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FATIGUE LIFE CYCLE PREDICTION EQUATION BASED ON GRAIN ANGLES AND STRESS LEVELS FOR *ACACIA MANGIUM*

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ABSTRACT

This study aims to investigate and understand the nature of *Acacia mangium* axial fatigue strengths under repeated stress. *Acacia mangium* trees, which were cut to produce oven-dried dog bone shaped specimens, were tested in repeated axial-tensile loading with sinusoidal waveform. Findings of this study had shown that *Acacia mangium* has a significant difference in the strengths parallel and perpendicular to the grain line. Extreme reduction in tensile strength for 0° and 90° grain angles saw a shift from 143.87 MPa to 6.32 MPa (a 95.6% reduction of the Ultimate Tensile Strength). It was observed that the *Acacia mangium* N-S (Wöhler) plots showed an exponential correlation, in which the N – intercept of the vertical axis was at five (5) million cycles, while the intercept of the horizontal S – axis, was at 143.87 MPa. It was also observed that *Acacia mangium* has a fatigue endurance limit at 10% of the ultimate tensile strength. From static testing, the Osgood's coefficient of species for *Acacia mangium*, (*a*), was identified algebraically to be 0.49. The finding showed that life cycles predicted by the Fatigue Life Prediction Equation as having almost similar magnitudes with the results defined by the verification test for each stress level. The comparison between the verification test results and the predictions by the equation indicated an impressive fit between them at 30° grain angle.

Keywords: *Acacia*, *mangium*, fatigue, endurance, Wöhler.

INTRODUCTION

According to Taylor (2013) and Dickson and Parker (2015), metals, plastics, concretes and composites are the mainstream materials that contribute to present day industrial world and modern structure assemblies. However, metals and irons are produced by utilizing fossil fuel which in turn releases a significant amount of carbon footprint and the mining of limestone to produce concretes may disfigure the landscape and as well losing wildlife habitat. Plastic materials are slow degradable material that may contribute to environmental issues. For the sustainability and survival of mankind in the future, the world now comes to choose more sustainable materials and environmental friendly production methods.

Wood material is one of the available sustainable materials and the means of production of this material do not contribute to green house effect but rather reduce it.

According to Shigley, Budynas and Nisbett (2014), fatigue phenomenon appears in any machine components and structural elements is when they are subjected to a type of loading known as variable, alternating, fluctuating, repeated or cyclic loading. This loading is either applied-removed or the magnitude is changed, many thousands of times in its service life. Materials or components that under the influence of cyclic stress tend to fail at stresses much lesser than the material ultimate strength and rather often even below the yield strength. It is therefore is a more dangerous phenomenon for it occurs without any advance warning into a sudden and total fracture.

Fatigue failure in wood structures may be significant as some wood structures are utilized in the repeated and dynamic loading environment. Wooden houses or structures built near coastal areas also have significant effect of repeated or fluctuating stresses due to variable intensity of force created by the strong coastal wind than contributes to fatigue in its structures. Wooden furniture also may suffer fatigue failure due to the repeated stress from loads put upon them.

In the recent years, there are numbers of studies being made for some solid wood materials and wood composites. Solid wood species studied are Japanese cypress, Japanese beech, white cedar, spruce, Douglas fir, Scots pine, beech, juniper, etc. Some studies also investigate the fatigue response of engineered timber such as glue laminated timber (GLULAM) and wood-based structural panel. In addition some other natural grown species namely Nyatoh (*Palaquium gutta*), Light Red Meranti (*Shorea platyclados*), Ramin (*Gonystylus bancanus*), and Sepetir (*Sindora coriacea*), and planted grown species such as Rubberwood *(Hevea brasiliensis)* had also comprehensively analyzed both in their static and fatigue strengths (Ratnasingam and Ioras, 2010). For the possibility to make any species being utilized in the dynamic environment, fatigue response of any species must be fully comprehended.

Acacia mangium as one of the planted grown species In Malaysia had undergone intensive study in their static strengths. In Sarawak, *Acacia mangium* is the most common planted grown wood species and also renowned for its fast maturing characteristic, robustness and adaptability (Lim, Gan and Tan, 2011). This study only focuses on *Acacia mangium* species planted in Sarawak with the intention to understand the fatigue strength under repeated stress and as to propose the Fatigue Life Prediction Equation specifically for this species that may be used to predict fatigue life cycles based on grain angles. The result of this research is essential to the engineers or designers that desire to use *Acacia mangium* wood in dynamic loading environment. The outcome of this research has significant information for utilization of this material not only as structure material but also machine parts. This research may also important for it is initial step towards the study of fatigue in wood material especially upon plantation grown species in Sarawak

The objectives of this research are (i) To generate the S-N (Wöhler) empirical plots and equation that explains the correlation between Fatigue Strength (S) and Life Cycles (N) based on different Stress Levels at 0° grain angle with 100 Hz frequency of controlled amplitude sinusoidal-repeated tensile stress, and (ii) To construct the Fatigue Life Prediction Equation that may be used to predict fatigue life cycle based on stress levels and grain angles for the species.

