Numerical analysis cable reinforced membrane in hybrid power generating system subjected to wind forces

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ABSTRACT

Numerical analysis of membrane blades of hybrid power generating system (Lotus-1) subjected to wind pressure is executed by using Bendable Element Method (BEEM) [1]. In winter season, this system works as windmill and in summer season, works as solar power generating system by changing its configuration. The surface of membrane blade can reflect solar radiation and to focus them to photovoltaic (PV) panels. In order to keep smooth surface, pre-tensile membrane stress is introduced by cables. The main aim of this numerical analysis is to investigate the safety of membrane material and focusing ability of the surface of blade subjected to wind force. As the results, it appeared that the maximum principal stress is small enough compare to the maximum strength of membrane. The focal point on the PV panel draft 0.25m and 0.65m at the case of 17m/s (15kgf/m^2) and 42m/s (90kgf/m^2), respectively.

1. Introduction

In the past, high standards of living and modern lifestyles were based on increased energy consumption. Today, statistics from highly developed countries show that standards of living can increase independently of energy consumption if energy efficiency measures are introduced. In 1999, the global demand for electricity was about 14,764×10^9 kWh [2]. This demand was met mainly though fossil fuels and nuclear power. Renewable energies were only 2% share. To decrease air pollution and peril of nuclear energy, highly developed industrial countries, have started to limit their energy consumption, without decreasing their living standards, by encouraging energy efficiency and energy efficient technologies. These energies include wind power generation and photovoltaic generation. Recently, the wind power generation uses two or three blades (Horizontal axis rotor) and the blades size are going during rotation of its blades. The new energy development is actively done for measures for safety of energy as for Japan since oil crisis. The interest rises rapidly from the local government and the private sector, and as for wind power generation as new energy, Japan can have ratified to the Kyoto Protocol in 1997, it reproduce more and more, and clean wind power generation as energy and the development of the photovoltaic generation become active backing up the subsidy system by the environmental problems in recent years. However, there are various problems in the use of clean energy.

1) Solar energy can be generated in the photovoltaic generation only in daytime, and its cost is still high in Japan.

2) Most of a large-scale wind power generation greatly receives the restriction to conditions of location, and it takes too much time for redemption caused by wind directivity, high the construction

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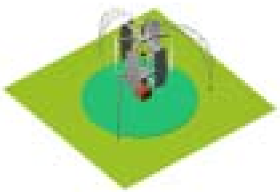
and only 20% or less utilization rates during one year. By above mentioned reasons, those power generators can not make benefit as commercial base. So, most of this power generating systems are constructed by the fund of subsidy system of the government. We are required more effective power generating system without these kinds of fund. In this paper, a new hybrid power generating system is proposed. To reduce cost of this system, reflecting membrane is used for more effective generating system of PV panel. The main aim of this paper is to investigate the safety of membrane material and focusing ability of the surface of blade at the summer season by using BEEM.

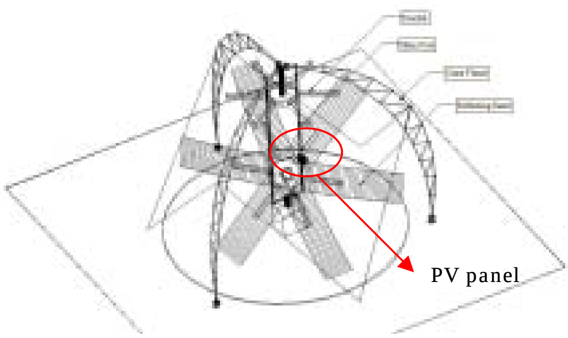
2. Model for analysis

Fig.1 shows configuration of hybrid power generating system. This system consists of six membrane blades which can use solar and wind energy as one system as shown Fig. 1 (a) and (b), respectively.



