A STRUCTURAL SYSTEM SUITABLE FOR RATIONAL CONSTRUCTION

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Abstract

A structural system developed and named "Pantadome System" by the author has been applied to six major spatial structures of various shapes and dimensions in different corners of the world. It is a structural system (not a construction method) incorporating a temporary "kinematic mechanism" in it for a rational construction of domical structures. Nara Convention Hall has recently been constructed successfully on the principle of Pantadome System. In the present paper raison d'être, principle and newly applied examples of Pantadome System are presented.

1. Introduction

It is well known that a spatial structure, or a structure of three-dimensional characteristics, is one of the most efficient structures capable of covering a very wide area, once it has been completed. The spatial structure is not always efficient, however, in the process of construction, because it requires big amount of scaffoldings, labor and time and often encounters difficulties in terms of accuracy, reliability and safety of work during its erection. Modern erecting methods such as lifting systems which are very often adopted in erection of roofs of flat, plate type can not equally be applied to a spatial structure.

Buckminster Fuller once tried to solve this kind of problems in a few ways when he encountered them in building some of his geodesic domes. For construction of one of his domes in Honolulu in 1957 he adopted a system in which a temporary tower was erected at the center of the dome from top of which concentrically assembled part of the dome was hung by means of wire ropes. As assembly of the dome proceeded the dome was gradually lifted, enabling the assembling work to be done along the periphery of the dome always on the ground. He also adopted another method when he built a huge dome of 117m in diameter at Wood River, U.S.A., in 1959, where the assembled part of the dome was raised on a balloon-like enclosure. Some other cases have also been reported where different lifting methods have been applied by several engineers to different domes. However, none of the above attempts for lifting domes have become popular unlike those lifting methods which became widely used to raise plate-type roofs.

A patented structural system called 'Pantadome System' which had been developed by the author for a rational construction of spatial structures was successfully applied to the structure of World Memorial Hall completed in Kobe in 1984. Pantadome System has since been applied to the Sant Jordi Sports Palace in Barcelona, the National Indoor Stadium of Singapore and some important structures of wide spans realized in Japan.

2. Principle of Pantadome System

The principle of Pantadome System is to make a dome or a domical structure geometrically unstable for a period in construction so that it is 'foldable' during its erection. This can be done by temporarily taking out the members which lie on a hoop circle. Then the dome is given a 'kinematic mechanism', that is, a controlled movement, like a 3-D version of a parallel crank or a 'pantagraph' which is popularly applied to drawing instruments or a power collector of an electric car (hence the name, 'Pantadome'). (Fig.1,Fig.2)
By 'folding' the dome in this way, the constituent members of the dome can be assembled on a lower level. The assembly work is thus done safely, quickly and economically, since it can be carried out near the ground level.

Since the movement of a Pantadome during erection is a 'controlled one' with only one freedom of movement in the vertical direction, guying cables or bracing members which are indispensable in conventional structures to assure their lateral stability against wind or seismic forces are not necessary in erection of a Pantadome structure. The movement and deformation of the whole shape of the Pantadome during erection are three dimensional and may look spectacular and rather complicated, but they are all kinematically determinate and easily controlled. Three kinds of hinges are incorporated in the Pantadome System which rotate during the erection. Their rotations are all uni-axial ones, and of the most simple kind. Therefore, all these hinges are fabricated in the same way as normal hinges for usual steel frames.

In Pantadome System a dome is assembled in a folded shape near the ground level. As the entire height of the dome during assembling work is very low compared with that after completion, the assembly work can be done safely and economically, and the quality of work can be assured more easily than in conventional erection systems since inspection by structural supervisors is much easier. Not only the structural frame but also the exterior and interior finishings, electricity and mechanical facilities are fixed and installed at this stage. The dome is then lifted up. Lifting can be achieved either by blowing air inside the dome to raise the internal air pressure, or by pushing up the periphery of the upper dome by means of hydraulic jacks. When the dome has taken the final shape, the hoop members which have been temporarily taken off during the erection are fixed to their proper positions to complete the dome structure. The lifting means such as air pressure or hydraulic jacks can be then removed, and the dome is completed. When the dome is very big, it can be "doubly folded" as shown in Fig.1(c), so that assembling works can be done at a level that is very close to the ground level.

