

Paper:

A Study on Adaptive Arch Structure Applying Variable Geometry Truss (Mechanism of Movable Arch Roof with External Panel)

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This paper describes a movable arch roof with external panels as an actual design of an adaptive structure using a VGT (Variable Geometry Truss) mechanism comprising an elementary truss structure with extendable members. This movable arch structure comprises several VGT units jointed in series and pin jointed at each end. It is a stable structure because its edge is restrained, but this reduces its variety of shape change. Various arch shapes can be determined by using inverse analysis to solve the structure shape from the member lengths. An actual movable roof pavilion composed of such a movable arch and an external panel was designed, and the behaviors of a movable roof and the joint mechanism of the roof elements were verified by numerical simulation and a model experiment. As a result, the performance of the proposed movable roof structure was confirmed, and the basic technology and design approach were established.

Keywords: VGT, adaptive structure, arch structure, external panel mechanism, movable roof pavilion

1. Introduction

Recent years have seen an increasing variety of applications of movable structures worldwide [1]. Typical examples are bridges that open to allow ships to pass, revolving restaurants on tops of buildings, sliding roofs of baseball and soccer dome stadiums, and artistic monuments. These structures simply move on rails and rotate around a hinge, but do not change in shape. That is, their behaviors are not flexible, but monotonous. However, in the near future, it may become possible to devise structures with lively motion, freedom as well as intelligence. In particular, they will respond to voice commands with instant and adaptive shape change to harmonize with the surrounding environment.

One mechanism that enables more complicated movement is the VGT [2]. The VGT is a very simple truss structure composed of extendable members, fixed members and hinges, as shown in Fig. 1. By controlling the lengths of the extendable members, it is possible to create various truss shapes. The VGT was originally developed

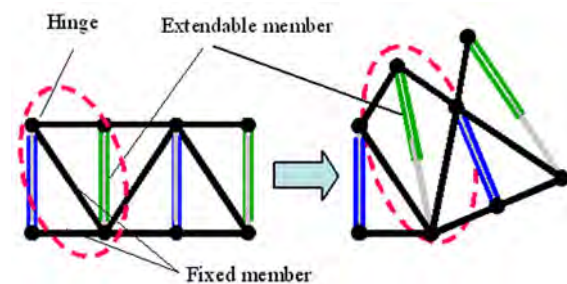


Fig. 1. Basic mechanism of VGT.

as a movable actuator for a spread-type universe construction in space, and it was equipped with a small motor to perform various tasks. Thus, it was considered to be a useful structural tool in various fields as a redundant intelligent structure.

The purpose of this study was to apply VGT technology to ground construction and to examine the development of the element technique and its applicability to movable arch structures. The authors have been studying and developing an adaptive structure using VGT and an example of the shape changes of a simple beam that combines two-dimensional VGTs is shown in Fig. 2. When extendable members are extended simultaneously, the truss beam was changed like a spring stretching from (a) to (b). When the extendable members are extended alternately, the truss beam was changed to a circular shape (c). Moreover, when they are extended optionally and their lengths are controlled, the truss beam can be changed into any intended shape (d). Based on the shape change of such a basic beam, the feasibility of shape change in an actual building was examined. This has been applied to architectural design and construction.

In our past studies applying VGT [3, 4], the elementary design of a hemispherical dome with an adaptive roof as shown in Fig. 3, called a 'Flowering Dome', was proposed in 2001. The model dome was composed of a partial roof whose structure sat on VGT actuators in series at the main solid truss, and the roofs were opened and closed variably by changing the shape of the petals. Another of our applications [5] was actually designed as a cantilever-type movable monument and was exhibited at the 2005 international Expo in Aichi, Japan as shown in

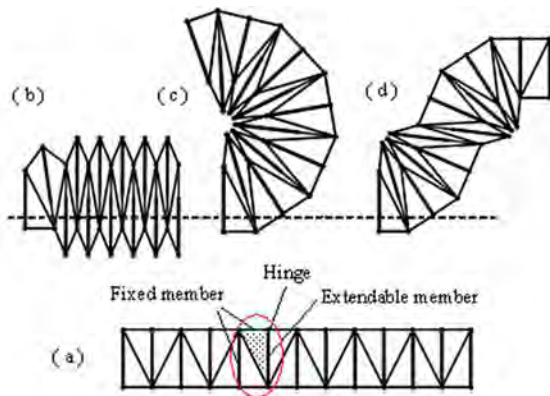


Fig. 2. Transformation of beam shape using VGT.

