Journal of Engineering Science and Technology
Vol. 15, No. 4 (2020) 2809 - 2822

TENSILE STRENGTH AND FATIGUE CRACK GROWTH BEHAVIOUR OF NATURAL FIBRE METAL LAMINATES

ANINDITO PURNOWIDODO*,
SUTEDJA, DJAROT B. DARMADI, KHAIRUL ANAM

Mechanical Engineering Department, University of Brawijaya,
Jl. MT. Haryono 167, Malang 65145, Jawa Timur, Indonesia
*Corresponding Author: anindito@ub.ac.id

Abstract

Natural fibres taken from a bark of *hibiscus tiliaceus*, which is well known in local words as *waru* fibre (WF) is used as reinforcement of the bisphenol-*waru* fibre composite (B-WF). The composite together with a commercial aluminium is combined to make fibre metal laminates (FMLs). In the present work, the effects of WF orientations and the number of WF layers to the static strength and fatigue life of the FMLs were investigated. The more WF layers lower the tensile strength of the FMLs due to the decreasing strength of the laminate of the B-WF composite. The tensile strength of the FMLs with WF orientation of $0^0/90^0$ is higher than that of $-45^0/+45^0$ because it relates the fibre orientation to the principal stress applied to the FMLs. The stress concentration in the front of the crack tip of the metal laminate of FMLs is higher with the more WF layer. This leads to the effective stress advancing the crack to be higher, as the result, the fatigue life is shortened.

Keywords: Fatigue crack growth, Fibre metal laminates, Number of fibre layers, Tensile strength, *Waru* fibre.

1. Introduction

The fibre metal laminates (FMLs) are the laminate composite type consisting of metal laminates and fibre reinforced composite laminates. In general, metal laminates used in the FMLs are lightweight metals. To reinforce composite laminates, carbon and glass fibres are common to be used together with resin as matrix [1, 2]. Because of those constituent materials, the unique properties are obtained, mainly combination of high strength and lightweight. The higher strength of the FMLs is obtained because of the much higher strength of the fibres compared to the lightweight metal used as laminates [2, 3]. Therefore, the FMLs is a promising material for aircraft fuselage skin [4].

In the previous studies [5, 6], the investigations relating to the FMLs have focused on the strength and lifetime in which the fibres used in the composite laminate are the artificial fibres such as carbon and glass fibres. Because of their strength are much higher than a monolithic metal, which usually a lightweight metal, those fibres dominate the strength of the FMLs [1]. The strength of the composites depends on the arrangement of the fibres, which relates to the orientation [5], stack order, number of layers and weave form of the fibres [6]. In addition, when a FMLs is subjected to dynamic load, the crack may initiate and then grow to its critical length.

In association with the crack growth caused by the dynamic loads, the interfacial condition between the metal laminates and the fibre reinforced composite laminates affects the crack growth behaviour of a FMLs [1]. The interfacial conditions may be affected by the surface roughness of a metal laminate and a binder or matrix for the fibres [7-9]. In the previous studies, the natural fibre instead of the artificial ones had been used for the fibre reinforced composites [10-12]. However, the studies are still focused on loads relating to the static loads.

In this study, natural fibres obtained from a bark of *hibiscus tiliaceus* were used to substitute the artificial fibres of the FMLs. The *hibiscus tiliaceus* in the local word is called as *waru*, and hereafter it is called as the *waru* fibre (WF). The bisphenol-WF (B-WF) composites laminate together with commercial aluminium were combined to make the FMLs. Due to the correlation of the strength of composites relates to the fibre arrangement [13, 14], the study focused on effects of fibre orientations and the number of fibre layers to the strength under static loads. In addition, those effects under dynamic loads are investigated to know the crack growth behaviour at the metal laminate.

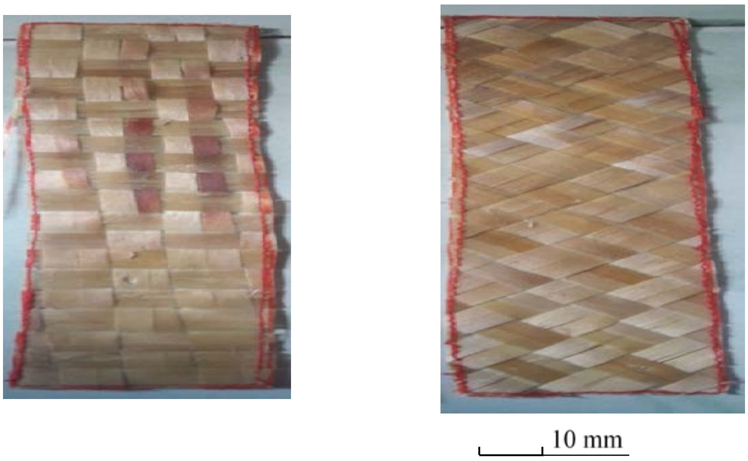
2. Methods

2.1. Material

The waru fibres (WFs) were obtained from the bark of *waru*, which provided by traditional craftsmen in Tulungagung, East Java. It is beyond the present study to explain how to change the bark to become fibres, and how to weave the fibres.

