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Step-Up 공법에 의한 단층래티스돔의 시공시 안정성 연구

A Study on the Stability of the Single-Layer Latticed Dome during Erection Using the Step-Up Method

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Abstract

The large-space single-layer lattice dome is relatively simpler in terms of the arrangement of the various framework members and of the design of the junction than the multi-layered lattice dome, can reduce the numbers and quantity of the framework members, and has the merit of exposing the beauty of the framework as it stands. The single-layer lattice dome, however, requires a stability investigation of the whole structure itself, along with an analysis of the stress of the framework members, because an unstable phenomenon called "buckling" occurs when its weight reaches critical levels.

Many researchers have systematically conducted researches on the stability evaluation of the single-layer lattice dome. No construction case of a single-layer lattice dome with a 300-m-long span, however, has yet been reported anywhere in the world.

The large-space dome structure is difficult to erect due to the gigantic span and higher ceiling compared with other common buildings, and its construction cost is generally huge. The method of erecting a structure causes major differences in the construction cost and period. Therefore, many researchers have been conducting various researches on the method of erecting such structure. The step-up method developed by these authors can reduce the construction cost and period to a great extent compared with the other general methods, but the application of this method inevitably requires the development of system supports in the center section as well as pre-existing supports in the boundary sections.

In this research, the safety during the construction of a single-layer lattice dome with 300-m-long span using pre-existing materials was examined in the aspect of structural strength, and the basic data required for manufacturing the supports in the application of the step-up method developed by these authors during the erection of the roof structure were obtained.

Keywords : Single-layer lattice dome, step-up erection method, stability, support

1. Introduction

The large-space single-layer lattice dome is a structure with dynamic, functional, and aesthetic characteristics, and its uses are constantly expanding.

Lattice domes are largely classified into single- and multiple-layer domes. The single-layer dome, which displays the framework members in a particular pattern on the surface to form a curved surface as an spatial structure, is similar to the continuum shell structures in both appearance and dynamics.

It is therefore considered a structure that can minimize material losses by effectively using the axial stiffness of the framework members and resisting the external forces on the surface, which are not considerably strong.

The large-space single-layer lattice dome is relatively simpler in terms of the arrangement of the various framework members and of the

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design of the cupolas compared to the multi-layer lattice dome, reduces the number of framework members, and has the merit of exposing the beauty of the skeleton as it stands. An unstable phenomenon called "buckling," however, can appear at the single-layer dome when its weight reaches critical levels.

Many researchers have been conducted on the erection method, and Nagoya Dome in Japan has been constructed as a single-layer lattice dome with a 187-m-long span. No construction case of a single-layer lattice dome with a 300-m-long span, however, has yet been reported anywhere in the world.

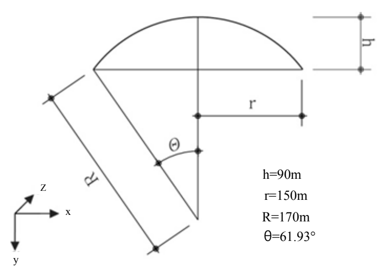
The large-space dome structure is difficult to erect due to the gigantic span and higher ceiling compared with other common buildings, and its construction cost is generally huge. Therefore, various researches have been conducted on the method of erecting such structure. The step-up method developed by these authors can reduce the construction cost and period to a great extent compared with the other general methods, but the application of this method inevitably requires the development of system supports in the center section and of pre-existing supports in the boundary sections.

In this research, the safety during the construction of a single-layer lattice dome with 300-m-long span using pre-existing materials was examined in the aspect of structural strength, and the basic data required for manufacturing the supports in the application of the step-up method developed by these authors during the erection of the roof structure were obtained.

