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Investigation into behavior of Suspen-Domes in Comparison with Single-Layer Domes

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Abstract**—**Prestressing in structure increases ratio of load-bearing capacity to weight. Suspendomes are single-layer braced domes reinforced with cable and strut. Prestressing of cables alter value and distribution of stress in structure. In this study two configuration, diamatic and lamella domes is selected. Investigated domes have span of 100m with rise-to-span ratios of 0.1, 0.2, and 0.3. Single layer domes loaded under service load combinations according to ISO code. After geometric nonlinear analysis, models are designed with tubular and I-shaped sections then reinforced with cable and strut and converted to suspendomes. Displacements and stresses of some groups of nodes and elements in all of single-layer domes and suspendomes for three load combinations, symmetric snow, asymmetric snow and wind are compared. Variation due to suspending system is investigated. Suspendomes are redesigned and minimum possible weight after addition of cable and strut is obtained.

Keywords**—**Braced dome, Prestressing, Single-layer, Suspendome.

I. Introduction

SUSPENDOMES in the group of space structure are a type of braced domes that obtain from adding cable and strut to single-layer domes. Prestressing of cables increases stiffness of suspendomes. Low weight and appropriate performance are advantages of suspendomes. Connections in single-layer domes and top surface of suspendomes are considered fixed. Prestressing systems by applying inverse force to structure increase load-bearing capac[1]ity so from economical point of view are cost-effective.

Objective of this study is to introduce new structural system to cover large spans. To simulation of exact behavior of domes under snow and wind loads ISO code is used so that the need for wind tunnel test that is recommended in the case of large span domes is met to some extent.

Structural analysis is performed by using SAP2000 software. To guarantee modeling accuracy existed models in some papers is compared with models created by SAP2000. Only geometric nonlinearity is considered. Modeling consists of two stages:

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Geometric modeling that Formian software is used, then in the next stage DXF version model imported to SAP2000 [1].

In suspendome three factors cause non-linear behavior:

- *State change:* cable elements have two state of loose and stiff that is dependent on loading conditions.
- *Geometric nonlinearity:* includes shortening of member length under compression force, change in member length due to bending of members, and perstressing that stiffness matrix [K] is function of displacement {u}.
- *Material nonlinearity:* Above mentioned factors cause that to investigate domes, geometric and material nonlinear analyses are used. But in this study only geometric nonlinearity is considered. Models are loaded under service loads according to ISO code then are designed. Cables are not loose under any of load combinations and because of no entrance to plastic region material nonlinearity is not considered [2].

II. Modelling

Frame element in SAP2000 is used. Connections in top surface of suspendomes are fixed but in other parts are hinged. Cable elements are modeled with frame elements but to prevent pressure resistance of element, compression limit is assigned zero, also zero twisting and bending stiffness are assigned to beam element(Frame) so that can exhibit cable behavior. Frame element has six degrees of freedom at each node. In order to generate cable element so as not to transfer any moment at its end nodes, we can use Release command that omits resistance of rotational degrees of freedom in the element, although no cable loosening is observed during analysis under all loading conditions. The proof of which are numerous numerical studies performed on suspendomes.

A. Configurations and Properties of Investigated Models

In this study two types of diamatic and lamella domes are considered as shown in Fig 1. Diamatic configurations consist of 7 sections 8 orbits, while lamella configurations consist of 15 orbits and 96 supports. All member cross-sections are tabular and circumferential ring in all domes are from I-shaped elements. Circumferential ring of dome have stronger sections than other parts of dome. Supports are restrained only against displacement in vertical and tangential directions of circumferential ring but displacement at radial direction are free to move. Top configuration of lamella dome is inspired from two layer Negera dome in kaulalumpur, malaysia that is trimmed lamella.

Restraining supports in all directions produce large forces under all load combinations. Prestressing of Frame element can be done by two method: initial strain, and initial temperature. In this study initial temperature is used. Three single layer diamatic and lamella dome with span of 100m and rise-to-span ratios of 0.1, 0.15, 0.2 is equipped with cable and strut. Diamatic domes equipped as one pattern but lamella domes equipped as two patterns. Totally 15 models is investigated. Single layer models under various load combinations including symmetric snow, asymmetric snow and wind are designed. We tried to minimize their weight, then cables and struts are added. Components of suspendome is illustrated in Fig. 12.

