Analysis and Optimization of Thin Concrete Roof Shell

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Abstract- *Shell structures are able to span over large areas, while having an exceptionally less thickness. This is primarily due to their form based structural behavior. The geometry, that is their initial curvature, along with the boundary conditions and type of loading, dictates the way they transfer load or the way they fail (in case the load exceeds their load carrying capacity). Shells exhibit membrane like behavior which will be explained further in this thesis. The beauty of shells lies in the fact that a designer is able to design the shell as thin as possible, even in the presence of loads that disrupt its characteristic membrane behavior. The shell is able to confine this disturbance within regions which can be designed or optimized separately. This paper involves the design of a roof for a basketball arena, which has a capacity of 20,000 spectators and it needs to be designed as a concrete shell structure. The size of the stadium is large enough to demand a long spanned shell structure. This paper attempts to find a solution to this problem.*

Keywords- Shell, thin concrete roof, membrane theory

I. INTRODUCTION

Concrete shell structures, often referred to as 'thin shells' are suitable structural elements for building spacious infrastructures. They are often economical and suitable solution for different facility structures such as water tanks, large-span roofs, containment buildings, and silos. Loads acting on the surface of shell structures are mainly carried by the membrane action. This is a general state of stress and consists of the in-plane normal and shear stress resultants only. In comparison, other structural forms such as beams and plates carry loads acting on their surfaces by bending action, which can be said to be structurally less efficient. Usually the in-plane stresses in shells are low such that with a relatively small thickness it is possible to span over large distances. In addition, concrete shell structures can have various shapes and geometries and that has contributed to them often considered as visually attractive.

Shells provide a means to obtain an aesthetical and structurally efficient design. They can take several shapes and forms, which lie at the mercy of the designer. Coupled with the fact that they take up less material for construction, shells became increasingly popular in the last seven decades. Since then there have been several hindrances in their growth, but these difficulties are a thing of the past. Development of advanced analysis methods, and new innovative developments in the construction field, have led to a resurgence in shell design. As a result, new designs for shells are gaining prominence, some of which were impossible in the past.

This project attempts to create the roof of a basketball arena, to have a capacity of 20000 spectators. The shell is proposed to be made of concrete.

Objectives of the project are:

1. To get preliminary design for the shell structure of basketball stadium. Criteria like span, seating arrangements, type of shell are decided based on requirements.
2. To analyse the shell structure for different loads. The structure is analysed for Self weight, imposed loads and wind loads.
3. To optimize the shape and size of shell structure. There are several structural solutions for any kind of criteria. Nevertheless, the designer has to formulate a design which is structurally sound, and transfers the load to the ground in the most efficient way possible. Different span to rise ratios and different shell thickness are compared for various parameters.

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1.1 Classical theory of thin shells

1.1.1 General

In order to design any structure in detail, it is necessary to have some specific set of guidelines based on scientific methods. As for any other structural element, the guidelines for designing shell structures is provided by the branch of mechanics called structural mechanics. Engineers are mainly concerned with the man-made structures. In order to construct these structures, they are highly dependent on developing conceptual models that rationalizes the phenomena of nature. The development of these models largely depends on the understanding of mathematics, conducting experiments, assumptions and approximations.

1.1.2 Background

The theory of thin shells is first formulated by L.E.H. Love in 1888 in his paper on thin elastic shell theory. Love developed the shell theory on the basis of Kirchhoff hypothesis for thin plate structures proposed in in the mid-1800s. Since then, there has been several shell theories developed with their own set of kinematic relations (strain – displacement relations). The central idea it that the deformation of shells due to loading is resisted by the membrane and bending effects, which can be separated. The theory of structures often deals with idealized forms of the physical structures. A beam is for example often represented as a line that possesses a certain mechanical property. Similarly, a shell is represented by a surface that possesses a certain mechanical property like stiffness and strength. In this way load effects can be calculated easily, however one has to be aware that for the design of local problems this idealization might not be adequate. Further development of the theory employs Hooke’s law (elastic material), equilibrium and compatibility. Hooke’s law relates strains with stresses, equilibrium relates stress resultants with external loading and compatibility relates strains with deformation/displacements. These three sets of equations together with appropriate boundary conditions make up the mathematical aspect of the problem. When dealing with dynamic loading the equilibrium equation is represented by the equation of motion. Compared to flat plates, the shell theory is more complicated due to the geometry of the shell. It is possible to argue that the problem of shell structures is dominated by the geometry of the surface of the shell.

