PROPOSAL OF RETRACTABLE LOOP-DOME

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ABSTRACT

Retractable loop-dome continuously changes in shape according to variations in the diameter of the oculus. It has several architectural advantages such as 1) environmental control by changing the diameter of the oculus, 2) rational construction utilizing peripheral folding and 3) artistic dynamic expression through change in overall shape. However, such a dome has not yet been realized because there exist problems relating to the structural efficiency of a shell.

The author proposes a rational structural system of a retractable loop-dome for a large span. This paper describes 1) the basic idea of the rational structural system of a retractable loop-dome with expandable circular rings, 2) an investigation on the structural efficiency of the inner ring by theoretical analysis and 3) a numerical simulation of the changing structural frame and roof panels.

1. INTRODUCTION

Retractable Loop-Dome allows the dome to continuously change its shape according to changes in the diameter of the oculus. It has several architectural advantages such as 1) environmental control by changing the diameter of the oculus, 2) rational construction utilizing peripheral folding, and 3) artistically dynamic expression through change in overall shape. However, such a dome has not yet been realized because there exist problems relating to the structural rationality.

There are two well-known ideas of structural elements for retractable loop-dome. The "Angulated Element" used in C. Hoberman's "Iris Dome", has an ingenious geometrical property [1], [2], [3]. This pioneering idea is greatly valuable in providing visual images. Z. You and S. Pellegrino discovered "Generalized Multi-Angulated Element" which is the member of a two-dimensional foldable structure. Then they proposed the interesting idea of projecting the elements onto a curved surface to simulate a retractable loop-dome of a required shape [4], [5]. These ideas, though the kinetic conditions are theoretically satisfied, have obstacles to overcome, relating to the rationality of structural details, such as the joints. C. Hoberman's angulated element must be pin-connected individually in a plane; therefore it may be assumed that the joint has disadvantages such as difficult production and reduction in joint stability. Z. You and S. Pellegrino's connectors between multi-angulated elements must be perpendicular to the plane of projection because of the theoretical requirement; therefore problems may arise relating to both the production of connectors and the structural strength, particularly in the case of a deeply curved surface. In addition to these problems, both ideas do not show a rational system relating to the structural efficiency of a shell.

Then the author proposes a rational structural system of a retractable loop-dome for a large span. This paper describes 1) outline of the rational structural system, 2) investigation by numerical analysis of the structural behavior and 3) numeric simulation of the changing shape with roof panels.

2. STRUCTURAL SYSTEM

2.1 3-Dimensional Multi-Angulated Scissor Element

A 3-dimensional multi-angulated scissor element is used as the main structural element for a retractable loop-dome, which can change the diameter of the oculus, by its lamella arrangement on a sphere. The geometric form of the 3-dimensional multi-angulated scissor element is determined by cutting a sphere with a plane. The scissors' hinge-points (1, 2, ..., i, i+1, ..., n) of the element are arranged on the surface of a sphere S as follows:

a) Cutting sphere S with inclined plane P that intersects apex T, as shown in Fig. 1(a).

b) Arranging hinge-point on circle Q (ellipse on the XY plane), as shown in Fig. 1(b). That is,

$\theta_{12} = \theta_{23} = \ldots = \theta_{i(i+1)} = \ldots = \theta_{(n-1)n}$ on XY plane. As demonstrated in the preceding paper [6], this element can move rigidly without elastic deformation on an axisymmetrically curved surface.