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REVIEW OF LITERATURE

The rising of new technologies for utilization of iron, steel and reinforced concrete during the late 19^{th} century is the main contributing factor for the significant decline of timber as primary construction material. These new age materials have more predictable properties and incombustibility characteristic compared to the more traditional wood material.

Dickson and Parker (2015) stated that in the present day, however, as newer technologies of advanced adhesives, preservatives and fire protection emerges, wood material is possible to be produced as newer engineered timber products such as the laminated veneer lumber, I-joists and glue-laminated (GLULAM) beams and arches. Being reintroduced in such way, wood material is once again making its way for new revival in large scale construction throughout the world. The new technologies also have prepared wood products and structures to be more predictable and stable in their properties hence advancing forward from a traditional housing material to a realistic alternative to steel and concrete in construction. Modern manmade buildings that are widely known for its utility of wood as structures are the Sheffield Winter Garden, England and the Crystal Bridges Museum in Bentonville, Arkansas, United States of America (USA). The making of a 14-storey apartment block with glulam structural frame in Bergen, Norway is the tallest manmade timber building ever produced.

In recent discoveries, Gross and Ezerietis (2003) concluded that knowledge on the mechanical behaviour of wood in combined stress is useful for the possibility to utilize wood as an implant material in human and in the development of new composite materials for artificial bone. Wood has been regarded as a conventional orthotropic material similar to bone as both have structures that can provide the transport and support of nutrients. This similarity would create possibility to use wood as an implant material.

Remarkably, there is also an increasing number in institution and body of expertise available to educate and familiarized engineers and designers the benefits of timber materials and to promote and publicized the public in the qualities and benefits of timber as sustainable material for better future. According to Sarawak Timber Industry and Development Corporation STIDC (2016), Sarawak state government is very serious about the advancement of timber industry in the state hence much collaboration via Sarawak Timber Industry Development Corporation (STIDC) has been done with a local university and international bodies in the research and development (R&D) of wood-based products. The 'Kursi PUSAKA' is one of the significant initiatives particularly as a fund for the R&D of wood-based furniture for future wood technology advancement.

Materials and Environmental Issues

According to Taylor (2015), metals and steels are produced from its ore that extracted from mines which involves high extracting and transportation costs. Metal ores also have to be concentrated prior metal is extracted. Lethal carbon monoxide from iron extraction process is released to the air hence pollute the environment. The manufacturing cost also being high as steel or iron need to be molten during manufacture. Aluminium material also extracted from its ore which then being processed using much electricity that causes the manufacturing cost to be high. During copper extraction from its sulphide ore a toxic sulphur dioxide gas is released and can cause acidic rain.

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Limestone is a very useful mineral used to produce concretes and in the iron extraction in the blast furnace also obtained by mining or quarrying. However, mining and quarrying may disfigure the landscape and as well losing wildlife habitat. Plastic materials are slow degradable material that may contribute to environmental issues. The green house effect becomes eminent as the world warms up making the climate changes unpredictably while human populations continue to grow. For the sustainability and survival of mankind in the future comes to a crucial priority, the world now comes to choose a more sustainable materials and environmental friendly production methods.

Trees has a high strength-weight ratio and a biodegradable material which reacts as a carbon sink which extract carbon dioxide and reduce the levels from the atmosphere, thus reducing global warming. At the end of its life, another important benefit of trees is that there is a possibility to reuse and re-fabricates it as a newer product. Wood material and wooden products, if they are treated with appropriate preservatives and coatings, can last for sufficient amount of time. However, the production of wood would reduce natural forests for they are biodiversity and an ecosystem provider as a whole if only it is managed and maintained wisely.

According to Zaini (2010), the Ministry of Plantation Industries and Commodities of Malaysia in 2006 has initiated a financing program for the development of commercial forest plantation. The purpose of this financing support is to encourage more companies in Malaysia to participate in forest plantations which in turn promises attractive and profitable income opportunities, employment generation and into contribution of environmental maintenance.

The Malaysian Timber Council (2018), stated that there are about 50 companies in Malaysia have took part in the commercial forest plantation programme with about 114 355.43 ha of land have been developed. Planted timbers are generally selected among the fast grown species. Two current species for this programme are *Acacia mangium* and Rubberwood (*Hevea brasiliensis*). Other species that had been considered but yet planted are Batai (*Paraserianthes falcataria*), Khaya (*Khaya ivorensis*/*Khaya senegalensis*), Binuang (*Octomeles sumatrana*), Teak (*Tectona grandis*), Kelempayan (*Neolamarckia cadamba*) and Sentang (*Azadirachta excels*).

As to conclude, wood material is one of the materials that its means of production does not contribute to green house effect but rather reduce it and a systematically manages the production of wood materials from natural forests or by introducing plantation forests that planted with good quality and fast grown wood species may therefore developed to make wood as a sustainable material.

Structure of Wood

According to Taylor (2013) and Dickson and Parker (2015), wood is a natural fibrous composite that basically composed of cellulose, hemicelluloses and lignin. Cells of crystalline and long molecules of cellulose $(C_6H_{10}O_5)_n$ chain with high molecular weight are bunched together making micro-fibrils. These micro-fibrils are the main composition that structured the strength of the wood. Both hemi-cellulose and lignin act as the adhesive that binds all micro-fibrils together that forms hollow and rigid cells.

