Journal of Science and Technology in The Tropics
Volume 12 Number 2 December 2016

CONTENTS

Journal of Science and Technology in The Tropics (2016) 12(2): 50 – 56

Systematic Layout Planning (SLP) Approach to Improve Facility Layout

Siti Mardini Hashim*, Dzullijah Ibrahim, Norasikin Hussin and Rosniza Rabilah

Faculty of Mechanical Engineering, Universiti Teknologi MARA (Pulau Pinang), 13500 Permatang Pauh, Penang, Malaysia
(*correspondence author: mardinih@ppinang.uitm.edu.my)

Received: 25.10.2016; accepted 20.12.2016

Abstract Facility layout planning enables a manufacturing company to reduce production cost and to be competitive. SLP was proposed in this study to improve facility layout of a medium size manufacturing company. The major problems faced by this company are parts damage and high inventory due to the long distance travelled during parts transfer. Two alternatives were generated and performances were compared based on total distance the parts travelled and workstations efficiency.

Keywords Facility layout planning – SLP - productivity - inventory.

INTRODUCTION

In today's competitive environment, rapid changes in modern technologies have necessitated manufacturing companies to implement strategic planning in order to survive. Strategic options for a company to be competitive include price, quality, delivery, product design [1], flexibility and cost efficiency [2]. Facility layout planning plays an important role in the manufacturing processes and seriously impacts a company's ability to reduce cost and to be competitive in the market. Around 70 percent of the total cost of a product is contributed by material handling equipment and the facilities it operates [3].

Hence, the need for layout planning arises both in the process of designing new facilities and in redesigning existing facilities. The most common reasons for redesign of layouts include inefficient operations (e.g., high cost, bottlenecks), accidents or safety hazards, changes in design of products or services, change in methods or equipment and introduction of new products or services [4]. Facility layout problems can be solved using algorithmic and procedural approaches. Algorithmic approaches usually involve only quantitative input data [5] while procedural approaches can integrate both qualitative and quantitative objectives in the design process [6, 7, 8].

Systematic Layout planning (SLP) is a procedural approach and was chosen in the case study as it is not only a proven tool in providing layout design guidelines but is still widely used among enterprises and academic world. SLP approach has been used to improve material flow distance, travelling time and travelling cost [9] and to increase productivity [10]. Overall there are eleven stages required to complete when using the SLP approach to solve facility layout problems [8]. The stages are elaborated in the case study presented in the next section.

METHODOLOGY

A. Case Study

A manufacturer of engineered wood flooring was selected as the case study. The company has changed their business (from furniture business to wood flooring) without changing the layout.

The existing production layout is shown in Figure 1. The operators are required to move the materials from one workstation to another on a pallet truck and forklift. To avoid the frequent transfer and distance movement, the operators tend to overload the pallet trucks, thereby damaging the parts. In addition, high work in process (WIP) inventories is another problem for this company. This causes additional manufacturing cost as a special wrapper is required to prevent the parts from being exposed to atmospheric moisture in order to control the quality of the parts. The company spends an average of RM 25,000 every month for the plastic wrapper.

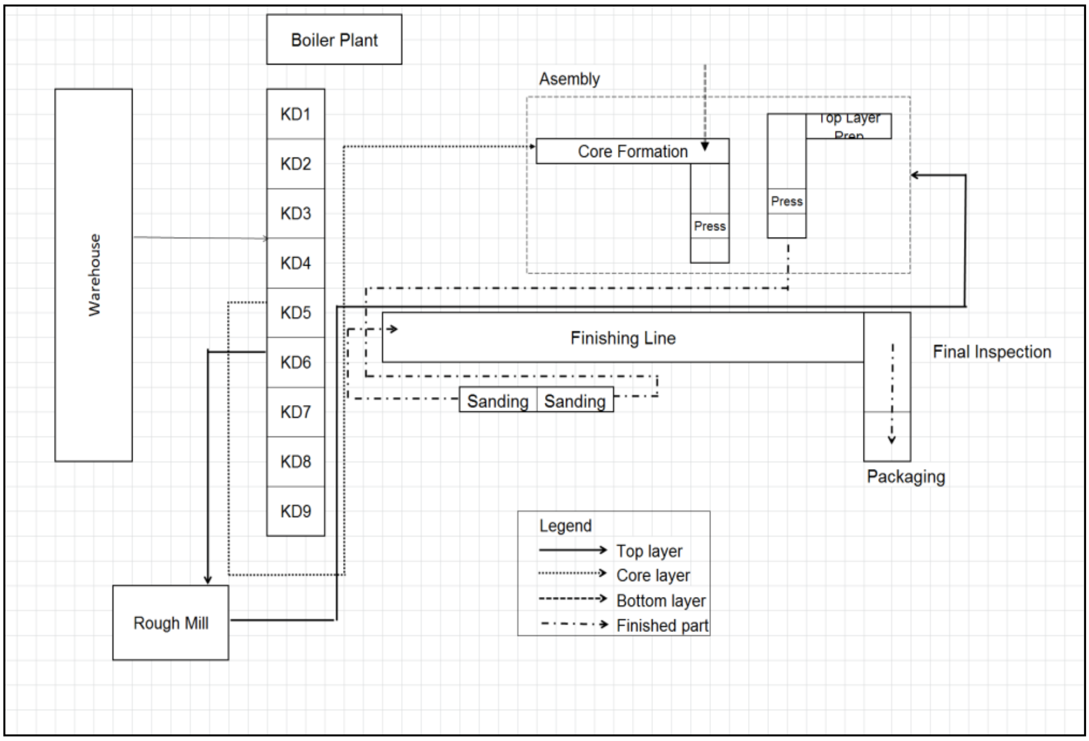


Figure 1. Existing layout (material flow)

B. Details of SLP Procedures

Stage 1: Input data: The basic data namely product P, quantity Q, route R, support S and time T are identified in this case study. P refers to the product which is engineered wood flooring. Q is the quantity of each type of product (For this case study, only 1 type of engineered wood flooring is measured). R is the route needed by the product and the machines to complete these operations. S is the supporting activities, and T, refers to how quickly the products are to be made.

Stage 2: Flow of materials: Basically, engineered wood flooring is made up of a top layer of hardwood, inner core of rubber wood and veneer as a base layer. The flow begins with moving the sawn material to kiln drier room. Kiln drying method only applies for both Top layer and Core layer whereas for base layer, which are veneer directly, moved to assembly process for storage. In rough mill process, top layer materials are cut to the required dimensions. Assembly process involves two activities that are gluing and pressing to form a single piece of board. The operators then would have to perform sanding operation before finishing the process. Inspection is the most important step in order to ensure only quality products will be sent to customer. Any defective products are required to be transferred back to sanding process.

Stage 3: Activity relationship chart: In this stage, relationships between workstations are identified and shown in Fig. 2. The relationship is defined as A – Absolutely necessary, E – Especially important, I – Important, O – Ordinary closeness, U – Unimportant and X – Undesirable.

Stage 4: Relationship diagram: Relationship Diagram is a visual display of workstations relationship with data on the flow of materials as shown in Fig. 3. The thicknesses of lines drawn represent the importance of each workstation.

Stage 5: Space requirement: The space for each workstation, which is required in developing layout alternatives, is measured.

Stage 6: Space available: For this study, the space available is less restricted due to the area not being fully utilized. The available space is 20,000 meter square.

Stage 7: Space relationship diagram: In this step, the relationship diagram is converted into space relationship diagram by taking space consideration into account.

Stage 8: Modifying constraints: Any constraints and practical limitations have to be considered before generating layout alternatives. In this company, some workstations are suitable in their current positions due to utility attachment.

Stage 9: Practical limitations: Among these are kiln drier which operates from the support of boiler. Any adjustment to the boiler requires approval from local authorities such as the Department of Environment (DOE) and the Department of Occupational, Safety and Health (DOSH).

Department	Kiln Drier	Rough Mill	Assembly Process	Sanding Process	Finishing Line	Final Inspections	Packaging
Kiln Drier		I	I	U	U	U	U
Rough Mill			A	U	U	U	U
Assembly Process				E	U	U	U
Sanding Process					X	E	U
Finishing Line						O	U
Final Inspections							O
Packaging							

Figure 2. Activity relationship chart for workstations

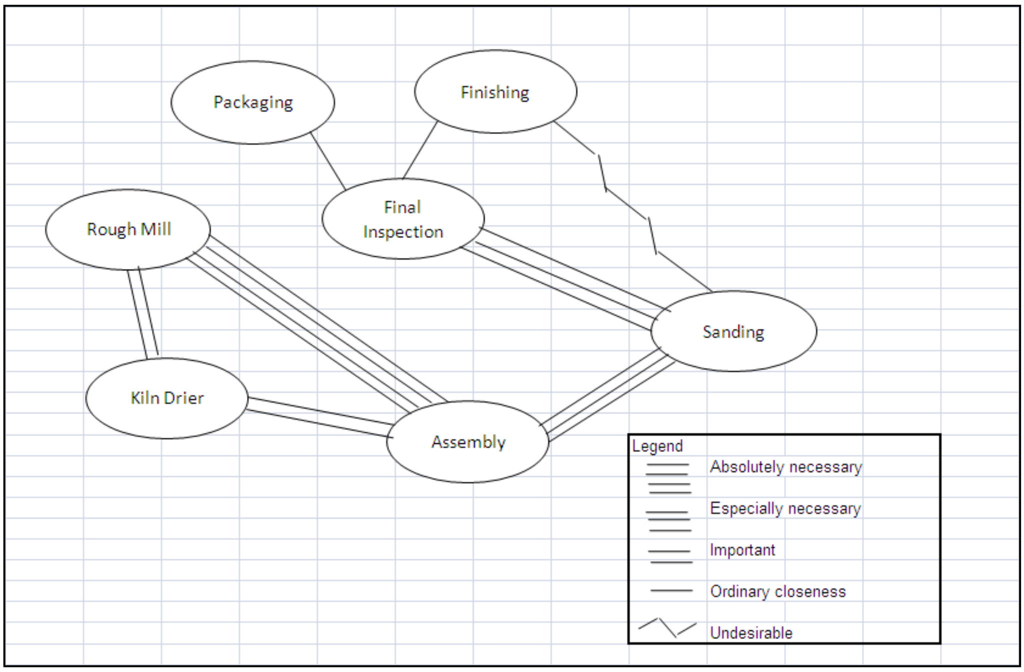


Figure 3. Relationship diagram

RESULT AND DISCUSSION

These sections discuss Stage 10 and Stage 11 in SLP procedures which are developing layout alternatives and evaluation.

A. Layout alternatives (Stage 10 of SLP)
Two layout alternatives were created based on the previous steps after taking into consideration the practical limitations and constrains in Stage 8 and Stage 9. In Alternative 1 (first design), the whole assembly workstation is relocated to a new area. The other workstations such as kiln drier, rough mill, sanding process, finishing line, final inspection and packaging remain in their current positions. The layout is shown in Fig. 4.

