Flexural Creep Behavior in Utilization of Woven Glass-Fibre as Reinforcement in Pultruded Glass Fibre-Reinforced Polymer Composite Cross-Arms: Experimental and Numerical Analysis

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Abstract

Pultruded glass fiber-reinforced polymer (PGFRP) composite is a relatively new material used to replace conventional wood in the fabrication of cross-arms for transmission towers. Much research has been undertaken on coupon-scale PGFRP composite cross-arms. However, a few have been completed on full-scale PGFRP composite cross-arms under actual operating load. Thus, this work investigates the effect of wrapping woven glass fiber fabric as an additional reinforcement on the creep reactions of PGFRP composite cross-arms installed in a 132 kV transmission tower. In the first stage of this research, the deflection of the original cross-arm under various loads ranging from 0 to 9 kN was evaluated and was followed by the actual working loads. This experiment was repeated on cross-arms wrapped with different numbers of glass fiber fabric layers around the weakest point of the beam. Then, the creep behaviors and responses of the woven glass fiber-reinforced cross-arms were evaluated and compared with the original cross-arms from the previous study. The actual operating load was applied to the PGFRP composite cross-arms for 1000 hours to study their capability to support the weight of electrical cables and insulators. In order to replicate the tropical climate, the cross-arms were mounted on a test rig in an open area. The findings of this study revealed that reinforcing the cross-arm by wrapping it with woven glass fiber fabric could extend its life and hence reduce the maintenance cost and effort for long-term usage. The findings of this study will also become essential knowledge on woven fabric wrapping applications on square profiles.

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1 Introduction

The tip's longitudinal or vertical deflection of the cantilever beam subjected to a specific load.

While the large deflection analysis forecasts behaviors. Several numerical models have been used due to their excellent mechanical performance. Composites made of fiber reinforced polymers have found application in various industries, especially in the fabrication of automotive components, fire extinguishers, and household generators. In previous studies, the impact of cross arms has also been undertaken over an extended period. Despite the scarcity of theoretical data, the beam, crossarms, and large deflection procedures provide the identical outcomes, therefore one can use the theoretical strategy for engineering design. Moreover, the small deflection strategy for engineering design has also been examined using computational simulation. The first pilots for cross arms were launched in 1999. Composites made of fiber laminate on cross arms were classified as an alternative to wooden cross arms. Batu Town's project, in which PGFRPC (Peninsular Malaysia reinforced polymer composite) are seen as an alternative to wooden cross arms. The tip's longitudinal or vertical deflection of the cantilever beam is proportional to the extension as long as the deflection is small and the beam is linear elastic. Hooke's law states that the load is proportional to the corresponding curvature, while Hooke's law states that the load is proportional to the extension as long as the beam is linear elastic. The Bernoulli theory states that the load is proportional to the extension as long as the beam is linear elastic. The small deflection strategy for engineering design is straightforward and is practiced in many industries. The tip's longitudinal or vertical deflection of the cantilever beam is proportional to the extension as long as the beam is linear elastic. The Bernoulli theory states that the load is proportional to the extension as long as the beam is linear elastic. The small deflection strategy for engineering design is straightforward and is practiced in many industries.
able engineering

