Failure Analysis of Hybrid Fibre Reinforced Plastics for Bolted Joint under Thermal Effect

D. Sivakumar, L.F. Ng, J.W. Ng, M. Z. Selamat*
Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka,
76100 Durian Tunggal, Melaka, Malaysia.
**sivakumard@utem.edu.my*

Sivaraos
Faculty of Manufacturing Engineering,
Universiti Teknikal Malaysia Melaka
76100 Durian Tunggal, Melaka, Malaysia.

ABSTRACT

Composite material is gaining a large attention in these few years due to its high strength to weight ratio. The cost of composite is also relatively lower than conventional metallic alloy. Several previous studies had shown introducing of synthetic fibre in the natural fibre-based composite polymer can enhance the mechanical strength of the composite structure. This research paper studies the effect of temperature and preload moment on the bearing strength of woven kenaf-glass fibre reinforced polypropylene hybrid composite. The kenaf fibre and E-glass fibre are in the form of plain weave fabric. Composite specimens were manufactured through hot press moulding compression method at 180°C. In bolted joint test, specimens were exposed to a temperature of 25°C (room temperature), 40°C, 50°C, and 60°C and tightened with 0Nm, 5.2Nm and 7.5Nm preload moment. Bearing response under different conditions was tested according to ASTM D5961 standard procedure and failure modes were observed. The results revealed that increase in the ambient temperature reduced the bolted joint strength whereas the increase in preload moment improved the joint strength.

Keywords: *hybrid composites; bolted joint; thermal effect; woven kenaf*

ISSN 1823-5514, eISSN 2550-164X

Received for review: 2016-09-01
Accepted for publication: 2016-11-17
Published: 2017-01-19

Introduction

Over the past few decades, environmental issue has become a major problem across the globe and raised concerns among researchers, scientists, engineers and environmentalists. Several attempts have been made to solve the environmental problem because of the high level of pollution which results in the greenhouse effect and climate change to the world [1]. To ensure a more sustainable future, researchers have looked into the possibility of embedding natural fibres into fibre reinforced polymer (FRP) structure as a replacement for conventional synthetic fibres [2]. This is because natural fibres offer many advantages over synthetic fibres such as excellent specific properties, light weight, abundant, non-abrasive, non-hazardous and inexpensive [3]. Furthermore, natural fibre reinforced thermoplastic polymer also shows excellent recyclability [4]. Kenaf is particularly attractive in Malaysia due to its abundance and easily be replenished [5]. Another approach for getting greener composites is by using thermoplastic polymers rather than thermosetting polymers as thermoplastic polymers are considered to be more bio-degradable than thermosetting polymers [6].

Practical application of FRPs requires joining of materials either by adhesive or mechanical fasteners. However, the problem in mechanical joining such as bolts, pins, rivets is that there will be geometry discontinuity and this generates stress concentration and subsequently reduces the overall strength of the material [7]. As such, it is crucial to have an adequate understanding on the material behaviour especially at the joining of structures to prevent catastrophic failure. Liang et al. [8] investigated the macro-mechanical performance of bolted joints of glass fibre/resin composites with different stacking sequences [0/45/90°] and preload moments (4, 6, 8, 10Nm) through experimental work and finite element simulation. The result showed that the load carrying ability of the composites improved with increasing tightening torque until the maximum load stabilised after 8Nm. Sen et al. [9] studied the bearing strength of single bolted joints of glass fibre/epoxy under different preload moments (0, 2.5, 5Nm). They also varied two geometrical parameters which were edge-distance-to-hole diameter (E/D) and width-to-hole diameter (W/D), and four different ply orientations. The result showed that bearing strength increased with increasing E/D and W/D ratio. It was also proved that increasing preload moments will lead to higher bearing strength and bearing failure mode. It was also discovered that stacking sequence of [30°] was the best orientation while stacking sequence of [90°] was the weakest.