The Pantadome System is sometimes misunderstood as a construction method, but it is not. It is a structural system in which a kinematic mechanism is incorporated so that it can largely change its shapes for a rational construction.

After completion the hinges installed in the structure at three different levels are very often left as they have been during the erection, and the hinges at the two lower levels act as structural hinges even after completion of the structure so that it can 'breath' freely according to temperature changes to avoid the thermal stresses in it.

3. Examples of Pantadome System

The Pantadome System has so far been applied successfully to five major spatial structures (Fig.3.) before Nara Convention Hall which is now under construction. It was first applied to World Memorial Hall in Kobe in 1985. It has an oval plan of 70m x 110m, having

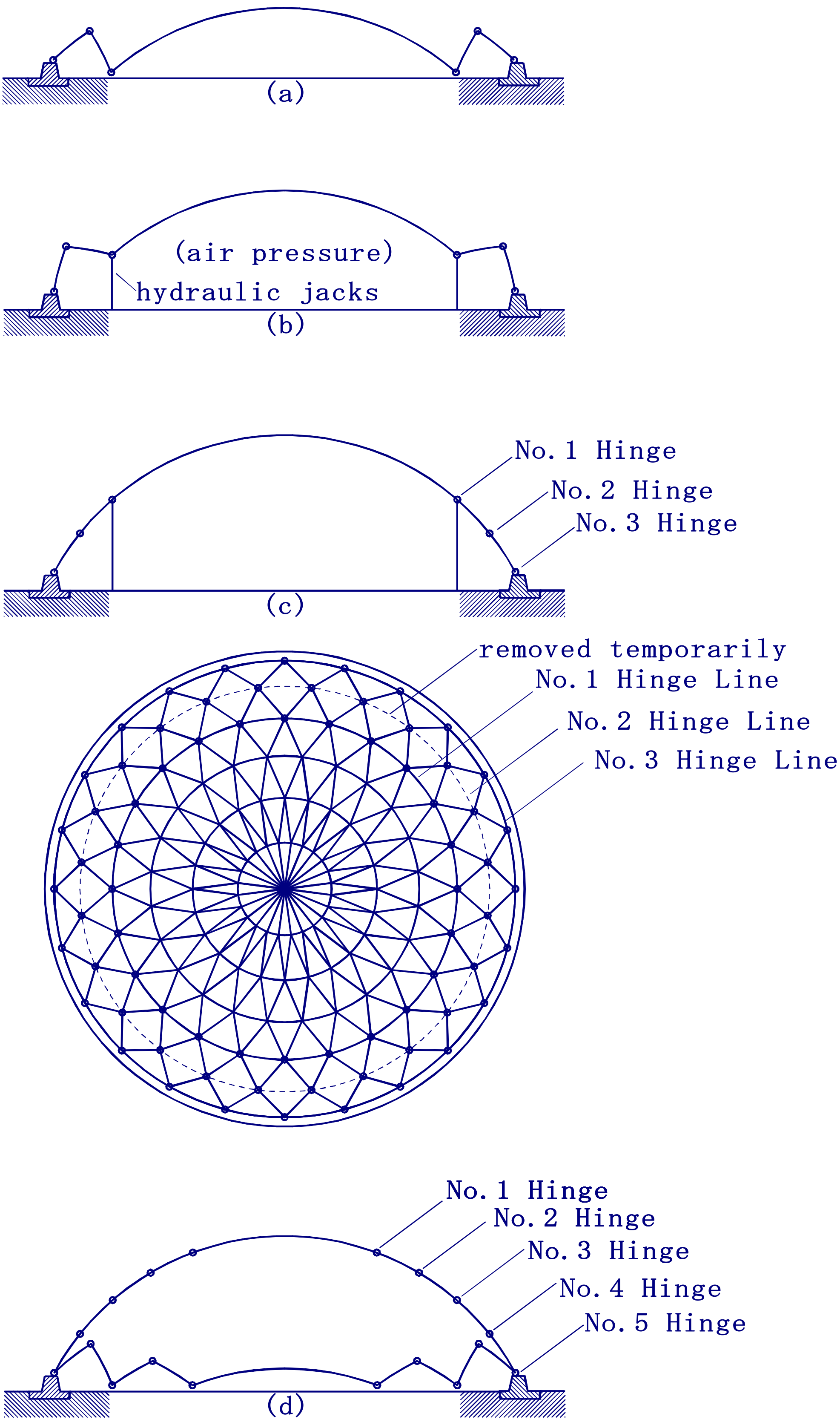


Fig.1. Principle of Pantadome System

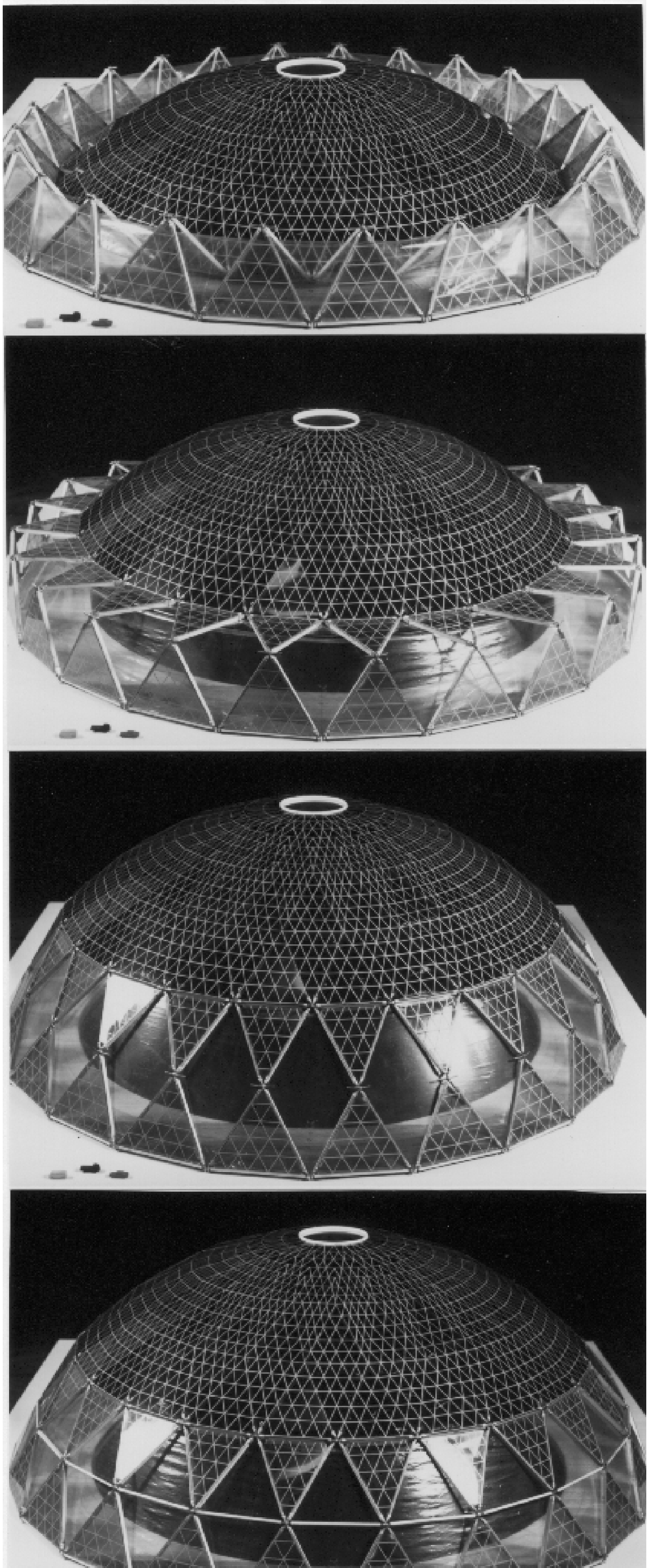


Fig. 2. Model Study of Pantadome Principle