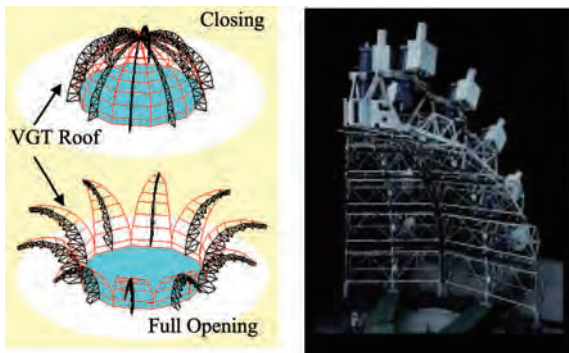


Fig. 3. Schematic of flowering dome and reduced model.



Fig. 4. Schematic of the movable monument at Expo.

Fig. 4. The whole of the monument was constructed of movable towers spaced at 120-degree intervals around the circumference. Each tower's movement was coordinated by an internal control signal, and various performances were played.

In the research and development described above, the VGT mechanism was mainly applied to a cantilever-type movable structure because of the simplicity and small number of binding conditions in the structure. However, for large-scale movable structures, it is easy to apply the VGT mechanism to an arch structure with both ends supported. Thus, as the second actual design of an adaptive structure using the VGT mechanism, we studied a movable arch structure with external panels. This paper describes in detail a movable arch structure using VGT, a control mechanism, the structural characteristics of the arch structure, the mechanism of the external panel and each kind of elementary performance.

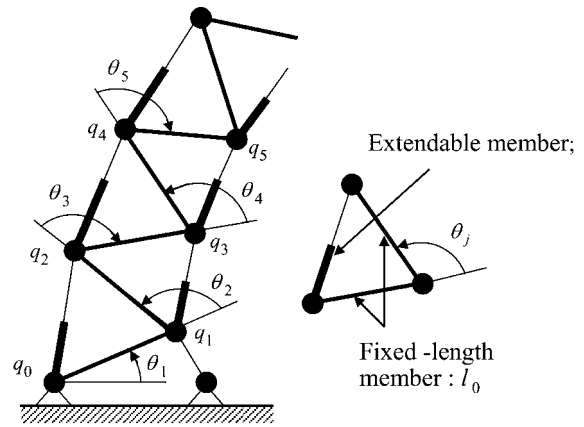


Fig. 5. Two-dimensional VGT unit and analysis model.

2. Motion Analysis of VGT Structure

A forward kinematics analysis to which a structure shape is decided by giving the displacement and angle of the VGT, and a reverse kinematics analysis to which a displacement and angle of the VGT is decided by giving the structure shape are used as a motion analysis of the VGT structure.

2.1. Forward Kinematics Analysis

The structural units of the two-dimensional VGTs and the whole of the cantilever structure treated below in section 3 are shown in **Fig. 5**. Each VGT unit is composed of a pair of members comprising a fixed-length member and an extendable member. In this case, the extendable member is a chord member. Then, the whole of the structure can replace a robot manipulator combining two fixed-length members in series. The tip of the x, y co-ordinates of the structure combined with n ($n \geq 2$) VGT sets is given by Eqs. (1) and (2) using each hinge angle θ_j ($j=1, 2, 3, \dots, n$),

$$q_{x,n} = l_0 \cdot \sum_{k=1}^n \cos \left\{ \sum_{j=1}^k \theta_j \right\} \quad \dots \quad (1)$$

$$q_{y,n} = l_0 \cdot \sum_{k=1}^n \sin \left\{ \sum_{j=1}^k \theta_j \right\} \quad \dots \quad (2)$$

$$S_j = l_0 \cdot \sqrt{2 \cdot (1 + \cos(\theta_j))} \quad \dots \quad (3)$$

The length of the extendable member; S_j is easily decided from θ_j as shown Eq. (3) and the structure's shape can be uniquely decided. However, for an intended structural shape fixed by Eqs. (1) and (2), it is quite difficult to solve these equations analytically and to decide the angle because the structure is a very highly redundant. In this case, inverse kinematics analysis is used as described in the next paragraph.