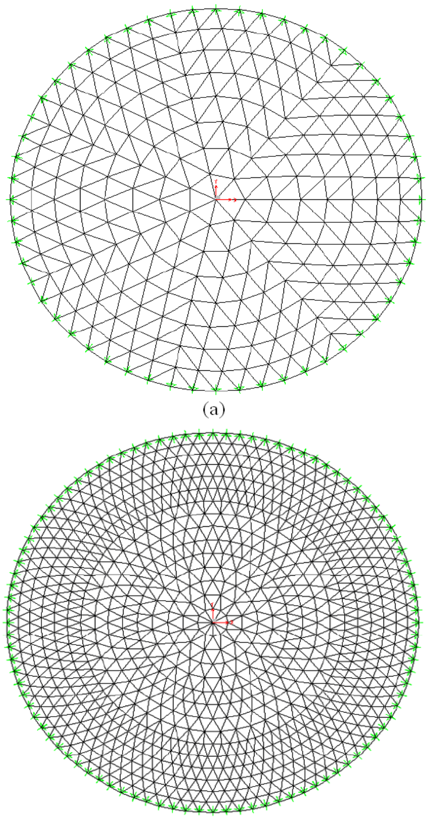


Fig. 1 Configuration of models a-diamatic b-lamella

B. Assigning Loads

Loads are forces or reactions that result from material weights, occupants, environmental and climatic effects, displacements, etc. For dome structures snow and wind loads are important. In this study wind load based on ISO4354 and snow loads based on ISO4355 is calculated[3]-[4]. Loading process of space structures by using programming tools is convenient. In this study Delphi programming language is used. To generate text version nodal loading input for SAP2000, the program takes span, rise and elevation of dome, assuming installation load of 0.15 KN, cladding load of 0.15KN, then calculates dead, wind, snow nodal loading accurately.

Structures weight is given to software as self-weight then cable and strut weight along with pre-stressing force is added. Amount of prestressing by means of proposed method in [5] is calculated. After finishing cable and strut installation and applying prestressing, dead load is added.

C. Design

These models are designed to cover stadium with span of 100m. Main reason of using Frame element is that SAP200 can only design Frame element not other types of elements with Auto capability. AISCASD89 code is used. Selected sections are from AusNZV8.Pro series and range from $76.1\times 2.3CHS$ to $610\times 6.4CHS$. For circumferential ring sections $617WS171$, $2\times 685WS153$, and $2\times 719WS240$ are used. The design process continues so that the analyzed and designed elements are the same. Circumferential ring must be designed for critical loading when prestressing is applied along with weight of elements so that circumferential ring is not subjected to high compression force.

Steps of analysis and design of suspendomes is according to below procedure in SAP2000 software [6]:

1. Apply prestressing.
2. Apply load combinations step by step.
3. Check that no cable has loosened under any load combination.

Strut length in suspension system changes so that angel of radial cables with horizontal line decreases from 30 degree in the base of dome to 20 degree in the top of dome. AISC-ASD code is used to design models.

D. Calculating Prestressing Force of Cables

We can determine prestressing force of cables with below method:

1. Dead load is imposed on structure.
2. Critical deflection is calculated.
3. To omit critical deflection, value of prestressing is selected so that its resulting deflection is equal and inverse with critical deflection of previous stage.

Obtained prestressing force by considering (1) is imposed on cables.

$$N_{hci} = N_{hc1}\left(1 - \frac{\sum_{j=1}^{i-1} d_j}{\sum_{j=1}^{n} d_j}\right) \tag{1}$$

Where N_{hci} is prestressing force of *ith* cable ring, N_{hc1} is prestressing force of first cable ring (bottom ring), d_j dead load of node in *jth* cable ring, and i is number of cable rings. Equation (1) is obtained by applying equilibrium relations in Figs. 2-3.

