Planning and Execution of Lift–Up Construction for Roof of Large–Scale Single–Layer Latticed Dome

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ABSTRACT

The Nagoya Dome currently under construction is a ball park featuring the world's largest single–layer latticed dome roof with a daylight admitting–and–cutting facility in its center. Because of the roof's iron frame having all of its splices connected by welding, the erection of the roof required highly sophisticated technology and precision accuracy. Before the work on its construction began, elaborate discussions were held on the installation plans and accuracy management. One of the chief characteristic features of this project was the adoption of the lift–up method for the erection of the roof. The project involved the use of 72 hydraulic jacks to lift–up a large–scale roof weighing approximately 10,300 tons as the first experience in the construction field. Numerous technological development programs were conducted, including synchronized control of many jacks and multiple–point instrumentation. This accounted for the successful work of erecting the roof and lifting it with the desired results attained, including a shorter construction period and the prescribed level of accuracy.

1. INTRODUCTION

The Nagoya Dome currently under construction is a ball park featuring the world's largest single–layer latticed dome roof with a daylight admitting–and–cutting facility in its center (see Fig. 1). The roof iron structure uses its basic grid as an isosceles triangle and its main skeleton is made up entirely of steel pipes with cast steel nodes used for joints and splices, all connected by welding. These structural features demanded a highly technology and precision accuracy.

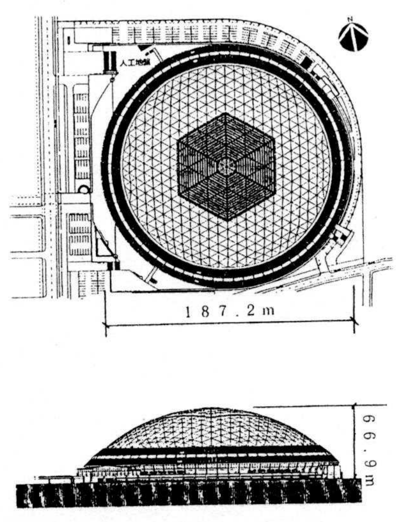


Fig. 1 Sketch Drawing

In the conventional construction of a big skeleton for a large–space facility, temporary platforms were set up to assemble it in an elevated place. This method however, presented some problems in that it required a long time period and many materials. To solve these problems and to raise the productivity level while also securing a better working environment, the construction methods for moving a frame by mechanical equipment, such as the lift-up and push-up construction method, have been developed and put into practical application at many construction sites. In the case of the Nagoya Dome, the lift-up construction method was applied to erect the single-layer latticed dome roof in the construction.

This paper describes the construction of the world's largest single-layer latticed dome roof with a focus on the lift-up construction technique.

2. OUTLINE FOR CONSTRUCTION

An outline for the construction project is set out in Table 1.

Table 1 Outline of Construction

Designed	Takenaka Corp.
Constructed	Joint Venture of Takenaka Corp. and Mitsubishi Heavy Industries
Building Space	48,257 ㎡
Total Floor Space	118,831 ㎡
Scale of Structure	RC,SRC,S 6F
Maximum Height	66.9m
Construction Period	8.1994-2.1997

3. ERECTION WORK

3.1 WORK PLANS

Described below are the main work plans discussed for the solution of a host of technological tasks in the execution of this project.

① To use as few temporary platforms as possible, the lift-up construction method was applied, involving ground-assembling the roof from the top down to its second floor and then lifting the finished roof up to it's prescribed height with the hydraulic jacks.

② Work began first on the central part of the roof involving a large work load leading to a shorter construction period.

③ In order to reduce welding work in an elevated position, iron frames were first assembled on the ground into large blocks. It was designed to arrange as many four-triangular block groups according to the construction's process.

In light of the above working plans, mock-up tests were carried out using actual set units two months before construction work commenced.