In Alternative 2, rough mill workstation is relocated to a new area whereas other workstations remain in their current positions as shown in Fig. 5.

B. Stage 11. Evaluation
Witness is used to simulate the performances for existing and alternatives layout. Total distances parts travelled and workstation efficiency (percentage of working and idle) are the performance measurement for both alternatives.

Table 1 shows the comparison of layouts from all workstations. Both alternatives managed to reduce the distance on most important workstations that have highest damaging parts. Alternative 1 show the total distances the parts need to travel between workstations is less by 42% compared to Alternative 2.

Based on the comparison in Table 2, Alternative 1 is better than Alternative 2 where it shows five out of seven workstations (which are assembly, sanding, finishing line, inspection and packaging) have higher percentage of busy time (the numbers are bold) compared to Alternative 2.

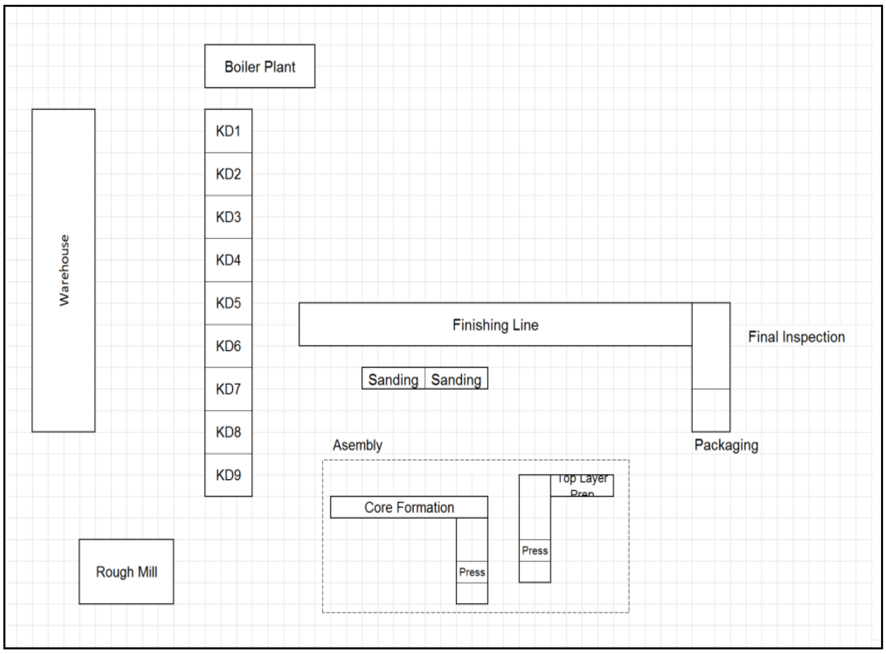


Figure 4. Alternative 1

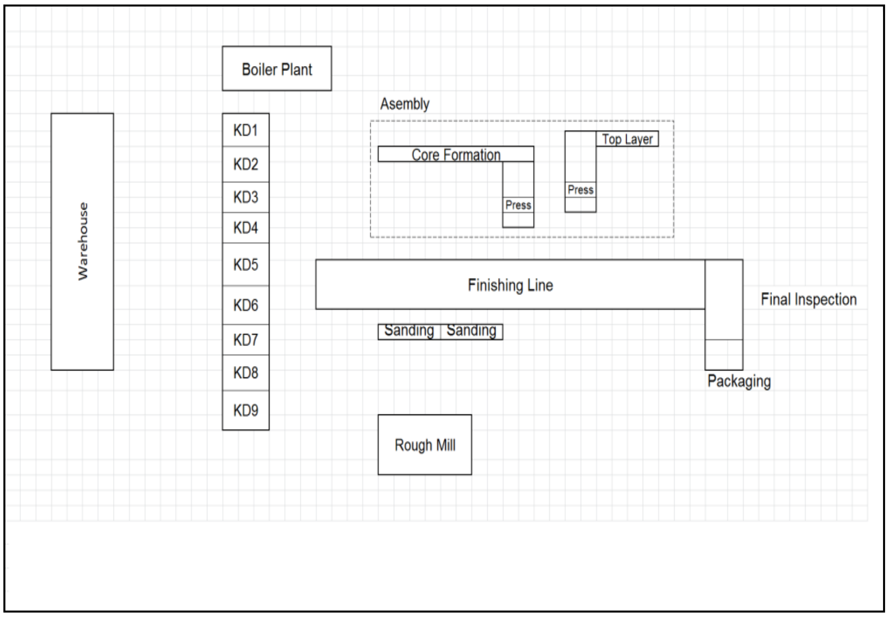


Figure 5. Alternative 2

Table 1. Comparison of the layouts in term of distance

No	Workstation		Distance (m)	
	(From)	(To)	Alternative 1	Alternative 2
1	Kiln drier	Rough mill	130	250
2	Rough mill	Assembly line	150	200
3	Assembly line	Sanding	10	82
4	Sanding	Finishing line	44	44
5	Finishing line	Final inspection	-	-
6	Final inspection	Packaging	-	-
	TOTAL		334	576

Table 2. Comparison of the layouts in term of workstation efficiency

Layout Workstation	Existing		Alternative 1		Alternative 2	
	% Idle	% Busy	% Idle	% Busy	% Idle	% Busy
Kiln Drier	11.57	33.33	11.57	33.33	11.57	33.33
Rough Mill	44.91	9.13	44.91	6.96	44.91	22.27
Assembly	6.48	93.52	5.62	94.38	8.74	91.26
Sanding	36.77	63.23	47.95	47.19	62.86	37.14
Finishing Line	73.89	18.7	61.81	26.96	69.95	21.21
Inspection	88.87	11.13	83.15	16.85	86.74	13.26
Packaging	98.66	1.34	97.98	2.02	98.41	1.59

CONCLUSION

Improving facility layout is vital for a company to reduce its production cost in terms of distance, workstation efficiency, work output and work in progress. SLP used for this study is a procedure which involves qualitative and quantitative data. Therefore, it has an advantage over other methods where the importance of the relationship of every workstation is considered. The results from this study showed improvement for the layout and this demonstrated the feasibility of the SLP approach. However, since SLP in this study is calculated only based on distance and workstation efficiency, future study can be done for the combination of the effect of other production cost parameters on facility layout improvement.

REFERENCES

[1] Karl T. (1995) Product Design and Development. McGraw-Hill, Ulrich.
[2] Steven C. Wheel Wright (1984) Manufacturing strategy: Defining the missing link. Strategic Management Journal,Volume 5, Issue 1: 77–91.
[3] Thomkins, J.A., White, J.A., Bozer, Y.A., Frazell, E.H., Tanchoon, J.M.A and Trevino, J. (2003) Facility Planning. Wiley, New York.
[4] Stevenson, W.J and Sum, C.C (2010) Operations Management: An Asian Perspective, McGraw Hill Education, Asia.
[5] Yang T., Chao-Tan Su and Yuan-Ru Hsu. (2000) Systematic Layout Planning: a study on semiconductor wafer fabrication facilities. International Journal of Operations Production Management Vol, 20 No.11,2000: 1359-1371.
[6] Padillo, J.M., Meyersdorf, D. and Reshef, O. (1997) Incorporating manufacturing objectives intothe semiconductor facility layout design process: a methodology and selected cases,IEEE/SEMI Advanced Semiconductor Manufacturing Conference and Workshop, IEEE, Boston pp. 434-439.
[7] Apple, J.M. (1997) Plant Layout and Material Handling, 3rd ed., John Wiley, New York.
[8] Muther, R. (1973) Systematic Layout Planning, 2nd ed. Cahners Books, Boston
[9] Singh, A.P and Yilma M. (2013) Production floor layout using systematic layout planning in can manufacturing company. Control, Decision and Information Technologies (CoDIT), International Conference
[10] Wiyaratn and Wanatapa (2010) Improvement Plant Layout Using Systematic Layout Planning (SLP) for Increased Productivity. World Academy of Science, Engineering and Technology 72.

Design and Optimization of Wind Turbine Blade of a Small Form Wind Turbine on Automotive Vehicle for Wind Energy Harvesting Application

S. M. Fawwaz*, A. Yasir Md. Said, Z. Karim, Izatul Hamimi, A. Razak Jonid and M. Shahril Yusop

Universiti Kuala Lumpur Malaysia France Institute, Section 14, Jalan Teras Jernang, 43650 Bandar Baru Bangi. Malaysia
(*corresponding author: syedmfawwaz@unikl.edu.my)

Received: 25.06.2016 ; accepted 28.07.2016

Abstract An investigation has been made to design and optimize the highest rotational speed of the wind turbine blade for this application. The development of machines which efficiently extract power from wind to wind turbines is now being used as a generic term for machines with rotating blades that convert the kinetic energy of wind into useful power. This application is to reduce the usage of car battery and also as a backup power supply if the car battery fails. In the development of a wind turbine blade for this project, the parameter taken is the angle of the blade, number of blades and material. For all this research, SolidWorks for 3D modelling and the analysis of flow simulation was used.

Keywords Kinetic Energy, Wind Turbine, Blade, Modelling, Simulation.

INTRODUCTION

Harvesting Energy stands alone as one of the most promising techniques for approaching the global energy problem without depleting natural resources. Energy harvesting application is the process in which energy is derived from external sources. Energy harvesting or energy scavenging technologies refer to applications that capture and exploit unused and depleted energy so as to convert it to a more usable form. The last decade of the 20th century saw the development of machines, which efficiently extract power from wind. ”Wind turbines” is now being used as a generic term for machines with rotating blades that convert the kinetic energy of wind into useful power.

The objective of this paper was to design a suitable blade for wind turbine system by conceptual and preliminary 3D modelling using SolidWorks. This method creates initial sketching design without dimension, followed up by preliminary design with dimension. Next, to perform flow analysis in blade model for wind turbine system using SolidWorks flow simulation. This method is to observe the behaviour of each and every design of the model. And last, to evaluate and optimize the most suitable blade model for wind turbine system. This method will select the best blade that fulfils all design constraints and criteria, which a table with marks will be used to select the design.

METHODOLOGY

The first step is to identify step by step the flow or progress of the project. A lot of journals, books, reports, newspapers and websites can be referred to determine the wind blade currently used worldwide. If the wind turbine is used, wind information is important, because the wind must have high speed. Therefore, ideas and brainstorming session must be done in order to design and find the best blades considering the angle of blade and number of blades to maximize wind to rotate the turbine.

Conceptual and Preliminary Design

Conceptual design is a type of art that focuses on hypothetical functionality. It is the creation and exploration of new ideas. In this point, the design selection of the product is important to get the best design.

3-D Modelling

SolidWorks is computer-aided-design software, and it utilizes a parametric feature-based approach to create models and assemblies. The software is written on Parasolid-kernel. For this method, from the sketch, a 3D model need to be constructed using Solidworks. There are 14 steps to model the three blades of wind turbine blade, as shown in Fig 1.

