Technical Paper

MATERIAL SUBSTITUTION FOR THE SUPPORTING FRAME OF POWER TILLER WITH FINITE ELEMENT ANALYSIS APPROACH

Midian Sihite[1], Setyo Pertiwi[2], Wawan Hermawan[3],
Masayuki Koike[4], Tomohiro Takigawa[5], Hideo Hasegawa[6]

ABSTRACT

Due to its advantageous characteristics, aluminum is considered to substitute the existing steel as material of the supporting frame of power tiller to meet the strength and environment concerns. The investigation was emphasized on the comparison of both material in view of stress and deformation. In this study, both experimental test and finite element (FE) analysis were employed to meet the research concern. Comparison between the experimental test and numerical analysis results indicated acceptable differences of about 7-33% which is lower than the previous research. Substitution with aluminum was confirmed using material index that aluminum has better performance in strength and stiffness than that of steel by prescribing minimum weight. FE analysis result revealed that aluminum model was capable of sustaining loads about equal to the steel model. It was based on its maximum von Mises stress which was insignificantly lower than the steel model. In term of strength characteristics, strength ratio of the aluminum model was higher than the steel model. Furthermore, the substitution also resulted in redistributing stress into wider area and mass reduction for about 36 %.

Keywords: *Material Substitution, Finite Element Method, Static Analysis, Supporting Frame, Mass Reduction*

INTRODUCTION

Machine performance of agricultural machinery in the developing countries is lower and their equipment is smaller and simpler than that in the industrialized countries. These machines are exposed to higher mechanical load due to heavy duty service, stones and roots, and inappropriate use may result in heavy strain. Hence, new machines must be developed for those countries (Kutzbach, 2000). Furthermore, environmental issues also have a contribution on new design

1 Department of Agricultural Engineering, Bogor Agricultural University, Darmaga Campus Bogor 16680, dianphoenix@yahoo.com.
2 Department of Agricultural Engineering, Bogor Agricultural University, Darmaga Campus Bogor 16680, sedhie@indo.net.id.
3 Department of Agricultural Engineering, Bogor Agricultural University, Darmaga Campus Bogor 16680, w_hermawan@ipb.ac.id.
4 College of Agrobiological Resources, University of Tsukuba, Tsukuba, Ibaraki, Japan 305-8572, toratuku@sakura.cc.tsukuba.ac.jp.
5 College of Agrobiological Resources, University of Tsukuba, Tsukuba, Ibaraki, Japan 305-8572, ttakigawa@sakura.cc.tsukuba.ac.jp
6 College of Agrobiological Resources, University of Tsukuba, Tsukuba, Ibaraki, Japan 305-8572, hsgw@sakura.cc.tsukuba.ac.jp

of agricultural machinery. The increasing requirement to improve fuel consumption triggered by concerns of global warming and energy use has an influence on the choice of materials (Miller *et al.*, 2000). Therefore, new design of agricultural machinery should be lighter to the certain extent in order to reduce fuel consumption and soil compaction as well as reliable strength to withstand external load.

Design improvement on structural strength and environment had been conducted by previous researches. Muhaemin *et al.* (1999 and 2000) applied lightweight material aluminum to substitute steel as chassis type frame material of tractor. The aluminum model provided better strength and mass reduction up to 28%. Cole and Sherman (1995) pointed out the advantageous characteristics of aluminum compared to iron and steel. In addition, if a vehicle moves into heavier, fuel economy decreases by about 0.17 *l*/100 km. Patton *et al.* (2004) investigated causes of weight reduction effects of material substitution with aluminum. It is further shown that reducing these thin-walled effects through better reinforcement and substituting aluminum for steel produces significant weight reduction effects.

As first step, design improvement can be initiated with specific component of agricultural machinery before applying to entire design. In these attempts, experimental test and FE analysis are necessarily to be done before coming up on the results. This paper uses term "steel" and "aluminum" which refers to all steel and aluminum alloys since material properties of these materials do not vary much among alloys. The objective of this research is to evaluate substitution for the existing steel with aluminum as the supporting frame material. Special emphasis was placed on comparison of both material in view of stress and deformation.

