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ORIGINAL ARTICLE

Fatigue Characteristic and Weibull Analysis of Sustainable Rubberwood Flour/Recycled Polypropylene Composites

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ABSTRACT – Although there is a perpetual interest in natural fibre composite, the fatigue data and their durability behaviour is still lacking, thus limiting their potential use in high-end applications. In this study, wood polymer composite made from rubberwood flour and recycled polypropylene was subjected to a tension-tension fatigue test in order to investigate their fatigue characteristic. Hysteresis loop was captured in order to establish their stress to number of failure (S-N) curve. The fatigue strength of the composite strongly depends on the stress amplitude. At the lowest stress level, the fatigue life of the composite exceeds the 1.5 million cycles limit, suggesting that the endurance limit for composite materials to be 11.06 MPa. The residual modulus and energy dissipated are plotted as a function of number of fatigue cycles. As the cycles progress, the residual modulus fall and dissipated energy increase indicated the cyclic damage in the composite structure. Two parameters Weibull probability were used to statically analyse the fatigue life and reliability of the rubberwood/recycled polypropylene composite. The S-N curve was plotted at different reliability index (RI = 0.1, 0.368, 0.5, 0.9, 0.99) using Weibull data. This data is used to identify the first failure time and design limits of the materials.

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INTRODUCTION

The demand for wood polymer composite (WPC) in automotive applications, furniture, outdoor building materials such as deck floor and others [1-3] increases due to their low price, robustness in design, and good environmental attributes. Wood polymer composite contains wood flour as the major component. It is inexpensive fillers materials that provide excellent mechanical reinforcement attributes such as high strength and stiffness. Wood flour is often resources from the waste of the timber industry. The wood flours is combined together during the compounding process with polymeric materials such as polypropylene, polyethylene, polyvinyl chloride [4-6] and fillers such as nanoclay, talcum, and calcium carbonate [5] to form a strong and stable composite system. Often, the thermoplastic matrix is sourced from the post-consumer product, also as an effort to reduce the plastic waste in the environment [4, 5, 7]. Wood polymer composite provide an excellent alternative to timber and possibly able to reduce the environmental impact due to deforestation.

However, with the increase of interest of using cellulosic fibre composite in wide range of applications, some of it might be exposed to cyclic or alternating loads during the service. Most of the materials experience dynamic stress during the service durations. Therefore, the initial strength of the composite, characterised under static conditions will degrade over time and be susceptible to fatigue damage. The failure may occur at lower stress conditions than the anticipated conditions using static strength. It can lead to catastrophic failure of the structure during service lives. Therefore, characterisation under the static conditions alone may not be sufficient. Thus, fatigue reliability is essential when designing a structure or component with higher static strength materials. While many studies have been conducted on the fatigue behaviour of the composite (particularly when subjected to cyclic stress), this is mainly concentrated for high-performance materials such metallic materials [8], aligned or fibre composite laminates [9-13], often used for aerospace, automotive, building and medical [14] applications. However, very little data is available for particulate wood polymer composite, particularly for rubberwood based and incorporating recycled polymer as matrix materials used in this study. Statistical evaluation using the Weibull distribution approach is one of the valuable and adaptable methods to predict the survival probability of material with fatigue data of different characteristics [15-18] and high scattering index due to their wide variety of shapes [19, 20]. The establishment probability of survival at different stress conditions is important information for the designer to identify the safety limits of the materials during service.

This work aims to examine the response of rubberwood reinforced recycled polypropylene subjected to load histories in order to help understand the complex behaviour of the materials. The fatigue stress is performed in tension-tension under load control mode. The fatigue life is presented in stress (S) to the number of cycles to failure (N) diagram. The hysteresis loops are recorded throughout the fatigue test to monitor the changes in their dynamic modulus and energy

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dissipated per cycle due to fatigue damage to the structure. The reliability analysis using a two-parameter Weibull distribution is also presented.

