

STRENGTH ENHANCEMENT OF HELICOIDAL COMPOSITE STRUCTURE USING FULL-FACTORIAL COMBINATIONS

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Abstract

Structural development of composite structure has evolved toward mimicking the natural-proven composite structures. This approach is part of the biomimicry discipline, where biological structures are incorporated with engineering design to obtain remarkable design performances. The helicoidal composite structure is a proven practice of applying the fundamentals of biomimicry. The present study investigates the strength enhancement of the helicoidal composite structure as the combined effect of its design parameters (i.e., number of layers, layer thickness, and fiber orientation). The design combinations were derived using the full-factorial method, and the ultimate tensile strength of the structures was simulated by ABAQUS. The best design combinations obtained from this study were exhibited by the structure with six layers of 0.75 mm thick CFRP and using 0/30/60/90 fiber orientation. The analysis also suggests that fiber orientation was the most significant design parameter to influence the strength. Eventually, this study provides applicative information on biomimicry designs and approaches to solve industrial design challenges.

Keywords: Composite material, Helicoidal structure, Full-factorial, Ultimate Tensile Strength, ANOVA

1. INTRODUCTION

One of the most critical requirements for materials used in advanced industries are high strength and lightweight, and for that reason, composite materials were used since it provided a highly attractive combination of stiffness, toughness with lightweight and corrosion resistance properties [6]. With these properties, composite materials are currently being used in various fields such as aircraft, automotive, mechanical, construction, and biomedical. Meanwhile, in the aviation industry itself, composite materials having major roles to establish an aircraft since their large percentage of usage in an aeroplane. Furthermore, research and development about composite material were having a significant transformation in the recent years since the implementation of Biomimicry on it [8][2][4]. Overall, the implementations of nature-inspired innovation in composite material were so diverse. The diversity came from different sources of inspiration, scope of development, and application. From those areas, one of the natural structures to be build along with these composite materials is Helicoidal Structure, a strength and stiff natural structure. The characteristics of helicoidal structure in supporting the function of composite material has been recorded, since it shows that despite of the given significant forces on several tests, the structure is fracture resistant by prevent the development of cracks and able to tolerate thousands of such blows [10]. The reason behind that behaviour is because of the rotated architecture which limits the cracks propagation so that it has a great ability to absorb the given energy [7][1].

As a structure with unique characteristic, Helicoidal structure affected by several factors, and one of the most important part is the structure design parameter. Structure design parameter is an aspect on the specific part of a structure that will have an impact on how the structure's shape and performance. Usually, structure design parameter used as an experiment's setting to find the wanted responses during a study, since it has measurable scale which relatively easier to arrange. On helicoidal structure, there are three design parameter that have been recorded, which are layer thickness, number of layers, and fiber orientation [5]. The combinations between all those 3 will determine how the helicoidal structure will shape and perform during the implementation in composite material. It was proven by several studies and researches which explain that there is a significant change of response from the helicoidal structure on composite material by modifying those design parameters [11][3][9].

However, those studies about helicoidal structure design parameters only focusing on a specific design parameter. Since it is not clear whether the development of these configurations is related to the performance of the helicoidal structure as a whole or not in order to optimize the structure performance. Also, those researches have not determined yet which design factors are significant for a specific response. Meanwhile, each design parameter has its specific measurable role against the structure's response of any given force. Finally, to optimize

the helicoidal structure performance, this study aims to find out the best arrangement of helicoidal structure design parameters and levels on a specific response, then determine the significant parameter of helicoidal structure against the output. Furthermore, the usage of composite material in many different fields will not only establish a better material structure, but also other advantages such as work quality and safety enhancement. For instance, the implementation in aircraft production can be optimized using composite material to reduce the weight and increase the quality of flight safety all at once.

2. RESEARCH METHODOLOGY

2.1 Conceptual Method

The conceptual model framework used to solve the problems that arise in this study as described in Figure 6.

