WRINKLING PREDICTION ALGORITHM USING LINEAR PERTURBATION TECHNIQUE IN ANSYS FOR INFLATABLE STRUCTURES

Nidhin Mohan

M.Tech Student, Department of Mechanical Engineering,

Marbaselios College of Engineering and Technology

ABSTRACT

In this study, the static and modal analysis of spindle shaped Tensairity beam with hull element divided into three layers of equal thickness with different orientation was done. The parametric studies are done for thetensairity beam with materials, internal pressure and dimensions.From the modal analysis done, it was seen that there is variation between frequencies under two different pressures applied on the hull element. So the effect of pressure has to be taken into consideration in the design of Tensairity beam.Tensairity beam with chord and hull element made of low modulus of elasticity material produce higher natural frequencies than chord element made of high modulus of elasticity material.From modal analysis,it was found that the dimensions of tension and compression element has great influence in designing of the beam.Tensairity beam with hull element made of low modulus of elasticity fabric material shows greater displacement than the Tensairity beam with hull element made of high modulus of elasticity fabric material.Tensairity beam with low internal pressure on hull element shows greater displacement than beam with high internal pressure on hull element.

Keywords: Internal Pressure, Modal Analysis, Modulus of Elasticity Static Analysis, Tensairity Beam.

I. INTRODUCTION

It seems to be part of our human nature to push the limits. Skyscrapers are growing higher, the maximal span of bridges and roof structures are increasing day by day. The limit of feasibility is set by physical constraints or by complexity or by the economic conditions. The development on all these frontiers are advancing very fast, new concepts and materials are developing day by day. Air as a structural element has quite some history. From hot air balloons to air houses and tires: pneumatic structures have found in the course of time their market niches. Attracted by the light weight and availability of the material, many engineers have looked for applications of inflated structures. However, in most respects, the limit of pneumatic structures turns out to be a physical one: the load bearing capacity.

While voluminous inflated structures such as airhouses work reasonably well with low air pressure, slender structures with small curvatures can only maintain some stiffness with increasingly large air pressure. In the new structural element Tensairity, the pneumatic fabric structures are combined with conventional elements as cables and struts, resulting in a load bearing capacity which is in any respect comparable to conventional structures.

1.1 Structure and Behaviour of Tensairity Beam

A Tensairity girder consists of a tension element and a compression element separated by an inflated fabric structure, so that these act as a spacer between tension and compression element. Compression element and tension element are connected with each other at both ends of the beam to close the flow of force. The role of the compressed air inside the hull is to facilitate the load transfer between the tension and the compression element and to stabilize the compression element against buckling. The first investigated Tensairity beams were done on a cylindrical form. The tension element used here are two cables which are spiralled around the cylindrical air beam and which are connected on each end with the linear compression element. The compression element is tightly connected with the membrane so as stabilize against buckling. The representation of a typical cylindrical tensairity beam simply supported at the ends is shown in fig 1.1.

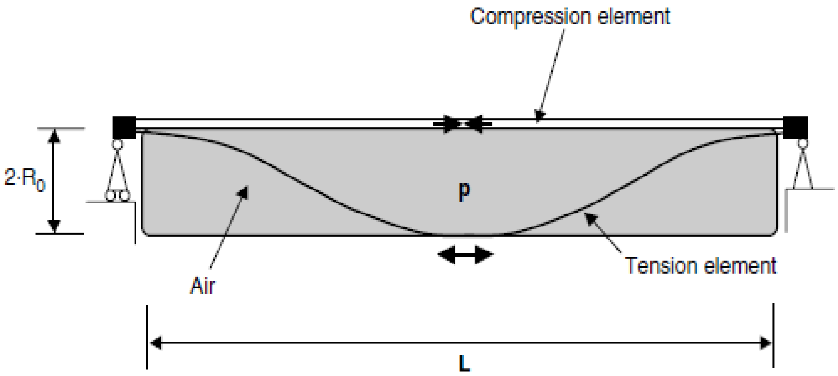

Fig 1. Representation of cylindrical shaped Tensairity beam

1.2 Spindle Shaped Tensairity Beam

While the first Tensairity beams were based on a cylindrical form, further investigations revealed, that cigar shaped or spindle shaped Tensairity girders as shown in Fig.1.2 are much stiffer than the former That is, the deflection of a spindle Tensairity girder is smaller than the deflection of a cylindrical girder with the same length, maximal diameter and pressure under same loading conditions. Another difference with the spindle Tensairity girder is that the two helical cables of the cylindrical girder degenerate to a single tension element in the spindle. As the tension element is no more spiraled around the tube, it can have some bending stiffness and can be used as a compression element, too. Therefore, spindle shaped Tensairity girders can withstand both positive and negative loads. This is especially good for roof applications with positive snow loads and negative wind loads.