Temperature effect is an important consideration when designing polymeric parts or structures that might be exposed to elevated temperature. This is because heat has a significant effect on the polymer chain and thus the strength of a polymer [10]. There are many in-car body parts that are made from polymers such as door panels, door claddings, seatback lining and floor panels and the in-car temperature can elevate to as high as 56°C, which is much higher than room temperature [11]. Previous research showed that the effect of temperature on the strength of composite cannot be overlooked. Soykok et al. [12] investigated the effect of temperature on the mechanical failure of single lap double serial fastener glass fibre/epoxy composite. In their study, specimens were placed in temperature chamber at 40, 50, 60, 70 and 80°C, and the specimens were also tightened at 0 and 6Nm of preload moment. Results showed that the load-carrying ability of joints decreased as the test temperature increased while tightening torque improved the joint strength at room temperature and elevated temperature. Soykok et al. [13] also conducted another experiment to investigate the degradation of the single lap joint glass fibre/epoxy resin composite due to hot water ageing. In the experiment, specimens were immersed in hot water at a temperature of 50, 70 and 90°C for one and two weeks. Results indicated that due to hydrothermal degradation, maximum failure loads, distance to failure values and stiffness of joints decreased in proportion to an increase of the immersion time and temperature. A recent study investigated the geometrical effect of two serial bolted joint hole on glass/kenaf hybrid composite and it revealed that the bearing strength of that hybrid composite increases with increase of the distance between centers of two holes diameter (K/D) ratio and edge distance-to-upper hole centre (E/D) ratio [14]. Most of the aforementioned studies were limited to synthetic fibre and thermoset polymer. This study will explore the potential of using natural fibre reinforced thermoplastic in structural application. The effects of temperature and preload moment on woven kenaf-glass fibre reinforced polypropylene hybrid composite were investigated.

Experiment methods and procedures

Materials

Homopolymer polypropylene (PP) with a molecular formula of C_3H_6 was provided by Al Waha petrochemical company. The density of PP used was 0.9g/cm^3. E-glass fibre with areal weight of 600g/m^2 was supplied by ZKK Sdn.Bhd whereas kenaf fibre with areal weight of 295g/m^2 was obtained from National Kenaf and Tobacco Board. Both of E-glass fibre (GF) and kenaf fibre (KF) used were plain weave fabric.

Methodology

PP granules were first compressed into PP sheets with a thickness of 0.3mm by melting the PP granules at a pressure of 50kg/cm^2 and temperature of 180°C using hydraulic hot press machine. E-glass and kenaf fabric were cut into a dimension of 170mm x 250mm and then placed into an oven at temperature 40°C for 24 hours to eliminate moisture content. The FRP panels were stacked in a 3mm thick picture frame mould with the stacking sequence of [PP/GF/PP/KF/PP/PP/GF/PP]. The picture frame mould was placed in a hydraulic hot press machine with a temperature of 180°C and pressure of 30kg/cm^2. Hybrid composite panels were cut into a dimension of 135mm x 36mm using Proxxon table saw in accordance to ASTM D5961. Specimens were then drilled with notch diameter of 6mm at a specific location using laboratory bench drill. Circular file was used to get a good surface finish on the drilled notch to eliminate stress concentration. The notch diameter shall be tight-fit with the M6 bolt. Figure 1 shows the schematic dimension of the specimens (L=135mm, W=36mm, E=18mm, D=6mm).

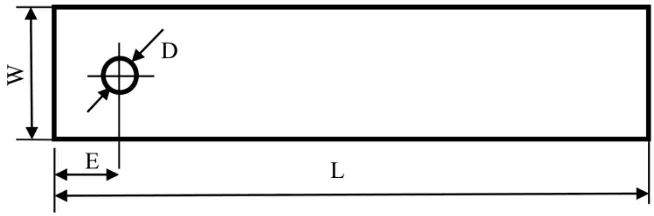
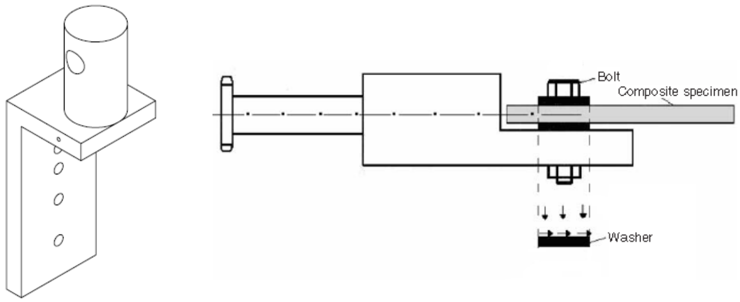


Figure 1: Composite specimen geometry

Bolted Joint Test

The bearing test was conducted according to ASTM D5961 using INSTRON 5969 Universal Testing Machine (UTM) with a load capacity of 50kN. Specimens were attached and bolted to the special designed and fabricated jig and then placed in the heat chamber at room temperature, 40°C, 50°C and 60°C. The design of the jig and the experiment assembly of specimens are as shown in Figure 2. Specimens were loaded at crosshead displacement rate of 2mm/min until a maximum load has clearly been reached in order to observe and analyse the exact failure mode. The tests were terminated when a 30% load drop from maximum load was detected. The test was repeated three times for each setting. The result from different temperatures and preload moments were recorded and represented in load- extension curves. The result was then analysed and evaluated to deduce the effect of temperatures and preload moments on bearing strength. Figure 3 shows the setup of specimen inside the heat chamber.