Timber logs usually defined in three-principle directions namely radial direction (R), tangential direction (T) and longitudinal direction (L). Tangential direction is classified as the direction that perpendicular to the grain line. In the contrary, longitudinal direction is considered as the direction parallel to the grain of a wood trunk or specimen. According to Keenan, Boyd, Cooper and Taylor (1986), the primary wall (P) of wood cell is chiefly consists of lignin with 15% cellulose content. The secondary wall - S1 layer has about 30% cellulose and the S2 and S3 layers have about 50% cellulose. As S2 wall consists the highest cellulose content and made the thickest wall compared to others, it gives trees the strength in longitudinal direction. On the other hand, lumen is a channel where water is stored or transported within a tree. Cells in wood are align in the longitudinal direction whereas in the perpendicular to grain direction, they are mostly attached together by adhesive called hemicelluloses and lignin. For this reason, trees have a lesser tensile strength in the radial and tangential directions compared to the strength in the longitudinal direction. The transmission and storage of mineral and food in trees are fulfilled by the sapwood which is the one that is lighter in colour and more outer with newly grown layers of cells. The inner layer is called heartwood that does not stores food but provide the support and strength for trees. Heartwood is normally darker in colour than sapwood.

In Keenan et al. (1986), an apparently useful intuitive concept to understand wood is that it is can be considered as a series of thin interlinked tubes with more strength in the longitudinal than the radial or tangential directions. Modulus of rupture and compressive strength of woods is directly related to their density with denser woods would have higher strength compared to the ones with lesser density.

Acacia Mangium Species

According to Alik and Nunggah (2014), a three year project named Basic and Working Properties of *Acacia Mangium* Planted in Sarawak, funded by Sarawak Timber association (STA) in collaboration with Sarawak Forestry Corporation (SFC) was initiated in 2011 to determine the basic and working properties of *Acacia mangium*. All test materials were gathered from Tatau area in Samarakan, Bintulu. The aim of this project was to evaluate relevant static strength from age group of 7, 10 and 13 years old of the species. All age group had undergone tests such as static bending, compression, shear and tensile parallel to grain, hardness, cleavage and impact bending. The discovery from this project showed that *Acacia mangium* trees in the 7, 10 and 13 - age groups had rupture bending strengths (MOR) at about 0.86% of the their elastic bending strength (MOE). This indicates that their rupture bending strengths (MOR) are so significantly small than their elastic bending strength (MOE). The age class made no significant difference in the values of strengths.

In the Peninsular Malaysia, a project called Properties of *Acacia Mangium* Planted in Peninsular Malaysia was started to make value adding and utilization improvement onto the species. *Acacia mangium* trees with age classes of 16 and 20 years old were gathered from Ulu Sedili Forest Reserve in Johor and Kemasul forest, Pahang had undergone some evaluation in their static strengths as reported by Lim et al. (2011). However there was no result of fatigue testing recorded in the report. It was also reported that the rupture and elastic bending strengths of green specimen have higher value than dried ones for 12 year age class. This finding contradicts the one from previous report by Alik and Nunggah (2014).

Study by Rokeya et al. (2010) was concerning on mechanical and physical properties of Hybrid *Acacia* wood which the species itself was a result from natural crossing between *Acacia auriculiformis* and *Acacia mangium* species. These Hybrid *Acacia* trees were planted at

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Silviculture Research Station, Keochia, Bangladesh. The Study clearly stated that all standard mechanical testing for timber has been done onto this Hybrid *Acacia* wood. In contrast, no fatigue data published along with the study.

Shukla et al. (2006) had studied the average mechanical and physical properties of planted grown *Acacia auriculiformis* (*A.Cunn. ex Benth*.) timber with 8, 12 and 13 years of ages. All trees were gathered from Sirsi, Karnataka, India. This study also has no fatigue data included where it was done solely on the standard mechanical testing for timber.

As to conclude, thorough search was made (other than the mentioned above) in all literatures available worldwide and it is found that for all *Acacia* sub-species of any type, they have undergone intensive testing for its static mechanical strength properties. However, there is no evidence on fatigue strengths or the endurance limit ever found available.

Failure Characteristics

Most engineering observation in static failure of materials considered to be either ductile or brittle fractures. When the specimen is being stressed**,** it would elongate elastically and proportionally and obeys the Hooke's Law. Provided that the applied stress onto the material does not surpass this limit, once the load is removed, no permanent deformation occurs in the material. The material will revert back to its original length and size. Once the applied stress goes beyond this yield limit, the material would elongates in a plastically manner until a maximum stress level achieved. This maximum stress level is called Ultimate Strength, S_u. In this yielding region, the material will maintain its permanent deformation even when the load is removed. After the ultimate strength level, if the material is ductile, it will elongates longer with lower stress levels until fracture occurs. However for brittle material, it will elongates no more as fracture will occur at the ultimate strength. Both ultimate and fracture strengths are identical. The similarities between static brittle and fatigue fractures are concluded that both are having no presence of necking and the fracture surface is flat and perpendicular to the load axis. The difference in turn, is that fatigue failure has three (3) stages of development, while static brittle fracture does not. Micro crack or cracks at Stage I initiated at two or five grains from the point of origin and invisible to the naked eye. This initiation was a result of stress concentration and cyclic plastic deformation developed in a component or part due to stress raisers. Rapid changes in cross section, holes, scratches or grooves are considered as stress raisers. Stage II is the propagation or growth of cracks from micro to macro level and they are observable. As the propagation of cracks becomes wider and longer, then comes the development stage (Stage III) as the material can no longer withstand the applied stress making it breaks in a sudden and rapidly manner.