The spindle shaped Tensairity girder of Fig. 1.2 can be made completely symmetric and a tension element becomes a compression element and vice versa depending on the loading conditions. Asymmetric spindles can also be considered as Tensairity. A typical form of an asymmetric spindle is when the upper chord is an arc and the lower chord is a straight line. As in a bow, the tension element can be prestressed even with zero pressure in the air beam and thus the structure remains stable even under complete air loss. The asymmetric spindle can be designed to withstand the dead load of the structure with zero pressure whereas the function of the compressed air is to withstand the live load. This important safety feature is adapted in the roof of the parking garage inMontreux. Finally, the spindle shape of beam allows more dynamic forms as compared to the cylindrical shape and provides a better architectural view.

The recent Tensairity applications as the roof of the parking garage in Montreux where based on spindle shaped Tensairity girders. The basic principles for spindle shaped and cylindrical shaped girders are same. The role of the compressed air in the spindle is to stabilize the element under compression against buckling, it acts as a spacer between the lower and upper chord and it facilitates the load transfer between the upper and lower chord by means of the pressurized membrane.

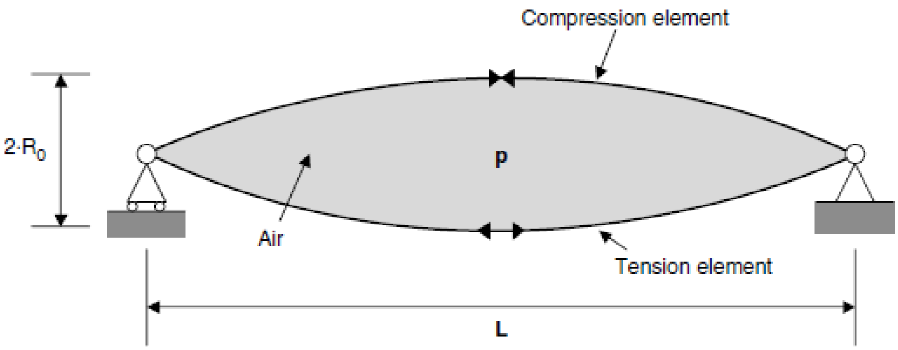

Fig 2. Representation of spindle shapeTensairity beam

II.WRINKLING PHENOMENON

Thin membranes wrinkle whenever they are subjected to compressive load. This is due to the inherently small bending resistance of membrane structures which buckle out-of-plane under the action of even small in-plane compressive stress. This phenomenon is common and it can be observed in many structures in daily use, ranging from umbrellas and temporary tents to large fabric roofs for airports and stadiums. Wrinkling is not a concern for designing small structures because it has no structural consequences. More often a compensation scheme is used, in which the fabric is cut to a smaller size than that required to generate purely the geometric shapes that are required according to the form-finding process. Additional stretching of the fabric is thus required in order to eliminate potential wrinkles.The presence of wrinkles in membrane structures may significantly influence static and dynamic behaviour of space systems containing membranes. It is, therefore important to develop computationally effective analysis methods for the prediction of wrinkle formation and evolution in membranes. A buckling solution and a non-linear post buckling solution were employed for the wrinkling analysis of a tensioned Kapton square membrane.

2.1 Types of Wrinkles

Wrinkles due to loading or boundary conditions are completely reversible if the membrane does not yield. These wrinkles are termed structural/elastic wrinkles; their magnitude varies with the loading and boundary conditions. Wrinkles where the material yields are permanent and irreversible, and are termed material/plastic wrinkles. This type of wrinkles can be random and can be thought of as an initial set of very extreme imperfections. Only structural wrinkles are considered in the present study.

As the application of Tensairity structure increases, it is proposed to study the behaviour of the spindle shaped Tensairity beam under different loading and by changing various parameters. A beam element is being analysed to identify the wrinkling effects on the beam when a load is being applied to an end that is free.