EXPERIMENTAL METHODS

Sample Preparation

The rubberwood / recycle PP (rPP) used is pellets composed of 50.3 wt.% rPP, 37.5 wt.% rubberwood flour, 7 wt.% calcium carbonate, 3.9 wt.% MAPP, 0.2 wt.% UV, 1 wt. % lubricant. The formulation for this rubberwood/ recycle PP composite (RWPC) materials has been optimised and palletised using a twin-screw extruder, as reported by an earlier study [5]. The pellets were compressed moulded in a window frame mould of 250×125×4 mm using a hot press machine (Carver, USA). The mould was heated from room temperature to 190 °C with gradual pressure, and optimum 1000 psi was applied at the optimum temperature. The mould was held for 20 minutes at maximum temperature before cooling down to room temperature using water quenching. The WPC plate was cut into dumbbell-shaped according to ASTM D638 using a CNC machine as shown in Figure 1. The samples were pre-condition at 50% RH prior to the testing. The laboratory temperature is varied between 20 and 25°C.

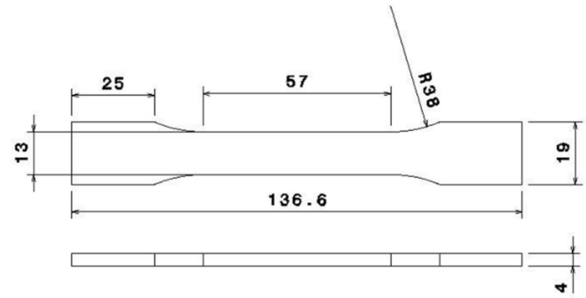


Figure 1. Specimen geometry, dimensions in mm.

Mechanical Testing

A 20 kN servo-hydraulic fatigue machine (Servopulser Shimadzu, Japan) was used for static and fatigue evaluation of the rubberwood-based composite. An aluminium tab was used at the end of the sample to prevent slipping out during the test. A quasi-static test was performed at 2 mm/min to determine ultimate tensile strength. The fatigue test was carried out in tension-tension stress control mode at 40 to 80% of the ultimate tensile strength and stress ratio (R) of 0.1. A frequency of 4 Hz was used, and the test was carried out till fracture, or in the case of non-failure, run-outs were defined after 1.5 million cycles. The machine is equipped with 4830 controllers, allowing the stress versus strain loop to be captured at log intervals with 50 data points recorded at each cycle.

Weibull Distribution

The survival probability (Ps) of the two-parameter Weibull distribution is given in Eq. (1) [16].

$$P_S(x) = 1 - P_f\,(x) = e^{\left(\frac{x}{\alpha}\right)^{\beta}} \tag{1}$$

$P_f(x)$ is the failure probability, x is the cycle number, and α and β are the scale and shape parameters. Their value can be determined by rewriting Eq. (1) to form a linear relationship as in Eq. (2) [16].

$$Ln\left(ln\left(\frac{1}{1-P_f(x)}\right)\right) = \beta Ln(x) - \beta Ln(\alpha) \tag{2}$$

The failure probability can be determined from Eq. (3) [20].

$$P_f(x) = \frac{i - 0{,}3}{n + 0{,}4} \tag{3}$$

where *(i)* is the serial number of cycles to failure and *(n)* is the total number of samples used. The mean life to failure (MTTF), the standard deviation (SD) and the coefficient of variation (CV) can be determined from Eq. (4) to Eq. (6) [20]:

$$[MTTF] = \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \tag{4}$$

$$[SD] = \alpha\sqrt{\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)} \tag{5}$$

$$[\mathrm{CV}] = \frac{[\mathrm{SD}]}{[\mathrm{MTTF}]} = \frac{\sqrt{\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)}}{\Gamma\left(1+\frac{1}{\beta}\right)} \tag{6}$$

where Γ is the gamma function.

RESULT AND DISCUSSION

Static Tensile Test

A mean ultimate tensile strength (UTS) of 26.33 MPa, with a standard deviation of ± 0.60, was measured from 10 tests, in agreement with the value obtained by Srivabut [5]. A mean tangent modulus of 1.69 GPa ± 0.16 and an elongation percentage at break of 1.59 ± 0.17 was calculated for the test and reported here. A typical stress-strain plot of the rubberwood /rPP composite is shown in Figure 2 suggested that the composite fractured in a more brittle manner with low strain at failure. The result of the UTS is crucial to carry out the cyclic fatigue test of the rubberwood/rPP composite materials.

