6 Conclusions

6.1 General

The reliability analysis of TMS is generally implemented to eliminate the concerns about the erratic use of the safety coefficients being implemented in the TMS design. The reliability requirements of a structure is always a complement and even a necessity in structural engineering as well as architectural point of view of a structural system. The reliability estimation tools are well capable of proposing a safe structural design by making the use of material properties related to strength and stiffness. The FORM is one of the effective reliability estimation approach to be used for the purpose. Undoubtedly, there are extremely high level of uncertainties involved with the structural and material behavior of the TMS. One of the major advantage of using the reliability based analysis for TMS is that it substitutes the huge number of uncertainties by a single stress reduction factor to contain all the possible design indecision. The value and analytical elegance of a reliability analysis means that uncertainties in all analysis parameters can readily be included in a mathematically consist manner as the test or simulation data becomes available.

6.2 Concluding remarks

Based on the results of the study undertaken in this dissertation on the finite element based reliability analysis of TMS, the important conclusions are presented:

- The form-finding procedure has a much greater significance in terms of providing the characteristic stiffness to the membrane structure. In the absence of a well-adjusted initial pre-stress, the membrane response behavior is highly impulsive. The ultimate tensile strength in that case will be reached immediately and it will consequently cause the structural collapse.
- The initial pre-stresses for form-finding analysis of hypar membrane (isotropic pre-stress) seem to be well accustomed and gives a good form-finding results in terms of deformation and surface stresses. Whereas, the hypar TMS (anisotropic pre-stress) results of form-finding points towards the adjustment of initially

imparted pre-stresses as the deformation results are exceeding the allowable limit, and stresses in the form of warp and fill stresses shows impulsive behavior.

- In the case of conic TMS (isotropic pre-stress) the form-finding is achieved very well in terms of warp and fill stresses, it manifests the close to minimal surface of the TMS. Whereas the form-finding for conic TMS (anisotropic pre-stress) shows that there are adjustments in the initial pre-stressing is required as the warp and fill stresses are deviating from the attainment of the most stable configuration.
- The variation in arch curvature by changing the height of the structure is evidently influencing on the attainment of the equilibrium pre-stress when performing the stress-deformation analysis for both hypar and conic TMS (both isotropic and anisotropic pre-stress). The increase in the height of the TMS will deviate the uniformly distributed initial pre-stress from the minimal surface area orientation.
- The stress-deformation analysis observations of each case of the TMS reveals that the prescribed membrane surfaces are most sensitive to the wind uplift force. This can be outlined by a closer look to the structural responses in terms of maximum warping stress, minimum fill stresses and deformation analysis of the membrane surfaces under wind-uplift loading.
- The structural responses for the load case *CO1* which is nothing but 1.6 times snow load of 0.6kN/m^2, cannot be overlooked, especially for the anisotropic pre-stressing of the conic TMS case. The value of maximum warp stress for the above mentioned load case was experienced to be crossing the maximum allowable fabric strength construing the ultimate fabric failure, while all the other load cases evidenced normal behavior against same loading and material conditions.
- The value and analytical elegance of a reliability analysis means that uncertainties in all analysis parameters can readily be included in a mathematically consist manner as the test or simulation data becomes available. The individual contribution of uncertainty in each analysis parameter to the probability of failure of the structure can be assessed, and probabilities of failure can be compared against widely accepted values given in “Euro-code – Basis for Structural Design” to weigh the adequacy of the design (Table 1 and Table 2).
- The finite element with first order reliability method (FORM) the chapter 3 of this dissertation is dedicated to the methodology used in this research. The results of reliability in terms of reliability index β, were calculated for each case of TMS

adopted for this work. In order to enlist the sensitivity of the various parameters adopted for this work the standard deviation of the statistical parameters were varied from 10% to 25% (COV = 0.10 to COV = 0.25). As an outcome of the sensitivity analysis, the load cases wind-uplift load heavy snow load conditions shows high sensitivity for both hypar and conic TMS, especially for the increased height of the structure.

- The reliability estimation of the hypar and conic TMS reveals that in case of isotropic pre-stressing of hypar the ultimate fabric failure limit state criteria is seems to be deflecting away from the adopted reliability index value of 3.8 and the serviceability limit state of the structure is also not met, as most of the β values are below 1.0. The anisotropic pre-stressing of hypar TMS seems to be fulfilling the wrinkling failure criteria, where most of the β values are found to be around or above 1.5 which is a serviceability limit state failure criteria for RC2 type building classified according to Eurocodes.
- The reliability index estimation for the square-base conic shaped TMS have contrasting reliability results. The isotropic pre-stressing of the conic TMS have resulted in the well-established reliability results in terms of wrinkling failure for both isotropic and anisotropic pre-stressing for conic TMS. The ultimate fabric failure limit was fulfilled for the RC1 type buildings where reliability index requirement is 3.3 and above, rather than RC2 building where it is 3.8 and above. The serviceability criteria for the conic TMS(anisotropic pre-stress) was found to be deflected far away from the required reliability index value. The large variations of the obtained β values was experienced in the case of wind-uplift and the load case *CO1* , tis signifies the sensitivity of the membrane surface to the high magnitude loads in both uplift and downward directions.

6.3 Future scope of work

This research work provides a strong foundation for academicians and practicing engineers in the field of design of tensile membrane structures. The study conducted in this thesis throws several open questions on the analysis and design of TMS. Following are some important areas of future research which emerge immediately from this study:

- **Including material uncertainty:** Quantifying uncertainty in material properties, such as modulus of elasticity, Poisson's ratio, etc. and propagating them through the numerical model can predict more accurate design estimates, albeit at the cost of computation. As an immediate extension of this thesis work, it will be useful to model the material uncertainty in the framework adopted for this study.

- **Robust optimization formulation**: A robust design optimization of TMS, is required to extend the formulation in Chapter 4 and 5 to a multi-objective optimization under uncertainty considering all possible load cases based on their failure consequences or cost function.
- **Fluid-structure interaction studies for TMS:** The wind pressure cannot be determined until the structural vibration is quantified, which makes this a coupled fluid-structure interaction (FSI) problem. Further studies must be conducted to develop efficient FSI solvers for TMS and integrate these solvers with the optimization under uncertainty framework.
- **Calibration of partial safety factors for TMS:** A wide range of 'stress factor' values are documented in the available design codes and standards for TMS across various countries and organizations, making the design inconsistent and also creating problem in proof checking. Furthermore, due to the complex form and force interaction that governs the behavior of TMS, a classification of the existing real TMS typically used in construction practice must be done based on various common forms, such as, conic, saddle and hypar..
- **Reliability Analysis:** The high order reliability assessment methodologies could be established for more inclusive demonstration of non-linear limit states parameters. A reliability approach involving both qualitative and quantitative sources of uncertainty should be considered for an inclusive reliability analysis.