(a) (b)

Figure 2: Experiment setup (a) jig design (b) specimen setup

Figure 3: Setup of specimen inside heat chamber

Results and discussion

Table 1 summarises the maximum load that can be borne by the composite before yielding and subsequently failure. From Table 1, bearing failure mode was observed in all specimens under different temperature and preload moment conditions.

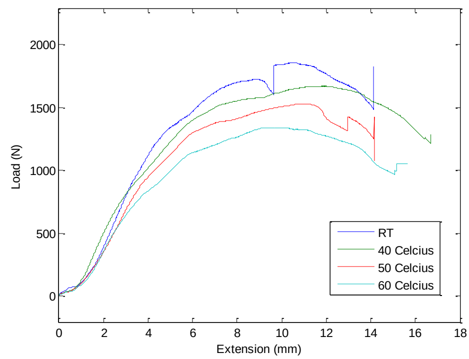
Table 1: Summary of maximum load and failure mode under different temperature and preload moment

Temperature (°C)	Preload moment (Nm)	Maximum load (N)	Failure mode
Room (≈25)	0	1796.776	Bearing
	5.2	1932.696	Bearing
	7.5	2155.430	Bearing
40	0	1538.560	Bearing
	5.2	1698.777	Bearing
	7.5	1673.757	Bearing
50	0	1680.264	Bearing
	5.2	1872.031	Bearing
	7.5	1758.320	Bearing
60	0	1350.293	Bearing
	5.2	1512.088	Bearing
	7.5	1400.972	Bearing

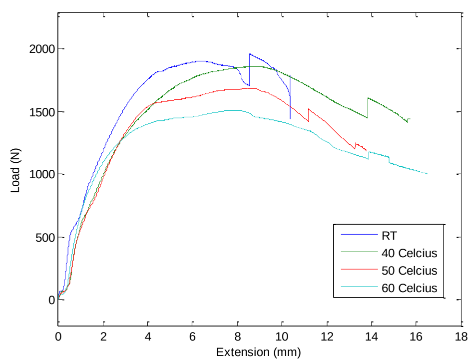
Figure 4 shows the effect of temperature on load-extension curve of the hybrid composite under different preload moment of 0, 5.2 and 7.5Nm. As can be seen from the graphs, specimens at room temperature (≈25˚C) have the highest load carrying capability, followed by specimens at 40°C, 50°C, and 60°C for all preload moments. At room temperature, the structure of the PP polymer matrix was not affected by the heat and the PP polymer matrix was able to fully perform its function as a binding agent and hence it allows the applied load to be distributed more evenly to all reinforcing fibres. As a result, the load carrying capability of specimens at room temperature condition was the highest among all tested temperatures. At 60°C, the load carrying capability decreased by about 28% on average compared to at room temperature. This can be attributed to the structure of the PP polymer matrix had been damaged and its role as a binding agent had been adversely affected. This shows the significance of temperature effect on the load carrying capability of FRPs. Generally, the increase in temperature will decrease the load carrying capability of a specimen in a proportional manner, which means the higher the temperature, the lower the load that can withstand.

As for the load-extension relationship, all specimens showed typical behaviour of ductile materials, which is linear at the beginning followed by non-linear relationship. Linear relationship was observed for the first 4 to 5mm of extension and then followed by intensive non-linear load-extension curve. The specimens were able to have higher elongation if exposed to elevated temperature but with bearing carrying capability compromised

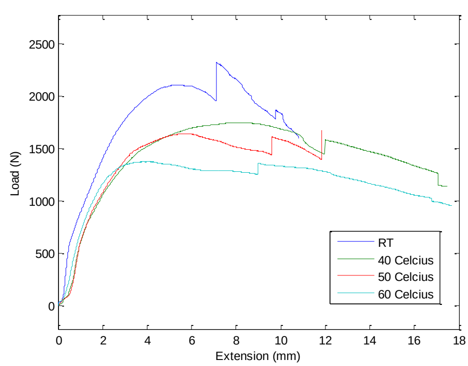
.



