A COMPUTATIONAL STUDY ABOUT THE EFFECT OF SURFACE SHAPE ON STRENGTH & STIFFNESS OF TENSIONED FABRIC STRUCTURES UNDER WIND LOADING

By

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ABSTRACT

This thesis is carried out to investigate the effect of surface shape on strength (in terms of maximum stress) and stiffness (in terms of surface displacement) of tensioned fabric structures under wind loading. In this paper, anticlastic forms like saddle, cone and membrane dome of tensioned fabric structures were analyzed. Finite element software – ADINA is used to create the models of tensioned fabric structure. It is followed by analyzing step by using a stress analysis computer program to investigate the form as well as the effect of wind loading for each model with different pre-stress level conditions under the same wind loading condition. From the study, the location of maximum stress and displacement of different shape is recognized in order to check the efficiency of different shapes in resisting wind loading. The graph of maximum tension/pre-tension versus sag/span is used to show the relationship between structure strength and effect of wind loading. While the graph for percentage of maximum displacement versus pre-tension is used to show the relation between the shape and the stiffness of the structure. This study has covered rectangular saddle surface, square saddle surface and conical surface for both strength and stiffness of the surface shape mentioned above. It has been found that the square saddle surface exhibits the best result to resist wind loading. This conclusion is based on the lowest ratio for maximum tension/pre-tension and sag/span as well as the lowest percentage for displacement result exhibited in the result for square saddle surface. The outcome of the study will provide technical guidance on efficiency of different shapes of tensioned fabric structures in resisting wind loading.

ABSTRAK

Tesis ini dijalankan untuk mengkaji kekuatan (dalam nilai tegasan maksima) dan kekukuhan (dalam nilai anjakan permukaan) pelbagai jenis bentuk permukaan struktur fabrik apabila ia dikenakan beban angin. Dalam tesis ini, beberapa bentuk ‘anticlastic’ untuk struktur fabrik tegangan seperti pelana, kon dan kubah Izumo telah dianalisis. Perisian elemen terhingga – ADINA telah digunakan untuk menjana bentuk geometri setiap model. Kemudian, langkah menganalisis dijalankan dengan menggunakan satu program komputer analisis kekukuhan yang dapat mengkaji keseimbangan bentuk dan kesan angin untuk setiap model dengan magnitud pra-tegangan yang berlainan. Tempat berlakunya tegasan maksima dan anjakan maksima akan dikenali bagi setiap jenis model yang ditindak oleh beban angin yang sama. Bentuk yang paling baik untuk merintangi angin dapat dipilih setelah output program komputer tersebut dianalisis. Graf tegangan maksimum/pra-tegasan melawan lendut/rentang diguna untuk memaparkan perhubungan antara kekuatan struktur dan kesan beban angin. Manakala, graf peratusan anjakan lawan pra-tegasan diguna untuk memaparkan perhubungan antara bentuk dan kekukuhan struktur. Kajian ini telah merangkumi pelana segiempat tepat, pelana segiempat sama dan kon untuk kedua-dua analisis kekuatan dan kekukuhan. Didapati pelana segiempat sama dapat merintangi beban angin dengan paling efektif. Kesimpulan ini dibuat dengan berdasarkan kadaran yang kecil untuk graf kekuatan struktur dan peratusan terkecil untuk graf kekukuhan sepertimana yang terpapar dalam keputusan pelana segiempat sama. Keputusan daripada analisis ini dapat memberi panduan teknikal tentang keberkesanan pelbagai bentuk permukaan struktur fabrik tegangan dalam merintangi kesan beban angin.

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CHAPTER 1

INTRODUCTION

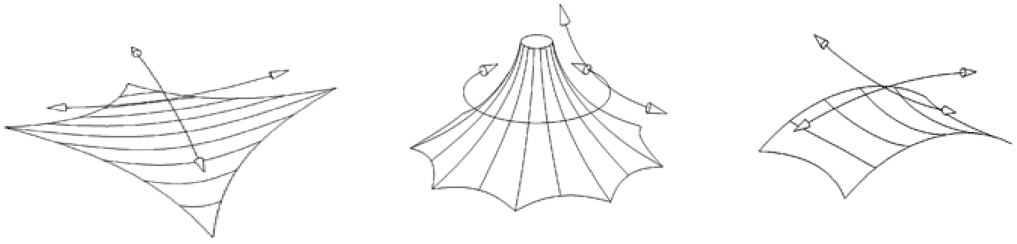
1.1 Background of Tensioned Fabric Structures

Tensioned fabric structures are environmentally sensitive medium and inexpensive way to create the best solution for open airy environment. The biggest performance advantage is its strength to weight ratio. Some of the largest stadiums, shopping malls, airports and other large commercial structures are tensioned fabric structures. This structure is chosen due to its characteristic of being lightweight and flexible combined with its daytime translucency and night-time luminosity, giving it a magical feeling of being outdoors in combination with the security and comfort of indoors.