3.2 ACCURACY MANAGEMENT

The structurally required groove accuracy needed exact root gaps of 7mm+3 mm and 7mm-2mm. To achieve these desired accuracy levels, the following steps were applied:

① Members which have length enough (+ 2mm per one welded spot) to make allowances for weld shrinkage were used to keep ground assembled frame parts within the desired levels of accuracy. Ground assembly coordinates were calculated with a ground assembly coordinate conversion program. Accuracy management including angle control was performed by measuring the top and bottom sides of nodes.

② Usually when workpieces are to be mounted, temporary platforms obstruct measurements from below. So high-tolerance 3-D surveying instruments with measuring errors of 1.2mm/100m or less and special targets were used to measure the top side of nodes and the tip of brackets from the floor of the perimeter's building frame. For position adjustment in this case, a configuration-management system was contrived to calculate differences between actual measurements and pre-entered design values and node-to-node distances.

③ The outer circumference tension-ring of the iron-frame roof serves as the standard for roof tolerances. A tension-ring helps restrain the outward expansion of the dome roof and stabilize its configuration. All points of the ridgeline were constrained radius-wise and six points constrained circumference-wise for the purposes of minimizing any tension ring deformation caused by welding or extreme temperatures.

④ Splice welding was performed by a team of specially-screened welders. Pre-welding edge tests were conducted and ultrasonic tests were then conducted after welding, in a bid to assure the quality of the structure.

3.3 RESULTS

Photo. 1 presents a view of the construction as of August 1995 and Photo. 2 gives a view of blocks mounted on the temporary platforms. The erection work was completed according to schedule. The following results were obtained.

① The prescribed levels of accuracy were achieved for ground assembly work and work on temporary platforms. Shown in Fig. 2 are accuracy for working before welding.

② The number of welders were cut by up to approximately 30% as compared with the case where all welding work must be done on temporary platforms.

③ Prior safety measures, such as the cubic assembly of temporary platforms reduced manpower for elevated work sites by approximately 45%.

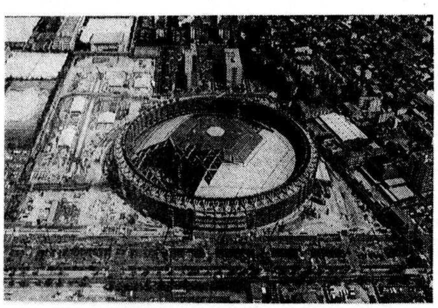


Photo. 1 View of Project
(by courtesy of the Chunichi Shimbun)

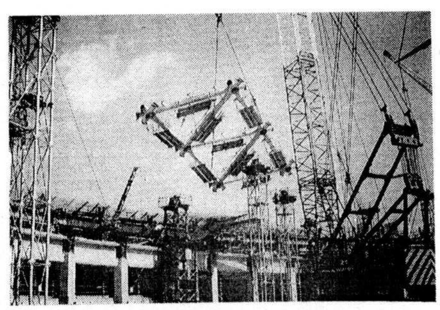


Photo. 2 Blocks Mounted

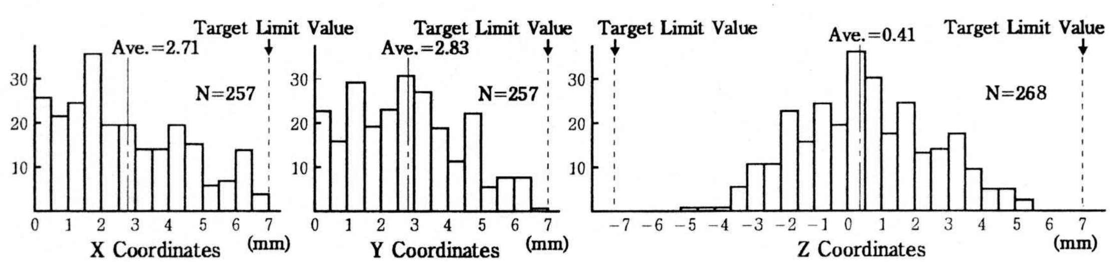


Fig. 2 Result of Accuracy (before Welding)

