

BIONIC DESIGN FOR A SLOTTING MACHINE COLUMN STRUCTURE BASED ON LEAF VEINS

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Abstract

Structural bionic design process is basically done for optimization of mechanical structures. It has been discovered, that over the years some biological structures, such as leaf veins, bamboo and animal bones, have excellent mechanical properties. By studying and mimicking the distribution characteristics of these biological structures, the performances of mechanical components can be improved using structural bionic design method. In this work, the internal stiffening ribs of a slotting machine tool column are rearranged based on the structure of leaf veins, and a bionic column is designed. Static analysis of the conventional and bionic column is conducted to investigate the static performances by finite element method (FEM). The simulation results have that, with the conventional column, the maximum displacement of the bionic column is reduced by 10.11% and the mass by 4.62%.

Keywords: Leaf Veins, Finite Element Method, Static Performance, Slotting machine, Machine Tool, Structural Bionic Design, Stiffening Ribs.

INTRODUCTION

Machining is a process in which a material (often metal) is cut to a desired final shape and size by a controlled material-removal process. (Massachusetts Institute of Technology, 2016). There are three principal machining processes i.e. as turning, milling and drilling. Other operations fall into miscellaneous categories which includes shaping, planning, boring, broaching, and sawing (Kalpakian and Schmid, 2008). These machining processes are the fundamental manufacturing techniques and are expected to remain so for the next few decades (Cheng, 2009). Machine tools are power driven metal cutting/forming equipment that cuts, shears, punches, etc., that are used to alter a workpiece and size either cutting away the unwanted sections; pressing, drawing, punching, or shearing; or controlled electrical machinery process. Material selection, design analysis are key to achieve high precision machining operation. These factors greatly influenced any machine tool configuration design, and they are evaluated at the early stage of the design phase because the structural design of mechanical components has great impact on the machining performance (Liang *et al.*, 2014).

As the development of high-speed machining operation improves, the demand for machine tool components with light weight and high stiffness is increases (Wang *et al.*, 2015). For most of the existing machine tool components, the stiffening ribs are uniformly distributed but however, the loads and constraints on the components are usually not uniformly distributed. Therefore, the conventional types of stiffening ribs are not a very efficient way to enhance the stiffness and strength of machine tools. (Lui and Hollaway, 2000). In recent years, it has been discovered that creatures have biological structure with good mechanical properties after evolution of eons, which provides a lot of design prototypes and improvement methods for humans to solve the structural optimization design problem in mechanical engineering field (Lu, 2004). Structural bionic design method is applied to this design so as to improve the performance of the machine structure, (Ren, 2009).

After several billion years of evolution, it has been demystified that the structures of organism in nature have excellent properties and ingenious frames, which provide a large number of innovative prototypes and creative approaches for solving engineering problems and improving design methods. Structural bionic has become a

new method for mechanical design, which has made great progress in intelligent robots, aircrafts, watercrafts, Micro Air Vehicle (MAV), bionic bulldozer blades and other structural design fields (Chen *et al.*, 2008; Ren and Liang, 2010).

The slotting machine as shown in Figure 1, is a reciprocating machine tool similar to a shaper or a planer in which, the ram holding the tool reciprocates in a vertical axis and the cutting action of the tool is only during the downwards stroke. The slotter has a hand or power operated rotary table.

The slotting machine is used for cutting grooves, keys and slots of various shapes making regular and irregular surfaces both internal and external cutting internal and external gears and profiles. The slotter machine can be used on any type of work where vertical tool movement is considered essential and advantageous, and machining of shapes which are difficult to produce on shaper or planer machine.

REVIEW OF RELATED LITERATURES ON STRUCTURAL BIONICS DESIGN

The biological structures with excellent mechanical properties, includes leaf veins, bamboo, animal bones, honey comb, tree root system, spider webs, ant colony, and so many others. The field of structural bionics recognizes these biological organisms have evolved efficient and optimized structural solutions over millions of years of evolution, and by studying and understanding these natural systems, engineers and designers can adapt and apply principles to human-made structures, resulting in improved performance, durability, sustainability, efficiency, durability, and functionality. The biological structures with excellent mechanical properties have been investigated in many studies and with the presence of CAD/CAM technology, it has made it possible to design and manufacture some more difficult structures for the mechanical components. The Finite Element Analysis (FEA) is popular and widely used for machine tools simulation (Zach and Hennauer, 2011).



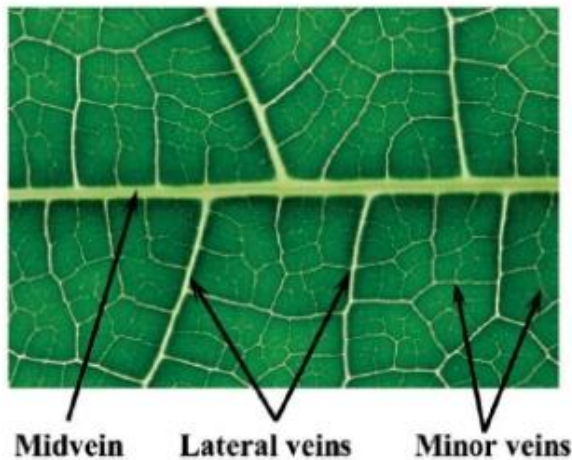
Figure 1: Samples Design of Bimimicry

In Twu and Yu (2015), conducted a structural optimization for a column part of a gantry grinding machine tool using Response Surface Method (RSM). The objective of the investigation was to minimize the volume of machine tool structure while subjected to the constraints of the y-axis displacement of the spindle tip and the second natural frequency. The result of the investigation resulted in 13.3% reduction in volume of the structure, while the y-axis displacement and second natural frequency were confined to given scopes. It was concluded that the RSM used as meta model was successful for modelling structural static and dynamic analysis results for structural optimization.

