

Performance of Kenaf Fibre Reinforced Epoxy Biocomposite for High Voltage Insulator Application

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Abstract

Current applications of natural fibre-reinforced composite are widely spread in various applications such as construction and building structures as well as automotive parts, in which compression and flexural properties are the primary concern of researchers. The aim of this research is to evaluate the performance of kenaf fibre-reinforced epoxy composite as the core of high voltage insulator subjected to identified wind load conditions by using finite element analysis which is then further validated using the theory of mechanics of materials. It was found that under tensile load, the kenaf fibre reinforced polymer (FRP) experiences 2 times higher elongation compared to synthetic glass FRP but the tensile stress is only 21% of its material strength; under torsion load, despite having a 2 times higher angle of rotation compared to glass FRP, the deflection of kenaf FRP is still 24% below the typical damage limits; under bending load, the kenaf FRP experiences slightly higher bending stress compared to the glass FRP but the maximum stress is only 19% of its material strength. Under electrical load, the kenaf FRP experiences 13.6% higher electrical stress than glass FRP and it shows that the electrical performance of kenaf FRP is almost comparable to the glass FRP. Even though the kenaf FRP naturally has lower strength, the performance of kenaf FRP is almost comparable to the conventional material from glass FRP and the results indicate that the kenaf FRP is able to sustain different types of loads when it is under operating.

Keywords: Insulator, High Voltage Insulation, Biocomposite, Kenaf fibre

1. Introduction

An electric power system is a network of electrical components that involved generation, transmission, and distribution systems. A transmission line system is an essential system that facilitates the bulk movement of

electrical energy from the generating station to the distribution system. The high voltage insulator is a component in the transmission line network used to provide insulation between the transmission lines and the transmission towers which are exposed to the atmosphere. It also provides mechanical support to carry the weight of the transmission lines galloping through the towers as

well as multiple types of external force on the transmission lines from the environment. Composite insulator is the modern type of high voltage insulator used and it consists of three parts: core, housing, and end fitting. The core as the main component to provide mechanical strength is a rod typically made of glass fibre-reinforced polymer using the pultrusion method. In such method, the glass fibres impregnated in resin matrix are aligned unidirectionally to provide superior tensile performance [1].

Cherney [1] and Papailiou and Schmuck [2] agreed that the core, as known as the mandrel, is the main component to provide mechanical strength and withstand the mechanical load brought by the transmission line and transfer the tensile load to the tower. The core is typically made of fiberglass rods where E-glass and stress corrosion E-glass (ECR) glass are the two common types of glass fibres used in the manufacture of insulator rods and polyester, epoxy resin and vinyl ester are the three types of resin systems in use [1]. The housing, also known as weather sheds, is the component surrounding the core rod to provide electrical insulation and protect the core from environmental erosion. Gorur [3] states that there are different material families, including high-temperature vulcanized (HTV) silicone rubber, ethylene propylene rubber (ERP), cycloaliphatic epoxy, and ethylene vinyl acetate (EVA), which are proven suitable for outdoor insulator housing. Hu *et al.* [4] mention that the housing made up of silicone rubber as the base material is usually added with other material additives to improve their material properties.

Over the last decades, due to the growing trend toward producing sustainable materials, the use of natural fibres as reinforcing elements in polymer composites has gained popularity to replaced synthetic fibre such as glass fibre [5]. Although natural fibre composites are found to have intermediate mechanical properties, they offer significant benefits over the glass and other synthetic fibres, including lower density, cheaper cost, renewable, recyclable and biodegradable [6]. Although glass fibre is the mainstream material of the reinforcing fibre in the insulator core, Macey *et al.* [7] mention that other insulating fibre can also be used. Many recent works are made in Malaysia to study the performance of kenaf fibre reinforced composites under different circumstances, including Osman *et al.* [8] who study the effect of chemical treatment on the mechanical properties of pultruded kenaf fibre reinforced polyester composites; Mahjoub *et al.* [9] who study the characteristics of continuous unidirectional kenaf fiber reinforced epoxy composites; Fairuz *et al.* [10] who study the effect of gelation and curing temperatures on mechanical properties of pultruded kenaf fibre reinforced vinyl ester composites; Fairuz *et al.* [11] who study the effect of pulling speed on mechanical properties of pultruded kenaf fibre reinforced vinyl ester composites; Zamri *et al.* [12] who study the effect of different kenaf fibre yarn tex of pultruded kenaf fibre reinforced composites. It was

found that the mechanical properties of kenaf fibre reinforced polymer (FRP) vary due to different manufacturing processes and parameters. The tensile modulus of kenaf FRP is ranging from 10-18.15 GPa and the Poisson's ratio at 0.32, which may be applicable for certain load-bearing applications.