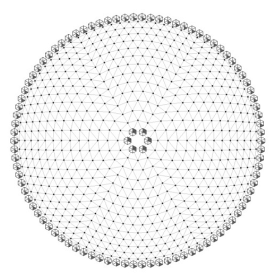
2. Analytical Model

2.1 Model Geometry and Network Pattern

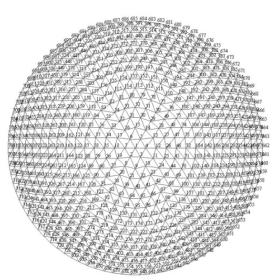
<Figure 1> (a) shows a section of the dome and network pattern. r is the radius of the dome at the base, h is height of dome, R is the radius of curvature.



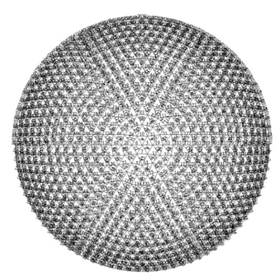
(a) Typical section of a dome



(b) Boundary condition for a dome during erection

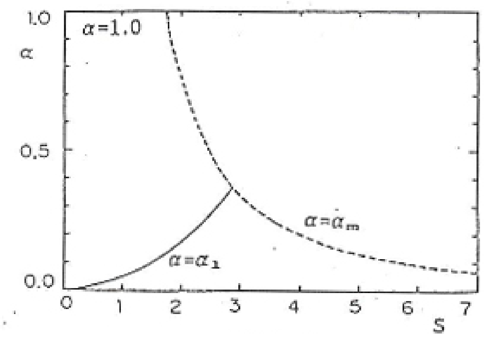


(c) Number of nodes of a completed dome

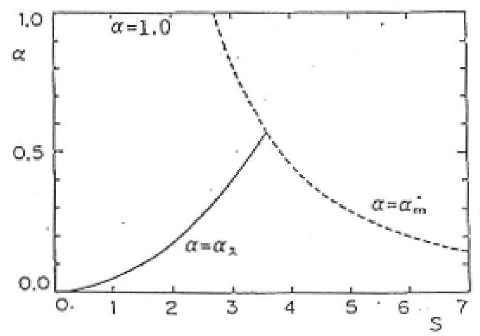


(d) Number of members of a completed dome

〈Figure 1〉 Geometric shape and network pattern of a dome.



(a) H-shaped steel



(b) Steel pipe

〈Figure 2〉 Relations of the section factors and buckling mode of a dome.

As shown in the drawing, the radius of the dome at the base is 150 meters, and height of the dome is 90 meters. From top of the dome to the base, the structure is divided into 15 sections. <Figure 1>(b) shows network pattern and boundary condition for dome during erection, and (c) and (d) shows respectively numbers of nodal point and numbers of member for a completed dome.

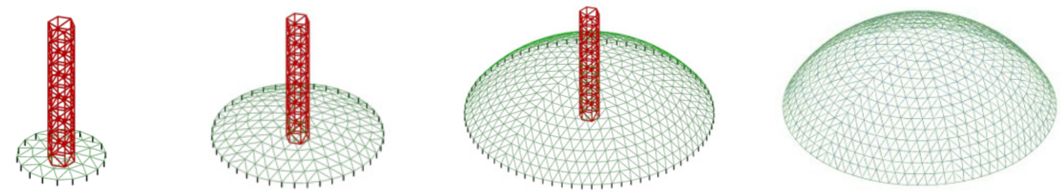
As shown in <Fig. 1>(b), the support points of the system in each step of the dome, whose erection is progressing considering the constructability, are assumed as pins, and the support points of the boundary sections as slides. The reaction by the support points and the horizontal displacement in every step according to the construction load are very important factors in support design. The investigations of the behavior and stability of the frameworks in each step are also essential.

The analysis model that was used in this research was composed based on each step of the step-up method, considering these results.