Sujeet (2014) selected a lathe machine bed from Indira Machine Tools Limited for static analysis. And mimicked the excellent structural principles of a bamboo and redesigned the bed for better load-bearing capacity. In the work, investigations were carried out to reduce the weight of the machine bed, thereby, reduce the stress induced in the lathe bed and to reduce the displacement for three materials: cast iron, steel, and Aluminium. It was concluded, from results obtained from the research that the weight optimization of the lathe machine bed has been achieved (approximately 15%) for all the three materials, hence reducing the cost of manufacturing.



Figure 2: Biological Structures of Bulrush

Figure 3: Netted venation of the leaf.
and Bamboo

A bionic column was designed by re-arranging the internal stiffening ribs based on the structure of leaf vein by Hanjun, *et al.* (2017) in order to improve the mechanical performances of the machine tool column. Static and modal analysis of the conventional and bionic column was conducted to investigate the static and dynamic characteristics using FEM software. And it was found that both the static and dynamic performances of the machine tool column were improved using structural bionic design method. Compared with the conventional column, the maximum deformation of the bionic column in experiment was reduced by 24.69%.

Wang *et al.* (2022) reported on the development of the fuzzy logic-based bionic optimization design of boring machine column which has the capacity to develop new mechanical structures, shapes, and sizes that are based on the principles described for the bionic structures. The link between the back and belly armour in the turtle shell was discovered to have structure comparable to the stiffener. As a result, a virtual

model of the connecting structure was created in order to thoroughly examine its materials, properties, and functions. A number of qualitative and quantitative analysis were performed using computer, current technology, mathematics, and geometry. It was concluded that the column and the turtle shell have a similarity of 0.796, indicating that bionic optimization of the column was possible. The maximum deformation was found to be 15.7% lower than that of the original column, and the maximum stress value is 21.8% lower than that of the original column.

The structural bionic method is also employed to improve the mechanical properties of machine tool components. Shihao *et al.* (2010) conducted the bionic design for the traditional stiffener plate's arrangement of a gantry machining centre's column by using structural bionic method, whose inspiration came from the plant root system structure. The configuration principles of a typical plant root system structure were applied to design the stiffener plate of the column, and the effect on structural lightweight and anti-vibration performance improving were verified by FEM. The light-weight design was improved and in conclusion, the bionic design principles of stiffener plates were summarized as follows: in order to transfer load effectively, the main stiffener plate should be arranged along the gradient direction between support area and maximum deformation area.

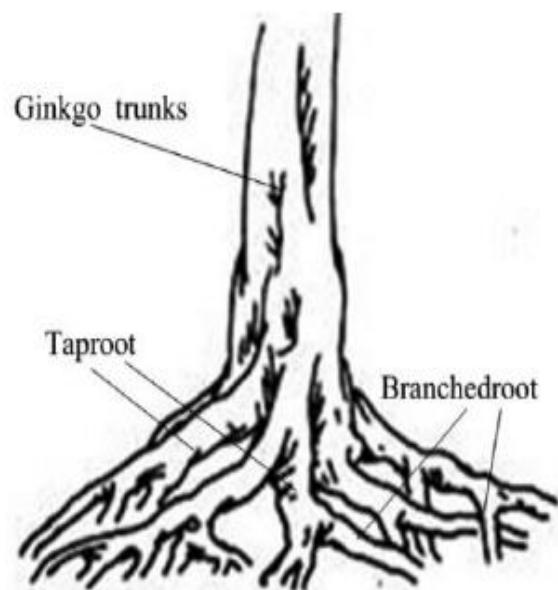


Figure 4: Ginkgo root system structure

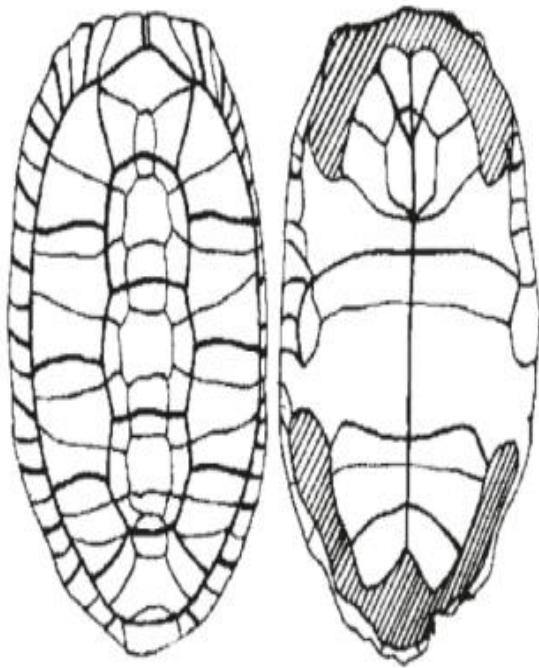


Figure 5: Horizontal Section of Turtle shell

To carry out the structural bionics, we must first select the imitated animal or plant objects, then analyse and study them according to a specific animal or plant selected, extract some features that need to be used, and combine the machinery to be optimized, so as to optimize the performance of the specified machinery. Based on the above design methods of machine tool structure, this paper conducted the bionic design for the conventional internal stiffener ribs arrangement for the column of a slotting machine, whose inspiration came from the leaf vein system structure. The configuration principles of a typical leaf vein system structure were applied to design the stiffening ribs of the column, and the effect on structural light-weight were verified by FEM using SolidWorks.

