Mechanical Analysis of a Wedge Device in Sawing Technology

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ABSTRACT

The oil palm trunk (OPT) currently represents a massive volume of agricultural waste with great potential to be rapidly developed in the wood composite industry. An improvement in sawing technology has potential to improve the yield of the commercially hard outer core of the OPT by about 27 % thus replacing the present sub-optimal square sawing pattern with a more efficient and higher-yielding polygon sawing pattern. To achieve this, a 'wedge' device was designed to be mounted on the existing sawing carriage. The proper methodology was followed including extraction of the design layout of the machine, development of the schematic drawing and wireframe model, modification of the design in computer-aided design (CAD) environment, the performance of stress, total deformation, and fatigue analysis, and production of a complete drawing for fabrication purpose. Results from the analysis showed that the designed part was safe to be fabricated with a small maximum equivalent stress of 2.546 MPa, maximum total deformation of 0.007935 mm and total life cycle of one million cycles. These evaluation results indicate that the material used for the wedge device (including the base part) satisfies the design requirements of static strength and is safe within its designed fatigue life.

INTRODUCTION

The main issue faced by most wood manufacturers all over the world is the shortage of wood. The gap between supply and demand is big where the supplies of wood material are significantly lower as compared to the demand. This gap is becoming bigger due to the aggressive depletion of forest that leads to a reduced wood supply. On the other hand, the wood demand increases due to the fast population growth (Antwi-Boasiako & Boadu, 2016). Wood which is a raw material is classified into solid wood and composite wood. Between these two categories, solid woods have a more severe supply problem than the composites wood. As a result, many efforts have been made to increase the application of composites wood such as plywood, laminated veneer lumber (LVL), parallel strand lumber (PSL), particleboard, oriented strand board (OSB) and medium density fiberboard (MDF) as an alternative to the use of solid wood, and is becoming increasingly important (Kampman, et al., 2008). However, certain properties of solid wood cannot be compared with that of composites wood. This is the main reason why composites wood cannot be the substitution and at the same time, the demand for solid woods have never been on the decline, although their price becomes more expensive.

One of the agriculture wastes that can be used as an alternative material for solid wood is oil palm trunk (OPT). In Malaysia, it is estimated that about 120,000 hectares of oil palm were planted annually between 2006 and 2010 totaling about 4.3 million trees in 2007 (Wahid, 2008). Compared to fronds and empty fruit bunches, the OPT offers the best properties of wood. Tens of million cubic meters of OPT were yielded from the replanting of the old oil palm trees annually. The study also reported that oil palm wood from the outer parts of matured oil palm stems, which is more than 25 years old, have considerable good properties. Thus, these parts of the stem could be used as solid wood after being properly treated (Haslett, 1990). The production of solid wood requires the conversion of logs into sawn timber through the sawing process. There are three main sawing patterns used which are life or plain sawing, round sawing and quartered or rift sawing. All three patterns are suitable for hardwood and softwood logs which have central heartwood cores and peripheral sapwoods characteristic of dicotyledon species (Bakar et al., 1998). Saw logs from heartwood core are preferred due to their high quality. However, the round or polygon sawing pattern for OPT would be the most suitable sawing pattern. The polygon pattern should potentially produce the maximum volume of quality outer lumber as compared with life and quartered sawing patterns.

To date, no literature or patent on the wedge device used as an integrated part in sawmill carriage has been published. However, several patents on devices to facilitate the rotation of lumber for life sawing are available. Invention introduced by Yoder (1999) is a device mounted on a sawmill carriage that enables an operator to turn a log carried by the sawmill carriage. The device is such a time-saving convenience in the operation of sawmill and

it is widely used in sawmills throughout the country. Bonneau (1992) invented a timber device for positioning on the carriage log-door of a sawing plant. The device gives the angular direction that allows to obtain an optimal sawing for an irregular shape of lumber. However, there are some disadvantages to be fixed and many sensors of operation cause the sawmill turned into a dusty environment.

The literature on the advantages of polygon sawing on the OPT has been discussed by Bakar et al. (2006). The objective in OPT sawing is to maximally produce high-quality outer lumber. Unlike conventional hardwoods and softwoods, the outer lumber of OPT does not contain defects such as knots, sapwood and split and the quality is basically determined by their width. For example, the wider the sawn lumber slab the higher is the quality. Sawing accuracy for the polygon pattern is hence important in controlling slab width which in turn determines pricing structure. This is clearly shown in Figure 1 where polygon sawing (PS) yielded the largest quantity of broad slabs compared with life sawing (LS) and cobweb sawing (CS). This is contradictory to ordinary softwood and hardwood logs sawing where life sawing normally yielded the wider lumber.