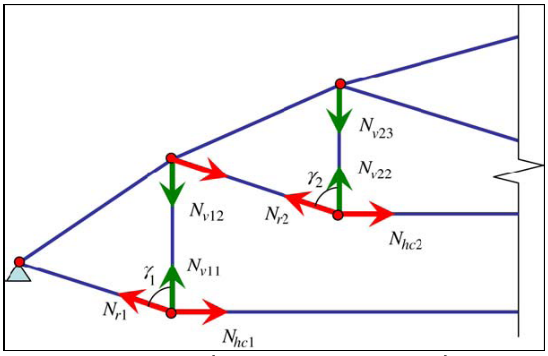


Fig. 2 Forces and angels of orbital and radial cables from side view

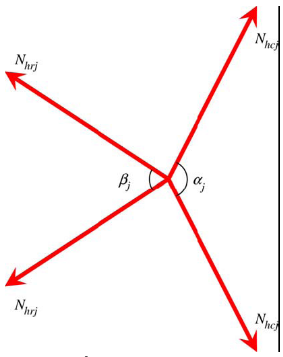


Fig. 3 Forces and angels of orbital and radial cables from top view

Because of large dimension of investigated structure in relation to structures in papers, when we want reach to zero stress in circumferential ring in some load combinations for example wind load, cable loosening is observed so we increase value of pre-stressing to some extent that cable loosening do not occur. Tables II, III, and IV show initial and changed prestressing temperature of cables for different models.

III. Verification

In this section linear analysis is performed on dome of Fureai stadium in china with trimmed lamella configuration that is investigated by other researchers, using SAP2000 software. Span and rise of dome are 35.4m, 4.6m respectively. Results shown in table I are in good agreement [5].

TABLE I
Critical Deflection for Different Nodal Point

Nodal Load (kN)	Critical Deflection with SAP2000(mm)	Critical Deflection with ANSYS(mm)	Erorr % ( )
3	5.10	5.07	0.59%
5	8.51	8.47	0.47%
7	11.91	11.87	0.34%
10	17.01	17.01	0%

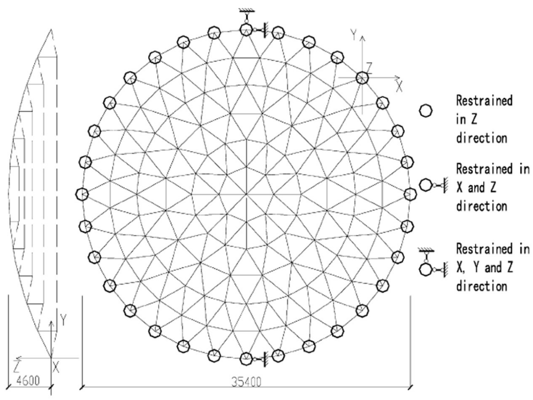


Fig. 4 Dome of Fureai stadium

IV. Analysis Results

A. Assessment of Displacements under Load Combination 1 (Symmetric Snow)

According to Figs 5-6 in diamatic configuration deflection of all objective nodes decreased considerably. Positions of objective nodes are shown in Figs. 13-14. Increase in rise-to-span ratio causes reduced decrease in deflection of objective nodes. It seems that effect of suspending system on single layer dome for low rise-to-span ratio is noticeable. The reason can be found in single layer dome curves. It is seen that with increasing rise-to-span ratio displacements decrease, so stiffness of dome is related directly to rise-to-span ratio, thus effect of suspending system in systems with high rise-to-span ratio is lesser than systems with low rise-to-span ratio. The curves indicate this point. Difference between nodal displacement of single layer diamatic domes and their related suspendomes decrease with increase in rise-to-span ratio, while nodal displacement in both of them decrease with increase in rise-to-span ratio. This trend is observable also in lamella domes. Lamella domes and their corresponding suspendomes like diamatic domes get stiffer with increase in rise-to-span ratio. Effect of suspending system gets weaker with increase in rise-to-span ratio. In contrary to diamatic domes behavior of rare-element suspendomes is very economical in bottom of dome. Dense-element suspendomes have better performance in the top of dome. By moving toward bottom displacement of all rare- and dense-element suspendome nodes are concurrent. Rare-element suspendomes have better decrease of deflection in comparison with dense-element suspendomes in rise-to-span ratios of 0.15 and 0.2. Dense-element suspendomes in nodes 15,16,17,18 cause increased deflection in comparison with single-layer domes, although with increase in structural stiffness i.e rise-to-span ratio deflection in the bottom of dense-element suspendomes get closer to deflection of single-layer dome while have appropriate performance in rise-to-span ratio of 0.1.

