1 Introduction

1.1 General

The existing lightweight roofing system to which we call Tensile Membrane Structures(TMS) today are habitually being used since thousands of years, in the form of ancient fabrics structures called "*tents*". The early human civilization used variety of basic materials for example cloths, animal skin, tree branches to construct ancient fabric structures. Most of the structures were designed and constructed for temporary roofing purposes. And the loading was primarily imparted by the environmental factors like, wind, snow, rain etc. due to this reason the reliability of these types of structures was relatively low.

The modern tensile membrane structures have gained popularity from around 1950s onwards since when these type of structures were designed for permanent construction of structural components. As compared with the fabric forms from ancient times, the modern fabric structures require more stability and enhanced aesthetic forms. These structures are the lightweight fabrics and contain the ability to cover a substantially large area without any requirement of intermediate supporting column. The efficiency of these types of structures is enhanced due to membrane action of in-plane stresses; hence the flexural point of view in designing is not required for the TMS. The primary mechanism to contain the efficiency and stability of a fabric membrane is the initiation of tensile forces to incorporate seamless geometries. From architectural point of view, the free-form TMS provides a large variety of deformable shapes from the outside and form of space from the inside.

The materials used for the construction of TMS are poor in offering compression or stiffness against bending. These materials are very likely to get folded or wrinkled under the action of some external forces whenever there is insufficient pre-tension is applied. These applied pre-tension stresses are intended to encourage the stability and impart stiffness to the membrane surface, and consequently the developed negative strain produced by loads can be taken care by the positive strain developed due to initial pretensions.

The three basic most shapes for which TMS are generally designed for are:- saddle, cone and arches, or the combinations of these three. And the double curvature (synclastic or anticlastic) along with unorthodox supporting boundaries imparts shape to the surface geometries. The curvatures are oriented in a manner so that the stress balance within the surface is achieved, at any point of the surface the curvatures should be opposite. For the purpose of uniform stress distribution over the membrane surface, there should be a zero mean curvature at any point on surface, meaning that two same large primary curvatures should be exactly opposite.

1.2 Design philosophy

There is no standard design philosophy for tensile membrane structures in most of the countries (Gosling, Bridgensben, et al., 2013), there are few design guidelines documented in the literature review in next chapter which are accepted and practiced by engineers and academicians. But again there is always a scope to modify these criteria according to the practical assessment of a TMS. So, it can be said that the design and construction of a TMS is completely an experienced and intuition based procedure where the researches accomplished till date provides a basic understanding of uncertainties and other relevant aspects associated with the loads and building components of the TMS.

Fabric structural design procedure is primarily constituted by three main steps:- form finding, cutting patterns and load analysis. The stretched membrane may form a double curved surface complying with the boundary constraints and the stress distribution on the surface. The detailed geometry of the membrane obtained through a “Form-finding” process using numerical or physical models.

The form-finding of a TMS is more of an inverse problem in structural mechanics. Unlike the conventional structures, where the forces and its effects are related directly using Newton’s laws, the shape of a TMS is estimated based on the initially induced pre-stresses and the applied boundary constraints (Linhard & Bletzinger, 2009). In the process of form-finding, an initial pre-stress value is chosen based on the intuition of designer, which is desired to be matched with the pre-stresses obtained after the complete process of form-finding. It is a proven approach for a stable and form found TMS. From the trailing discussion, the problem of form-finding can be perceived as an initial equilibrium problem complying with a given set of parameters. According to (Haber & Abel, 1982), the initial form of a structure, boundary conditions, and pre-stress are primarily responsible for TMS design. Past research mentions that an ideal surface must be a stable surface or a minimum surface as an outcome of a form-finding process (Grundig, 1988). A minimum surface signifies an area with uniform stress throughout the membrane span.(Lewis, 2013). In consequent design practices the idea of the pseudo-minimal orientation of TMS surface is achieved by over-stressing weaker regions of the membrane surface. This type of design practice reduces the serviceability of the membrane. The pre-stress can be adjusted to obtain stable structures of various forms of TMS with control on deflection (Kai-Uwe Bletzinger, 1999). This signifies the importance of restricting the deflection of flexible membranes and is considered the most important parameter to improve TMS serviceability (Dutta et al., 2016, 2018). Along with this, the material and structural geometry play an important role in the design and analysis of tensile membrane structures (B. Bridgens & Birchall, 2012).