3.0 MATERIALS AND METHODS

3.1 Material Selection

The commonly used materials for machine tool structure are cast iron and steel. While in recent times, granite and epoxy concrete are also developed and used for structures. The cast iron (SN) will be used in this study. Its properties are given in Table 1. From early times cast iron has been the most commonly used material for machine tool structures. It may be cast into complex and intricate shapes. It is easily machined and may be hand-scraped and lapped to a high degree of accuracy. It has fairly good damping properties and also has reasonably good

antifriction properties helped by the graphite contained in it. It can be given very good long-term dimensional stability by giving it a special long cycle stress relief annealing treatment. Cast iron should be preferred for complex structures subjected to normal loading, when these structures are to be made large in numbers.

Table 1: Some properties of Cast Iron

Mod ulus of Elasti city N/m m ²	Spec ific grav ity	Spec ific stiff ness N/m m ²	Coeffi cient of therm al expan sion °C ⁻¹	Therm al conduc tivity Wm ⁻¹ K ⁻¹	Tens ile stren gth N/m m ²
1170 00	7.21	1600 0	12 x 10-6	75	230

3.2 Structural Analysis on Characteristics of the Bionics Prototype

In nature, the materials of most existing biological structures are arranged so well that they can own a high strength or stiffness body with light weight (Roth-Nebelsick *et al.*, 2001). For instance, nature is able to operate bone at a stress which is about 17 times greater than the stress at which it could be used in an engineering component (Taylor, 2011). Engineers can draw lessons from the biological structures to improve their designs.

The structure of leaf veins has aroused widespread interests of researchers. The venation can be parallel, netted, etc. The netted structure shown in Figure 5, which exhibits a hierarchical structure, with large primary veins (mid vein) branching into secondary veins (lateral veins), which further branch into tertiary veins (tiny veins), will be considered in this work. A close observation will show that the midvein is the main support of the leaf. It mainly plays the role of maintaining global stiffness of the blade. The lateral veins can strengthen the local stiffness of the leaf. The tiny veins link between the main vein and the lateral veins ensures the overall stiffness of the leaf. The structure of the connection mainly plays the role of support and connection.

The leaf vein possesses excellent structural properties such as light-weight, scalability, strength and flexibility.

3.3 Design Method

Based on successful bionic designs, the method of structural bionic design was summarized in Figure 8.

The design process is divided into three stages.

I. Requirement Identification:

The natural structural characteristics of plants and animals gives design engineers inspiration because of the strength and performance. These structures are been mimicked in the design of structures. When the bionic requirements are identified, analogous structures must be selected for function and structure design analysis. This study focuses on improving the column weight and stiffness performance of slotting machine by mimicking leaf vein system.

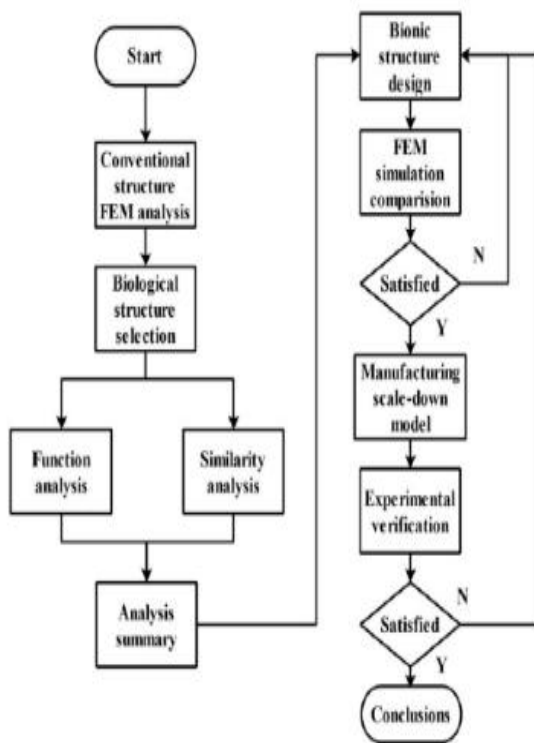


Figure 6: Flow chart of Structural Bionic Design Process.

II. FEM Analysis

FEM modeling of the structures are used to verify the effectiveness of structures been copied. If the results are not satisfied, new biological structures must be used.

The static and dynamic stiffness are usually presented by the minimum static deformation of the structure, (Wu, *et al.*, 2012). The FE models of the conventional and bionic column presented in Figures 9 and 15, which were established using SolidWorks 2020 to perform the static analysis.

The modeling were conducted using the following steps:

- I. Sketch the 3D model.
- II. Material property specification
- III. Mesh size determination
- IV. Apply constraints
- V. Run simulation
- VI. Results visualization

Four representative load positions are defined according to the distribution of the stiffening ribs. For each load position, 25N, 50N, 75N, and 100N forces are applied, respectively.

III. Experiments Verification

The internal stiffening ribs are arranged according to Figure 9 and 15. And static analysis subsequently conducted. The mass of the conventional column is 439.64 kg, and that of the bionic column is 419.32 kg. Compared with conventional one, the mass of the bionic column is reduced by 4.62%. If the simulation results are satisfied, bionic models should be fabricated for structural experiments. After the bionic effectiveness is validated, those biological structures can be used for practical application. Otherwise, another design procedure should be carried out, until the most reasonable structure is found. And bionic principles can be concluded.

4.0 THE CAD MODELING AND ANALYSIS PROCEDURE

4.1 Design of the Conventional Machine Tool Column Structure

Figure 7, presented CAD model of the column of the slotting machine tool, which is fixed at the base, and its carries the weight of the other components attached to it. The stiffness of the column as obvious influence on the global stiffness of the machine tool. The internal stiffening ribs of the column are the conventional type, which consists of vertical and horizontal ribs as shown in the Figure 7.

Before redesigning, the existing machine tool column is created by part modelling and static

analysis investigated. The major dimensions are given in the drawing shown in Figure 8.