In this study, the shape factor of the single-

〈Table 1〉 Analysis Model and Specification

Model	N.N	N.E	S.R	Symbol Description & Analysis Conditions
Step1	36	84	24	□ Symbol Description • C.D : The completed dome • Step : The dome during erection • N.N : The number of node • N.E: The number of element • S.R: The number of support □ Analysis Conditions • Junction Condition : Rigid Joint • Load Condition : Vertical Load • Precision of Analysis :One member has one element • Material : Steel(ss400) • Member Section :ø355.6*8.0 • Young's Modulus : 206000N/mm^2 • Poisson Ratio : 0.3
Step2	60	150	30	
Step3	90	234	36	
Step4	126	336	42	
Step5	168	456	48	
Step6	216	594	54	
Step7	270	750	60	
Step8	330	924	66	
Step9	396	1116	72	
Step10	468	1326	78	
Step11	546	1554	84	
Step12	630	1800	90	
Step13	720	2064	96	
C.D	721	2070	90	



Step 1 (SR=24) Step 5 (SR=48) Step 11 (SR=84) Completed Dome (SR=90)

〈Figure 3〉 Construction concept of step up method

layer lattice dome was expressed in Yamada's method[1], and the shape factor (S) was 2.53. Steel pipes were used for the roof frame. As shown in <Fig. 2>(b), S=2.53 was within the overall buckling range of α=1.0. This indicates that when the degree of freedom increases and lengthens the computer operation time for calculating the buckling load, the results do not significantly differ from the precision answers even though an additional degree of freedom is given to the framework members.

The step-up method developed by the authors inevitably requires the development of system supports in the center section and of pre-existing supports. While the erection on the ground is beneficial to the finishing materials for the roof, only the load of the framework itself, excluding the load of the roof materials, was considered in this research.

2.2 Construction concept of dome structure

<Fig. 3> shows the concept of the construction of a dome structure using the step-up method. This method, which erects the system support in the center of the dome and the jack supports along the boundaries, is considered a new method of constructing a dome with on-ground work only, not using other erection materials. In the figure, SR refers to the number of support points.

2.3 Analytical method

A finite element analysis considering geometrical non-linearity of three dimensional frames was performed[2~10]. Numerical calculations were made applying incremental methods for the joint transformation with maximum transformation increments. A determinant was obtained from the stiffness matrix at each incremental stage for the purpose of detecting the bifurcation point or the maximum point. This bifurcation point was determined by checking determinant of stiffness matrix, and from the eigen vector, the buckling mode of the frame was obtained. The computation's accuracy performed in the double precision.

Only the vertical loading was applied. Accuracy of the analysis can be checked considering non-linearity of the structure before buckling. The member of the structure consists of one element.

The completed points of the dome are considered the pins, the support points of the system in each step during erection are also referred to as "pins," and the points of the jack supports along the boundaries are referred to as "slides." All the joints of the framework members are assumed to be the rigid joints.

〈Table 2〉 The structural behavior according to Self-Load

Model	P_{SL} (N/㎡)	Reaction (kN)		Displacement (mm)		Axial Force (kN)	
		R_y	$R_{x,z}$	U_{max}, W_{max}	V_{max}	T_{max}	C_{max}
Step 1	171.8	28.6	191.7	3	37	225.05	117.68
Step 2	180.6	43.5	209.4	9	65	431.86	147.87
Step 3	182.6	58.4	185.3	16	84	618.61	201.61
Step 4	183.1	72.8	186.3	26	101	786.82	197.65
Step 5	183.3	86.9	187.8	38	114	940.87	192.86
Step 6	183.5	100.8	187.8	50	125	1082.56	190.74
Step 7	183.7	114.5	187.8	63	132	1209.90	197.68
Step 8	184.1	127.9	187.8	77	136	1320.90	205.06
Step 9	184.5	141.2	187.8	90	136	1413.46	211.79
Step 10	185.1	154.3	187.8	102	133	1485.32	218.00
Step 11	185.9	167.1	187.8	113	127	1534.15	223.77
Step 12	186.7	179.7	187.8	122	117	1557.63	229.12
Step 13	187.7	192.0	187.8	128	108	1553.33	234.07
CD	189.3	219.9	122.1	8	24	194.15	82.22