(a) Using wind energy

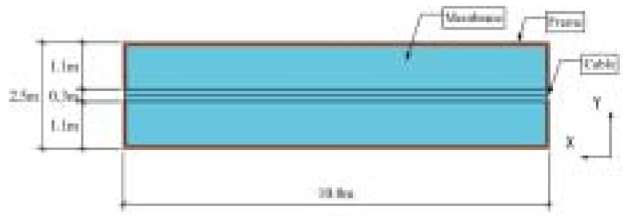
(b) Using solar energy



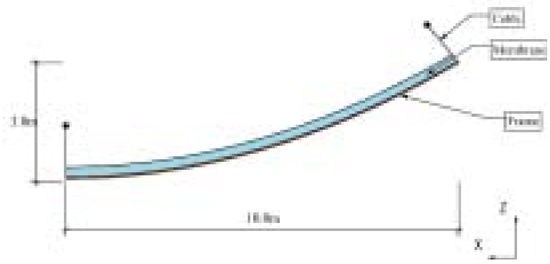
(c) Perspective

Fig.1 Configuration of Lotus-1

Each blade size is 10m length and 2.5m wide. The analysis model is shown as Fig 2. The Young's modulus of cable is 1,600tonf/cm^2 and membrane (membrane of 'A' series) is 143tonf/m (warp), 97tonf/m (weft). For the membrane material it is convenient to use unit of tonf/m instead of tonf/m^2 by virtue of uniform thickness. Poisson's ratio of membrane is 0.84 (warp) and 0.57 (weft). And shear modulus of membrane is 6.47tonf/m. The maximum tensile strength is assumed as 15,000kgf/m.



(a) Analysis model size (floor plan)



(b) Analysis model size (elevation)

Fig.2 Analysis model of one blade

3 Introduction of Bendable Element Method

3.1 Concept of bendable element

FEM is often used for shape finding problem of membrane structures. However, if we want to analysis cable reinforced membrane structures by using conventional FEM, the following problems may arise.

Let consider the system that consists of a sheet of membrane and a cable as shown in Fig.3 (a). The membrane consists of four FE meshed and has the cable just on its mesh-boundary-line. When the cable fixed on the surface of the membrane and if slides on it, it is considered that nodal points of the cable and membrane may move together as shown in Fig. 3. (b). But if the cable be fixed on membrane surface stress concentration may be aroused when wind force act on them. So in usual case the cable is not fixed on the surface of the membrane. In that case, the two nodal points will be separated according to slide like as Fig. 3 (c) and it is necessary to regenerate finite element meshes at every discrete time step because of small gap between them. Moreover, the relative slides between two objects give rise to some friction force which influences the behavior of the system. It is very difficult to consider the influences of friction between them. In order to deal with those problems, new element for FE analysis is introduced. In this element nodal points of a cable and membrane are permitted to move separately and such nodal points make 'new bendable line' as shown in Fig. 3 (c). This element is defined as 'bendable element'.

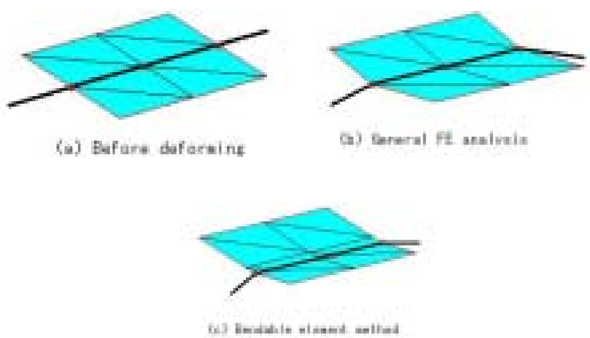


Fig. 3 Concept of bendable element

3.2 One triangular element and one cable element system

Let consider a simple system that consists of one triangular membrane element and one cable element shown as Fig.4. Fig.4 (a) shows the shape at the k-step, and Fig.4 (b) shows at the (k+1) step.

