DESIGN PARAMETER OPTIMIZATION OF THIN-WALLED STRUCTURAL BY IMPLEMENTING BEETLE FOREWING SANDWICH STRUCTURE MODEL USING THE MULTI-FACTOR EXPERIMENTAL DESIGN

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Abstract

The adaptability of the beetles lets this ancient genus avoid extinction. The robust body construction of the beetles is the physical result of the creation process which enhances the performance potential of this insect. Human beetles are unique and comprise of forewings and hind wings. Forewings are layers of light and solid wings that cover underneath the hind legs. The framework for the forewings promotes a lightweight system known as the Beetle Forewing Sandwich Structure (BFS). The structure of the BFS is related to the existing honeycomb sandwich structure at different hexagonal wall sites with additional trabeculae. Previous studies showed remarkable mechanical performance of this structure over conventional lightweight structure (e.g., hexagonal plate) in BFS. In the present review, an enhancement analysis will be carried out to optimize the role of the BFS design through multi-factor experimental design method, with material used is Aluminum 6061 Alloy (UNS A96061) proposing a BFS structure with greater intensity but less weight. Eventually, the findings of this study that contribute to the alternative lightweight framework for many engineering applications, especially the load-bearing goods.

Keywords: Adaptability of the Beetles, Beetle Forewing Sandwich Structure, Existing Honeycomb Sandwich Structure, Enhancement Analysis, Lightweight Structure.

1. INTRODUCTION

Thin-walled structures can be used in many contemporary engineering areas, and it is notable that they are already formulating a growing proportion of the architecture design of today. The desire for lightweight, more effective structural systems that provide high strength and rigidity in conjunction with low structural weight has continued to promote this growth as well as strengthen the potential for continuing research and development in the future. With an appreciable introduction in a wide range of areas of thin-walled structural elements and structures, the scope of use of thin-walled structures has become increasingly diverse. There are also intrinsic drawbacks to the system. First, it needs to be laminated to improve resistance to impact or forces applied, without being laminated, it has become poor resistance to tensile loads out of the plane. The design also has inherent weaknesses, first it has to be laminated to enhance impact resistance or force applied, without being laminated it has become low tensile load resistance from outside the aircraft. Then the susceptibility to damage and the high potential for internal damage will go unseen. Because of its lightweight structure, thin-walled still gives it benefits for almost all applications [1]. Demand for low weight, high performance, and new design of materials are becoming a new standard and growing rapidly for applications ranging from spacecraft, aviation, automobiles, vehicles, and construction to just a few. [2]Such applications before explaining how to implement sandwich structures that are compatible with all structures of thin-walled composites. The advantages of a single metal system are extracted from a proper mechanical quality coupled with lower costs or better durability. However, the performance of the thin-walled structure cannot pass through the honeycomb-cored sandwich (HS) structure. Known to have durability issues related to water intrusion, delamination and relatively expensive when the design needs to be curved panels or shells but is anisotropic [3]. Lately, a few reports on the design and optimization of sandwich structure parameters were scientifically published in the past year. Some of them adopted bio-inspired designs and generated the structure of the beetle forewing sandwich (BFS). The beetle was observed on its physical characteristics, particularly on its forewing [4], which can be defined in [5] as an integrative sandwich layer with higher, lower lamination layers, and a core layer with honeycomb cells and trabeculae. It is known as the key component that allows the beetle to withstand much any force of action. Stable performance of the beetle forewing aid through the low density and good toughness bio-composite of chitin fiber-enhanced keratinized protein [6]. With regard to its good performance, many types of research in this novel structure emphasize only on optimizing the common HS by using the bio-characteristic and material features of the beetle forewing, it is not clear whether the core geometry design is linked to the quality of the sandwich structure itself. The first BFS research found a good mode of compressive deformation and a greater ability to absorb energy compared to traditional HS [7]. Common HS performance depends on the material used to increase energy absorption capacity and weight due to the high density utilized in the structure. BFS not only gives HS a potential benefit by constructing a beetle forewing that uses trabeculae on the core surface but also manages to achieve the right balance of lightweight material and framework to achieve improved mechanical properties for HS reinforcement and to retain the key feature of a thin-walled system strengthened for the intent of the sandwich structure. Previous BFS study represents a significant advance and aims to be applied to different energy-absorbing sandwich systems but does not announce a particular combination of each beetle forewing characteristic to maximize the absorbed function and resources. The goal of this analysis is to find out more about parameters for geometry design to optimize the beetle forewing sandwich structure.