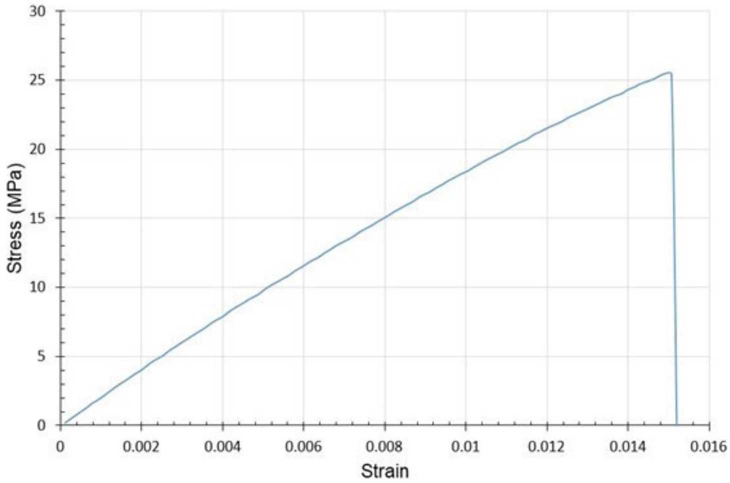


Figure 2. Static stress- strain behavior of rubberwood/recycled polypropylene composite.

S-N Curve, Hysteresis Loop and Fatigue Damage Characteristic

The S verse log N for the fatigue test at R= 0.1 using the Wöhler liner model are shown in Figure 3. It can be observed as the number of the cycles to failure progress, there is a gradual reduction in fatigue strength. The number of cycles to failure is reduced with the increase of the stress amplitude, suggesting that the composite has experienced more damage under high stress than at lower stress amplitude. The rubberwood/rPP composite sample did not fracture under the lowest stress level (40 % UTS). It is indicated by arrowhead to mark as run-out test data at 1.5×10^6 cycles when failure does not occur. This suggests that the endurance limit for composite materials is 11.06 MPa.

The composite damage due to cyclic loading can be evaluated macroscopically through the changes of their hysteresis loop recorded as the number of cycles progress and presented in terms of residual modulus and energy dissipated per cycle. The residual modulus can be extracted from the secant slope of the hysteresis loop, and the area within the circle is the energy dissipated. The hysteresis loop captured at the beginning and end of the cycles at each stress level is presented in Figure 4, at the lowest peak stress of 11 MPa (in Figure 4(a)), equivalent to 40% of the mean quasi-static strength resulting in non-failure at the end of the 1.5 million cycles limit. The last captured loop is shifted along the positive strain axis, and the loop appears to be nearly identical. The composite experienced negligible fatigue damage at this level, as they were possibly stressed below the elastic limits [21]. At the intermediate stress level (60% UTS), a more open up loop was observed in Figure 4(b). The composite has longer fatigue life than those at 40 % UTS, and extensive creep has occurred. At the highest stress level of 80% UTS in (Figure 4(c), the loop area increased with the cycles indicated more intensive damage has happened in the composite structure, and the failure is immediate ($N_f = 10^2$ cycles).