II. LITERATURE REVIEW

Hanibal Muruts, Ghebreselasie Yuting Situ From the perspective of structural engineering, shells due to their spatial curvature, possess a structurally efficient way of carrying loads acting perpendicular to their surfaces. However, the nature and geometry of shells makes them complicated to understand or predict their structural behaviour. The structural analysis of thin concrete shells can be conducted numerically using finite element analysis(FEA) or/and analytically on the basis of classical theory of thin shells. As finite element software are increasingly becoming primary tools for performing structural analysis, the knowledge of the analytical solution methods are becoming somehow less known among young structural engineers today. Hence, this paper aims to revisit the analytical analysis methods for concrete shell structures, and to investigate on how its results compare to that of the FEA. For a complete investigation of the structural analysis of thin concrete shells, the design and the accompanying verification by using nonlinear FEA is also briefly included. The study is limited to structural static analysis.

Vitória Vazquez Pereira As part of the research "Design and Performance of Ultra-Thin Concrete Shells", the proposed study seeks to explore the architectural dimension of an ultra-thin free-form shell structure. By applying spatio-functional analytic methods, its performance was evaluated in different real situations (natural and urban environments), studying how the visual fields, spatial movements and the shade produced, would be affected in the chosen site. Thus, it was sought to identify and validate with concrete hypothesis, different implantation layouts of the several possibilities introduced. Through the study of the historical evolution of shells and the existing technology and construction methods, it was intended to highlight the importance and advantages given of using this type of structures. Their natural form, associated to the development of new materials and prefabrication technology, transform this shell into a promising opportunity of future development. This work seeks to make part of that future, contributing for the understanding of the multifaceted spatio-functional dimension of these structures and their inseparable architectural component.

R.N. ter Maten Shell structures present immense structural and architectural potential. Generally speaking, shells are spatially curved surface structures which support external applied loads. The exceptional behavior of shell structures can be referred to as „form resistant structures". This implies a surface structure whose strength is derived from its shape, and which resists load by developing stresses in its own plane. Due to the initial curvature and low thickness to radius ratio a thin shell has a much smaller flexural rigidity than extensional rigidity. When subjected to an applied load it mainly produces in-plane actions, called membrane forces.

Antonio TomasPascual Martí Although concrete shells may adopt any form, it would be interesting to know to what extent changes in their shape may avoid the appearance of bending moments or reduce them. The use of optimization techniques may be effective in providing alternative geometric forms of shells that improve their mechanical behaviour, complying with the design conditions in an optimum way. In this paper, these techniques were used to find optimum geometrical designs having an aesthetic shape similar to the form initially designed for the structure. As an example, a shell based on Candela’s blueprints was optimized under a state of predominant gravitational loads. The results confirm that significant improvements in the structural behaviour of the shell may be achieved with only slight changes in its form.

Ha-Wong Song, Sang-Hyo Shim, Keun-Joo Byun and Koichi Maekawa In this paper, a finite element analysis technique is presented for the path-dependent nonlinear failure analysis of reinforced concrete shell structures. A so-called pressure node is added into a layered shell element utilizing in-plane constitutive models of reinforced concrete and layered formulation in the failure analysis. By controlling the volume of the shell structures using the pressure node, postpeak softening behavior after the ultimate load of the shell structures is obtained. Since the constitutive models cover loading, unloading, and reloading paths, the element is capable of predicting the behaviors of reinforced concrete shells under cyclic loading. For verification of the techniques in this paper, failure analyses of reinforced concrete slabs subjected to in-plane and out-of-plane loads and cyclic transverse loads are performed and numerical results are compared with experimental data. In addition, reinforced concrete dome structures designed with different reinforcement ratios are also analyzed to check the applicability of the technique in this paper. Results show that the techniques can be applied effectively to the failure analysis of various types of reinforced concrete shell structures.