2.2 Wrinkling Computation Procedure

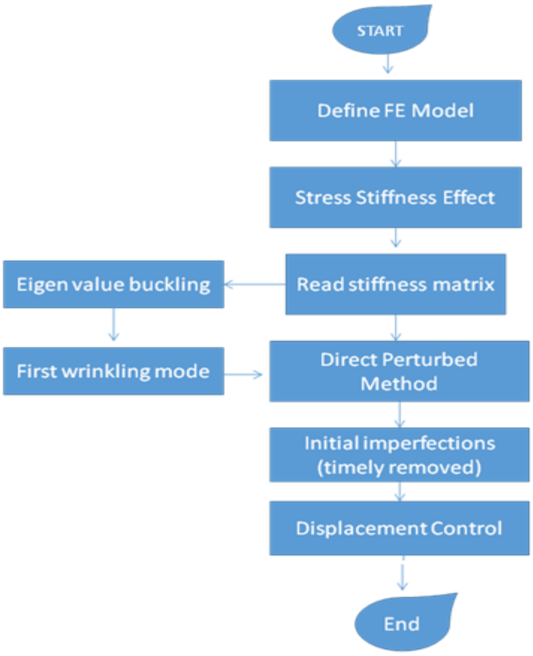

Fig 3.Flowchart of wrinkling computation

In the past methods, the imperfections are generated from the first wrinkle mode or the combination of the several modes by multiplying by a scale factor. These imperfections cannot be removed from the model which will influence the post wrinkling behaviours. In order to accurately perform the wrinkling analysis, the idea of the Modified Displacement Component method by using the direct perturbed method in the simulation. The basic of the direct perturbed method is to apply some small out-of-plane forces on the membrane surface to induce the imperfections, and further to induce the wrinkle. After that, these imperfections are timely removed from the model by deleting those out-of-plane forces.

Where, we should take care of two key problems. Firstly, the detailed imperfections should be based on the first wrinkling mode which is obtained from an eigenvalue buckling analysis, including the imperfection amplitude, the imperfection region and the imperfection direction. In other words, these imperfections generated by the out-of-plane forces have the quantitative characteristics, and they are not random distributions. Above all, we have a default rule that the imperfection amplitude should be at the same magnitude of the membrane thickness. Secondly, the equal numbers of positive and negative out-of-plane forces should be applied on the membrane surface so that the net out-of-plane forces remains equal to zero, which meets the force equilibrium condition and mainly initiate the analysis into the post-wrinkling phase. The location of these out-of-plane forces are also based on the first wrinkle mode characteristics. In this respect, the direct perturbed method is thus restricted to wrinkling modes with an even number of wrinkle waves, so that they meet the moment equilibrium as well.

III. OBJECTIVES AND METHODOLOGYOF THE PROJECT

- Analysis of Tensairity structure by using the finite element software ANSYS
- Loading of the Tensairity structure.ie, beam by using the software.
- Modal analysis of the Tensairity structure using the software and obtain the different mode shapes.

- Determine the natural frequency, deflections under different pressure, different materials and different dimensions.
- Wrinkling analysis of the validated 3D inflated beam is done by inducing imperfections.

The initial step after literature survey is to familiarize with the software ANSYS 15.0 thoroughly. A spindle shaped Tensairity beam having a length of 5m and a central diameter of 0.5m is to be modelled. Thefabric is to be made of same material divided into three layer of equal thickness but with different orientation. The fabric is made with PVC coated polyester having a density of 1440kg/m^{3}and with an overall thickness of 5mm. The tension and compression element is to be made with aluminium of rectangular shape with width 30mm and a depth 10mm. A pressure of 150mbar is to be applied internally. The loading on the tensairity structure, i.e. for a spindle beam will be done using the software and the corresponding deformations will be obtained. Modal analysis of the tensairity structure will be done and different mode shape will be obtained. The natural frequency and deflections are determined under different pressure, different materials and different dimensions. The modal analysis of spindle shaped tensairity beam with two different pressures of 100mbar and 200mbar is to done.