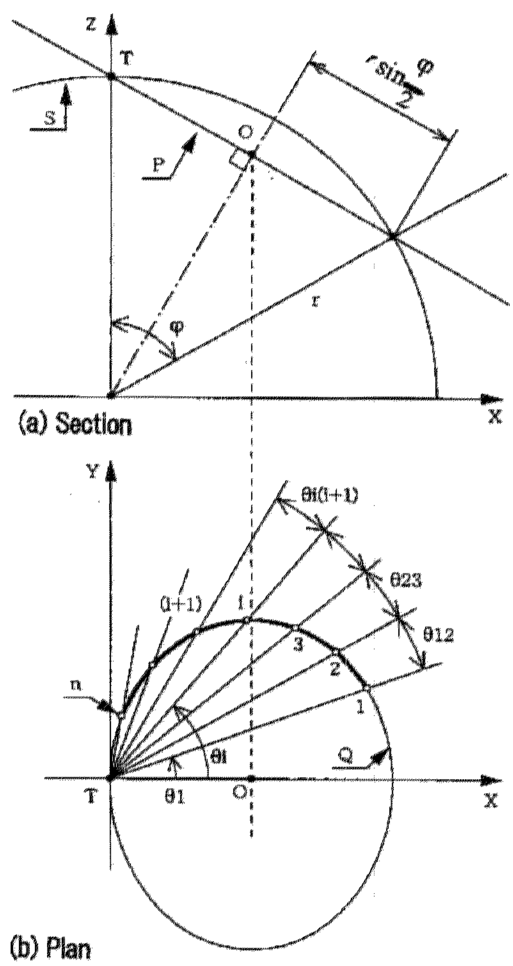


Fig.1 Geometry of 3-d multi-angulated scissor element

2.2 Scissor Point

The scissors' hinge-axis of all elements coincides with the normal direction of one sphere S at the reference state shown in Fig. 1. However, during the retraction, departing from the reference state, the hole-axis of each element goes toward the centre of each sphere. Therefore, a small variation in angle is caused by a slight difference in direction between the scissors' hinge-axis and the hole-axis. A loose-hole or an embedded spherical roller bearing (or self-aligning ball bearings) at the scissor point shown in Fig. 2 may be needed in order to absorb the difference.

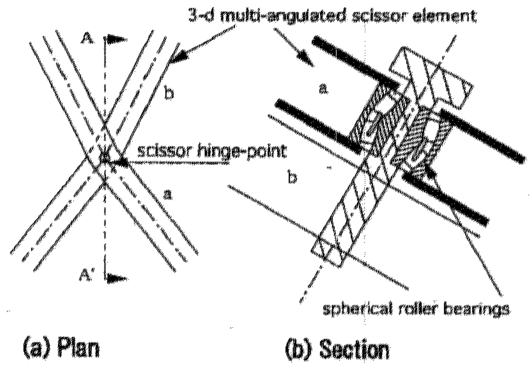


Fig.2 Sketch of scissor point

2.3 Expandable Circular Rings

The 3-dimensional multi-angulated scissor element is used as the main structural element for a retractable loop-dome, which can change the diameter of the oculus, by its lamella arrangement on a sphere. In order to apply such a dome in practice, the unstable structure must be changed to a stable structure. The problem to be discussed here is how to establish a rational structural system for a large span, considering the retraction technology of today. Then, as shown in Fig. 3, a system is proposed, in which an expandable ring is added to both the inner and outer circles of the dome, so as to produce the structural efficiency of shell-like behaviour. Each expandable circular ring consists of expandable rods that form a regular polygon. In the case of the outer ring acted in tension, such a rod may in practice be possible to make by using electrical actuation technology because of its small expansion-traction ratio. On the other hand, in the case of the inner ring, an expandable rod may be difficult to make because of large expansion-traction ratio and action in compression. Fig. 4 sketches an example of such a rod.

