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Erection Methods for Space Structures

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Abstract
TOMOE Corporation has constructed more than five thousand space structures since 1932, employing many kinds of erection methods. They are not only popular ones, such as element method and block method, but also a number of unique ones, such as move-scaffold method, sliding method, lift-up method. In this paper, the erection methods employed during the early period of TOMOE Corporation will be firstly reviewed, and then some past examples of particular erection methods will be introduced. Also, important considerations for the erection methods will be discussed.

Keywords: space structure, erection method, element method, block method, move-scaffold method, sliding method, lift-up method, control deformation of roof, computer analysis for erection

1. Intoroduction
TOMOE Corporation is a general construction company that has been fabricating steelworks, such as steel frames, steel towers, steel bridges and space structures for more than 90 years since its foundation in 1917. TOMOE started fabricating steel space structures as its major products in 1932. The first structural system is Diamond Truss, which was designed and developed by Ichiro Nozawa, the founder of TOMOE. An element of Diamond Truss is generally composed of a number of unit members. During the early period, each element was less than 300kg and it was erected without using any temporary supports and scaffolding, Photo 1 and Photo 2. As the erection process went on, the members constituted a stable structure, and other members was able to be added to the structure. Neither any temporary supports nor any scaffolding were required. This non-scaffold method is not employed nowadays since the safety of the erection is more strictly concerned.

Photo 1: Diamond Truss under erection, from 'SINKENTIKU' (1936)

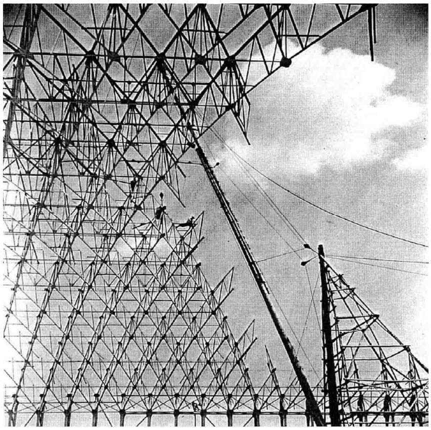

Photo 2: Non-scaffold method, 60m spanned hanger (1941)

Since 1932, TOMOE has constructed more than five thousand space structures, using our own structural systems: Diamond Truss, Diamond Shell, Tomoe Uni-truss and H Diamond Shell. These structural systems are formed of a large number of steel members, each of which length is short enough to be transferred from manufactories to construction sites and they are assembled into large structures. An erection method is chosen for a particular structure, considering several matters as follows: characteristics of the structure, time schedule of the construction, safety, cost, reliability of the method and many other factors. Not only popular erection method, such as element method and block method using scaffold or temporary supports, but also a number of unique erection methods were chosen and developed, such as move-scaffold method, sliding method and lift-up method.

2. Element erection method and block erection method

The popular erection methods for space structures are element method and block method. The element method is the erection wherein single-unit members are individually assembled. On the other hand, the block method is the erection wherein sub-assemblies, which are relatively large and called blocks, are initially assembled at the lower level near the ground. These elements and blocks are connected together at the designed position by a crane, using scaffold or temporary supports.

Tatsumi Indoor Swimming Pool has the maximum span of 100m and the maximum height of 36.5m, and covers a large area about 12,400m^2. Tomoe Uni-truss was adopted for this large-spanned roof structure. The element method was adopted for the erection because the shape of the roof was complicated. The roof structure was assembled with being supported by scaffold (full-scaffold) at all the joints of the elements, Photo 3.

Sky-Hall Toyota was constructed as a Toyota-city general gymnasium, measuring 81.4m in the short span direction, 125.5m in the long span direction. This roof structure consists of steel pipes for the main frames (keel-arches and tension-rings) and Tomoe Uni-truss for the connecting trusses between the main frames. The roof structure was assembled on temporary supports. The block method was adopted for the erection of Tomoe Uni-truss to minimize the temporary supports and the volume of scaffold, Photo 4.

Shiga Pref. Nagahama Dome has a pseudo elliptical plan that is defined by a number of arcs, measuring 107.5m in the short span direction, 162.5m in the long span direction, and 32.2m in the height. Diamond Truss was adopted for the structure. This roof structure was erected by the block method because a large number of members, about 36,000, were used for the structure. Each block of the roof was assembled together using temporary supports to minimize the volume of scaffold, Photo 5.