2.2. Inverse Kinematics Analysis

Considering a temporal change of the whole of the structure, Eqs. (1) and (2) are shown as Eqs. (4) and (5)

respectively.

$$\dot{q}_{x,n} = -l_0 \cdot \sum_{k=1}^n \left\{ \sum_{k=1}^n (\dot{\theta}) \sin \left(\sum_{j=1}^k \theta_j \right) \right\} \cdot \dots \quad (4)$$

$$\dot{q}_{y,n} = l_0 \cdot \sum_{k=1}^n \left\{ \sum_{k=1}^n (\dot{\theta}) \cos \left(\sum_{j=1}^k \theta_j \right) \right\} \cdot \dots \quad (5)$$

These equations are expressed in Matrix form by the following Eq. (6) in terms of an independent variable $\boldsymbol{\theta}$,

$$\dot{\mathbf{q}}_n = \mathbf{J}(\boldsymbol{\theta}_n) \cdot \dot{\boldsymbol{\theta}}_n \quad \dots \quad (6)$$

where $\mathbf{J}$ indicates the Jacobean Matrix ($2 \times n$). However, an inverse matrix $\mathbf{J}^{-1}$ isn't necessarily decided because $\mathbf{J}$ is not a regular system in $n > 2$. In this case, the pseudoinverse matrix $\mathbf{J}^\#$ is generally induced instead of $\mathbf{J}^{-1}$ shown by Eq. (7) and the angles $\boldsymbol{\theta}$ of VGTs in the structure are indicated by Eq. (8)

$$\mathbf{J}^\# = \mathbf{J}^T \cdot (\mathbf{J} \cdot \mathbf{J}^T)^{-1} \quad \dots \quad (7)$$

$$\dot{\boldsymbol{\theta}}_n = \mathbf{J}^\# \cdot \dot{\mathbf{q}}_n \quad \dots \quad (8)$$

Integrating both sides of Eq. (9) for time, the value of $\boldsymbol{\theta}$ is solved by numerical simulation from Eq. (8).

$$\boldsymbol{\theta}_n^t = \boldsymbol{\theta}_n^{t-1} + \mathbf{J}^\# \cdot \dot{\mathbf{q}}_n \cdot \Delta t \quad \dots \quad (9)$$

As shown in the study of the movable arch structure in section 3, this method was applied to the motion analysis.

3. Verification of Movable Arch Structure Applying VGT

3.1. Outline of Movable Arch Structure

A schematic design for a large adaptive space structure that we assume to target is shown in **Fig. 6**. The space structure is composed by arranging movable arch structures serially, and finished members accompanied by the moving arch are set on the structure's external face. Each arch structure can move within the range where the finish member is movable when viewed from outside, and the whole of the space structure was designed to move like a living thing. To realize such an adaptive space structure, we apply the VGT mechanism to the component of the movable arch structure. In this section, the shape variation of a movable arch structure, its arrangements, the structural characteristics for the conditions of the end supports and these scale model experiments are examined.