Thomas E. Boothbyl and Barry T. Rossonz Thin-shell concrete structures were developed in the mid-twentieth century in response to the need for economy in large-span structures and in response to the design and aesthetic program of the modern movement in architecture. Although of European invention, these structures were widely employed in the United States for industrial and military structures, stadiums, auditoriums, and shopping centers. Because of changing building economics and changing tastes, significant thin-shell concrete structures have not been built in the United States since the mid-1970s. In spite of their relatively recent construction, many surviving thin-shell structures can be considered as historic according to the Criteria for Eligibility for the National Register of Historic Places. However, a lack of awareness of the significance of these structures has caused the recent removal of two important thin-shell concrete structures, the New Orleans Convention Center and "The Paraboloid," an entrance canopy for the May D&F store in downtown Denver. Others, such as Seattle's Kingdome Stadium, are clearly threatened. In this paper, we examine the historical and social context of thin-shell concrete structures, discuss the threats to the preservation of these structures, and outline a strategy of professional and public awareness and strategic repair.

K. S. Lay A four-noded quadrilateral pure shell element based on the thin-shell theory of Koiter (1966) has been developed. The element, having a variable number of nodal degrees of freedom with a maximum of 12, is formulated on the plane reference domain by a mapping of the curved shell middle surface from the threedimensional space. Any arbitrary global coordinate system can be used due to the implementation of tensorial coordinate transformation. Excellent behavior of the element is observed when tested against a set of severe benchmark tests. The benchmark tests demonstrate that the element is able to handle rigid-body motion without straining, inextensional modes of deformation, complex membrane strain states, and skewed meshes. The two-dimensional interpolation functions are formed from the tensor product of Lagrange and Hermitian one-dimensional interpolation functions, and the order of interpolation can be varied.

III. PROBLEM STATEMENTS

The project aims for the economical design of thin concrete shell roof of an indoor arena. For this various value of thickness (for various failure modes) and different span-rise ratios will be calculated, to find an optimum value of span-rise ratio and an optimum thickness, for various load combinations.

Based on the results of the findings a thin concrete shell roof is to be designed.

IV. METHODOLOGY

To fulfil the objectives, a specific design approach is defined. The overall strategy of the project is mentioned below:

All theory related to shell design is acquired and studied. This includes study of different shell surfaces, their structural behaviour and also the possible ways they can fail.

The entire history of concrete shell industry is studied, along with important associated people and structures. In the 1950s several shell designers rose to prominence. An attempt is made to learn about their ways and methods. Between these designers, they have an impressive list of shell structures that exist and function today. Some of these bear similar characteristics and aspects, compared to the expected shell design for this project.

Currently functioning basketball arenas are studied to have a better understanding of loads expected on the roof. If there are any special loads that need to be taken into account, then they are found out in this step.

Based on the steps mentioned above, pre-design considerations are drawn up. Sight line analysis is done for obtaining the span. They essentially serve as design boundaries or constraints, only within which, the designer can freely operate. Different shells with varying thicknesses and span to rise ratio are analysed in ANSYS 16.0. The behaviour of the designed shells is studied and recorded, under various load combinations, to ensure proper functioning of the structure. Among the shells analysed, the most optimized shell is selected. Finally, the shell is validated by comparing it to other similar shells.

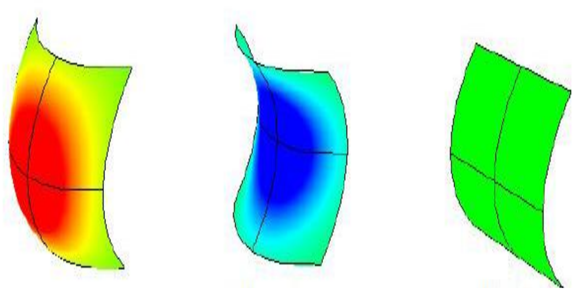
These steps are derived from the literature study performed, before commencing the actual design of the roof of the basketball arena. They help to create a sound design process which is then applied to obtain the final proposal.

V. HEORETICAL CONTENTS

5.1 Classification of shell surfaces:

5.1.1 Gaussian Curvature:

Shell surfaces are usually classified based on their Gaussian curvatures. For a three-dimensional surface, the product of the maximum and minimum principal curvatures gives us the Gaussian curvature. They are orthogonal to each other and can be found out by intersecting infinite planes with the surface at any point. Based on the product of the principal curvatures we can further classify the Gaussian surfaces as discussed



a) Positive b) negative c) zero

Figure 1: Types of Gaussian curvatures

Synclastic: A Synclastic surface has a positive Gaussian curvature and is shown in figure 2-1 (a). Both the principal curvatures have the same sign. They generally exhibit in-plane meridional and circumferential stresses to carry loads. Spheres and elliptical paraboloids are common examples of this kind of surface.