Shigley et al. (2014) concluded that, in engineering applications, it is common for loads to be applied repeatedly making fatigue failure is an important factor to consider in any design. Machine members that under the influence of repeated or fluctuating stresses tend to fail at stresses much lesser than the material ultimate strength, and rather normally even below the yielding strength. The most distinctive attribute of these failures is that the loads have been applied repeatedly in very large number of times. Machine parts that failed statically frequently exhibit a huge deflection or elongation as the stress applied has exceeded the yield strength thus giving a visible warning in advance so that the part may be replaced before actual fracture occurs. Fatigue failure however acts in a more different and dangerous manner that it occurs in sudden and total

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fracture without any advance warning. During design stage, engineers or designers would select materials that meet certain required service loads for certain expected life span that were obtained from fatigue testing data. Values of fatigue endurance limit and crack resistance are generally required apart from the usual ordinary fatigue test purpose which is to determine the expected lifespan of a material subjected to cyclic loading. Fatigue tests normally uses cyclic loading in axial-tension or compression, bending, torsion, or combinations of these loadings. Stresses in materials may come in a complex shape of waveform. However, some may be as simple as a sinusoidal shape. This sinusoidal shape usually occurs in rotating components of machineries.

There are three (3) major methods in the analysis of fatigue life used during designing a part or component that may subjected to cyclic loading during its service. The methods are Linear–Elastics Fracture Mechanics, Strain-Life and Stress-Life methods. Both Stress-Life and Strain-Life methods are empirically-based approach whereas the Linear-Elastic Fracture Mechanics (LEFM) method is considered to be a distinguished modern method. Stress-Life method is considered to be the most traditional and simplest method among others is based on level of stress only. Series of tests are conducted to determine the fatigue strength of a material. Test specimens are tested at stress level that is a little less than its ultimate strength until failure occurred to determine its life cycle. The same specimen will be tested again with the same procedure but at lesser stress level compared to the initial test. This procedure continues with lesser and lesser stress levels and the results are plotted on a log-log paper or semi-log paper as an S–N diagram. Stress-Life method may be a least precise approach especially for low cycle fatigue life ($N \leq 10^3$) but it is satisfactory for fatigue life with high cycle ($N > 10^3$). Endurance limit or strength is a fatigue strength by which any material will achieve one (1) million of its fatigue life cycles. The method also has a sufficient amount of supporting data and it may be used in a wider range of design applications compared to other methods (Shigley et al., 2014).

According to Bodig and Jayne (1982), some wood species for engineering and construction that have undergone fatigue testing are shown in Table 1. In the table, the ultimate compression strength is considered to be the modulus of rupture as compression strength is known to be lesser than tensile strength in all wood species. The range of endurance limit in these woods is can easily be said between 22% and 38% of their respective rupture strengths (MOR).

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Table 1: Fatigue Strengths and Endurance Limit of Some Construction Woods

Species	Specific Gravity	MC (%)	MOR	Endurance Limit, S_e	R_e
Coniferous woods					
Douglas-fir (*Pseudotsuga menziesii (Mirb.) Franco*)	-	14.3	103.1	27.6	27%
Spruce (*Picea excelsa Link.*)	0.44	10 - 12	76.5	19.1	25%
Pine (*Pinus sylvestris L.*), heartwood	0.65	10.8	113.8	41.2	36%
Broadleaved species					
Birch (*Betula pubescens Ehrhardt*)	0.63	12	127.5	31.4	25%
Oak (*Quercus alba L.*)	-	Green	73.1	22.0	30%
Ash (*Fraxinus excelsior L.*)	0.65	9.5	119.6	35.3	30%
Walnut (*Juglans regia L.*)	0.60	8.1	137.3	41.2	30%

Note:
MOR: Modulus of rupture
MC: Moisture content

$$R_e = {S_e}/_{\mathrm{MOR}}$$

Source: Bodig and Jayne (1982)

Data of endurance limit or fatigue resistance of other foreign species stated above is relevant for the purpose of observing and comparing the endurance limit that *Acacia mangium* species may have. It may be anticipated also that the stress levels for fatigue testing in this research should include until stress level of 20%.