2. RESEARCH METHODOLOGY

2.1 Procedure

The conceptual model is a diagram that illustrates a number of relationships between some factors affecting or leading to a target condition. The aim of creating this model is to include guidelines for the implementation of standardized studies. Figure 2 shows that the study 's focus is on finding design factors that are of significant value and finding the best combination of parameters. The studies begin with generating the scenario of multifactor experimental design to determine the study requirement and objective. Followed by specifiying the parameter, and controlled parameter, setup simulation to generating the value of force applied and deformation, calculated quantitatively with grey relational analysis (GRA) and ANOVA to support the GRA result statistically.

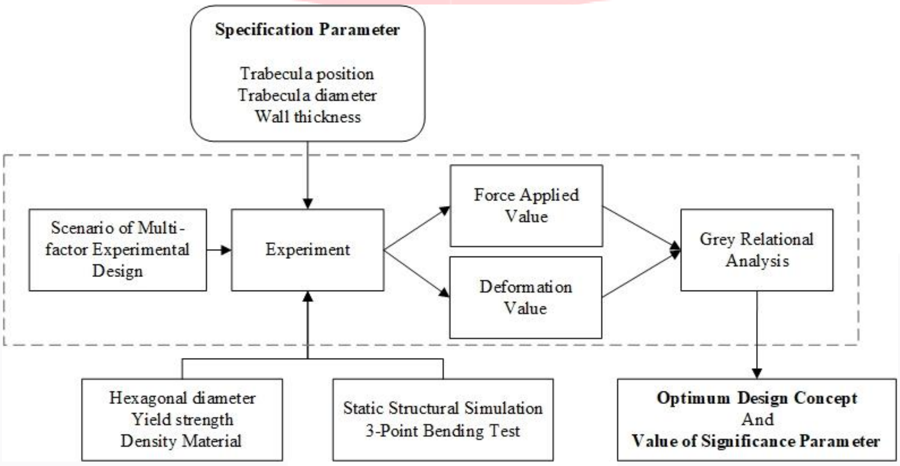
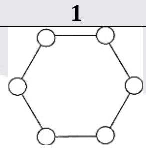
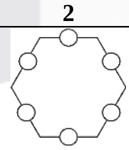


Figure 1 Model of Conceptual Study

2.2 Static Structural Simulation

The multi-factor experimental design method has 2 stages of the process that must be passed, namely the finite element method and statistical tests. The finite element method is done using simulations that are tailored to the needs of the BFS structural design and adjust to the ASTM D 790-17 as a standard test for bending test. And in this study what is needed is an analysis of the BFS structural design. In figure 2 can be seen the steps or the simulation workmanship scheme. The purpose of structural analysis can be seen from a theoretical perspective and also a practice perspective. From a theoretical point of view, the main objectives of structural analysis are the value of deformation and applied force. In practice, this analysis is used to reveal the structural behavior of the design in the arcing test. While in the sense of structural analysis is a study consisting of several mechanical theories that obey the laws of physics needed to predict the behavior of design structures. To do the simulation, a 3D model is needed that has been made based on predetermined design parameters. In table 1 it can be seen that the parameters of trabeculae diameter, wall thickness, and trabeculae position respectively have 3, 3, and 2 level levels, respectively.

Table 1 Factor and Level Selection.

No.	Factor	Level		
		1	2	3
1	Trabeculae Position	 Hexagonal Elbow	 Hexagonal Side	-
2	Trabeculae Diameter	0.5 mm	0.6 mm	0.7 mm
3	Wall thickness	0.2 mm	0.3 mm	0.4 mm

Once the 3D model is created, the next step is to determine the load value to be applied to the specimen. Afterward, the simulation of bending is set to run the simulation of the static structural. This simulation will yield output in the form of values of deformation and the amount of force received as shown in figure 2.