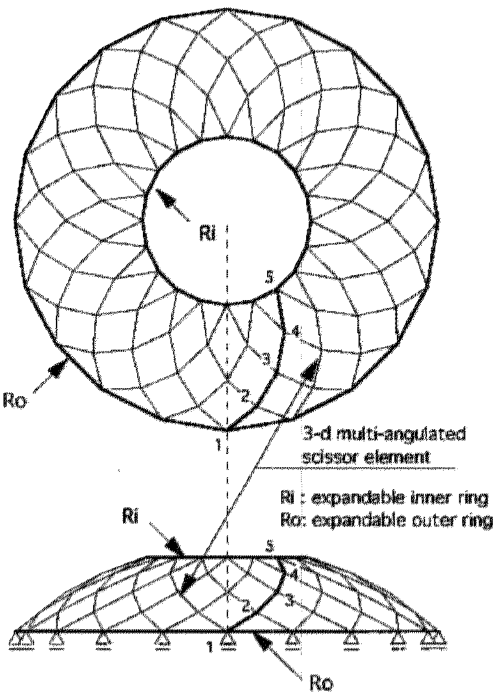


Fig.3 Expandable rings for rationality

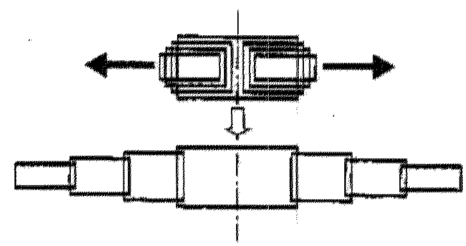


Fig.4 Telescopic cylinder

3. CONSIDERATION OF INNER RING

The rings are indispensable members of the rational structural system for a large span as described in the preceding paper [6]. This section is going to show theoretically how the inner ring enhances the structural efficiency of the loop-dome under dead type of loading.

3.1 Outline of Model

The models for numerical investigations are described as follows.

Reference geometry: $\varphi=60°$, $\theta_1=27°$,$\theta_5=72°$, n=5, Do (base diameter)=150cm and Di(inner diameter)=63.76cm, Radius of sphere: r=92.19cm, Parameter for changing shape (referring to [6]): t=—0.275,0,0.275, Section of 3-d multi-angulated scissor element : 4.5×20, Section of outer ring : 4.5×20, Young's modulus: 2100t/cm^2, Vertical point load(see Fig.3): P_5=5kg, P_4=P_3=P_2=10kg

The following report will refer to 'model A' as (with inner ring) and 'model B' as (without inner ring). And the section of inner ring is 4.5×30 in the case of 'model A'.

3.2 Method of Structural Analysis

The method of the structural analysis is briefly described here. First of all, let's consider the beam-column members that consist of a 3-dimensional multi-angulated scissor element, as shown in Fig.5. Equation (1) represents the stiffness equation for the beam-column element i-(i+1) at the local (1,2,3) coordinate.

$$\{f\} = [k] \{x\} \tag{1}$$

In Eq. (1) { f } is the 12 set of nodal forces vector, { x } is the corresponding 12 set of nodal displacements vector and [k] is the 12 × 12 size of beam-column member stiffness matrix.

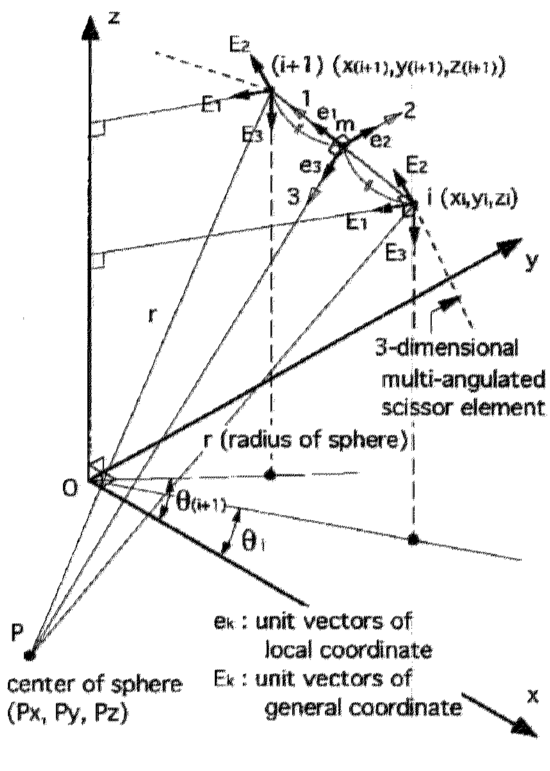


Fig.5 Transformation of coordinate

As the coordinates of the scissor point i and the centre point of the sphere are given analytically as shown in the preceding paper [6], three set of normally unit vectors (e_1, e_2, e_3) on the member are computed easily. Equation (2) represents the stiffness equation for the element at the global coordinate.