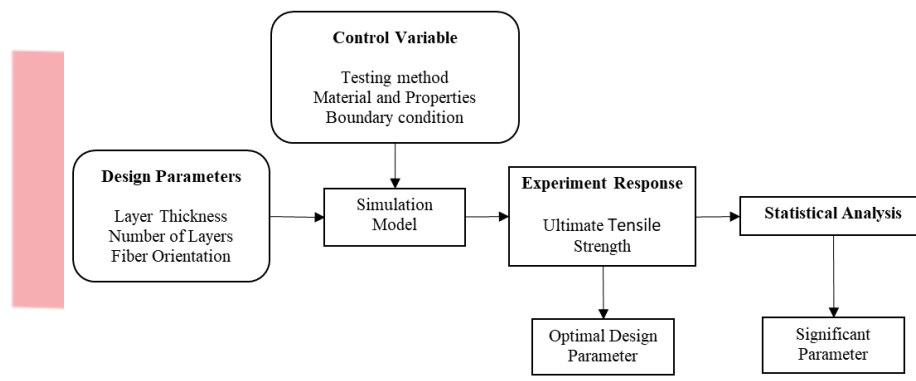


Figure 1. Conceptual Model

Figure 1 shows the conceptual method used during the working of the final project. In general, this project consists of design parameters, control variables, simulation model, experiment response, and statistical analysis, which produced the optimal design parameter and significant parameter. The full factorial design method has been selected since this experiment has three independent factors within two different levels of each, consist of two levels of layer thickness, two levels of the number of layers, and two levels of fiber orientation. Those values of independent factors and levels were chosen based on the previous kinds of literature about helicoidal structure design parameters.

According to the DOE which being used, the full factorial technique was selected and created a complete combination indicated eight experiments in total. Afterward, the experiments were done according to the combinations between factors and levels using Abaqus 19 software by considering the control variables too. Finally, the responses taken from the experiment in terms of the Ultimate Tensile Strength value will be evaluated by using the statistical variance analysis (ANOVA). So, the significant and effective value of layer thickness, number of layers, and fiber orientation factor will be determined.

2.2 Factor and Level Combination

There are three parameters that constructing helicoidal structure both in design and performance, which are showed on the Figure 2 below.

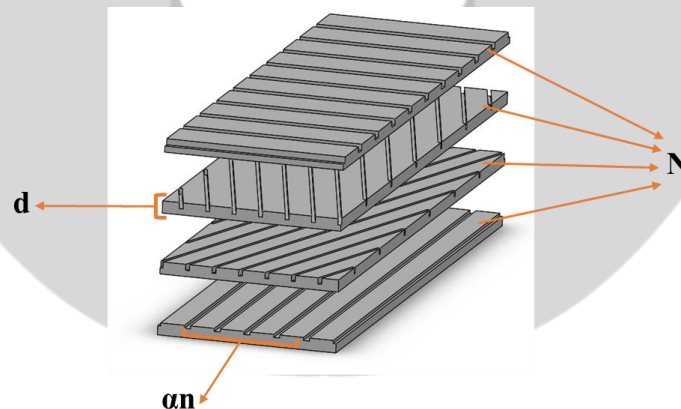


Figure 2. Helicoidal Structure Design Parameters consist of number of layers (N), layer thickness (d), and fiber orientation (α_n)

Furthermore, in order to find specific levels from each parameter, Abaqus software used to run initial experiments, which resulted in stated chosen parameters and levels in Table 1 below. In addition, the factor and level chosen are directly proportional to the outcome of the simulation. The more factor and level the experiment discussed, the more accurate the study results will be.

Table 1. Factor and Level Identification

Parameter	Description	Level	
		1	2
A	Number of Layers	4	6
B	Layer Thickness	0.5	0.75
C	Fiber Orientation	0/ 45/ -45/ 90	0/ 30/ 60/ 90

Upon defining the factor and level, the full-factorial method was applied to achieve optimal results, the process begins by using Minitab statistical software to evaluate the orthogonal range. The orthogonal range is using a combination of identified factors and levels that can be seen in Table 2 below. The result of the Minitab software is the L6 notation (2^3), which means that the experiments performed are 8 times with 3 factors and each factor has 2 different levels.