The modal analysis of tensairity beam with three different compression and tension members is to be done. The three different materials to be used are aluminium, steel and copper.Forthe analysis, PVC coated polyester fabric tensairity beam of 150mbar internal pressure is to be used. Modal analysis of tensairity beam with threedifferent fabric materials is to be done. The three different fabric materials to be used are PVC coated polyester, nylon and polypropylene. For the analysis, tensairity beam with tension and compression element of aluminium rod and 150mbar internal pressure is to be maintained. Also modal analysis of tensairity beam with three different cross section of tension and compression rod is to be done. The three different cross sections to be adopted for tension and compression rod are 30×20, 25×25, and 35×15mm.A beam element is being analysed to identify the wrinkling effects on the beam when a load is being applied to an end that is free.

V. FINITE ELEMENT ANALYSIS USING ANSYS

The elements used for the modelling of the spindle shaped Tensairity beam are SHELL281 and BEAM189.

5.1 SHELL281

SHELL281 element with quadrilateral configuration is used for this analysis. SHELL281 is suitable for analysing thin to moderately-thick shell structures. The element has eight nodes with six degrees of freedom at each node: translations in the x, y and z axes, and rotations about the x, y, and z-axes. SHELL281 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. The element accounts for follower (load stiffness) effects of distributed pressures.

SHELL281 may be used for layered applications for modelling composite shells or sandwich construction. The accuracy in modelling composite shells is governed by the firstorder shear-deformation theory. The element formulation is based on logarithmic strain and true stress measures. The curvature changes within a time increment are assumed to be small.

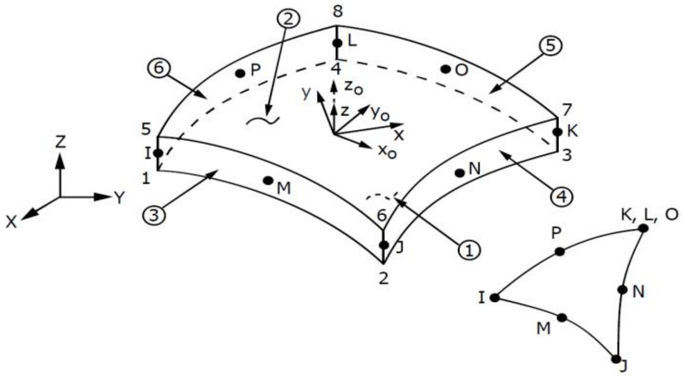

Fig 5.Configurations of shell 281 element

5.2 BEAM189

The BEAM189 element is suitable for analyzing slender to moderately stubby/thick beam structures. The element is based on Timoshenko beam theory which includes shear-deformation effects. The element provides options for unrestrained warping and restrained warping of cross-sections.The element is a quadratic three-node beam element in 3-D. With default settings, six degrees of freedom occur at each node; these include translations in the x, y, and z directions and rotations about the x, y, and z directions. An optional seventh degree of freedom (warping magnitude) is available. The element is well-suited for linear, large rotation, and/or large-strain nonlinear applications.The element includes stress stiffness terms, by default, in any analysis with **NLGEOM**ON. The provided stress-stiffness terms enable the elements to analyze flexural, lateral, and torsion.Elasticity, plasticity, creep and other nonlinear material models are supported. A cross-section associated with this element type can be a built-up section referencing more than one material.

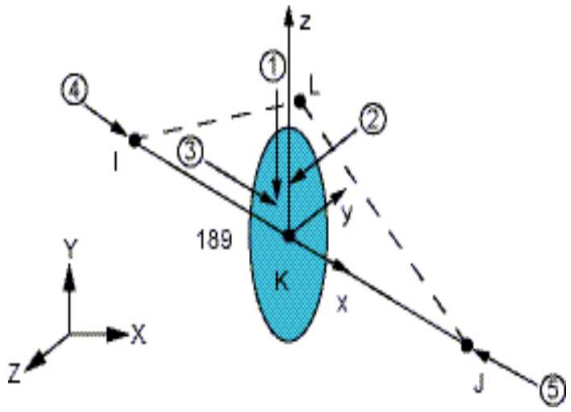

Fig 6.Configurations of beam189 element

We then apply the MDC method to the wrinkling numerical simulation codes (ANSYS) by incorporating the direct perturbed method and the nonlinear post-wrinkling calculation. Although the method has eliminated the singularity of the stiffness matrix,we also use several effective strategies to advance the convergence. The first is the introduction of the stress stiffening effect. This effect can deal with the coupling conditions between the in-plane membrane tension and the out-of-plane wrinkle deflection. After meshing of the elements, this effect is introduced by reducing the structural temperature. Reducing the temperature to introduce the stress stiffening effect does not affect the computations, i.e., it does not lead to a thermal stress problem. The second is the introduction of the displacement control technique. The key to this technique is to use the displacement loadings to substitute the force loadings. That is to say, we increase the tension displacement to generate the loading function, which can push the wrinkling computation into the post-buckling phase smoothly.