an overall shape of an elongated semi-sphere. The architectural design of the hall was done by Showa Sekkei Design Co. It was built as one of the sports facilities for Universiad '85. The second example of Pantadome application was the Singapore National Indoor Stadium having a rhombic plan of 200m x 120m in the diagonal directions. It was architecturally designed by Kenzo Tange. The Singapore Indoor Stadium has an arena of 3000m^2 and grandstands for 12000 seats. The geometry of the roof is constituted by four cylindrical surfaces, each convex inward, having their generatices parallel to the four straight side of the rhombic plan.

The third example was Sant Jordi Sports Palace in Barcelona, architecturally designed by A. Isozaki and completed in 1990 for the Barcelona Olympics celebrated in 1992. It has a covered area of 12000m^2 in the shape of a rounded trapezoid. In this sports hall Isozaki wanted to have his building express the way it had been built. So he chose the shape of the roof which looked as if it had been still in the process of Pantadome erection. He also arranged the sky-light belts along the hinge lines of the roof to suggest the process of erection of the roof.

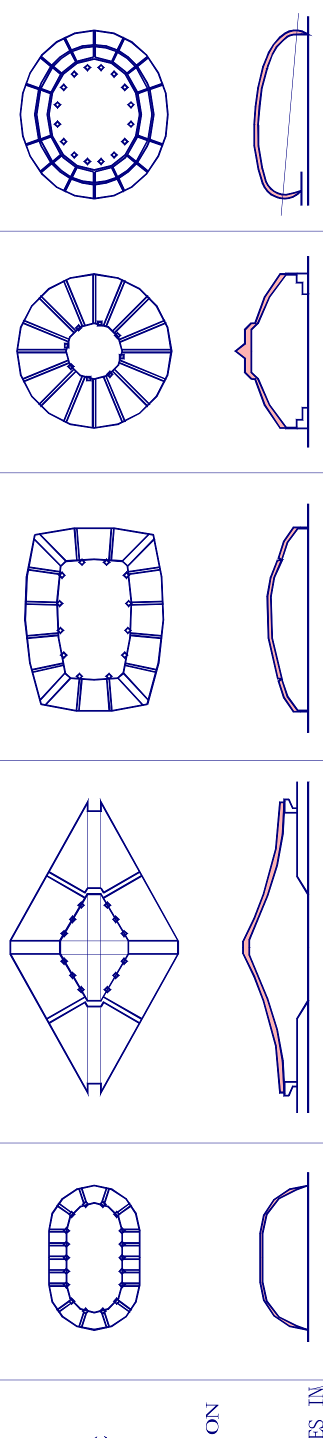
The fourth example was Sundome Fukui, designed by Architect S. Okazaki, and completed in 1995. Fukui is located on the side of the Sea of Japan, and it is in a heavily snowed area. It is a multipurpose hall planned to be used for music concert, exhibitions and sports events. The dome covers a circular plan of 116m in diameter and it has an overall height of 55m. For various reasons the dome was designed to retain whole the snow fallen on it. So the shape of the dome was decided to have a geometry to satisfy the above purpose, while keeping conformity with configuration of the structural frame of the dome. Since the snow load to be supported by the dome was very heavy (600kg/m^2), the weight of the dome structure itself was also high. When the dome was erected, its total weight was some 4000 tons.