Table 2. Factorial Design Table Matrix

Experiment	A	B	C
1	4	0.5	[0/45/-45/90]
2	4	0.5	[0/30/60/90]
3	4	0.75	[0/45/-45/90]
4	4	0.75	[0/30/60/90]
5	6	0.5	[0/45/-45/90]
6	6	0.5	[0/30/60/90]
7	6	0.75	[0/45/-45/90]
8	6	0.75	[0/30/60/90]

2.3 Specimen and Simulation Setup

Process of specimen design considered several specifications which already gathered from the standard of ASTM D3039. Figure 3 illustrates one of the composite specimens and the helicoidal structure used during the simulation. In terms of size, the specimens have 250 mm height and 25 mm width, while the thicknesses were varied ranging from 2 – 4.5 mm depending on the input parameter. Besides, the helicoidal structure's arrangements which established the specimen were also diverse depending on the parameter. However, to create a clear representation of the helicoidal structure, the writer stated the insert Figure of helicoidal structure in the Figure 3. Furthermore, the material applied in those specimens during the simulations were CFRP (Carbon Fiber Reinforced Prepreg).

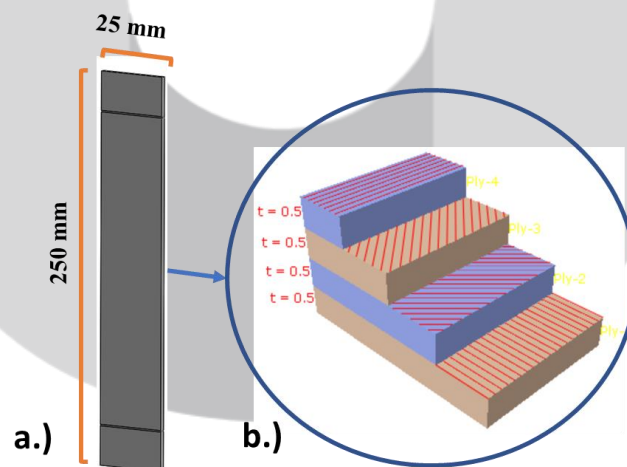


Figure 3. Specimen Design a.) Specimen Dimension b.) Specimen Structure Arrangement

The material used during the simulation was CFRP (Carbon Fiber Reinforced Prepreg) with the material properties in Table 3. Overall, those material properties consisting of Elastic properties, Hashin damage for Composite, Damage evolution for Composite, and Damage stabilization for Composite.

Table 3. CFRP Material Properties

Properties	Notation	Value	Units
Young Modulus	E1	54000	Mpa
	E2	26000	Mpa
Poison's Ratio	Nu12	0.3	-
Shear Modulus	G12	4800	Mpa
	G13	4800	Mpa
	G23	4500	Mpa
Longitudinal Tensile Strength	Xt1	700	Mpa
Longitudinal Compressive Strength	Xc1	320	Mpa
Transverse Tensile Strength	Xt2	33	Mpa
Transverse Compressive Strength	Xc2	131	Mpa
Longitudinal Shear Strength	Xs1	29	Mpa
Transverse Shear Strength	Xs2	29	Mpa
Longitudinal Tensile Fracture Energy	-	91.6	-
Longitudinal Compress Fracture Energy	-	79.9	-
Transverse Tensile Fracture Energy	-	0.22	-
Transverse Compress Fracture Energy	-	1.1	-
Viscosity Coefficient	-	0.005	-

After designing the specimen, the process continued to implement the tensile test setting in Abaqus Software. In order to simulate the Tensile test, the specimens divided into three areas which can be seen in Figure 4. That figure illustrates the top area (indicated by A), bottom area (indicated by B), and a middle area, where both A and B regions gripped using the crosshead. In addition, both A and B areas were having 50 mm length which was enough to avoid slippage between the crosshead and the specimen, then leaving the middle area of 150 mm. as the test area to measure the response of the specimen.

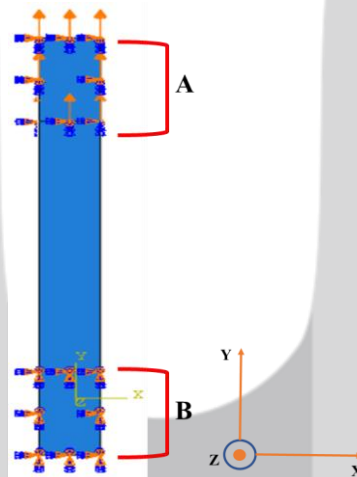


Figure 4. Tensile Test Setting on Specimen shows (A) as displacement region, while (B) as fixed region