METHODOLOGY

These works were carried out by two methods, namely experimental test and finite element (FE) analysis. The experimental test was conducted to measure strain of the supporting frame at certain points while being exerted by the loading condition. The experimental strain result was used to verify the validity of the numerical strain analysis. FE software was employed to analyze stress and deformation of the steel and aluminum supporting frame (referred hereafter as steel and aluminum model). An elastic static approach integrated in FE software was used to comply with the specific stress analysis.

A. The power tiller

A 6.25 kW power tiller, type ST60 (Figure 1), was adopted for this study. Main specifications of the power tiller and

Figure 1. The power tiller

Figure 2. The supporting frame

Table 1. Main specifications of the power tiller and supporting frame

Power tiller	
Type	ST60, gasoline engine
Power (kW)	6.25
Wngine mass (kg)	36
Engine speed (rpm)	1800
Supporting frame	
Material	Mini steel
Material code	JIS 3131 SPHC
Mass (kg)	3.86
Thickness (mm)	3.2

the supporting frame (Figure 2) is shown in Table 1.

B. Experimental test

Strain measurement was conducted on the original steel frame. The main hardware for experimental strain test comprised of strain gauge, bridge box, strain amplifier, and sensor interface. Four strain gauges were installed on the supporting frame at certain points where high concentration of strain predicted to be occurred. Loads exerting on the frame were considered to originate from mass of engine (36 kg) and ballast (26 kg) as well. Mechanical strain of a structure under loading is captured by strain gauge through its resistance change. In order to measure strains more conveniently, the bridge boxes DB-120P were utilized. The bridge box incorporates with high stable resistors to allow the use of variety strain-gauge bridges.

To measure the magnitude of the strain in electric signal, a strain amplifier KYOWA DPM 711B was employed. A portable personal computer was utilized to analyze strain easily. A sensor interface KYOWA PCD-30A was incorporated to convert the electric signal from the strain amplifier to digital signal. Arrangement of the experiment test is shown in Figure 3 including strain gauge, engine compartment, and subframe locations.

C. Finite element analysis

The FE model was built by using ANSYS 8.1 University Intermediate software. To support the FE simulation, ANSYS was run on a stand alone computer with 1.3 Gigahertz processor and 512 Megabytes memory. Construction of the frame consists of two side members and two cross members. The frame model was built embracing with the engine compartment. Regarding

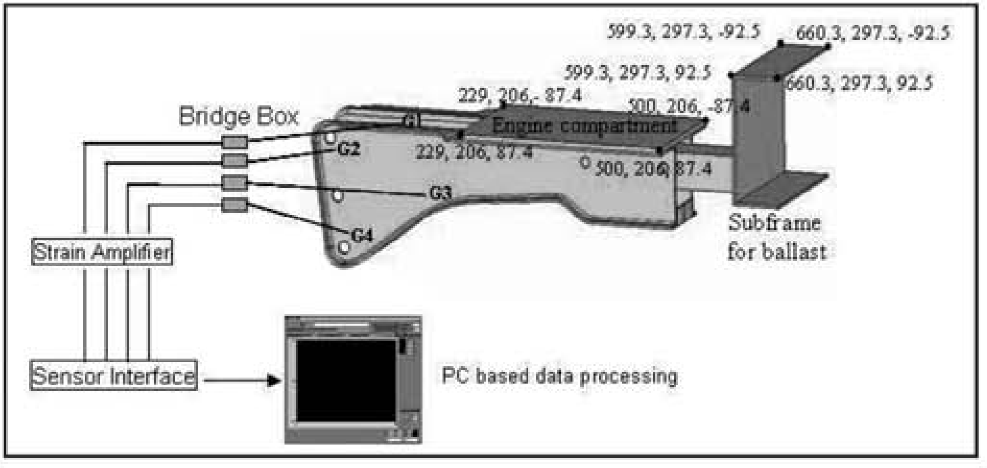

Figure 3. Arrangement of the experimental test

the limitation of maximum node number of this version, 3D eight-node brick element (SOLID 45) was selected to approximately develop the FE model of the frame. The frame model consisted of 30710 elements and 10604 nodes which have three degree of freedom on each node.