Anticlastic: In this type of surface both the principal curvatures have different signs resulting in a negative gaussian curvature. Having opposite signed principal curvature enables these surface to act with a combination of compressive and tensile arch behavior under perpendicular loads. Hypars are good examples of anticlastic surfaces.

Monoclastic: If one of the principal curvatures is zero then it gives rise to monoclastic surfaces. They have zero gaussian curvature as seen in figure. Cylindrical shells are the most common examples of this type of surface.

5.1.2Developed and Undeveloped Surfaces

This basis of classification depends on whether the surface can be ’opened’ or deformed to obtain a plane form. Figure show examples of both.

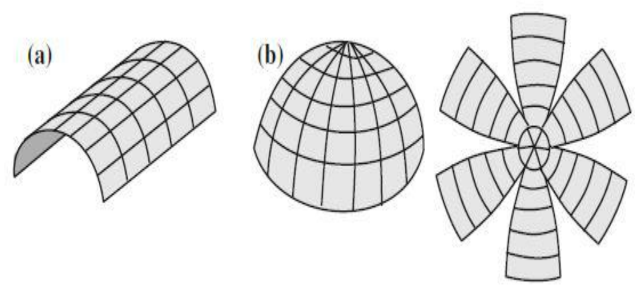


Figure 2: Examples of developable and undevelopable surfaces

Developable surfaces can be deformed and developed to obtain a plane surface, without any cutting or stretching. Cylindrical roofs as shown in figure are an example of this type of surface. We can imagine that the roof can be easily deformed to obtain a plane. All monoclastic shells are developable surfaces.

Undevelopable surfaces, unlike their developable counterparts, cannot be deformed into their plane forms without alterations, which were mentioned before. All synclastic and anticlastic surfaces fall in this category. They have significant advantage over comparable developable surfaces in having more strength and stability. This stems from the fact that more external energy is required to cause any kind of deformation.

5.1.3 Generation of surfaces

Surfaces described above can be created using geometric or non-geometric techniques. The former uses mathematical functions while the latter uses natural processes like form-finding.

Geometrical Surface generation

They include surfaces of revolution, surfaces of translation, ruled surfaces and freeform surfaces as shown in figure. Surface of revolutions are created by rotating a meridional curve about the axis of revolution. Translational surface requires sliding of a constantly oriented generator curve over a directrix curve. Constructing ruled surface requires another method, where we slide two ends of a straight line on their own curve while keeping them parallel to an arbitrary direction or plane. Lastly, freeform surfaces can be generated using NURBS (Non-Uniform Rational B-Spline). They are different from the other geometrical methods as they cannot be described by fixed equations but can be used to make any possible shape.

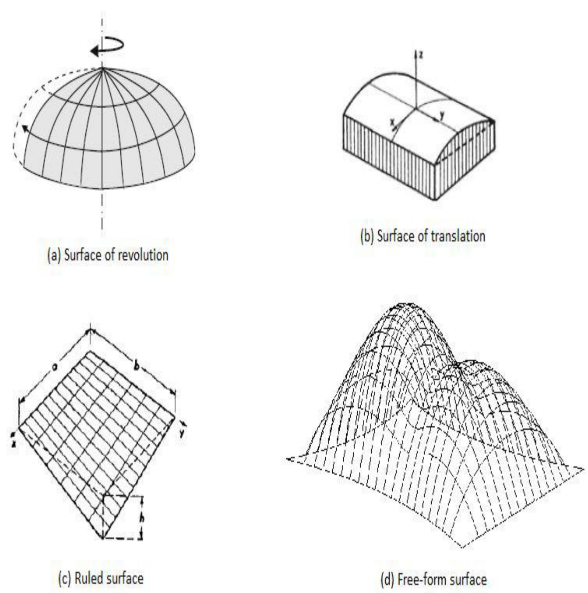


Fig3: Examples of geometrically generated surfaces

5.1.4 Non-Geometrical Surface generation

There are several physical and computational methods of form finding. They involve finding a shape which is at equilibrium with the forces that act upon it. Here we study the hanging model analysis which is the most native form physical form-finding. This method is extremely useful to obtain shapes for thin shells. Generally cloths or chain nets can be used for this analysis. These materials cannot absorb bending moments, so when they hang it is safe to assume they experience only tension due gravity. Keeping this in mind we can create hanging models as shown in figure. This shape represents the equilibrium shape of the cloth at that particular moment. If we were to freeze the model and invert it, logic dictates that the entire cloth is in compression. For a structural designer this is a very important aspect as the cloth acts like a membrane which, as discussed earlier, is very structurally efficient. Although, it should be known that presence of other dominant loads can cause problems.