Design Optimization

The final stage is on design optimization. This step will select the best design due to design constraint and requirements. It uses flow simulation to optimize the best blade for the design using SolidWorks flow simulation. The step to perform the analysis and flow simulation is shown in Fig 2.

RESULTS AND DISCUSSION

This step is about the result and discussion on design and optimization of design and optimization of wind blade of a small form wind turbine on automotive vehicle. The result contains the steps to select the final design. Data results by design are processes of analysis and simulation based on the data collection.

The analysis is based on the design of wind turbine which has been decided the selected material is aluminium as the material at 40km/h the constant variable has different parameter, which is on number of blade, 3 blades and 4 blades is being used and angle of blade is 10º, 15º, and 20º.

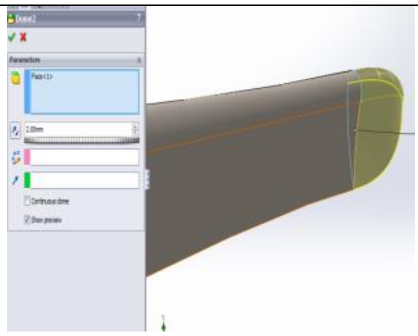
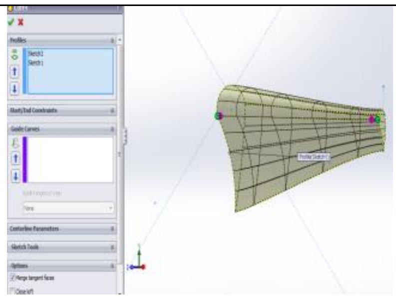
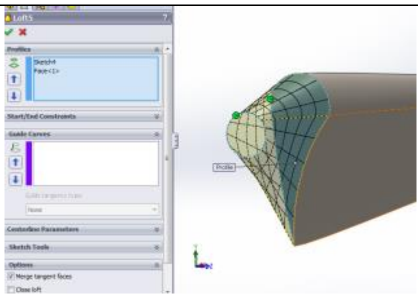
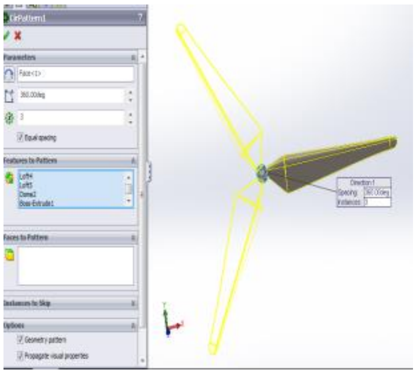
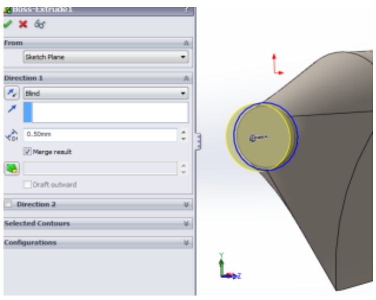
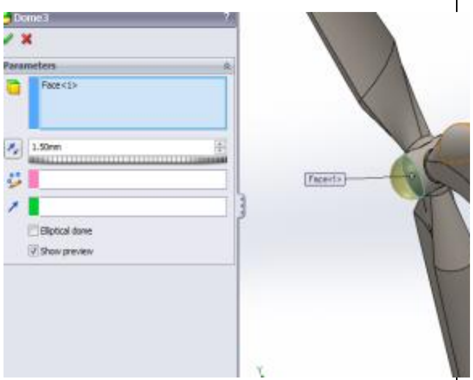
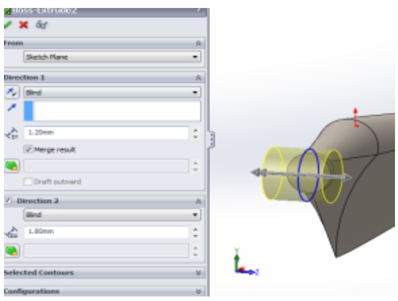
Steps	Details	Steps & Details
	1. Sketch the aero foil shape of wind turbine with 10 degree angle of blade	 6. Make a dome on the face of blade for the tips of blade with 2mm lgth.
	2. Make a loft at the edge of both aero foil shapes.	
	3. Using loft, meet the edge of circle with the surface of blade.	 7. Make a circular pattern.
	4. Boss-Extrude the 2.4mm circle in blind direction with 0.5mm distance. Make sure merge result is check.	 8. Lastly, make a dome for wind turbine hub.
	5. Boss-Extrude the circle in two direction to build the hub of wind turbine blade.	

Figure 1. Step-by-step 3-D Modelling using SolidWorks

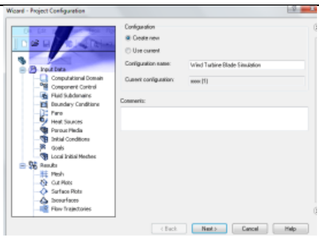
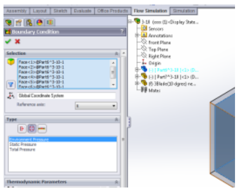
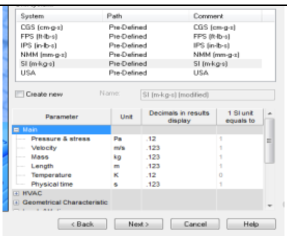
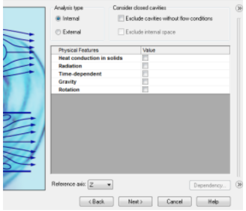
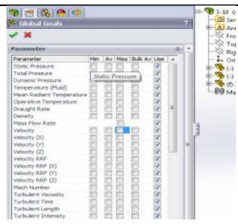
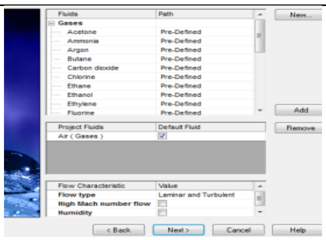
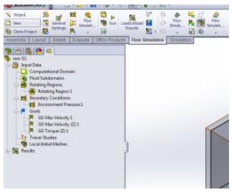
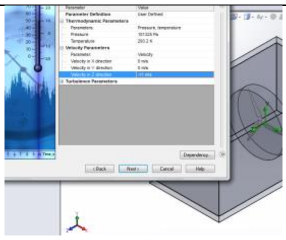
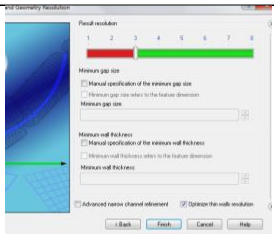
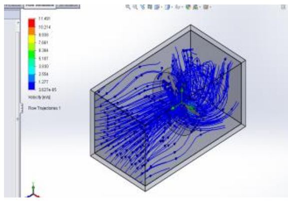
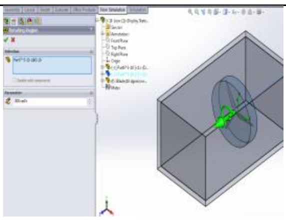
Steps	Details	Steps & Details
	1. Click on wizard at the left of task bar. Create new configuration and click next.	 8. Right click on boundary condition and select the face and identify as environment pressure. Then click ✓.
	2. Assign the unit. Use SI unit for this simulation. Click next.	
	3. Make sure uncheck (Exclude cavities without flow conditions). Click the rotation box in physical features. Next	 9. Select a goal, right click on the global goal and click on maximum velocity and torque (z).
	4. Determine the air as a project fluid. Next	 10. Click on the Run button to do simulation.
	5. Edit the parameter. For the velocity, I use Z direction and I put -11m/s as a value because the direction is opposite. Next	
	6. In geometry resolution, I set at 3 as result resolution. Finish	 11.Select the starting point as the reference for wind flow and set the velocity at the appearance. Then click ✓ Lastly result will appear.
	7. Select the rotating region part and insert the value parameter and click ✓ after done edit.	

Figure 2. Step-by-step Flow Analysis and Simulation using SolidWorks

Conceptual and Preliminary Design

The result of modelling on wind turbine blades on their number of blades with angle-of-attack is shown in Fig 3 (a) and (b) below.

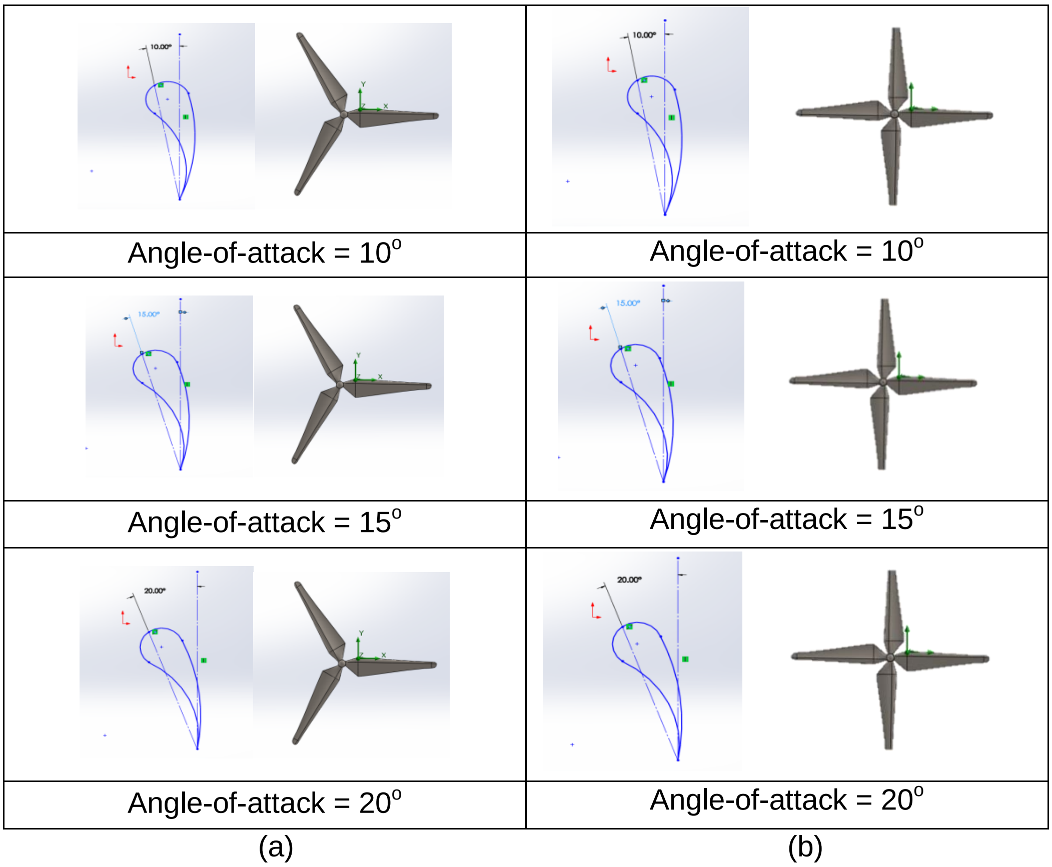


Figure 3. Angle-of-attack for (a) three blades model; and (b) four blades model

Design Optimization

This analysis aims to determine the manner and technique of using SolidWorks flow simulation. Moreover, this analysis enables users to identify the results of design in terms of durability, speed, efficiency and so on. In this case, my project is to identify with a blade that can produce more speed with different number of blade and angle of attack and the torque data for the gear system. Below is the result of the flow analysis and simulation using 3 and 4 blades for the wind turbines, as shown in Fig 4 and Fig 5. The material that been selected to use is aluminium, as been informed previously.