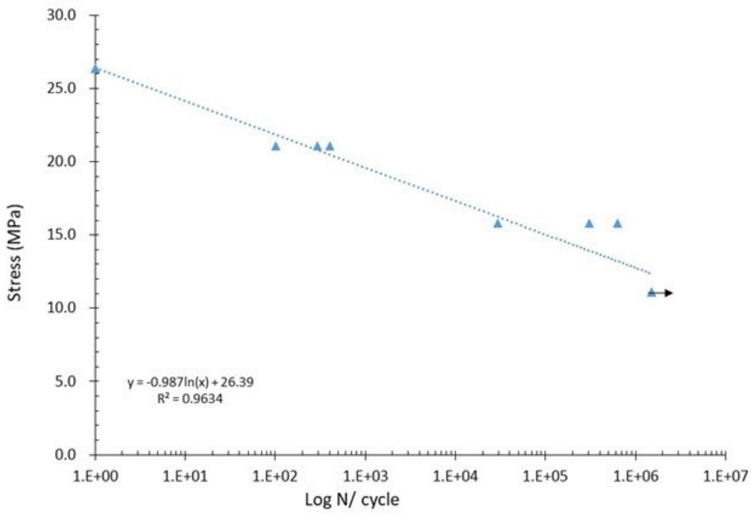
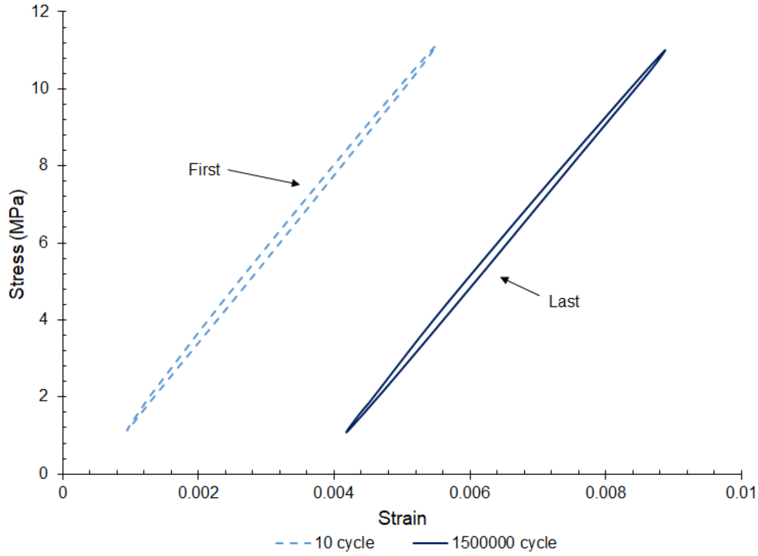
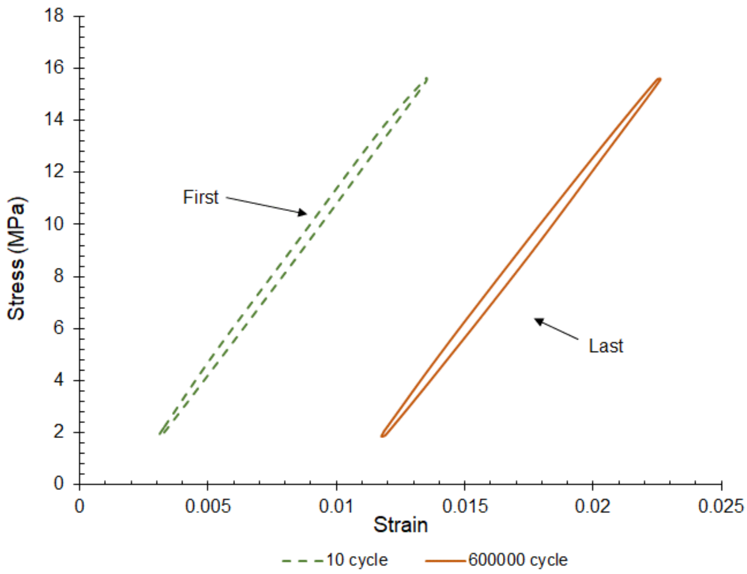


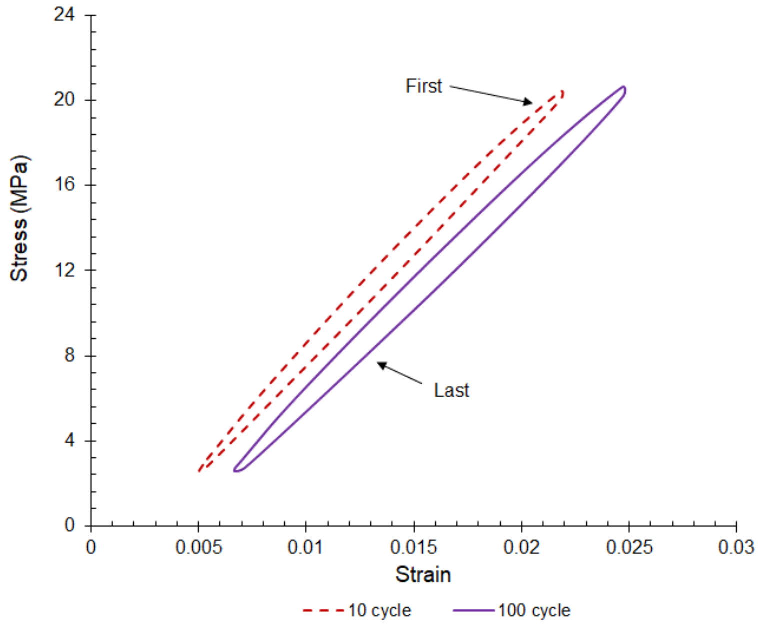
Figure 3. Stress versus log cycles to failure (arrow indicate run out test).