Similar to the previous experimental test, loading and boundary condition were examined under specific boundary condition. Total pressure load from the engine and its supporting components was about 0.014 N/mm^2 or 0.014 MPa. Meanwhile, total pressure load from the ballast and its supporting component was about 1.153 N/mm^2 or 1.153 MPa. The finite element model and the loading and boundary condition are presented in Figure 4 and Figure 5, respectively.

Static FE analysis was used to determine displacements, strains, stresses, and deflections and further to evaluate the structural strength of the frame model. For more specific stress analysis, von Mises yield criterion was taken into account. All of the static analysis results and the von Mises stress were derived by using FE software ANSYS. Another approach of strength characterization using strength ratio was introduced as well. The strength ratio reflects comparative strength between yield stress and actual stress. The strength ratio (R) equation is defined as follows (Tsai and Hahn, 1980):

$$R = \frac{\sigma_a}{\sigma_i} \qquad (1)$$

Where, σ_a is allowed or ultimate stress and σ_i is referred as imposed stress. In this analysis, maximum von Mises stress was considered as the imposed stress. Allowed or ultimate stress is referred to yield stress of material at which first deformation starts to occur.

Several features of the strength ratio are mentioned as follows. At $R < 1$, actual stress is extremely high while permanent deformation progressed. Specific relation of $R = 1$ implies to permanent deformation starts to occur, but also indicates the quantitative measures of safety margin. At $R > 1$, actual stress is safe and still within elastic limit.

In order to examine performance of the both materials, material index (Ashby, 1999) was developed to enhance the analysis. Design and geometry effects were not exist because of both materials use the same FE model. Therefore performance of the material has only dependency on the material properties (Table 2). The design requirement was concentrated on minimum weight and the essential structural requirement must be met the stiffness and strength. For stiffness-limited design, material index (M_1) is defined as follows:

$$M_1 = \frac{E^{1/2}}{\rho} \qquad (2)$$

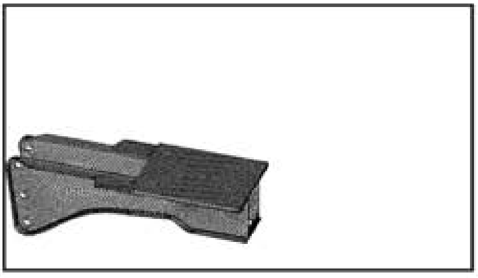

Figure 4. The finite element model

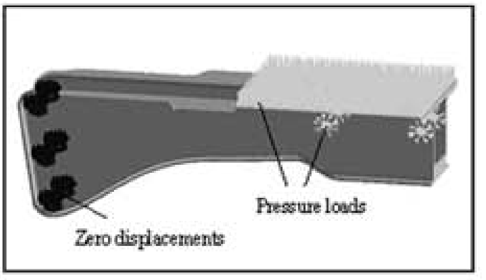

Figure 5. The loading and boundary condition

Material index (M_2) for strength-limited design is expressed in the following equation:

$$M_2 = \frac{\sigma_y^{2/3}}{\rho} \qquad (3)$$

Where E, ρ, and σ_y are referred to modulus of elasticity (GPa), density (Mg/m^3) and yield stress (MPa), respectively. The main function of the expressions is to minimize weight. Better performance has higher values of the material index.

RESULTS AND DISCUSSIONS

A. Experimental test

Generally, the difference between experimental and FE result was about 7 - 41 %. Amount of strains at points G2 and G3 were close to those of the numerical result by 7 % error. However, magnitude of strain at point G4 was somewhat higher by 33 % than the corresponding strain of the FE result. A significant error was found on point G1 where the experimental strain underestimates numerical strain by 41 %. Comparison between the experimental and numerical strain was graphically shown in Figure 6.