When displacement $\{\Delta x_a\}$ and $\{\Delta x_b\}$ at the both ends of the cable are given, the membrane element is bent, and its nodal points *i, j, k, p, q* in the element transfer to *i', j', k', p', q'* as show in Fig.4 (b). The points *p', q'* where the cable intersects with the membrane element are defined as 'sliding nodal point'. Following assumptions are introduced.

1) Strain and stress of a membrane element is treated as a plane stress problem.
2) Strain and stress of the triangular membrane element (bendable element) distribute equally throughout the element.
3) When the folded membrane element is unfolded, it becomes just a flat triangle.
4) The cable and membrane are linearly elastic.

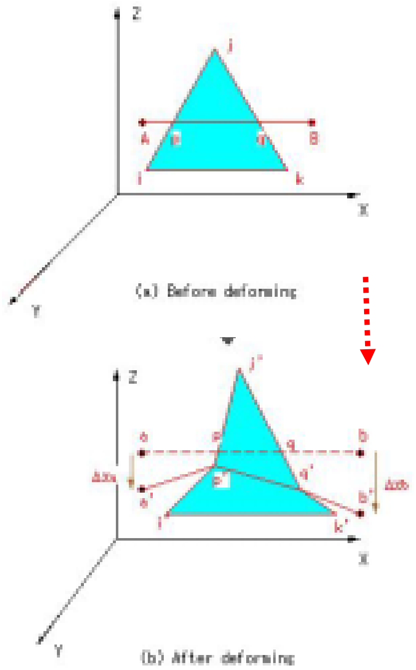


Fig.4 Bendable element and slide nodal point

3.3 Incremental potential energy of a bendable element

Incremental potential energy ΔW_e of a triangular membrane element for one incremental loading step can be obtained by term of its nodal displacements. Stress and strain in this triangular element distribute uniformly, which the coordinate of the element transform to the system of x-y coordinates concerning this triangular plane. Let consider local coordinate shown in Fig.5 (b), length of two sides r'_1 , r'_2 of unfolded triangular element after deforming is calculated by using the following expressions.

$$\Delta u_k = k''_x - k_x$$
$$\Delta u_j = h_x - j''_x \qquad (1)$$
$$\Delta v_j = h_y - j''_y$$

Each incremental nodal displacement of the triangular element can be expressed with only these relative values of Δu_k, Δu_j, Δv_j as shown in Fig.5 (b).

$$r_1' = \left|\overline{i'p'}\right| + \left|\overline{p'j'}\right|$$

$$r_2' = \left|\overline{k'q'}\right| + \left|\overline{q'j'}\right| \tag{2}$$

Incremental strain $\{\Delta\varepsilon\}$ for this incremental step is calculated by using the following formula.

$$\{\Delta\varepsilon\} = [B]\{\Delta\delta^e\} \tag{3}$$

where: $\{\Delta\delta^e\}^T = \{0, 0, \Delta u_k, 0, \Delta u_j, \Delta v_j\}$,

$$[B] = \begin{bmatrix} b_i & 0 & b_k & 0 & b_j & 0 \\ 0 & c_i & 0 & c_k & 0 & c_j \\ c_i & b_i & c_k & b_k & c_j & b_j \end{bmatrix},$$

where: $b_i = y_k - y_i, c_i = x_j - x_k$.

Incremental stress is calculated from incremental strain $\{\Delta\varepsilon\}$

$$\{\Delta\sigma\} = [D]\{\Delta\varepsilon\} \tag{4}$$

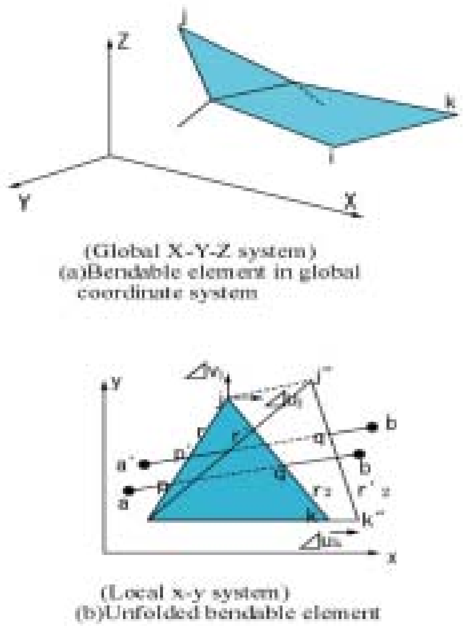


Fig.5 Global and local coordinate

For anisotropic material [D] can be expressed as follows.