(a)



(b)



(c)

Figure 4: Effect of temperature on load-extension curve of hybrid composite at (a) 0Nm, (b) 5.2Nm and (c) 7.5Nm

Figure 5 shows the effect of preload moment on load-extension curve of the hybrid composite at different temperature (25, 40, 50 and 60°C). Figure 5(a) shows the effect of variation of preload moment at room temperature. From Figure 5(a), it can be seen that specimens with preload moment of 7.5Nm had the highest load carrying capacity, followed by 5.2Nm and 0Nm. This can be attributed to the clamping force produced by the tightening preload moments that prevent the delamination of fibre layers. The tightening preload moments held all the layers together at their original position, resulting in an increase in load carrying capacity. When delamination is avoided, the mechanical strength of specimens can be preserved, resulting in higher load carrying capacity. However, this phenomenon only happened in specimens at room temperature. For specimens exposed to temperature at 40, 50 and 60°C, preload moment at 5.2Nm showed the highest load carrying capacity, which was followed by 7.5Nm and 0Nm. Referring to Figure 5(b), (c) and (d), it can be noticed that the maximum loads were lower for specimens with 7.5Nm preload moment compared to specimens with 5.2Nm preload moment. Preload moment at 5.2Nm is the recommended tightening torque for M6 bolts [15]. This is because of the "plunging" effect of the washer that damaged the geometrical integrity of hole due to over-torque beyond recommended value. At elevated temperature, the PP matrix starts to soften due to the breaking of polymer chains. When the preload moment which is higher than the recommended value was applied, obvious engraving marks can be observed on the surfaces of the specimens. During bolted joint test, the washers "plunged" into the specimens, forming a cut-like opening around the hole that damaged both the PP matrix and fibres. As a consequence, the load carrying capability was undermined for over-torqued specimens at elevated temperatures.

In this experiment, preload moments do not have any impact on the extension of specimens. Except for the specimens at room temperature with 0Nm preload moment, all specimens at elevated temperature have a similar total extension before reaching the 30% peak load drop point. To exemplify the extension, from Figure 5(a), the specimens (except for specimens with 0Nm preload moment), reached the 30% peak load drop point at the extension of around 10mm. This also applies to other specimens at 40°C (around 12-14mm), 50°C (around 16-17mm) and 60°C (around 17-18mm). Therefore, this implied that preload moment does not affect the extension of specimens for the same temperature.

All specimens showed the same failure mode which was bearing failure mode. This shows that the load was the highest at the contact point between the top side of the hole and the bolt. The bearing deformation continued to propagate and subsequently bearing failure mode was superseded by net-tension failure mode. During the experiment, small crack lines perpendicular to the length of the specimens were observed, the small crack starts to propagate at the two sides of the holes. However, there was no large net-tension crack line observed due to the 30% peak load drop criterion was reached and the experiment was automatically stopped by the system. This is to comply with ASTM D5961 standard in order to observe the true failure mode and prevent the masking of true failure mode. Table 2, 3 and 4 summarise the test results at various temperatures under preload moment of 0, 5.2 and 7.5 Nm respectively.

