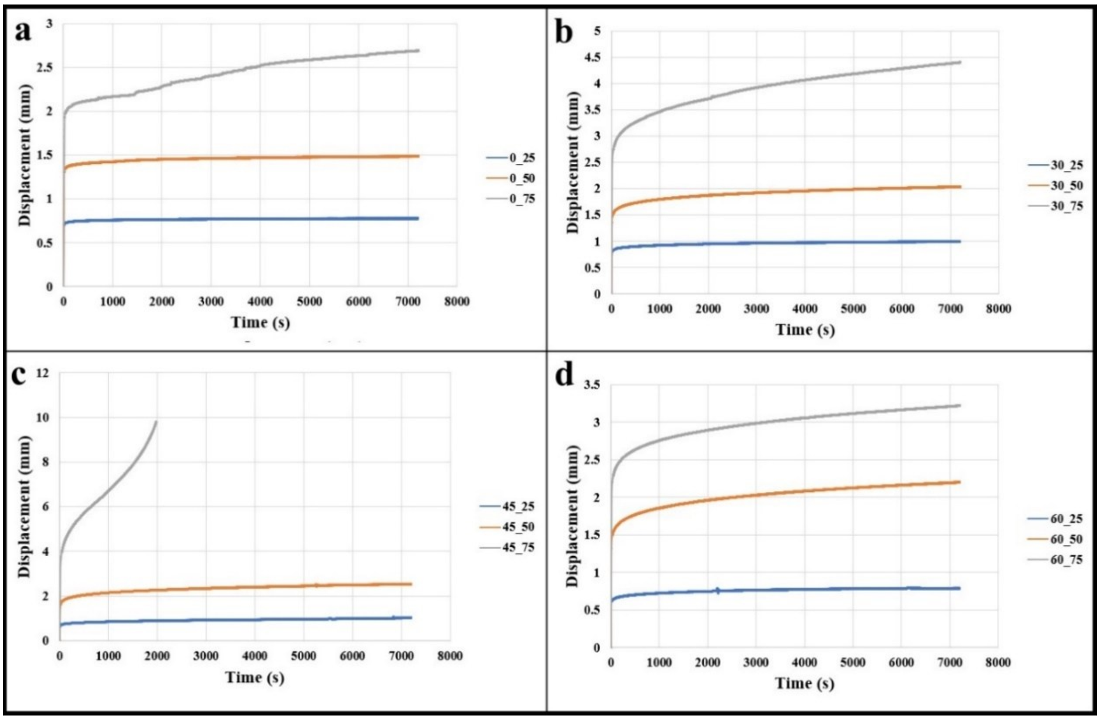

Figure 5. Displacement-time curves obtained from flexural creep tests of GFRP specimens with different fiber orientation angles: (a) 0° orientation at 25%, 50%, and 75% load levels; (b) 30° orientation at 25%, 50%, and 75% load levels; (c) 45° orientation at 25%, 50%, and 75% load levels; (d) 60° orientation at 25%, 50%, and 75% load levels

In creep tests, displacement–time curves are essential for evaluating the time-dependent deformation behavior of materials under constant load. These curves reveal the instantaneous elastic deformation, the primary creep stage, and the possible secondary steady-state creep region. They also provide critical information about creep rate, dimensional stability, and the onset of damage. In composite materials, the influence of fiber orientation and load level on long-term performance can be clearly assessed through these curves. Figure 5 presents the displacement–time curves of the specimens at different fiber orientations (0°, 30°, 45°, and 60°) and load levels (25%, 50%, and 75%). All specimens exhibit an initial instantaneous elastic deformation followed by a time-dependent creep region with a decreasing slope. Increasing the load level leads to higher initial displacement and greater creep deformation, with the 75% load level showing a noticeably higher creep rate. Berardi et al. [17] conducted experimental study for the creep behavior of GFRP and they validated the results using an analytical model, and both of them showed that the higher stress level yields higher deformation.

In terms of fiber orientation, the 0° specimens demonstrate the lowest time-dependent deformation and thus the best creep resistance. As the fiber angle increases to 30° and

60°, displacement increases due to the greater influence of shear stresses and matrix-dominated behavior. The epoxy matrix is more prone to deformation than glass fiber, hence matrix dominant behavior makes the creep deformation to increase [17]. The 45° specimens, particularly at the 75% load level after nearly 35 minutes, show a sudden and significant increase in displacement due to failure of the sample indicating unstable creep or the onset of damage. Moreover, the flexural strength of the 45° oriented sample is lower than others in which the durability under 75% stress level is low for it. Overall, increasing fiber orientation angle results in higher creep deformation and reduced long-term dimensional stability.