$$[D] = \frac{E_2 t}{1 - \tilde{E}tV_{21}^2} \begin{bmatrix} \tilde{E}\,t & \tilde{E}\,tV_{21} & 0 \\ \tilde{E}\,tV_{21} & 1 & 0 \\ 0 & 0 & \tilde{G}\,t\left(1 - \tilde{E}\,tV_{21}^2\right) \end{bmatrix}$$

where

$$\tilde{E}\,t = \frac{E_1 t}{E_2 t} \quad , \quad \tilde{G}\,t = \frac{G_{12} t}{E_2 t}$$

E_1t ,E_2t = Tensile Young's modulus in direction 1,2

$G_{12}t$ = in-plain shear modulus

v_{12} = Poisson's ratio for the stress in direction 1.

When the direction of strain is inclined to the x-axis then to obtain [D] matrices in the global coordinates a transformation is necessary. Taking [D*] as relating the stresses and strains in the inclined coordinate system (x', y') it is easy to express as

$$[D] = [T]\,[D^*]\,[T]^T \tag{5}$$

$$[T] = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & -2\sin\alpha\cos\alpha \\ \sin^2\alpha & \cos^2\alpha & 2\sin\alpha\cos\alpha \\ \sin\alpha\cos\alpha & -\sin\alpha\cos\alpha & \cos^2\alpha - \sin^2\alpha \end{bmatrix}$$

α = Inclination angle to x-axis

Incremental potential energy of this membrane element is expressed as follows.

$$\Delta We = \frac{1}{2}\left[\{\sigma\} + (\{\sigma\} + \{\Delta\sigma\})\right]^T \{\Delta\varepsilon\} \cdot S \tag{6}$$

where

S: area of triangular element

$\{\sigma\}$: Stress of the element at k-step

In usual formula of (6) the thickness of element is appeared but here it is included in material property.

3.4 Incremental potential energy of the cable

The tensile stress of the cable distributes uniformly when there is no friction. Incremental potential energy ΔW_c of the cable for one incremental step can be obtained by its nodal displacements. Incremental tension ΔT_c and potential energy of the cable ΔW_c are calculated from following expression.

$$\delta_{ab} = \left|\overline{a'p'}\right| + \left|\overline{p'q'}\right| + \left|\overline{q'b'}\right| - \left|\overline{ab}\right| \tag{7}$$

$$\Delta T_c = \frac{E_c A_c}{\left|\overline{ab}\right|} \times \delta_{ab} \tag{8}$$

$$\Delta W_c = \frac{1}{2} \times \left((\Delta T + T) + T\right) \times \delta_{ab} \tag{9}$$

Ec: Young's modulus of the cable,

Ac: The cross-sectional area of the cable

T: Tension of the cable at k-step

3.5 Incremental potential energy of external force

By using following expressions,

$$P_m = S_m \times \mathrm{Pa} \tag{10}$$

P_m : Nodal force equivalent to pressure.