Experimental Fatigue Testing

Yildirim et al. (2015) investigated fatigue strengths for two (2) species of wood namely Beech (*Fagus orientalis L.*) and Scots pine (*Pinus sylvestris L.*). The study was aimed to determine the allowable design stress for furniture design. Test method used was the three (3) points bending for both static and fatigue testing. Stress levels used in the fatigue test were 80, 70, 60, 50 and 40% of ultimate bending strength/Modulus of Rupture (MOR) for both species. The findings showed that at stress level of 40%, the life cycle for Scots pine (*Pinus sylvestris* L.) was able to sum up to over 1 million cycles while on the other hand it was 50% for Beech (*Fagus orientalis* L.). It was concluded that the design stresses that allowable for beech and Scots pine as furniture design may be set to 50 and 40% of the Modulus of Rupture (MOR) respectively. The study concluded that as stress level, S being increased, life cycle, N will be decreased and conversely, if stress level, S being decreased, life cycle, N will increased.

Ratnasingam and Ioras (2010) had undertaken a study that evaluated and compared the static and fatigue strengths of oil palm wood (OPW) with some other typical Malaysian wood materials that were used for furniture applications such as Rubberwood, Light Red Meranti, Nyatoh, Sepetir and Ramin. The study was aimed to value-add the oil palm wood (OPW) as a furniture material. Test method used was the three (3) points bending for both static and fatigue testing. Stress levels used in the fatigue test were 80, 70, 60, 50, 40 and 30% of ultimate bending strength/modulus of rupture (MOR) for all materials. Due to its low density of OPW, results showed that the material had a much lower ultimate bending strength compared to Rubberwood *(Hevea brasiliensis)*, Light Red Meranti (*Shorea platyclados*), Nyatoh (*Palaquium gutta*), Sepetir (*Sindora coriacea*) and Ramin (*Gonystylus bancanus*) woods. OPW also showed that it has a lower value in term of fatigue resistance compared to other materials tested in the study. The findings of the study showed that life cycles of over 1 million counts was achieved by OPW with stress level at 30% of the MOR while at 50% stress level cycles were reduced to 203 000 counts. The study concluded that the allowable design stress at 40% MOR may be set to for oil palm wood material.

It is observed from the study by Ratnasingam and Ioras (2010) concerning some Malaysian species such as Rubberwood *(Hevea brasiliensis)*, Light Red Meranti (*Shorea platyclados*), Nyatoh (*Palaquium gutta*), Sepetir (*Sindora coriacea*) and Ramin (*Gonystylus bancanus*) were having the same nature of difference between their rupture bending strengths (MOR) and elastic bending strength (MOE).

Bao et al. (1996) investigated the fatigue behaviour of several wood composites such as plywood, medium-density fibreboard (MDF), oriented strand board (OSB) and particle board as a potential foundation for determining allowable design stresses for the mentioned wood composites. Specimens were tested at five (5) stress levels (as a ratio to rupture strength) and the findings concluded that at 30% stress level all the materials have high cycle life ($N \geq 1$ million cycles). Some of the materials failed when stress level was increased to 40%. In general, the finding was concluded that as stress level increased, fatigue life will be decreased and vice versa. In particular, for furniture designs that will utilize in fatigue/cyclic environment, allow-able design stresses may be based on some values in the range between 30 to 40% of the average MOR.

For all literatures, wood material although is generally a stiff and brittle material, it also has been proven to be a visco-elastic material which can obviously seen in low frequency loadings. This visco–elastic attribute would make wood to experience creep and relaxation over time for static stress, and some delay response of straining and releasing during cyclic loading. It is also observed that the highly affecting independent parameters or variables for wood performance in fatigue environment are stress levels which are relative to ultimate strength of the wood, temperature, relative humidity, loading frequency, the shape of loading waveforms.

Strength at Angles from the Grain Line

According to Bodig and Jayne (1982) and Kim (1985), the U.S. Army had developed the Hankinson's Equation/Criterion in 1921 intended for calculating the allowable compression stress of Spruce wood at differing angles from the grain. The finalized form of the equation is shown in Equation 1.

$$S_\theta = \frac{S_{⫽} \cdot S_{\perp}}{S_{⫽} \cdot sin^2\,\theta + S_{\perp} \cdot cos^2\,\theta} \tag{1}$$

With,
S_θ= Ultimate Compression Strength at angle, θ to the grain
$S_{\perp}$ = Ultimate Compression Strength at 0° grain angle (perpendicular to the grain), MPa

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$S_{\parallel}$ = Ultimate Compression Strength at 90° grain angle (parallel to the grain), MPa
θ = Angle to grain line

Suryoatmono and Pranata (2012) also justified that Hankinson’s Equation being generally accepted as a base formula in the Australia’s ANSI/AF&PA - National Design Specification for Wood Construction (NDS-2005).

The Osgood Equation (Equation 1) as a generalized version Hankinson’s Equation was publicized by Osgood in 1928, who was an Assistant Professor of Structural Engineering at Cornell University. It is in the form of:

$$S_\theta = \frac{S_{\parallel} \cdot S_{\perp}}{S_{\perp} + (S_{\parallel} - S_{\perp})(\sin^2\theta + a \cdot \cos^2\theta) \cdot \sin^2\theta} \tag{2}$$

With,
a = coefficient of species, by which Osgood finalized the value for Southern Yellow Pine wood as 0.35.
S_θ, $S_{\perp}$, $S_{\parallel}$ and θ are of the same as in Hankinson’s Equation.