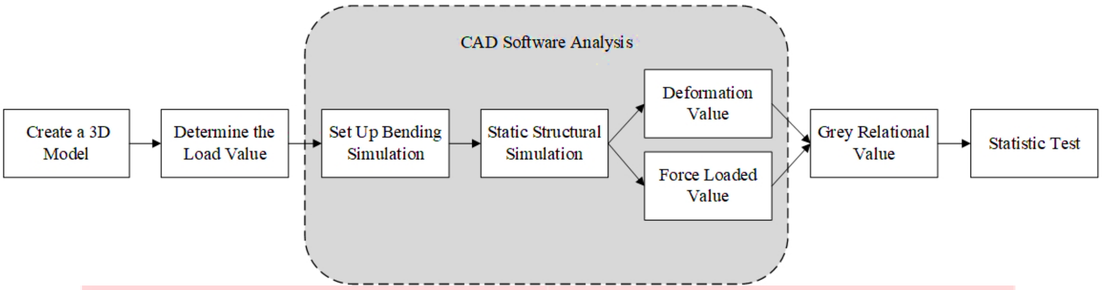


Figure 2 Step by Step of the Simulation

Structural simulations are performed to see how the BFS structure, when applied to the maximum strain value of 0.05 mm / mm, is behaving towards deformation. The maximum stress value is a standard stipulation that is used to determine the maximum load limit which the BFS structure can accept. In order to determine the behave of the BFS structure to the given load, the limit load will be tested to the heaviest structure assuming the strongest structure is. The test is performed on the BFS3-3 Side structure with a load value of 4500 N because it is heavier than the other structures which are 8,235 gr. After checking the study termination value is reached which is illustrated in figure 5 below.

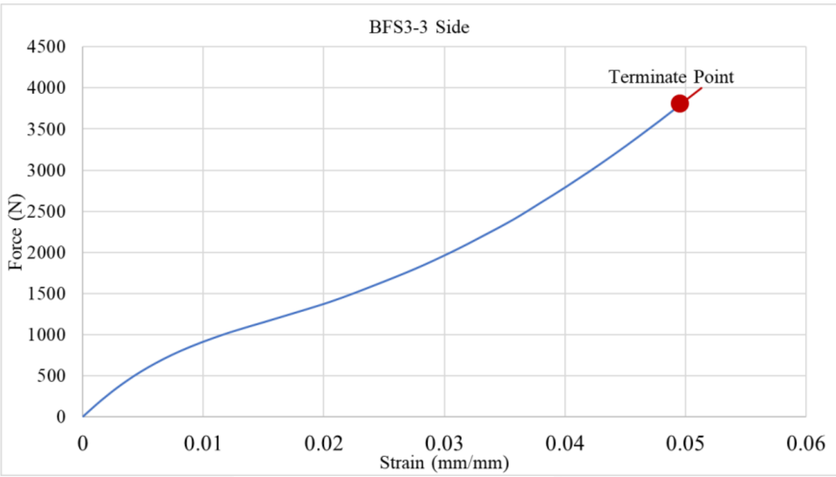


Figure 1 Bending Test of BFS3-3 Side Structure

The structure meets the standard requirements for termination testing in experiments on the BFS3-3 Side structure, provided that the outer surface strain value reaches 0,05 mm / mm. When this value is reached, at a given load of 3800 N, the terminate point can be determined. It can be assumed that the load that can be given to all BFS structures must exceed 3800 N, so that a load of 4000 N for each BFS structure tested can be found at the end point when the stress requirements are met. In addition, the table below will explain for the simulation set up.

2.3 Grey Relational Analysis

Grey Relational Analysis (GRA) is a theory in which the quantity of data used is relatively small and has no strict ties to specific statistical legislation. This analysis is often used to optimize the parameters or conditions of a system with multiple performance properties [8]. The next step will be to do the gray relational analysis (GRA) after the deformation and applied force values are obtained. This step is done because there is more than one output or dependent variable to be analyzed and has a different quality value (multiple quality requests). The dependent variable at issue, in this case, is the value of deformation and the force applied to the structure of the BFS. The final output of this analysis is to get one variable dependent value.