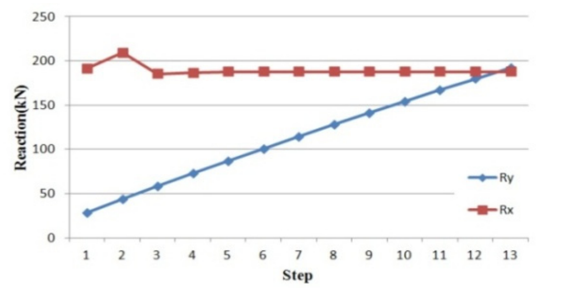
3. Results and Review of Analysis

3.1 The review of point reaction and displacement according to Self Load

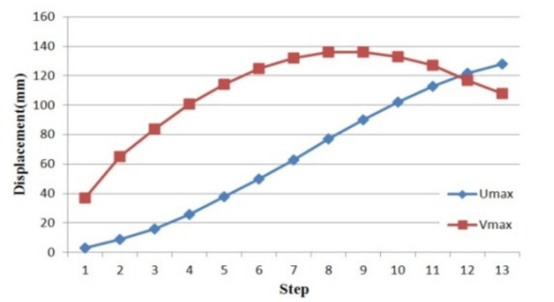
Table 2 shows the results of structural analysis of the model. P_{SL} is Self-Load of each model. R_y, R_x and R_z is respectively the maximum reaction of jack-support and system-support. U_{max}, V_{max} and W_{max} is respectively the maximum displacement of X, Y and Z direction. T_{max}, C_{max} is the maximum tensional and compressive force of the member.

Table 2 is the results of the reaction forces and displacements, member axial forces values for self-Load(P_{SL}) . In Step 12, the maximum tension stress is 0.2kN/mm2 because T_{max} is 1557.63kN.

In <Fig. 4> R_y stands for the vertical reaction of the jack support, and R_x for the lateral reaction of the system support in the center of the dome. It may not be necessary to consider



〈Figure 4〉 Reactions at the points in each model



〈Figure 5〉 Maximum displacement in each model

the lateral reaction of the jack support along the boundaries as the lateral reaction will not take place at the lower sections of the dome, but it should be designed considering the vertical-reaction value (R_y) so it would stay in a safer

〈Table 3〉 Result of buckling strength and structural behavior

Model	Q_{cr}(kN/㎡)	NOD buck	Axial Force(kN)		Displacement(㎜)			
			N_{max}	Mem_{max}	U_{max},W_{max}	NOD_u	V_{max}	NOD_v
Step1	84.03	7	3769	68	73	30	689	7
Step2	48.69	19	5286	128	140	39	891	19
Step3	31.84	45	6577	206	214	63	1093	37
Step4	22.51	66	7839	302	303	94	1258	61
Step5	16.70	91	8814	416	391	130	1299	91
Step6	12.95	168	9789	548	488	173	1392	127
Step7	10.36	192	10630	698	585	221	1463	169
Step8	8.53	218	11380	866	683	276	1536	217
Step9	7.22	300	11870	1052	771	336	1435	271
Step10	6.21	342	12150	1256	847	403	1273	331
Step11	5.46	12	12728	1478	932	475	1373	397
Step12	4.78	8	12222	1718	953	554	1149	8
Step13	4.19	10	11640	1976	949	638	1049	8
C.D	5.06	9	2635	157	190	555	489	9

zone. As the system support in the center of the dome does not increase in the lateral reactions in spite of the increase in the rigging steps, it is noted that securing the strength in the steps in the earlier stage will be sufficient for the safety aspect. It is, of course, considered rational to reflect not only the structural strength but also the lateral displacement in the design of the jack supports along the boundaries, which can be achieved by investigating the results of the displacement.