Zhao *et al.* [13] mention that the insulators while in operating is mainly subjected to three kinds of mechanical stresses, which are tensile stress, torsional stress and bending stress. The primary basic load, among the mechanical stresses, for a high voltage insulator is reported to be tensile load [14]. Tensile load is usually caused by the weight of the transmission lines galloping through the transmission towers. The wind condition is another factor affecting the tensile load subjected to the insulator by adding extra wind load on the transmission lines. The vertical load, horizontal load and the resultant total force can be calculated as following [7]:

$$F_v = (m_c + \pi \cdot b_i \cdot (q_{ice}^2 + q_{ice} \cdot d_{con})) \cdot S_m \quad (1)$$

$$F_h = P_w \cdot (d_c + 2q_i) \cdot s_f \cdot g_f \cdot S_w \quad (2)$$

$$F_t = \sqrt{F_v^2 + F_h^2} \quad (3)$$

Due to the strong tensile properties and light weight of the FRP material, the axial deformation of the mandrel is small and thus the transverse charges can be ignored. As a result, by considering the weight from the overhead power lines with addition to the wind load as maximum tensile loading, the tensile stress can be calculated with Hook's law [13].

$$E = \frac{F_t/A}{\Delta L/L} \quad (4)$$

Although a suspension type insulator is mainly subjected to tensile force, a torsional or a twisting type of load can be still experienced by the insulators during line construction. Papailiou and Schmuck [2], Macey *et al.* [7], and Zhao *et al.* [13] stated that the composite core rod is relatively sensitive to the torsional stress due to the longitudinal arrangement of glass fibres. Macey *et al.* [7] emphasize the importance of handling the components with care and twisting should be avoided especially during installation and conductor stringing. It is reported that the maximum torque that can be applied on the composite insulator core without permanent damage is 65 Nm for a 16 mm diameter core and 175 Nm for a 24 mm diameter core. The formula for torsional moment, torsional stress and angle of rotation are given as follow [13]:

$$M_t = F_h \cdot D \quad (5)$$

$$\tau_{max} = \frac{M_t \cdot R}{I_p} \quad (6)$$

$$\varphi = \frac{M_t \cdot l}{G \cdot I_p} \cdot \frac{180}{\pi} \quad (7)$$

Similar to torsional load, a suspension-type insulator is not mainly designed to bear bending load. However, Zhao *et al.* [13] state that the composite insulator will swing over a swing angle under the situation of the conductor galloping. Thus, a bending load may occur in the process. Composite insulators also experienced the bending load during improper handling or installing process. According to Zhao *et al.* [13], the large deflection theory should be considered during the calculation of insulator under large bending load. The large deflection equation at the free end is given as follow [13]:

$$\frac{\widehat{W}_B}{L} = \sin \theta_B - \frac{2\theta_B^2}{3\left(\frac{FL^2}{EI}\right)^\alpha} \quad (8)$$

$$\theta_B = \left(\sqrt{\left(\frac{35}{12\frac{FL^2}{EI}}\right)^2 + \frac{35}{12}} \right) - \frac{35}{12\frac{FL^2}{EI}} \quad (9)$$

$$I = \frac{\pi \cdot D^4}{64} \quad (10)$$

$$\alpha = \begin{cases} 1, & \text{when } \frac{FL^2}{EI} \leq 1 \\ 0.92, & \text{when } \frac{FL^2}{EI} > 1 \end{cases} \quad (11)$$

2. Methodology

2.1. Specifications of transmission system

The transmission system with a voltage level of 132 kV is selected as the main research object in this study. The composite long rod insulator is installed in suspension position of which the top end is connected to the transmission tower and the bottom end is linked to the conductor by the end-fitting. Based on the calculation, the maximum tensile load that the composite required to bear is 6400 N. Therefore, by selecting a composite long rod insulator with a standard mechanical strength rating higher than the maximum load will provide adequate strength to withstand the load. The specifications of the selected insulator are listed in Table 1.