$$\{F\} = [K] \{X\} \tag{2}$$

In Eq. (2) $\{f\}=[T]\{F\}$, $\{x\}=[T]\{X\}$ and $[K]=[T]^t[k][T]$. Here, $[T]$ represents the 12×12 size of transformation matrix and $[T]$ is derived from the dot product vector e_k by Ej referring to Fig. 5, as 3 sets of normally unit vectors (E_1, E_2, E_3) are computed easily. After all, the total structure stiffness equation is assembled by superimposing Eq.(2). Finally, after imposing boundary conditions, these equations are solved for the unknown nodal displacements.

3.3 Results and Discussions

Fig.6 and Fig.7 show the numerical results of 'model A', 'model B' respectively, concerning to vertical and horizontal nodal displacements, axial forces and bending moments of member. Comparing between Fig.6 and Fig.7, the big difference of the scale size in the vertical axis is recognized at a glance. In the case of 'model A', as shown in Fig.6, displacements and member forces are the smallest at the reference state t=0. On the other hand, displacements and member forces of 'model B' decrease as t changes –0.275 to 0.275, as shown in Fig. 7. In the case of t=-0.275, the differences between 'model A' and 'model B' are not so large compared with other case of t (=0, 0.275). Referring to table 1, the axial outer ring force No of 'model B' behaves very complicatedly according to the change in Di, and in the case of 'model A', inner ring force in compression Nri and outer ring force in tension Nro increase as Di decrease. Table 2a, 2b and 2c show the ratios of maximum nodal displacements and maximum member forces between 'model A' and 'model B', corresponding to t. Referring to these tables, the big difference between these models is easily recognized except the case t=0.275. As the result of this numerical analysis, it is concluded that the inner ring is very important member for the rational structural system of the proposed retractable loop-dome.

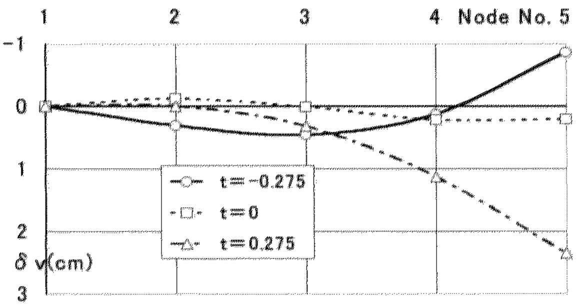


Fig. 6(a) Vertical displacement (cm)

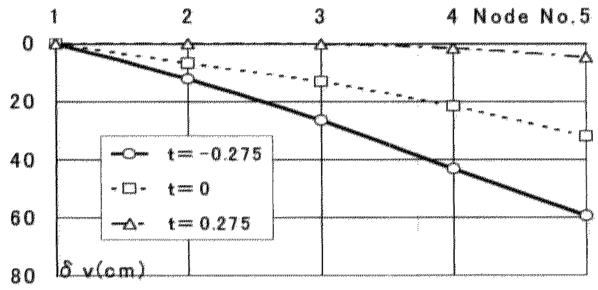


Fig. 7(a) Vertical displacement (cm)

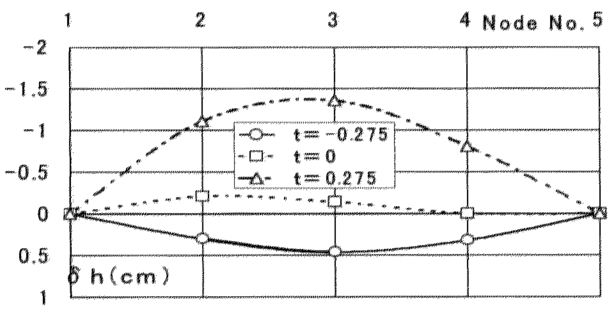


Fig. 6(b) Horizontal displacement (cm)