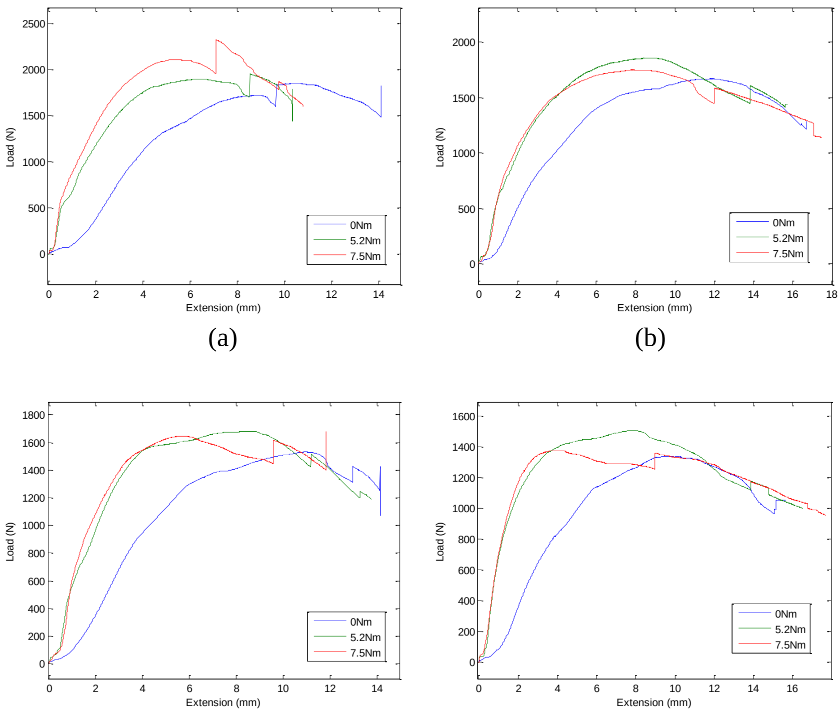


Figure 5: Effect of preload moment on load-extension curves at different temperature of (a) room (≈25°C) (b) 40°C (c) 50°C (d) 60°C

Table 2: Recorded test results at various temperatures under 0Nm preload moment

Temperature(°C)	**Room**	**40**	**50**	**60**
Max. value (N)	2117.039	1753.726	1549.024	1435.176
Min value (N)	1632.437	1630.530	1532.885	1289.488
Range (N)	484.602	393.196	16.139	145.688
Mean value (N)	1796.776	1680.264	1538.560	1350.293
Standard deviation (N)	227.388	64.935	9.073	75.770

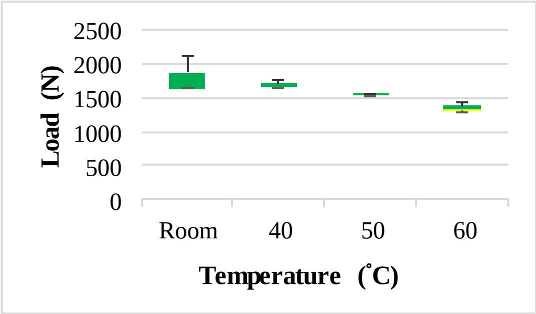
Table 3: Recorded and calculated test results at various temperatures under 5.2Nm preload moment

Temperature(°C)	**Room**	**40**	**50**	**60**
Max. value (N)	2062.830	2030.689	1754.279	1677.446
Min value (N)	1718.573	1604.029	1647.566	1427.966
Range (N)	344.257	426.660	106.713	249.480
Mean value (N)	1932.696	1872.031	1698.777	1512.088
Standard deviation (N)	186.865	233.402	53.486	143.212

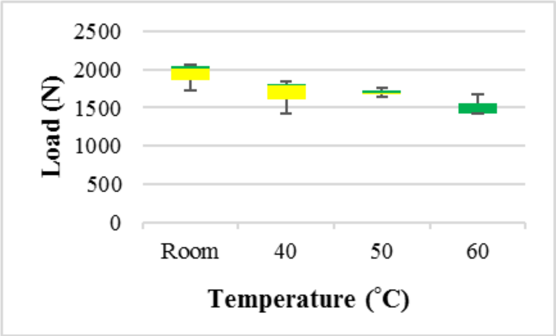
Table 4: Recorded and calculated test results at various temperatures under 7.5Nm preload moment

Temperature(°C)	**Room**	**40**	**50**	**60**
Max. value (N)	2420.513	1973.932	1844.649	1518.109
Min value (N)	1754.802	1631.929	1570.758	1317.154
Range (N)	665.711	342.003	273.891	200.955
Mean value (N)	2155.430	1758.320	1673.757	1400.972
Standard deviation (N)	352.948	187.648	1.380	104.539

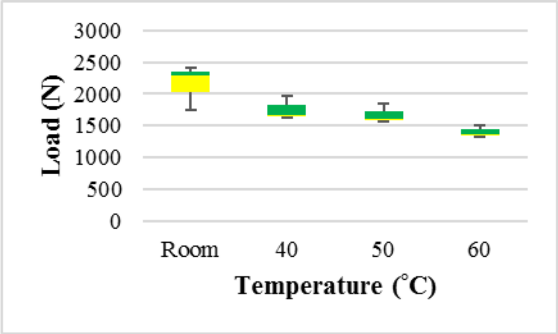
Figure 6 shows the box plots for maximum loads at the temperature of room temperature, 40, 50 and 60°C and different preload moments (a) 0Nm, (b) 5.2Nm and (c) 7.5Nm. Generally, most of the test values were close to each other and average value. The deviation and spread in test results were probably due to minor specimen inconsistency since each FRP panels are unique in the way that each panel was fabricated individually using laboratory-level machines and tools. In order to reduce the deviation, precise temperature and preload moment control was executed during the experiment which theoretically reduces the spread of test values. Figure 7 shows the computed 95% confidence interval for the average maximum load at various temperatures under preload moment of (a) 0Nm, (b) 5.2Nm and (c) 7.5Nm. The small deviation of test values from the average values indicates that the obtained test results are in the acceptable range.