3.2. Shape Variation of Movable Arch Structure

A proposed movable arch structure for an adaptive space is shown in **Fig. 7**. The movable arch comprised serially disposed VGT mechanisms in which the lower frame was an extendable member and the upper frame was a fixed member, and the ends of the arch were supported at points A and B. On the structure's external face, the panels were attached to the upper frame and the flexible member covering the hinge space that expands according

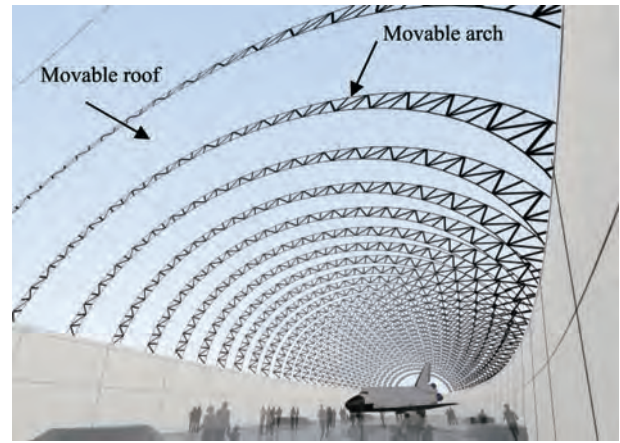


Fig. 6. Schematic designs for a large adaptive space structure by VGT.

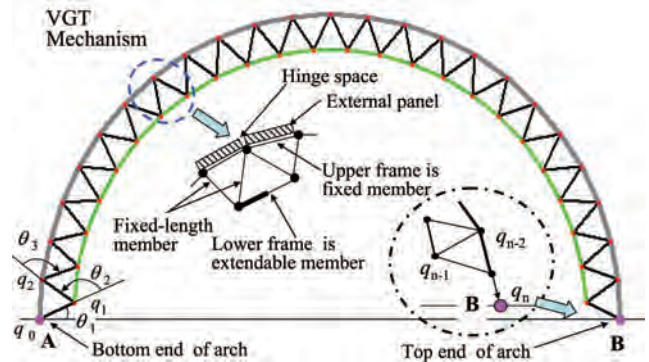


Fig. 7. Composition of a proposed movable arch structure.

to the length of the extendable members was applied. The whole of the roof face was composed of those finished members.

In order to investigate the shape variations of the movable arch structure, the arch was assumed as a cantilever structure expressed by Eqs. (1) and (2) in forward kinematics, as shown in **Fig. 5**, such that the bottom end of structure q_0 was supported at position A and the top end of the structure q_n was located at position B. Here, when the first angle θ_1 was changed a little as an initial condition of motion analysis, the structure's shape was also changed according to the shape of the VGT truss. However, the top end q_n of the structure wasn't sited in the initial position B. To satisfy the basic condition of the arch structure, both ends of the arch should be sited at initial positions. Making the end position correction to the initial position B, the correcting angles of each VGT except the first angle were calculated by inverse kinematics analysis, as indicated in Eqs. (3)–(6). As a result, the end of the arch could be fixed at initial position B and the shape of the arch became a little different before the calculation step.

Repeating this process given by initial condition of each step, very variable shapes of the arch could be created by numerical simulation.

Figure 8-(a) shows the simulation results of shape changes of the arch when the extendable members were arranged at only the lower side frame. It looks like a wave

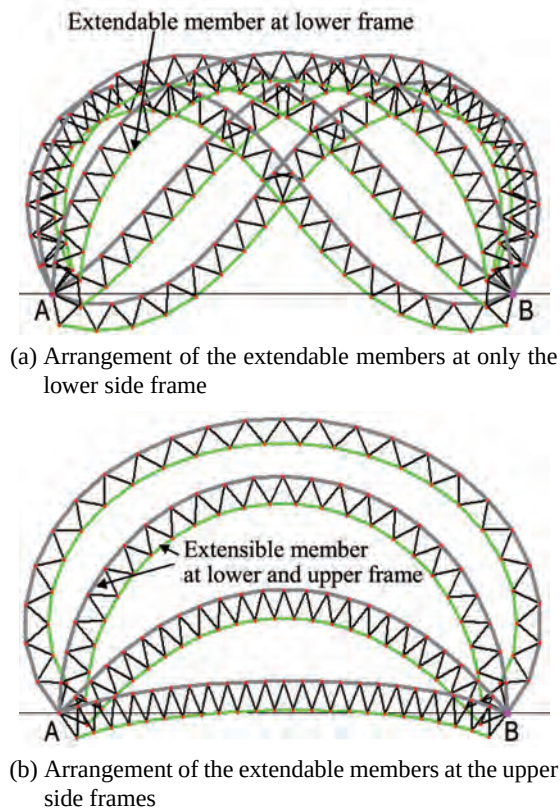


Fig. 8. Shape change of movable arch structure applying VGT mechanism.