Table 1. Specifications of composite insulator

Insulator model	FXBW-132/70
Rated voltage (kV)	132
Specified mechanical load (kN)	70
Core diameter (mm)	16
Section length (mm)	1240

2.2. Finite element analysis

2.2.1. Mechanical performance analysis

The engineering data is used to define the material properties. The material properties of glass FRP, kenaf FRP, and plain epoxy rod are manually created and added to the data library as listed in Table 2.

Table 2. List of material properties

Material	Young's Modulus (GPa)	Shear Modulus (GPa)	Poisson's Ratio
Glass FRP	36.6	14.524	0.26
Kenaf FRP	18.15	6.875	0.32
Plain Epoxy	2.131	0.7665	0.39

A 3D finite element model of the insulator is established with ANSYS DesignModeler software. Since the analysis is done only on the insulator core, a cylinder is built to represent the core. The diameter of the cylinder is 16 mm and the length is 1240 mm. The 3D model is used in the simulation of tensile and torsion load. For bending load, due to the large deformation properties of the core, a 2D finite element model is built to simplify the model and limit the movement in the plane. The Ansys DesignModeler software is used to build the 2D model as well. The line body is generated with a length of 1240 mm along the X-axis and the cross section is set to be a round shape with a diameter of 16 mm. The 3D model is then meshed into total of 11526 nodes and 2178 elements while the 2D line body model is meshed as linear element and is separated into 40 parts. For the boundary condition of the model, the top end of the core is set as fixed support. The bottom end is applied with 6000 N of tensile load, 64000 Nmm of torsion load and 6400 N of bending load calculated from the theoretical analysis. The process is then repeated for all three materials.

2.2.2. Electrical performance analysis

The ANSYS Maxwell software is used to determine the voltage distribution and electrical stress of the insulator. As shown in Fig. 1, the finite element model of the core is built according to the dimension of 1240 mm in length, then an enclosure is added to the core to represent the surrounding environment. The core is assigned with the material of glass FRP, with a relative permittivity of 7.1

according to Netravati *et al.* [15]; and the surrounding environment is assigned as the built-in material of air with relative permittivity of 1.0006. The voltage excitation of 132 kV is set at the high voltage end of the core, and the ground end is set as 0 V. The model is then run and analyse for all results. The simulation is then repeated by changing the core material to kenaf FRP, with the relative permittivity of 4.2 adopted from Merizgui *et al.* [16].

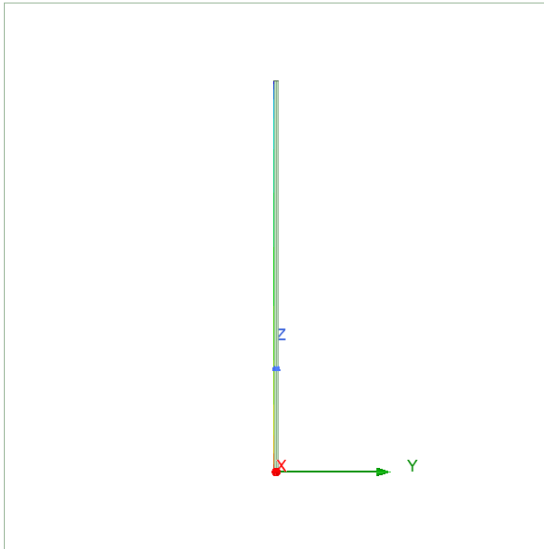


Fig.1 Insulator finite element model.

3. Results and Discussion

3.1. Insulator performance under tensile load

Fig. 2 shows the total deformation of the insulator core under the tensile load of 6400 N. The greatest deformation for all materials occurs at the end where the tensile load is applied and gradually decreases to the fixed end. The maximum deformation obtained from the glass FRP and kenaf FRP is 1.079 mm and 2.1756 mm respectively. On the other hand, 18.526 mm of deformation has been observed on the plain epoxy rod. The results showed that kenaf fiber reinforced epoxy composite has achieved around 7.5 times of improvement of its tensile performance compared to plain epoxy. However, due to the nature of having lower strength than synthetic fiber, the elongation of kenaf FRP has increased around 2 times compared to glass FRP.

