6.1 GENERAL

Relevant conclusions are discussed from time to time in the previous chapters. This chapter deals with the brief summary of conclusions and also suggestions for possible extension of research.

6.2 CONCLUSIONS

The present work deals with arriving at the optimum shapes of structures with respect to thickness, shape, topology optimization treating them separately and also by combining them. The targets are achieved by combining computer aided modeling, structural analysis, sensitivity analysis and built-in optimization modules.

Thickness and shape optimization is performed on the illustrative examples, Shell structures obtained by inverse technique, cylindrical shells and examples of straight and curved forms of box girder bridges. Inverse technique is the method in which the static analysis of the structure is done and the hanging model is created from the deflection profile which in turn is inverted to get deflection free model as a first step of optimization. These inverse models are further optimized for various objective functions such as minimizing the structural volume, minimizing the weighted frequency etc as single objective optimization. Four cases of support conditions are considered for optimizing the respective inverse models. Cylindrical shells are considered for three cases of support conditions for the same objective functions. Structural
Energy norms are calculated for each case and found to be within user specified limits.

Topology optimization concentrates on optimum shapes of shell structures obtained by inverse technique for four support conditions and cylindrical shells for three support conditions. Topology optimization of cantilever beam, deep beam and bridge pier examples are dealt for various percentages of volume reduction i.e 30%, 50% and 70% for the minimization of structural compliance as objective with material densities as the design variables.

The third part of the thesis dealt with integrated Thickness, Shape and Topology optimization of shell structures. The shell structure topology is optimized first and then the shape optimization is performed. The examples of inverse models and cylindrical shells are considered with various support conditions for investigation.

**6.2.1 Thickness/Shape optimization**

- Investigation on numerical example of inverse shell model generated from flat plate loaded downwards revealed that the inverse models are optimized models with respect to static and dynamic stiffness.

- Inverse shell models with minimum strain energy as objective did not show any reduction in strain energy when compared with the initial model.
Inverse shell models with maximization of fundamental frequency as objective did not show any significant change with respect to the initial value.

With the objective of minimizing the volume of the shell structure considerable reduction in volume is observed in the case of with fixed edge boundary conditions.

In the case of inverse shell models it can be concluded that the generation of the model inherits minimum strain energy i.e static stiffness and dynamic stiffness as they are deflection free models.

As a special case, for the shell supported on right edges it is demonstrated that the fundamental frequency can be increased by as much as 200% using shape optimization.

In the case volume minimization, as the thickness remains constant the geometry attains plane form for all the edge conditions.

The optimum values of the design variables depend on the range between upper and lower bounds of the design variable.

The results obtained using shell-43 element compare well with the reference author and previous researchers and also showed considerable improvement over their work.

With the objective of maximizing the fundamental frequency, for the optimum shape the difference between the first two natural frequencies is reduced to 2% almost for all the cases.
6.2.2 Topology Optimization

- Results are dependent on finite element mesh density i.e., a fine mesh will result clear topological results.
- In the case of minimizing the weighted frequency, shell supported on curved edges the frequencies are low when compared to other boundary conditions and also the percentage reduction in weighted frequency is found to be almost 50%.
- In the case of minimizing the structural compliance, shell supported on curved edges showed considerable reduction (53.3%) in compliance for 50% reduction in volume.
- Un-averaged density plots for higher volume reduction sometimes result into a truss like structure, which gives an idea of material distribution.
- A large reduction in volume (up to 80%) as constraint can be studied for various cases.
- Topology optimization techniques can be used to automatically generate optimal strut-and-tie models for structural design and detailing.
- The computer simulation results are very schematic and simplified, but show the unconventional or unexpected designs, which normally are possible for execution. In the draft and design process topology optimization supports engineer’s creativity.
For industrial/construction applications, the structures are very complicated and they require equations with large Degree of freedom (greater than 200,000) and even more which have to be solved. Iterative solvers which lower the computation efforts can be adopted for this purpose and the time can be saved.

6.2.3 Integrated Thickness/Shape and Topology Optimization

- Though the constraint on volume reduction in two cases of topology optimization, the final frequencies were increased considerably.
- In the case of minimizing the structural compliance, inverse models with fixed corners showed considerable reduction i.e. 74.53% in structural compliance for 50% reduction in volume.
- A large reduction in volume (up to 80%) as constraint can be studied for various cases.
- Combined shape and topology optimization results into much better optimum shapes when compared with shape and topology optimizations performed separately.
- The component in an economic way. There is a need to convert the structure geometry to simple and smooth outlines to achieve cost-efficient design and manufacturing/construction.
- The automated structural optimization modules minimize the designer interface requirement.
6.3 RECOMMENDATIONS

Based on the discussions of results of numerical examples, the following recommendations are made.

- Some of the optimum shapes presented in this work are not practically possible and are included to give an idea for the designer how different design variables have an impact on objective functions.

- Manufacturing/construction constraints can be imposed to produce more practical optimum designs.

- It is advisable that completely automated procedure in arriving at the optimal shape should be only be used as guide to the designer who must exercise the judgment in the selection of appropriate and practically possible designs.

- In the case of inverse models design variables (thickness) at the four corners of quarter plate is considered. Thickness function is dependent on the coordinates of the nodes of finite element mesh. Therefore infinite number of design variables exists in the optimization process and hence attention may be paid to select the thickness parameter at points of interest.

6.4 FURTHER SCOPE OF STUDY

- Error estimation studies need to be carried out using other type of finite elements.
- Topology Optimization Studies should be carried out with adaptive analysis.
- In the present work for shape optimization gradient-less method (sub-problem approximation method) is adopted. However, other methods such as gradient-based methods which depend on the derivatives of design variables should be investigated.
- For topology optimization Optimality Criterion (OC) method for structural compliance minimization and for weighted frequency maximization Sequential quadratic programming (SCP) method are used in the present study. Other algorithms such as MMA and Evolutionary techniques can be applied to obtain the optimum shapes.
- Optimization of composite and layered materials should be considered for studies. Optimization of number, thickness of piles and orientation of layers can be considered.
- CAD interactive program can be generated to perform the integration process of thickness/shape and topology optimization simultaneously (which does not exist in literature).