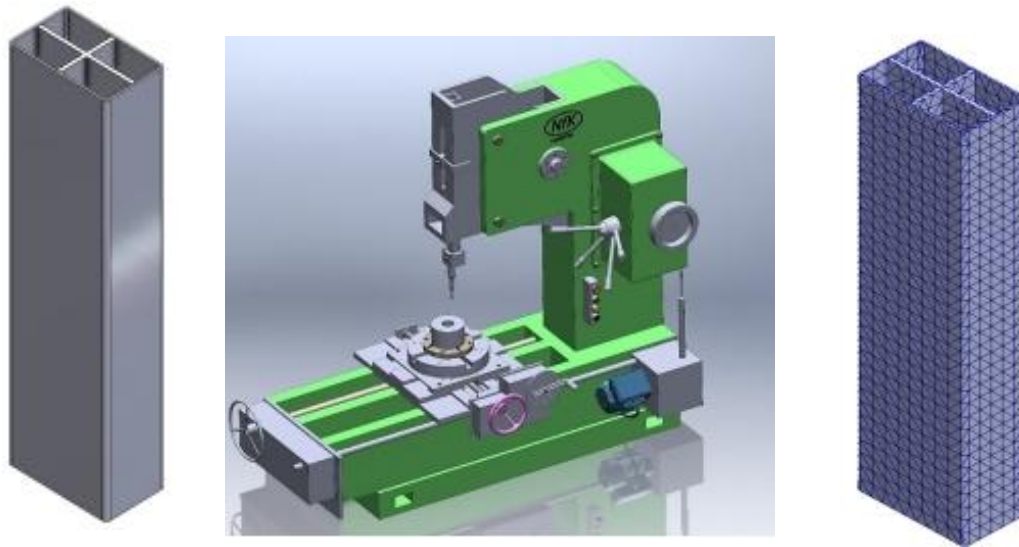


Figure 7: (From Left to Right) 3-D model of slotting machine, the conventional column, the mesh, and stiffening plate structure of conventional column