4. LIFT-UP WORK

4.1 OUTLINE

The outline of lift-up work shows in Table 2. The roof to be lifted up weighed approximately 10,300 ton and occupied an area of 29,000㎡. It is the first case to lift-up such a large single-layer latticed dome controlling 72 jacks in the construction field. Elaborate work plans were worked out prior to the start of the large-scale lift-up work. Various detailed analyses were conducted for the construction period conditions including the relationships between the lifting load and the configuration of the tension-ring of the roof while lifted. Their aim was the identification of the right lift-up construction method.

4.2 LIFT-UP JACK

VSL hydraulic jacks (see Fig. 3) capable of continuously climbing were applied to reduce the time of lifting-up. Nineteen PC steel stranded cables with an outer diameter of 15.2mm fixed to the bracket of the tension-ring were inserted into one jack, whose wind-up would lift-up the roof. A total of 72 jacks were mobilized, each capable of lifting up was 240tf, one stroke was 180 mm and the rising rate was approximately 2m/h. One hydraulic pump controlled three jacks in a basic hydraulic unit. Jacks with PC steel stranded cables inserted in advance in the ground assembly were mounted at intervals of approximately 8m (see Photos. 3 and 4) on the platforms.

Table 2 Outline of Lift-Up Work

Total Weight Lifted-Up	10,300t
Height of Lift-Up	24.77m
Roof Area	29,000㎡
Number of Jacks	72

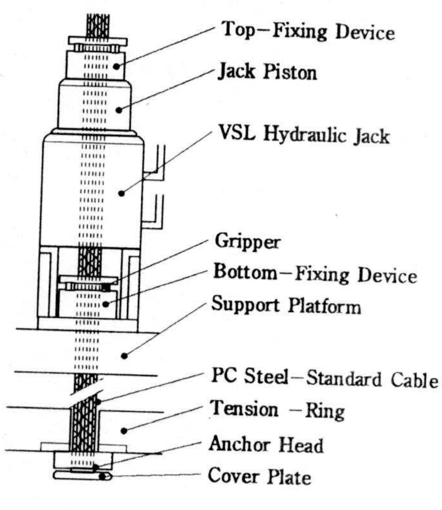


Fig. 3 VSL Hydraulic Jack

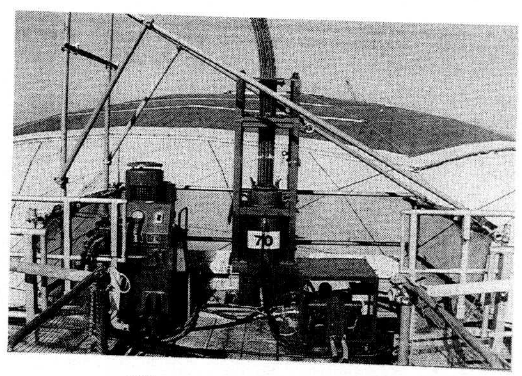


Photo. 3 Jack Installed

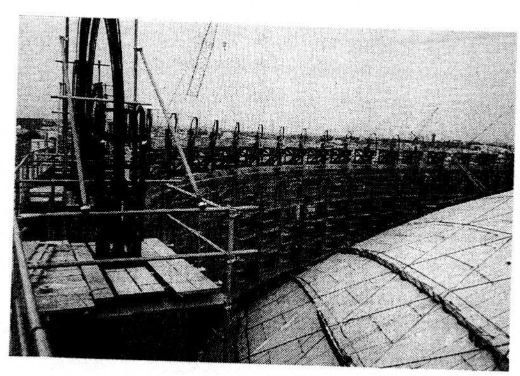


Photo. 4 Jacks Installed

4.3 WORK PLANS

1) LIFTING THE ROOF OFF THE GROUND

After the radius-wise constraint of the tension-ring was released, the load was then transferred to the jacks from a total of 291 temporary platforms (ie. the work of lifting the roof off the ground). What is important in the work of lifting the roof off the ground is the transfer of the load to the jacks without tipping the hanging load balance among them. This requires dividing the transfer of the load into many steps and proceeding with the operation step by step while constantly monitoring the jack load, the rising of the roof, and the deformation of temporary platforms.