<Fig. 5> presents the maximum displacement at the nodal points in each model. The investigation of the lateral displacement of the boundary sections is considered important for the design of the jack supports, which correspond to U_{max} in <Fig. 5>

Moreover, it is necessary to become aware of the increase in lateral displacement in each step. In this analysis, the increases in lateral-displacement volume in each step (δU) were found to be 6, 7, 10, 12, 12, 13, 14, 13, 12, 11, 9, and 6 mm, respectively, which show 6 to14 mm differences. Therefore, the safety of the horizontal displacement can be secured by considering the increased volume of the maximum displacement.

Meanwhile, the vertical displacement to the vertical direction represents the maximum value at steps 7 to 10, which are very minor in value, considering the span of the dome. This indicates that the construction will remain safe in terms of displacement.

3.2 Structural stability review

<Table 3> shows the buckling strength, the axial force and displacement just before buckling for each model

3.2.1 Buckling Strength

<Fig. 6> shows the buckling strength in each model. As shown in the figure, the buckling strength in each step sharply decreases with the increase in the erection steps. The buckling strength at step no. 13 is even reduced on a

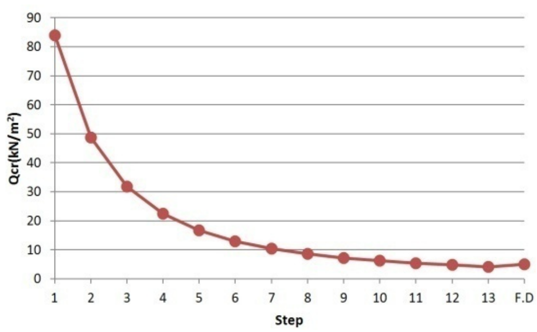
minor scale compared to that of the completed dome.

<Fig. 7> shows the load-displacement curve of the completed dome before buckling at the typical nodal points. As shown in the figure, nodal point no. 9 presented a 500 mm displacement before buckling, and the displacement depending on the load was nonlinear.

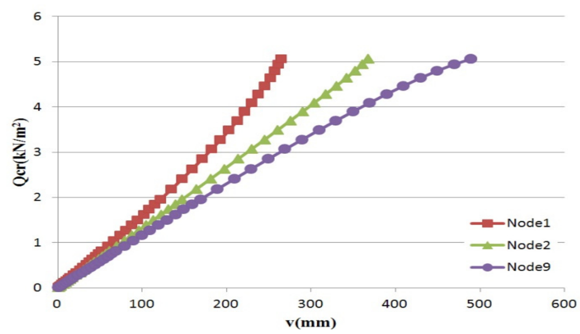
3.2.2 Buckling Mode

<Fig. 8> shows the buckling modes in each step in the two-dimensional view. In <Fig, NODbuck indicates the typical nodal point in which buckling occurs. The dotted line refers to the shape of the dome before buckling, and the single unbroken line refers to the buckling modes. And the dots in figures represent the buckling point.