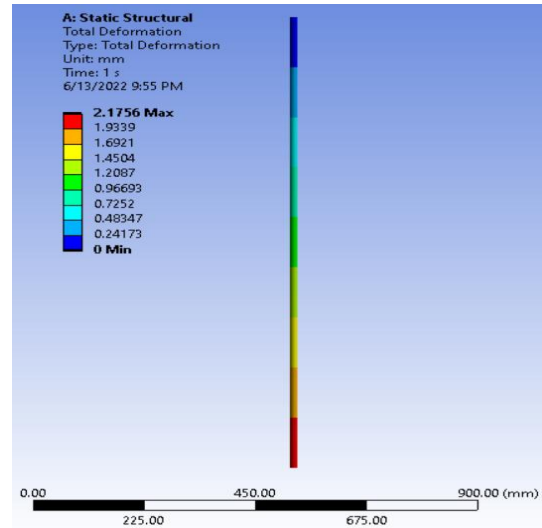


Fig.2 Total deformation of kenaf fibre/epoxy insulator under tensile load

As shown in Fig. 3, the major portion of the core is subjected to around 31 MPa of tensile stress according to the stress distribution contour. Nevertheless, it is remarkable that the maximum stress has been observed at the outer layer of the top end which is set as the fixed support. It indicates that in reality, stress concentration will be encountered at the top end and failures are most likely to happen at the area as well. The maximum tensile stress subjected to the cores is 34.133 MPa, 34.789 MPa and 35.825 MPa for Glass FRP, Kenaf FRP and plain epoxy rod respectively. It also proved that the kenaf FRP has better performance than the plain epoxy rod. The maximum stress of kenaf FRP experiences is only 21% of the tensile strength of the material and thus it will provide sufficient strength to withstand the load from the conductor as well as the wind load.

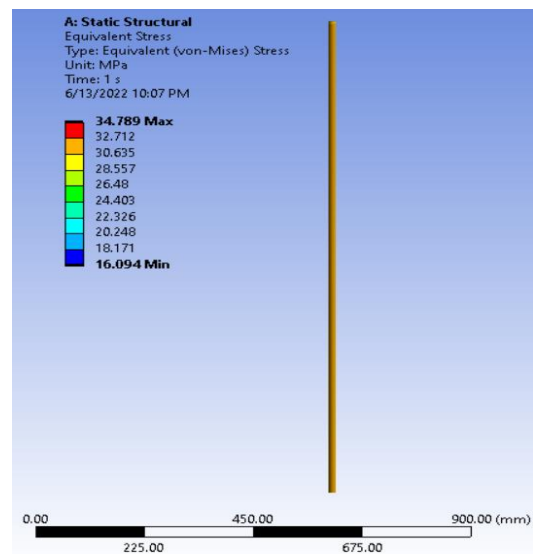


Fig.3 Induced equivalent stress on kenaf fibre/epoxy insulator under tensile load.

The theoretical tensile performance of the FRP core is calculated by applying Eq. (1), Eq. (2), Eq. (3) and Eq. (4) and listed in Table 3. Because the dimension and cross-sectional area of the FRP rod remained constant for all materials, the tensile stress is unaffected by material properties and remains constant at 31.83 MPa. The evaluated elongation of the glass FRP rod, kenaf FRP rod, and plain epoxy rod are 1.08 mm, 2.17 mm and 18.52 mm respectively. The highest deviation between the theoretical and FEA result for the elongation is 0.26 % from kenaf FRP. The error for the tensile stress from the glass FRP and kenaf FRP are 7.24 % and 9.30 % accordingly. Since the deviation between the result fall within 10 %, thus the results are considered authentic.