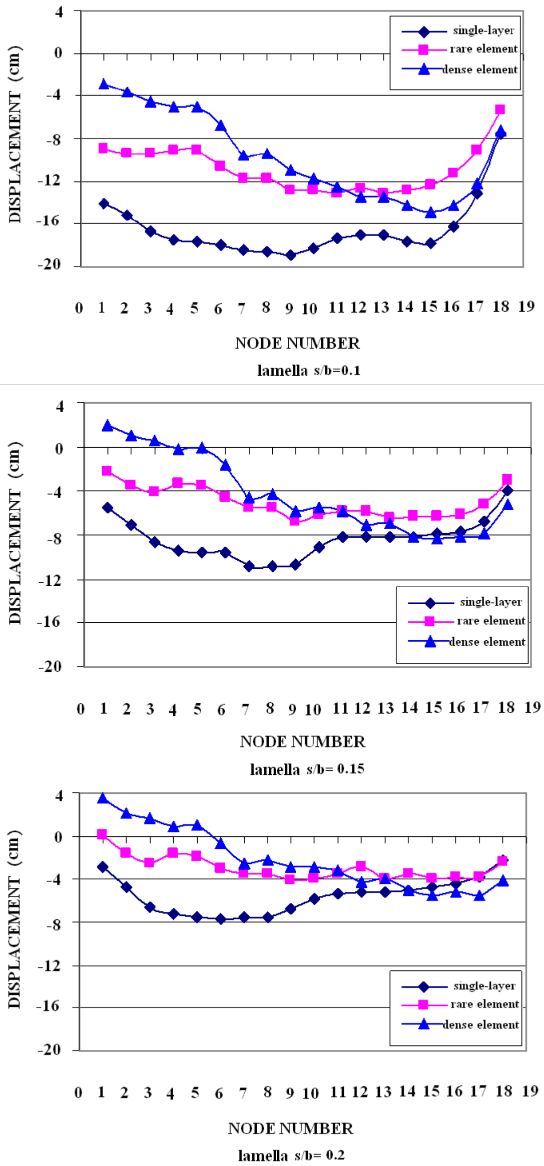
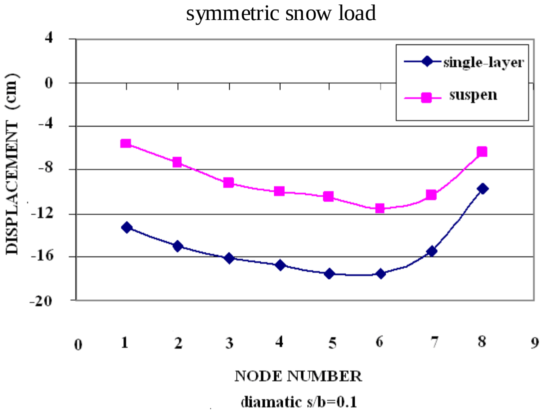


Fig. 5 Deflection of objective nodes in lamella domes under symmetric snow load



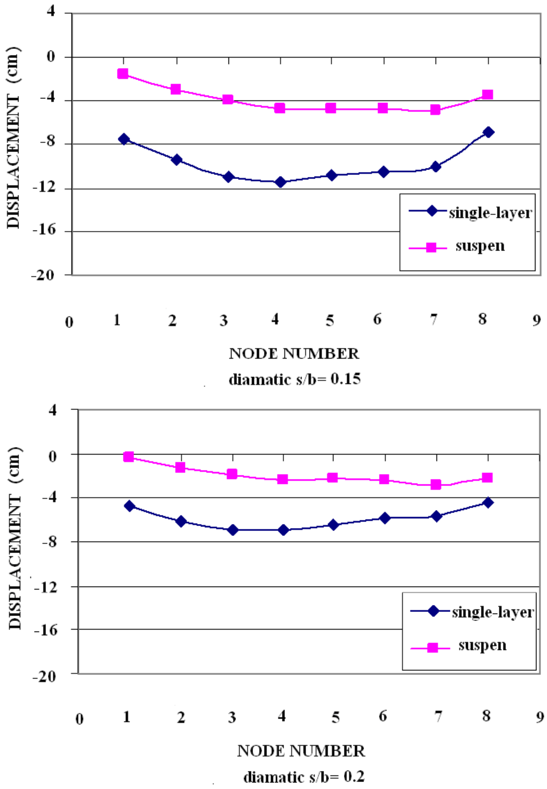
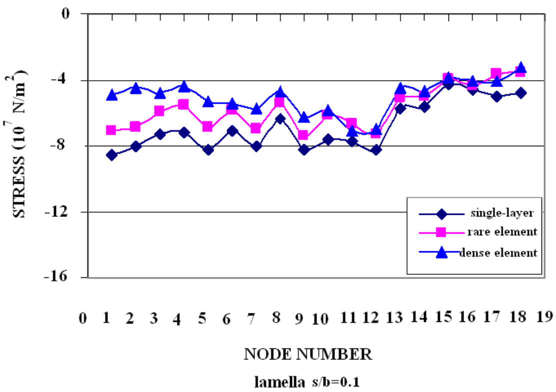