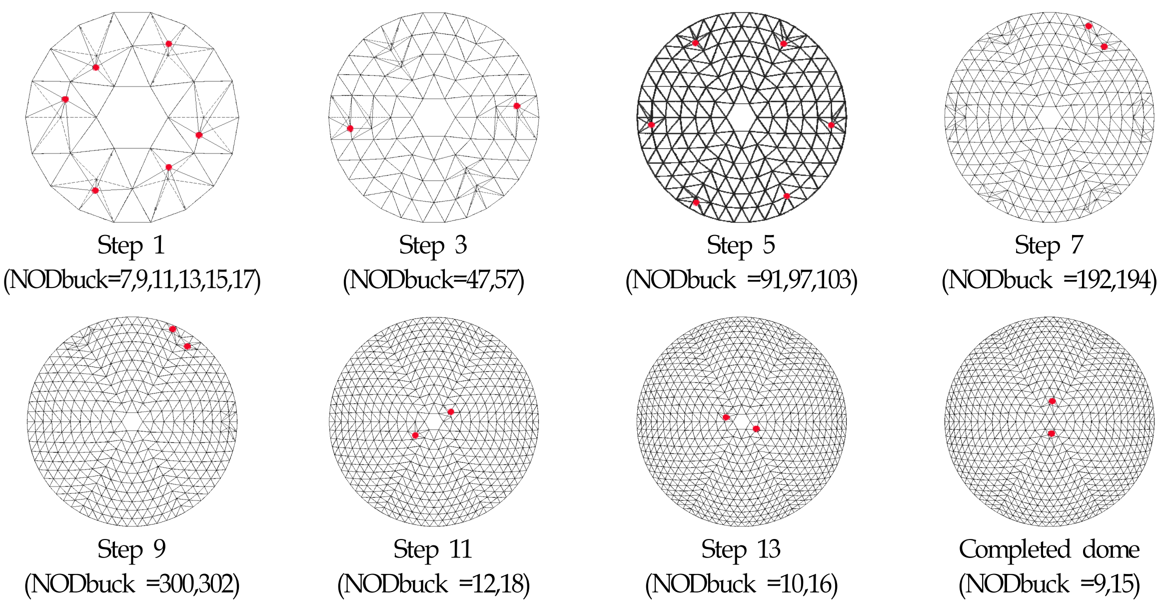
The buckling mode of the completed dome yielded results that were almost similar to that of the single-layer lattice dome, which had the equivalent S value of the safe factor, and which was systematically performed by these authors. That is, the dome that bears vertical loads showed that buckling mostly took place at lower than S=2.7 around the center of the dome. This showed that the buckling characteristics can be



〈Figure 6〉 Buckling strength in each model.



〈Figure 7〉 Load displacement curves for typical nod in completed dome

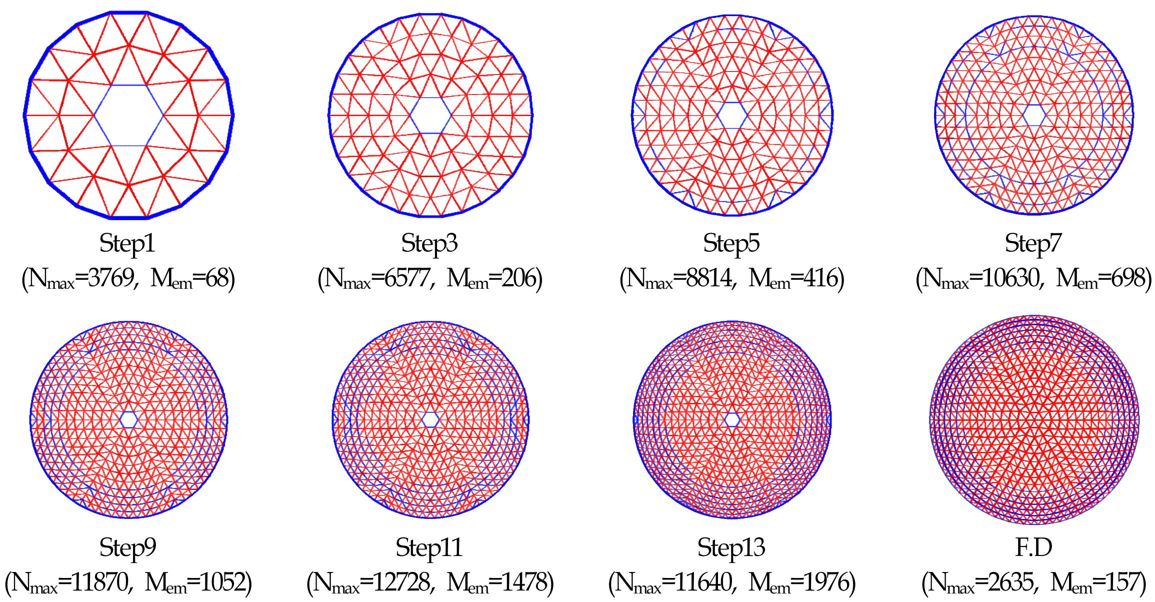


〈Figure 8〉 Buckling mode in each model.