To make sure that the fibres did not contain any moisture, after being immersed in 6 % NaOH solution for two hours and rinsed by distilled water, they were dried in a room in which the temperature was maintained for 35^0C for 24 hours. Afterwards, the fibres were woven [15]. The adhesive selected to produce the laminate of WF reinforced composite was LP-1Q-EX consisting of resin-bisphenol, catalyst and promoter. The tensile strength of the adhesive was 41 MPa. [15].

Figure 1 shows examples of the woven fibres when they were directed to $0^0/+90^0$ and $-45^0/+45^0$, respectively. The commercial aluminium 1100 series with 0.5 mm of thickness was selected for the metal laminate of the FMLs. The yield and tensile strength of the aluminium were 69.8 and 84.3 MPa., respectively. The elastic modulus and maximum elongation were 66.5 GPa., and 2.0 %, respectively. Those properties were obtained after the aluminium was heat-treated in 300^0C for 1 hour followed by cooling in the furnace to room temperature.



(a) $0^O/90^O$. **(b) $-45^O/+45^O$.**

Fig. 1. The weave of *waru* fibres.

2.2. Composite fabrication

The vacuum-assisted resin transfer moulding (VARTM) technique was employed to fabricate the specimens of FMLs. The main parts of the VARTM are shown in Fig. 2 consisting of a resin container (A), an inlet tube (B), a specimen mould (C), an outlet tube (D), a resin trap (E) and a vacuum pump (F).

This technique was carried out in the laboratory room temperature. Before being poured into the container, every 100 g of bisphenol was mixed with 0.4 g catalyst and 0.8 g promoter. In the specimen mould, the WF orientation was directed to $0^0/90^0$ and $-45^0/+45^0$, respectively, from the load direction as shown in Fig. 1.

The shape of the mould and the sequence of the laminate depending on the type of the specimens are shown in Fig. 3. The mould was wrapped by the plastic-bag film, and sealed to prevent air to be sucked, thus, the vacuum condition could be maintained. When the mould had been filled up completely by the bisphenol, the vacuum pump was turned off. Afterwards, it was left at least 24 hours for curing.

Because the effect of the number of layers of the WF was investigated, the specimen thickness, *t*, of FMLs varied depending on the number of layers. Those were 0.96, 1.12, 1.49, and 1.6 mm for 1, 2, 3 and 4 layers, respectively.

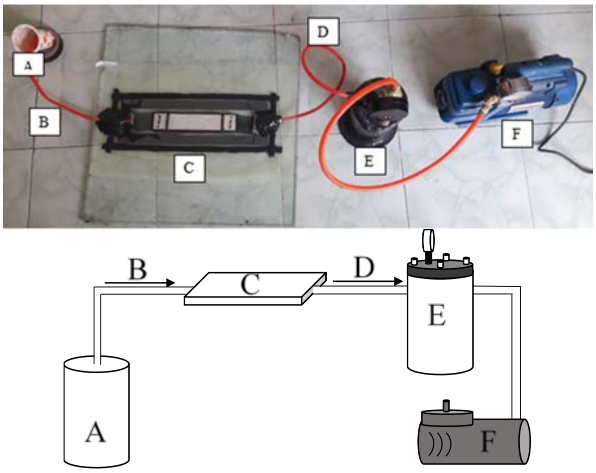


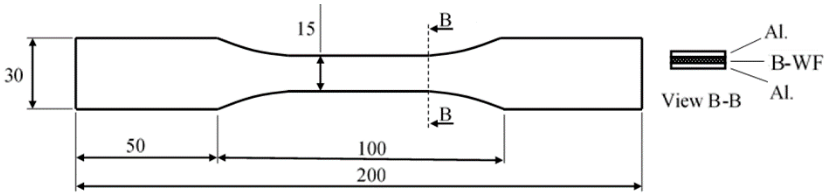
Fig. 2. The vacuum-assisted resin transfer moulding (VARTM) equipment.

2.3. Tensile and fatigue test

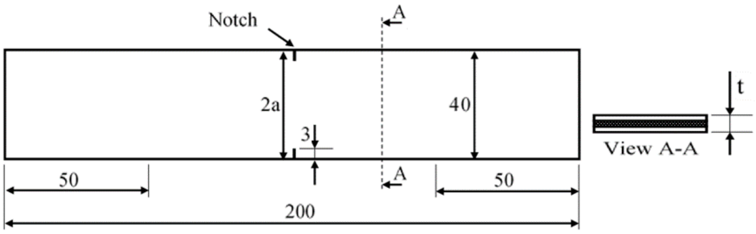
Figures 3(a) and (b) show the type of specimens for the tensile and fatigue test, respectively. The tests were carried out on the laboratory room temperature condition by the push-pull servo-hydraulic machine, which was also capable to conduct a static tensile test. Fifty millimetres from each end of both specimens was used for gripping on the testing machine. The static tensile stress was conducted by pulling every specimen with a speed of 0.02 mm/s. To measure the length extension, an extensometer with 50 mm-gauge length and 5 mm-measuring range was used. Because the effect of the number of WF layers on the FMLs strength was investigated, the laminate of the bisphenol-WF (B-WF) composite alone was also tested statically. For this aim, the shape and dimension as same as the tensile test specimen were used to know the strength of that laminate composite.