- Occasionally displays polyester structures since they are pultruded from an E
- The current composite cross
- The material to fracture. The current composite cross
- The pattern,
- woven fabric to
- interlayer friction in producing woven
- product, in
- techniques
- performance
- have shown
- estimated
to
- productivity and low stability. Nonetheless, the cost of this method is
- Historically, the composite
- Due to the induced creep rupture, this composite material
- Compressive and tensile reactions of glass fiber
- reinforced polymer composites, have been extensively
- studies
- testing. V.A.Nelyub has discussed different methods of produc
- Seams in composite
- composite’s
- primary (transient), secondary (steady state), and
- During the
- primary creep stage, the creep rate
- several factors are
- compressive
- and
- as they are
- void chain
- These occurrences cause
- as a balance between the rates of dislocation production and recovery is
- As a balance between the rates of dislocation production and recovery is
- tertiary creep stage until the material ruptures due to
- shear yielding in creep results, void chain
- Several studies
- seamless
- varies from
- the composite’s
- perform an
- investigate. Several factors
- weave and matrix mechanical
- woven glass
- compared to others [28]. The
- estimated
- woven fabric to
- interlayer friction in producing woven
- weaving the fibers in various patterns. Woven
- wide
- strong
- technical applications [23]. Glass fiber, particularly, is a lightweight,
- more
- weaving the fibers in various patterns. Woven
- woven linear density. On top of these factors, the fiber and matrix mechanical
- woven glass
- unique
- properties,
- accurate
- low
- equipment due to their distinctive architectural characteristics, simplicity of
- wide
- strong
- technical applications [23]. Glass fiber, particularly, is a lightweight,
- moveable
- breakage over time.
- These occurrences cause
- as a balance between the rates of dislocation production and recovery is
- tertiary creep stage until the material ruptures due to
- shear yielding in creep results, void chain
- Several studies
- seamless
- the composite’s
Creep tests performed on composite cross-arms are necessary to codify, analyze extensively, and recast creep tendencies over long-term service. To improve the long-term durability of PGFRPC cross-arms, this study compares and evaluates their long-term mechanical performance with the current cross-arms utilized in 132 kV transmission towers. By conducting a creep test on a full-size cross-arm under real load in a tropical environment, crucial data may be gathered and analyzed. This strategy will help in accumulating information and predicting the long-term mechanical durability of the current cross-arm systems strengthened with composite. It will also offer an intuitive and incredibly thorough lens through which to view the behavior of the entire system.

In latticed transmission towers, PGFRPC cross-arms have only lately taken the place of conventional hardwood cross-arms. The creep behavior of full-scale PGFRPC cross-arms in 132 kV transmission towers has thus received little attention in the literature.

The purpose of this study is to ascertain the impact of reinforcing using the manual woven composite winding method on the performance and creep behaviors of PGFRPC cross-arms in transmission towers under actual stress condition. Additionally, the creep properties of the full-scale PGFRPC cross-arms are to be characterized. The findings of this study are expected to give academicians and engineers a practical viewpoint on the long-term mechanical behavior and a life prediction of PGFRPC cross-arms.

2 Methodology

2.1 Material Preparation

The main test subject of this research is the 132 kV PGFRPC cross-arm used for a suspension tower in Malaysia. The cross-arm was purchased from Electrius Sdn Bhd in Selangor, Malaysia, a regional producer of cross-arms. One tie and two main members, which made up the entire cross-arm assembly, were made using the pultrusion method with E-glass as the reinforcement fibre and unsaturated polyester resin as the matrix. The dimension of the square section of the cross-arm was 102 × 102 mm² and had a fine, homogenous, and unidirectional fiber texture along the direction of the polymer matrix composites, which in accordance with the specification stated in Tenaga Nasional Berhad (TNB) standard. The tie member was 3472 mm long, whereas the length of the main cross-arm members was 3651 mm. Each cross-arm member was fastened to the test rig with bolts, nuts, and fastening brackets. A load was applied at the free end of the cross-arm, following the TNB standard of workload in actual condition. Figure 1 shows the complete schematic and actual view of the cross-arm assembly.
The PGFRPC cross-arm assembly was lay-up manually with woven glass fiber method inspired by the hand lay-up method. The chosen location of the reinforcement was at the center of the main beam, which is the cross-arm beam's weakest point, as demonstrated by previous researchers. The length of the woven glass fiber lay-up was about 1.20 m. As the cross-arm did not have the common cylindrical shape, they were manually wrapped with woven glass fiber fabric using the lay-up method. The layers were carefully wrapped around the cross-arm as tight as possible as shown in Figure 2.

Epoxy resin and hardener were mixed and applied to the layers on all four sides of the cross-arm with a roller. Fig. 2. Complete assembled PGFRPC cross-arm (a) current cross-arm without improvement at the center of beam, (b) an improvement with manual woven glass fiber wrapping method, (c) woven glass fiber fabric used in this research.