(a)

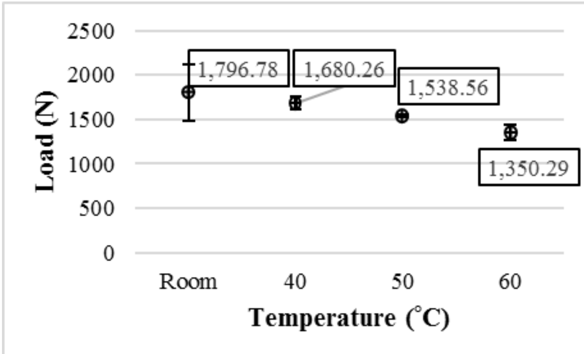


(b)

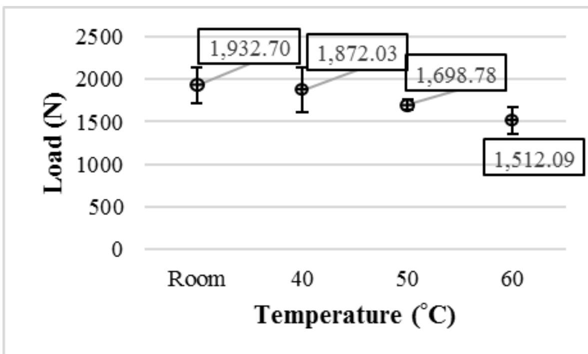


(c)

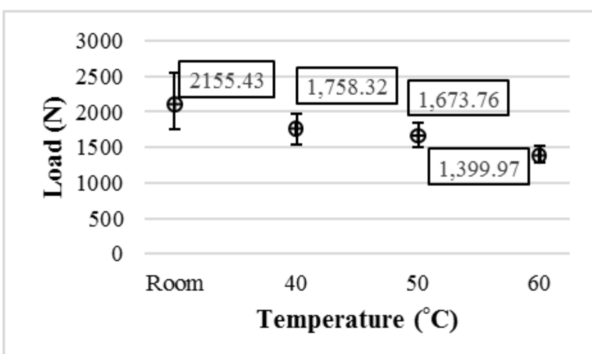
Figure 6**:** Box plots of maximum loads at various temperatures under (a) 0Nm, (b) 5.2Nm and (c) 7.5Nm preload moment.



(a)



(b)



(c)

Figure 7**:** 95% confidence interval of average maximum loads at various temperatures under (a) 0Nm, (b) 5.2Nm and (c) 7.5Nm preload moment.

Figure 8, 9 and 10 show the failure mode of the specimens after bolted joint test was performed. It can be seen that increasing the ambient temperature will lead to more damage in terms of notch deformation regardless the effect of preload moment. Figure 11 illustrates the "plunging" effect caused by the washers when specimens were torqued at 7.5Nm. The washer at the front side "sunk" into the specimen, forming a cut-like damage to the notch while the sunk washer forced the specimen to form a "bulge" at the back of the notch. Figure 12 presents the onset of net-tension failure mode at the two sides of the hole. The crack lines can be observed on the front and back of the specimen.

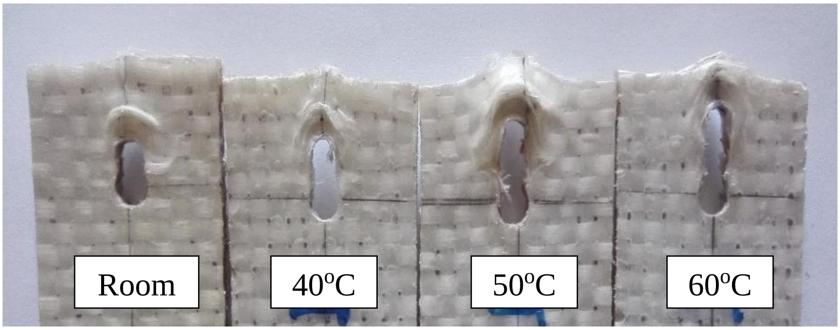


Figure 8: Photo of deformed specimens at various temperatures under 0Nm preload moment