S_m : One area of divided triangular element as Fig.6 where nodal force at nodal point m is equivalent to the pressure

Pa: pressure acting on the membrane element

Δ_m : Nodal displacement in the direction of force P_m

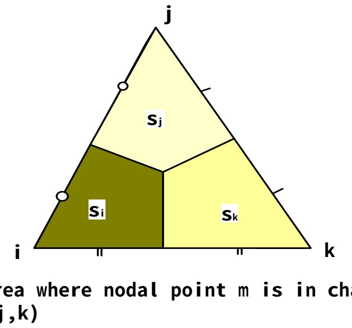


Fig.6 Calculation of nodal force

incremental external potential energy ΔW_p is calculated by

$$\Delta W_p = -\sum_m \left(P_m \times \Delta_m\right) \tag{11}$$

3.6 Penalty function

In order to geometrical constraint conditions, penalty function G_p is defined as follow.

$$G_p = \mu\left(\angle ip'q' + \angle j'p'q' - \pi\right)^2 + \gamma\left(\angle j'q'p' + \angle p'q'k' - \pi\right)^2 \tag{12}$$

where, μ, γ are arbitrary large constant values. If the element is unfolded the edge of the element must be straight. The inside terms in both parenthesis mean this constrain conditions.

3.7 Definition of target function and minimization procedure

The target function *f* which should be minimized is defined as Eq.(12). Unknown incremental nodal displacements are given by minimizing this target function.

$$f = \Delta W_c + \Delta W_e + \Delta W_p + G_p \Longrightarrow \text{Minimize} \tag{13}$$

In this paper, quasi-Newton algorithm is used for this aim.

4. Boundary conditions

The analyzed meshed model is shown as Fig. 7 and Fig. 8. This model was consisted of 66 nodal points, 100 triangular membrane elements and 23 cable elements. As boundary conditions, end points of cable are pulled down to z-axis ($\delta_{cable,z}$) in five steps (Step-1 to Step-5) and then six kinds of wind pressure of $Wp = \pm 15\ kgf/m^2$, $\pm 45 kgf/m^2$ and $\pm 90 kgf/m^2$ are given (Step-6 to Step-10). $\delta_{cable,z}$ are assigned as 25cm and 50cm. The 17th nodal point, 21st nodal point and 8th triangular element, 41st triangular element are used as a results.

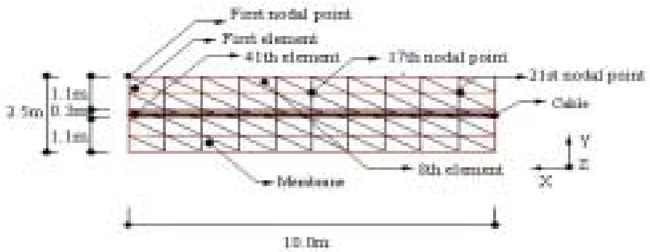
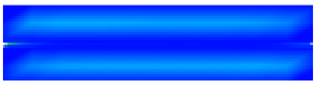


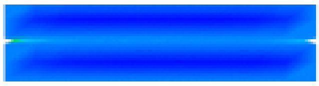
Fig.7 Meshed model

5. Results of analysis

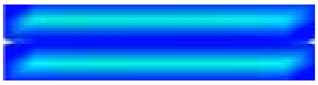
Distributions of principal stress σ_1 in the membrane elements are shown as Fig. 8 for different values of $\delta_{cable,z}$. The light zone represents higher level of principal stress σ_1. The maximum principal stress σ_1 are nearly same values and those are small enough comparing to the maximum strength 15,000kgf/m in spite of the difference of $\delta_{cable,z}$. But the distributions of principal stress are not uniform. The reason of this situation can be explained as follows. At the Step-5 (no wind pressure are given) the nodal displacement δz are slightly concave as shown in Fig.9. So, the symmetrical nature regarding to z-axis is broken. Nodal displacements δz for each loading step (Step-6 to Step-10) are shown as Fig. 10.