The study showed that life and cobweb sawing produced a larger amount of smaller lumber (less than 10cm) which is 77% and 88%, respectively. In comparison, polygon sawing only produced 47% of such lumber. Cobweb sawing, in fact, did not produce any lumber less than 15cm width. By comparison, polygon sawing produced three slabs of 20cm width and two slabs of 16 to 20 cm width. Polygon sawing is clearly the most suitable pattern for sawing OPT in terms of the width of outer lumber (Bakar et al., 2006). The polygon sawing, however, has disadvantages. Firstly, the log or cant on the carriage needs to be rotated quite frequent at a certain angle during the sawing process. Secondly, the angle for log rotation is not a simple perpendicular (90°) angle that can easily be controlled by the conventional carriage. A specific non-perpendicular angle is more difficult to achieve with the present carriage facility.
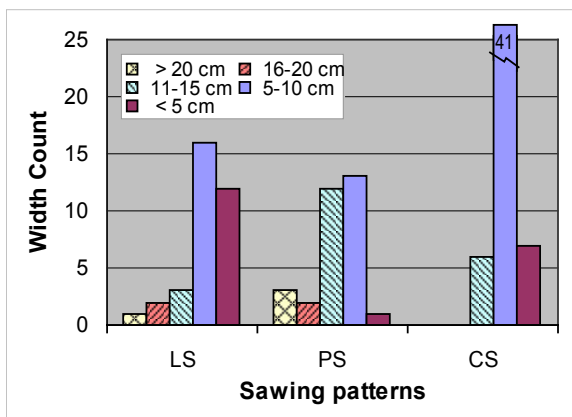

Figure 1. Width count against sawing patterns

For greater accuracy, hence productivity, polygon sawing requires adjustment to the log carriage. Without this, sawing time is longer, and the lumber produced more wedged or tapered. A better controlled and more accurate polygon sawing will improve on the overall productivity of OPT milling. Under conventional polygon sawing only the highly skilled operator can achieve such high productivity

(Bakar et al., 2005). A modified carriage attachment system is necessary to make a polygon sawing process better controlled and more accurate. The attachment system will facilitate the log rotation and hold it firmly at a required angle against the cutting line of band saw. However, to date, neither concept design nor device has been suggested for this innovation. The innovation of the modified carriage system is now quite timely since the number of sawmill processing OPT is still limited. However, the number of such sawmills is set to increase rapidly in the near future. The introduction of a new device prototype for the attachment system should greatly improve on the productivity of OPT milling and the overall lumber yield for the industry.

In this study, stress, total deformation and fatigue analysis of the base part of the wedge device when the base part receives maximum force is discussed. The analysis was done using SolidWorks simulation software. The base part that created using SolidWorks software and analyzed using SolidWorks simulation software allows finite element method analysis for this study. Analysis of stress, total deformation and fatigue were simulated under the restriction of materials mechanical characteristic, base part dimension and force to determine the point of maximum stress, deformation and total lifecycle experienced by the base part.

MATERIALS AND METHODS

Materials

The material used for the wedge device in the finite element method stress analysis is aluminum alloy (201.0-T7 Insulated Mold casting (SS)). This material was selected based on the previous research conducted by Ssomad et al. (2015). Among three materials tested for stress distribution on a hand tool harvester which are aluminium alloy (201.0-T7 Insulated Mold casting (SS)), cast carbon steel and plain carbon steel, the aluminium alloy was found to be the most suitable material for fabrication due to lightweight and the stress distribution was the lowest as compared to other two materials (Ssomad et al., 2013). Table 1 shows the material properties of the aluminum alloy (201.0-T7 Insulated Mold Casting (SS)).

Table 1

Material properties of aluminum alloy (201.0-T7 Insulated Mold Casting (SS))

Property	Value	Units
Elastic modulus	7.099999739e+010	N/m^2
Shear modulus	2.300000022e+010	N/m^2
Mass density	2800	kg/m^3
Tensile strength	344999997.1	N/m^2
Yield strength	344000003.3	N/m^2

Methods

In developing a new conceptual design, problems faced by the oil palm lumber producer were identified. Therefore, a visit to Forest Research Institute of Malaysia (FRIM) was conducted to have a close look at the existing sawmill machine. The design specification is determined and ensures the objectives of the innovation is encountered. The following stages were conducted in accordance to the journal written by Ssomad et al. (2015). The design layout of the machine was extracted, the schematic drawing and wireframe model was developed, design in computer-aided design (CAD) environment was modified, the mechanical simulation was conducted and complete drawing for fabrication purpose was produced. Figure 2 shows the engineering drawing of the wedge device at scale 1:3 with complete dimensions in millimeter.