To observe the fatigue crack growth behaviour, the double-edge-crack type specimen was selected. For initiating crack, the sharp notch with 3 mm in length and 0.2 mm in width was made by machining at the both edges of the specimens as depicted in Fig. 3(b). The crack length is defined as $2a$ including the notch length. The fatigue test was carried out by subjecting the specimens to the cyclic loads with constant amplitude and a frequency of 6 Hz. The maximum load of the cyclic loads ($S_{max.}$) was equal to the 1/3 of the tensile strength of the FMLs for every number of layers of the WF, and the stress ratio (R) was zero. The stress ratio was defined as the ratio of the maximum loads to the minimum loads ($S_{min.}$) of the cyclic loads. To observe the crack growth behaviour on the surface of the metal laminate of the FMLs, the travelling digitally microscope was used with the accuracy of 10 μm.

The surface on which the crack growth was expected to take place was polished with an emery paper to obtain an observable mirror-like surface. In the present investigation, the fatigue and static tensile tests were conducted with three specimens for every number of WF layers. Hence, the results of the tests were based on their average. To know the percentage area of the fibre on the cross-section of the B-WF composite laminate, the Image J software was employed.



(a) Tensile test.



(b) Fatigue test.

Fig. 3. The shape and dimension (mm) of the specimen.

The crack growth behaviour of any FMLs occurs on the surface of the metal laminate, and this is affected by the delamination taking place over the crack region behind the crack tip. The crack growth was only observed on the laminate of the metal surfaces, whereas the fibre reinforced composite was still intact over the crack region [16, 17]. If so, the stress carried by the metal laminates was transferred to the fibre reinforced composite. This transferred stress is called as the bridging stress, and it leads to the shear stress to develop at the interface between the metal laminate and the fibre reinforced composite laminate [1, 17]. The shear stress can reduce the crack opening of the crack [1, 16-18]. The reduction of the crack opening of the crack tip indicates that the stress advancing effectively the crack is high [19]. If the delamination occurs, the crack growth rate increases due to the decreasing of the bridging stress [1, 16]. In the present investigation to indicate the crack opening, the displacement of the notch was detected by the extensometer. The detection was carried out by connecting the extensometer to the region over the notch by the links as depicted in Fig. 4.

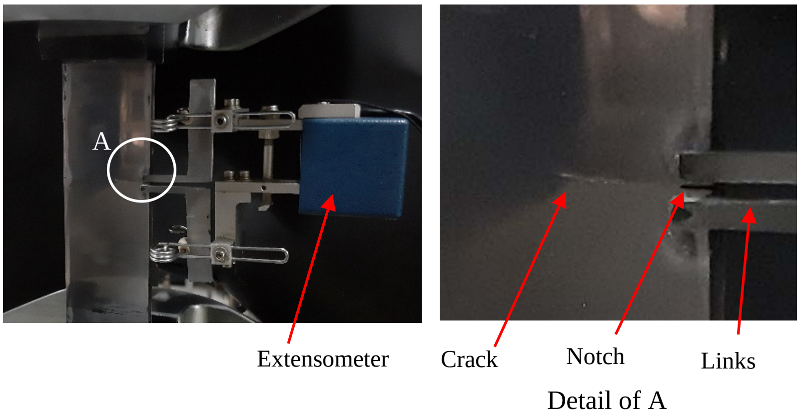


Fig. 4. The extensometer arrangement of a fatigue test specimen.

The stress concentration in front of the crack tip in connection with the delamination was investigated by computer simulation using ANSYS software based on the finite element method. The simulation was carried out by the code of that software. The element type was solid186 for solid model, and the element type for interfacial surface was conta174 and targe170. The model was made as shown in Fig. 5. The half model was used because of the symmetry of the specimen. L points the meshing region in which the delamination takes place at the interface between the B-WF composite and the metal laminate. The shape of the delamination is assumed as proposed by Huang et al. [16]. S points the meshing region in which the stress distribution is affected by the crack tip, and the stress concentration is expected to occur.