Leonard [1988] mentions that tension structures include air-supported structures, pneumatic shells, pre-stressed membranes, cable networks, tethers, suspension cables, guyed towers and tents, and ocean platforms and breakwaters. Each structure exhibits its function and usefulness in different cases.

Tensioned fabric structures are normally made of metal frames with flexible covers tightened over the frame, therefore creating a tensioned structure. Incredibly strong fabrics make extremely large clear-span structures possible. Tensioned fabric structures have many different possible shapes. Each different possible shape will response differently when wind loading acts on them, whereby maximum stress and displacement will occur in different region on the surface.

Membrane structures rely on double curvature to resist imposed loads efficiently. Figure 1.1 shows three examples of surface with double curvatures.



Hyperbolic Paraboloid
(a)

Cone
(b)

Saddle
(c)

Figure 1.1: Surfaces with Double Curvatures

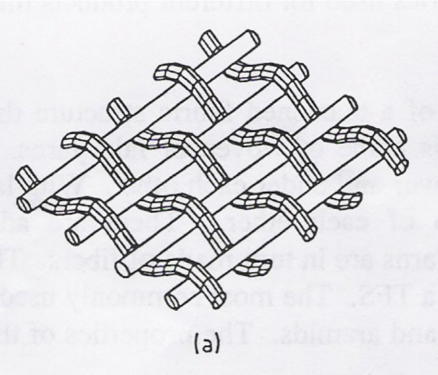
Anticlastic forms such the hyperbolic paraboloid (Figure 1(a)), cone (Figure 1(b)) and saddle form (Figure 1(c)) all have opposing curvatures. This is the principle feature of the surface of tensioned fabric structures. Nearly all surfaces of tensioned fabric structures are derived from either one or any combination of these three shapes.

Contemporary tensioned fabric structures have been designed for a wide range of loadings and climatic conditions. Load bearing characteristics of tensioned fabric structures are governed by the high deformability of membranes under load and may be generalized as follows: Dead load from membrane, roof live loads, seismic loads (not included due to low mass of fabric), wind (predominant loading) and moderate snowfall (not applicable in tropical country).

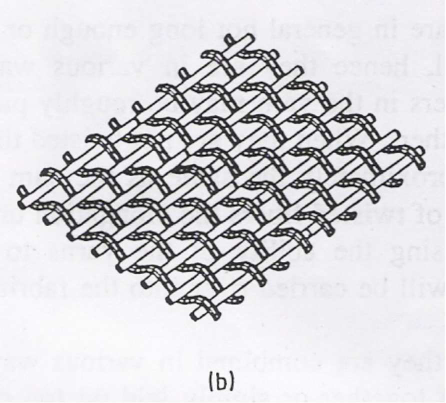
Materials of construction for a tensioned fabric structure comprise of cables, membranes or both. Cables can be made of steel, Kevlar® (registered DuPont trademark; a synthetic aramid fiber), fiberglass or polyester. Structural strands and structural ropes are commonly utilized as cables. A strand consisting steel wires wound helically around a centre wire in symmetrical layers while a rope consisting several strands wound helically around a core. A high-tensile breaking strength is a primary property of the wire rope. Other important properties include small cross section, low weight, long fatigue life, resistance to corrosion and abrasion, high flexibility good stretch and rotational behavior. Cables act principally as axial elements. Cable materials typically have linear stress-strain relationship over only a portion of their usable strength. Beyond the elastic limit, the proportional relationships do not hold. Breaking-strength efficiency is the ratio of cable strength to the sum of individual wire strengths and the ratio is greater for ropes and strand lay.

As for membranes, various materials can be used in the fabrication of a tension structure, such as hyperelastic (rubberlike) materials, fabrics, composites, and etc. Each fabric material presents unique characters. Among the important characteristics are fire resistance, life span, UV protection, transparency, translucency, tensile strength and ecological. However, composites are normally chosen due to its fulfillment of particular set of conditions and the final material is much better than the sum of the components. Most of the tensioned fabric structures in use today are either PVC coated polyester, silicon coated glass or PTFE-Teflon coated glass.