(a)



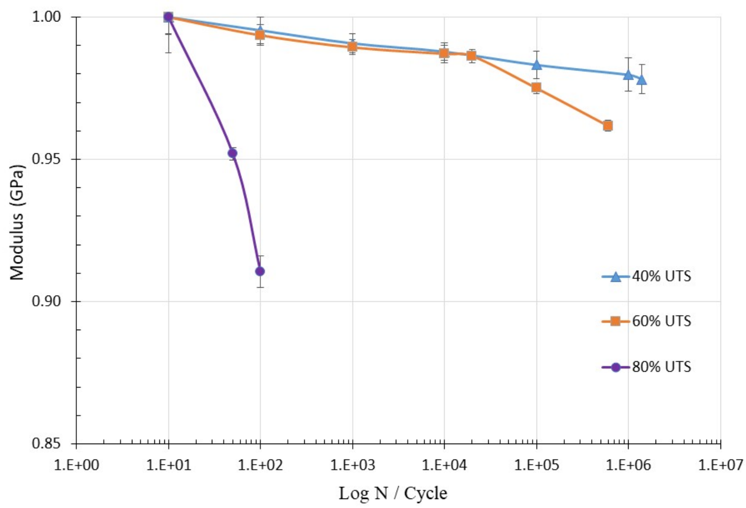
(b)



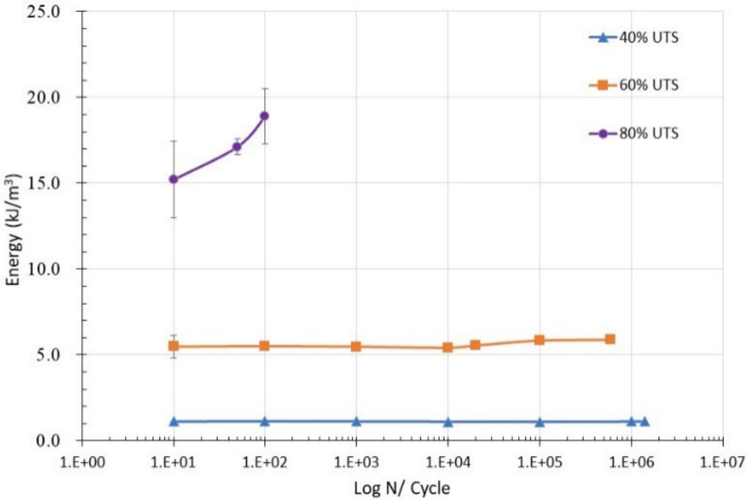
(c)

Figure 4. First and last captured hysteresis loops at peak stress at (a) 40 % UTS, (b) 60 % UTS and (c) 80 % UTS.

The normalised residual modulus and dissipation energy at different stress level is plotted in Figure 5(a) and 5(b). It can be observed that a high-stress level produces a faster stiffness degradation and more pronounced dissipation energy. For example, the sample tested at 80% UTS experienced a more rapid decrease in axial modulus and higher energy dissipation as the cycles progressed compared to the sample tested at 60% UTS. On the other hand, the stiffness degradation is very slow for the lowest stress level (40% UTS), and there are no significant changes in their energy dissipation curve. It might explain the non-failure condition given by the sample at this stress level. It also highlighted that with applied stress amplitude above 50% UTS, the dissipated energy curve does not reach a stabilised value. Higher stiffness deterioration corresponding with higher stress levels is consistent with analysis by previous studies [22, 23]. This finding suggested that the crack is not critical at a low-stress level and propagates more stably as observed with more gradual changes in their fatigue characteristic parameters such as hysteresis loop area, residual modulus, and energy dissipation agreement with finding by [21]. At a higher stress level, however, the gradual built up of the crack is not observed (showed by rapid changes of the modulus and energy curve) that led to instantaneous breakage.



(a)



(b)

Figure 5. The (a) normalised secant modulus and (b) energy dissipation of rubberwood/rPP composites with log cycles.