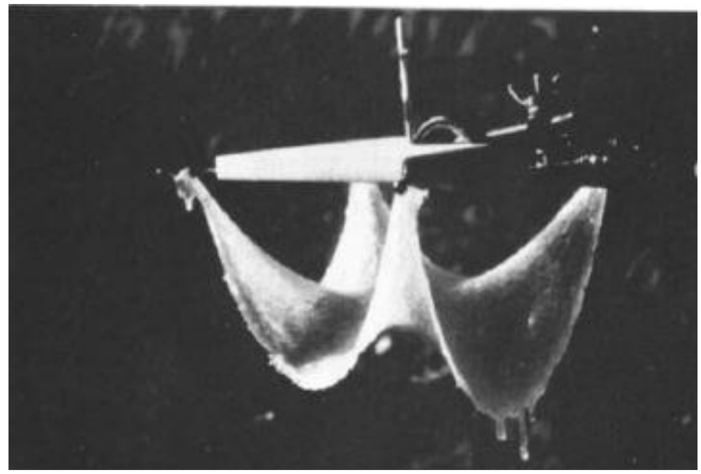


Fig4: Example of a hanging model using cloth

5.2 Structural behaviour of Shells

A good knowledge of the structural behaviour of shells is imperative for good shell design. It can vary hugely depending of kind of loads the shell is expected to carry. Shells are form based structures where the shape influences the shell’s load carrying capacity. This structural geometry largely dictates the development of stresses in the shell elements. This has to be kept in mind to avoid unwanted deformations and structural failure.

5.2.1Membrane behavior

Membrane theory attributes to the membrane-like behavior of shells, which enables it to carry out-of-plane loads. They transfer these loads by generating in-plane membrane forces, a fact that separates them from plates. Shells, unlike membranes, stretch and contract without producing significant bending or changes in local curvature. Ideally a designer would prefer to design the shell only for membrane forces, as this enables the shell to be thin and hence be more economic. This is not possible always due to presence of unfavorable loading and boundary conditions. These conditions are shown in figure 2-5. In such cases the membrane stress are not enough to reach a state of equilibrium giving rise to disturbed regions with additional stresses. Thus a bending theory is required for a complete analysis of the shell.

5.2.2 Bending behavior

The bending behaviour of shell is very interesting. It only occurs at parts of the shell where the membrane stresses are insufficient to carry the applied loads. The bending moments developed in these regions only compensate for the inadequacy of membrane behaviour and do not carry any load. In figure 2-5 we can see, the presence of concentrated forces or geometry changes creates a disturbed region with bending moments. But these moments are confined to small region around the point of disturbance defined by its influence length' (li).

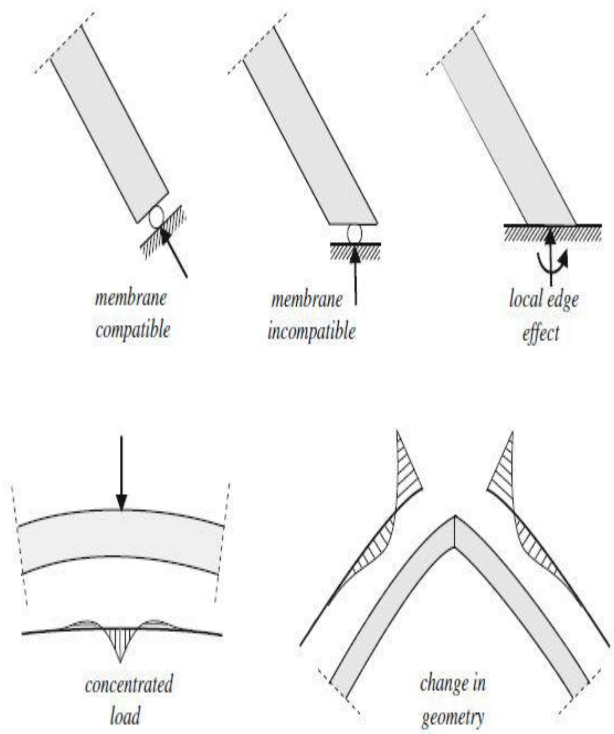


Fig5: Conditions for membrane and bending theory

This means the rest of the shell will still possesses a true membrane field. The influence length for a spherical dome is shown in figure. This behavior of shells is a boon to designers as it highlights the structural efficiency of shells. In a practical sense, this enables the designers to design a relatively thin shell, even in the presence of membrane incompatible conditions. Special optimizations or other structural solutions can be found to tackle these conditions, while expecting large parts of the shell to still behave like a true membrane.