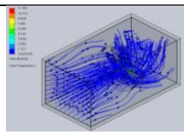
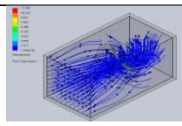
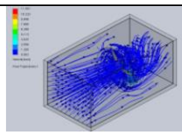
	Angle of attack	Blade velocity, v (m/s)	Torque, T (Nm)	Simulation
Wind speed =11 m/s	10º	0.725705296	1.06999E-05	
	15º	1.203121049	1.05434E-05	
	20º	1.936014128	1.08955E-05	

Figure 4. *Three (3) blades model*

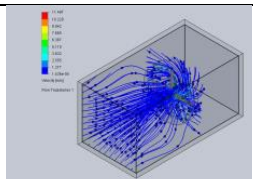
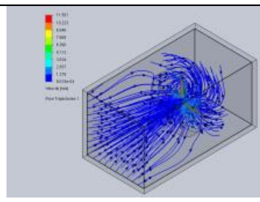
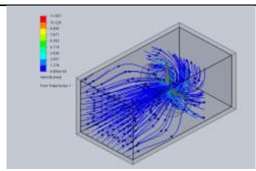
	Angle of attack	Blade velocity, v (m/s)	Torque, T (Nm)	Simulation
Wind speed =11 m/s	10º	0.618826883	4.82504E-05	
	15º	0.874497447	4.56213E-05	
	20º	1.04999244	4.89539E-05	

Figure 5. *Four (4) blades model*

The blade velocity and torque is different. This shows that the higher number of blade angle the greater number of wind hits the blade. Meanwhile, the increase in the number of blades will affect the performance of the blade. A high value of torque is required to move the blade. If the torque is higher, the speed will be slower and the four blades is not suitable. Besides, the increased number of blades will increase the price of the product. According to the result, the higher velocity from three blades and four blades has been identified with 11 m/s speed of wind, as shown in Table 1 below.

Table 1. Comparison between 3 and 4 blades

No. of blades	Angle of attack	Velocity,v (m/s)	Torque,T (N.m) x10^{-5}
3	20º	1.936014128	1.08955
4	20º	1.04999244	4.89539

From the two designs above, the higher velocity is produced by three blades design with 1.936 m/s compared to 4 blade with 1.0499m/s using SolidWorks simulation. This showed that the increase in the number of blades will affect the performance of wind turbine blade to capture the maximize wind through the blade. The increased number of blades will require more torque to rotate the blade and the cost to produce the blade will also increase. So the conclusion is, the best design is the three blades with 20-degree angle of blade with the velocity value 1.936m/s.

CONCLUSION

Based on the research of "Design and Optimization of Wind Turbine Blade Assembly of a Small Form Wind Turbine on Automotive Vehicle for Wind Energy Harvesting" the conclusion is review from the objectives that is to produce a blade model for wind turbine system by using sketching and 3-D model in SolidWorks software. To determine the best design there are many aspects that need to be considered. For this research, the parameters take the difference in the angle of the blade and the blade. Then, to get the speed of rotation of the turbine blades with the different parameters is to use SolidWorks flow simulation. From that, there are many results that come out with different parameter. From the result, the best design is the wind turbine blade that has the higher velocity and low torque. As such the objective successfully achieved which is to find out the best design for the project.

REFERENCES

[1] Veritas, N., (2002). *Guidelines for design of wind turbines*. 2nd Edition, Det Norske Veritas: Wind Energy Department, Ris National Laboratory.

[2] Chiras, D., (2010). *Wind power basics: a green energy guide*. New Society Publishers.

[3] Burton, T., Sharpe, D., Jenkins, N. and Bossanyi, E., (2001). *Wind energy handbook*. John Wiley & Sons.

[4] Bagiorgas, H.S., Assimakopoulos, M.N., Theoharopoulos, D., Matthopoulos, D. and Mihalakakou, G.K., (2007). Electricity generation using wind energy conversion systems in the area of Western Greece. *Energy Conversion and Management*, 48(5): 1640-1655.

[5] Gitano-Briggs, H., (2009). Low Speed Wind Turbine Design. *Univesity Kuala Lumpur - MSI, Malaysia*, pp. 270.

[6] Brøndsted, P., Lilholt, H. and Lystrup, A., (2005). Composite materials for wind power turbine blades. *Annu. Rev. Mater. Res.*, 35: 505-538.

[7] Chena, K.N., Gaub, W.H. and Chena, P.Y., (2011). Optimal Aerodynamic Design and Material Layout of Composite Wind Turbine BladesKun-. Europe's Premier Wind Energy Event, PO. ID 470

[8] Ismail, D., Muhammad Irwanto, M., Mohd Irwan, Y., Gomesh, N.S. and Noor Syafawati, A., (2011). Performace of wind turbine based on wind speed data and turbine tower height in Kangar, Northern Malaysia.

[9] Ponta, F.L., Seminara, J.J. and Otero, A.D., (2007). On the aerodynamics of variable-geometry oval-trajectory Darrieus wind turbines. *Renewable energy*, 32(1): 35-56.

[10] Ingram, G., (2011). Wind turbine blade analysis using the blade element momentum method.

Journal of Science and Technology in The Tropics (2016) 12(2): 64 – 72

Cable Reinforced Handkerchief Surface in Tensioned Fabric Structure

Abdul Hadi MN and Yee HM*
Faculty of Civil Engineering, Universiti Teknologi MARA, 13500 Permatang Pauh, Pulau Pinang, Malaysia
(*corresponding author: yhooimin@yahoo.com)

Received 11.10.2016 ; accepted: 24.12.2016

Abstract Tensioned Fabric Structures (TFS) are structures that are composed of tensioned fabric as structure members. TFS are suitable to be applied in large space area. Tensioned fabric structure with different surface form could be realized. Their variations as possible choice form of minimal surface for TFS have been studied. In this analysis, the form of Handkerchief surface has been used in this study. Handkerchief surface is the form of minimal surface. Handkerchief surface has not been studied by other researchers. Besides, no other work on Handkerchief surface as an idea in tensioned fabric structure has been found. The aim of this paper is to determine initial equilibrium shape and cable reinforced Handkerchief surface in tensioned fabric structure with variable u=v=0.6. The first structural analysis process in tensioned fabric structure is form-finding. Form-finding is to determine initial equilibrium shape under prescribed pre-stress and boundary condition. In this analysis, cable reinforced has been applied in tension fabric structure also. From the result, the initial equilibrium shape and cable reinforced Handkerchief surface, u=v=0.6 is corresponding to equal tension surface. The variable of Handkerchief surface, u=v=0.6 to be obtained in this study will provide an alternative shapes for designer to be considered for adopted in tensioned fabric structure.

Keywords form-finding, cable reinforced, Handkerchief surface, tensioned fabric structure

INTRODUCTION

Tensioned fabric structure become increasing popular since the first ground breaking structure was built [1]. This structure shows a good solution for architecture and structural engineering. Boundary conditions that determine the fabric shape and stress distribution has been discussed [2]. A uniform stress is applied to the fabric. In order to achieve a uniform pre-stress, the fabric must take the form of a minimal surface. Figure 1 shows the example of tensioned fabric structure.

[3] has described the architecture inspired from minimal surface embodies that unite economy and beauty. [3] also described the properties of minimal surface. Minimal surface have the least surface area, it can used for large scale and light roof construction. Minimal surface also has a separable property and a balanced surface tension. Finally, minimal surface has no centre point. Minimal surface are of special interest to physical scientists, materials scientists, biologists, and mathematicians, because the geometry of triply periodic minimal surfaces strongly influences the physical properties of the material [4]. For the last 20 years, the concept of fabric structure is strongly dependent on the use of computers and many specialised software [5]. The structural engineer has to verify the structure stress level in its final state and under climatic loading.

Figure 1. Tensioned Fabric Structure

[6] investigated the minimal surface problem, where a surface with minimal curvature is sought and given the position of its boundary. [6] determined the shape of surfaces in order to satisfy certain design criteria. The surface has been used is Catenoid and Schwarz minimal surface. In this analysis, Finite element method for computing minimal surfaces based on computing a discrete Laplace-Beltrami operator operating on the coordinates of the surface has been carried out. [6] computed minimal surfaces using a discretization of the Laplace-Beltrami operator on a 2D surface embedded in a 3D mesh.

Tensioned fabric structure with different surface form could be realized. Their variations as a possible choice form of minimal surface for tensioned fabric structure have been studied. In this analysis, the form of Handkerchief surface has been used in this study. Handkerchief surface is the form of minimal surface. Handkerchief surface has not been studied by other researcher. Besides, no other work on Handkerchief surface as an idea in tensioned fabric structure has been found.

In this study, computational form-finding using nonlinear analysis method proposed by [7] has been carried out. The criteria adopted for checking of convergence of form-finding is least square error (LSE) of total warp and fill stress deviation less than 0.01 based on [7]. Previous studies have shown that, [8-21] have carried out form-finding using nonlinear analysis method in Catenoid, Helicoid, Scherk, Enneper, Oval, Costa, Moebius Strip, Monkey Saddle and Chen-Gackstatter TFS models.

Tensioned fabric structure is highly suited to be used for realizing surface of new forms. However, none of the new example mentioned present any result on Handkerchief surface as load carrying members. Understanding of the possible form of Handkerchief surface will provide alternative shape for designers to be considered. In this paper, form-finding of Handkerchief surface with variable u=v=0.6 and cable reinforced Handkerchief surface TFS model (u=v=0.6) with one cable has been carried out.

METHODOLOGY

Generation of Handkerchief Surface

Figure 2 shows the form of Handkerchief surface. The form of Handkerchief surface can be obtained from [22] and [23]. Equation (1) shows the equation for Handkerchief surface.

$$X = u \,, \; Y = v \,, \; Z = \frac{1}{3}u^3 + uv^2 + 2(u^2 - v^2) \tag{1}$$

X, *Y* and *Z* are the coordinates in *X*, *Y* and *Z* directions, respectively. For *u* and *v* = variables.