The fifth and the most recent Pantadome examples before the Nara Convention Hall which is now under construction was Kadoma Sports Center in Osaka, which was lately renamed as 'Namihaya Dome' after the name of the National Athletic Meet '97 held in Osaka Area for which this Sports Center was one of the main venues. The Namihaya dome was designed by Showa Sekkei Co., and it has an oval plan of 127m and 111m in major and minor diameters, respectively. The main function of this building is swimming pools, having a racing and a diving pools of international standards. In other seasons than summer it is used for athletic games and exhibitions, and for ice skating in winter. One of the special features of the dome was that its 'equator' was not horizontal but inclined 5 degrees. The Pantadome structure was designed accordingly, and it was erected in the direction inclined 5 degrees from the vertical. By means of a special hoisting system developed for this building, the dome was lifted in only 8.5 hours(Fig.4).

In Fig.3. previous examples of Pantadome System as stated above are summarized. It can be seen that this structural system has been applied to spatial structures of different shapes, dimensions and loading conditions. It was also used successfully for domes built in three different countries.

4. Construction of Nara Convention

Nara Convention Hall designed by A. Isozaki is a building to accommodate two music halls of high standard. It has an elliptic plan of 138m and 42m in major and minor diameters, respectively. The height of the roof is 24.8m. The vertical section of the wall has a single



NAME	WORLD	SINGAPORE	ST. JORDI	FUKUI	NAMIHAYA
SHAPE AND DIMENSION (SMALL CIRCLES IN PLANS INDICATE PUSH-UP POSTS)	110 m	200 m	128 m	116 m	127 m
BUILT	1984	1989	1990	1995	1996
COVERD AREA	7,700 m^2	14,000 m^2	12,000 m^2	10,500 m^2	11,000 m^2
TOTAL WEIGHT	1,680 t	2,600 t	3,000 t	5,430 t	4,690 t
STEEL WEIGHT	760 t	1,250 t	950 t	2,770 t	1,160 t
LIFTING HEIGHT	20 m	20 m	32 m	28 m	29 m
LIFTING POINTS	18	12	12	8	16
SPECIAL FEATURES	OVAL PLAN FIRST ATTEMPT	RHOMBIC PLAN ABROAD	UNFINISHED SHAPE ABROAD	PURE CIRCLE HEAVY SNOW	INCLINED ROOF QUICK LIFT

Fig.3. Realized Pantadome Examples

Fig. 4. Erection of “Namihaya Dome” by Pantadome System

configuration everywhere, in the shape of a clothoid having a very little curvature at the bottom and bigger ones upward.

For a better acoustic insulation every part of the envelope (roof as well as wall) was designed heavier than in ordinary buildings. The roof is covered by a structural steel plate of 6mm in thickness on top of which are put precast light-weight concrete panels (100mm) and in-situ concrete (80mm) with insulating layers in between.

The interior of the wall is constituted by exposed precast concrete panels of 120mm in average thickness reinforced by steel sections, while its exterior is covered by 33mm thick roof tiles which are lined by concrete precast panels of 50mm. The overall stability of this domical structure is assured by a curved skin (or thin shell) structure of the wall which is stiffened by the roof diaphragm at the top.

Since the dome has a long and narrow elliptic plan, the wall resists effectively lateral forces in the longitudinal direction, but its resistance is not sufficient in the transverse direction. To increase the lateral resistance of the building in the transverse direction, the double wall which separates the two music halls from each other is utilized in design as a pair of shear walls in that direction. The peripheral wall was divided into the top and bottom halves and into 120 sections along the periphery, and each of the 240 wall panels was prefabricated in a factory, and transported to the building site. The whole structural scheme of this building was designed as a Pantadome.