Where, the forces in the calculation of the non-equilibrium force equation come from the nodal reaction forces which are generated by the incremental displacements. In the end, the nonlinear equation is solved by using the Newton–Raphson iteration and the dichotomy method. The dichotomy method is an effective auto-correction for the failed convergence. This method will divide the time step into two halves and then restart computation from the last convergent sub-step when the iteration is divergence. The dichotomy will end until iteration reaches convergence. In addition, the increment of displacement loadings is limited to smaller value to satisfy with the requirement of convergence.

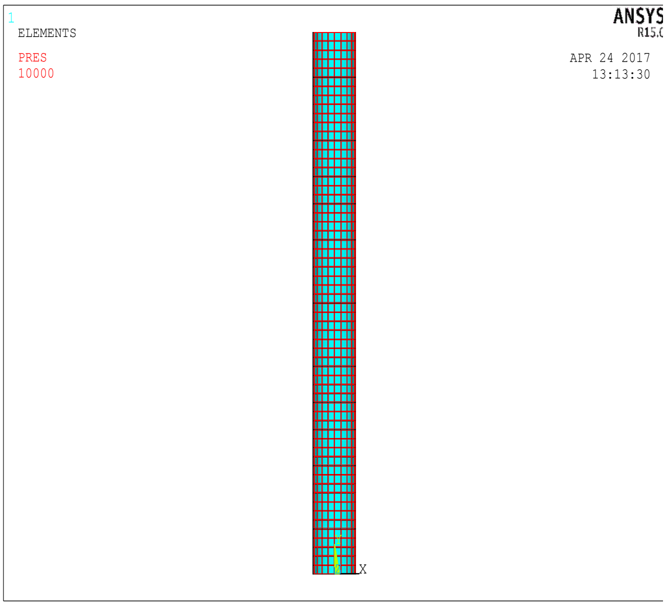

Fig 7. Meshed model of inflatable beam

VI. RESULTS AND DISCUSSION

6.1 Modal Analysis of Spindle Shaped Tensairity Beam

Modal analysis of spindle shaped tensairity beam was done by dividing the fabric material of the hull element into three layers of same material of equal thickness but by varying the orientation of fabric in each layer.The total thickness of the fabric is 0.5mm.For the analysis,aluminium was taken as the tension and compression element and PVC coated polyester was chosen as the fabric material and internal pressure of 150mbar was provided in the hull element.The first four natural frequencies are obtained for different orientation and are shown in Table.

Table 1 Comparison of Frequencies for Different Orientation of Fabric

$45^0,0^0,-45^0$	$0^0,45^0,0^0$	$60^0,0^0,-60^0$	$0^0,60^0,0^0$	$30^0,45^0,-30^0$	$30^0,0^0,-30^0$
9.2421	9.2352	9.8202	9.9256	10.6643	10.1263
10.7260	10.7466	11.3625	11.4420	12.1236	11.9234
28.7362	28.6953	29.5864	30.1222	30.4444	29.8352
29.1250	29.2242	30.1252	30.4262	31.8562	30.8256

The frequencies corresponding to orientation $45^0,0^0,-45^0$ and$0^0,45^0,0^0$ are the lowest and are found close to each other. Considering symmetry, orientation of 0^0, 45^0, 0^0 was chosen for further analysis.

6.2 Study of Load-Displacement Characteritics of the Spindle Shaped Tensairity Beam

To study the load displacementbehaviour of a spindle shapedTensairity beam, a central loadwas introduced at the center of the compression chordof the beam as shown in Fig 6.9. For the analysis, aluminium was taken as the chord element and PVC coated polyester in three layers with an orientation $0^0,45^0,0^0$ was used as the hull element. The study was conducted for an initial load of 0.2KN and the deflection was obtained. Now by changing the load to 0.4KN, 0.6KN, 0.8KN and 1KN, the corresponding deflections were obtained for a pressure of 150mbar.