variation. In this case, the total length of the upper side frame was constant at all times and the ends were fixed at an initial position. **Fig. 8 (b)** shows the other simulation results of shape changes when the extendable members were arranged at only the upper side frames and the same length of the all lower side frames were given as initial conditions. In this case, the length of the upper side member was changed by following the length of the lower member while the end were hold at their initial positions.

Figure 9 shows the experimental result for the scale model of the arch structure. The scale model was composed of four VGT mechanisms with the extendable members operated by a servo motor. The upper frame length of each VGT unit was 500 mm and the total length of the model arch was 2500 mm. The extended range of the lower frame was from 350 mm to 510 mm and the extending speed was varied from 0.1 to 20 mm/s. The bottom end of the arch at A was fixed by a pin support and the top end at B was free as a pin roller. When the arch shape was controlled by inverse analysis in the range of extending speed, the top end of the arch could be situated at the same position B in spite of the arch shape. Therefore, even if the top end was supported, it has been shown that there was no motion obstacle using inverse analysis in the model experiment.

3.3. Structure Characteristics of Movable Arch

In order to investigate the axial stress in the each arch member for the support condition, the stress was calcu-

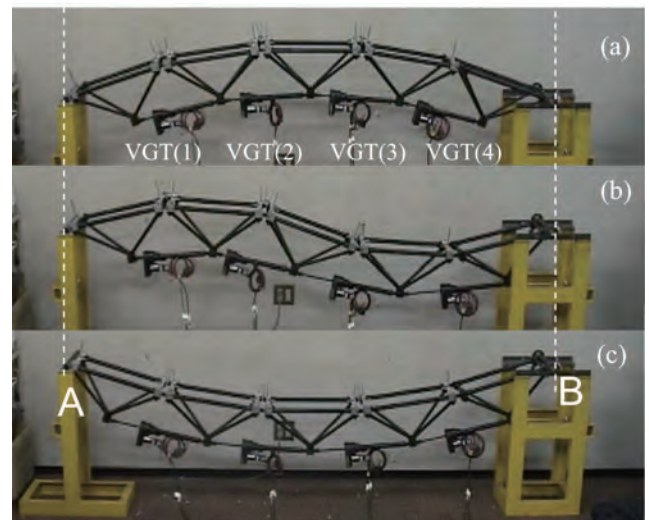


Fig. 9. Experiment verification of a movable arch structure using scale model by inverse control.

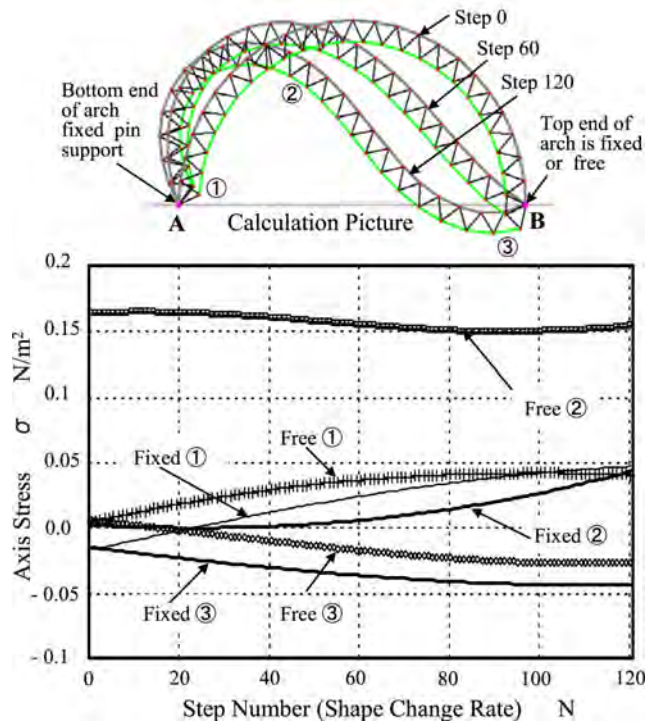


Fig. 10. Structural characteristics of movable arch.