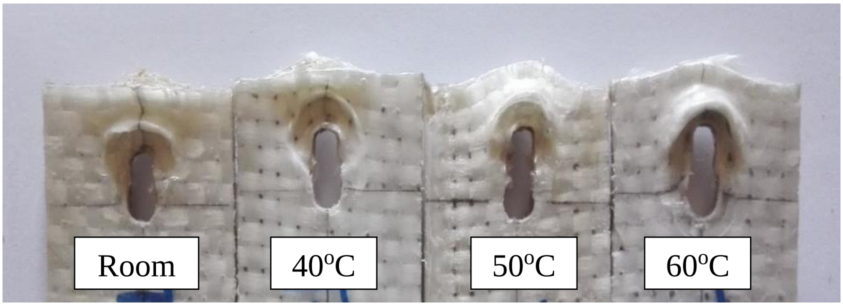


Figure 9: Photo of deformed specimens a t various temperatures under 5.2Nm preload moment

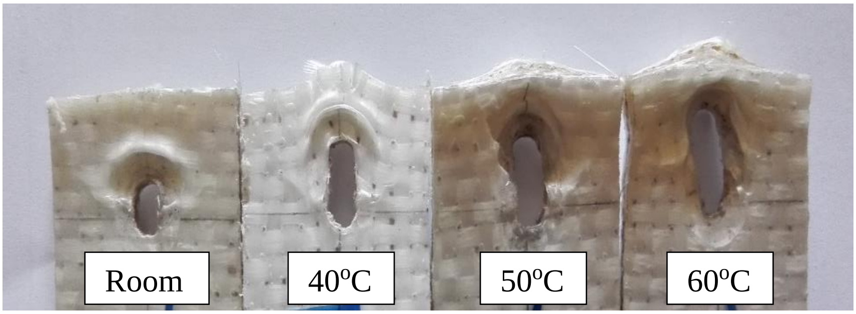


Figure 10: Photo of deformed specimens at various temperatures under 7.5Nm preload moment

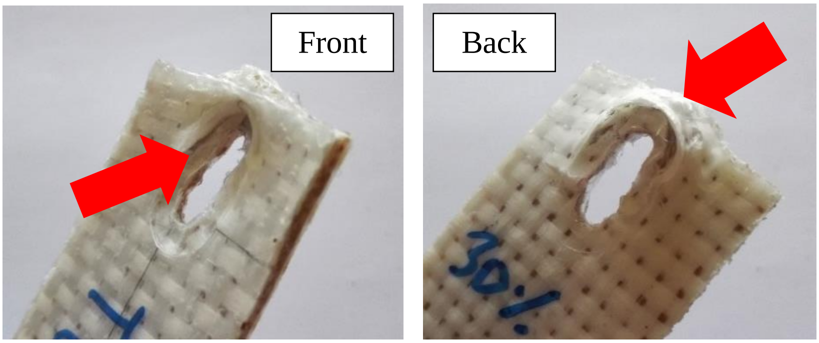


Figure 11: Photo showing "plunging" of washer into the specimen (Left: front side; Right: back side)

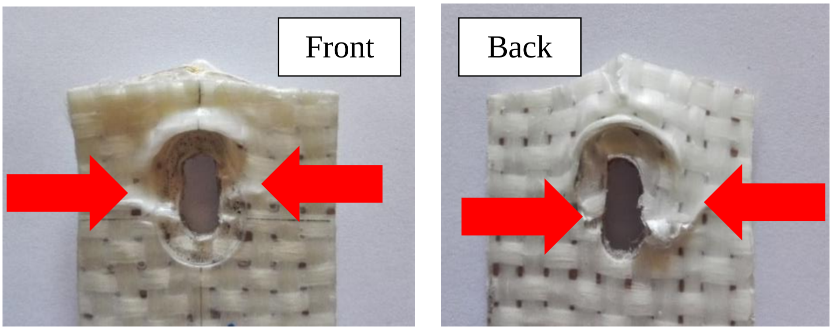


Figure 12: Photo showing the onset of net-tension failure mode (Left: front side; Right: back side)

Conclusion

This paper is aimed to investigate the effect of ambient temperature and tightening preload moment on the failure load and load-extension behaviour of bolted woven kenaf-glass fibre reinforced polypropylene hybrid composite. Single hole bolted joint composite specimens were tightened to 0, 5.2 and 7.5Nm and exposed to different ambient temperature of ≈25, 40, 50 and 60°C. Based on the test result, following conclusions can be deduced.

