Enneper in Tensioned Fabric Structures Engineering Development

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Abstract: - Numerical and experimental form-finding of tensioned fabric structure in the form of Enneper minimal surface has been investigated. In this study, form-finding using nonlinear analysis method and soap film is used to determine the surface form corresponding to a boundary shape defined by the mathematical equation for Enneper minimal surface with variable $u$ and $v = 0.4$. It provides an alternative choice for civil engineer to consider the Enneper minimal surface, $u = v = 0.4$ to be applied in tensioned fabric structure. Such in-sight will lead to improvement of rural basic infrastructure, economic gains, sustainability of built environment and green technology initiative.

Key-Words: - Form-finding, minimal surface and nonlinear analysis method

1 Introduction
Tensioned Fabric Structure (TFS) is a suitable structure to be used for long span application. TFS also known as tensioned membrane structure. Actually, TFS has been used over the past 50 years ago. [1] has stated the structure of TFS can be composed of fabric structural as structural members. The material is usually used is fabric, fabric is used to joined together with the structure. Fabric is tensioned through with the cable to a rigid supporting system to typically and to provide a roofing structure.

Enneper minimal surface is suitable used for TFS. The first step for structural analysis in TFS is form-finding. Form-finding is to determine the initial equilibrium shape under pre-stress pattern and boundary condition. [1] has proposed nonlinear analysis method for form-finding of tensioned fabric structures in the form of Enneper minimal surface. Applicability of the computational strategies proposed by [1] has been verified by form-finding carried out models of tensioned fabric structures in the one of the form of Enneper minimal surface [2]. Convergence was able to achieve in form-finding of Enneper TFS models. [1] showed that when $u = v \leq 0.87$, the converged shape is found to be similar to the mathematical shape. For Enneper TFS model ($u = v \geq 0.88$), the shape obtained after form-finding are found to be different from the form of Enneper surface defined by mathematical shape equation. [1], [2], [3], [4] and [5] has carried out form-finding using nonlinear analysis method also in Catenoid, Helicoid, Scherk, Enneper, Oval and Moebius Strip TFS models. In this study, only form-finding using nonlinear analysis method of Enneper minimal surface with variable $u$ and $v = 0.4$ has been carried out.

2 Generation of Enneper Minimal Surface in TFS

Fig. 1 Different views for Enneper minimal surface

Fig. 1 shows Enneper minimal surface. The boundary of Enneper minimal surface in Fig. 1 can be obtained using Eq. 1 [6].
\[ X = u - \frac{v^2}{3} + uv^2 \]
\[ Y = -v + \frac{v^2}{3} - vu^2 \]
\[ Z = u^2 - v^2 \]  

(1)

For \( u \) and \( v \) are variables.

From this study, the software ADINA [7] has been used for the purpose of model generation. Aspect of modeling of surface of Enneper minimal surface and form as well pre-stress pattern of the resulting TFS through form-finding using nonlinear analysis method are studied. Material properties for Enneper Poisson’s ratio corresponds to warp direction, \( v_w = 0.84 \), Poisson’s ratio corresponds to fill direction, \( v_f = 0.57 \) and Modulus of elasticity of cable, \( E_c = 1.4 \times 10^{11} \text{ N/m}^2 \).

3 Numerical Method using Nonlinear Analysis Method

A nonlinear finite element analysis program by [1] for the analysis of tensioned fabric structures has been used in this study. The procedure adopted is based on the work by [1]. 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 Enneper minimal 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 [1]. First stage (denoted as SF1) is analysis which starts with an initial assumed shape in order to obtain an updated shape for initial equilibrium surface. The initial assumed shape can be obtained from any pre-processing software and reference [1] is chosen for this study. This is then followed by the second stage of analysis (SS1) aiming 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 of (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 of 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 initial equilibrium under the prescribed warp and fill stresses and boundary condition if 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 assumed shape is needed. For the generation of such initial assumed 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 assumed shape.

4 Experimental Method using Soap Film

The experimental soap film model is based on [1] work. The material and equipment have been used in the project is steel, aluminium wires, plywood, super glue, rubber band, wire, glycerin, concentrated

Fig. 2 Soap film model

Fig. 3 Soap film model with boundary frame
car detergent, distilled water, theodolite, plumb bob and camera.
The boundary frame on the surface has been built based on the coordinate. The coordinates has been calculated using mathematical equations. Plywood has been used as x-coordinate and y-coordinate of the boundary, standing steel rods has been used to support the wire frame at the desired height corresponding to z coordinate of the wire frame. Aluminum wires have been used to build the boundary of models. Super glue has been used to fix the steel and plywood. The rubber band has been used to secure the wire to steel rods. The wire has been tied to the steel rod at specified coordinates with rubber bands in order to produce the desired boundary defined by equations Enneper minimal surface. Then, glycerin, concentrated car detergent and distilled water used to prepare a soap solution. The preparation of soap solution has been contained the composition of water, detergent and glycerin. The composition used is 25.7% of glycerin, 22.8% of concentrated car detergent and 51.1% of distilled water.

Fig. 4 Experiment Setup

Experimental setup form-finding using soap film model has been carried out as shown in Fig. 4. In this experimental setup contain theodolite, hydraulic jack, container with soap solution, steel frame and physical model. Soap film model has been used to determine the surface form corresponding to the boundary shape defined by mathematical equations for Enneper minimal surface in detail.

5 Comparison between Nonlinear Analysis Method and Soap Film Model

Fig. 5 Soap film model, \( u=v=0.4 \)

Fig. 6 Comparison of experimental and computational results of Enneper minimal surface, \( u=v=0.4 \). The result is found to be in close agreement. The geometry between experimental and computational result has been found to match very closely.

6 Conclusion

Soap film model with surface shape in close agreement with mathematically defined Enneper surfaces, \( u=v=0.4 \) has been produced. Enneper surfaces, \( u=v=0.4 \) provides an alternative choice for civil engineer to consider the tensioned fabric green structure in the form of Enneper minimal surface. The Enneper surfaces, \( u=v=0.4 \) would enhance the understanding on the suitable choice of Enneper minimal surface for TFS among practicing engineers.

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References:


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