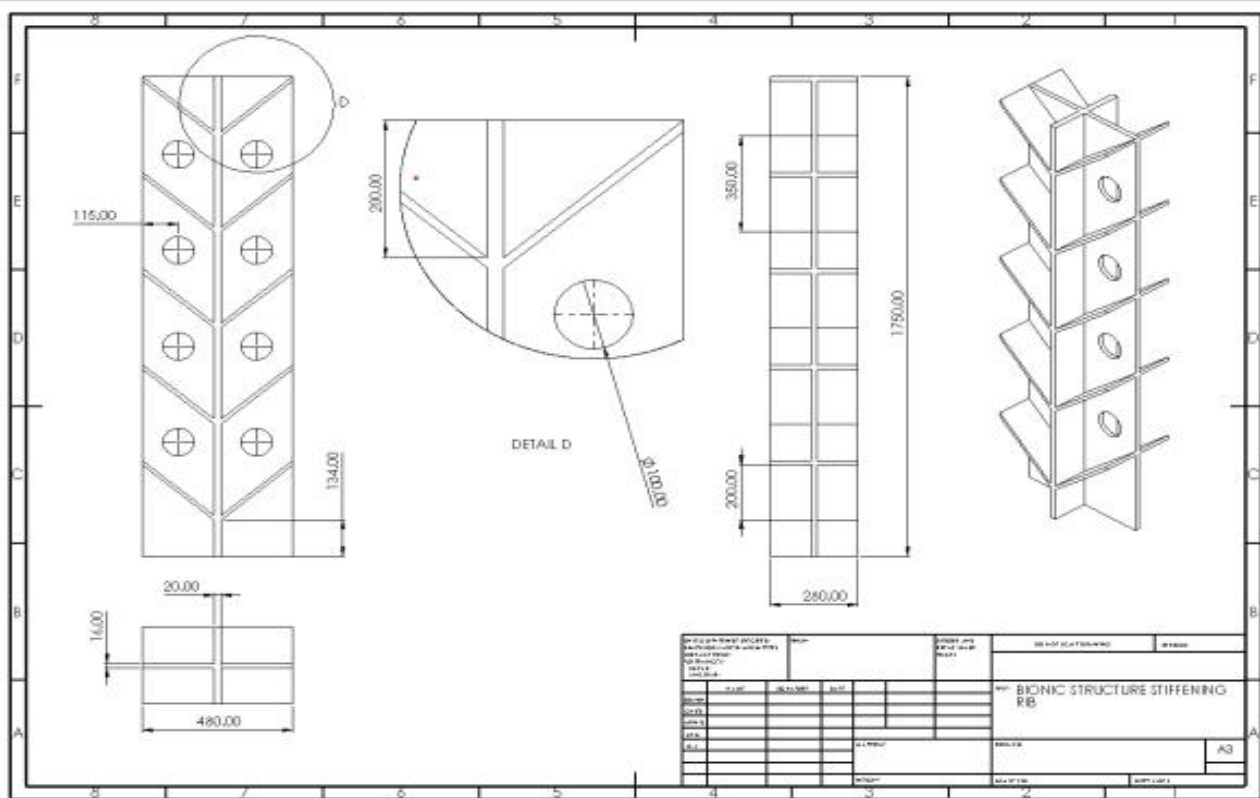


Figure 8: Bionic Column Stiffening Ribs Dimensions



Figure 9 Conventional Column Major

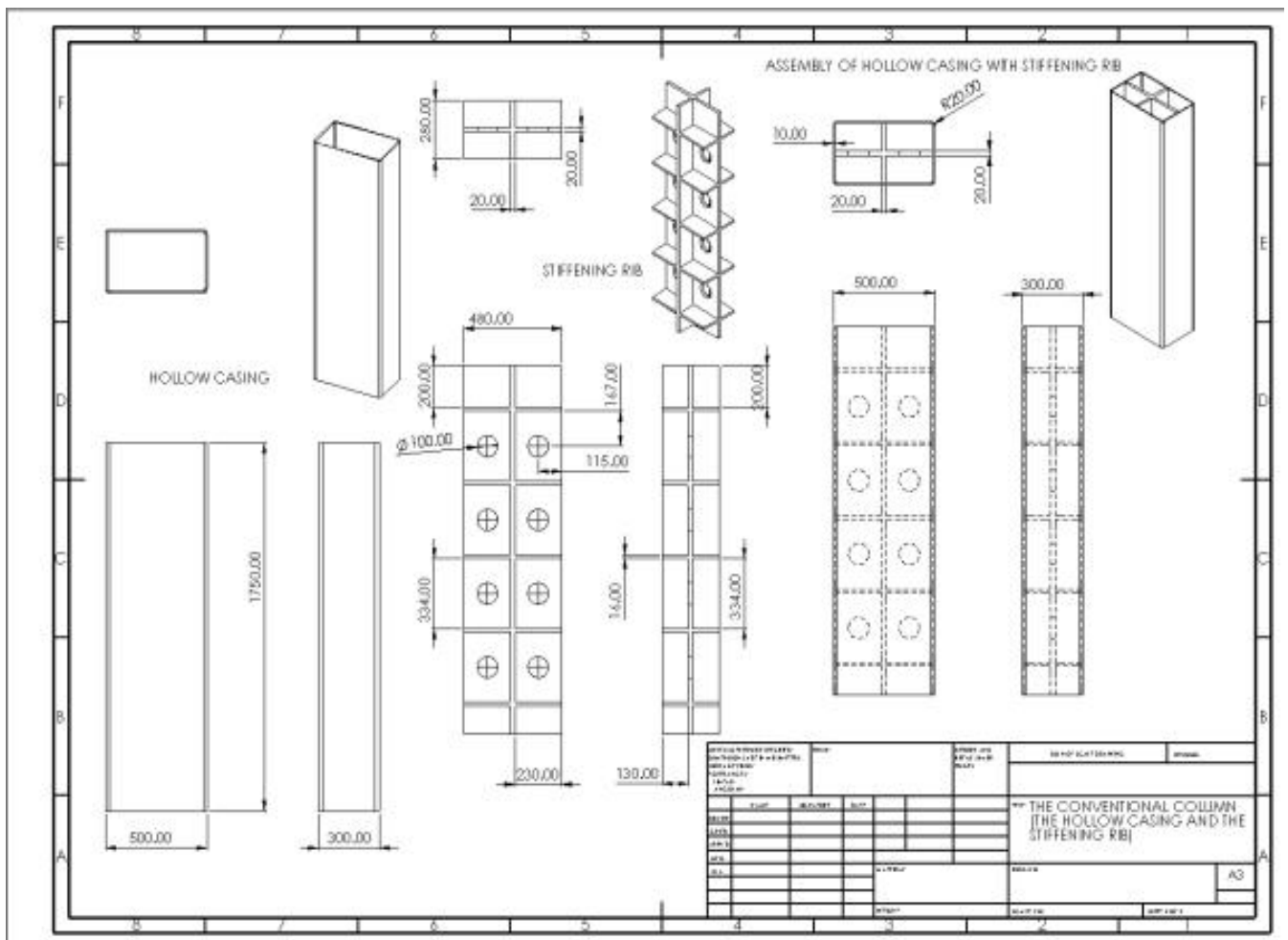


Figure 10: Bionic Static Stiffening Dimensions

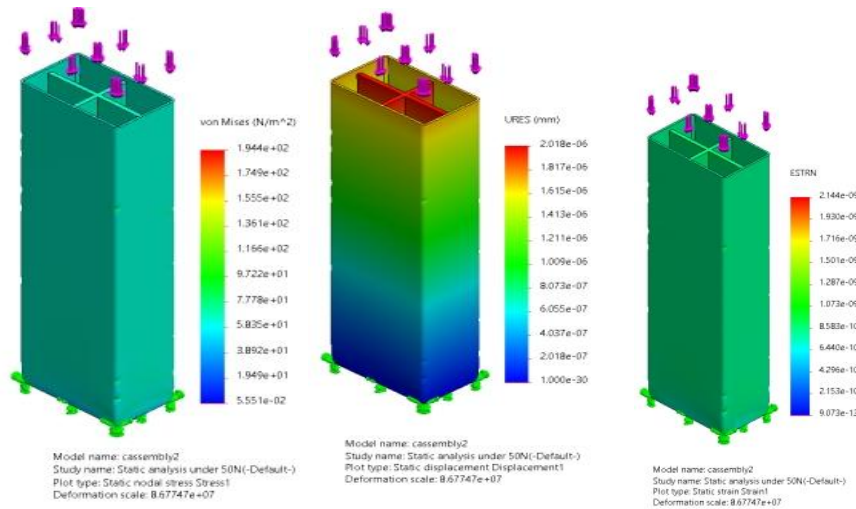


Figure 11: FEM static analysis results under 50N Dimensions

4.2 Bionic Design of Machine Tool Column Structure.

On basis of similarity principle and netted venation system distribution principles of a leaf, bionic design for conventional stiffener plate arrangement is conducted, and the result shown in Figure 9.

4.3 RESULTS AND DISCUSSION

The results of the analysis conducted on the conventional structure and the modified structure using CAD software are presented as follows.