In transferring the load, the first stage was imposing a 10tf load to the jacks and then following it up by increasing the load by 10tf for each step up to the maximum of 115% of the designed load (approximately 165tf). While this is being done, the operators check the status of the work of lifting the roof off the ground and the load for each jack.

2) LIFT-UP

About 2.7m lift-up work was conducted for installation of the receiving girders and the fitting of gondola rails which it was not possible to carry out during the ground fabrication because they were supported by temporary platforms. One month later, approximately 13 hours of lift-up work were undertaken over two days to lift the dome roof by approximately 22m.

4.4 WIND LOAD

In wind load-control measures during lift-up work, a new system was used to have the horizontal wind load minimized by having a shock absorber (see Photo. 5), installed at a certain clearance point in the direction of the circumference and radius of the tension-ring of the roof, coming into contact with 12 H-section guide rails installed perpendicularly to the columns of the perimeter's building frame. The guide rails were made of shoring H sections 350mm x 350mm x 12mm x 19mm and three units of urethane porous were used in one shock absorber.

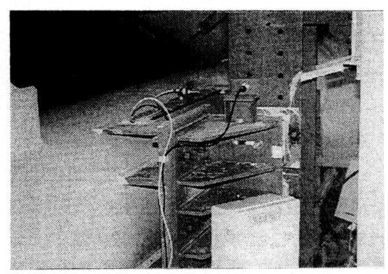


Photo. 5 Guide Rail and Shock Absorber

5. CONSTRUCTION MANAGEMENT

5.1 ITEMS AND VALUES FOR MANAGEMENT

Listed in Table 3 are management items needed for this lift-up work and management values set for them. High-low differences between adjacent

Table 3 Management Items (during Lift-Up)

Management Items	Management Values	Sensors	Points
Jack Load	Over 120tf and under 165tf	Pressure Transduce	24
High and Low Differences between Adjacent Measuring Points	Under 35mm	Rotary Encoder	48
Maximum High and Low Differences between All Measuring Points	Under 80mm	Rotary Encoder	48
Horizontal Displacement of Roof	Under Minmum Clearance	Ultrasonic Range Finder	8

measuring points (entered in the table 3)refer to those between two points; one the spot where the quantity of rising is being measured with a rotary encoder and the other in its immediate neighboring measuring point. The maximum high−low difference between all the measuring points refer to those between the highest point and the lowest one of all points concerned.

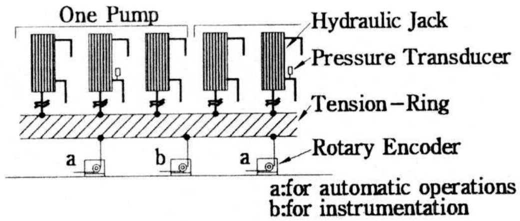


Fig. 4 Position of Encoders

A method of the measuring the quantity of rising using rotary encoder is shown in Fig. 4. A wire from the wire winder set up on the second floor was linked to the tension−ring on the midway point of the center of gravity next to that of the three−jack−one−pump unit by way of a rotary encoder. The wire was extended as the roof rose, and the distance of the wire sent out was measured by the rotary encoder for conversion into the quantity of rising. The automatic operation of the jacks was controlled on the basis of data obtained through instrumentation by the rotary encoder placed at the center of gravity of the three−jack−one−pump unit (see "a" in Fig. 4).