lated by the FEM method when the shape of the arch was changed. In this calculation, the bottom end at A was fixed and the top end at point B was assumed to be fixed or free, and the length of the extendable member was successively changed from step 1 to step 120. The axial stress in typical members, that is, a member at bottom end ①, a member at central position ② and a member at top end ③, is shown in **Fig. 10**. When the top end was fixed, the axial stress in member ① increased from compression to tension and the member ③ decreased in the compression range against member ①. Member ② increased gradually. The levels of these member stresses were in the low range.

On the other hand, when the top end was free, the char-

acteristics of the axial stresses in members ① and ③ were equal to that of the stress when the top end was fixed. However, the stress in member ② was almost constant and became very high. At a free support, the stress grew as it became the centre member of the arch structure to maintain the arch shape. In this case, the design of the extendable member became very difficult because the stress changed with member arrangement. However, when the top end was fixed, a useful design for shape change was desirable because the stress changed with shape change. An advantage of both ends of movable arch structure fixed using a reverse control was confirmed.

3.4. Application Examples of Movable Arch Structure

A VGT mechanism can be used not only for shape control of a structure, but also for stress control. Thus, it has a wide application in several construction areas. The following are examples of arch structures applying VGT.

- (1) Component of movable structural member;
 - Flexible roofs in large stadiums
 - Sound absorbing panels in music halls with stages
 - Shape-changeable gondola accompanying building walls
- (2) Actuator device in facility or building equipment;
 - Control of structural stress and vibration
 - Transportation for construction materials
 - Future robotic mechanism; multiple manipulator, flexible arm, etc.

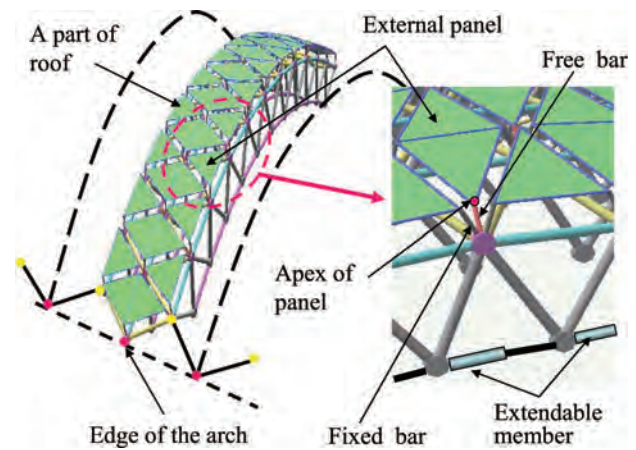
4. Movable Roof Mechanism Composed of Movable Arch and External Panel

In order to realize a large adaptive space, as shown in Fig. 6, the mechanism of the movable roof is investigated by numerical simulation and experimental model [6].

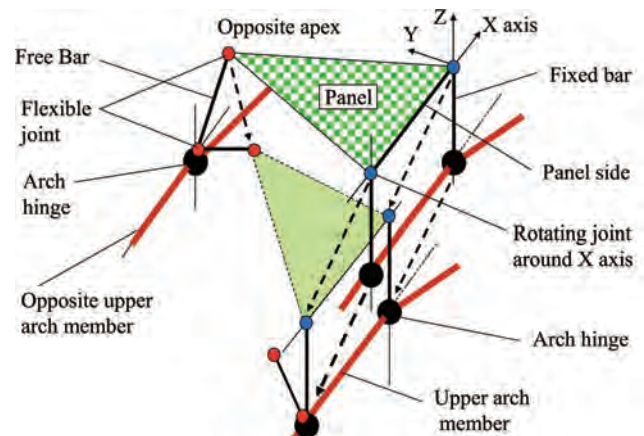
4.1. Proposed Movable Roof Mechanism

Figure 11 shows a part of the movable roof and joint mechanism of both arch structure and panel. The roof was constructed by arranging the movable arches in parallel as the roof skeleton and attaching external panels between each arch. The edges of the adjoining arches were set at half the height of the VGT member. With this arch arrangement, the triangular plane was formed by the three hinges of the adjoining arches, and where the triangular external panel was sited as indicated in Fig. 11 (a).