Once the Osgood's coefficient, (*a*) is increased to one (1), the Osgood Equation is reduced to become the Hankinson’s Equation.

Hankinson’s Equation is well-known for predicting the compression strength of wood at different angles to the grain line. Tests were conducted by Kim (1985) aimed to review the application capability of the Hankinson’s Equation for predicting the wood tensile strength according to the angles from the grain line. Tensile stress with the rate of 0.1 inches per minute was applied at varying angles from grain of the Southern Yellow Pine board wood specimens. The study revealed that Osgood Equation was a better fit than Hankinson’s Equation for tensile loading.

RESEARCH METHODOLOGY

Experimental Stress-Life method was used in this study to observe the response of Small Clear Specimen of *Acacia mangium* wood under cyclic-repeated axial stress. Experimental procedures used were the BS 373 for specimen preparation and the ASTM E466 for fatigue testing. Specimens were tested in repeated axial-tensile loading with sinusoidal waveform. All tests were conducted at relative humidity (RH) of (65 ± 2) %. Test specimens were produced from selected *Acacia mangium* trees that were 15 year of age. A total of ninety (90) pieces of oven-dried Small Clear Specimen was used in the static tensile test. In this case, each orientation used a total of thirty (30) pieces. As there were three (3) grain angle orientations in the static tensile test, namely the 0°, 30° and 90° angles, thus the total specimens used were ninety.

Axial fatigue test comprised thirty (30) pieces of oven-dried Small Clear Specimen that were prepared for each pre-determined Stress Level. As six (6) Stress Levels were required for this fatigue testing, thus the total overall specimens required were 180 pieces. In this study, the independent variables that were manipulated are (i) stress level, and (ii) grain angle. The other

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independent variables were controlled. A series of tests were conducted to determine the fatigue strength of the material. The load fluctuated between zero and the values of the pre-determined stress levels with a frequency of 100 Hz. Fatigue specimens were tested in six (6) different stress levels namely at 80%, 60%, 40%, 30%, 20% and 10% of the Ultimate Tensile Strength parallel to the grain line (0° grain angle).Test specimens were tested at stress level that was a little less than its ultimate strength until failure occurred. This is to determine its life cycle. The other identical specimen will then be tested again with the same procedure but at lesser stress level compared to the initial test. This procedure was carried out with decreasing stress levels. The results were then plotted.

RESEARCH FINDINGS

Static Tensile Test at 0°, 30° and 90° Angles to Grain Line

Results were gathered from static axial-tensile test in the directions that parallel (0° angle), perpendicular (90° angle) and slant (30° angle) to the grain line. A total of 30 oven-dried dog bone shaped specimens that were tested for each parallel, perpendicular and slant directions. The test results showed that the Ultimate Tensile Strengths at 0° grain angle ($S_{=}$) as 143.87 MPa. At 90° grain angle, the tensile strength ($S_{\perp}$), was 6.32 MPa and at 30° grain angle ($S_{30°}$), was 32.985 MPa. All test result confirms that *Acacia mangium* wood was a brittle for no obvious necking was observed on all of the test specimens.

Acacia Mangium Life-Stress Plots

The results of the fatigue test are shown in Table 2.

Table 2: Mean life cycle for parallel to grain fatigue test.

Ratio, r	Stress Level	Mean, Fatigue Life Cycle
80%	115.096 MPa	15 491 Cycles
60%	86.322 MPa	85 495 Cycles
40%	57.548 MPa	159 022 Cycles
30%	43.161 MPa	260 518 Cycles
20%	28.774 MPa	534 227 Cycles
10%	14.387 MPa	1 043 866 Cycles

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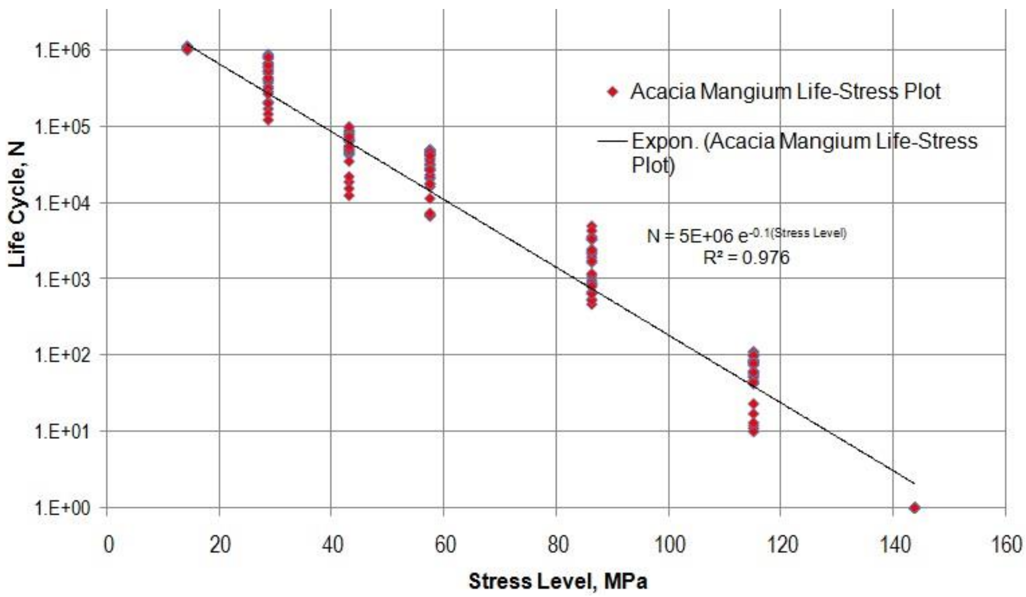
DISCUSSION