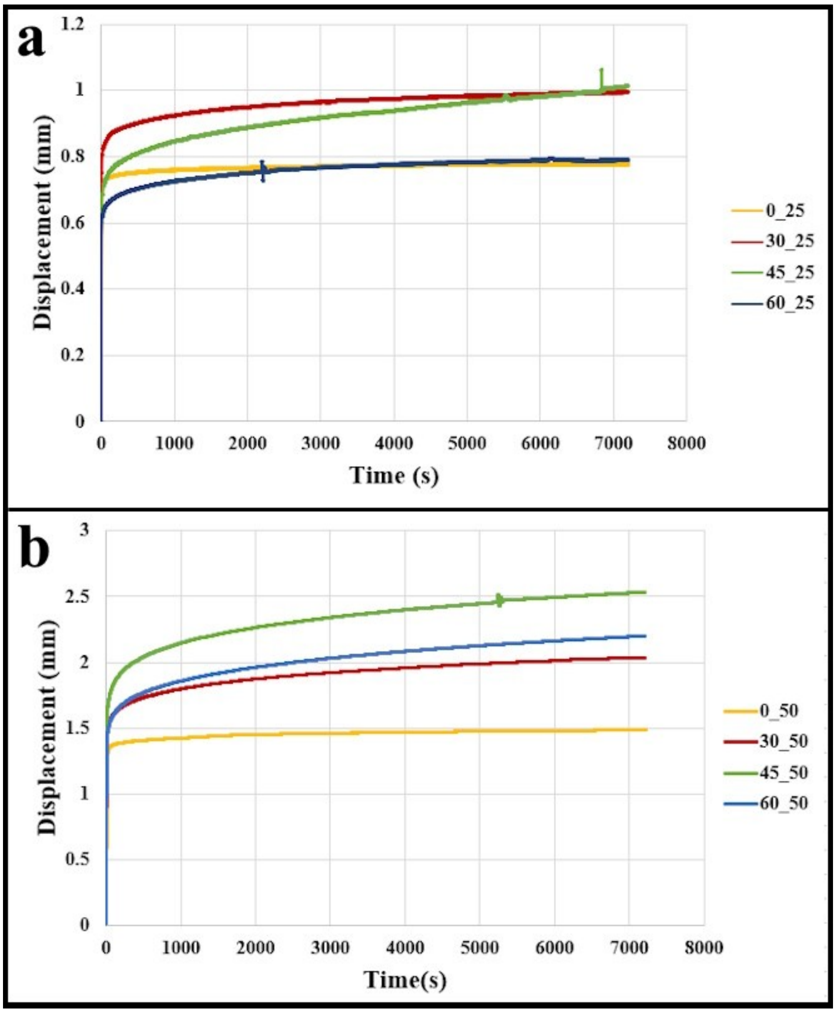

Figure 6. Displacement-time curves for comparison; (a) 25% load levels, (b) 50% load levels

Examination of the Figure 6 indicates that the creep behavior is significantly influenced by both the applied stress level and the fiber orientation. At 25% of the maximum stress, a comparison of the curves shows that the difference in deformation among specimens with different fiber orientations remains relatively limited. However, when the stress level is increased to 50% of the maximum stress, the differences in creep deformation between fiber orientations become more pronounced.

Overall, as the applied stress ratio increases, the influence of fiber orientation on creep behavior becomes increasingly evident. While the orientation effect is relatively minor at low stress levels, the anisotropic nature of the composite becomes a dominant factor governing creep performance at higher stress levels. This finding highlights the necessity of considering both fiber orientation and service stress level simultaneously during the design stage.

4. Conclusion

In this study, the flexural and flexural creep behavior of glass fiber-reinforced epoxy composite materials with various fiber orientations were investigated by experiments. Composite laminates were manufactured by the VARTM method and tested by the three-point bending method.

The results of the flexural test indicated that the fiber orientation significantly affected the mechanical properties. The specimens with 0° fiber orientation had the highest flexural strength and stiffness because of the effective load transfer in the fiber direction. As the fiber orientation angle increased, the stiffness and strength reduced, which indicated a transition from fiber-reinforced to matrix-reinforced deformation.

The results of the creep test indicated that the time-dependent deformation significantly depended on both the stress level and the fiber orientation. As the applied stress level increased, the initial displacement and creep displacement also increased for all specimens. The 0° specimens had the best creep resistance, and the specimens with higher fiber orientation angles had higher displacement and lower dimensional stability.

At lower stress levels, the effect of fiber orientation on creep properties was not significant. However, at higher stress levels, the anisotropic properties of the composite material became more significant, and there were large differences in creep properties. The 45° specimens had unstable creep properties at higher stress levels, which indicated the onset of damage.

Overall, the results show that the orientation of fibers is a significant factor in controlling the long-term flexural properties of GFRP composites. The results also emphasize the significance of taking into consideration the service stress level and the orientation of fibers in designing GFRP composite materials.

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