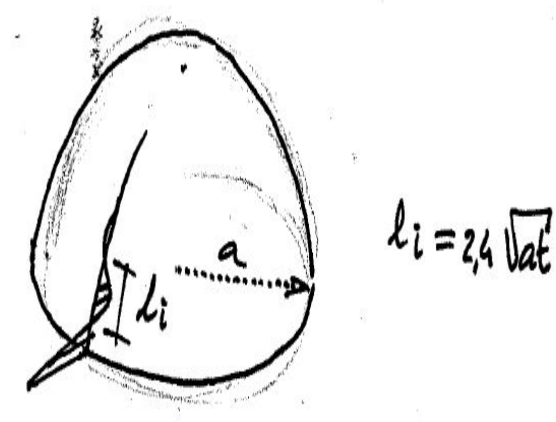


Fig6: Influence length of edge in for a spherical dome

5.3Structural Failure of Shells

It is important to know a structure might fail, because this knowledge helps the designer to design the structure accordingly. In this project, the aim is to design a thin shell which motivates us to study the various modes of shell failure. Shells can fail due to increasing deformations, failure of material or a combination of both. The former is called 'buckling instability' while the latter is referred to as 'strength failure'.

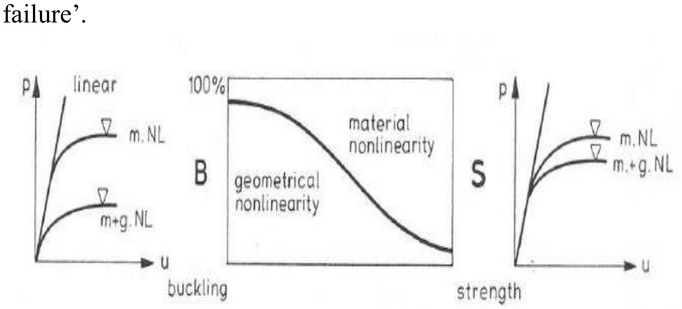


Fig7: Structural failure modes for shells

5.3.1Strength Failure

Strength failure occurs as a result of deterioration of material properties and is characterized by lower deformations. Tensile forces can cause the concrete to crack, or it might undergo compressive crushing which, in turn, will reduce the strength of concrete. In most cases of thin shells the stresses are not too high; hence this type of failure does not govern design, although this can lead to buckling failure. Usage of high strength concrete further decreases the possibility of this type of failure.

5.3.2Buckling Instability

Shells, for the most part, are expected to carry in-plane compressive forces. Initial imperfections in geometry can give rise to eccentricity of these forces, which threaten the stability of the structure. Usually one or more structural components can fail, at a lower stress than the design ultimate compressive value of the failing concrete member. Following this the structure undergoes a drastic loss in load carrying capacity finally leading to collapse. Nonlinearities in materials further add to this phenomenon. There are some more important points associated with shell buckling which are discussed below.

5.3.3Snap-back behaviour

This type of behaviour is typically seen in shell structures. When the shell is loaded it starts following a path of equilibrium. This part is shown by the linear line in figure. This path is followed till the bifurcation point is reached, after which the shell experiences sudden loss in its load carrying capacity. This is shown in figure as the curved line which represents snap-back. This behaviour is dramatic and catastrophic, as it happens suddenly and quickly without any warning. This curve represents the post buckling behaviour of the structure. The transition between the two paths of equilibrium can be smooth or sudden depending on the geometry of the shell. This phenomenon is further intensified with the presence of imperfections, hence the dotted line in figure is a closer assumption of the path of equilibrium a shell will follow in real life.

5.3.4Imperfection Sensitivity

Imperfection sensitivity of shells was first established when scientists found discrepancies, between the calculated critical load and the actual load that a shell could carry.