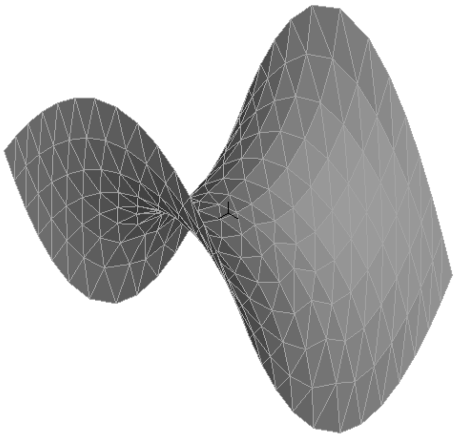


Figure 2. Handkerchief Surface

From this study, the program [24] has been used for the purpose of model generation. Aspect of modelling of surface of Handkerchief surface and form as well pre-stress pattern of the resulting TFS through form-finding using nonlinear analysis method proposed by [7] has been studied.

Computational Method using Nonlinear Analysis Method

The principle of nonlinear analysis method is based on [7]. The large displacement finite element formulation used for analysis of structural behaviour under external loads. Since the method can be used for both the initial equilibrium problem and load analysis, the approach using nonlinear analysis is quite common. The basic equation (2) used is expressed as follows:

$$({}_0^t\boldsymbol{K}_L + {}_0^t\boldsymbol{K}_G)\boldsymbol{u} = {}^{t+\Delta t}\boldsymbol{F} - {}_0^t\boldsymbol{f} \tag{2}$$

Where ${}_0^t\boldsymbol{K}_L$ is linear strain incremental stiffness matrix, ${}_0^t\boldsymbol{K}_G$ is nonlinear strain incremental stiffness matrix, ${}_0^t\boldsymbol{f}$ is vector internal forces, ${}^{t+\Delta t}\boldsymbol{F}$ is load vector and $\boldsymbol{u}$ is vector of increment in displacement.

A nonlinear analysis method by [7] for the analysis of tensioned fabric structure has been used in this study. The procedure adopted is based on the [7]. 3-node plane stress element has been used as element to model the surface of TFS. All x, y and z translation of nodes lying along the boundary edge of the Handkerchief surface have been restrained. The member pretension in warp and fill direction, is 2000N/m, respectively. The shear stress is zero.

Two stages of analysis were involved in the procedures of form-finding in one cycle proposed by [7]. First stage (denoted as SF1) is analysis which starts with an initial guess shape in order to obtain an updated shape for converged shape. The initial guess shape can be obtained from any pre-processing software and reference [7] is chosen for this study. This is then followed by the second stage of analysis (SS1) aimed at checking the convergence of updated shape obtained at the end of stage (SF1). During stage SF1, artificial tensioned fabric properties, E with very small values are used. Both warp and fill tensioned fabric stresses are kept constant. In the second stage (SS1), the actual values of tensioned fabric properties are used. Resulting warp and fill tensioned fabric stresses are checked at the end of the analysis against prescribed tensioned fabric stresses. Then, iterative calculation has to be carried out in order to achieve convergence where the criteria adopted is that the average warp and fill stress deviation should be < 0.01. The resultant shape at the end of iterative step n (SSn) is considered to be in the state of converged shape under the prescribed warp and fill stresses and boundary condition if the difference between the obtained and the prescribed membrane stresses relative to the prescribed stress is negligibly small. Such checking of difference in the obtained and prescribed stresses has been presented in the form of total stress deviation in warp and fill direction versus analysis step. As a first shape for the start of form-finding procedure adopted in this study, initial guess shape is needed. For the generation of such initial guess shape, knowledge of the requirement of anti-clastic nature of TFS is used. The incorporation of anti-clastic feature into the model will help to produce a better initial guess shape.

Cable reinforced Handkerchief surface TFS model (u=v=0.6) with one cable as shown in Figure 3 has been analysed also. Area and pretension of cable used for Handkerchief surface are 0.005 m^3 and 15000 N, respectively.

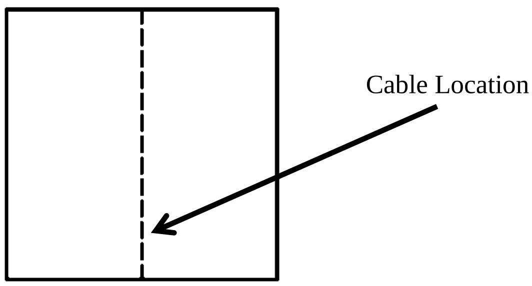


Figure 3. Handkerchief Surface TFS model with one reinforcing cable

RESULTS AND DISCUSSION

Computational Result

Form-finding in the form of Handkerchief surface has been carried out. In this analysis, the variable used is Handkerchief surface, u=v=0.6. For computational form-finding, the converged shape and cable reinforced is determined. The number of nodes and triangular elements for Handkerchief Surface, u=v=0.6 is 225 and 392, respectively.

The converged shape of Handkerchief surface, $u=v=0.6$ has been carried out. Figure 4 shows initial guess shape of Handkerchief Surface, $u=v=0.6$. After form-finding, Figure 5 shows the converged shape of Handkerchief Surface, $u=v=0.6$. Figure 6 shows the graph of convergent curve of converged Shape Handkerchief Surface, $u=v=0.6$. The LSE of total warp and fill stress deviation is 0.005766 and 0.007449, respectively. The surface of Handkerchief Surface, $u=v=0.6$ shows the LSE of total warp and fill stress deviation is less than 0.01. From the result, the converged shape of Handkerchief Surface, $u=v=0.6$ is corresponding to equal tension surface.