A side of the panel was attached to the joints rotating around the X axis through fixed bars supported at hinges of the upper arch member, and the opposite apex of the panel was attached to the flexible joint through a free bar jointed at the opposite upper arch member, as shown



(a) A part of movable roof composed of the arch and panel



(b) Joints mechanism to move panel flexibly

Fig. 11. Mechanism of movable roof and external panel.

in Fig. 11 (b). When the shapes of the movable arches were changed relatively as indicated by the dashed arrow, the panel inclined toward the other situation because the apex of the panel was moved according to the panel side movement. In this case, the position of the apex could be changed within the hemispherical plane of the free bar radically with respect to the panel side positions.

A small movable roof was designed as an example and its motion was analyzed by numerical simulation. Fig. 12 shows the production process of a movable arch. First, the movable arches were arranged along the base ring (Fig. 12 (a)). Next, the support bars were attached (Fig. 12 (b)) and the external panels were sited (Fig. 12 (c)). Finally, the flexible members were covered with the panel space (Fig. 12 (d)). Fig. 13 shows the results of motion simulation for the movable roof using the proposed external panel when the shape of the movable arches was changed between +phase and -phase. The external panels followed the movable arch perfectly without panels coming into contact. The space between the two panels could be covered enough by using an expansion material within the range that could be allowed by the space between the panels extended by the curvature change of the arch.

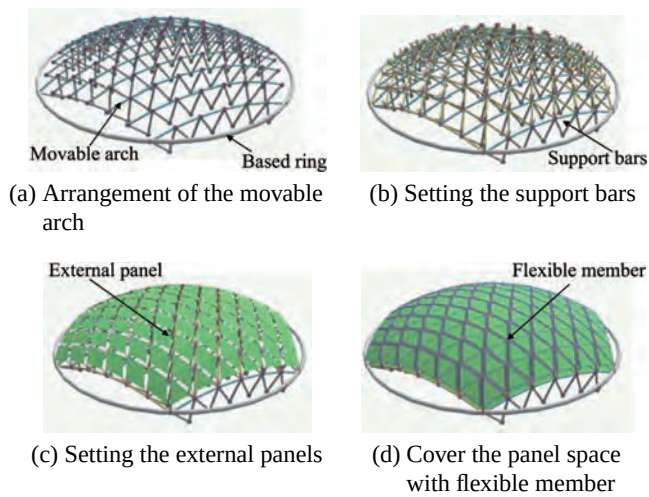


Fig. 12. Production process of a small size movable roof.

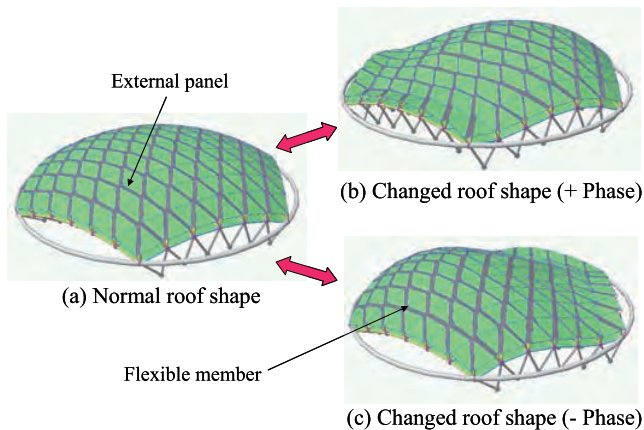


Fig. 13. Results of motion simulation for the movable roof using the proposed external panel.