In order to set a correct simulation of ASTM D3039, several arrangements on the specimen have been done. Fixed support was implemented to the B area as support using the boundary conditions (BCs) $U1=U2=U3=0$ and $UR1=UR2=UR3=0$ so that there will be any displacement and rotation. Meanwhile, the A area has a displacement on Y-axis but does not has any rotational movement, so that the BCs setting was $U1=U2=UR1=UR2=UR3=0$. During the simulation, the upper crosshead dragging the A area in a specific load into the Y-axis direction, while the lowers crosshead holding the B area so that it steady still, which will create a stretch force mechanism into the specimen. The process of simulation runnings was totally done by the software. The Abaqus simulated the whole phases from the first specimen's condition until it breaks as the final condition.

In addition, to finish the simulation process, the time needed was varies depending on the specimen complexity from all the specimens. In total, there are 8 number of simulations were run during the data collection phase which were according to the factorial design table in the previous step. In addition, each of the experiment was in the form of CAE simulation which resulted in various responses depend on the factor and level arrangement. Furthermore, the ABAQUS software produced information in the form of a Stress-Strain Curve after the data extraction step to get a readable result. From that point, the force magnitude in the peak point of the stress-strain curve determined as the ultimate tensile strength of a specific simulation.

As the last step, the analysis was carried out for the results of the simulation process using Abaqus in the form of CAE analysis, stress-strain curve, and ultimate tensile strength comparison between all specimens in order to get the first study objective. Furthermore, some statistical analysis was performed from the ultimate tensile strength values. Those were processed using ANOVA analysis in order to define the second study objective. Finally, in order to create a clear answer from the objectives of the study, conclusions were generated by summarize the analysis and discussion in the end of the study.

3. RESULT AND DISCUSSION

3.1 Simulation Results

After finishing the simulation process, the data extraction phase can be started by choosing a specific node on the specimen, then continued to compare the stress and strain from the specimen during the simulation. Furthermore, the stress-strain curve was used to define the performance of a specimen during the simulation process, which elaborates the whole condition of used specimens starting from the initial condition until the rupture point. In addition, the ultimate tensile strength can be indicated by the highest point of the curve before it drastically decreases.

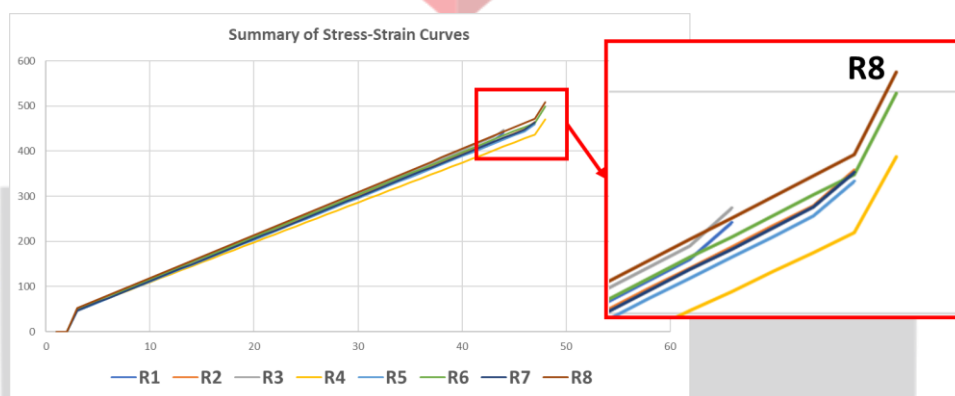


Figure 5. Comparison of Stress-Strain Curves shows R8 has the highest ultimate tensile strength

Figure 5 shows the comparison of all stress-strain curve from eight different simulations. From that figure, clear comparison from all specimen's performance can be done before determining which specimen has the best performance in the form of ultimate tensile strength. Since ultimate tensile strength is the highest point of the stress-strain curve, then the comparison area can be focused on the highest point of those graphs. It can be seen that from the graph comparison of R1, R2, R3, R4, R5, R6, R7, and R8 by them each distinctive colour, R8 indicated by brown line gained the highest peak point, followed by the R6 indicated by the green line in the second place, while R1 has the lowest UTS with its dark blue colour. Furthermore, to get a better comparison of UTS, a quantitative number is needed, so that the stress-strain curve needs to be extracted in the form of a specific value of UTS.