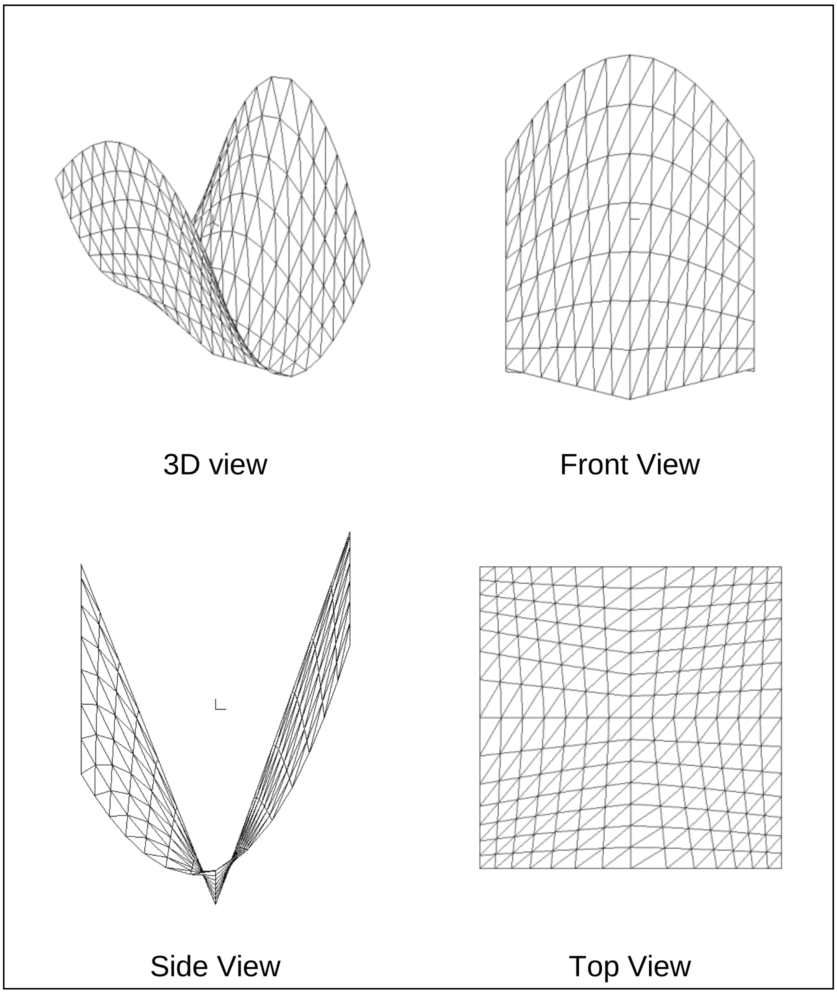


Figure 4. Initial Guess Shape Handkerchief Surface, $u=v=0.6$

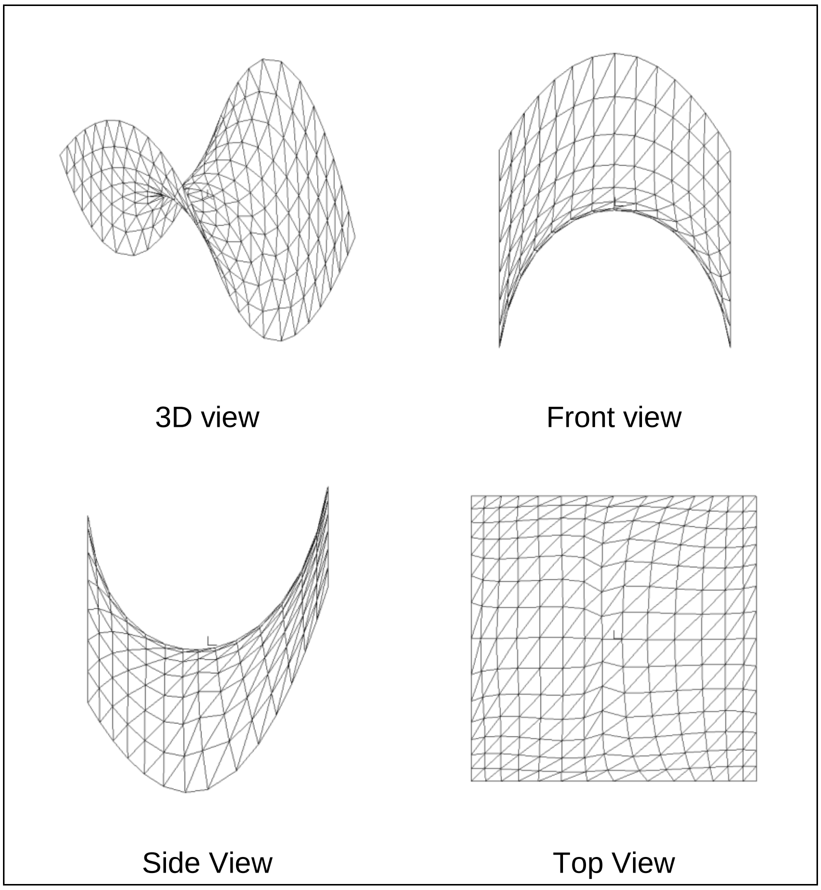


Figure 5. Converged Shape Handkerchief Surface, u=v=0.6

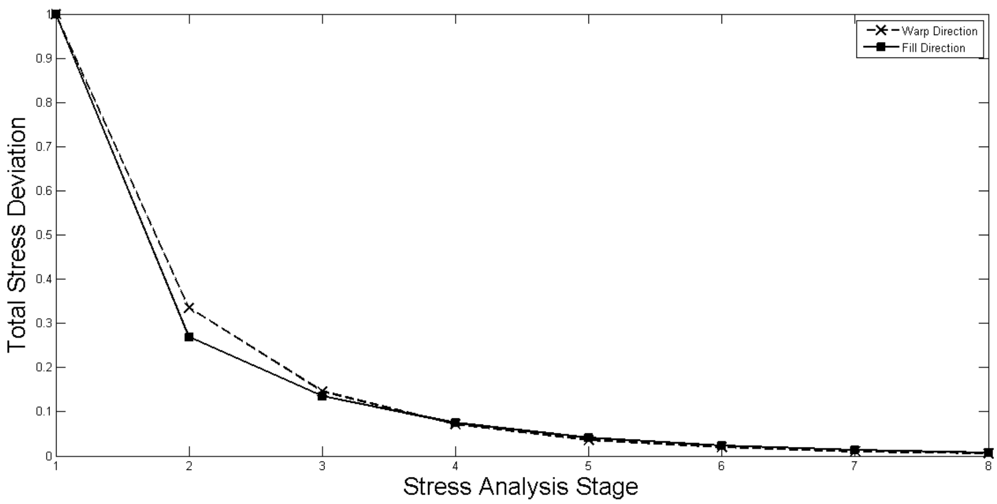


Figure 6. Convergent curve of Converged Shape Handkerchief Surface, u=v=0.6

Cable reinforced Handkerchief surface TFS model, *u*=*v*=0.6 has been carried out. In this analysis, one cable has been applied for cable reinforced Handkerchief surface, *u*=*v*=0.6. The dimension of cable reinforced for Handkerchief surface, *u*=*v*=0.6 is 8.6 x 8.6 x 10.8 m. Figure 7 shows the initial equilibrium shape cable reinforced Handkerchief surface, *u*=*v*=0.6. From the result, cable pretension of Handkerchief Surface, *u*=*v*=0.6 is 14529.9305 N. Figure 8 shows the graph of convergent curve of cable reinforced Handkerchief surface, *u*=*v*=0.6.

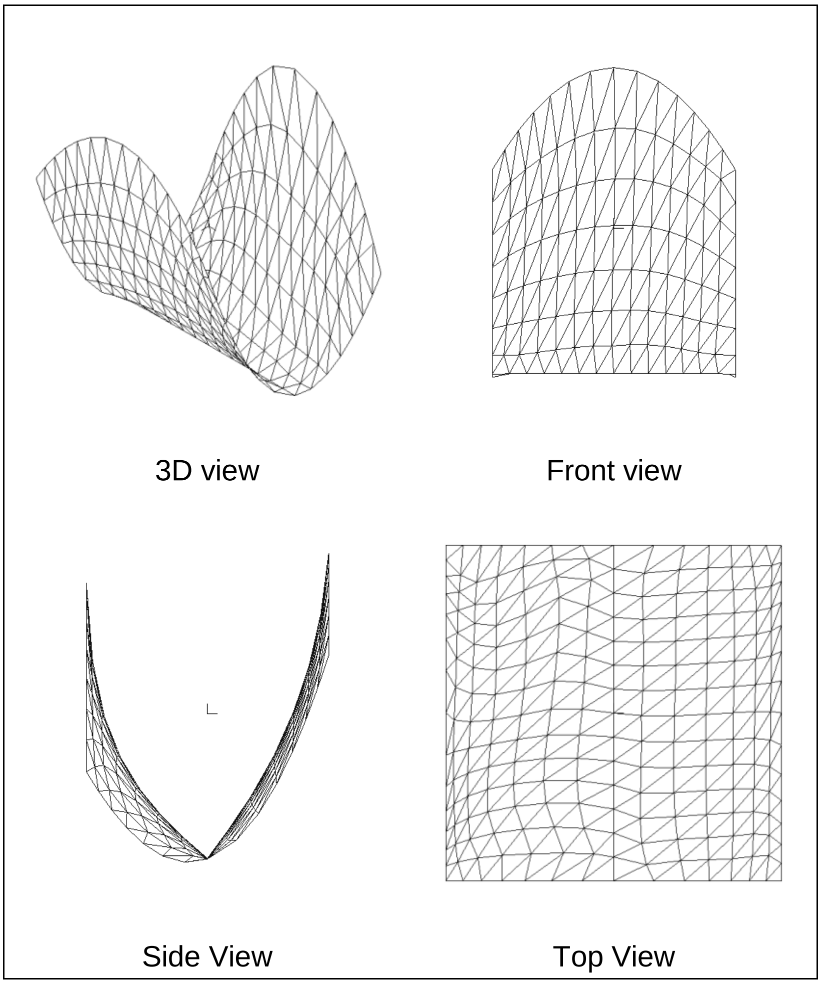


Figure 7. Initial Equilibrium Shape Cable Reinforced Handkerchief Surface, *u*=*v*=0.6

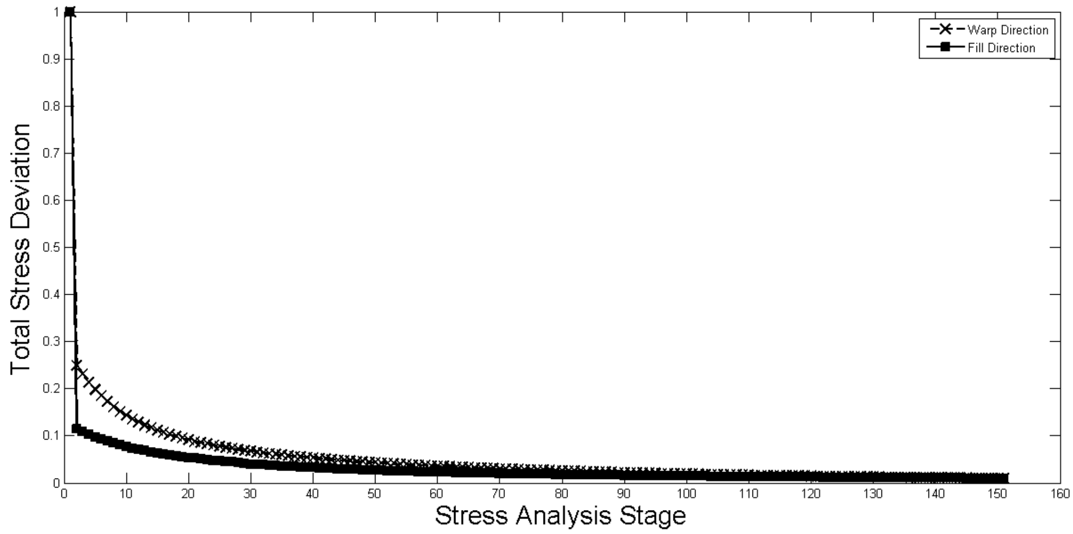


Figure 8. Convergent curve of Cable Reinforced Handkerchief Surface, *u*=*v*=0.6

CONCLUSION

The converged shape and initial equilibrium shape cable reinforced of Handkerchief surface, *u*=*v*=0.6 has been carried out successfully using the form-finding adopted which is based on nonlinear analysis method by [7]. Aspect of modelling of surface of Handkerchief surface and form as well as pre-stress pattern of the resulting TFS through form-finding using nonlinear analysis method proposed by [7] has been studied. The variable of Handkerchief surface, *u*=*v*=0.6 obtained in this study will provide alternative shapes for designers to consider in the adoption of tensioned fabric structure.

REFERENCES

[1] Pargana. J.B. and Leitão. V.M.A. (2015). A simplified stress-strain model for coated plain-weave fabrics used in tensioned fabric structures. *Engineering Structures.* 84: 439–450.

[2] Bridgens. B. and Birchall. M. (2012). Form and function: The significance of material properties in the design of tensile fabric structures. *Engineering Structures*, 44: 1–12.

[3] Pan. Q. and Xu. G. (2011). Construction of minimal subdivision surface with a given boundary. *Computer-Aided Design,* 43(4): 374–380.

[4] Li Y. and Guo. S. (2017). Triply periodic minimal surface using a modified Allen–Cahn equation. *Applied Mathematics and Computation.* 295: 84–94.

[5] Sindel. F., Nouri-Baranger. T. and Trompette. P. (2001). Including optimisation in the conception of fabric structures. *Computers & Structures*, 79(26–28): 2451–2459.

[6] Cenanovic. M., Hansbo. P. and Larson. M.G. (2015). Minimal surface computation using a finite element method on an embedded surface. *International Journal for Numerical Methods in Engineering*, 104(7): 502–512.

[7] Yee. H.M. (2011). A computational strategy for form-finding of tensioned fabric structure using nonlinear analysis method. *Ph.D. dissertation, School of Civil Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia.*

[8] Yee. H.M. and Choong. K.K. (2016). A Computational Mechanics using Nonlinear Analysis Method in Tensioned Fabric Structure. *International Journal of Mechanics*, 10: 261–265.

[9] Yee. H.M. Choong. K.K. and Abdul Hadi. M.N. (2015). Sustainable Development of Tensioned Fabric Green Structure in the Form of Enneper. *International Journal of Materials, Mechanics and Manufacturing*, 3(2): 125–128.

[10] Yee. H.M., Choong. K.K., and Kim. J.Y. (2011).). Form-Finding Analysis of Tensioned Fabric Structures Using Nonlinear Analysis Method. *Advanced Materials Research*, 243–249: 1429–1434.

[11] Yee. H.M. And Abdul Hadi. M.N. (2015). Enneper in Tensioned Fabric Structures Engineering Development. In *Conference on Mathematical and Computational Methods in Science and Engineering*. Renaissance Kuala Lumpur Hotel, Malaysia, April 23-25, 2015.

[12] Yee. H.M. and Abdul Hadi. M.N. (2015). Tensioned Fabric Structures with Surface in the Form of Chen-Gackstatter and Monkey Saddle. *International Journal of Structural and Civil Engineering Research*, 4(4): 331–335.

[13] Yee. H.M., Abdul Hamid. H. and Abdul Hadi. M.N. (2015). Computer Investigation of Tensioned Fabric Structure in the Form of Enneper Minimal Surface. *Applied Mechanics and Materials*, 754–755: 743–746.

[14] Yee. H.M., Kim. J.Y. and Mohd Noor. M.S. (2013).). Tensioned Fabric Structures in Oval Form. *Applied Mechanics and Materials*, 405–408, 1008–1011.

[15] Yee. H.M., and Samsudin. A. (2014). Development and Investigation of the Moebius Strip in Tensioned Membrane Structures. *WSEAS Transactions on Environment and Development*, 10: 145–149.

[16] Abdul Hadi. M.N., Yee. H.M., Ghani. K.A. and Abdul Hamid. H. (2016). Architectural Tensioned Fabric Structure in Monkey Saddle Form. *International Journal of Control Theory and Applications*, 9(6): 2753–2758.

[17] Yee. H.M. and Abdul Hadi. M.N. (2016). Tensioned Fabric Structures with Surface in the Form of Chen-Gackstatter. *MATEC Web of Conferences*, 64: 7001.