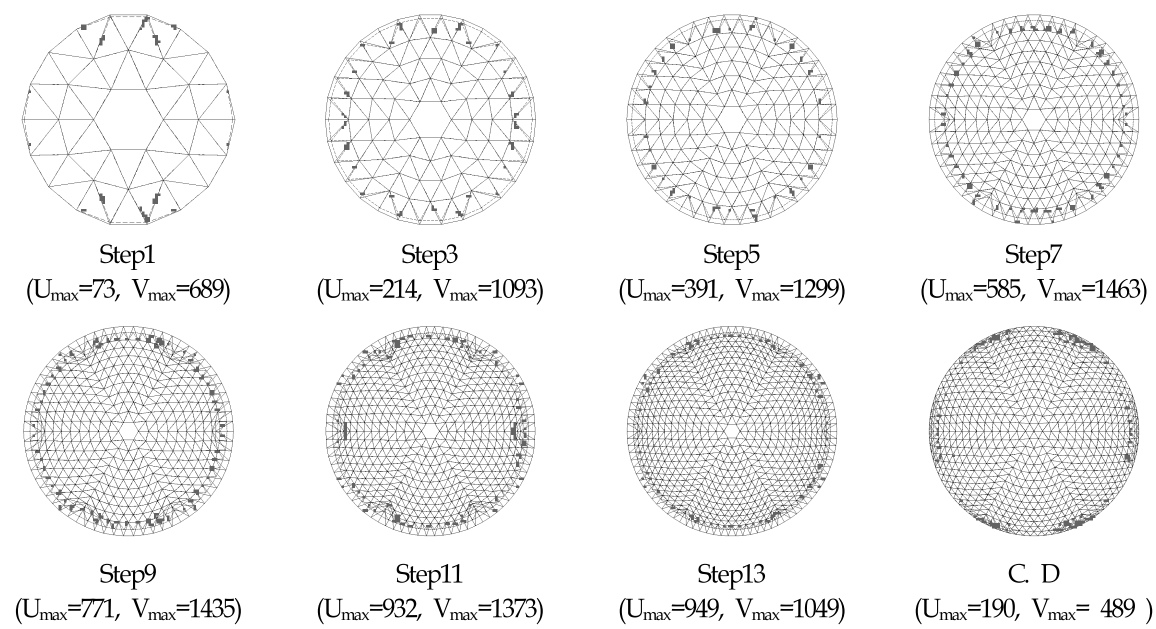
sufficiently apprehended with the shape factor S proposed by Yamada in the case of the large-space single-layer lattice dome with a 300m long span, of which no construction cases have been reported to date.

3.2.3 Axial force of member

<Fig. 9> shows the axial forces of the framework members just before buckling for a typical model. The longitudinal members of the framework mainly bear the compressive force and the circumferential members' tensile forces, and T_{max} and C_{max} represent the maximum tensile force and compressive force, respectively. And N_{max} represents the axial stress of the member (kN), and M_{em} represents the number of the representative member that is under the



〈Figure 9〉 Axial force of member of each model (kN)



〈Figure 10〉 Deformation mode of typical model(mm) maximum axial stress.

In this research, equal sizes of the cross-sections of all the members were applied. As such, in the design for the real structure, it is necessary to rearrange the members according to the sizes of the cross-sections, depending on the size of the axial force.

3.2.4 Deformation mode

<Figure 10> shows the deformation modes by each staff member, and the dotted line before the transformation, since the solid line represents the deformation is two-dimensional picture. In the figure, the displacement unit is mm.

4. Conclusions

(1) The safety of the construction in each step during the erection of a single-layer lattice dome with a 300-m-long span using the step-up method was confirmed.

(2) The basic data required for the development of pre-existing supports during the erection of a single-layer lattice dome using the step-up method were obtained.

(3) It was verified that it is safe to use the pre-existing steel materials currently produced in South Korea for the construction of a single-layer lattice dome with a 300-m-long span in the aspect of structural strength.

5. Acknowledgement

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