Table 4. Simulation Responses

Simulation	Input Parameter			Ultimate Tensile Strength (Mpa)
	N	d	αn	
1	4	0.5	0/45/-45/90	440.92
2	4	0.5	0/30/60/90	464.69
3	4	0.75	0/45/-45/90	447.54
4	4	0.75	0/30/60/90	470.76

5	6	0.5	0/45/-45/90	459.64
6	6	0.5	0/30/60/90	499.01
7	6	0.75	0/45/-45/90	463.77
8	6	0.75	0/30/60/90	508.42

The given Table 4 displays the ultimate tensile strength responses from each simulation measured in Mega Pascal (Mpa). In general, the values of the ultimate tensile strength were varied from 440.92 Mpa as the lowest UTS, to 508.42 Mpa as the highest UTS. The lowest ultimate tensile strength response was gotten from the simulation 1 which was needed 440.92 Mpa to break the specimen. Meanwhile, experiment 8 has the highest ultimate tensile strength response, since the force needed to create a fracture in the specimen was 508.42 Mpa. In sequence, the level of UTS from the highest to the lowest is R8, R6, R4, R2, R7, R5, R3, and R1, so that this result validates the conclusion in the stress-strain analysis since it has the same results. Furthermore, from those experiments, the specimen on experiment 8 has the strongest tensile behaviour due to its helicoidal structure arrangement in the form of consisting of 6 layers, with 0.75 mm thickness from each layer, and having [0/30/60/90] fibre orientation. Meanwhile, the specimen on experiment 1 has the weakest structure arrangement against a tensile force. In addition, the first objective of this study has been achieved from that conclusion, so that a further study in the form of data processing using the statistical method is needed to get the second objective.

3.2 Statistical Analysis

ANOVA (Analysis of Variance) method used to determine the factors that significantly influence the resulting UTS (Ultimate Tensile Strength) value. Before calculating the ANOVA, the normality test was carried out first on the UTS value as the resulting response, due to finding out what kind of statistical test to calculate the level of significance. This normality test was carried out using Anderson-Darling test. In this test, the following hypotheses were used:

- H0: The data is normally distributed
- H1: The data is not normally distributed
- Critical Area: H0 rejected if P-Value $\leq \alpha$, where α used is 0,05

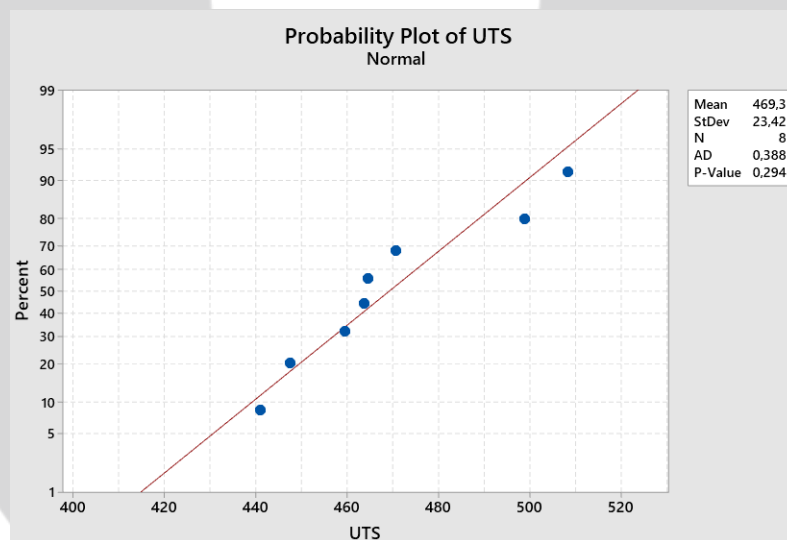


Figure 6. Normality Test Output informs that the data distribution is normal

Based on the results of the normality test using the Anderson-Darling on Figure 6, it found that the p-value was 0.294. Since the p-value is larger than 0.05, as the basis for decision making in the normality test, it can be concluded that the Ultimate Strength Response data is normally distributed. Furthermore, due to the normally distributed data, the process continued to the next phase of the parametric test.