2.2 Methods of Research Activity

The properties of the improved PGFRPC cross-arm were investigated using a two-point bending test since the cross-arm application is the same as a cantilever beam. The testing methods were based on those developed by [4]. Dial gauges were used to determine the cross-arm deflection value and were positioned at five points (labeled as Y1 to Y5) on the cross-arm.
each cross-arm member, as shown in Figure 3. Point Y1 was closest to the free end of the cross-arm and the gap between the gauges was set to 0.61 m. The applied load at the cross-arm free end was measured using a 3-ton crane scale. The load was gradually increased until the actual working load of 7.98 kN, as per the TNB standard, was achieved. Following that, the creep test was carried out for 1000 hours in the open area at the Aircraft Hangar, Faculty of Engineering, Universiti Putra Malaysia, in accordance with ASTM D2990. A static working load was hung at the free end of the PGFRPC cross-arm during the creep test, as shown in Figure 3 (b). Dial gauge deformation values were obtained at intervals of 0, 0.1, 0.2, 0.5, 1, 2, 5, 20, 50, 100, 200, 500, 700, and 1000 hours. The initial strain, often known as the “immediate strain,” was measured 15 seconds after the working tension was applied. As the test was conducted in an open area, the cross-arms were exposed to the actual tropical weather and environmental conditions. The results of these tests would include the value of creep strain, modulus comparisons, and creep quantitative analysis on current and improved cross-arm designs.

2.3 Cross-Arms Creep Properties
Hooke’s Law said that the applied force or load is proportional to the deflection:

\[ P = ky \]  \hspace{1cm} (1)

where \( P \) is the force exerted on the beam (N), \( k \) is the elastic coefficient (N/m) and \( y \) is the deflection (m).

The elastic coefficient can be formulated based on:

\[ k = \frac{3E_l}{l^3} \]  \hspace{1cm} (2)

where \( E \) is the Static Elastic Modulus (N/m²), \( I \) is the moment of inertia (m⁴), and \( l \) is the total cantilever beam length (m).

By substitute Equation (1) into Equation (2), the elastic coefficient can be formulated as in Equation (3):

\[ P = \left( \frac{3E_l}{l^3} \right) \times y \]  \hspace{1cm} (3)

Thus, Equation (3) can be used to forecast the maximum bending stress. The cross beam typically experiences its highest stress at the fixed point, \( x=0 \), and its minimum stress at the loading end, \( x=L \). Equation (5) can be used to express the beam’s maximum and minimum stresses (\( \sigma \)).

\[ \sigma = \frac{P(L-x)^2}{I} = \frac{6P(L-x)}{bh^2} \]  \hspace{1cm} (5)

Equation (6) can be used to determine the strain across the beam at a certain time and place based on Hooke’s Law.

\[ \varepsilon_t = \frac{\sigma_t}{E_e} \]  \hspace{1cm} (6)
2.4 Empirical Creep Model

The study of creep properties of the PGFRPC cross-arm was further extended through the application of an established empirical creep model that was proven by previous researchers. This work used the nonlinear Findley power law model as an empirical model to support and explain transient creep in relation to the stress component and material constant. This model can be applied generically in every system, despite the fact that its application is constrained by the straightforward and direct numerical calculation. In addition, the PGFRPC cross-arm was regarded as an isotropic substance. Thus, the Findley model was used to simulate the creep pattern and was represented by Equation (7).

\[ \varepsilon_t = A t^n + \varepsilon_0 \]

Where \( A \) and \( n \) are the time exponents and transient creep strain, respectively, and \( \varepsilon_0 \) is the instantaneous strain upon load exertion.

Further discussion is presented in subsection 3.3 later.

3 Results and Discussion

This chapter presents and discusses the results of both load deflection and creep tests for the woven glass fiber fabric-reinforced cross-arms. This chapter also compares the creep-strain values as well as creep model for both the current cross-arm and the woven glass fiber fabric reinforced cross-arm. Finally, the adjusted regression (\( Adj. R^2 \)) values of the Findley’s model for current and wrapped cross-arms were also calculated and compared.

3.1 Load Deflection Behavior

The load-deflection values were measured using the dial gauges at all five points: Points Y1, Y2, Y3, Y4, and Y5. The cross-arms involved were those without woven glass fiber reinforcements and those reinforced with two, four, six, and eight layers of woven glass fiber. Each measurement was repeated thrice to obtain the average load deflection value. Then, the load-deflection values were plotted against the positions of the marked points: Y1 was the closest to the cross-arm free end while Y5 was the closest to the fixed point of the PGFRPC cross-arm. Figure 5 shows that the relationship between deflection behavior and load applied to the PGFRPC cross-arm was directly proportional. This relationship was valid as long as...
The deflection was small, and the beam material did not yield. Thus, the PGFRPC is considered a linear elastic material that is homogeneous, isotropic and obeys Hooke’s Law. The ultimate or maximum deflection was always at the free end, while the smallest deflection was at the cross-arm beam’s fixpoint. The deflection behavior of this cross-arm was similar to that of the cantilever beam and covered a three-dimensional problem. The effect of Poisson’s ratio can be ignored as the length of the beam was larger than the thickness of the perpendicular cross-section and shorter than the curvature radius of the beam.