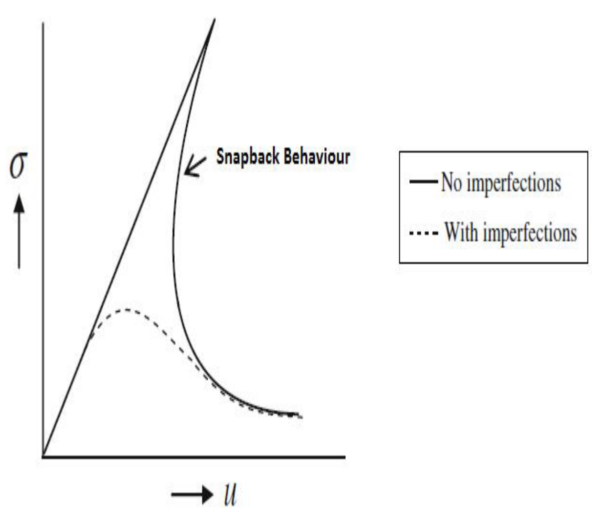


Fig8: Stress-Deflection curve showing snapback behaviour of a shell

Experiments were performed on axially loaded cylinders resulting in failure, much before reaching the critical load. Eventually it was realized that these cylinders were extremely sensitive to even a minute imperfection, which would otherwise be hidden from the naked eye. The effect of imperfections was first quantified by Professor Koiter during the Second World War.

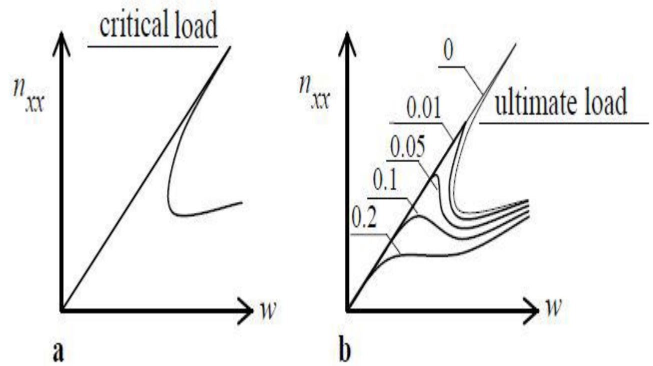


Fig9: Buckling of cylinders over different imperfection amplitudes

Figure shows us how increasing imperfection amplitudes can drastically reduce the load carrying capacity of the cylindrical shell. Although, not all shell are so sensitive to imperfections.

5.3.5Compound Buckling

Thin shells are especially sensitive to imperfections due to the occurrence of 'compound' or 'multi-mode' buckling. This happens due to interactions between the different buckling modes as all of them are associated with the same linear critical buckling load. Thin shells exhibit membrane dominant behaviour, hence have closely related buckling modes. This is due to the absence of shorter influence lengths of bending regions. As a result, thin shells are more susceptible to compound buckling than thick shells. Consequently, this is a major reason for snap back behaviour in thin shells.

5.3.6 Knock down factor

It was discussed earlier how experiments showed a large difference between the theoretical and actual critical load. This posed significant problems to shell designers as the various factors (a few discussed above) could not be separately incorporated in design. A solution to this problem was found by applying a factor, which accounted for all the factors causing snap back behaviour. This factor is called 'Knock down' factor. The knock down factor for a particular design is the sum of the individual factors, for each negative effect on the load carrying capacity of the shell. These effects are shown for a spherical dome in figure 2-10. For this project the value of knock down factor (C) is chosen as 1/6, as is the norm in the absence of a stipulated value.

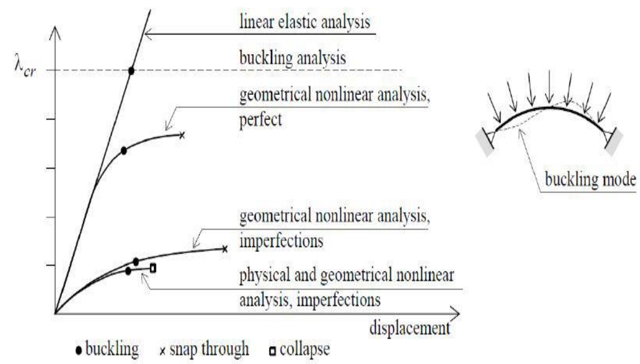


Fig11: Negative effects causing fall-back in load carrying capacity

VI. ANSYS RESULTS

The analysis of 9 shells has been carried out and the results were shown in Table 6.1 and Table 6.2. It is clearly shown in both cases of Total Deformation and Differential Deformation that values have been reduced with an increase in Shell Rise (sagitta), it was also seen to reduce with reduction in Shell Thickness. All the deformations are well below critical, so they are safe. The Shell with Rise of 35m, and 100mm thickness is considered the best with respect to deformation having deformation of 5.259mm only.