6.3 Load-Displacement Characteritics for Different Tension and Compression Material

The material properties of different materials used in the parametric study of tensairity beam are given in Table.

Table 2 Material Properties

Material	Modulus of elasticity(N/m^2)	Density (kg/m^3)	Poisson's ratio
Steel	$210X10^9$	7800	0.3
Copper	$120X10^9$	8940	0.35
Aluminium	$69X10^9$	2700	0.33
PVC coated polyester	$4.14X10^9$	1440	0.39
Polypropylene	$1.1x10^9$	900	0.4
Nylon	$2.8X10^9$	1120	0.34

The load deflection behaviour of the spindle shaped Tensairity beam was done with three different compression and tension members.The three different materials used for chord material were aluminium,steel and copper.For the analysis,PVC coated polyester in three layers with an orientation $0^0,45^0,0^0$ was used as the hull element and aninternal pressure of 150mbar wasused.The load displacement response of spindle shaped tensairity beamfor different chord materials is shown in Table below.

Table 3 Load Displacement Response for Different Chord Materials

Load(kN)	Displacement (mm)		
	Aluminium	**Steel**	**Copper**
0.2	2.20	1.60	1.88
0.4	4.49	3.22	3.80
0.6	6.94	4.88	5.82
0.8	9.56	6.62	7.94
1.0	12.40	8.42	10.18

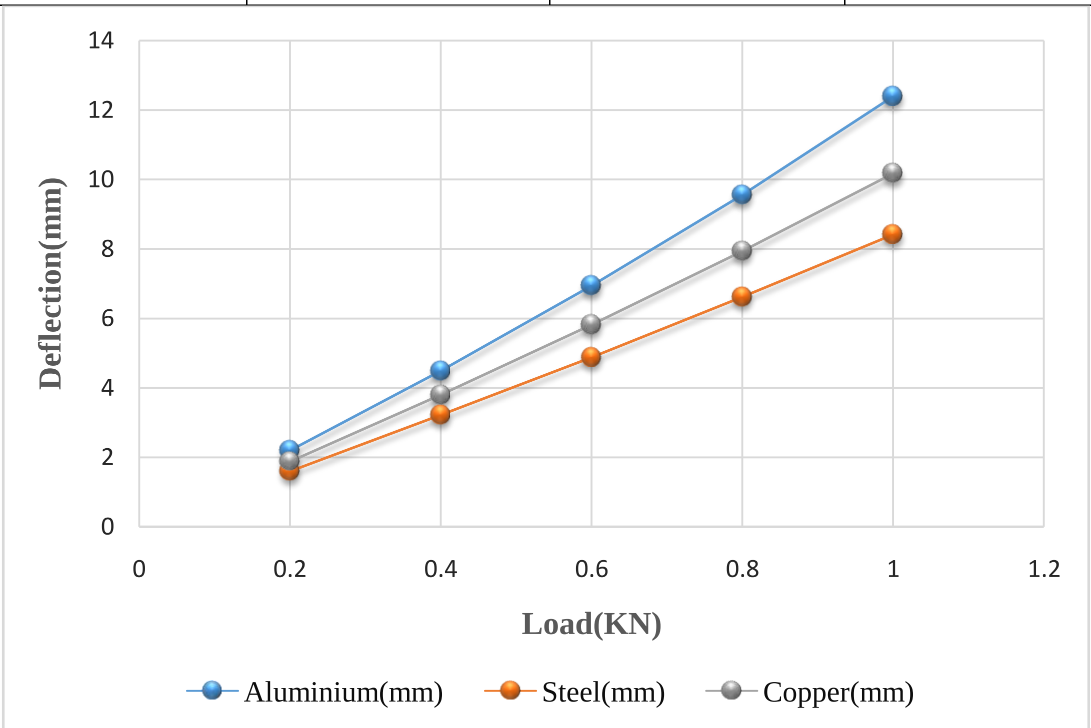

Fig 8 Load-Displacement response graph for different chord materials

From above the graph,spindle shaped Tensairity beam with aluminium rod shows greater displacement than other two material.Tensairity beam with steel rod shows minimum displacement. So spindle shape Tensairity beam with steel rod will produce greater stiffness than aluminium and copper rods.

6.4 Wrinkled Patterns(Clusters)

Wrinkled patterns are the pattern obtained by the beam when subjected to localized buckling through a series of substeps Each substep corresponds to a particular wrinkle pattern which are called clusters.