Table 3. Analysis results under tensile load

	Glass FRP	Kenaf FRP	Plain Epoxy
Deformation (mm)			
Theoretical	1.08	2.17	18.52
FEA	1.079	2.1756	18.526
Error	0.09 %	0.26 %	0.03 %
Tensile Stress (MPa)			
Theoretical	31.83	31.83	31.83
FEA	34.133	34.789	35.825
Error	7.24 %	9.30 %	12.55 %

3.2. Insulator performance under torsion load

The insulator core is subjected to 64000 Nmm of torsional load. Similar to the FEA result discussed for tensile stress, stress concentration also occurs when given a torsional load. Fig. 4 shows the shear stress contour plot experienced by the kenaf FRP subjected to torsional load. The outer shell of the rod is observed to have the highest torsional stress and the centre of the rod to have minimum stress. The maximum shear stress is 84.749 MPa, 84.682 MPa and 84.529 MPa for the glass FRP, kenaf FRP and plain epoxy respectively.

As shown in Fig. 5, the deformation of the rod is presented in millimetre along the radius of the rod, which can then be converted into degree. The FRP rod is predicted to have maximum deformation at the end where the torsional load is applied, and the fixed end experienced the least deformation. The angle of rotation is found to be 48.74°, 103° and 923.54° respectively. Despite having a 2 times higher angle of rotation compared to glass FRP, the deflection of kenaf FRP is still 24 % below the typical damage limits of 135° for the twisting of long rod insulators according to Macey *et al.* [7]. Meanwhile, the plain epoxy rod under the torsional load of 64000 Nmm is encountering 922° of rotation, which is almost 8 times greater than the kenaf FRP. It further proved that the kenaf fiber has significantly improved the capability of the rod to withstand a twisting type of load compared to a plain epoxy rod.

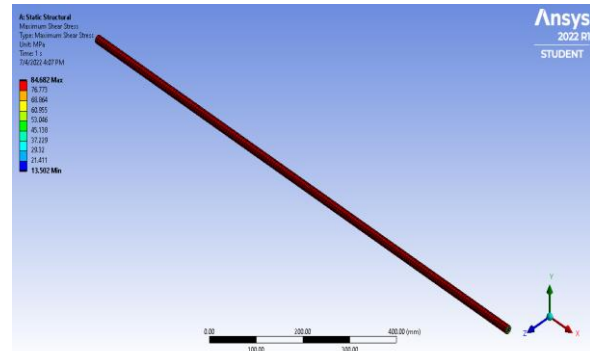


Fig. 4 Induced maximum shear stress on kenaf fibre/epoxy insulator under torsion load

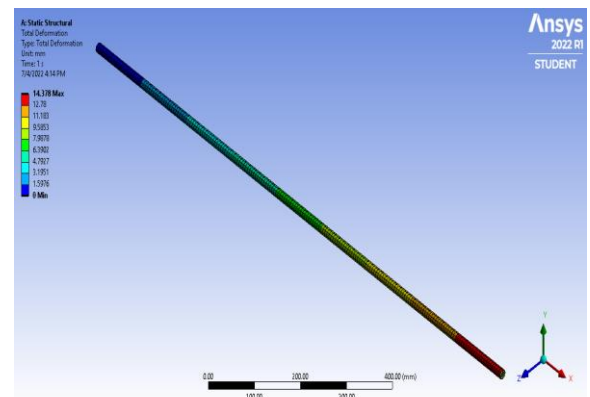


Fig. 5 Deformation on kenaf fibre/epoxy insulator under torsion load

By applying Eq. (5), Eq. (6) and Eq. (7), the theoretical results of the insulator core are listed out in Table 4. Under 64000 Nmm of torsional load, the rod will experience 79.58 MPa of torsional stress theoretically for all three rods since the stress is only affected by the dimension but not the shear strength of the material. The angle of rotation calculated for all three materials is 48.66°, 102.8° and 922° for glass FRP, kenaf FRP and plain epoxy accordingly. 6.50 % and 6.41 % of deviations are obtained from the torsional stress for glass FRP and kenaf FRP. For the angle of rotation, finite element analysis and theoretical analysis almost resulted the same and the highest error between them is 0.19% which is achieved from the kenaf FRP.