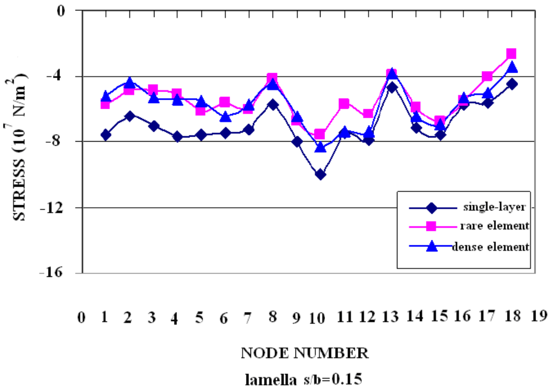
Fig. 6 Deflection of objective nodes in diamatic domes under symmetric snow load

B. Assessment of Meridian Stresses under Load Combination 2(Asymmetric Snow)

Difference of stresses in top nodes of dome is noticeable. The reason is reduction of asymmetric snow load in top of dome, so weakest part of suspending system can generate effective reduction in meridian stresses of this region. Reduction in stresses of intermediate elements is better than other elements.

In lamella dome the effect of suspending system on meridian stresses decreases with increases in rise-to-span ratio. Here also reduction in stress due to suspending system is effective in lamella dome with rise-to-span ratio of 0.1. Rare-element suspendome shows better performance in meridian stress reduction with increase in rise-to-span ratio.





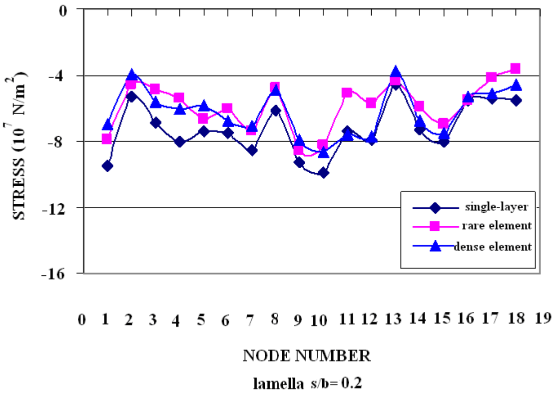
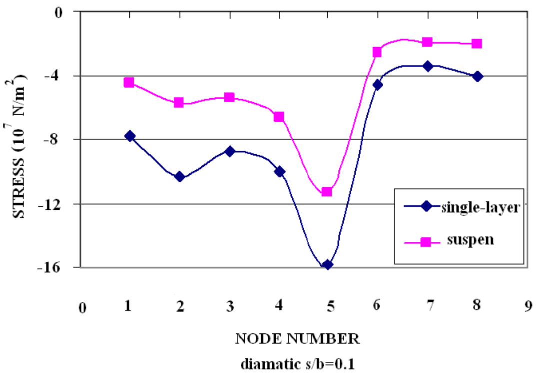
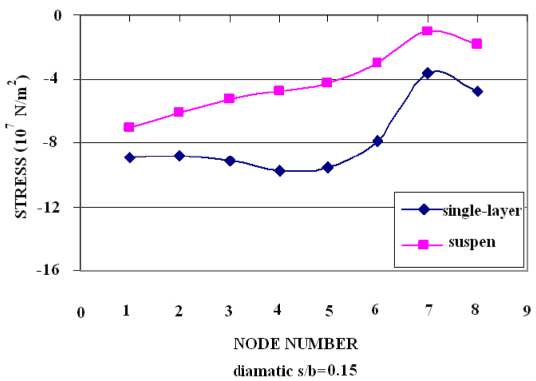