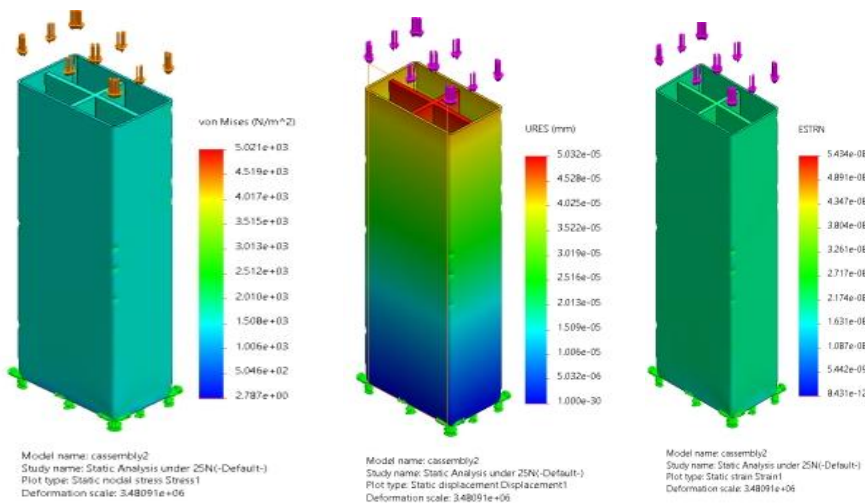


Figure 12: FEM static analysis results under 25N load

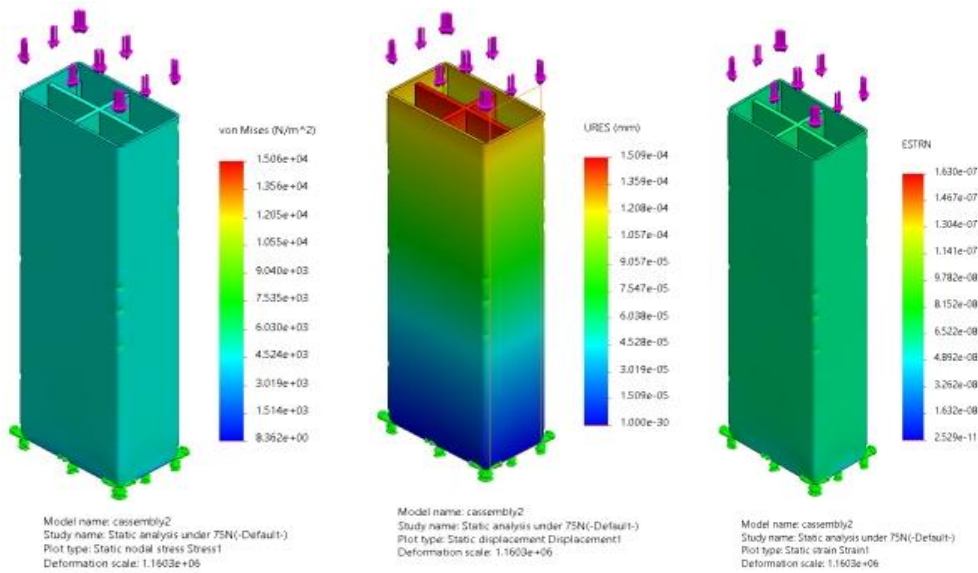


Figure 13: FEM static analysis results under 75N load

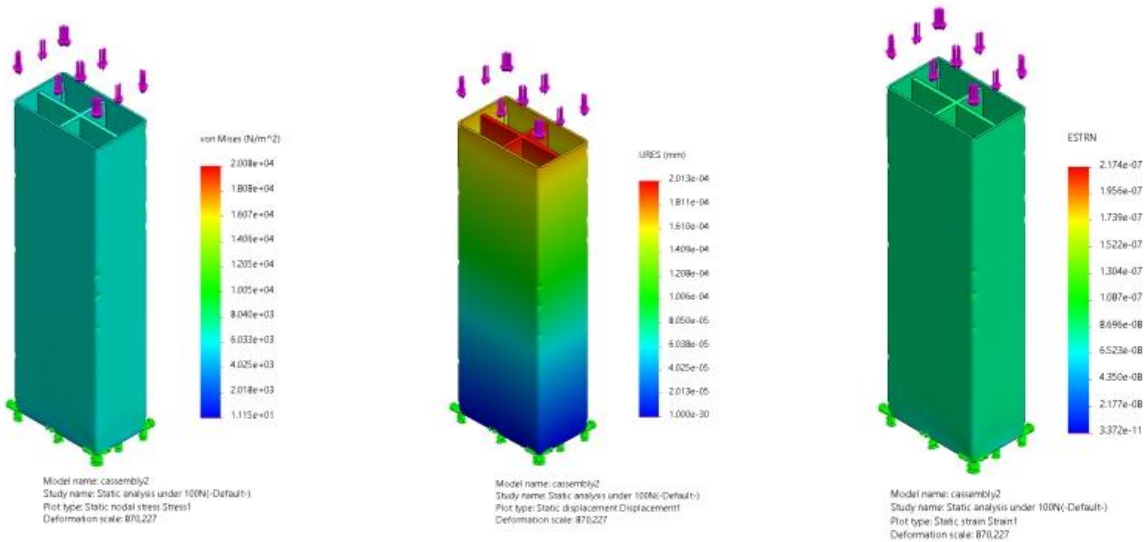


Figure 14: FEM static analysis results under 100N.