Normal Stresses are seen to decrease when the Shell Rise (sagitta) increases. But they are increasing with increase in Shell Thickness. Here, shell with Rise of 23m and 100mm thickness will be best with respect to Normal Stress.

The values of Shear Stress, Shear Strain, Equivalent Stress, Normal Strain, and Strain Energy decrease with decrease in Shell Thickness considerably and also with increase in Shell Rise. The Shell with Rise of 35m, and 100mm thickness is considered the best with respect to these values.

The volume for 150mm and 200mm thick Shells obviously are 1.5 and 2 times that of 100mm thick Shell. Increasing the cost of concrete 1.5 and 2 times respectively. The volume of concrete and costs increase at average 10% with increase in Shell Rise.

Above results indicate that the Shells with thickness of 100mm are most appropriate for all concerns. The Shell Rise of 35m is optimized value, as with only 20% increase in concrete quantity it provides 25% decreased Total Deformation, 42% decreased Normal Strain, 60% decreased Equivalent Stress, 77% decreased Shear Stress and 77.4% decreased Shear Strain.

The shell with Rise of 35m and Thickness 100mm is most optimized.

Validation with respect to existing structures

The Dome of Palazzo dello Sport, Rome, Italy built in 1960 with a Shell Span of 100m and Thickness 90mm has Shell Rise of 20.9m. It is already studied in case study 4.5.2. The Deitingen Petrol Station Dome, Switzerland was built in 1968. It has Shell Span of 31.6m and 11.5m Shell Rise. Its thickness is 90mm. Both structures were designed as segment of a sphere just like the Shells analysed in this dissertation. However, it must be noted that Deitingen Station Dome is of a smaller size. These shells were also analysed and their results are compared. The values found were proportional to our shell. The dissertation is thus validated.

VII. CONCLUSIONS

1. A thin concrete shell structure has been designed, for a basketball arena of 20,000 spectator capacity. This is the overlying conclusion of this thesis. A synclastic shells is used. To ensure that the designed roof is able to house 20,000 spectators at one time, its dimensions were calculated in accordance to the capacity. This required a sightline analysis and capacity analysis. Subsequently it was concluded that the final capacity requirements are met. This meets the first objective.
2. The dome is an elegant solution for the roof. This is an attempt to enhance the aesthetical efficiency of the roof system. The realistic behaviour of the shell, based on the Membrane theory, Failure theory and Theory of shell under point load at apex prove it to be safe. The shell was analysed for Self load, Wind load and Imposed load, and is concluded safe. This fulfils the second objective.
3. It is verified that with slight changes in the shape of a concrete shell, considerable improvements are obtained in its mechanical behaviour. In particular, deformations in the optimum shells decrease considerably to values lower than those of the greater thickness design. This facilitates better membrane behaviour and decreases the overall bending moment on the structure. results indicate that the Shells with thickness of 100mm are most appropriate for all concerns.
4. The Shell Rise of 35m is optimized value, as with only 20% increase in concrete quantity it provides 25% decreased Total Deformation, 42% decreased Normal Strain, 60% decreased Equivalent Stress, 77% decreased

Shear Stress and 77.4% decreased Shear Strain.The shell with Rise of 35m and Thickness 100mm is most optimized. This satisfies the third objective.

VIII. FUTURE SCOPE

Additional research is needed to incorporate realistic creep effects in the structure. Also the visco-elastic and visco-plasticity settings needs further studies, to provide the designer with more knowledge on how and when to incorporate this effects in nonlinear analysis.An attempt could be made to provide a hole or opening at the apex of the shell, and then proceed with the design process. The shell can then be analysed and studied to see any changes in structural responses.

This shell roof is proposed to be built up using concrete. A study should be performed to analyse the shell to recreate a situation if the shell needs to be repaired.Although the designed shell roof has been proven to be satisfactory, the imperfections included were based on buckling patterns. Additional analysis should be performed by incorporating more realistic imperfections, based on practical experiences of working with domes.A dynamic analysis needs to be performed on the shell, to assess its behaviour against abnormal loading conditions like wind storms and earthquakes. This will make the design more comprehensive.A study when the shell is acted upon by Snow loads can be done. This could be useful for cold countries.

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