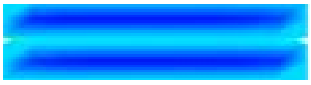
(a) Wp = 15kgf/m^2, $\delta_{cable,z}$=50cm, Max σ_1=1753kgf/m



(b) Wp = -15kgf/m^2, $\delta_{cable,z}$=50cm, Maxσ_1=1767kgf/m



(c) Wp = 90kgf/m^2, $\delta_{cable,z}$=50cm, Maxσ_1=2021kgf/m



(d) Wp = -90kgf/m^2, $\delta_{cable,z}$=50cm, Max σ_1=2068kgf/m

Fig. 8 Distribution of the principal stress σ_1 in the case of $\delta_{cable,z}$=50cm

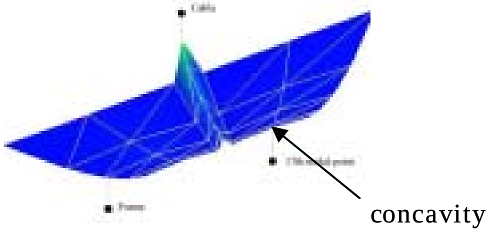
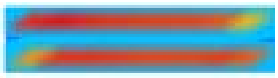


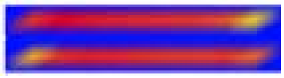
Fig.9 Deformed figure

It appeared that nodal displacements δz are not affected by wind pressure if Wp is positive values and $\delta_{cable,z}$ is large enough. In the case of Fig. 8 (c), Wp = 90kgf/m^2, the maximum displacements δz=16cm is arisen at the 17th point where is central point of this model. For the shake of this displacement, the original angle may change 14 degrees, and this degree means that the focus point moves 0.65m on the PV panel where locates 3m far from the membrane surface. This drift is too big to concentrate solar radiation. In the case of Fig. 9 (a), Wp = 15kgf/m^2, the maximum displacement of δz is 7.9cm at the same point. And it cause movement of focus 0.25m. Since 15kgf/m^2 is corresponding to 17m/s and 90kgf/m^2 is corresponding to 42m/s, respectively. While the average value of wind speed in summer season in Japan is around 5m/s. So, these values are over estimated except encountering typhoon. At the typhoon, the blade will be fixed at the anchor which is constructed on the ground.

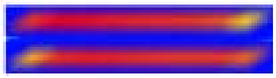
Fig. 10 shows that principal stress σ_1 of step 6 to 10 because the principal stress σ_1 is changed extremely small in step 1 to step 5. The cable is pulled down to Z-axis to 16cm ($\delta_{cable,z}$ =16cm) and wind pressure is increased 18kgf/m^2 for each step (step 6 to 10). The red color part (horizontal two stripes) indicates high revel zone of the principal stress.



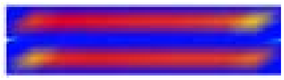
(a) Wp = 18kgf/m^2, $\delta_{cable,z}$=16cm, Max σ_1=517kgf/m, step 6



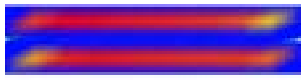
(b) Wp = 36kgf/m^2, $\delta_{cable,z}$=16cm, Max σ_1=704kgf/m, step 7



(c) Wp = 54kgf/m^2, $\delta_{cable,z}$=16cm, Max σ_1=866kgf/m, step 8



(d) Wp =72kgf/m^2, $\delta_{cable,z}$=16cm, Max σ_1=1007kgf/m, step 9



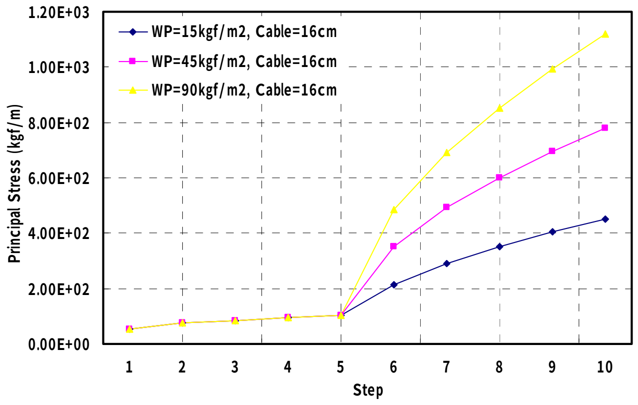
(e) Wp = 90kgf/m^2, $\delta_{cable,z}$ =16cm, Max σ_1=1135kgf/m step 10