Table 4 Analysis Results under Torsion Load

	Glass FRP	Kenaf FRP	Plain Epoxy
Torsional Stress (MPa)			
Theoretical	79.58	79.58	79.58
FEA	84.749	84.682	84.529
Deviation	6.50 %	6.41 %	6.22 %
Angle of Rotation (Degree)			
Theoretical	48.66	102.8	922
FEA	48.74	103.0	923.54
Deviation	0.16 %	0.19 %	0.17 %

3.3. Insulator performance under bending load

In the bending simulation, 6400 N of bending load is applied to the bottom end of the core in the horizontal direction. Fig. 6 shown the deformation patterns of the rod under the large deflection theory. The rod is observed to be significantly bent in the horizontal direction. The bottom end of the rod experiences the greatest deformation and gradually decreases to the fixed end. The result of the deformation is determined as the horizontal directional deformation, which has been recorded as 1161.9 mm, 1186.5 mm and 1240.5 mm accordingly for the three materials.

Fig. 7 shows the stress distribution of the rod under the bending load with the large deformation theory applied. The direct stress, which represent the stress component due to the axial load encountered in the model, is obtained from the simulation. The maximum stress distribution occurs along the free end of the rod, which is obtained to be 31.844 MPa, 31.912 MPa and 32.343 MPa accordingly. The results show that the kenaf FRP experiences slightly higher bending stress compared to the glass FRP. However, the maximum stress of 31.912 MPa is only 19% of its strength of 164 MPa, which means that the load is unlikely to cause a fracture to the kenaf FRP core and it will not break immediately.

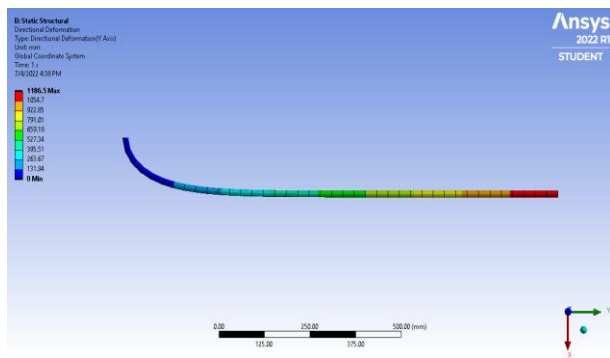


Fig. 6 Y-direction deformation for kenaf fibre/epoxy insulator under bending load

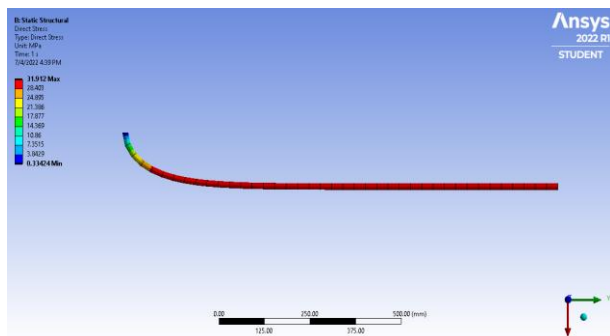
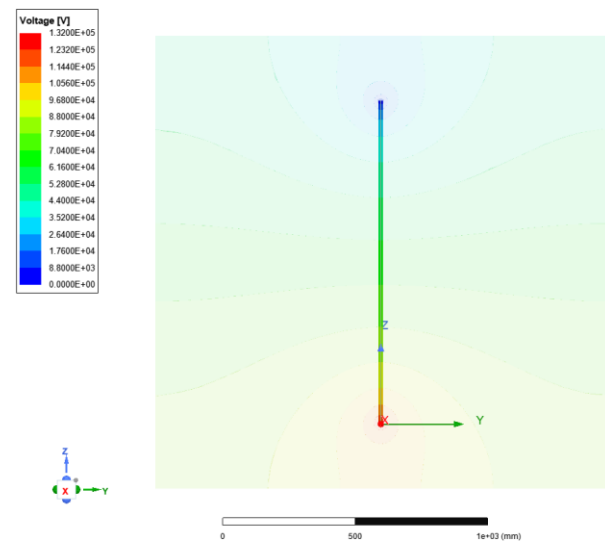