Every detailed dimension of the drawing must be shown for the determining of the machine size. SolidWorks 2014 and SolidWorks Simulation software was used to construct all the drawings and perform the analysis, respectively. Stress analysis is an engineering methodology to determine the maximum or minimum stress in structures or components subjected to static forces, dynamic forces or given loads (Molaghab et al., 2017). The analysis is usually performed to determine the safety factor or whether the elements or materials can safely withstand the specific forces. The material is safe from any failure when the calculated stress is less than the maximum allowable tensile stress, maximum compression strength, fatigue strength or maximum deformation (Goswami, 2004). Thus, every material has its own safety factor before it can be used.

The safety factor depends on many aspects such as load or force that act on the component, type of material, temperature or other surrounding influences. The safety factor of any component is equal to the fraction of ultimate tensile strength and maximum
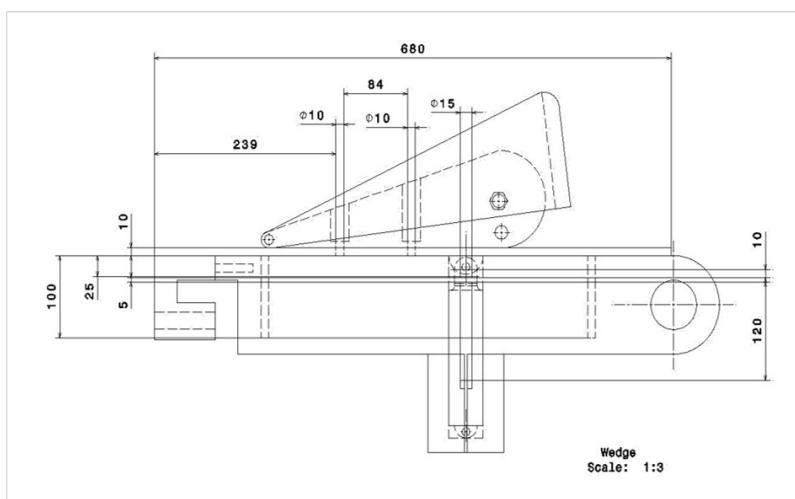

Figure 2. Engineering drawing of the wedge device

allowable stress. The main part of this analysis involves determining the type of loads acting on the component including tension, compression, shear, torsion, bending or combination of such loads. The information regarding the applied load, distribution of forces between components, stress distribution and the deformation of the components can be obtained from SolidWorks Simulation software.

Calculation of Wedge and Inner Angle of the OPT

The five-angled polygon (pentagon) pattern is used to saw OPT. The diameter range of oil palm stems between 40cm and 50cm was been taken into consideration. In the pentagon shape, the total angle, ω and each corner angle, α can be calculated as in Equation 1. This angle is the same for all corners, regardless of stem diameter as shown in Figure 3.

$$\omega = (n - 2) \times 180°$$
$$\alpha = \omega/n$$
$$\omega = 3 \times 180° = 570°$$
$$\alpha = 570°/5 = 108° \tag{1}$$

On a band sawmill, the log is laid down in a series of the L-shaped knee on the carriage and the saw cut the log vertically. After the first cutting is made, the log is rotated clockwise to position it for the second cutting in which the angle 'α' (angle between the two lines) is 108°. At that position, the angle α can be easily set by putting a "wedge" with an angle 'β' to support the log that makes it perpendicular to the first cut as shown in Figure 3. The wedge angle β can be then calculated as in Equation 2.

$$ß = \alpha - 90°$$
$$ß = 108° - 90° = 18^c \tag{2}$$

Since the pentagon shape is symmetrical, the angle of the "wedge" for all cutting must be at the same angle of β equal to 18°. The position of the knee on the base is adjustable, depending on the diameter of log or cant being sawn. In some carriage system, the knee is also equipped with a hydraulic mechanism to rotate the log or cant above the knee base. The wedge can be moved ´up´ and ´down´ at each set of the knee on the carriage. At the
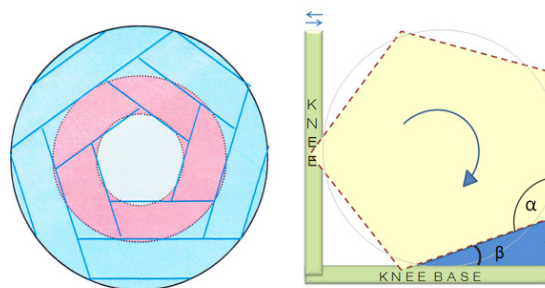