After it is known that the data obtained is normally distributed, the significance level is calculated using the ANOVA Parametric test. This test aims to determine whether a factor has a significant effect on the UTS score or not. In ANOVA Parametric testing, the following hypothesis was used:

- H0: Parameter give significant difference to experiment response
- H1: Parameter does not give significant difference to experiment response
- Critical Area: H1 rejected if P-Value $\leq \alpha$, where α used is 0.01

Table 5. ANOVA Test Results

Parameter	F-Value	P-Value	Description
Number of Layers	32.03	0.005	Significant
Layer Thickness	1.93	0.237	Less Significant
Fibre Orientation	48.08	0.002	Significant

Based on the results of the two-way ANOVA test in Table 5, it is known that two of the three helicoidal structure design parameters (i.e., Number of Layers and Fibre Orientation) examined in this study have a significant effect on the ultimate tensile strength value since both have P-Value which was lower than 0.01. Furthermore, to find out the level of significance of the effect, it can be seen through the F-Value of each factor. With provisions, the greater the resulting F-Value, the greater the effect it will have on the output. The table shows that the F-Value of the Fiber orientation factor has the highest value. Besides, the F-Value of the Number of layers factor has a higher value than the F-Value of the Layer thickness. In conclusion, to increase the Ultimate Tensile Strength value of the helicoidal structure design, changes on Fiber orientation parameters should be prioritized, then continued to the Number of layers and the last parameter is the Layer thickness. Besides, since there are two significant parameters (Number of Layers, Fiber Orientation), then these two parameters were needed to be further tested using the Post-hoc Test, however since there are only two levels from each of them, then Post-hoc test is not necessary to do.

Furthermore, Main Effect Plot analysis were performed on all parameters either significant or not to give a general visualization of the parameters significance. This visualization is required to verify the analysis of simulation results in stress-strain curve with statistical numbers produced. Therefore, by plotting the means for each meaning of the categorical levels, Minitab 19 produces the main effects plot. To compare the relative intensity of the impacts of different parameters, one can use this plot since this main effect's plot will tell us the following: (1) the effect's direction, that is, if the average response value increases or decreases. (2) The magnitude informs us about the effect's strength.

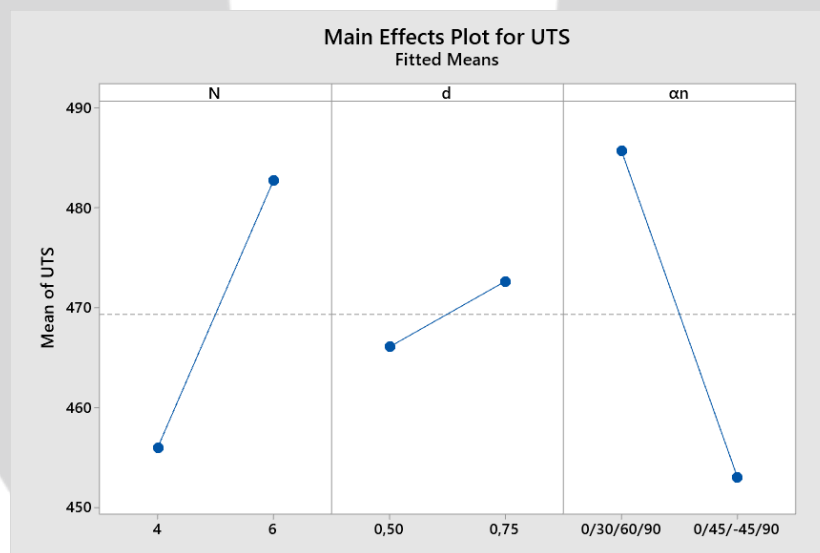


Figure 7. Main Effect Plot graphics show that both N and αn have significant effect on UTS

According to the graph on Figure 7, the number of layers is a statistically significant parameter in this main effect plot for ultimate tensile strength, approved by the ANOVA test results. Furthermore, 6 number of layers tend to correlate with the highest mean of ultimate tensile strength. Afterwards, the fibre orientation also has a significant effect on the ultimate tensile strength with its drastic trend changes, which also approved in the ANOVA result before. Meanwhile, the [0/30/60/90] fibre arrangement correlate with the highest mean of ultimate tensile strength compared with another fibre arrangement. In addition, it is unnecessary to prioritize the layer

thickness arrangement, since the effect is not statistically significant to the structure strength, according to the ANOVA and Main Effect Plot findings.