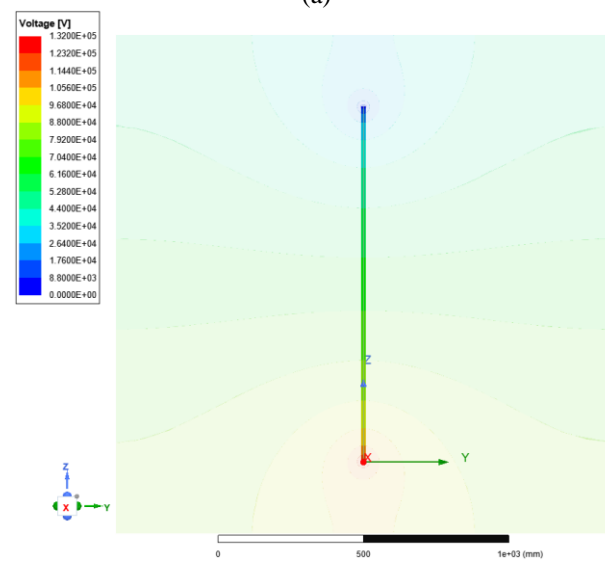
Fig. 7 Direct stress induced on kenaf fibre/epoxy insulator under bending load

3.4. Insulator performance under electrical load

The voltage distribution pattern in the rod is shown in Fig. 8 and it is observed that both glass FRP and kenaf FRP rods have uniform voltage distribution along the rods. The maximum voltage occurs at the high voltage end with 132 kV and keeps decreasing towards the ground end. As shown in Fig. 9, the voltage distribution at the surrounding of the rod is also affected by the high voltage load from the insulator. High potential voltage is observed at a certain area around the high voltage end, and it gradually decreased along the direction to the ground end. The distribution contours show that the kenaf FRP has a smaller area of the voltage spread to the surroundings compared to the glass FRP, which means that it is subjected to higher electrical stress inside the core.



(a)



(b)

Fig. 8 Voltage distribution in the (a) glass fibre-epoxy insulator and (b) kenaf fibre-epoxy insulator

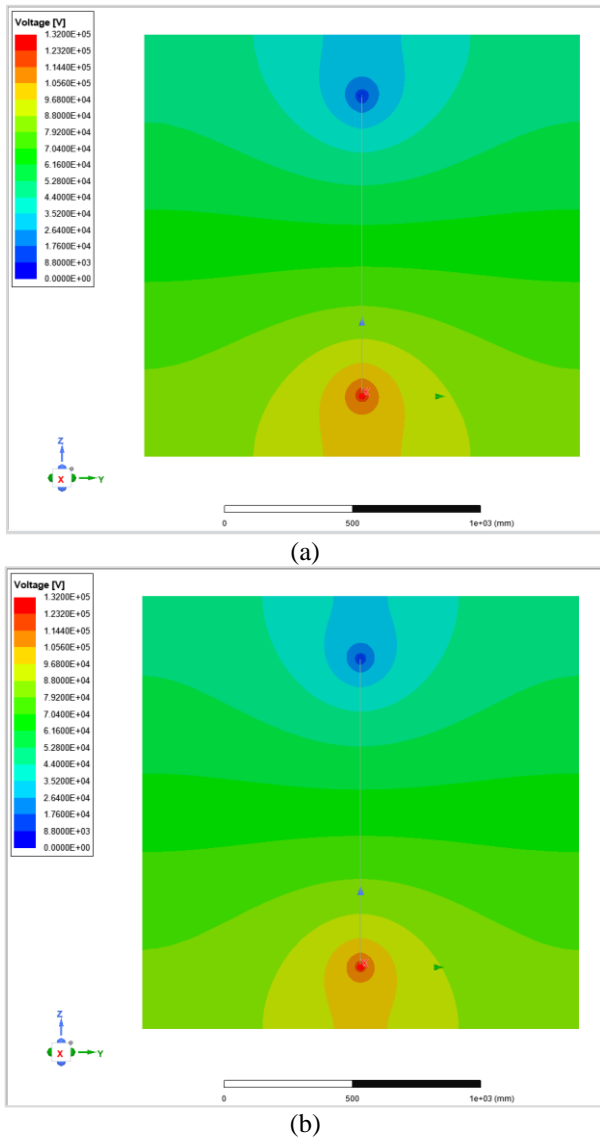


Fig. 9 Potential voltage distribution of the surrounding (a) glass fibre-epoxy insulator and (b) kenaf fibre-epoxy insulator