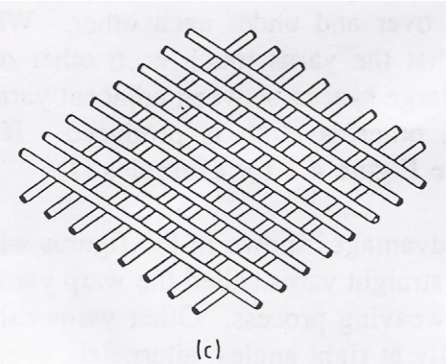
The fabric is made of woven or laid yarns. Yarns are made of fibers that are twisted together. In woven fabrics, the yarns pass alternately over and under each other whereas in laid fabrics, the yarns are merely placed on top of each other. Figure 1.2 shows the examples of woven fabrics.



Loosely woven scrims



Tightly woven fabrics plain weave



Plain weave

Figure 1.2: Examples of Fabrics

As shown in Figure 1.2, long straight yarns are called warp yarns. Direction parallel to the warp yarns is called warp direction; whereas perpendicular yarns are called fill yarns and they are weaved alternately over and under the warp yarns. In laid cloths, the yarns are simply placed on top of each other. Fill yarns are bent or “crimped” around the relatively straight warp yarns in the plain weave. This causes the thickness of a woven fabric to be approximately three times the thickness of yarn, whereas the laid cloth has only two thicknesses.

A fabric is coated when a weathertight structure is required. In that case, the fabric will consists of three layers - one layer of woven yarns and two layers of coating materials. This coated fabric is also named as ‘membrane’. Schematic sketch of a coated fabric is shown in Figure 1.3 below:

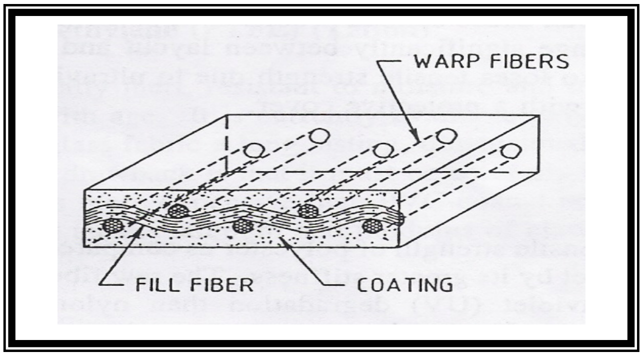


Figure 1.3: Schematic Sketch of a Coated Fabric

The function of yarns is to absorb tension forces while coating material absorbs shear forces. Weaving method in fabric causes different behavior of the warp and fill yarns when tensions are applied on them. The warp yarns are initially straight and in tension condition. They are forced to bend in a small amount when the fill yarns which are initially in a state of bending are being pulled. This is because the fill yarns tend to elongate and flatten when tension forces are applied on them.

Fabric having the same strength in all directions are said to be isotropic. If the strength differs in both warp and fill directions, the fabric is anisotropic or otherwise known as orthotropic. The geometrical distortions mentioned above causes an orthotropic behavior of the fabric with the first application of load. To overcome the drawback, warps and yarns are pre-stretched prior to coating. The pre-stretched step will make the behavior of the fabric more or less the same in both warp and fill directions. However, the cross-sectional area of the warp and fill fibers per meter length will not be the same, thereby the strength of warp direction is usually greater than the fill direction for most of the fabrics cases. That leads to the introduction and adaptation of modulus Young and Poisson's ratio in warp and fill direction, E_w, E_f and v_1, v_2 respectively. Shear modulus, G is another independent mechanical property of fabrics.

Fabric structures are made mainly of fabric and cables which have little or no rigidity. Therefore, they must rely on their form and internal pre-stress to perform their function. Their form depends on supporting system, pre-stress pattern and magnitude. Pre-stress have to be introduced into the fabrics so as to stabilize the fabrics and also to resist load. The higher the pre-stress, the more the amount of imposed load which can be resisted by the fabrics. However, the maximum tensile stresses that can be applied to the fabrics are governed by its breaking strength. Although fabrics cannot develop bending moment, fabrics perform well in tension. Therefore, fabrics perform its functions mostly in tensile forces. The significant changes in their geometry mean that they are non-linear even though the fabrics remain more or less linear.

Fabric will undergo axial elongation in warp direction when it is stretched in warp direction. The axial elongation is accompanied by lateral contraction in fill direction. Figure 1.4 shows the shape of the fabrics when tension forces are applied to the fabrics.