1. Ambient temperature has a significant effect on the load carrying capability of those bolted joint composite specimens. Overall, it is clearly shown that increasing the ambient temperature will have an adverse effect on the bolted joint strength of composite specimens.
2. Tightening preload moment does increase the joint strength with the condition that the tightening torque does not exceed the recommended value which is 5.2Nm for M6 bolt. When the preload moment exceeds the recommended value, the washers will tend to "plunge" into the specimens and thus damage the notch geometrical integrity.
3. The failure mode for all specimens started as bearing failure and continued to become a net-tension failure. However, there was no complete net-tension failure observed due to tests were automatically ended upon reaching 30% peak load drop.

Acknowledgement

Authors would like to thank Universiti Teknikal Malaysia Melaka for the continuous support on this research project. Authors would also wish to express their gratitude towards National Kenaf and Tobacco Board for the sponsorship of kenaf fibre. Skim Zamalah UTeM provided by Universiti Teknikal Malaysia Melaka.

References

[1] N. Sapawe, S. Syahrullail and M.I. Izhan. (2014). "Evaluation on the tribological properties of palm olein in different loads applied using pin-on-disk tribotester", Jurnal Tribologi 3, 11-29.
[2] S.K. Garkhail, R.W.H. Heijenrath and T. Peijs. (2000). "Mechanical properties of natural-fibre-mat-reinforced thermoplastics based on flax fibres and polypropylene", Applied Composite Materials 7(5-6), 351-372.
[3] M. Jawaid and H.P.S.A. Khalil. (2011). "Effect of layering pattern on

the dynamic mechanical properties and thermal degradation of oil palm-jute fibers reinforced epoxy hybrid composite", BioResources 6(3), 2309-2322.

[4] S.D. Malingam, M.H.R. Hashim, M.R. Said, A. Rivai, M.A. Daud, Sivaraos and M.A.C. Mahzan. (2014). "Effect of Reprocessing Palm Fiber Composite on the Mechanical Properties", Applied Mechanics and Materials 699, 146-150.

[5] R.M. Nasir and N.M. Ghazali. (2014). "Tribological performance of paddy straw reinforced polypropylene (PSRP) and unidirectional glass-pultruded-kenaf (UGPK) composites". Jurnal Tribologi 1, 1-17.

[6] J. Sahari and S.M. Sapuan. (2011). "Natural fibre reinforced biodegradable polymer composites", Reviews on Advanced Materials Science 30(2), 166-174.

[7] M. Ozen and O. Sayman. (2011). "Failure loads of mechanical fastened pinned and bolted composite joints with two serial holes", Composites Part B: Engineering 42(2), 264-274.

[8] W. Liang, Z. Duan, Z. Wang and P. Lin. (2014). "Experimental and numerical investigation on bolted joint in glass–fiber reinforced composites," Advanced Composite Materials, 1-13.

[9] F. Sen, O. Sayman, R. Ozcan and R. Siyahkoc. (2010). "Failure response of single bolted composite joints under various preload", Indian Journal of Engineering & Materials Sciences 17, 39-48.

[10] M. Sepe. (2011). "The effects of temperature," from http://www.ptonline.com/columns/the-effects-of-temperature.

[11] J. Null. (2015). "Estimated Vehicle Interior Air Temperature v. Elapsed Time," Retrieved from https: // www.avma.org /public/PetCare /Pages/Estimated-Vehicle-Interior-Air-Temperature-v.-Elapsed Time.aspx. (San Francisco State University).

[12] I. F. Soykok, O. Sayman, M. Ozen and B. Korkmaz. (2013). "Failure analysis of mechanically fastened glass fiber/epoxy composite joints under thermal effects", Composites Part B: Engineering 45(1), 192-199.

[13] I.F. Soykok and F. Ibrahim. (2015). "Degradation of Single Lap Adhesively Bonded Composite Joints Due to Hot Water Ageing", The Journal of Adhesion.

[14] D. Sivakumar, L.F. Ng and N.S. Salmi. (2016). "Eco-hybrid composite failure behaviour of two serial bolted joint holes", Journal of Engineering and Technology 7(1), 114-124.

[15] Torque Technical Data. (2008). "Tohnichi America Cooperation", Retrieved from http://www.tohnichi.com/torque-technical-data.asp, 28-39.