Loading analysis for the TMS defined in the form-finding process should compulsorily consider both material and geometric stiffness in order to define an equilibrium state. In general self- wind load and snow load are taken into account for TMS load analysis (ASCE/SE, 2010). Mainly the wind load is considered for load analysis of TMS and the action due to wind is shape dependent (Brew & Lewis, 2003). The load is typically applied to the form-found TMS along with its existing (equilibrium) stress state. Due to the large (nonlinear) deformation behavior of these structures, the load cases need to be accounted individually. Wind load on TMS is calculated similar to other civil structures (American Society of Civil Engineers., 2010).

In practical design cases, a deterministic approach is adopted in which a single value of the wind uplift pressure is applied to the membrane surface and the structural response parameters are obtained to comment on its stability. However, due to the inherent uncertainty in wind forces, the real structural responses can be completely different. The transient deformations of a flexible TMS under uncertain wind forces make the structure unstable (Huntington, 2013). Hence the uncertainty in wind load must be considered during the static analysis of a TMS to understand the structural behavior more accurately and to take appropriate engineering decisions. The current design practice assumes that all uncertainties are accounted for via the selection of partial safety factor(s), also known as ‘stress factor’ in the case of TMS (ASCE/SE, 2010).The stress factor is typically in the range of $4 - 7.8$ as per (ASCE 55-16, 2017),and it varies with the design standards across various countries (Gosling, Bridgensben, et al., 2013)**.**These large values of the stress factor often create confidence among designers that a large margin of safety has been incorporated in the design and the structure can withstand the effects of all kinds of uncertainty during its design life.

Such a misconception avoids the critical need to perform a detailed analysis of TMS considering uncertainties. Few catastrophic failures of TMS mainly due to improper design show that the current design practice is not reliable and there is a definite requirement to properly understand the complex behavior of membrane structures. The present research work is in this direction. Fabric materials have negligible compression or bending stiffness. They are, therefore, prone to slack and wrinkle under external (uncertain) forces, when not adequately tensioned by applying sufficient initial pre-stress. Also the applied pretension must not be high enough to cause membrane tear on the application of gusty winds. The applied initial pre-stress can largely improve the stability and stiffness of the fabric surface, and the negative strain produced by loads can be compensated by the initial positive strain due to pretensions. Therefore the key aspect to achieve the intended performance is a proper selection of the initial pre-stress to induce smooth double curved anticlastic geometries.

1.3 Structural safety

Driven by aesthetical demands, TMS are required to meet the increasing level of performance and serviceability attribute, with corresponding advanced and more accurate analysis techniques and construction technologies. Based on Euro-code guidelines, it is recommended that large safety coefficients and conservative failure criteria should be used especially for TMS with complex geometries. In order to account for the significant uncertainties associated with the structural design, material properties and construction techniques and also other structural requirement like development of tear on surface , large safety margins are necessary to consider in design process. The uncertainties are being taken care by the newly conducted researches by developing the methodologies towards reduction of these uncertainties. Usage of the significantly large safety factors could possibly reduce the failure chances of the TMS, in contrast to that there are so many cases when a membrane material with good strength and other mechanical properties are wasted due to low application ratio, and aesthetic functions may be limited in architectural point of view of TMS design.

Tensile membrane structures (TMS) are lightweight pre-tensioned structures that serve as large span roofing components in buildings, exhibition halls, airports, etc. This class of structures has the potential to emerge as the most elegant roofing solution. The practices of design and construction of TMS are governed significantly by deflection criteria due to their higher flexibility. Structural deflections are typically categorized in the serviceability limit state, wherein the functionality of structures is of primary importance according to NBS Building Science Series, 47 1974. The serviceability conditions of a structure experience deflection, but these deflections are categorically different than those occurring at the ultimate limit state of safety.