The voltage distribution along the distance for both materials is plotted on a graph in Fig. 10. According to the result, the kenaf FRP rod have slightly higher amount of voltage drop from both ends of the rod compared to glass FRP and drops smoothly at the middle range of the core. Fig. 11 represents the electrical stress plotted along the length of the rod. It can be seen that both materials have high similarity in the patterns since the glass FRP and kenaf FRP are both considered to have low conductivity. The greatest electrical stress obtained from the glass FRP is 2.55 kV/mm and kenaf FRP is 2.95 kV/mm. The result shows that the kenaf FRP will experience 13.6 % higher electrical stress compared to glass FRP. The result shows that the electrical performance of kenaf FRP is almost comparable to the glass FRP.

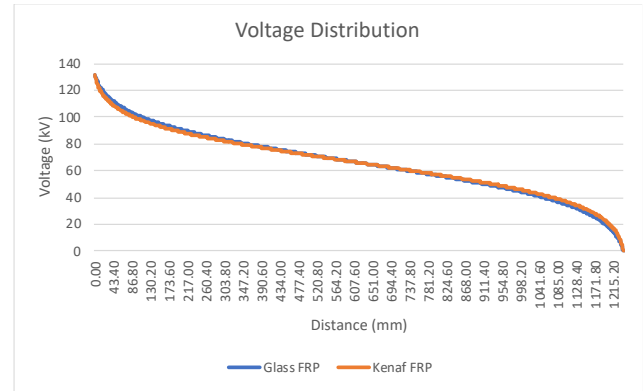


Fig. 10 Voltage distribution across insulator

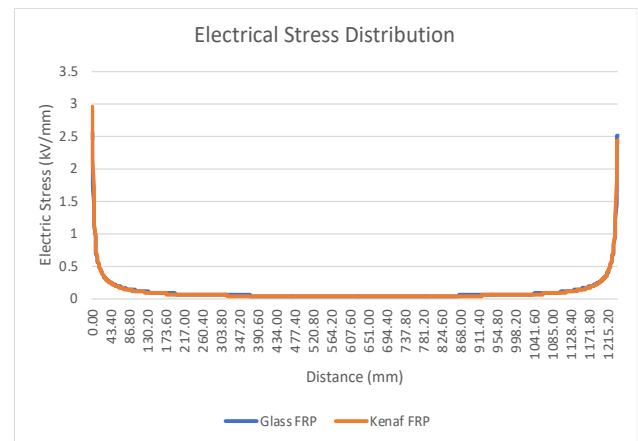


Fig. 11 Electrical stress distribution across insulator

4. Conclusion

In this analysis, the performance of biocomposites that is kenaf fiber reinforced epoxy composites has been evaluated. It was found that the biocomposite is capable to withstand different types of mechanical loads on the high voltage insulator due to the weight from the transmission conductor and wind loading. Under tensile load, although the elongation of kenaf FRP has increased around 2 times compared to glass FRP, it only experiences 34.789 MPa of maximum tensile stress which equals 21% of the tensile strength of the material. It shows that the kenaf FRP will not be fractured immediately by the given tensile load. Under torsion load, despite having a 2 times higher angle of rotation compared to glass FRP, the deflection of kenaf FRP at 103° is still 24 % below the typical damage limits of 135° for the twisting of a long rod insulator. Under bending load, even the kenaf FRP experiences slightly higher stress compared to the glass FRP, the maximum stress of 31.912 MPa is only 19% of its strength of 164 MPa, which means that the load is unlikely to cause a fracture to the kenaf FRP core and it will not break immediately. From the electrical simulation, the kenaf FRP is having similar behavior as the glass FRP under electrical load. Although the greatest electrical stress obtained from the kenaf FRP is 2.95 kV/mm, which is 13.6 % higher than glass FRP, the result shows that the electrical

performance of kenaf FRP is almost comparable to the glass FRP. Even though the kenaf FRP is naturally having lower strength, the performance of kenaf FRP is almost comparable to glass FRP and the addition of kenaf fiber to the epoxy matrix has significantly improved the mechanical performance of plain epoxy.

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