2.4 Statistic Test

After performing a simulation that produces an output deformation value and applied force, the data will then be processed statistically to see if the parameters of the trabeculae diameter, wall thickness, and trabeculae position influence the structure 's behavior when receiving loads. But to find out which statistical tests are suitable for use, the normality of the data needs to be tested first. You can see the statistical test machining scheme in figure 6. The

Kruskal-Wallis test may be used for abnormally distributed data. The Kruskal-Wallis test has the same working principle as the ANOVA one way but without regard to the normality of data. Thus, the meaning value of the resulting parameter is an independent value between the independent variables, without any interaction between those variables. The level of confidence used was 95 percent and α = 0.05

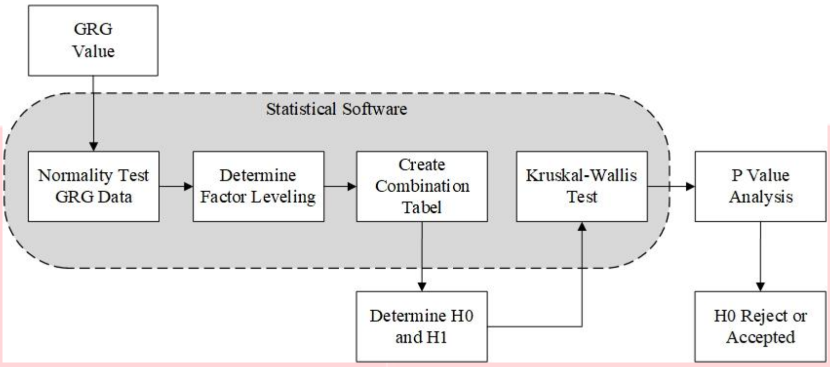


Figure 2 Statistical Test Scheme

3. RESULT AND DISCUSSION

3.1 Bending Setup

In this study, the designed Beetle forewing sandwich structure will look for values of deformation, and how much load it may receive before it breaks or reaches its maximum strain value. In this stage, the standard test procedures from ASTM D 790—17 need to be adjusted to enable the proper and measured curvature test to be carried out. There are several things that have to be determined as follows through this standard.

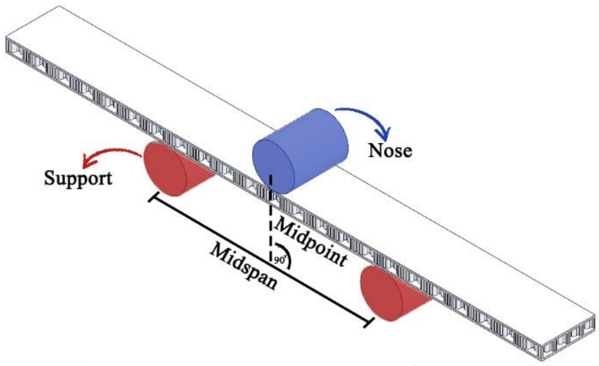


Figure 3 Specimen Setup with ASTM D 790—17

Based of figure 7, the midspan length is a measure of the distance between two supports to the specimen's midpoint which is parallel to the specimen 's direction before the midspan length test must be determined. The gap to the specimen is measured in a 16:1 ratio. The midspan value used in the test was 51.2 mm which is the ratio between 16:1 and the specimen thickness. Next, support = nose size and use a 5 mm radius for this test because the structure thickness doesn't exceed 3.2 mm. Specimens established in accordance with the ASTM D 790—17 standards will then be given axial load perpendicular to the specimen and at the midpoint shown in Figure 7. The loading at this stage is aimed at seeing if the behavior of the measured framework to tolerate the curvature induced by the force added to the nose and the pseudo-point of the two supports. After the rupture, the test will end or reach the maximum strain value determined by this standard which is 0.05 mm/mm.

3.2 Static Structural Simulation

After creating a 3D model according to the standard ASTM D 790-17 and specifications of the design parameters, it is necessary to determine every combination that will be used as simulation input that can be seen in Table 2 and also set up the simulation which can be seen in Table 3. For all specimen the load value will be applied is 4000 N

Table 2 Combination of Each Factor and Level

Specimen	Trabeculae Position	Trabeculae Diameter (mm)	Wall Thickness (mm)
BFS1-1	Hexagonal Elbow	0.5	0.2
BFS1-2	Hexagonal Elbow	0.5	0.3
BFS1-3	Hexagonal Elbow	0.5	0.4
BFS2-1	Hexagonal Elbow	0.6	0.2
BFS2-2	Hexagonal Elbow	0.6	0.3
BFS2-3	Hexagonal Elbow	0.6	0.4
BFS3-1	Hexagonal Elbow	0.7	0.2
BFS3-2	Hexagonal Elbow	0.7	0.3
BFS3-3	Hexagonal Elbow	0.7	0.4
BFS1-1 Side	Hexagonal Side	0.5	0.2
BFS1-2 Side	Hexagonal Side	0.5	0.3
BFS1-3 Side	Hexagonal Side	0.5	0.4
BFS2-1 Side	Hexagonal Side	0.6	0.2
BFS2-2 Side	Hexagonal Side	0.6	0.3
BFS2-3 Side	Hexagonal Side	0.6	0.4
BFS3-1 Side	Hexagonal Side	0.7	0.2
BFS3-2 Side	Hexagonal Side	0.7	0.3
BFS3-3 Side	Hexagonal Side	0.7	0.4