Three hinge lines necessary for Pantadome kinematic mechanism were put at the top, bottom and the middle of the wall panel. The construction of the dome was proceeded with in the following sequences:
The roof trusses are assembled on temporary supports. When the trusses are completed, they are made simply supported at the two ends, the secondary structural members are fixed to them and the top finishing is continued (Phase 1 in Fig.5.). The lower panels of the wall are brought into the positions, and they are secured to the concrete lower structure by means of the bottom hinges (hinges No.3). Then the upper wall panels are brought to the positions, and connected to the roof and the lower panels by the top (hinges No.1) and the middle (hinges No.2) hinges (phase 2 in Fig.5.). By this stage the roof is finished to the maximum possible extent, both exterior and interior. It is not necessary to finish the interior surface of the peripheral wall, because it is of precast exposed concrete. When the assembling work is completed, the whole dome structure is lifted by means of hydraulic jacks and temporary posts(phase 3). 64 hydraulic jacks are employed, and each pair of them are set on top of one of the 32 lifting units. The lifting forces of all the jacks, the lifting speeds at all the lifting units and the stresses at a few important points of the dome structure are measured and controlled in the central control room with the aid of computers.

The steel skeletons of the transverse double wall at the middle of the dome are provided with hinges to make 'Pantawalls' so that they can resist the possible lateral forces in the transverse direction during the lifting work (Fig.6.).

When the roof has reached the specified height, the lifting work is finished, and adjacent wall panels are put together with each other by bolting and welding. Then the dome structure is completed (phase 4). All the secondary structures and finishings inside this huge envelop are then worked out without being disturbed by the weather.