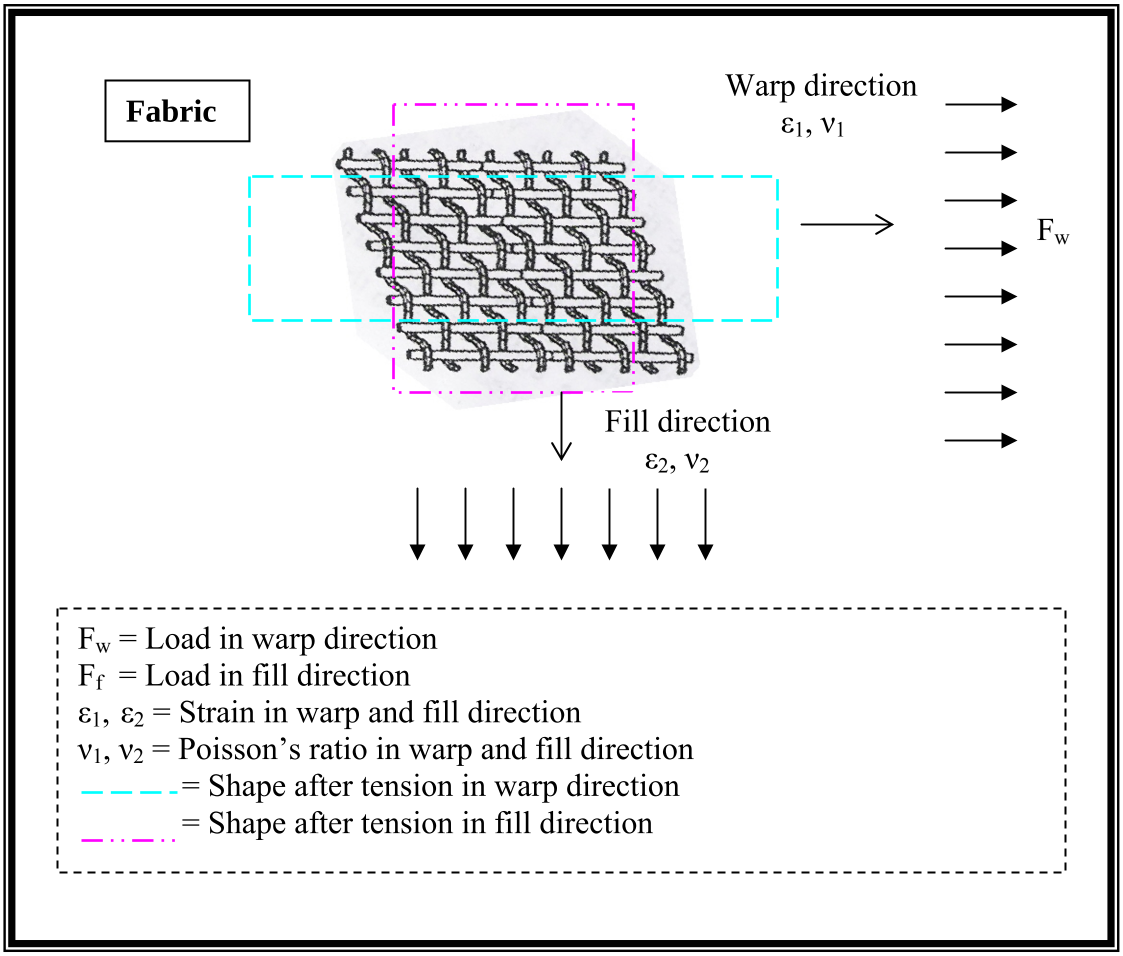


Figure 1.4: Warp and Fill Poisson's Ratio

When F_w is applied in warp direction, axial elongation in warp direction is denoted as ε_1, while lateral contraction in fill direction is denoted as ε_2. Therefore, Poisson's ratio in warp direction, ν_1 is presented as:

$$\nu_1 = -\frac{\varepsilon_2}{\varepsilon_1} \tag{1.1}$$

When F_f is applied in fill direction, axial elongation in fill direction is denoted as ε_2, while lateral contraction in warp direction is denoted as ε_1. Hence, Poisson's ratio in fill direction, ν_2 is presented as:

$$\nu_2 = -\frac{\varepsilon_1}{\varepsilon_2} \tag{1.2}$$

For elastic material, reciprocal relation holds, i.e.

$$\frac{\nu_1}{\nu_2} = \frac{Et_1}{Et_2} \tag{1.3}$$

where t_1, t_2 = thickness of fabric in warp and fill direction respectively

In membrane elements, E and G are more conveniently expressed in terms of Et and Gt. This is because fabric is a thin material if compared to its length and width. A typical unit of E in SI units has the same unit as stress, i.e. MPa or kN/m^2. Since the thickness of the fabric is negligible, it makes more sense to define the modulus of elasticity, E over unit width rather than unit area. Therefore, E and G as used in analysis of fabric structures have the unit of force/length, e.g. kN/m or kgf/cm.