Fig. 7 Stress in meridian elements of lamella domes under asymmetric snow





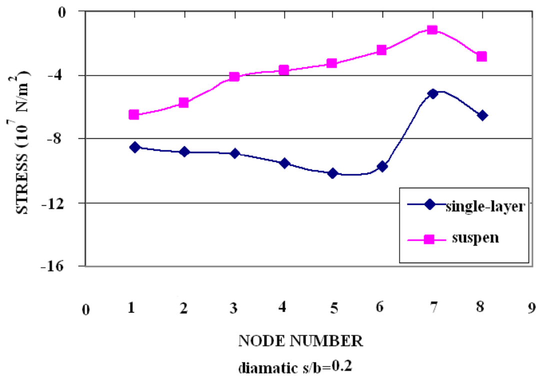
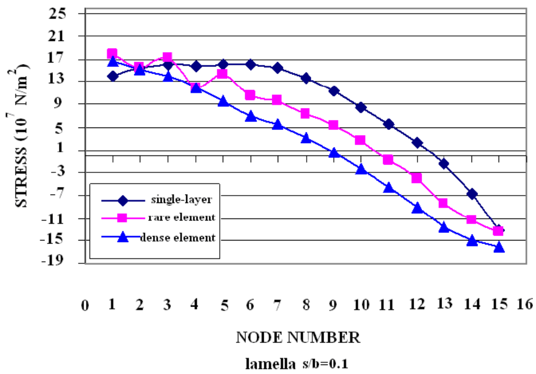
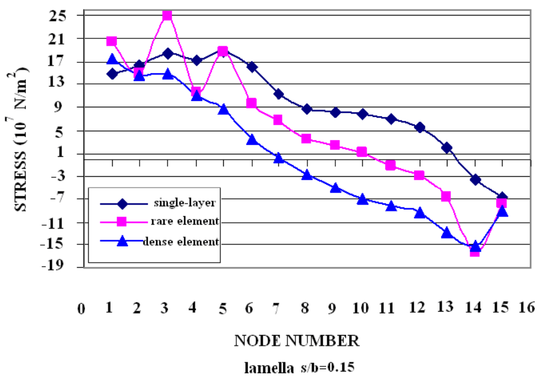


Fig. 8 Stress in meridian elements of diamatic domes under asymmetric snow

C. Assessment of Orbital Stress under Load Combination 3 (Wind)

In contrary to snow load, wind load because of generating suction on top region of suspendomes has decreasing effect on orbital stresses and produce tension in orbital elements. suspending system cause compression in orbital elements so has desirable effect on orbital stresses. According to Figs. 9-10 circumferential ring is in compression due to wind effect and suspending system that adjacent elements are very sensitive to buckling.