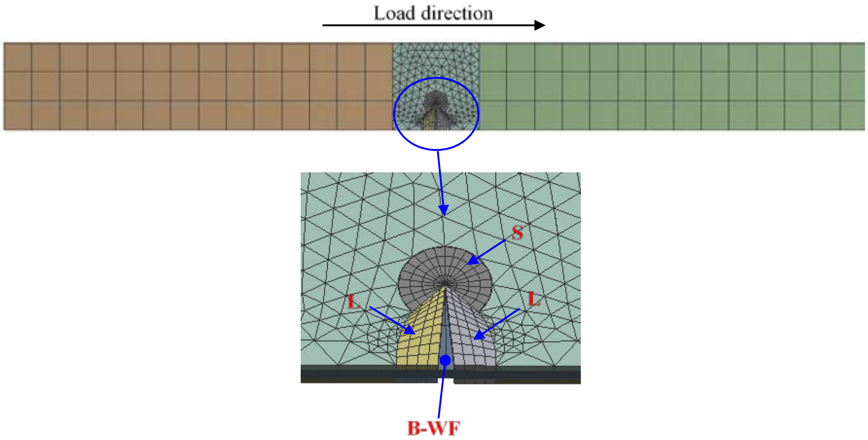


Fig. 5. The finite element model of FMLs.

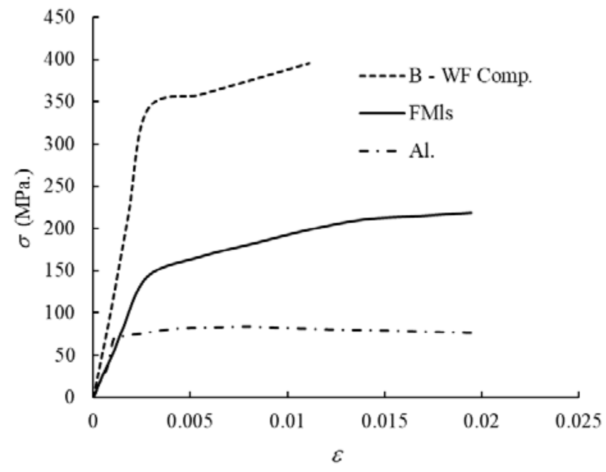
3. Results and Discussion

3.1. Tensile strength

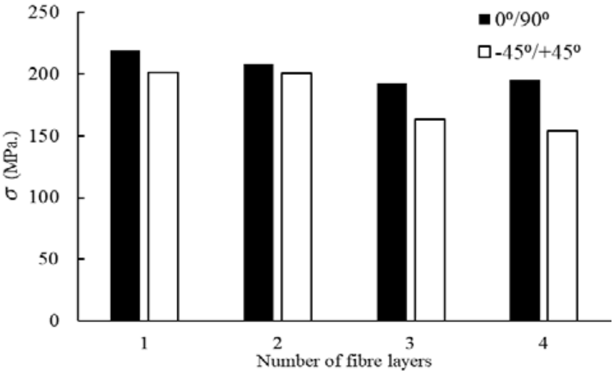
Figure 6(a) shows an example the tensile test result, and it shows a tensile strength comparison between FMLs and its constituents, which are the monolithic aluminium and the B-WF composite laminate. In this case, the number of woven WF is one layer only, and the fibre orientation is $0^0/90^0$.

The figure shows that the tensile strength (σ) of the B-WF composite alone is higher than that if it is combined with the aluminium in the FMLs. This associates with the monolithic aluminium strength, which is much lower than the composite. The effect of orientation and the number of WF layers of the B-WF composite on the strength of FMLs is summarized in Fig. 6(b). Instead of increasing the tensile strength, the number of WF layers decreases it in both of fibre orientation of the FMLs.

Because the strength of the FMLs is dominated by the strength of the B-WF composite laminate as shown in Fig. 6, the strength of the composite alone was tested for every number of WF layers, and the result is shown in Fig. 7. The increasing number of layers lowers the strength of the composite, and the strength of the composite with the fibre orientation of $-45^0/+45^0$ is lower than that of $0^0/90^0$ cases. The decreasing strength on both fibre orientation cases relates to the fraction of the fibre in the composite.



(a) Examples of tensile test results.



(b) Effect of orientation.

Fig. 6. The tensile test and the strength of the FMLs.