The static structural simulation set up to be conducted will obey the steps described in Table 3. Where the information to be included in the study in the section on engineering details, simulation feedback, meshing settings, and research settings need to be defined to get the wanted value in the section on a solution. The setup is essential to be able doing static structural simulation due to the complex core structure of Beetle Forewing Sandwich Structrue.

Table 3 Simulation Setup

<table>
<tr><th>No</th><th colspan="2">Display</th><th>Description</th></tr>
<tr><td>1</td><td colspan="2">Engineering Data</td><td>Select and enter material properties for the four materials specified in the design parameters, namely Aluminum 6061 Alloy (UNS A96061)</td></tr>
<tr><td>2</td><td colspan="2">Geometry</td><td>Insert 3D models that have been created using CAD software.</td></tr>
<tr><td rowspan="5">3</td><td rowspan="5">Model</td><td>Mesh</td><td>Meshing by arranging the mesh that will be applied to the geometry. The accuracy of the use of mesh is the initial foundation of engineering simulation. Set the size fucntion: Adaptive, set the mesh control: Fine, and set the element size: 0.4 mm</td></tr>
<tr><td>Analysis Settings</td><td>Determine the steps to be taken during the simulation in the step controls section and adjust the solver controls. Set the initial step: 20, set the minimum step: 20, and set the maximum step: 100</td></tr>
<tr><td>Fixed Support</td><td>Determine and select two straight lines from the geometry that serves as fixed support. the location shown in the figure 7.</td></tr>
<tr><td>Force</td><td>Set the load value (Force) given to the geometry with a load centred on a line found on the surface of the upper layer across the centre of the specimen shown on figure 7. the load given is 4000 N.</td></tr>
<tr><td>Solution</td><td>Determine what outputs you want to know and analyse after the input settings above, such as total deformation, Maximum Principal Stress, and Reaction Force.</td></tr>
</table>

4	Setup	This section will be automatically done when running simulation and all the set-up needs are met.
5	Solution	This section will be automatically done. Consists of the setup of solutions carried out at the model stage.
6	Results	Shows the final results of the analysis and report preview of the simulation carried out.

3.3 Grey Relational Analysis

After the deformation and applied force values are obtained, the next step is to do the gray relational analysis (GRA). This step is done because the output or the dependent variable to be analyzed consists of more than one and has a different quality value (multiple quality requests). In this case, the dependent variable in question is the deformation value and the force applied to the BFS structure. The final output of this analysis is to get one dependent variable value. After setting up the simulation, it can run and find desired value from the output following deformation value and applied force. The results of this deformation can be seen in Table 4. From the results of this simulation, it was found that the BFS3-1 structural design concept is a combination of the third diameter trabeculae, the first wall thickness, and the first trabeculae position is the most optimal structural design concept because it has a GRG value the largest shown in the calculation is ranked 1 with grade 1. Grade 0.904 means the value of the reference sequence and comparability sequence is identical. Following this result showing that trabeculae position [9] affecting the behaviour of BFS structure under bending test

Table 4 Combination Level Factor and GRG Value

Specimen	GRG	Specimen	GRG	Specimen	GRG
BFS1-1	0.762	BFS3-1	0.904	BFS2-1 Side	0.396
BFS1-2	0.682	BFS3-2	0.820	BFS2-2 Side	0.413
BFS1-3	0.594	BFS3-3	0.609	BFS2-3 Side	0.437
BFS2-1	0.520	BFS1-1 Side	0.397	BFS3-1 Side	0.321
BFS2-2	0.412	BFS1-2 Side	0.546	BFS3-2 Side	0.415
BFS2-3	0.599	BFS1-3 Side	0.433	BFS3-3 Side	0.442

3.4 Statistic Test

In the normality test, it is known that the data is not normally distributed. So, the next rarity is to do a non-parametric test, the Kruskal-Wallis test. Before entering the Kruskal-Wallis test stage, assumptions regarding H_0 and H_1 must be determined. This assumption will use a confidence level of 95% so that the value of $\alpha = 0.05$.