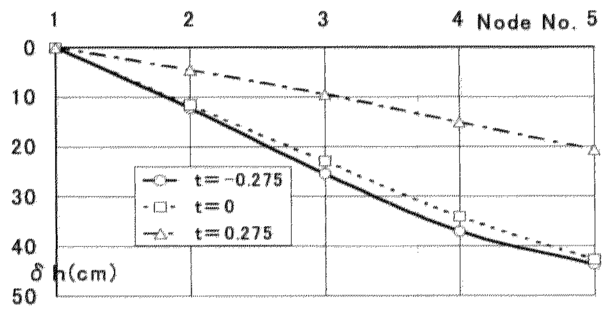


Fig. 7(b) Horizontal displacement (cm)

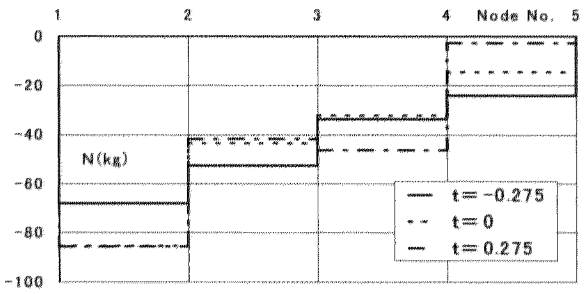


Fig. 6(c) Axial force (kg)

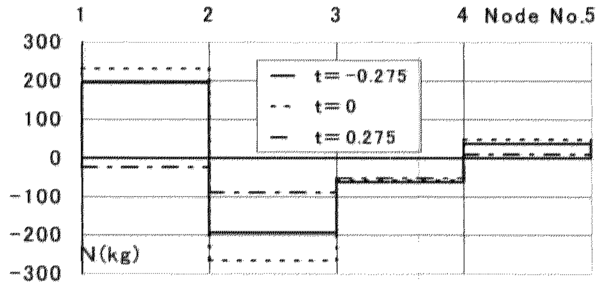


Fig. 7(c) Axial force (kg)

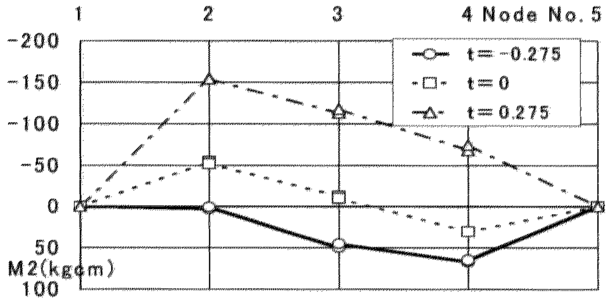


Fig. 6(d) Bending moment-weak axis (kgcm)

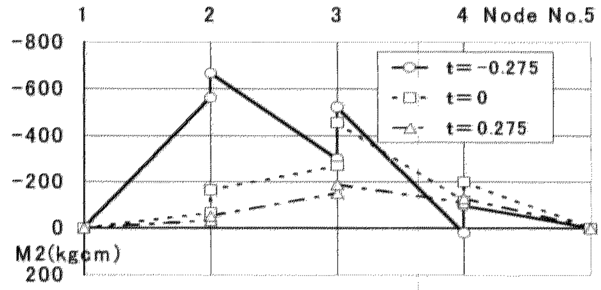


Fig. 7(d) Bending moment-weak axis (kgcm)

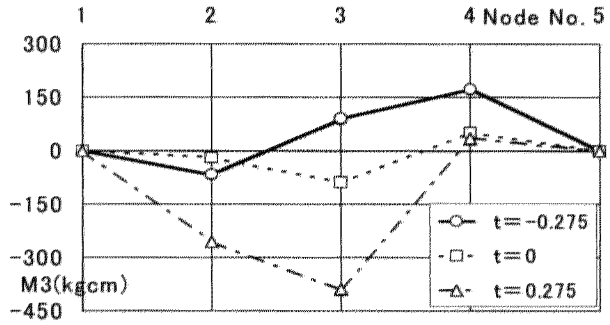


Fig. 6(e) Bending moment-strong axis (kgcm)