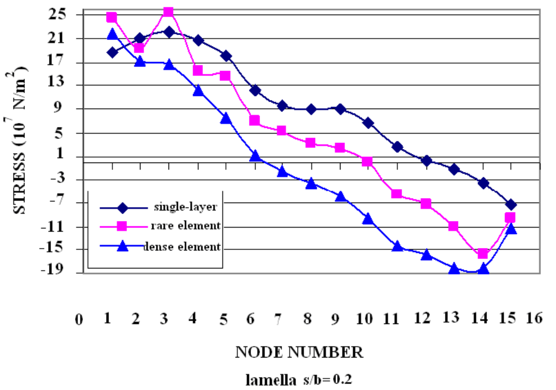


Fig. 9 Stress in orbital element of lamella domes under wind load

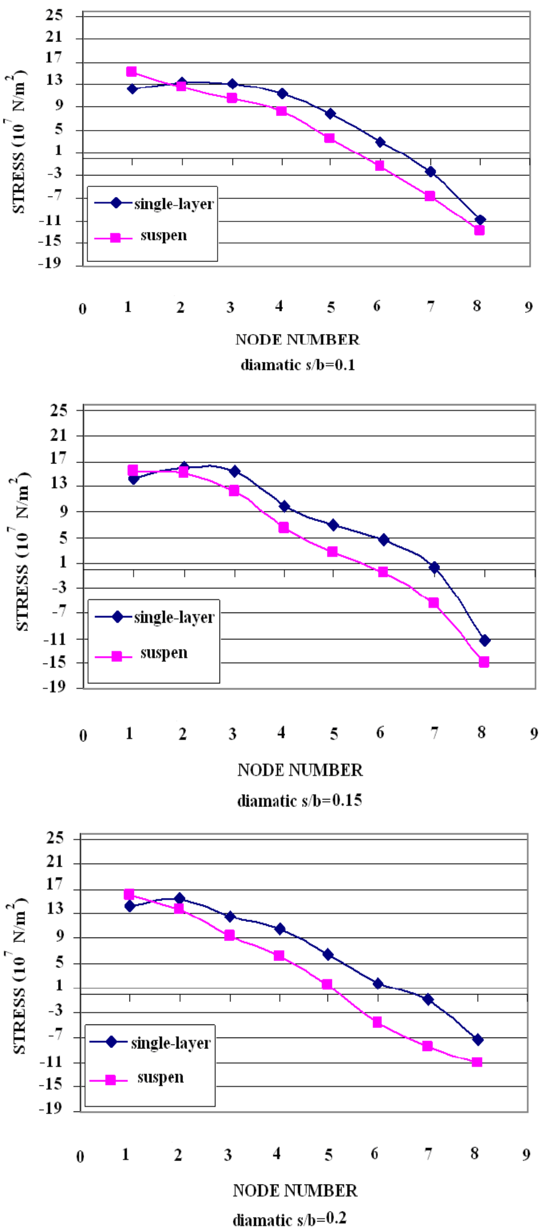


Fig. 10 Stress in orbital element of diamatic domes under wind load

D. Comparison of Domes' Weight

In this section prestressing values and section of cables and struts is constant, but top layer elements are redesigned to investigate effect of suspending system on weight of structures. We can see that only in diamatic suspendomes with r/b=0.1 less weight is obtained. In other suspendomes, suspending system increased weight of structures.

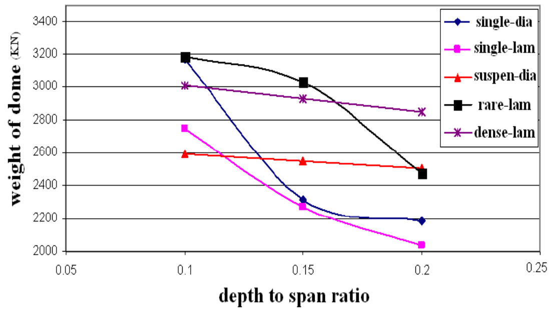


Fig. 11 Comparison of models weight

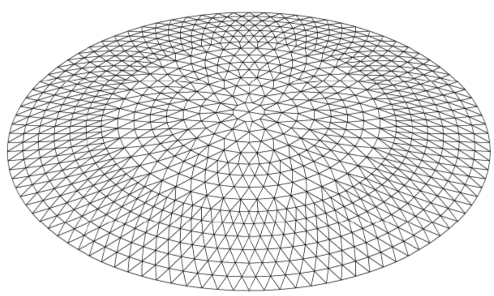
V. Conclusion

15 models are compared under three load combinations symmetric snow, asymmetric snow and wind. Compared variables are displacement of group of nodes, stress of group of meridian elements, stress of group of orbital elements from top to bottom in the leeward of domes. After comparison of single-layer domes and suspendomes under different load combinations below results are obtained.

- Suspendomes for r/s= 0.15 have better performance than single-layer domes but in r/s>0.15 due to increase in stiffness of single-layer domes have little effect on performance of suspendomes.
- Rare-element suspendomes under different load combinations especially wind loads are economical solutions and have better performance than dense-element suspendomes.
- Redesigning of suspendomes to reach to minimum weight only in diamatic dome with r/s= 0.1 result in decreased weight, so for r/s> 0.1 suspendomes are not cost-effective.