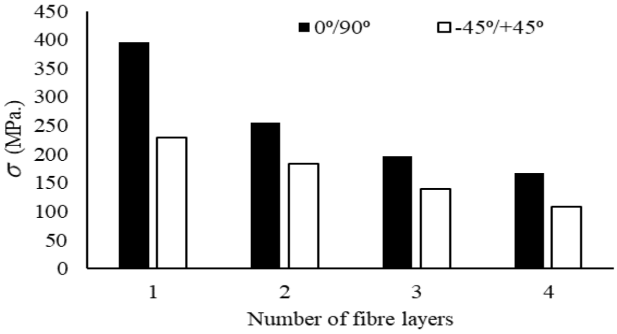
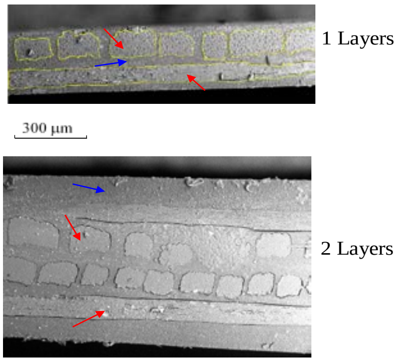
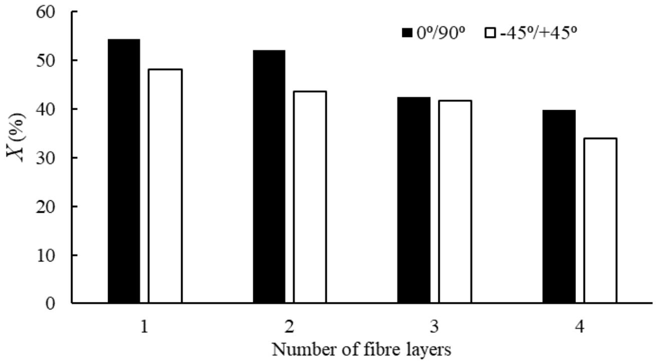


Fig. 7. The strength of B-WF composite.

Figure 8(a) shows the examples of the cross-section of the B-WF composite alone for 1 and 2 layers, respectively, with the fibre orientation of $0^0/90^0$. The sectioning was carried out by cut the cross-section of the B-WF using a saw, and then the surface of the cross-section was polished carefully by an emery paper on the flat surface. The blue and red arrows point the bisphenol and WF, respectively. The yellow line encircling the fibre area in Fig. 8(a) is used to mark the area fraction of the fibre. The result of the calculation is depicted in Fig. 8(b) indicating that the increasing number of the WF layers decreases the percentage of area fraction of the WF, *X*. Therefore, it causes the strength of the B-WF composite to be lowered by the increasing number of the WF layers. Because the strength of WF is higher than the bisphenol, and the WF's percentage of area decreases, consequently, the strength of the FMLs is lowered.



(a) The cross section of the B-WF composite



(b) The fraction area (X) of WF in the B-WF composite

Fig. 8. The area fraction of WF in the B-WF composites.

The fibre orientation being parallel to the principal stress is capable to support higher load than the other [3, 6, 8]. Due to the parallelism to the load direction, the tensile strength of the composite with the fibre orientation of $0^0/90^0$ is higher in comparison to the orientation of $-45^0/+45^0$ for every number of WF layers. This is indicated by the fracture condition of the B-WF composite as shown in Fig. 9. The fracture surface with fibre orientation of $0^0/90^0$ is perpendicular to the load direction or principal stress because there is the weave of WF having the same orientation to the load direction. Hence, the load is transferred completely to the fibres as indicated by all broken fibres being parallel to the load direction. However, in the case of fibre orientation of -45^0/+45^0, the fracture surface is inclined about 45^0 to the load direction, and the fibres in this direction are almost not broken. This indicates that the load is not transferred completely to the fibres, and the composite fracture due to the matrix (bisphenol) is not capable to sustain the load. Therefore, it decreases the strength of the composite with that fibre orientation.

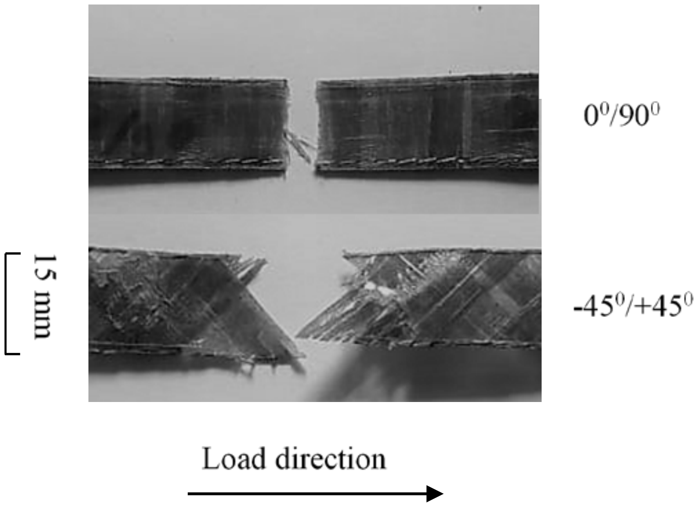
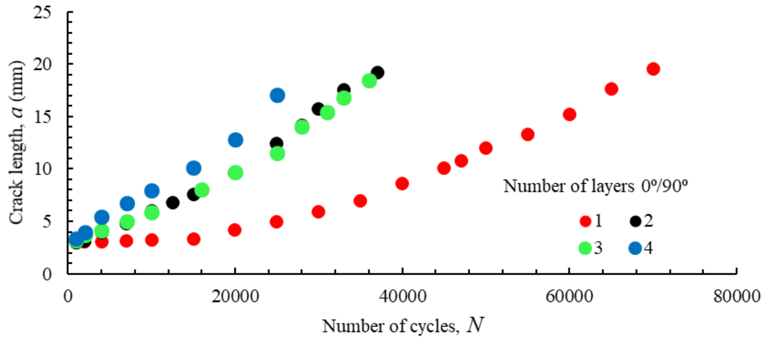


Fig. 9. The fracture of the B-WF composite.