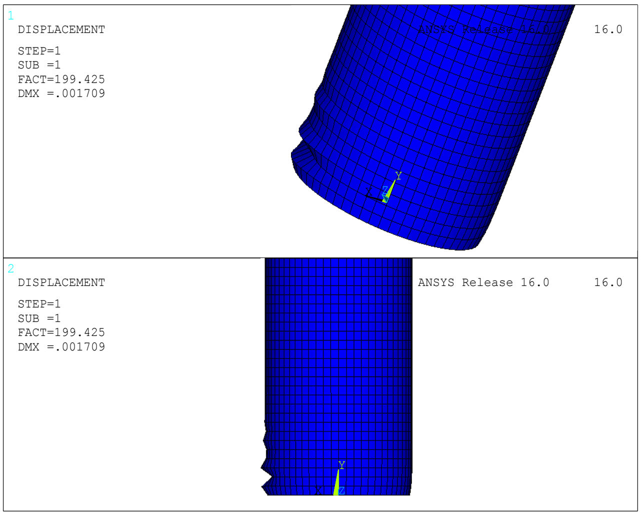

Fig 9 wrinkled Pattern (Cluster)

VI. CONCLUSION

In this study, the static and modal analysis of spindle shaped Tensairity beam with hull element divided into three layers of equal thickness with different orientation was done. The parametric studies of the tensairity beam with materials,internal pressure and dimensions were done.

The important conclusions drawn from the various parametric studies are sumarised.

- From the modal analysis done, it was seen that there is variation between frequencies under two different pressures applied on the hull element. So the effect of pressure has to be taken into consideration in the design of Tensairity beam.
- Tensairity beam with chord and hull element made of low modulus of elasticity material produce higher natural frequencies than chord element made of high modulus of elasticity material.While designing this should be taken into account.
- From modal analysis,it was found that the dimensions of tension and compression element has great influence in designing of the beam.
- The spindle shaped Tensairity beam with chord element made of low modulus of elasticity shows greater displacement than the Tensairity beam with chord element made of high modulus of elasticity material.
- Tensairity beam with hull element made of low modulus of elasticity fabric material shows greater displacement than the Tensairity beam with hull element made of high modulus of elasticity fabric material.
- Tensairity beam with low internal pressure on hull element shows greater displacement than beam with high internal pressure on hull element. So spindle shaped Tensairity beam withhigher internal pressure will produce greater stiffness.

REFERENCES

[1] Beyons.Thomas, Anumod.A.S (2015), "Finite element based static and dynamic analysis of tensairity spindle structure", International Journal of Research in Engineering and Technology, vol.4, pp.97-103.

[2] Credic.Galliot, Rolf.H.Luchsinger (2013), "Structural behavior of symmetric spindle-shaped Tensairity girders with reinforced chord coupling", Engineering Structures, vol.56, pp.407-416.

[3] C.Galliot, R.H.Luchsinger(2009), "A Simple model describing the non-linear biaxial tensile behaviour of PVC- coated polyester fabrics for use in finite element analysis", Composite Structures, vol.90, pp. 438-447.

[4] Joep.C.M. Breuer, Rolf.H.Luchsinger (2010), "Inflatable kites using the concept of Tensairity", Aerospace Science and Technology, vol.14, pp.557-563.

[5] Joep.Breuer, Wubbo.Ockels, Rolf.H.Luchsinger (2009), "An inflatable wing using the principle of Tensairity", American Institute of Aeronautics and Astronautics, vol.1, pp.1-12.

[6] K.L.Apedo, S.Ronel, E.Jacquelin, A.Bennani, M.Massenzio (2010), "Nonlinear finite element analysis of inflatable beams made from orthotropic woven fabric", International Journal of Solids and Structures, vol.47, pp.2017-2033.

[7] M.C. Bernasconi, G.G. Reibaldi (1985), "Inflatable, Space-Rigidized Structures: Overview of Applications & Their Technology Impact", Paper IAF-85-210 presented at the 36th International Astronautical Congress, Stockholm, 7-12 October, pp.455 - 465.

[8] Rolf H. Luchsinger, René.Crettol (2006), "Experimental and Numerical Study of Spindle Shaped Tensairity Girders", International Journal of Space Structures, vol. 21, pp.119-130.