Appendix

A. Formation of Suspendomes



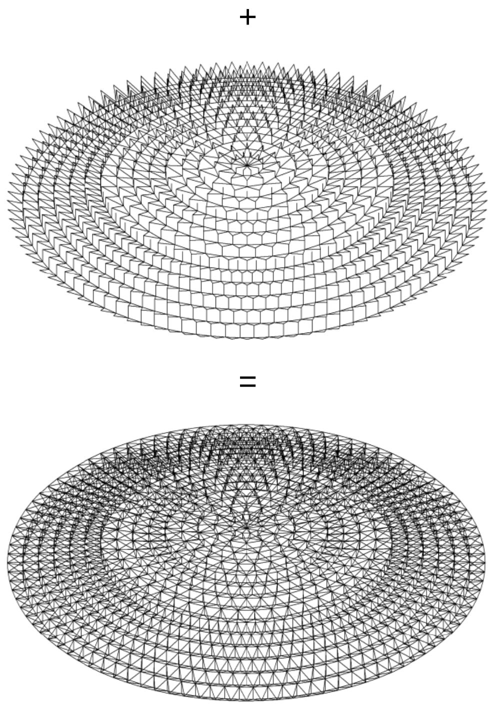


Fig. 12 Components of suspendomes

B. *Prestressing Value of Cables*

TABLE II
PRESTRESSING VALUE OF CABLES IN DIAMATIC DOMES

cable no.	Diamatic 0.2	Diamatic 0.15	Diamatic 0.1
1	-169.28	-169.28	-169.28
2	-228.37	-227.69to -252	-227.16
3	-191.51to -217	-190.44	-189.62
4	-273.81	-271.69	-270.07
5	-206.24to -217	-204.28	-202.78
6	-310.37	-307	-304.44
7	-155.54to -259	-153.7to -245	-152.31to -420

TABLE III
PRESTRESSING VALUE OF CABLES INRARE-ELEMENT LAMELLA DOMES

cable no.	rare-lamella 0.2	rare-lamella 0.15	rare-lamella 0.1
1	-169.28	-169.28	-169.28
2	-228.37	-227.69	-227.16
3	-191.51	-190.44	-189.62
4	-273.81	-271.69	-270.07
5	-206.24	-204.28	-202.78
6	-310.37	-307	-304.44
7	-155.54	-153.07	-152.31

TABLE IV
PRE-STRESSING VALUE OF CABLES IN DENSE-ELEMENT LAMELLA DOMES

cable no.	dense-lamella 0.2	dense-lamella 0.15	dense-lamella 0.1
1	-169.28	-169.28	-169.28
2	-224.23	-243.76	-243.40
3	-225.18	-224.17	-223.75
4	-207.40	-206.35	-205.55
5	-339.45	-337.42	-335.70
6	-312.60	-310.33	-308.60
7	-288.23	-285.92	-284.16
8	-244.59	-242.34	-240.63
9	-206.15	-204.06	-202.48
10	-173.02to -199.5	-171.15to-217	-169.72to -196
11	-326.88	-323.19	-320.38
12	-226.63	-223.94	-221.89
13	-151.22	-149.37	-147.96

C. *Objective Nodes, Meridian and Orbital Element*

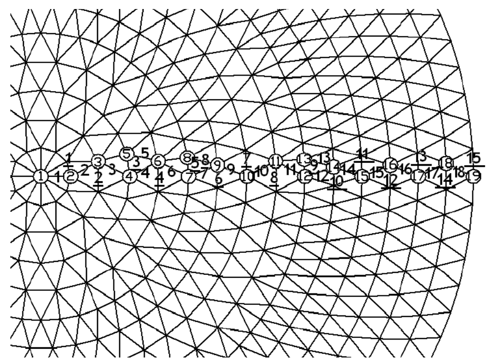


Fig. 13 Positions of objective nodes (circled), meridian elements (underlined) and orbital elements on lamella dome(plain)

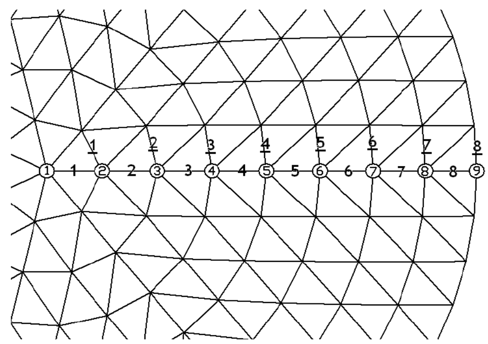


Fig. 14 Positions of objective nodes (circled), meridian elements (underlined) and orbital elements on diamatic dome (plain)

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