The reliability assessment for TMS is being practiced for the past few decades. Generally, either the enactment capacity of structure or limit state functions evaluate the reliability of a structure (Gosling, Bridgens, et al., 2013).The implementation of reliability assessment tools is extremely valuable for the TMS design. Suitable safety factors are evaluated based on different structural elements and environmental loading factors and associated with the analysis results for the different confidence on the structural safety. The usage of high safety factors allowing for the possible effects of the randomness can be acceptable, and the fabric strength can be improved largely in terms of utilization ratio. The additional cost introduced by excessive safety margin through high safety factors can be controlled and a cost effective TMS design can be proposed.

1.4 Aim and objectives of the study

Each spatial structure is a prototype by itself, rather than a duplicate produced on an assembly line. Due to the lack of design guidance, the design of membrane structures is performed by experience, engineering judgment and pragmatism. There are two obstacles to the more general future use of tensile membrane structures in architecture. One is the special expertise required for the design. The other is the availability of fabric which is easy to handle and has a long life span **.** In this research, firstly there is an attempt to put together all information about the design, modeling and analysis of tensile membrane and supporting structures. For the clarity of this, two case studies with a detailed description is shown. Besides, by the analysis of those case studies, conclusions on the critical loading cases and safety are given. As explained in the literature review, tensile membrane structures are considered to have three basic shapes: the hypar (hyperbolic paraboloid), the conic and the barrel vault. The last part of the research gives an intensive reliability assessment for each case. Specifically, this research aims to accomplish the following objectives

a) Explaining in detail the procedure for design, modeling and analysis of tensile membrane structures. Reaching this objective is important because there is a lack of guidance on the design of this type of structures.
b) Describing the methodology for the geometrically nonlinear finite element analysis for membrane elements and showing how this is integrating in the computational tools used for the analysis in this thesis.
c) Bringing two case studies that put into practice all the knowledge explained a priori. Illustrating every steps of the modeling and analysis with a real case example, and bringing up comparative conclusions.
d) Proposing a parametric study by varying heights of the two basic shapes i.e.”Hypar” and “Conic” TMS. Finding the geometry limitations of the different models, and proposing possible design applications by the combination of the different created modules.

1.5 Organization of the thesis report

This dissertation is constituted of 6 chapters

- **Chapter 1** introduces a brief overview of the tensile membrane structures. The structural design issues are outlined and the need for the present study is presented. The chapter concludes with the overall objectives that are planned for this dissertation.
- **Chapter 2** presents a detailed review of the past researches done in the design and analysis of tensile membrane structures. Emphasis is laid on the past research done in form-finding, static analysis and reliability assessment of TMS. The basic formulations using finite element method for containing non-linearity in structural response is reviewed in order to envisage the possibility to conglomerate it with a robust safety assessment technique is done. A brief review of FORM problem formulations and their solution schemes are outlined.

A thorough exploration in the domain of design problems associated with TMS is concluded. A good assessment of various design processes in terms of simulation modeling, probabilistic design approach and reliability approach is accomplished. The various design consideration and recommendations are reviewed with an objective to verify the findings of the current research.

- **Chapter 3** is consisted of mathematical formulations required to formulate the non-linear finite element methodology along with the basic formulations related to first order reliability method and Newton-Raphson method is studied in order to organize the form finding procedure for TMS. The limit state parameters are identified in order to facilitate the reliability index calculation for the structural system.
- **Chapter 4** involves the application of the current methodology, to carry out the form-finding and the stress-deformation analysis of a benchmark structure which is hyperbolic paraboloid in shape. The finite element method obtained responses are employed for finding reliability index, based on the limit state design parameters. A completed summary of the overall assessment in terms of form-finding, stress-deformation analysis and reliability calculations are presented in the last part of the chapter.
- **Chapter 5** consists of another benchmark TMS analysis, which is adopted from a recent research. A square-base conic shaped membrane structure is studied. The applicability of non-linear finite element based reliability calculation method to this conic structure is studied. The reliability assessment based on the proposed methodology is accomplished and the results are verified with couple of recent researches and are compared with prevailing design approaches in various countries.
- **Chapter 6** contains the overall summary and contributions made as an outcome of this thesis along with some suggestions for future work directions