4. CONCLUSION

Based on the results of the studies that have been conducted, the following conclusions are obtained. The best design configuration obtained from this study was exhibited by the structure with 6 layers of 0.75 mm thick CFRP and using 0/30/60/90 fibre orientation. In addition, to increase the strength of a helicoidal structure in terms of its resistance against tensile forces, more layers are required to establish the structure to distribute the received energy. Also, it requires a smaller fibre orientation arrangement, as well as a thicker layer for each arrangement, since a smaller arrangement of fibre orientation will create better resistance to fracture damage. Furthermore, the most significant factor in influencing the ultimate tensile strength is the fibre orientation, then continued by the number of layers, and the least significant parameter between those three parameters is the layer thickness. Furthermore, since layer thickness is not a significant parameter, hence it is necessary to prioritize other parameters (Number of layers and Fibre Orientation) in further studies and improvements.

BIBLIOGRAPHY:

- [1] Apichattrabrut, T., & Ravi-Chandar, K. (2006). Helicoidal composites. *Mechanics of Advanced Materials and Structures*, 13(1), 61–76. <https://doi.org/10.1080/15376490500343808>
- [2] Dai, D., & Fan, M. (2013). Wood fibres as reinforcements in natural fibre composites: Structure, properties, processing and applications. In *Natural Fibre Composites: Materials, Processes and Applications*. <https://doi.org/10.1533/9780857099228.1.3>
- [3] Ginzburg, D., Pinto, F., Iervolino, O., & Meo, M. (2017). Damage tolerance of bio-inspired helicoidal composites under low velocity impact. *Composite Structures*, 161, 187–203. <https://doi.org/10.1016/j.compstruct.2016.10.097>
- [4] Gohal, H., Kumar, V., & Jena, H. (2020). Materials Today : Proceedings Study of natural fibre composite material and its hybridization techniques. *Materials Today: Proceedings*, (xxxx). <https://doi.org/10.1016/j.matpr.2020.02.277>
- [5] Guarín-Zapata, N., Gomez, J., Yaraghi, N., Kisailus, D., & Zavattieri, P. D. (2015). Shear wave filtering in naturally-occurring Bouligand structures. *Acta Biomaterialia*, 23, 11–20. <https://doi.org/10.1016/j.actbio.2015.04.039>
- [6] Hale, D. K. (1976). The physical properties of composite materials. *Journal of Materials Science*, 11(11), 2105–2141. <https://doi.org/10.1007/PL00020339>
- [7] Jiang, H., Ren, Y., Liu, Z., Zhang, S., & Lin, Z. (2019). Low-velocity impact resistance behaviors of bio-inspired helicoidal composite laminates with non-linear rotation angle based layups. *Composite Structures*, 214(1), 463–475. <https://doi.org/10.1016/j.compstruct.2019.02.034>
- [8] Li, S. H., Zeng, Q. Y., Xiao, Y. L., Fu, S. Y., & Zhou, B. L. (1995). Biomimicry of bamboo bast fiber with engineering composite materials. *Materials Science and Engineering C*, 3(2), 125–130. [https://doi.org/10.1016/0928-4931\(95\)00115-8](https://doi.org/10.1016/0928-4931(95)00115-8)
- [9] Liu, J. L., Lee, H. P., Kong, S. H. R., & Tan, V. B. C. (2019). Improving laminates through non-uniform inter-ply angles. *Composites Part A: Applied Science and Manufacturing*, 127(September), 105625. <https://doi.org/10.1016/j.compositesa.2019.105625>
- [10] Patek, S. N., & Caldwell, R. L. (2005). Extreme impact and cavitation forces of a biological hammer: Strike forces of the peacock mantis shrimp *Odontodactylus scyllarus*. *Journal of Experimental Biology*, 208(19), 3655–3664. <https://doi.org/10.1242/jeb.01831>
- [11] Shang, J. S., Ngern, N. H. H., & Tan, V. B. C. (2016). Crustacean-inspired helicoidal laminates. *Composites Science and Technology*, 128, 222–232. <https://doi.org/10.1016/j.compscitech.2016.04.007>