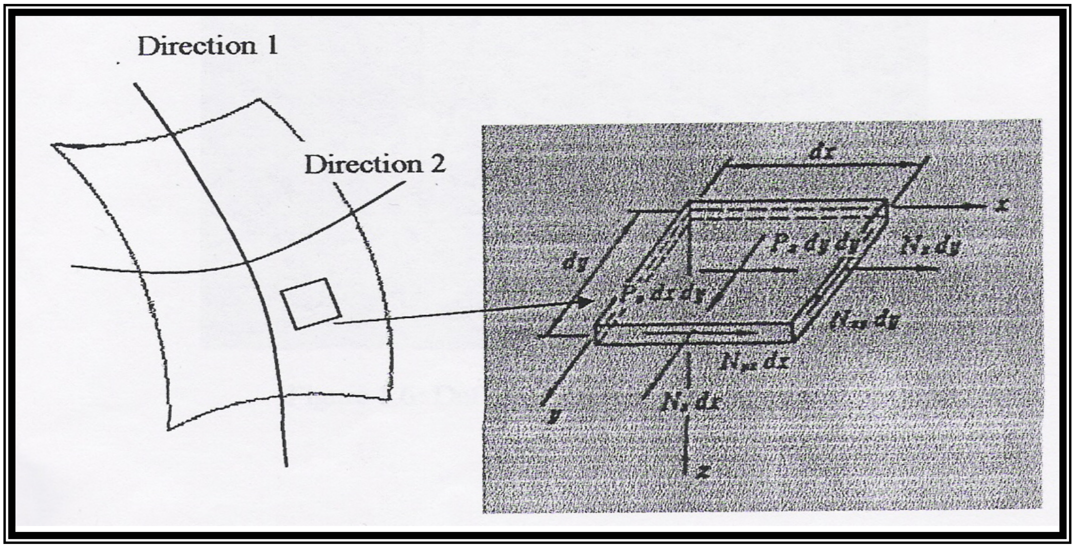


Figure 1.5: Stresses Acting on a Small Element of Fabric Surface

Referring to Figure 1.5 above,

N_x = axial stress in x direction = $\sigma_x t$

N_y = axial stress in y direction = $\sigma_y t$

N_{xy} = shear stress

Corresponding to the above three components of in-plane-stress, the three components of strains are denoted as ε_x, ε_y and γ_{xy}. The geometrical representation of these three strain components is shown in Figure 1.6.

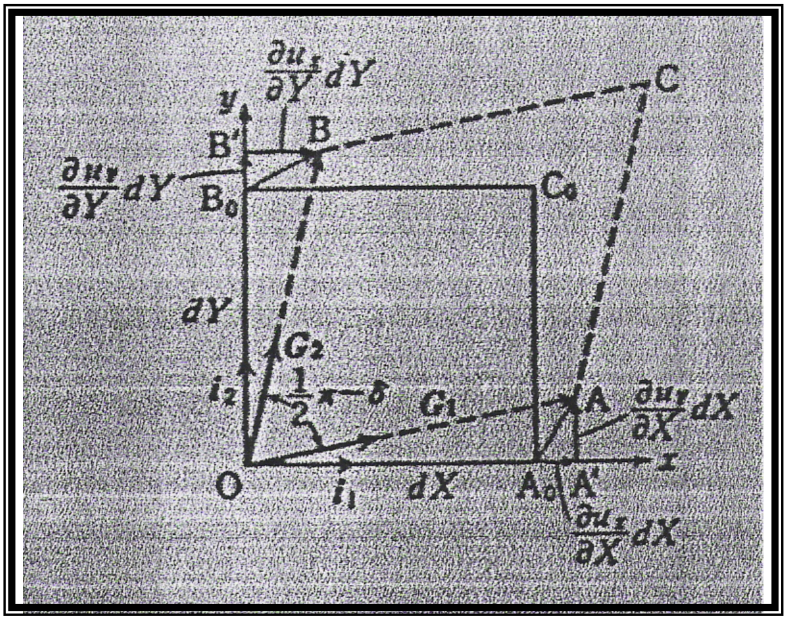


Figure 1.6: Deformation Due to Shear Stress

$$\varepsilon_x = (OA-OA_0)/OA_0 \qquad (1.4)$$

$$\varepsilon_y = (OB-OB_0)/OB_0 \qquad (1.5)$$

$$\gamma_{xy} = OA/OA_0 * OB/OB_0 * \cos(1/2\pi-\delta) \qquad (1.6)$$

1.2 Analysis of Tensioned Fabric Structures

Tensioned fabric structures are structures in which the main load-carrying members transmit loads to the foundation or support system by tensile stresses with no compression or flexure allowed. The stress-strain relationship of fabric material is non-linear. The special characteristic of pre-stressed structure is that all the elements remain stressed when various loading are acting on it. Tensioned fabric structures cannot resist loading by compression; else, the structures will wrinkle, thus reducing the load bearing capacity of the structure.