The management items of particular importance to safety and quality assurance during the lift−up work are the jack load and the high−low differences between points of measuring the quantity of rising. These two management values were set at levels where forced deformation between lifting points push the stress of members up beyond the tolerable figure. Regarding the jack load, the relief pressure of the jacks were set at 170tf in safety measures in case the load exceeded the controllable level. As for the high−low differences between the points where the rate of rising is measured, to keep its level below that of the control value, all jacks were automatically operated with a newly−developed multi−link control system, while feeding rising rate figures back into the jack control panels. The multi−link control system is designed to perform automatic remote control of multiple points. The system is composed of a multi−link unit to monitor the operations and transfer multi−point control data, a posture control device to regulate the jacks, and a display monitor. This time, 72 rising points were controlled with the use of basic hydraulic units, each comprising of one pump and three jacks. So a total of 24 hydraulic units were automatically remote−operated using the multi−link control system.

5.2 MULTI−PURPOSE MEASURING CONTROL SYSTEM

Measuring items needed for construction management purposes were automatically installed by a PC−integrated measuring control system. This time, a multi−purpose measuring control system was used for serving the general purposes for measuring during the construction period.

This system can easily set surveying plans like measuring items, control values and the specifications of measuring instruments, interfaces, and output graphs, depending on needs for the project concerned. The system performs the required measuring based on those preset specifications and outputs results onto the screen in the form of graphs and values. The controller can proceed with operations while monitoring the progress of construction work on a real−time basis. As "*Windows*" is used as the operating system, the operator can easily alter the sizes and positions of the graphs, figures, letters and characters displayed on the screen, axis scales of each graph, control values and other specifics without interfering with the measuring operations.

5.3 SYSTEM COMPOSITION

The system composition of instrumentation is depicted in Fig. 5 and screens of PC No.1 and No.3 are shown respectively in Fig. 6. Results of the measuring are also shown, divided among the three PCs, to clearly convey information. Two video distributors were also used to transfer screen pictures to the control room so that information on the status of construction might be widely shared by the operator and all people concerned.

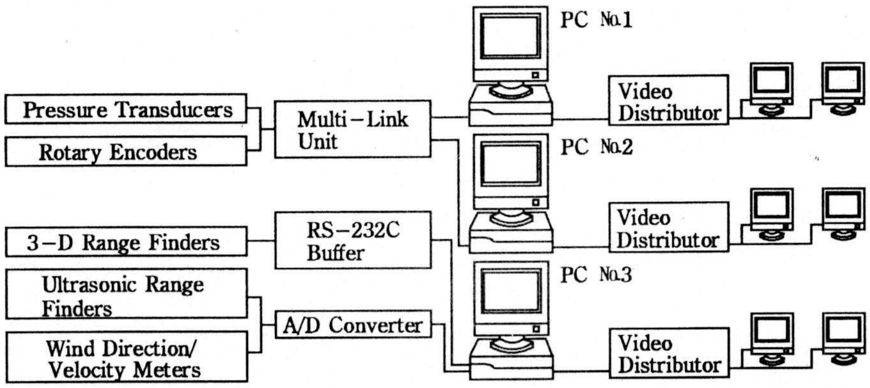
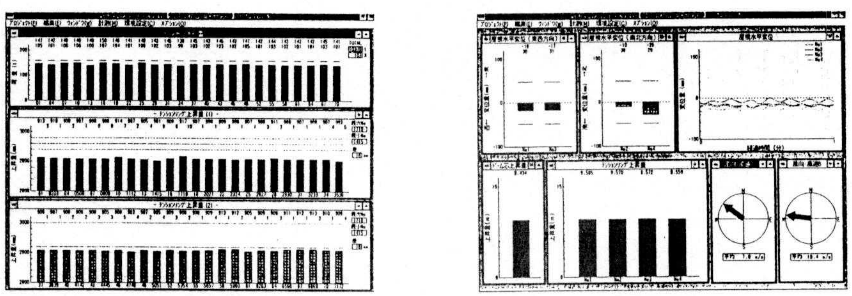