Fig. 5. The PGFRPC cross-arm load deflection results with and without woven fiberglass reinforcement (a) main 1 member, (b) main 2 member.
3.2 Creep Strain Properties
Fig. 6. The creep strain-time curves for current PGFRPC cross-arm for (a) main 1 and (c) main 2; wrapped composite PGFRPC cross-arm (b) main 1 and (d) main 2.

Figure 6(a) to (d) depicted creep strain patterns change from an elastic to a viscoelastic stage. The red arrows in Figure 6 illustrate how the creep strain curves of the original composite cross-arm showed an extended transition period from the elastic to the viscoelastic phase. The viscoelastic stage was efficiently reduced and made more stable by adding woven glass fibre to the structure, which decreased the possibility that the structure would fail. The strain value at Point Y3, which was larger in the current cross-arm than in the wrapped composite system, lends credence to this assertion. According to Figures 6 (a) and (b), the creep strain in the original Main 1 cross-arm exceeded 0.0014 mm/mm, while the creep strain in the reinforced cross-arm did not even reach 0.0014 mm/mm. For Main 2 cross-arm, the creep strain in the reinforced cross-arm was less than 10% of the current cross-arm. Overall, it can be said that to counter the lateral force from dead weight, which caused the structure to buckle, the creep resistance of the cross-arm assembly may be enhanced by adding greater composite layers.

3.3 Empirical Creep Model for PGFRPC Cross-Arm
The transient creep of the cross-arm is shown in Table 1. The model was used to evaluate a number of parameters and is expressed by Equation (7). These variables included transient creep \( A \) and the material exponent \( n \) that is stress independent.

Table 1. The transient creep (A) and stress-independent material exponent (n) from Findley power law for current and wrapped PGFRPC cross-arm [22].

<table>
<thead>
<tr>
<th>Main Cross-Arm Member</th>
<th>Current Cross-Arm ( A )</th>
<th>Wrapped Cross-Arm ( A )</th>
<th>Current Cross-Arm ( n )</th>
<th>Wrapped Cross-Arm ( n )</th>
<th>( \text{Adj.} R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( 3.207 \times 10^{-4} )</td>
<td>( 7.583 \times 10^{-6} )</td>
<td>0.021</td>
<td>0.224</td>
<td>0.961</td>
</tr>
<tr>
<td>2</td>
<td>( 8.497 \times 10^{-3} )</td>
<td>( 4.393 \times 10^{-3} )</td>
<td>0.122</td>
<td>0.106</td>
<td>0.950</td>
</tr>
<tr>
<td>3</td>
<td>( 5.602 \times 10^{-3} )</td>
<td>( 6.753 \times 10^{-3} )</td>
<td>0.195</td>
<td>0.142</td>
<td>0.959</td>
</tr>
<tr>
<td>4</td>
<td>( 4.115 \times 10^{-3} )</td>
<td>( 4.637 \times 10^{-3} )</td>
<td>0.227</td>
<td>0.191</td>
<td>0.959</td>
</tr>
<tr>
<td>5</td>
<td>( 2.663 \times 10^{-3} )</td>
<td>( 2.791 \times 10^{-3} )</td>
<td>0.232</td>
<td>0.189</td>
<td>0.951</td>
</tr>
<tr>
<td><strong>Main 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( 1.167 \times 10^{-4} )</td>
<td>( 1.431 \times 10^{-5} )</td>
<td>0.061</td>
<td>0.168</td>
<td>0.964</td>
</tr>
<tr>
<td>2</td>
<td>( 1.506 \times 10^{-4} )</td>
<td>( 5.171 \times 10^{-5} )</td>
<td>0.088</td>
<td>0.139</td>
<td>0.942</td>
</tr>
<tr>
<td>3</td>
<td>( 1.057 \times 10^{-4} )</td>
<td>( 6.729 \times 10^{-5} )</td>
<td>0.129</td>
<td>0.152</td>
<td>0.934</td>
</tr>
<tr>
<td>4</td>
<td>( 1.183 \times 10^{-4} )</td>
<td>( 8.011 \times 10^{-5} )</td>
<td>0.119</td>
<td>0.130</td>
<td>0.903</td>
</tr>
<tr>
<td>5</td>
<td>( 4.419 \times 10^{-4} )</td>
<td>( 4.053 \times 10^{-5} )</td>
<td>0.172</td>
<td>0.166</td>
<td>0.890</td>
</tr>
</tbody>
</table>