Fig.6 Model A

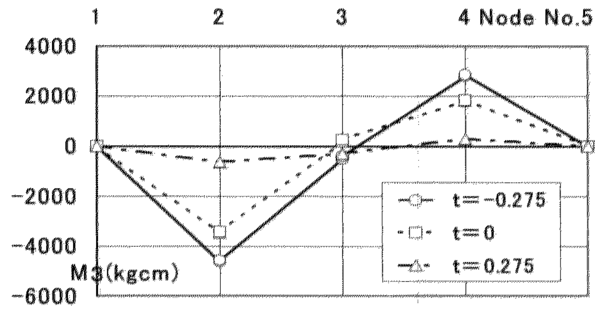


Fig. 7(e) Bending moment-strong axis (kgcm)

Fig.7 Model B

Table 1 Axial force of rings

	model B	model A	
t	No(kg)	Ni(kg)	No(kg)
-0.275	-2.94	-130.2	221.1
0	19.61	-68.8	197.6
0.275	135.65	-4.1	162

No:axial force of outer ring, Ni:inner ring

Table 2a (model B)/(model A) [t=-0.275]

	model B	model A	|B/A|
δv(cm)	59.39	-0.86	69.1
δh(cm)	43.82	0.46	95.3
N(kg)	-194.4	-68.1	2.85
M2(kgcm)	-561.2	67.06	8.37
M3(kgcm)	-4625.6	-174.16	26.6

Table 2b (model B)/(model A) [t=0]

	model B	model A	|B/A|
δv(cm)	31.98	0.22	145.4
δh(cm)	42.83	-0.21	204
N(kg)	-266.9	-85.5	3.12
M2(kgcm)	-269.4	-54.08	4.98
M3(kgcm)	-3476.4	-89.28	38.9

Table 2c (model B)/(model A) [t=0.275]

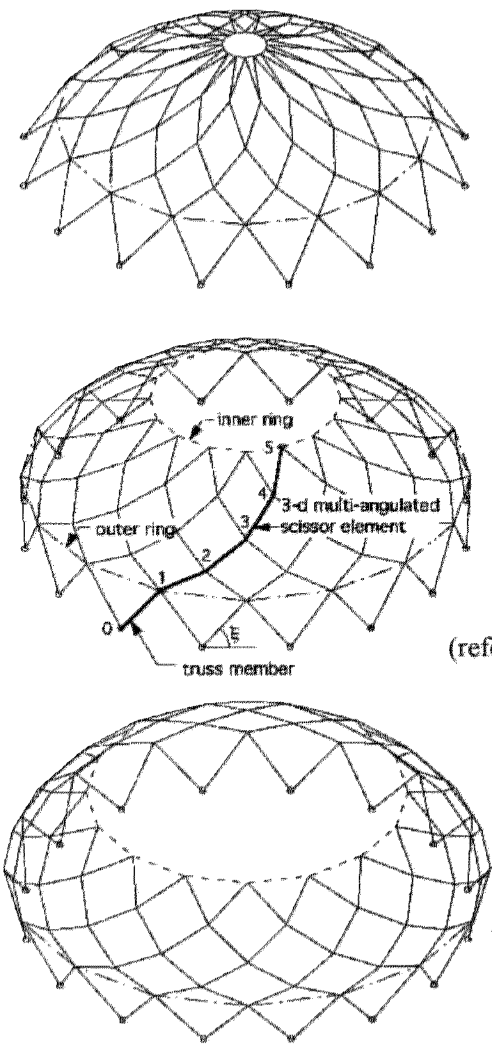
	model B	model A	|B/A|
δv(cm)	4.8	2.35	2.04
δh(cm)	20.64	-1.36	15.2
N(kg)	-89.2	-85.7	1.04
M2(kgcm)	188.9	-154.86	1.22
M3(kgcm)	-639.8	-390.76	1.64