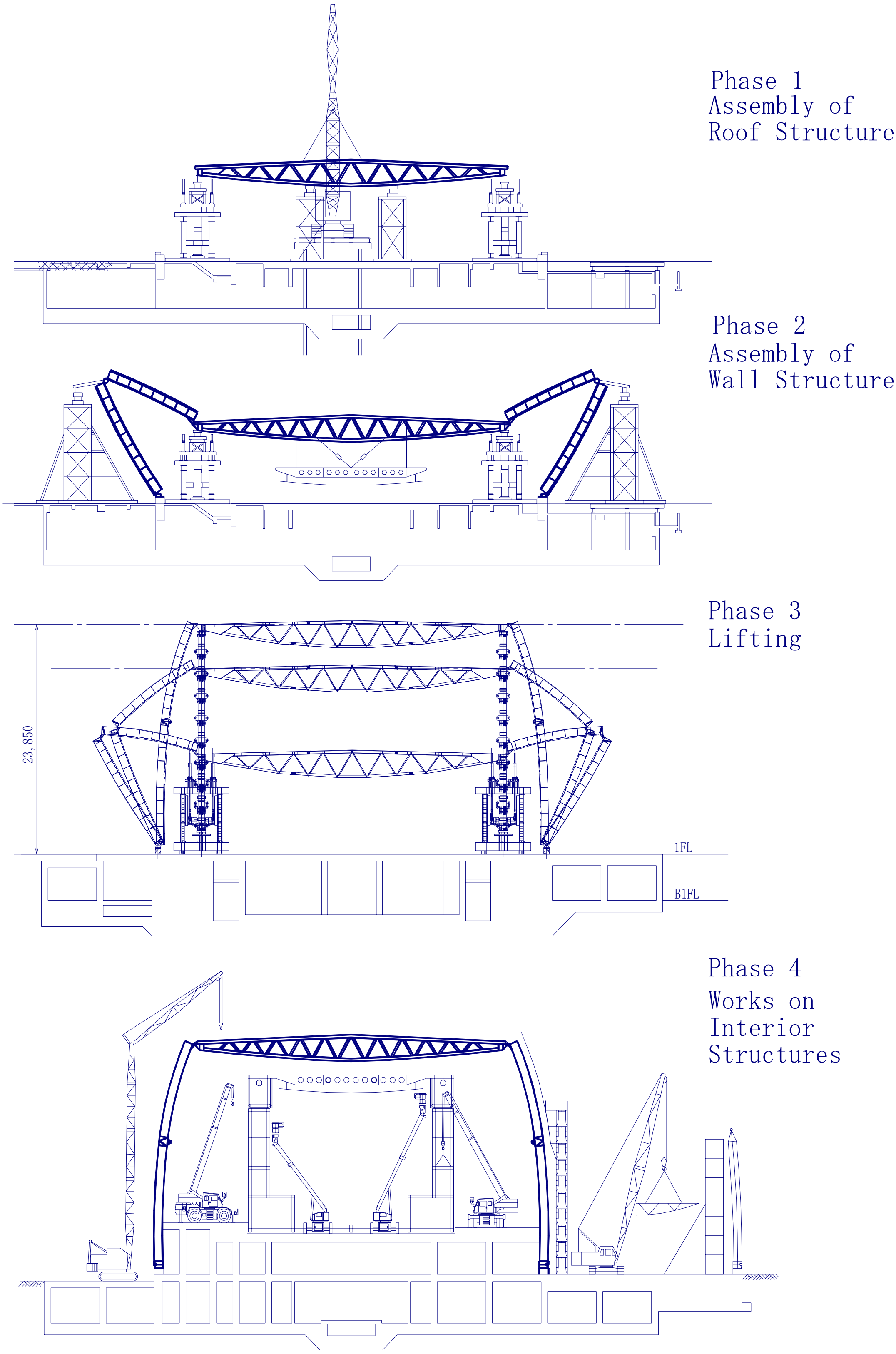


Fig.5. Construction of Nara Convention Hall

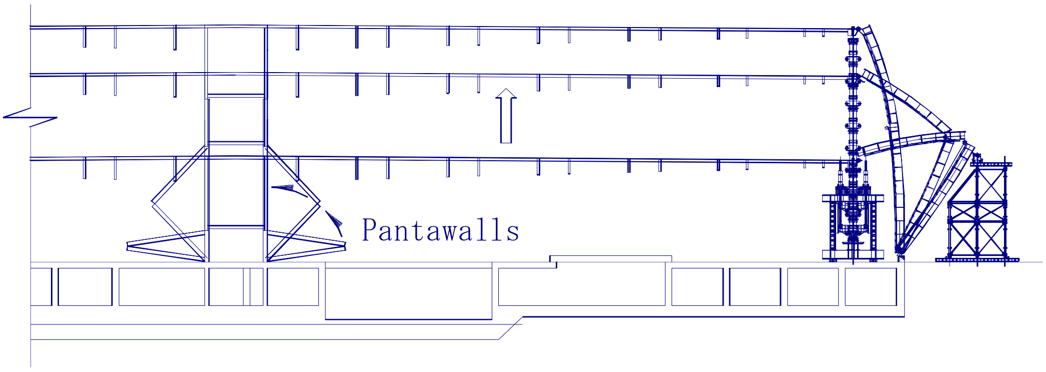


Fig.6. Nara Convention Hall
(Longitudinal Section)

Lifting work of the Nara Convention Hall started on December1, 1997. The dome was lifted only in the morning, everyday, to receive the visits of the citizens, many of whom wanted to see the dome largely change its shape everyday. Thousands of people visited the dome during the lifting work. On December 6 the dome reached its final height. It is now in the stage of fixing and finishing.

5. Conclusive Remarks

Six spatial structures which were designed and built on the principle of Pantadome System have been reviewed. Pantadome is a patented structural system which incorporates controlled kinematic mechanism in a spatial structure, so that it can be assembled and erected safely, quickly and economically. Being based on the same structural principle, the six buildings have six different forms. Through description of interrelation between the form and engineering of each particular buildings, it has been shown that close cooperation between the engineer and architect is indispensable for appropriate expression of an innovative structure.

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