Fig. 5 System Composition



– PC No. 1 – – PC No. 3 –

Fig. 6 Screen Output

6. RESULTS OF CONSTRUCTION

6.1 LIFTING THE ROOF OFF THE GROUND

Lift-up jacks and other places were inspected and the radius-wise constraints of the tension-ring were released before a 10tf load was transferred onto the jacks. Later, measurements of deformation on the temporary platforms, the jack load, and the load transferred at a rate of 10tf per step, as the rate of rising was examined and compared with the analytical values. With the progress of load transfer,lifting the roof off the ground proceeded in the direction of the center from the tension-ring.

The jacks load totals are shown in Fig. 7. About four hours after the commencement of work, the work of lifting the roof off the ground was completed in all 291 places. The total weight of the roof stood at approximately

10,100 tons, virtually identical with the design value of 10,300 tons.

Fig. 8 lists rates of the rising when 50tf, 100tf, and 140tf loads were transferred, and when the work of lifting the roof off the ground was completed. The work of lift the roof off the ground was performed by equalizing the load on each lifting point until the load transferred reached 140tf. After that, the roof was lifted up by making sure that all lifting points kept their height equal as it was measured with a rotary encoder (see Fig. 4) for automatically controlled operations. The control values for the high−low differences between adjacent measuring points were set in the stages, at 80mm up untill the load transfer of 60tf, and at 70mm − 35mm untill the load was lowered to 70tf. No actual figures exceeded the control values during the work of lifting the roof off the ground, which proceeded as planned.

A pre−installation analysis indicated that seven temporary platforms in the center of the dome were the last pieces to be lifted the roof off the ground. Hydraulic jacks were used to measure the load of the roof on the temporary platforms. Measurements are shown in Fig. 9. It was confirmed that the load on the temporary platforms would decline as the work progressed and that the roof would leave the ground when the jack load was in the vicinity of 140tf.

Fig. 10 shows measurements of the radius−wise horizontal displacement of the tension−ring. The tension−ring extended approximately 50mm after the roof was lifted the roof off the ground, practically the same as with the pre−planned estimate. It is also shown that in the last step after the work of lifting the roof off the ground was completed, the tension−ring moved approximately 7mm in a northward (+ direction).