4.2. Experimental Verification of Roof with External Panel Mechanism

To verify the movable roof including the external panel mechanism, the behavior of the movable arch and its panel was investigated by a scale experimental model in which the total frame length was 2.0 m. Three sets of the actual model for the movable arch were manufactured as indicated in Fig. 11. A joint mechanism composed of a free bar and a fixed bar was installed on the model structure and the external panel was set. Fig. 14 is a photograph of the skeleton of the actual scale model and the joint mechanism of the external panels.

When the extendable members of the movable arch were changed in various configurations, the behaviors of the external panel were as shown in Fig. 15. The centers of the panels were dropped gradually as shown in photographs ① to ④, and next the centers of the panels were raised in reverse as shown in photographs ⑤ to ⑧. Each fixed bar and free bar jointing the panel was moved smoothly according to the arch shape, and then the panel's angles also turned. The panels followed the movable arch without coming in contact, as shown by the simulation results.

In this experiment, the moving range of the panel was

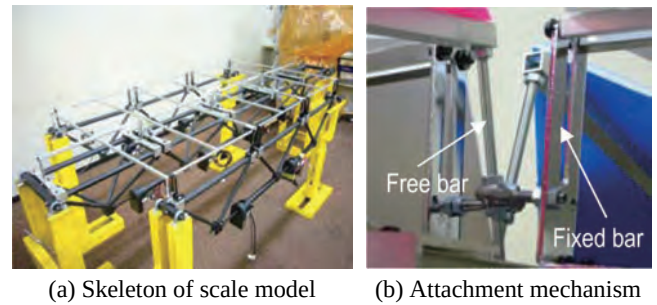


Fig. 14. Experimental model of movable arches and panels.

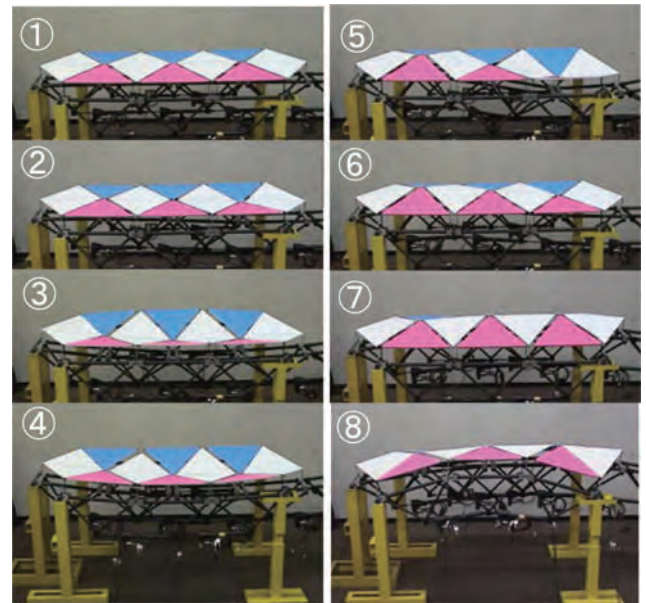


Fig. 15. Behaviors of the arch and external panel using model.

limited because of the narrow range through which the fixed bar moved. In actual design, an attachment mechanism that can take a wide range of movement is needed. Further, the behavior of the expansion cover for the panels needs to be considered. Through several model tests, the feasibility of a large adaptive space structure was obtained by a VGT mechanism, and several problems to be solved were clarified.

5. Conclusion

A new idea for a large adaptive space structure was developed by applying a movable arch structure with VGT and its external panel. In order to verify the basic technologies, the motion and structural characteristics for the movable arch structure and external panel mechanism were clarified by numerical simulation and scale model experiments. Although the arch structure has a lot of structural advantage because both edge supports are fixed, the edge support condition is very difficult to achieve when the movable arch structure is adopted. However, by controlling the VGT mechanism, shape change was realized without structural problems. The proposed VGT mechanism was shown to be very useful for such mov-

able structures whose shape can be changed variably. In the future, with progress and dissemination of VGT technology, we will propose various applications.

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