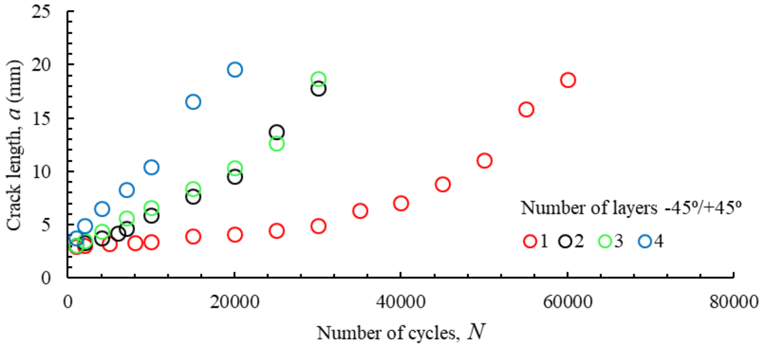
3.2. Fatigue life

The fibre reinforced composite laminate is still intact, and the crack grows only on the metal laminate of the FMLs [1-3, 7, 8]. In the present study, the same case is observed and shown in Fig. 10. The crack growth behaviour of the FMLs for every number of WF layers is plotted in Fig. 11(a) and (b) for the WF orientation of 0^0/90^0 and -45^0/+45^0, respectively. It can be seen that the fatigue life associated with the crack growth is affected by the number of WF layers in the laminate of B-WF composite. The fatigue life is lowered by the number of WF layers on both cases of the fibre orientations. Fig. 12 shows the fatigue life comparison for every fibre orientation of the FMLs. The fatigue life of the FMLs with fibre orientation of 0^0/90^0 is higher than that of the -45^0/+45^0 for every number of the WF layers.

Fig. 10. The crack growth on the aluminium laminate of the FMLs.



(a) The WF orientation of $0^0/90^0$



(b) The WF orientation of $-45^0/+45^0$

Fig. 11. The Crack growth behaviour.

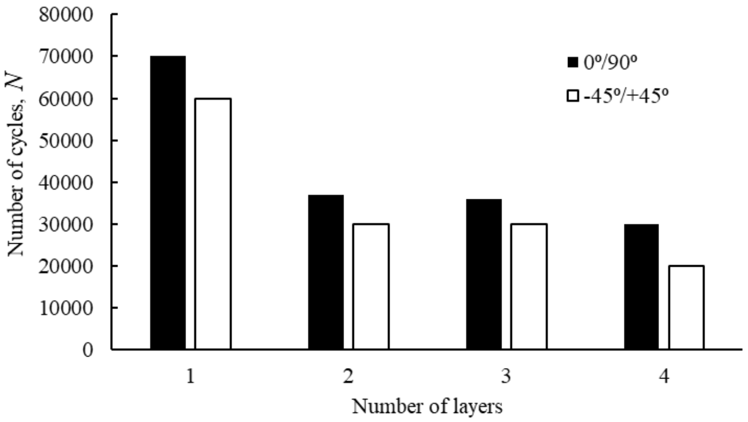


Fig. 12. The fatigue life of FMLs.

3.3. Stress analysis

Figure 13 shows an example of the stress distribution contour for the cracked model when the half crack length, *a*, is 6 mm with the two layers of WF and the fibre orientation of $0^0/90^0$. The stress contour shown in the figure is the case with the maximum load ($S_{max.}$). The red contour in the region just in front of the crack tip indicates that the stress is concentrated in that region and has the highest value. The colour shifts gradually from the red to the light green as the effect of the crack tip to the stress concentration is less pronounced.

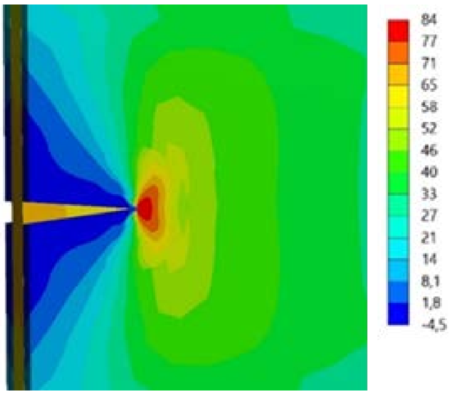
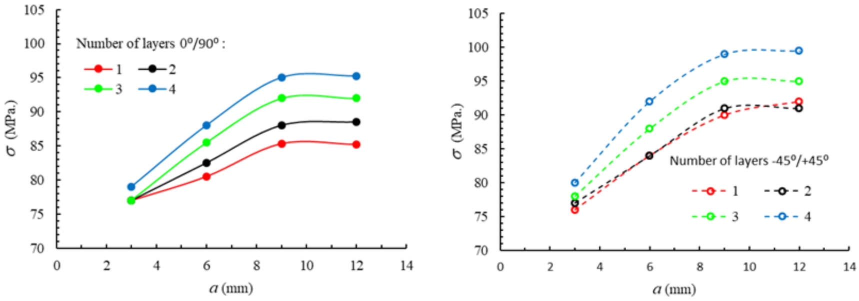


Fig. 13. The stress distribution contour (MPa).