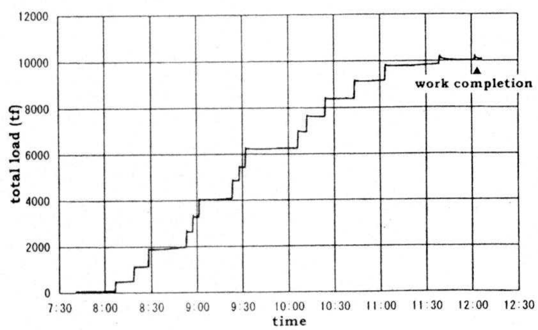


Fig. 7 Jack Load Totals

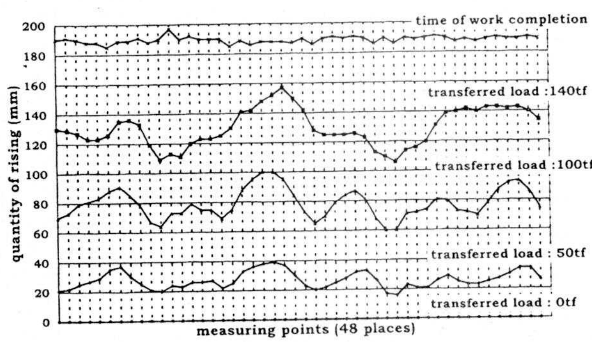


Fig. 8 Quantity of Rising at Measuring Points

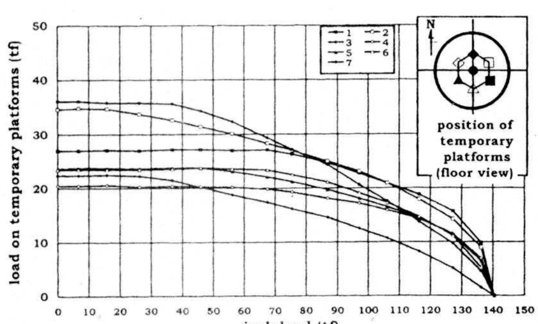


Fig. 9 Load on Temporary Platforms − 7 places in the center −

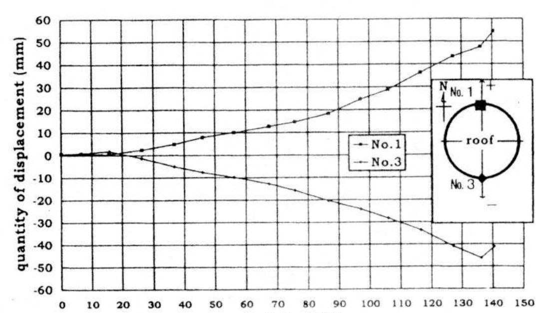


Fig. 10 Tension− Ring Wise Horizontal Displacement

6.2 LIFT-UP

Photo. 6 shows the status of the lift-up work, while Figs. 11 and 12 show the quantity of rising for the first day and the second day. A lift-up of 22m took approximately 13 hours. The lift-up work proceeded successfully as initially planned. The dome roof continued to rise at a fixed rate by the continuous automatic operations of the jacks. The rate of rising was calculated at 1.7m/h, including the adjustment time.

Photo. 6 Status of Lift-Up Work (by courtesy of the Chunichi Shimbun)

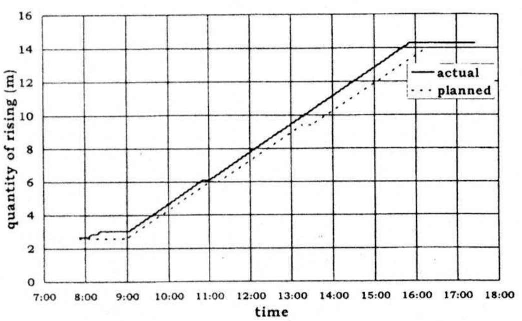


Fig. 11 Quantity of Rising (first day)

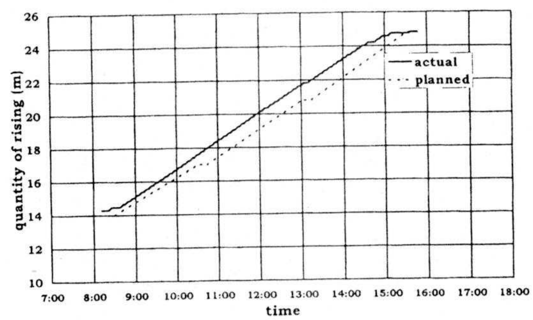


Fig. 12 Quantity of Rising (second day)

Shown in Fig. 13 are trends in the highest and lowest part of the jack's load. With the progress of the lift-up, the highest-lowest differences expanded, but never exceeded the control level. The lifting margin of the PC steel stranded cables holding the roof became shorter, gradually constraining the roof. A load fluctuation resulting from a slight deformation of the tension-ring and a little vacillation of the roof came to produce a greater effect on the reaction of the PC steel-stranded cables. As a consequence, the jack load widely varied, producing greater differences between the maximum and minimum.

With regard to the quantity of rising, Fig. 14 shows the maximum values of the high-low differences between the point of measurement and its immediate neighboring point, while Fig. 15 lists the maximum high-low differences among all the points of measurement. Because the jacks were automatically operated in such a way as to keep all the high-low differences below the control levels, the lift-up work was always conducted within the control values.