The physical behaviour of tensioned fabric structures during the application of loads can be divided into a few primary phases. The first phase is the deployment phase, in which the cable or membrane system unfolds from its compact configuration into a state of incipient straining. The second phase is the pre-stressing phase, in which the cable or membrane system deforms into a predominant equilibrium configuration under the action of dead weight, pressure, or the other fixed lifetime loads. The final (in service) phase is the stage in which the fully pre-stressed system is subjected to variable live or dynamic loads throughout its service life.

The design process of tensioned fabric structures in engineering office involve six different phases:

1. Determination of the geometry
2. Mechanical analysis of the whole structure (form-finding analysis)
3. Checking of the structure against wrinkles
4. Determination of maximum stresses under wind and snow loads
5. Determination of the cutting patterns
6. Flattening of the fabric structure into panels

A flow chart summarizing the design flow for the fabric structures is shown in Figure 1.7. The present study in this research is focused on the fourth phase, which is to determine the maximum stresses in a fabric surface under loading. Specific loading considered in this study is wind loading.

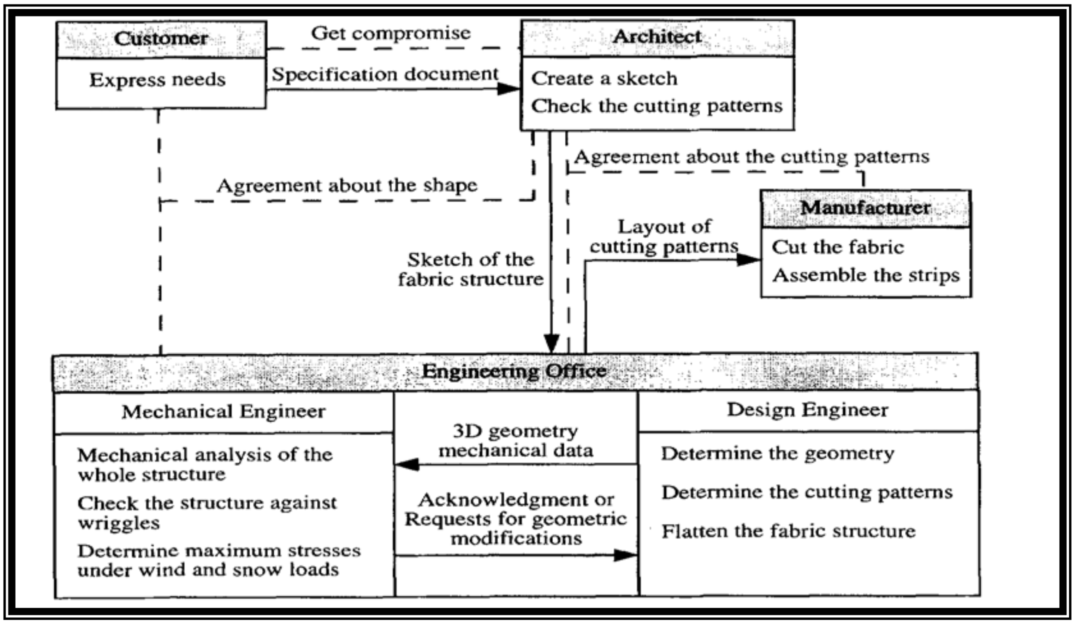


Figure 1.7: Tasks Breakdown and Repartition among the Various Actors for Fabric Structures [Veron et al, 1998]

1.3 Wind Loading Analysis

Wind is moving air. The air has a particular mass (density or weight) and moves in a particular direction at a particular velocity. It thus has kinetic energy of the form expressed as $E = \frac{1}{2} mv^2$. When the moving fluid air encounters a stationary object, there are several effects that combine to exert a force on the object.