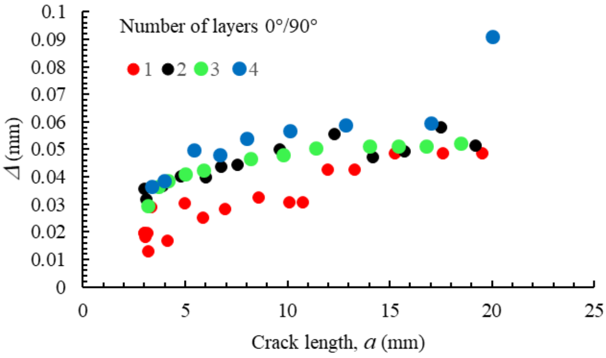
The magnitude of the stress concentration in front of the crack tip is responsible to the advance of the crack during the cyclic loads. Hence, the magnitude comparison of the stress that occurs while being loaded at the maximum load of the cyclic loads ($S_{max.}$) is made by plotting the stress magnitude for every half-crack length, *a*, for every number of WF layers as shown in Fig. 14. The stress magnitudes plotted are based on the stress magnitude just in front of the crack tip. Both cases of WF orientation of $0^0/90^0$ and $-45^0/+45^0$ show a similar tendency in which the increasing crack length raises the stress magnitude in front of the crack tip, and the raising number of the WF layers increases also the magnitude of the stress. The stress magnitudes in the cases of $-45^0/+45^0$ are slightly higher than those of the $0^0/90^0$. It is the reason that the FMLs with the WF orientation of $-45^0/+45^0$ has lower fatigue life. In addition, due to the higher stress concentration in the FMLs with more WF layers, the fatigue life is lower too.



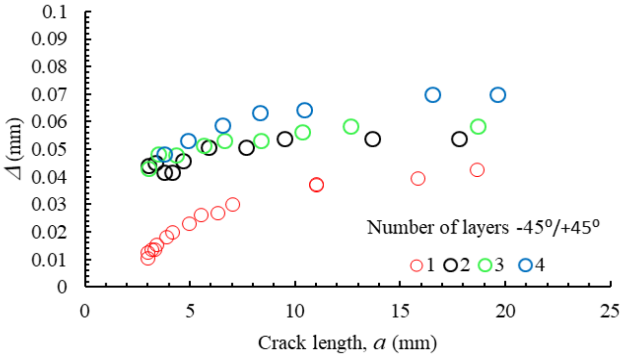
(a) The WF orientation of 0°/90°. (b) The WF orientation of -45°/+45°.

Fig. 14. The stress concentration just in front of the crack tip.

The higher displacement of notch indicates that the lower stress is required to open the crack, and as consequent, it causes the easier crack to propagate [18]. In the present study, the notch mouth displacement obtained, *Δ*, is plotted in Fig. 15. The displacement on both cases of the WF orientations have the similar tendency, that is, the displacement is higher when the number of the WF layers increases and becomes higher as the crack propagates. The higher values of the displacements indicates the lower stress required to begin to open the crack, hence, the stress advancing effectively the crack is higher, and it causes the crack to be easy to grow [19]. Therefore, the FMLs with the more WF layer tends to have a lower fatigue life in the both cases of the fibre orientations.



(a) The WF orientation of $0^0/90^0$



(b) The WF orientation of $-45^0/+45^0$

Fig. 15. The maximum displacement of the notch.

4. Conclusion

The tensile strength of the FMLs decreases as the number of WF layers increases. It is caused by the decreasing strength of the laminate of the B-WF composite due to the lower fraction area of the WF when the number of WF layers raises. The tensile strength of the FMLs with the WF orientation of $0^0/90^0$ is higher than that of $-45^0/+45^0$ due to the woven fibre direction being parallel to the principal stress in the case of $0^0/90^0$. The FMLs with more WF layers has shorter fatigue life. It relates to the stress concentration distribution developing in the zone in front of the crack tip of the aluminium laminate. The stress concentrated in the zone is higher on the FMLs with more WF layers. Therefore, the effective stress advancing the crack is higher as indicated by the increasing notch displacement leading to the crack to grow more easily, consequently, the fatigue life becomes shorter.

Nomenclatures

a	Crack length, mm
N	Number of cycles
R	Stress ratio ($S_{min.}/ S_{max.}$)
$S_{min.}$	Minimum cyclic loads, MPa.
$S_{max.}$	Maximum cyclic loads, MPa.
t	Specimen thickness, mm
X	Fraction area, %

Greek Symbols

Δ	Notch mouth displacement, mm
ε	Strain
σ	Tensile strength, MPa.