Figure 3. Polygon sawing pattern (left) and polygon sawing process using a wedge (right)

´up´ position, the wedge will serves as a slanted base and accurately support the log/cant to allow the new cutting line form to an α angle to the previous cutting line. At ´down´ position, the knee base is at the free horizontal condition to allow the log to be easily moved or rotated on the base. Since the OPT is long and heavy, the attachment system must be securely and strongly positioned for each set of knees, and all moving components (log and wedge) can be moved simultaneously with one button.

Components of the Wedge Device

The wedge is basically made of five components as shown in Figure 4. These are the rod, wedge support, movable table, hydraulic cylinder, adjustable wedge, and base. The rod secures the adjustable wedge which holds the log at a specific angle; 108° with the wedge support and 120° with the adjustable wedge. The movable table supports the log which is moved in the vertical plane by the attached hydraulic cylinder. The base supports the movable table. Figure 5(a) shows the position next to the carriage base where the innovative wedge device was assembled. The top dog is a conventional device that assists in holding securely the OPT during the sawing process. It is mounted on the vertical knee.
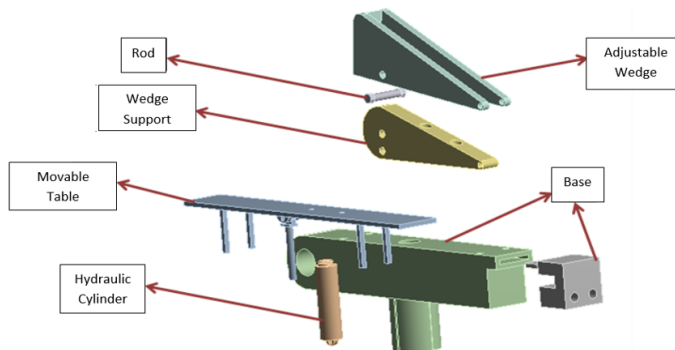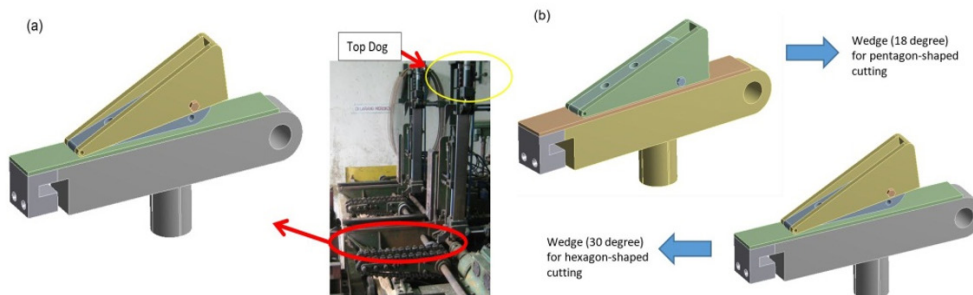

Figure 4. Components of the wedge device

Figure 5(a). Wedge mounted on the existing sawmill carriage *(b).* and adjustable wedge for pentagon-and hexagon-cutting