Weibull Analysis

The two-parameter Weibull curve fitting for the rubberwood/rPP composite's fatigue strength is calculated using Eq. (2) and shown in Figure 6. The samples tested at 40% UTS did not fracture after 1.5 million cycles; thus, this data cannot be used for further analysis. The value of β and lifetime α, obtained from the linear regression line for the composite, is shown in Table 1. All the plots have a reliability index (R^2 >0.75), indicating good linearity and satisfying Weibull fitting.

Table 1. Weibull parameters in rubberwood/rPP composite fatigue test.

Stress amplitude (% UTS)	α	β	R^2	[CV]	Weibull mean life (N_0)
80 %	326	1.3065	0.956	0.772	301
60 %	425007	1.2183	0.998	0.824	398263

It observed that both at 60% and 80% UTS stress amplitude, the obtained value of α > 1, suggesting a good distribution of the damage in the stressed region imposed by the fatigue stress. While this might alter the rubberwood/rPP composite's stiffness as the cycle progresses, their tensile strength is not always immediately reduced. Nevertheless, if such reduction of the composite strength occurs, it normally concentrates in the wear-out zone and progresses to viscoelastic and creep deformation in the matrix [20, 24]. The shape factor (β) indicated the dispersion behaviour of the fatigue data, and a significant value of β shows an excellent consistency of the dispersion. It is observed that both at 60 and 80% UTS fatigue data, the value of β is small and does not significantly differ, indicating the data dispersion pattern are similar, suggesting homogeneity of the samples used in both batches. The value of β > 1 indicated that the failure rate of the composite increase with time and faster when higher stress amplitude is used. This finding is similar as shown by previous studies [16, 18, and 20].

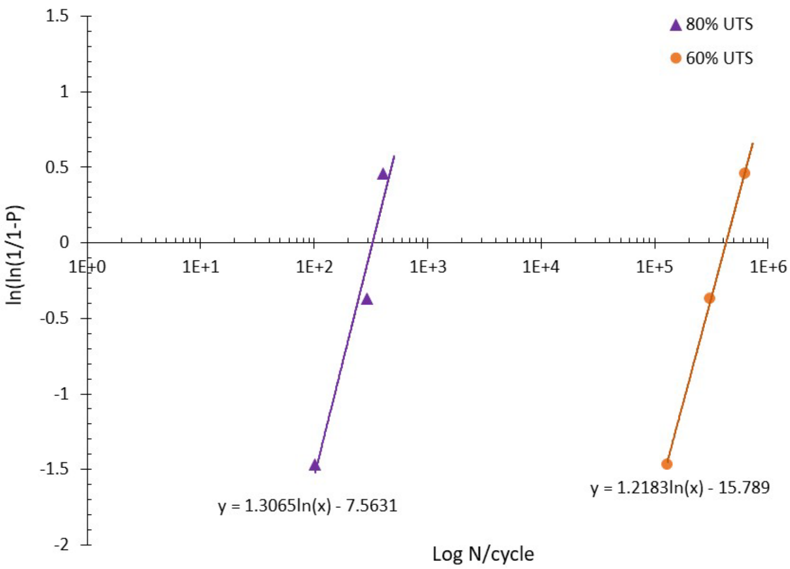


Figure 6. Weibull distribution curve at different load amplitudes.

Mean lifetime to failure, standard deviation and CV were also calculated. It can be observed that a considerable dispersion of that fatigue data in both stress levels suggests that the samples have a manufacturing defect. The survival probability curve of the composite at different stress levels is shown in Figure 7. When the composite is subjected to a load of 80% UTS, the value of the life cycle number with a 50% probability of survival is 247 cycles. This number of life cycles becomes 314,589 cycles when stress is reduced to 60% UTS. Therefore, the survival percentage at each fatigue life is valuable information for a designer to ensure that the component survived without catastrophic damage.