[18] Yee. H.M. and Abdul Hadi. M.N. (2016). Soap film Enneper model in structure engineering. *Advanced Materials, Structures and Mechanical Engineering: Proceedings of the International Conference on Advanced Materials, Structures and Mechanical Engineering, Incheon, South Korea, May 29-31, 2015*. CRC Press, pp. 1.

[19] Yee. H.M., Abdul Hadi. M.N., Ghani. K.A. and Abdul Hamid. N.H. (2016). Tensioned Fabric Structures with surface in the form of Monkey Saddle surface. In *Advanced Materials, Mechanical and Structural Engineering: Proceedings of the 2nd International Conference of Advanced Materials, Mechanical and Structural Engineering (AMMSE 2015), Je-ju Island, South Korea, September 18-20, 2015*. CRC Press, pp. 191.

[20] Yee. H.M. and Samsudin. A. (2014). Mathematical and Computational Analysis of Moebius Strip. *International Journal of Mathematics and Computers in Simulation*, 8: 197–201.

[21] Mohd Noor. M.S., Yee. H.M., Choong. K.K. and Haslinda. A.H. (2013). Tensioned Membrane Structures in the Form of Egg Shape. *Applied Mechanics and Materials*, 405–408: 989–992.

[22] Gray A. (1998). Modern Differential Geometry of Curves and Surfaces with Mathematica. *United States of America*.

[23] WolfarmMathWorld. In: Handkerchief Surface from http://mathworld.wolfram.com/HandkerchiefSurface.html. [Accessed 29 April 2017].

[24] Bathe. K.J. (2003). ADINA system. *ADINA R&D Inc.*

Journal of Science and Technology in The Tropics (2016) 12(2): 73 – 79

Form-Finding of Tensioned Fabric Structure in the Half-Costa YZ-Plane

Yee Hooi Min, Nurul Afiqah Abd Malek

[1] Universiti Teknologi MARA, 13500 Permatang Pauh, Pulau Pinang, Malaysia
(*corresponding author: yhooimin@yahoo.com)

Received: 25.10.2016 ; accepted 20.12.2016

Abstract Tensioned fabric structures (TFS) are structures that have flexible membranes and highly suited for construction areas to maintain the concept of sustainability development, the new form and complex TFS need to be found in order to generate continuity in the development of TFS. However, research study on a new form of half-Costa TFS model in YZ-plane with different, has not obtained attention from researchers over the world. The objectives of this study are to propose suitable boundary of half-Costa TFS model in YZ-plane and carry out its form-finding. This study also incorporates computational form-finding using nonlinear analysis method. The results of this study serve as a reference for proper selection of most suitable parameters to increase the performance of TFS by considering the factor of selecting suitable boundaries. In order to achieve the objectives of this study, proper computational analysis needs to be adopted such as the convergence curve theory that value obtained must be less than 0.01. The possible initial equilibrium shapes for half-Costa TFS models in YZ- plane are obtained thru form-finding analysis. Additionally, different boundaries and geometries of half-Costa in YZ-plane will provide an alternative form for design engineer and architects to adopt in the design of TFS. The outcomes of this study indirectly relate to the betterment in achieving the sustainability development and green building concept that is beneficial for future consideration.

Keywords Tensioned Fabric Structure; half-Costa Minimal Surface and Form-Finding using Nonlinear Analysis Method**.**

INTRODUCTION

The basic components to provide a roofing structure of TFS are composed of fabric structure as a structural member, seam, supporting system, and cable. [1] has stated that TFS are the composition of tensioned fabrics that are joined together at seams and tensioned through cable and attached to a rigid supporting system in order provide a roofing structure. Figure 1 shows the product of TFS.

Figure 1. Munich Olympic Complex in 1972

The idea of the TFS has begun in nomadic cultures as they created structures for their shelter. The earlier constructions of TFS are made from animal skin draped between sticks. The most popular TFS is a tent. Tent is a roofing structure that serves as a temporary support, used to provide protection against the elements. Nowadays, there are many well-known structures that have applied the concept of TFS. The development of TFS is slightly influenced by the development in the areas of computer technology and programming. TFS is a configuration of structural elements that carry loads through pure tension. According to [2], the yarns are weaved in such a way that threads are perpendicular to one another apart from being alternately passed over and under each other; the long straight yarns are called warp yarns and the parallel direction yarns are called fill yarns. The common materials used as fabric structures are polyester and fiber glass. Attractive coating fabric materials used in the industry for polyester and fiber glass fabrics are Polytetrafluoroethylene (PTFE) and Polyvinyl chloride (PVC). The objectives of this study are to propose suitable boundary of half-Costa TFS model in YZ-plane and to carry out its form-finding by using nonlinear analysis method.

Generation of Half-Costa TFS Model in YZ-Plane

The minimal surface is a group of surfaces that has smallest area spanned by a given boundary. Most of tensioned fabric structures are design to have a uniform prestress in their fabrics. This way, the shear stress in fabric can be eliminate [2]. [3] has mentioned that the theory of minimal surface is branch of mathematics that have been intensively developed and also applied in architecture and engineering concepts. Oval and egg shape are among the earlier shapes studied compared to other forms [4, 5]. It is then followed by the form-finding of tensioned fabric structures in the form of Moebius Strip by [6] and the same form has been studied for its application on tensioned membrane structures by [7]. Then, the problem of Moebius Strip in mathematical modelling is then highlighted also by [7]. On top of that, the form-finding of Enneper minimal shape has been carried out using nonlinear analysis method that too aims for an alternative design for engineer to consider [8] as well as sustainable development [9]. In 2015, the form-finding of TFS are carried out in the form of

Chen-Gackstatter and Monkey Saddle [9]. The form of Monkey Saddle is then investigated again in 2016 by [2].

The complete minimal surface basically consists of three different groups which are embedded, properly immersed and non-properly immersed. The embedded minimal surface can be further categorised into finite topology, finite topology in a quotient spaceform and infinite topology. In other words, Costa minimal surface is a complete minimal surface of finite total curvature [10]. This means that the surface has no boundary and it does not intersect with itself. Costa minimal surface was found on 1982 when it satisfies three properties of complete minimal surface that are the shape must continue forever in every direction, it does not has infinite twisting and it never intersects itself.

Figure 2 illustrates the form of half-Costa TFS model in YZ-plane by [1]. This minimal shape can be denoted by three equations as follow:

$$x = \frac{1}{2}\boldsymbol{\mathcal{R}}\left\{-\zeta(u+iv) + \pi u + \frac{\pi^2}{4e_1} + \frac{\pi}{2e_1}\left[\zeta\left(u+iv-\frac{1}{2}\right) - \zeta\left(u+iv-\frac{1}{2}i\right)\right]\right\} \quad \ldots(1)$$

$$y = \frac{1}{2}\boldsymbol{\mathcal{R}}\left\{-i\zeta(u+iv) + \pi v + \frac{\pi^2}{4e_1} - \frac{\pi}{2e_1}\left[i\zeta\left(u+iv-\frac{1}{2}\right) - i\zeta\left(u+iv-\frac{1}{2}i\right)\right]\right\} \quad \ldots(2)$$

$$z = \frac{1}{4}\sqrt{2\pi}\ln\left|\frac{\wp(u+iv)-e_1}{\wp(u+iv)+e_1}\right| \quad \ldots(3)$$

Where ζ(z) is the Weierstrass zeta function and $\wp(g_2, g_3; z)$is the Weierstrass elliptic function with $(g_2, g_3) = 189.072772\ldots, 0$, the invariants correspond to the half-periods ½ and i/2, and the first root is $e_1 = \wp\left(\frac{1}{2}; 0, g_3\right) = \wp\left(\frac{1}{2}\middle|\frac{1}{2}, \frac{1}{2}i\right) \approx 6.87519$ where$\wp(z; g_2, g_3) = \wp(z|\omega_1, \omega_2)$ is the Weierstrass elliptic function [10]. Finally, the half-Costa is obtained from Costa that has been divided vertically. These polar coordinates equation will be applied in MATLAB software to view the shape with respective to the x, y and z coordinate. The changes to u and v parameters will affect the generated shape. Then these coordinates will be transferred to ADINA to create half-Costa TFS model in YZ-plane.

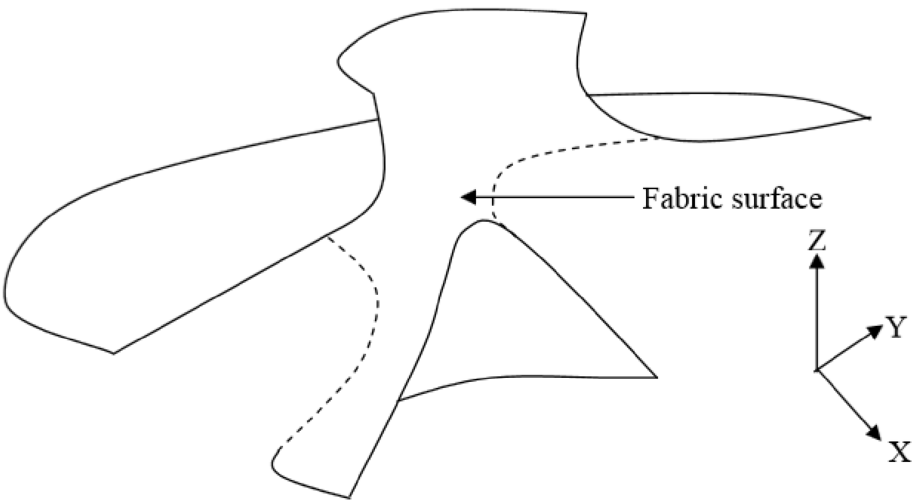


Figure 2. Half-Costa Model in YZ-Plane

METHODOLOGY

Form-Finding using Nonlinear Analysis Method

The principle of proposed nonlinear analysis method by [11] is based on the large displacement finite element formulation used for analysis of structural behaviour under external loads. The computational approach using nonlinear analysis method can be used in order to determine and solve for both the initial equilibrium problem and load analysis.

Nonlinear finite element analysis procedures for different pre-stress analysis of TFS have been introduced and used as a basis for form-finding analysis in this study. There are two half-Costa TFS models in YZ-plane are proposed. The initial guess shape for every model are first determined before the form-finding analysis is carried out. Apart from that, in order to generate a better initial guess shape anticlastic feature is incorporated into every model of TFS. The model generation obtained by implementation of ADINA software. The concept of anticlastic feature are defined the specification of selected sag, Δ, relative to two suitably chosen points on the fixed boundary with span, L. ADINA software is the primary software behind the analysis of TFS models utilize to purposed mesh generation for selected model.