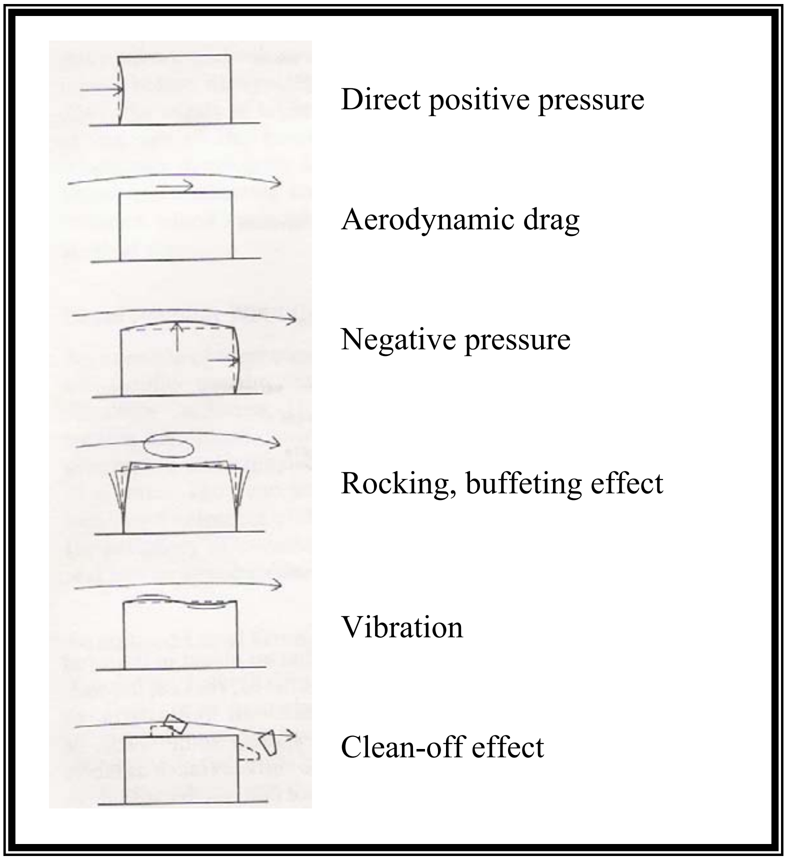


Figure 1.8: General Effects of Wind

Tensioned fabric structures are considered as light weight structures. By the very nature of lightweight structures, the ratio of applied loading to self-weight is usually larger than conventional building structures. Changes in the magnitude of wind loading are therefore likely to have a proportionately larger impact on the size of the structural members required and the scale of deflections experienced.

Hence, wind loading is the most important external loading to be considered in the design and analysis of tensioned fabric structures. Wind causing uplift is regularly the critical case for membrane and cable stresses in lightweight membrane structures. It happens on the leeward side of the object (opposite from the wind direction) and usually there is a suction effect, consisting of pressure outward on the surface of the object. By comparison to the direction of pressure on the windward side, this is called negative pressure in this study.

For structural analysis of tensioned fabric structures, wind loading is carried out after form-finding. The purpose of form-finding is to find out the initial configuration of model that satisfies the law of equilibrium where the structure experiences a significant pre-stress all the time even when no external load is imposed on the structure.

1.4 Problem Statement

According to the literature review carried out, there is limited research on wind loading on different shapes especially in the case of different pre-stress level applied to a model and how they behave under the same wind loading. There are no codes and standards relating specifically to tensile fabric structures. The lack of widespread knowledge in this medium and the lack of recognition of this type of construction in building codes require the manufacturers to provide a high degree of technical validation in order to fulfill their obligation to assure public safety and adherence to building codes. Thus, it is useful to find out the effects of shapes with different pre-stress level under the same wind loading. This will serve as a useful guideline during the preliminary design phase.

1.5 Objective of Project

The objective of the thesis is to study the effect of shapes on strength (in terms of maximum stress) and stiffness (in terms of surface displacement) under wind loading. The outcome of the study will provide technical guidance for structural engineers to makes preliminary judgment about the location of high stress and displacement as well as the relative merits of different shapes on resisting wind loading since the analysis have been carried out in different models.

1.6 Scope of Project

The scope of this project is limited to the investigation of the effect of wind loading for each model of tensioned fabric structures with different pre-stress level conditions. In addition to that, it is assumed that the same magnitude of wind loading is applied to the whole surface of the models of tensioned fabric structures.

1.7 Layout of Thesis

This report consists of 5 chapters as follow:

In chapter 1, the background and fundamental concept of tensioned fabric structures and wind loading analysis are introduced. Besides that, problem statement, objective of project, and scope of project are then mentioned.

In chapter 2, literature review on relevant articles has been done.

In chapter 3, the method used to carry out the study of wind loading analysis has been described. A series of stages and phases are explained.

In chapter 4, results are compiled and discussions are carried out.

In chapter 5, a summary of the results is given, and the project is concluded.

There are two appendixes incorporated into the project, i.e. Appendix A amd Appendix B:

In Appendix A, procedure to generate a model using ADINA is briefly introduced.

In Appendix B, brief explanation of input file for wind loading analysis is shown.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Membrane structures or tensioned fabric structures have been in use for thousands of years. These structures consist of a membrane that is attached over a stiff framework, thus enclosing the space inside the framework. Tents are the oldest examples of this type of structure and are one of the earliest building types known to man [Shaeffer, 1996]. Technology advancement on tensioned fabric structures results in these structures can be seen anywhere in developed as well as developing countries.