H_0 : These three factors do not have a significant effect on the BFS structure behavior under bending test.

H_1 : There is at least one factor that significantly influences to the BFS structure behaviour under bending test.

Critical Area : H_0 rejected if $P\text{-}Value \leq \alpha$, where $\alpha = 0.05$.

Table 5 shows the significant value of the independent variable trabecula diameter factor to the dependent variable or parameter of the GRG value with a P-Value = 0.372. So, it is known that the P-Value form factor 0.372> α 0.05. And based on the average value of the diameter trabecula ranking which has the smallest median value is the trabecula with a diameter of 0.6 mm

Table 5 Kruskal-Wallis Test of Trabecula Diameter Factor

Trabeculae Diameter (mm)	N	Median	Mean Rank	Z-Value
0.5	6	0.5698	10.7	0.66
0.6	6	0.4241	7.0	-1.40
0.7	6	0.5255	10.8	0.75
Overall	18		9.5	

H = 1.98 DF = 2 *P* = 0.372

Table 6 Kruskal-Wallis Test of Wall Thickness Factor

Trabeculae Diameter (mm)	N	Median	Mean Rank	Z-Value

0.2	6	0.4582	8..3	-0.66
0.3	6	0.4801	9.7	0.09
0.4	6	0.5181	10.5	0.56
Overall	18		9.5	

H = 0.50 DF = 2 P = 0.778

Table 6 shows the significant value of the independent variable trabecula diameter factor to the dependent variable or parameter of the GRG value with a P-Value = 0.372. So, it is known that the P-Value form factor 0.372> α 0.05. And based on the average value of the diameter trabecula ranking which has the smallest median value is the trabecula with a diameter of 0.6 mm

Table 7 shows the significant value of the independent variable wall thickness factor to the dependent variable or parameter of the GRG value with a P-Value = 0.778. So, it is known that the P-Value form factor 0.778> α 0.05. And based on the average value of the diameter trabecula ranking which has the smallest median value is the wall with a thickness of 0.2 mm.

Table 7 Kruskal-Wallis Test of Trabecula Position

Trabeculae Diameter (mm)	N	Median	Mean Rank	Z-Value
Hexagonal Elbow	9	0.6090	13.2	2.96
Hexagonal Side	9	0.4146	5.8	-2.96
Overall	18		9.5	

H = 8.75 DF = 1 P = 0.003

Based on the results of the Kruskal-Wallis test it is known that the trabecula position factor has a statistically significant effect on the design outcome with a P-value off 0.003 < α 0.05. Thus, it can be concluded that the assumption of H0 is rejected There is at least one factor that significantly influences the BFS structure behaviour under the bending test.

3.5 Selected Design and Significant Parameter

In the aim of this study, we also developed a honeycomb sandwich structure that had already existed by applying the trabecula structure of the beetle found in the forewing section. As stated from a researc [6] which is very good for the survival and survival of beets. The structure helps the beetle survive when hit or fall from a branch which explains that the structure of the trabecula is good at absorbing the forces and stresses that occur on structures that apply the trabecula. The BFS3-1 structural design concept is the 7th design concept chosen based on the results of the static structural simulation. This concept has the smallest deformation value compared to 17 other structural design concepts. At the time of simulation and set-up simulation, the amount of load given is 4000 N, assuming that the structure can be stronger than the heaviest structure. If depicted in graphical form as shown as figure 8, the deformation and force applied in accordance with the standard provisions that 0.05 mm/mm are terminate points will be in the following form.