Fig. 10 Distribution of the principal stress σ_1 in membrane

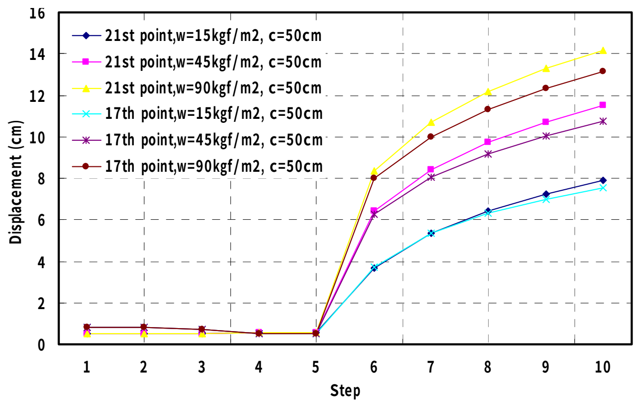
Fig. 11 shows the principal stress and displacement of nodal point. Fig. 11 (a) shows principal stress at 41st triangle element. The case of wind pressure 90kgf/m^2 the maximum principal stress is about 1,150kgf/m. This value is smaller than assumed strength of material 15,000kgf/m. Fig. 11 (b) shows displacement of 17th nodal point. The displacement at the step 1 to 5 is owing to concavity of surface as shown in Fig. 9. In the step 6 to 10, the displacement changes largely and dose not increase proportionally regarding to wind pressure. And the maximum displacement is about 14.2cm at 21st nodal point when the wind pressure is 90kgf/m^2.

6. Conclusions

Numerical analysis of membrane blades of hybrid power generating system (Lotus-1) subjected to wind pressure is executed by using Bendable Element Method (BEEM). The surface of membrane blade can reflect solar radiation and to focus them to PV panels. In order to keep smooth surface, pre-tensile



(a) Principal stress of 41st triangle element ($\delta_{cable,z}$ =16cm)



(b) Displacement of 21st nodal point and 17th nodal point ($\delta_{cable,z}$ =50cm), step 1 to 10

Fig. 11 Displacement and principal stress

membrane stress is introduced by cable. As the results, it appeared that the maximum principal stress is small enough compare to the maximum strength of membrane. The focal point on the PV panel draft 0.25m and 0.65m at the case of 17m/s (15kgf/m^2) and 42m/s (90kgf/m^2), respectively.

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Appendix

Following photos show the prototype of hybrid power generating system (Lotus-1) which is constructed at Shirahama, Japan. Photo A shows the wind power generating pattern, photo B shows the solar energy generating pattern and photo C shows experimental test at old glide slope of Nanki-Shirahama airport.

Photo A　Wind pattern

Photo B　Solar energy pattern

Photo C　Lotus-1 running test

ハイブリット型発電装置の翼として用いるケーブル補強膜に風荷重が作用した際の膜面変形及び応力解析

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橘　英三郎*2)

概要

筆者らは、太陽エネルギーと風力エネルギーを一つの装置で利用できるハイブリット型発電装置の開発を行っている。この装置の特徴は、開閉形式のブレードを有し、日照時間の長い夏季にはブレードをパラボラ曲面状に開き太陽エネルギーを集めて発電し、日照時間が短く季節風の強い冬季にブレードを閉じ、サボニュース・ダリウス型の風力発電を行うところにある。このことにより、年間の稼動率を大幅に上げることが期待できる。又、ブレードには布製の反射膜を用いているため、軽量でコストの低減化も計ることができる。
本研究では膜面の風荷重下における変形及び応力解析を折れ曲がり要素法（BEEM）を用いて行い、膜面の安全性及び変形による反射光のブレなどを検証した。その結果、風圧 90kgf/m² (42m/s)程度では強度的には問題はなく、また 3mはなれた焦点に対する変形による光束のブレは約 65㎝程度であった。台風の時にはブレードを地面のアンカーに固定することで安全策もとっている。

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