RESULTS AND DISCUSSION

Stress and Total Deformation Analysis

Figure 6(a) and (b) show the static components which act on the base and the mesh generation, respectively. The base is used as a support for the wedge. It is soldered at the bottom to the hydraulic cylinder which lifts the wedge at a maximum force of 2598N. Therefore, the bottom part of the inner tube where the cylinder placed will experience a maximum force of 2598N. Green arrows at the left and right side of the base are where the part is fixed to the existing sawmill carriage. Mesh is one of the critical aspects of engineering simulation. Too many cells may result in long solver runs and too few may result in inaccurate results. Type of mesh either tetrahedral, hexahedral or mixed elements are important as well in determining the quality of results displayed. The tetrahedral mesh was used in this analysis as compared to hexahedral mesh since it gave a good quality for the domain interior and near the boundary. Similar results were obtained by Duggleby et al. (2011).
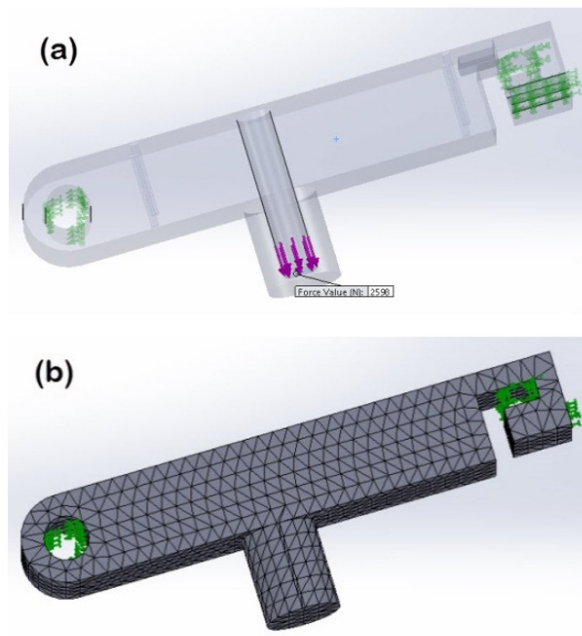

Figure 6(a). Force component on wedge base *(b).* mesh on wedge base

Further analysis was performed using SolidWorks Simulation and the results are illustrated in Figure 7(a) and (b). The analysis showed that the maximum equivalent stress exerted on the wedge base was 2.546 MPa and the maximum total deformation was about 0.007935 mm. According to Sukumar and Ramachandran (2016), for a manufacturer to approve any mechanical design, the value of maximum equivalent stress (von Mises stress) in a system during a worst-case situation should be lower than that of the yield strength of the material used. Since the yield strength is 344 MPa, which is much higher than the value of maximum equivalent stress of 2.546 MPa, the design is safe under designated stress or force. The total deformation is also very small and will not affect the accuracy of the cutting process. The result shows that the maximum equivalent stress is around the holes and the minimum point is on the left- and right-hand sides.
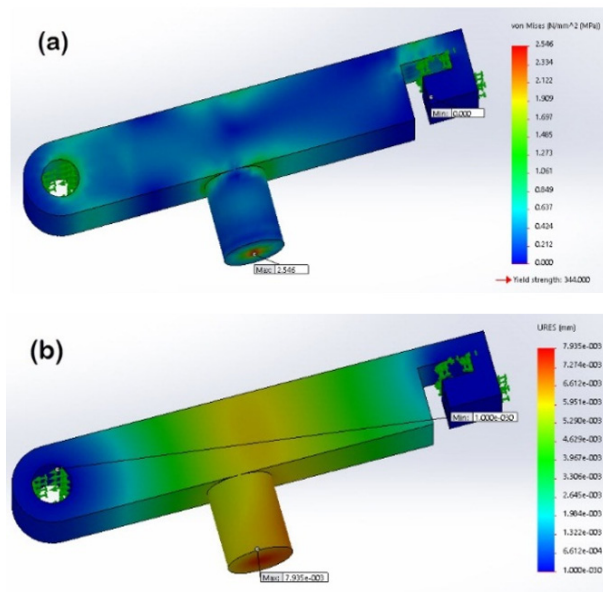

Figure 7(a). Total deformation *(b)*. equivalent stress

Calculation of Static Component Strength against Crack

The static component strength is calculated to identify whether the wedge base can withstand deformation or otherwise. The component strength is determined and compared with the analysis results from SolidWorks Simulation. Following equations were available in Roloff/Matek Maschinenelemente (Muhs, 2003).

The calculation for the static component strength against crack is defined in Equation 3 where f_σ is the factor to calculate the material strength value which equal to 1, R_m is the tensile strength of the material, and K_B is the static construction factor. The static component strength against crack is proportional to the tensile strength of the material.

$$\text{Crack, } \sigma_B = \frac{f_\sigma \cdot R_m}{K_B} \qquad [3]$$

For components deviating from the standard dimensions, the strength value of R_{mN} must be converted with the factor of K_t. Tensile strength can be calculated using Equation 4 where k_t is the technological size factor for tensile strength and yield strength which equal to 1, R_{mN} is the tensile component which is 355 N/mm^2.

$$\text{Tensile strength, } R_m = K_t \cdot R_{mN} \qquad [4]$$

The static construction factor, K_B can be determined from the plastic support, n_{pl} as shown in Equation 5 where n_{pl} is the notch sensitivity (factor). The plastic support number should consider that stress peaks in components made of tough materials, as they occur in bending and torsion and notch effect, may locally exceed the yield point without destruction of the component (local plastic deformation).