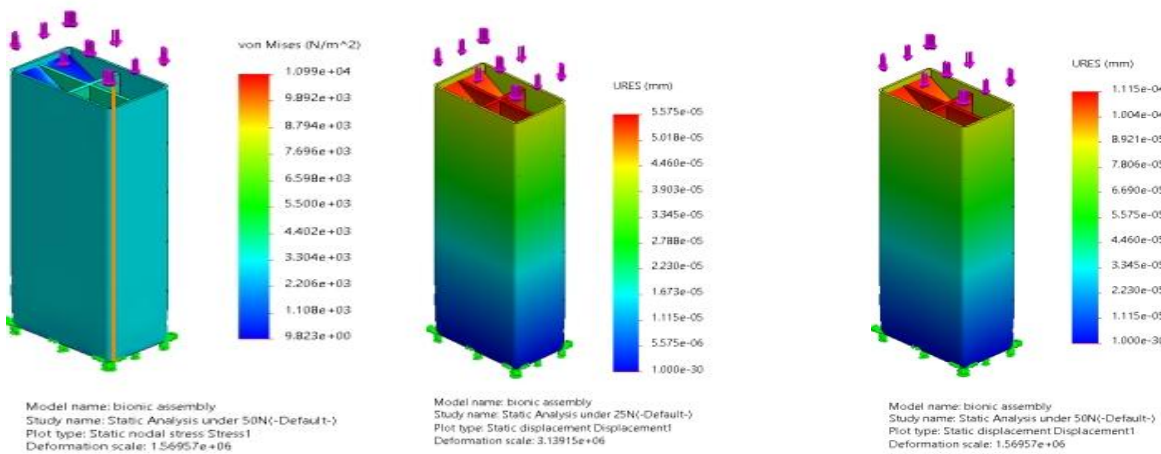


Figure 15: FEM static analysis under 25N

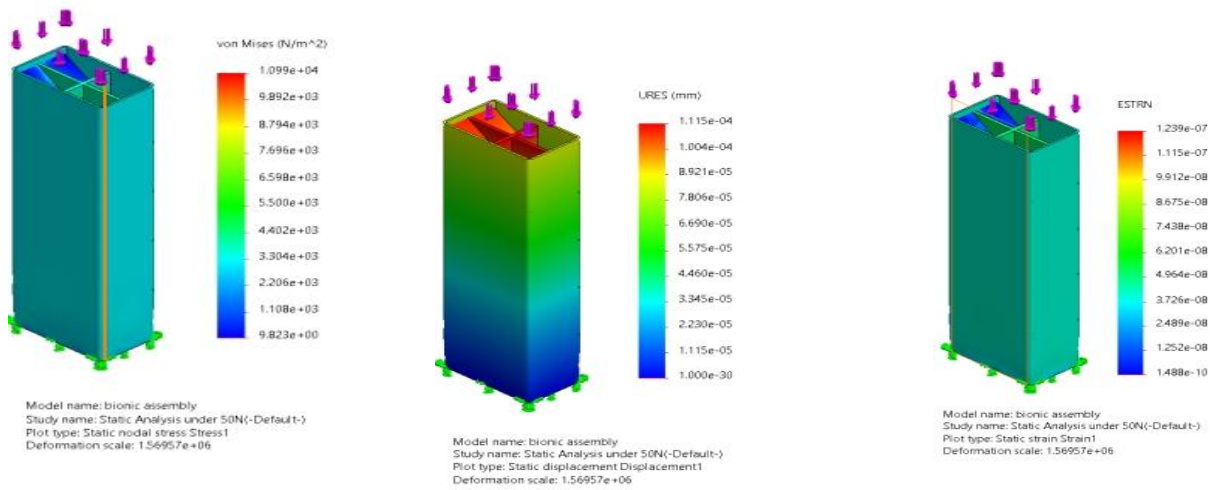


Figure 16: FEM static analysis under 50N

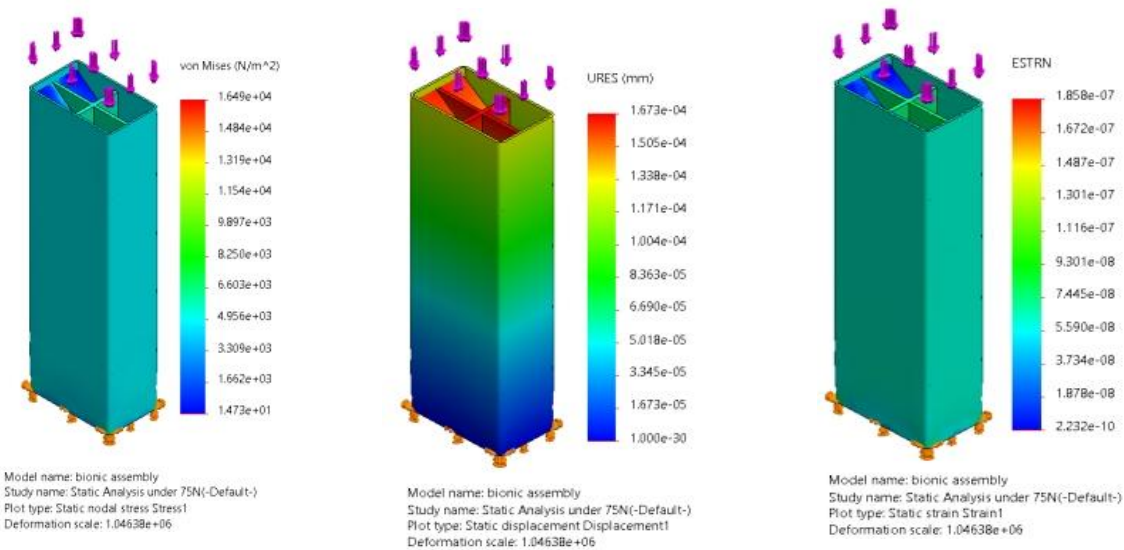


Figure 17: FEM static analysis under 75N

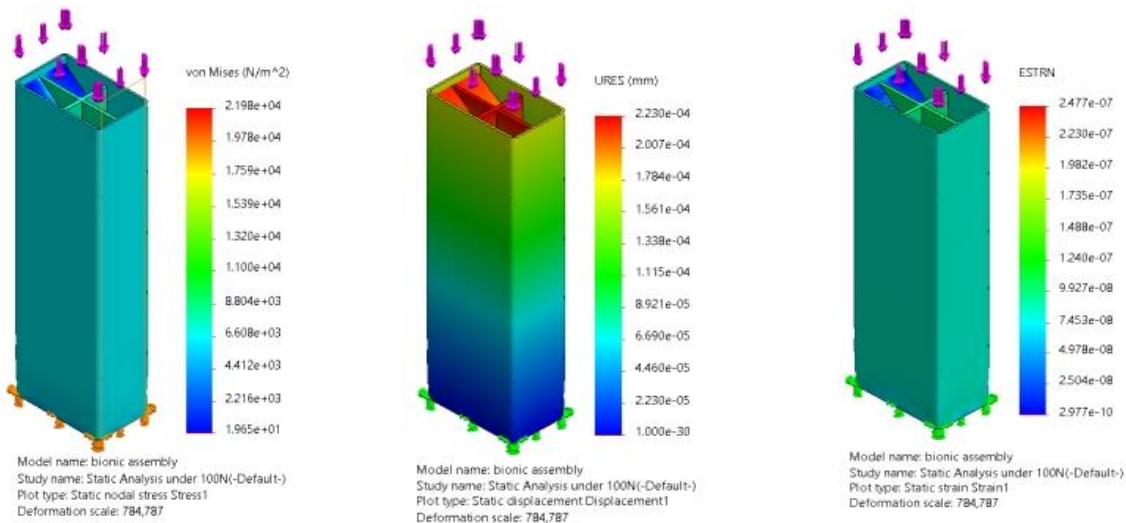


Figure 18: FEM static analysis under 100N

The results of the static analysis of the conventional column and the bionic type column are shown in the Tables 1 – 4.

Table 1: Comparison of Weight of Column

S/N	Model	Weight (kg)	Volume (m ³)	Surface Area (m ²)
1.	Conventional Column Structure	439.63	0.061	9.21
2.	Optimized Column Structure	419.32	0.058	9.61

Table 2: Von Mises Maximum Stress of Column

S/N	Load (N)	Conventional Column (N/m ²)	Bionic Column (N/m ²)
1.	25	5.021×10^3	5.495×10^3
2.	50	1.944×10^2	1.009×10^4
3.	75	1.506×10^4	1.649×10^4
4.	100	2.008×10^4	2.198×10^4

Table 3: Maximum Displacement of Column

S/N	Load (N)	Conventional Column (mm)	Bionic Column (mm)
1.	25	5.58E-05	5.03E-05
2.	50	1.12E-04	1.00E-04
3.	75	1.67E-04	1.51E-04
4.	100	2.23E-04	2.01E-04

Table 4: Maximum Strain of Column

S/N	Load (N)	Conventional Column	Bionic Column
1.	25	5.434×10^{-8}	6.193×10^{-8}
2.	50	2.144×10^{-4}	1.239×10^{-7}
3.	75	1.630×10^{-7}	1.858×10^{-7}
4.	100	2.174×10^{-7}	2.477×10^{-7}

The mass of the conventional column is 439.63703 kg and that of the bionic column is 419.32243 kg. Compared with the conventional one, the mass of the bionic column is reduced by 4.62% (that is a whole 20.3146 kg reduction) and still yet with a higher surface area of 4.38%.