Acacia Mangium Wöhler Life-Stress Plots and Empirical Correlation

The finalized *Acacia Mangium* Wöhler Life-Stress plots and its empirical correlation as a result of the axial-fatigue test in the direction parallel to the wood grain are shown in Figure 1.

Figure 1: *Acacia Mangium* Wöhler (N-S) Correlation



The finalized equation for explaining the relationship of fatigue life cycle, N, to stress level, S, for *Acacia mangium* wood based on 0° angle from the grain line is identified as Equation 3.

$$N = 5 \times 10^{6} \cdot e^{-0.1 \cdot r \cdot S_{=}} \qquad (3)$$

With,
r = ratio, in percentage
$S_{=}$ = ultimate tensile strength at 0° grain angle (parallel to the grain)

The N - axis actually corresponds to zero (0) Stress Level. Thus, the N-S equation is only applicable for Stress Level domain of:

$$0 < StressLevel \leq 143.87 \text{ MPa}$$

Modified Osgood Equation for *Acacia Mangium*

The Osgood Equation is in the form of:

$$S_{\theta} = \frac{S_{=} \cdot S_{\perp}}{S_{\perp} + (S_{=} - S_{\perp})(\sin^2\theta + a \cdot \cos^2\theta) \cdot \sin^2\theta}$$

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With,
a = coefficient of species
S_{θ}= Ultimate Compression Strength at angle, θ to the grain
$S_{\perp}$ = Ultimate Compression Strength perpendicular to the grain or at 0° grain angle, MPa
$S_{\parallel}$ = Ultimate Compression Strength parallel to the grain or at 90° grain angle, MPa
θ = Angle to grain line

The results indicated that the values of the Ultimate Tensile Strength at 30° grain angle ($S_{30°}$) and 90° grain angle ($S_{\perp}$) are 32.985 MPa and 6.32 MPa respectively. The value of the Ultimate Tensile Strength parallel to the grain line (0° grain angle), $S_{\parallel}$ is identified as 143.87 MPa. By inserting these values into the Osgood Equation and with the algebraic method it was found that the coefficient of species, (*a*), is equal to 0.49. As the final step, the finalized form of the Modified Osgood Equation for *Acacia Mangium* was generated by substituting the values of $S_{\perp}$, $S_{\parallel}$ and *a* into the Osgood Equation.

$$S_{\theta} = \frac{909.258}{6.32 + (137.55)(\sin^4\theta + 0.49 \cdot \sin^2\theta \, . \, \cos^2\theta)} \tag{4}$$

Equation 4 is the Modified Osgood Equation for *Acacia Mangium* that is 15 years of age.

Fatigue Life Prediction Equation

When the N-S (Wöhler) and the Osgood Equation of *Acacia Mangium* are integrated, the Fatigue Life Prediction Equation can be obtained. This prediction equation is based on the parameter of grain angle (θ) and tensile strengths based on grain angle (S_{θ}). In *Acacia Mangium* N-S (Wöhler) Empirical Equation (Equation 1), the index term $S_{\parallel}$ is the Ultimate Tensile Strength at 0° grain angle. It was identified that all Life-Stress equations have a slope that changes based on its grain angle (θ). Thus, the slope as a function of a grain angle is:

$$m = -\frac{\text{Y – intercept}}{\text{X – intercept}}$$

$$m = -\frac{6.699}{S_{\theta}}$$

$$m = (0.04656 + 1.0134 \cdot \sin^4\theta + 0.4966 \cdot \sin^2\theta \cdot \cos^2\theta)$$

Hence, for the grain angles of $0° \leq \theta \leq 90°$, Life-Stress equations based on grain angles (S_{θ}) are generalized to be Equation 5.

$$\log_{10} N_{\theta} = 6.699 - (m) \cdot r \cdot S_{\theta}$$

$$\log_{10} N_{\theta} = 6.699 - (0.04656 + 1.0134 \cdot \sin^4\theta + 0.4966 \cdot \sin^2\theta \cdot \cos^2\theta) \cdot r \cdot S_{\theta} \tag{5}$$