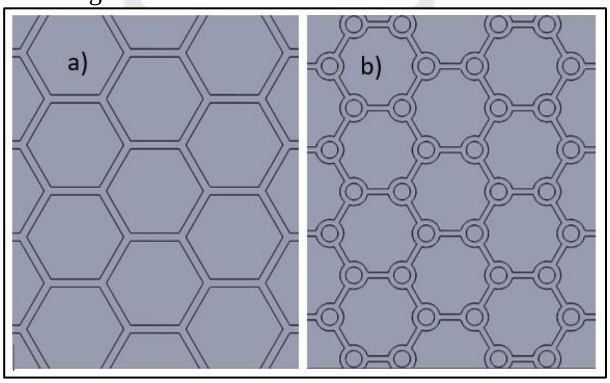


Figure 4 Comparison of The Core Sandwich Structure; a) Honeycomb Sandwich Structure, and b) Beetle Forewing Sandwich Structure with Trabecula

This behavior also occurred in this study where the normal honeycomb sandwich structure (HS) without trabecula was compared with the beetle forewing sandwich structure (BFS) with trabecula at the same wall thickness level. However, for the HS structure added by 40% of the total thickness, based on [10] this was done to replace the absence of trabecula in the HS structure by increasing the thickness so that they could be comparable in weight to the two structures.

There are several things that are compared related to the differences between the two structures, the first is the weight. For the weight of the selected BFS3-1 structure is 5,533 gr while the HS-1 structure is 5,131 gr, there is an increase in BFS3-1 weight of 7% from HS-1. Both of these structures were simulated with the same static structural simulation and setup including the same load received by both structures of 4000 N.

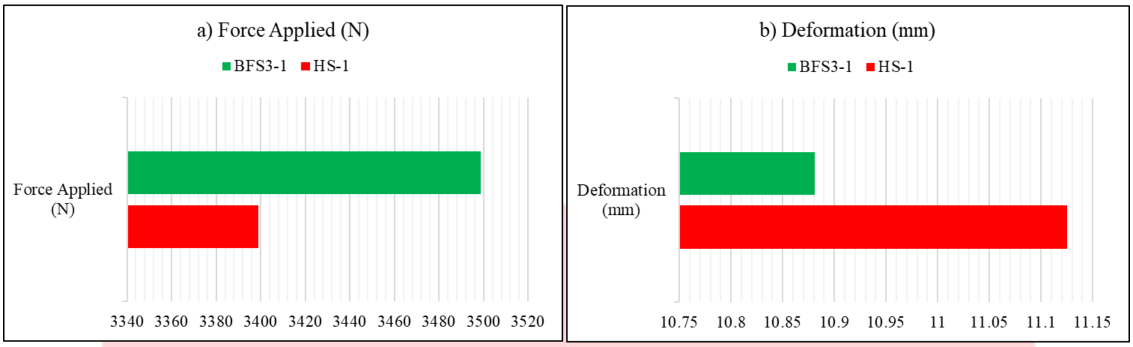


Figure 5 Comparison Value Between BFS3-1 With HS-1; a) Comparison of Force Applied Value, and b) Comparison of Deformation Value

Next is the behavior of the two structures for a given load, in figure 9 the results shown in the simulation are the HS-1 behavior for the given load until it reaches the terminate point. Behavior that occurs in the first HS-1 is at a deformation value of 11,125 mm with an applied force of 3399.1 N. Whereas in BFS3-1 behavior when given a load of deformation occurs with a value of 10.88 mm with an applied force of 3498.9 N. Can be concluded that the behavior the BFS3-1 structure is better than the HS-1 structure. For deformation because the smaller the better there is an increase of 2% of the BFS3-1 structure to the HS-1 structure. Whereas the applied force because the greater the better, there was an increase of 3% of the BFS3-1 structure with trabecula to the HS-1 structure without trabecula. In this case, it can be seen that trabecula give different behavior of the two structures to the acceptance of the load in the bending test conducted.

4. CONCLUSION

In this study, the process of analyzing the effect of trabeculae diameter, wall thickness, and trabeculae position parameters to improve the behavior of beetle forewing sandwich structures by the load given to the deformation value and applied force made from Aluminum 6061 Alloy (UNS A96061). Thus, the combination of structural design parameters that can optimize the behavior of BFS structures against deformation and applied force values based on simulations that have been done are 0.7 mm diameter trabeculae, 0.2 mm wall thickness and trabeculae position on hexagonal elbow. This combination of machining parameters produces a GRG value of 0.904 meaning the value of the reference sequence and comparability sequence is identical. In brief, the Kruskal-Wallis test conducted, significant parameters of BFS behavior towards deformation and applied force values are trabeculae position. For the wall thickness and trabeculae parameters the diameter is not significant so it requires in-depth analysis to make these two parameters significant.

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