For the original and reinforced cross-arms, the adjusted regression (Adj. \( R^2 \)) values of Findley’s model were summarised in Table 1. The Adj. \( R^2 \) for the reinforced cross-arm ranged from 0.986 to 0.922. These numbers were quite near to 1, showing how effectively \( A \) and \( n \) were modelled.

Table 2. Material stress independent exponent, \( n \) for current and wrapped cross-arms.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Current Cross-Arm</th>
<th>Wrapped Cross-Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material stress independent exponent, ( n )</td>
<td>0.1594</td>
<td>0.1138</td>
</tr>
<tr>
<td><strong>Main 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material stress independent exponent, ( n )</td>
<td>0.1704</td>
<td>0.1510</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material stress independent exponent, ( n )</td>
<td>0.1366</td>
<td>0.1607</td>
</tr>
</tbody>
</table>

The graph shows that glass fiber application did not influence the secondary creep stage because of the enhanced creep resistance of the PGFRPC cross-arm. The current composite cross-arm has a lower material stress independent exponent, \( n \) than the reinforced composite cross-arm, which was approximately 0.1366 and 0.1607, respectively (refer to Table 2). However, the \( n \) value for both original and reinforced cross-arms lay below the standard range of stress-independent material exponents of 0.20–0.29. Although improvements in load deflection results and transient creep value were observed in the reinforced composite cross-arm, a better composite wrapping method is required. In addition, the compatibility of woven glass fiber material needs to be further studied.
Findley's model explained the experimental data. On the other hand, the $\text{Adj. } R^2$ values for the original cross-arm were in the range of 0.964 to 0.890. These findings demonstrate that the reinforced composite cross-arm adhered to the creep principle during the primary and secondary creep stages, and the creep data showed that increased structural integrity reduced exaggeration.

4 Conclusion

The purpose of this study was to evaluate the effect of adding woven glass fiber fabric as an additional reinforcement on the creep reactions of PGFRP composite cross-arms installed in a 132 kV transmission tower. Based on the results obtained from the experiments and the empirical study, the following conclusions can be drawn:

- The load-deflection for Main 1 and Main 2 does not really show a gradually improved when compared with current cross-arm suspected due to glass fiber woven fabric wrapping process since it was done manually. In visual view, the first 2 layers were wrapped around the point Y3 nice and tight without any air bubbles or air pockets however the subsequent layers of 4, 6 and 8 had some air pockets unevenly.

- Although that, the creep strain patterns depicted a transitional phase from the elastic to the viscoelastic stage at all points and obviously shows decreasing almost 10% in the creep strain for wrapping cross-arm compared to current cross-arm at point Y3.

- The presence of wrapping glass fiber woven fabric and reinforced with epoxy has improved the strength of weakest point at the PGFRPC cross-arm beam due to fabric interlayer contact mechanism on the glass fiber woven fabric of lower layer that are overlapping those the upper layer.

- By using the nonlinear Findley power law model, the wrapped cross-arm has shown lower transient creep value compared to current composite cross-arm design due to the superior steady-state creep response. However, the material stress independent exponent for both current and wrapped cross-arm lies below the common range as referred to previous study. Therefore the composite wrapped method needs to be improved in fabrication method and the compatibility used of woven glass fiber material.

- Several limitations that should be studied in the future such as the woven glass fiber fabric layup orientations, allowable slippage distance during overlapping states, dynamic results, flexibility reaction, failure mood, and creep analysis of the cross-arm structure during normal and broken wire conditions.

Considering these results and implications, this paper has highlighted the creep properties of current and improved PGFRPC cross-arm along with the possibility of further research to evaluate other mechanical properties. Research into this field is not developed as compared to other structures especially for PGFRPC material in high transmission tower application, and this gap must be narrowed in future works.

References
S.E3S Web of Conferences 477, 00007 (2024)  
STAR’2023  
https://doi.org/10.1051/e3sconf/202447700007  

Abas, Mohamad, the IOP Conference Series: Materials Science and Cross Arm Structure  