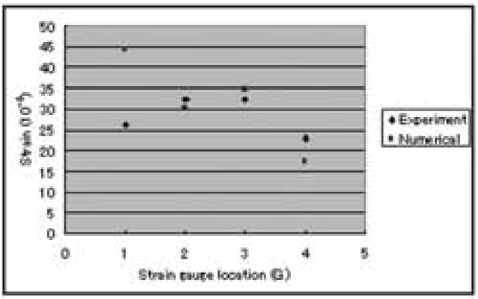

Figure 6. Comparison between the experimental and numerical strain

Table 2. Material properties for FE analysis

Property	Mild Steel	Aluminum Alloy
Modulus of elasticity (GPa)	205	63.8
Yield stress (MPs)	220	255
Tensile stremgth (MPa)	400	310
Poisson's ration	0.30	0.33
Density (Mg/m^3)	7.8	2.79

Theoretically in bending load the stress is largest at surface of a structure which lies furthest distance from the neutral axis. Therefore maximum strain is easily derived at the largest stress occurs. This satisfactorily agreed with the numerical strain result as presented in Figure 7 where the maximum strain was located on the top surface of the frame. The significant difference on amount of strain

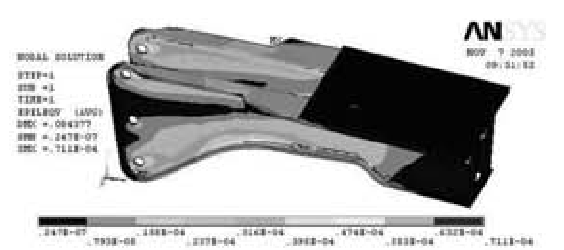

Figure 7. Numerical strain result

at point G1 between experimental and FE result was conceivably caused by mechanical disturbance during repetitive loads treatment.

The maximum error in this experimental work exceeded the previous research carried out by Muhaemin *et al.* (1999). The difference between FEM and experiment loading test ranged from 12 to 36 %, although both results have similar trend on the values. Regardless of the strain result at point G1, the differences between the experimental and numerical results in this work were lower than the previous research. Nevertheless, it is well known that the differences were inevitable and thus, based on the above considerations those differences can be accepted for this research. Therefore it can be expected that the numerical simulation could produce reasonable results and reflects the true condition of the frame.

B. Finite element analysis

1. The existing steel model

The result of FE analysis on the existing steel model which was loaded with equivalent vertical loads from the engine and the ballast showed that the free end was deformed downward. The maximum deflection at the edge of the steel model caused by this bending loading condition was about 84 ìm (Figure 8).

Based on the von Mises stress distribution, higher stresses were concentrated on upper and lower parts of the steel model. Maximum von Mises stress was about 14.5 MPa which occurred on the area around the middle of the flange. Distribution of the von Mises stress is shown in Figure 9 and summary of the FE analysis is presented in Table 3.

Allowable stress which represents the condition of maximum loading in a conservative design for the mild steel is 130 MPa at safety factor of 3 (Muhaemin *et al.*, 1999). Meanwhile maximum von Mises stress for the steel model was about 14.5 MPa; it means that current loading applied on the frame was only about 11 % of the allowable stress. Based on this finding, the current loads imposed on the frame could be increased by approximately nine times before approaching the allowable stress. In other word, the allowable stress can be used as the upper bound of load increment in order to asses the effective use of the structural material. Compared to its allowable stress, the percentage of loads was insignificant. It can be said that there were only small parts of the steel structure that have function as load-carrying material. Therefore, the current material

Figure 8. Deformed shape of the steel model

steel which is utilized for the frame was ineffective.

According to the properties, there was a potency to substitute the material of the frame with aluminum. In fact, aluminum has lower stiffness than steel as basis of specific modulus. The specific modulus (modulus elasticity/ density) of steel and aluminum are about 26.3 MN-m/kg and 22.9 MN-m/kg, respectively. However, aluminum has higher yield stress than steel. This substitution caused ratio of the maximum von Mises stress and allowable stress higher than that of the steel model as well as the increase of its component stresses. Therefore, there were wider parts of the aluminum structure have function as load-carrying material. Accordingly, use of the structural material became more effective to accommodate the same loading condition.