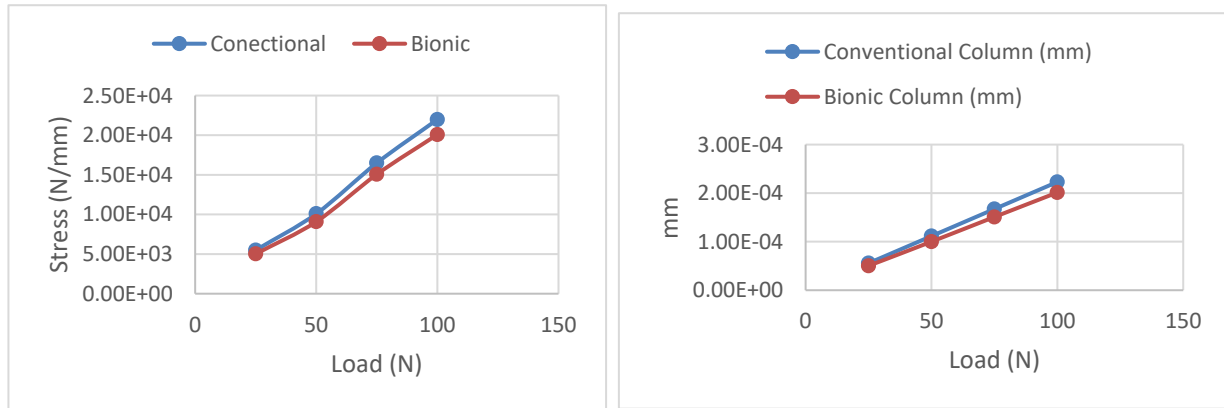


Figure 19: Comparison of the Stress and Displacement for the Convectional and Bionic Structure

The maximum deformation area located in the interface column and top cantilever. The maximum deformations of the bionic column under the four loads are close to each other and a bit higher than that of the conventional column, by averagely 10.11%. But however, the vertical ribs play an important role in ensuring stiffness of machine tool column.

6.0 CONCLUSION

The leaf vein system structure of biological netted venation was applied to a machine tool structure to improve traditional stiffener plate of a column. In order to improve the mechanical performances of the machine tool column, the internal stiffening ribs are re-arranged based on the structure of leaf veins, a bionic column designed. Static analysis

was conducted to check the static characteristics using FEM software. Upon conclusion of the static simulation results, the following conclusions were made:

- i. The mass of the machine tool column is improved using structural bionic design, by 4.62%. as compared with the conventional column, the maximum displacement of the bionic column is reduced averagely by 10.11%.

Biological structures, like bamboo, animal bones, honey comb, and leaf veins, have excellent mechanical properties that can be mimicked to improve the mechanical performances of conventional structures and weight.

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