$$\text{Static construction factor, } K_B = \frac{1}{\eta_{pl}} \qquad [5]$$

Equation 6 applies to the calculation of local stresses where R_{pmax} is the maximum yield strength which is 320 N/mm^2 for aluminum alloy, R_p is the yield strength, and α_p is the plastic stress concentration factor for a component without groove. With the *Neuber* approach, the plastic stress concentration factor can be calculated as the ratio of the transient stress to the yield stress. With an assumed tolerable elongation for a notched component, the plastic stress concentration factor or the notch sensitivity for the verification with nominal stresses can be determined.

$$\text{Notch sensitivity, } \eta_{pl} = \sqrt{\frac{R_{pmax}}{R_p}} \leq \alpha_p \qquad [6]$$

For components deviating from the standard dimensions, the yield value of R_{pN} must be converted with the factor of K_t. Yield strength can be calculated using Equation 7 where K_t is the technological size factor for tensile strength and yield strength which equal to 1 and R_{pN} is the yield component (355 N/mm^2).

$$\text{Yield strength, } R_p = K_t \cdot R_{pN} \qquad [7]$$

Based on Equation 6 and the value of α_p is equal to 1.5, the notch sensitivity, n_{pl} is equal to 0.96 which is lower than 1.5. Therefore, value of notch sensitivity of 0.96 is used in Equation 5 to find the value for the static construction factor, K_B.

$$K_B = \frac{1}{0.96} = 1.04$$

Once the value for the tensile strength of the material, R_m, factor to calculate the material strength value, $f\sigma$, and the static construction factor, K_B has been determined, the maximum stress against crack for the base can be calculated using Equation 3 and shown below.

Crack, $\sigma_B = \frac{1 \cdot 345 \text{ N/mm}^2}{1.04} = 331.731 \text{ N/mm}^2$

In comparison with the maximum equivalent stress calculated from the SolidWorks Simulation which is 2.546 MPa, the maximum tensile stress at the crack for the aluminum alloy is much higher which is 331.731 MPa. It can be concluded that using the aluminum alloy for the base is very reliable and safe against deformation and crack. The result is similar to that of Ssomad et al. (2013) based on the factor of safety analysis. They found that under safety factor of 5, the critical value of stress was removed for only aluminum alloy as compared to cast carbon steel and plain carbon steel. The aluminum alloy base would only crack or break if the equivalent stress is higher than 331.731 N/mm² (MPa).

Besides stress and total deformation analyze, fatigue analysis was performed in determining the durability of the aluminum alloy material under prolong compression and tension. Figure 8(a) and (b) show the damage percentage and total life cycle of the base part made of aluminum alloy. After 500,000 cycles, the damage experienced by the base part is 50 percent. The total life cycle is one million cycles. It means that, after one million cycles, the base part will be fully damaged and requires a replacement.

Based on the analyses conducted on the wedge device, it proved that the aluminium alloy was significantly appropriate to be used in manufacturing the base part of the wedge device. The analyses contribute a cheap yet accurate results for a manufacture to approve the mechanical design of this wedge device for manufacturing purpose. In addition, the theory behind the calculation of maximum stress against crack can be applied in any stress analyses and be practiced in various field of applications including machinery design. The theory is unduly important to ensure that the maximum equivalent stress obtained from the analysis if safe for the subsequent manufacturing process of the wedge device. The developed wedge device is expected to be integrated in various type of sawmill machines due to its ability to be adjusted based on the shape of the existing sawmill machine. However, performance evaluation of this wedge device is required to prove the efficiency of the conceptual design.

CONCLUSION

This work has focused on stress and fatigue behaviors of a base part of a wedge device based on finite element analysis which experiences the highest force during the working process. The analysis has been carried out using SolidWorks Simulation software. The stress analysis results show that aluminum alloy used as the manufacturing material for the base part of the wedge device is suitable since it able to withstand a maximum force of 2598N without a crack. The fatigue analysis results also show that the base part will fail due to fatigue after one million cycles. These evaluation results indicate that the material used for the wedge device (including the base part) satisfies the design requirements of

static strength and is safe within its designed fatigue life. This has essentially laid the foundation for future work in terms of shape optimization and performance evaluation after prototype fabrication.

ACKNOWLEDGEMENTS

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