2. Substitution with aluminum

The advantageous characteristics of aluminum are high stiffness to weight ratio, good formability, good corrosion resistance, and recyclable. The advantages make it the best substitute material for steel and copper in response to weight reduction demand in automotive industry (Miller *et al.*, 2000). Furthermore, aluminum has higher quantifiable properties when compared to its counterpart steel in term of material index. According to equations (2), material index (M_1) of aluminum was higher by about 1.5 times than steel one. It showed that aluminum was stiffer at minimum weight. Whereas material index (M_2) obtained from equation (3), aluminum was three times higher than that of steel. It revealed that aluminum has better performance in strength. Thus, by considering their material indexes, it was obvious that aluminum has superior performance characteristics in stiffness and strength than steel to sustain equal load at minimum weight.

FE analysis result of the aluminum model is summarized in Table 3. The maximum deflection was higher more than 3.2 times compared to that of the steel model. This was inline with the modulus of elasticity of aluminum which is about three times lower than that of steel. Similar condition has also been found on the displacement of x and z directions where maximum deflections on respective directions were about 3.3 times and 3.0 times higher than the corresponding deflections of the steel model. The deformed shape of the aluminum model while being under the loads is shown in Figure 10. The increase of the deflections was followed by the increase of the component stresses. The maximum longitudinal stress rose about

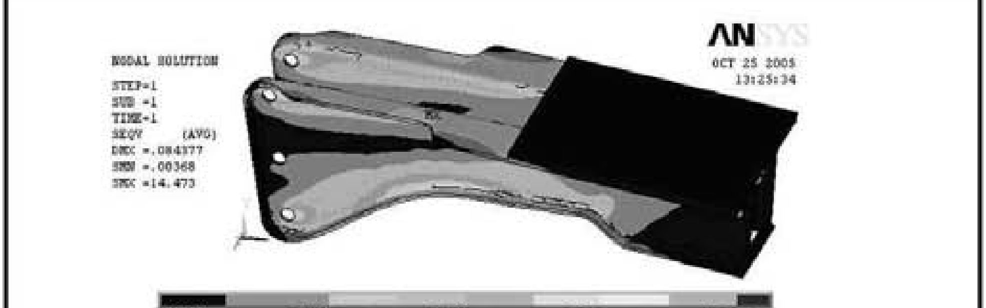

Figure 9. Distribution of the von Mises stress of the steel model

Table 3. Summary of FE analysis results

FE analysis	Steel	Almunum
Max. X-component of displacement (μm)	15	49
Max. Y-component of displacement (μm)	84	270
Max. Z-component of displacement (μm)	3.9	12
Max. X-component of strees (MPa)	16	17
Max. Y-component of strees (MPa)	8.8	10
Max. Z-component of strees (MPa)	5.9	72
Max. von misses strees (MPa)	14.4	14.4

6 % of the steel model. Significant increase of stress was taken place on the lateral direction where the maximum value rising up to about 22 % of the previous one. It has been realized that material substitution might bring about the increase of stresses in some areas and decrease in other area. However, as stated previously, the increase caused redistributing of stresses into wider areas of the material. As the consequence, the effective area as load-carrying material was also enlarged as the use of the structural material widened. Thus, it can be said that the aluminum model uses its structural material more effective than the steel model.

The von Mises stress of the aluminum model is shown in Figure 11. It can be visually observed in the figure that distribution of the von Mises stress was more extensive in wide area of the structure. Compared to its allowable stress, the maximum von Mises stress was about 14 % which is higher than that of the steel model. Strength of the structural element (machine part) is achieved if the equivalent stress of structure carrying load is closely lower or equal to the allowable stress determined for the material (Chechin, 1997). It was obviously acknowledged that the aluminum model use its material better than the steel in sustaining the load condition.