Fig. 16 shows the horizontal displacement of the roof during its lift-up and the 10-minutes average wind velocity. The + side of horizontal displacement is eastward, while the – side is westward. A northwestly wind was blowing while the life-up work was under way, thus the results of measurements signified that the roof gradually displaced slightly westward, from the beginning of the commencement of the lift-up. The horizontal displacement was obtained by calculating the clearance between the shock absorber installed on the tension–ring and the H–section guide rail.This was likely a cause to be sought from a slightly tilting of the guide rail of the measuring points. The wind velocity was high in the vicinity of the average rising rate at 9–11m and correspondingly the roof shook 10–15mm. This proued to be two or three times more than at other times, evidence that it was under an actual wind load.

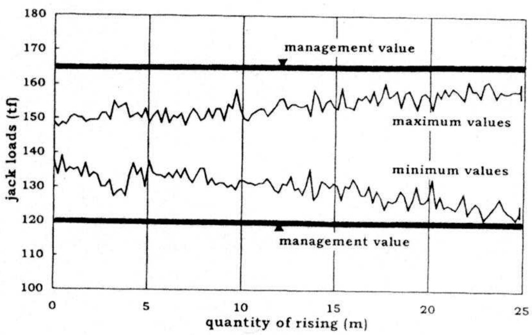


Fig. 13 Maximum and Minimum Values of Jacks Load

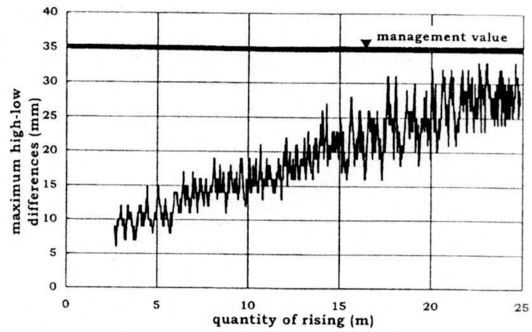


Fig. 14 Maximum High–Low Differences between Adjacent Measuring Points

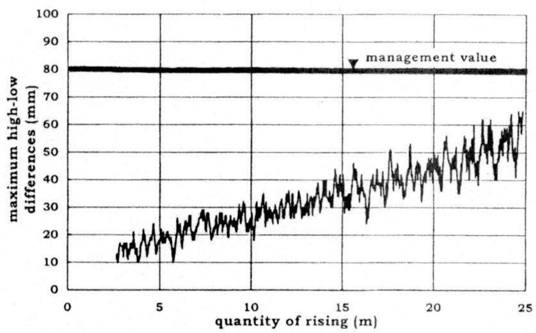


Fig. 15 Maximum High–Low Differences of All Measuring Points

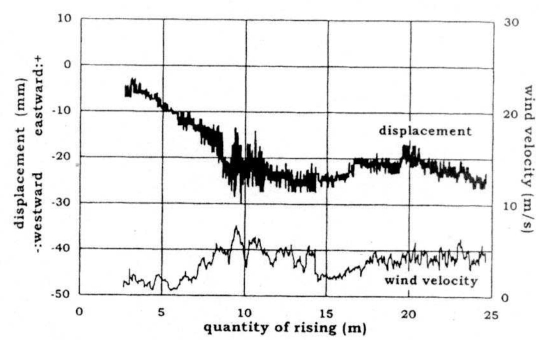


Fig. 16 Horizontal Displacement of the Roof and 10–Minutes Average Wind Velocity

7. CONCLUSION

Set forth are the results derived from the lift–up construction of a large–scale dome roof.

① The period of construction was shortened by approximately six months as a whole, as compared with the conventional method of erecting the proposed roof iron framework at the prescribed height from the outer circumference.

② The multi–link control system made it possible to automatically run each of the jacks within it's control value.

③ Instrumentation during the lift–up work helped to secure the safety of the construction project and its quality.

The first large–scale lift–up project of the sort in the construction field was able to carried out successfully. Our hope is to consolidate this existing technological knowhow and also the expertise developed during this time and to see it further expanded for other such projects.