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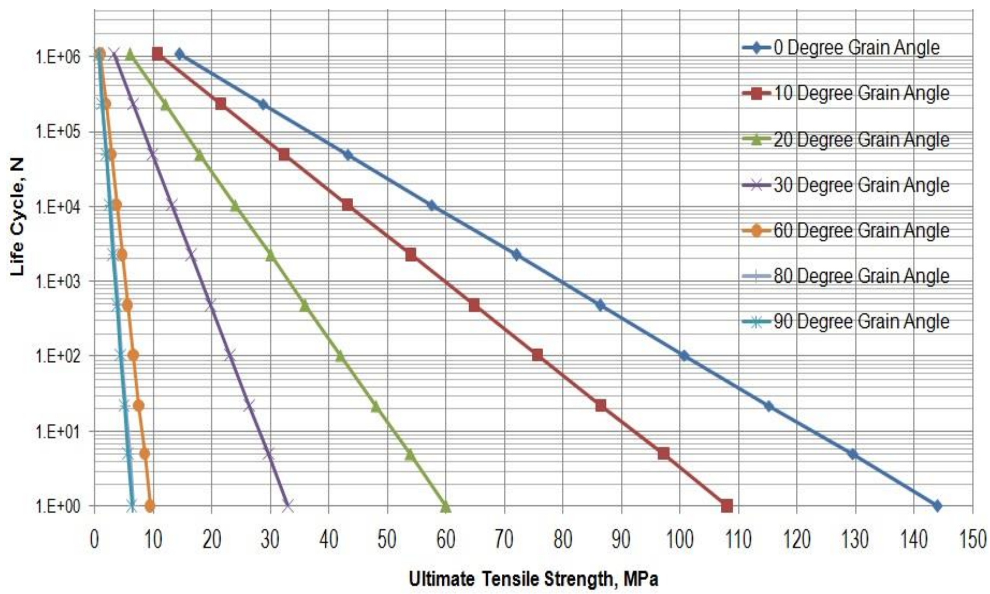
Equation 5 is the Fatigue Life Prediction Equation specifically for *Acacia mangium* 15 years of age.

Result Simulation of Fatigue Life Prediction Equation

The result simulation of Fatigue Life Prediction Equation is shown in Figure 2.

Figure 2: Result Simulation of Fatigue Life Prediction Equation



Verification of Fatigue Life Prediction Equation

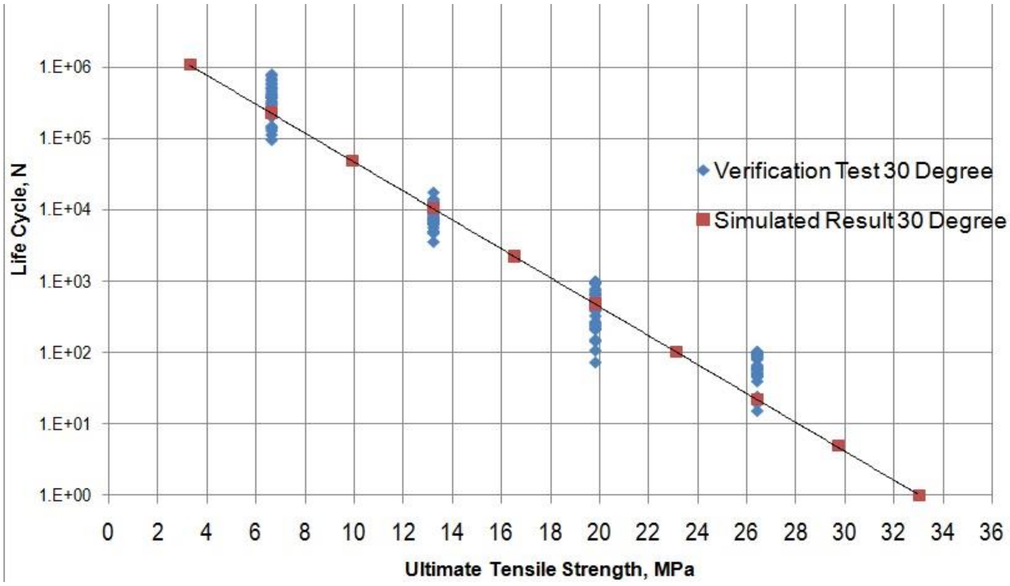
Verification of test was conducted at four (4) stress levels, namely the 80%, 60%, 40% and 20% of the Ultimate Tensile Strength at 30° grain angle. A set of 30 specimens was tested for each stress level. The result of the verification fatigue test is shown in the following Table 3.

Table 3: Verification Test Fatigue Strengths

Stress Level	Mean, Fatigue Life Cycle
80%	256 285
60%	7941
40%	686
20%	55

The finding shows that the verification test results fitted impressively with the predictions made by the equation at 30° grain angle test (Figure 3).

Figure 3: Comparison of Verification Test with Fatigue Life Prediction Equation Simulated Results



CONCLUSION

It was observed that the *Acacia Mangium* N-S (Wöhler) plots have an exponential correlation with the N – intercept of the vertical axis at five (5) million cycles while the intercept of horizontal, S – axis, was at 143.87 MPa. It is also observed that the *Acacia mangium* has a fatigue endurance limit at 10% of the Ultimate Tensile Strength. From the static testing, the Osgood's coefficient of species for *Acacia mangium,* (*a*), was identified algebraically to be 0.49. The finding had shown that life cycles predicted by the Fatigue Life Prediction Equation had almost similar magnitudes with the results defined by the verification test for each stress level. There was an impressive fit between the verification test results and the predictions made by the equation at 30° grain angle.

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