In view of the strength ratio, both steel and aluminum model exhibited the ratios of 15.2 and 17.7, respectively, which are higher than unity. It indicated that the actual stresses acting on the both models were safe and under the elastic limits. Considering that the ratio of the aluminum model was somewhat higher, it implied that the capability of sustaining unexpected load increment during field operation is also higher. The preceding material substitution accompanied by design optimization acquired the strength ratio roughly 1.5 times higher than the steel model for the heaviest loading (Muhaemin *et al.*, 2000). Owing to the ratios, the strength of the aluminum model exceeded than that of steel model. Therefore, it can be confirmed that the frame made of aluminum provides better

Figure 10. Deformed shape of the aluminum model

structural strength and more reliability on its properties to substitute steel.

Besides of its merit in strength, material substitution with aluminum has resulted in mass reduction as stated earlier. With the present material, mass of the frame reduced approximately 36 % lower than the original material. The percentage was higher than the previous study that could achieve only 20 % since the model has been furnished the additional cross-member. For strength-based design, mass reduction may be improved about 40 to 50 % (Muhaemin *et al.*, 1999). Another research on material substitution which is concerned on constant stiffness just as steel found weight reduction approximately 27 to 40 %. Further emphasis is placed on the fact that there is no fixed percentage of weight saving resulting from aluminum substitution (Patton *et al.*, 2004).

During field operation, the supporting frame is exerted by random external loading. Effect of the material substitution on such condition can be predicted through dynamic behavior of the supporting frame. Dynamic behavior of any structure depends on its natural frequency. Moreover, if change in mass is proportional to change in stiffness then material substitution from steel to aluminum does not necessarily imply a change of its natural frequency (Muhaemin *et al.*, 2000). As stated previously, the mass reduction and the stiffness decrease of the aluminum frame were proportionally one-third of the steel model. Accordingly, it can be expected that natural frequency of the aluminum frame will not significantly different with the steel frame. Therefore, the aluminum frame is presumably capable to withstand the random external loading during field operation.

CONCLUSIONS

Regardless the strain of point G1, the experimental test result showed that there were differences in the numerical result of about 7 to 33 %. The differences were lower than those resulted by Muhaemin *et al.* (1999).

Material substitution exhibited that deflection of the aluminum model was three times higher than the steel model and its component stress increased up to 22 %. The maximum von Mises stress was insignificantly lower and the strength ratio of aluminum model was higher than the steel model. The substitution also resulted in redistributing stress into wider area and mass reduction of about 36 %. Therefore, the aluminum model provides better structural strength and preferable on its material performance.

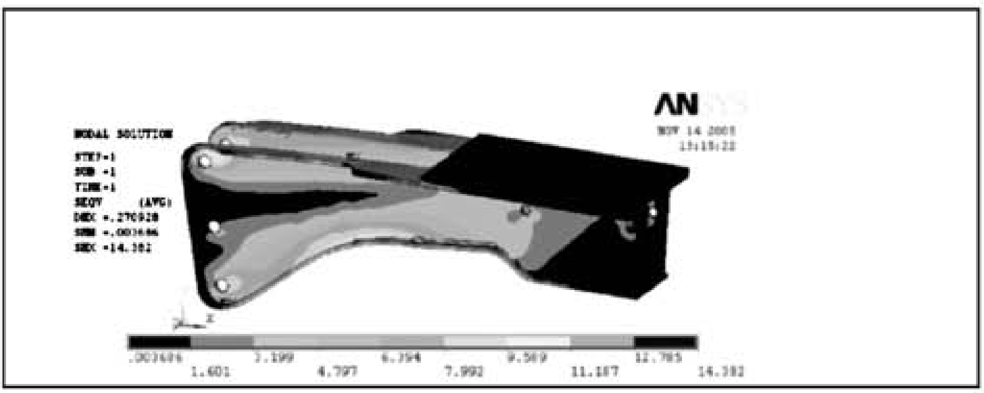

Figure 11. The von Mises stress of aluminum model

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