Abbreviations

B-WF	Bisphenol-*waru* fibre
FMLs	Fibre metal laminates
VARTM	Vacuum-assisted resin transfer moulding
WF	*Waru* fibre

References

1. Alderliesten, R. (2005). *Fatigue crack propagation and delamination growth in glare* (1st ed.). Delft: DUP Science.
2. Dadej, K.; and Bienias, J. (2017). Residual fatigue life of carbon fibre aluminium laminates. *International Journal of Fatigue*, 100(1), 94-104.
3. Jones, R.M. (1999). *Introduction to composite materials-mechanics of composites materials* (2nd ed.). Philadelphia: Taylor & Francis.
4. Alderliesten, R. (2017). *Fatigue and fracture of fibre metal laminates* (1st ed.). Cham: Springer International Publishing.
5. Anindito, P.; Khairul A.; Djarot B.D.; and Ari W. (2018). The effect of fiber orientation and stress ratio on the crack growth behavior of fiber metal laminates (FMLs). *International Journal of Technology*, 9(5), 1039-1048.
6. Solis, A.; Sánchez-Sáez, S.; and Barbero, E. (2018). Influence of ply orientation on free-edge effects in laminates subjected to in-plane loads. *Composites Part B*, 153, 149-158.
7. Pan, Y.; Wu, G.; Huang, Z.; Li, M.; Ji, S.; and Zhang, Z. (2017). Effect of surface roughness on interlaminar peel and shear strength of CFRP/Mg laminates. *International Journal of Adhesion and Adhesives*, 79(8), 1-7.
8. Canche, N.G.G.; Flores-Johnson, E.A.; Cortes, P.; and Carrillo, J.G. (2018). Evaluation of surface treatments on 5052-H32 aluminum alloy for enhancing the interfacial adhesion of thermoplastic-based fiber metal laminates. *International Journal of Adhesion and Adhesives*, 82, 90-99.

9. Kinloch, A.J.R.J.; Hu, W.; and Surowska, B. (2016). Cyclic-fatigue crack growth in composite and adhesively bonded structures: the FAA slow crack growth approach to certification and the problem of similitude. *International Journal of Fatigue*, 88(10), 10-18.
10. Bledzki, A.K.; and Gassan, J. (1999). Composites reinforced with cellulose based fibres. *Progress in Polymer Science*, 24, 221-274.
11. Jauhari, N.; Mishra, R.; and Thakur, H. (2015). Natural fibre reinforced composite laminates - a review. *Proceedings of the 4th International Conference on Materials Processing and Characterization Materials*. Hyderabad, India, 2868-2877.
12. Vieira, L.M.G.; Santos, J.C.; Panzera, T.H.; Rubio, J.C.C.; and Scarpa, F. (2017). Novel fibre metal laminate sandwich composite structure with sisal woven core. *Industrial Crops and Products*, 99, 189-195.
13. Cugnoni, J.R.; Amacher, S.; Kohler, J.; Brunner, E.; Kramer, C.; Dransfeld, K.; Scobbie, L.; Sorensen, J.; and Botsis, W.S. (2018). Towards aerospace grade thin-ply composites: effect of ply thickness, fibre, matrix and interlayer toughening on strength and damage tolerance. *Composites Science and Technology*, 168, 467-477.
14. Belgacem, L.; Ouinas, D.; Olay, J.A.V.; and Amado, A.A. (2018). Experimental investigation of notch effect and ply number on mechanical behavior of inter ply hybrid laminates (glass/carbon/epoxy). *Composites Part B*, 145, 189-196.
15. Arief, R.F.; Sofyan, A.S.; and Anindito, P. (2017). Composite characteristics of waru tree fiber skin (hibiscus tiliaceus) based on synthetic resin types on tensile strength and composite fracture (in Indonesian). *Jurnal Rekayasa Mesin*, 8(2), 101-108.
16. Huang, Y.; Liu, J.; Huang, X.; Zhang, J.; and Yue, G. (2015). Delamination and fatigue crack growth behavior in fiber metal laminates (glare) under single overloads. *International Journal of Fatigue*, 78(9), 53-60.
17. Nojavan, S.; Schesser, D.; and Yang, Q.D. (2016). A two-dimensional in situ fatigue cohesive zone model for crack propagation in composites under cyclic loading. *International Journal of Fatigue*, 82(3), 449-461.
18. Wilson, G.S.; Alderliesten, R.C.; and Benedictus, R. (2013). A generalized solution to the crack bridging problem of fibre metal laminates. *Engineering Fracture Mechanics*, 105(9), pp. 65-85.
19. Bao, H.; and Mc.Evily, A. J. (1995). The effect of overload on the rate of crack propagation under plane stress conditions. *Metallurgical and Materials A*, 26(7), 1725-1733.