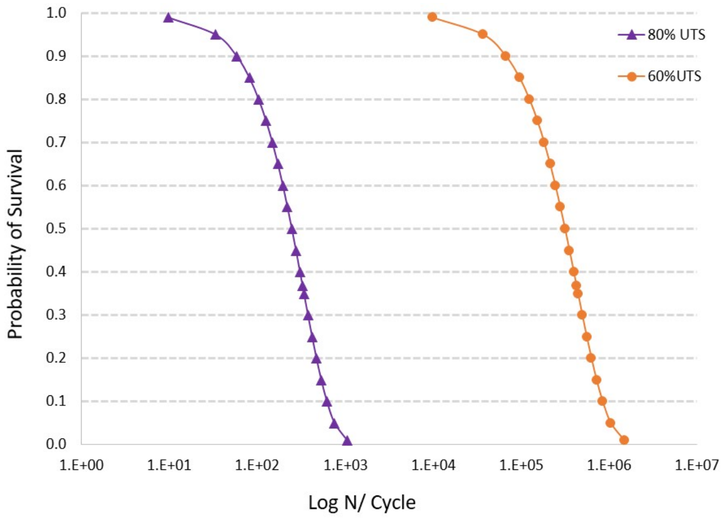


Figure 7. Survival probability graphs for rubberwood/recycled PP composite material.

The safe design can be measured at a particular value of reliability index (RI). The value of the characteristic life can be calculated using Eq. (1) by substituting x = α. The survival probability, Ps(x) = 0.368, indicated that a part of the sample had survived the characteristic strength or life. In line with this concept, when the characteristic life (x = α.) is the value of cycles where the likelihood of the population to fail is 63.2%. The survival probability of all the stress levels can be calculated using Eq. (7) as an extension from Eq. (1).

$$N_{P_X} = \alpha\big((-\text{Ln}(P_S(x))\big) \quad (7)$$

A higher probability of survival could be considered for a more critical part, such as Ps = 50, 90 or 99%. The survival probability curve at different stress as a function of a lifetime for other reliability indexes (RI) is shown in Figure 8. This diagram is essential as it allows identifying the first failure time and safety limits in the application. When failure is disastrous for the application that contains a critical part, the safe design life should be determined at a higher confidence level, such as at 99% and RI of 0.99 [16, 20, 25].

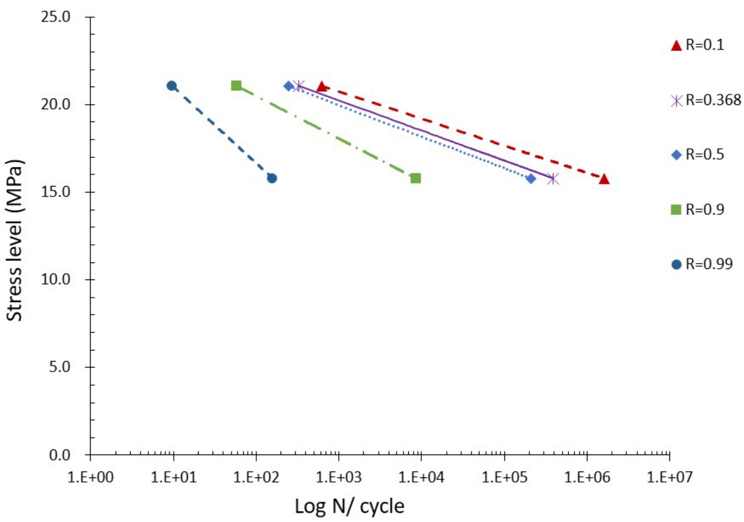


Figure 8. S-N curve for different reliability levels for rubberwood/ recycle PP composite material.

CONCLUSION

This paper reports the fatigue characteristic of the rubberwood reinforced recycled polypropylene composite using the Wohler curve to determine the endurance limits of the materials. The experimental data is high dispersion due to the anisotropic nature of the materials and manufacturing defects. The strain versus strain hysteresis loop was used to observe the fatigue damage accumulation in the materials. Their fatigue characteristic is mainly depending on the stress amplitude. At the low-stress level, the changes in the composite structure is are generally small and negligible. At intermediate stress level (UTS = 60%), pronounced changes in tensile creep, dynamic modulus and energy dissipated were observed.

In contrast, at the high-stress level, the changes are almost instantaneous. The estimated endurance limit of the composite is at a stress of 11 MPa with a failure cycle of 10^6 cycles. Two parameters Weibull distribution allows the forecast of the survival under different maximum pressure. The stress to the number of cycles to failure diagram with a survival probability of 99, 90, 50, 10 and characteristic life of 36.8 % has been plotted, crucial information to the designer to identify the first failure time and the safe design limits for the materials.

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