Additionally, the warp and fill direction must be properly presented based on its refrence element. This is to ensure that the results are accurate and precise [12]. This computational strategy involves two stages of analysis that are occuring in a cycle. The updated shape for initial equilibrium surface is obtained in first stage (denoted as SF1) by using pre-processing software. The convergence of updated shape obtained at the end of stage SF1 is checked in the second stage of analysis (denoted as SS1). The very small values of elastic modulus, E are used, while warp and fill stresses, σ_W and σ_F are kept constant during SF1 stage. On top of that, the actual tensioned fabric properties values are used in the second stage SS1. Consequently, the warp and fill stresses are checked against prescribed stresses at the end of the. In order to the obtain convergence criteria iterative calculation has been carried out and the resultant shape at the end of iterative step n (SSn) is considered to be in the state of initial equilibrium under the prescribed warp and fill stresses and boundary condition. At last, the total stress deviation in warp and fill direction versus stress analysis stage is presented for checking of difference in the obtained and prescribed stresses [1].

RESULT AND DISCUSSION

Computational Analysis of Half-Costa TFS Model in YZ-plane

The proposed computational analysis strategy is continued by the stress analysis whereby it is repeated until the convergence curve theory value obtained, the value must less be than 0.01 for every different boundary proposed. Table 1 and Table 2 are presenting different views of half-Costa TFS Model 1 and Model 2 with their respective initial assumed shaped and initial equilibrium shape.

Table 1. Views of the Initial Assumed Shape and Initial Equilibrium Shape of Model 1

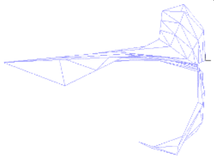
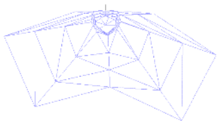
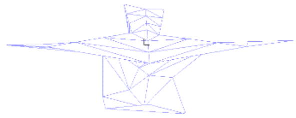
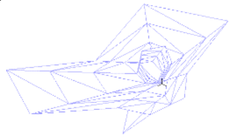
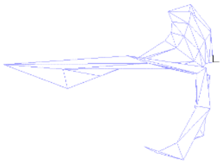
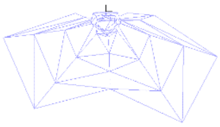
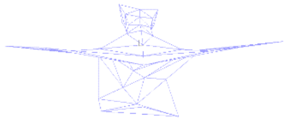
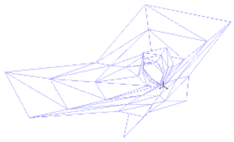
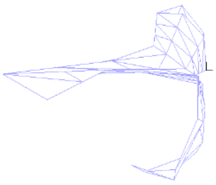
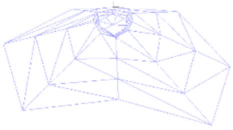
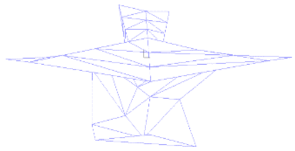
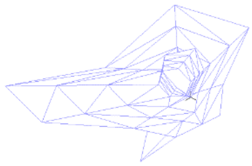
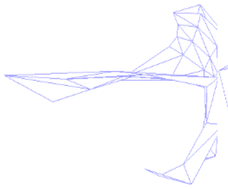
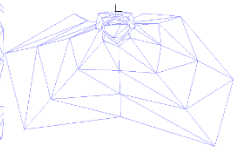
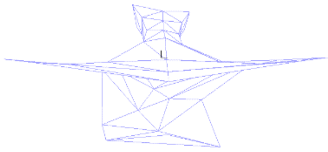
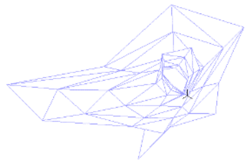
Model 1	YZ-View	XY-View	XZ-View	3D View
Initial Assumed Shape				
Initial Equilibrium Shape				

Table 2. Views of the Initial Assumed Shape and Initial Equilibrium Shape of Model 2

Model 2	YZ-View	XY-View	XZ-View	3D View
Initial Assumed Shape				
Initial Equilibrium Shape				

Initially, Model 1 and Model 2 are proposed to have very distinct boundaries. Model 1 is proposed with circular boundary and Model 2 having a rectangular boundary. Consequently, after the meshing is carried out, both models appear to be very similar to one another. This might be due to the selection of u=v=3 that has created a rough shaped of these models. Nevertheless, the graph of total stress deviation versus stress analysis stage of Model 1 and Model 2 are very different from one another. Figure 3 illustrates the graph of total stress deviation versus stress analysis stage for Model 1 and Figure 4 is showing the graph of total stress deviation versus stress analysis stage for Model 2.

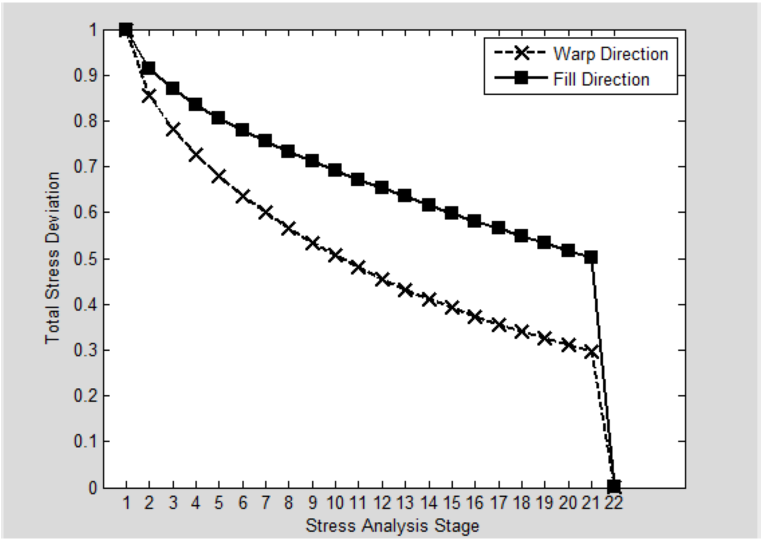


Figure 3. Graph of Total Stress Deviation versus Stress Analysis Stage for Model 1

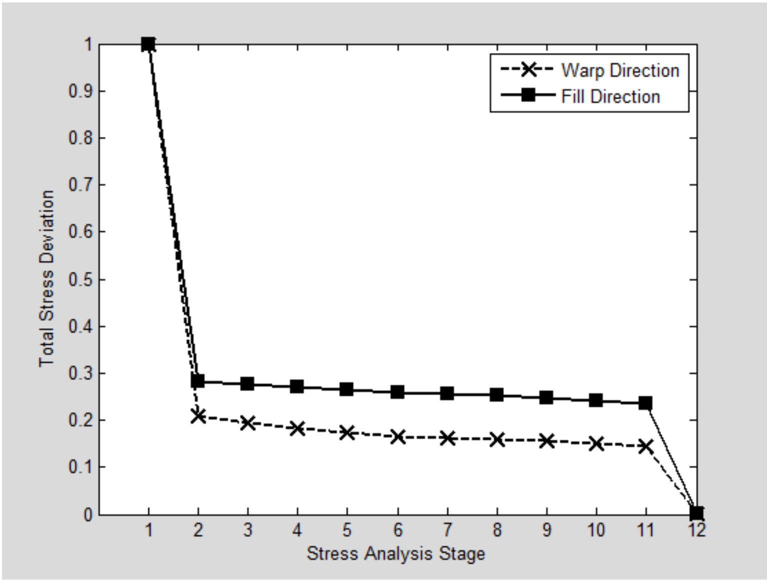


Figure 4. Graph of Total Stress Deviation versus Stress Analysis Stage for Model 2

Apart from the difference shown by the graphs, Model 1 and Model 2 are varied by the values of its total stress deviation in warp and fill stresses. Those values are presented in Table 3.

Table 3. The Total Stress Deviation in Warp and Fill Directions

Total Stress Deviation	Model 1	Model 2
Warp Direction	0.000343	0.000311
Fill Direction	0.002584	0.001428

CONCLUSION

Half-Costa TFS models have been analysed for its difference in boundaries. Iterative calculation has been carried out in order to achieve convergence criteria of form-finding adopted. As mentioned earlier, the total warp and fill stress deviation for half-Costa TFS models should be less than 0.01. After convergence has been achieved, the initial equilibrium shape is obtained. Form-finding of TFS in the form of half-Costa TFS model with different have been carried out successfully based on nonlinear analysis method. The results from this computational study showed that TFS in the form half-Costa minimal surface in YZ-plane with circular and rectangular boundaries are structurally viable surface form to be considered.

REFERENCES

[1] Yee, H. M. (2011). *Form-Finding Analysis of Tensioned Fabric Structures using Nonlinear Analysis Method.* PhD Thesis, University of Science Malaysia, School of Civil Engineering, Nibong Tebal.

[2] Yee, H. M., & Abdul Hadi, M. (2016). Tensioned fabric structures with surface in the form of Chen-Gackstatter. *MATEC Web of Conferences. 64*, pp. 1-5. EDP Sciences.

[3] Velimirović, L. S., Radivojević, G., Stanković, M. S., & Kostić, D. (2008). Minimal surfaces for architectural constructions. *Architecture and Civil Engineering , 6*, 89-96.

[4] Yee, H. M., Kim, J.-Y., & Mohd Noor, M. (2013). Tensioned fabric structures in oval form. *Applied Mechanics and Materials , 405-408*, 1008-1011.

[5] Mohd Noor, M., Yee, H. M., Choong, K. K., & Abdul Hamid, H. (2013). Tensioned membrane structures in the form of egg shape. *Applied Mechanics and Material , Vol. 405-408*, 989-992.

[6] Yee, H. M., & Choong, K. K. (2013). Proposed algorithm for warp direction checking in tensioned fabric structures. *International Journal of Scientific Research in Knowledge , 1*, 13-19.

[7] Yee, H. M., & Samsudin. (2014). Development and investigation of the Moebius Strip in tensioned membrane structures. *WSEAS Transactions on Environment and Development , 10*, 145-149.

[8] Yee, H. M., Abdul Hamid, H., & Abdul Hadi, M. (2015). Computer investigation of tensioned fabric structure in the form of Enneper minimal surface. *Applied Mechanics and Materials , Vols. 754-755*, 743-746.

[9] Yee, H. M., Choong, K. K., & Abdul Hadi, M. (2015). Sustainable development of tensioned fabric green structure in the form of Enneper. *International Journal of Materials, Mechanics and Manufacturing , Vols. 3* (No. 2), 125-128.

[10] Weisstein, E. (2017, March 17). *MathWorld*. Retrieved March 22, 2017, from Wolfram Mathworld: http://mathworld.wolfram.com

[11] Yee, H. M., & Choong, K. K. (2016). A computational mechanics using nonlinear analysis method in tensioned fabric structure. *International Journal of Mechanics , 10*, 261-265.

[12] Yee, H. M., & Choong, K. K. (2013). Form-finding of tensioned fabric structure in the shape of Möbius Strip. *Iranica Journal of Energy & Environment 4 {(3) Geo-hazards and Civil Engineering)}* , 251-257.

[13] Yee, H. M., & Samsudin. (2014). Mathematical and computational analysis of Moebius Strip. *International Journal of Mathematics and Computers in Simulation , 8*, 197-201