4. SIMULATION OF CHANGING CONFIGURATION

4.1 Structural Frame

It is possible to produce a structural model of the new type of retractable loop-dome by combining the structure (upper structure) shown in Fig.3 and a one-layer truss structure (lower structure) inserted between the outer ring and the foundation ring. In this model, the truss structure is pin-connected to both rings, and supposed to have a mechanism of changing geometry. An example of a simulation of this model is shown in Fig. 8.

Here, the geometric parameters of the upper structure are the same as the model in section 3.1 referring to Fig. 1, D_1 (the diameter of the outer ring) equals to D_0 (the diameter of the foundation ring) at the reference state t=0, and ξ (the parameter of the truss; see Fig.8) is 55° . As seen in Fig.8, the diameter of this oculus boldly changes in size, and the entire structure makes a dramatic change in its geometric shape. This dome gives a dynamic expression never before seen in usual domes.



t=-0.275

η_1=-3.04°

t=0

η_1=0°

(reference state)

t=0.275

η_1=3.89°

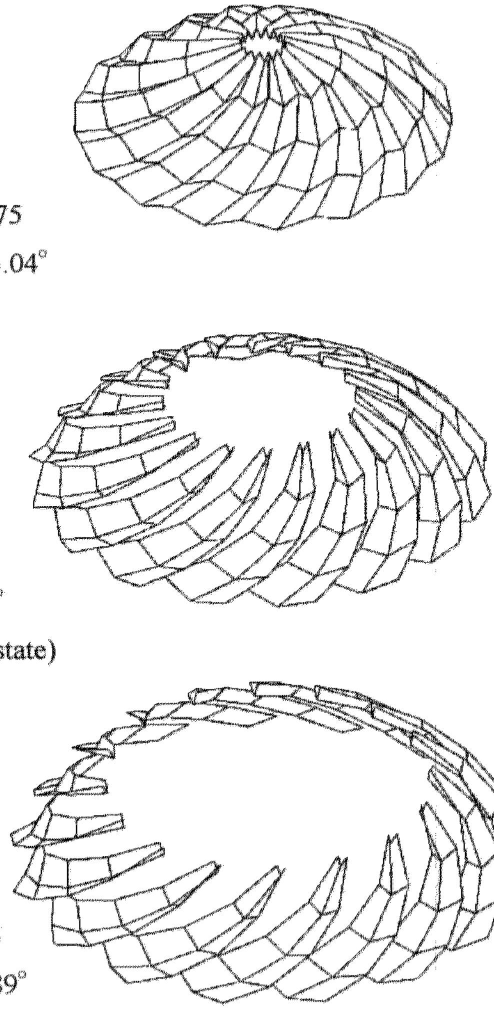


Fig.8 Structural frame η : intersecting angle [6] **Fig.9 Roof panel**

4.2 Roof Panel

Fig.9 shows the changing configurations of 16 roof panels that are supported on the scissor hinge-points of the clockwise 3-dimensional multi-angulated members from the central top view. The motion of these panels seems to be very elegant like a spiral flow. The roof panel has a V-shaped section which depth is 1/20th of r, and its geometry is determined by the conditions that the panels leave no gaps when t=-0.275 and do not interfere with other panels during retraction.

5. CONCLUSION

First, this paper described the basic idea of a rational structural system of the retractable loop-dome for a large span. Secondly, according to the structural analysis of the dome under the dead type of loading, it is theoretically concluded that the inner ring drastically enhances the structural efficiency of a shell. Therefore, the expandable inner ring with a large expansion-traction ratio must be developed technologically for its realization. Thirdly, according to the graphic simulation concerning to the changing geometry of a structural frame model and the movement of a group of roof panels with a V-shaped section, it shows visually this dome has a possibility to give a dynamic expression never before seen in usual domes.

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