The modern tensioned fabric era began with a small bandstand designed and built by Frei Otto for the Federal Garden Exhibition in Cassel, Germany in 1955 [Shaeffer, 1996]. Nowadays, tensioned fabric structures play an important role in the field of civil engineering for both permanent and temporary buildings. Due to its high performances in structural, architectural and economical aspects, research works in the field of tensioned fabric structures have been carried out intensively for the last two decades in order to contribute improvement in its development [Wakefield, 1999].

Presented here are examples of research works conducted on tensioned fabric structures, namely the materials, the collaboration and integration, method of design and analysis with or without wind loading, analysis and construction technology on supporting systems.

2.2 Review of Past Research Works

Recent developments in fabric materials technology have fundamentally altered the nature of tensioned fabric structures. The paper of Huntington [1987] explores the performance of these fabrics in several areas. Glass fiber scrims with '*Teflon*' or silicone coatings have yielded fabrics with strip tensile strengths up to 150kg per cm width and lifespan of 25 to 30 years. Fabric may now be used in permanent structures with long spans and low curvature. Both Teflon® and silicone coated products demonstrated translucency adequate for plant growth besides being able to meet most building code of requirements for flame spread, combustibility and resistance to burning brands. The new fabric roofs provides low energy for sunny, temperate climates, while new developments in insulated fabrics and other innovations improvised the energy performance in cold, low sunlight climates.

A new anisotropic constitutive model is introduced by Zhang, Leonard, and Accorsi [2005] to simulate the geometrically non-linear dynamic behavior of general anisotropic membranes experiencing large deformations. This model relates the second Piola-Kirchhoff stress with the Green-Lagrange strain in a 3-D converted curvilinear coordinate frame. It illustrates the construction of the anisotropic constitutive law from the predefined principal material coordinate system to the final converted curvilinear coordinate system using coordinate transformations. The proposed theory is implemented into a finite element code and several numerical examples are given for validation.

Fabric behaviour is typically defined using elastic constants based on plane stress assumptions. The paper of Bridgens and Gosling [2004] considers two new methods in representing fabric response: (i) use of spline functions to define response, (ii) use of stress-strain mean and difference. Both techniques provide direct correlation between stresses and strains and eliminating the assumption of plane stress. Extensive biaxial fabric testing is proposed to assess the validity of these approaches and extend their use.

The design of fabric structures incorporates specific aspects due to the tight interdependency between geometric, mechanical and manufacturing data used by the different professional partners. This is highlighted through the analysis of the various steps of the design process by Veron, Trompette and Leon [1998]. The approach proposed relies on the identification of the flow of information and on the organization of data sets that are compatible with the design process breakdown into tasks in order to preserve their integration. Approximation methods are associated with some of this information to create design phases adapted to each actor through software tools implementing various modeling processes. Associated with the integrated design architecture, a collaborative environment helps to set up communication between some of the actors according to the design process organization.

There are several types of fabric structures, namely the air structures, cable nets, tensioned fabric structures, cable domes, convertible roof and etc. These structures have been used in many permanent buildings for almost 30 years. Some of these applications are significant for their size and importance. Berger [1999] presented a paper to describe the principal structural forms of tensile structures based on his experience with numerous executed or proposed designs and discusses their impact on the building's structure and function. The purpose of the paper is to help engineers to pick the right structural system for a specific purpose. Some solutions to special problems related to fabric structures in permanent buildings are also discussed.

Numerical simulation and design of an inflatable open ocean aquaculture cage is presented by Suhey, Kim, and Niezrecki [2005] using nonlinear finite element analysis of membrane structures. Wrinkling, defined as an onset of compressive stress, is monitored as design criteria. The finite element model is validated using a modified beam theory for the inflatable structure by comparing the maximum deflection and stress. Good agreement is observed between the numerical and theoretical results.

Analyses of fabric tensioned structures have been done by Fujikake et al [1989] and Spillers et al [1978]. Fujikake et al paper presents a method of nonlinear analysis of fabric tension structures and numerical examples. An updated Lagrangian formulation is used to include large displacements in the load analysis. A shape-finding analysis is performed using a technique with a small Young's modulus. A uniaxial stress-strain relationship is derived and used in a wrinkling formulation. The procedure is incorporated into the ADINA program and the results of some practical analysis are given. While Spillers et al's paper deals with some practical aspects of the analysis of tensioned fabric structures, the scope is limited to problems of small strain with large rotation for linear isotropic fabrics. The effect of pre-stressed is discussed, followed by the geometric stiffness matrix and developed using only equilibrium equations.