Chuo University Gymnasium has a rectangular plan, measuring 57.6m in the short span direction, 121.5m in the long span direction. This roof structure consists of a number of keel trusses on RC columns and the other parts of Diamond Truss, which bridge the space between the keel trusses. The block method was adopted for the erection of the keel trusses. They were assembled on the ground and were hang up by two cranes, without using temporary supports, Figure 1.

Photo 3: Element erection method, using full-scaffold, Tatsumi Swimming Pool (1993)

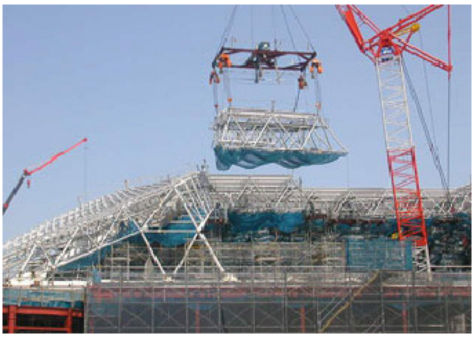

Photo 4: Block erection method, using temporary supports, Sky-Hall Toyota (2006)

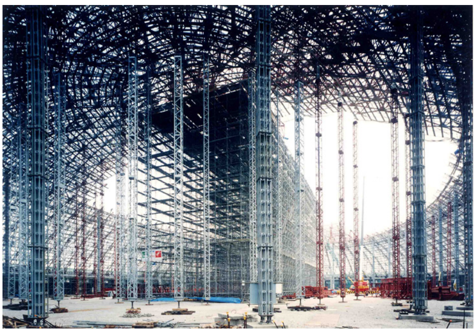

Photo 5: Block erection method, using temporary supports, Shiga Pref. Nagahama Dome (1991)

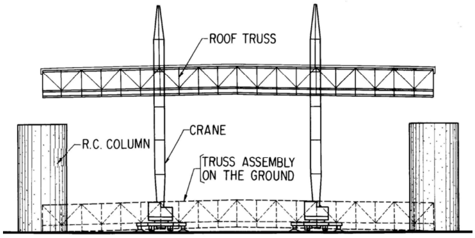

Figure 1: Block erection method for keel trusses, using RC columns, Chuo University Gymnasium (1991)

3. Move-scaffold method

Move-scaffold method is the erection for roof structures using the moveable scaffold, which is normally equipped with a number of wheels and motors to travel on rails. This erection method can minimize the amount of scaffold effectively, especially for a large roof structure.

Koriyama Wholesale Market has two large buildings. They have rectangular plans, that is, one has 67.5m span and 210m length, and the other has 59.5m span and 201m length. Tomoe Uni-truss was adopted for theses large roof structures that are slightly curved in the short span direction. The moveable scaffold and temporary supports were used for the erection, Figure 2 and Photo 6. The size of the moveable scaffolds and the location of the temporary supports were decided through many studies, including computer analysis of the structures under the erection.

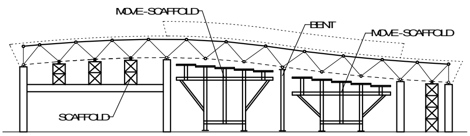

Figure 2: Move-scaffold method, Koriyama Wholesale Market (1999)


Photo 6: Move-scaffold method, Koriyama Wholesale Market (1999)

4.Sliding method

Sliding method is the erection wherein a roof structure is partly assembled on a temporary stage and is sequentially slid. The roof structure is slid on the rails that are settled along the perimeter beams or on temporary supports by using a number of oil jacks or winches. This method requires a large number of studies, including computer simulations of the process. Also, the structure is needed to be manufactures under proper supervision in terms of accuracy and the sliding work is demanded to be controlled suitably. Reinforcement of the structure may be required in some cases.

4.1. Sliding method for flat roofs

Fujikura Futtsu Factory has an almost flat roof with a radius of curvature of about 671m, measuring 360m in the ridge direction, 80m (40m x 2) in the span, covering a total floor area of 24,000m^2. Tomoe Uni-truss was adopted for this roof structure. The standard grid of the space structure is 5m by 5m, the truss depth is 3.5m, and the eaves height is 21.23m. The sliding method was adopted for the erection of the roof structure, because the shape of the roof is suitable for the method, that is, the sectional shape in the span direction is almost flat and it remains the same in the long direction, Figure 3. The truss and secondary members were assembled on the stage which was installed between line 0 to line 4 (40m). This stage facilitated the site works considerably and made the safety improved. The painter's work, roof finishing and electrical equipment work were also completed on the stage. The roof after necessary operations on the stage was pulled by wires in the ridge direction from line 0 to line 22.

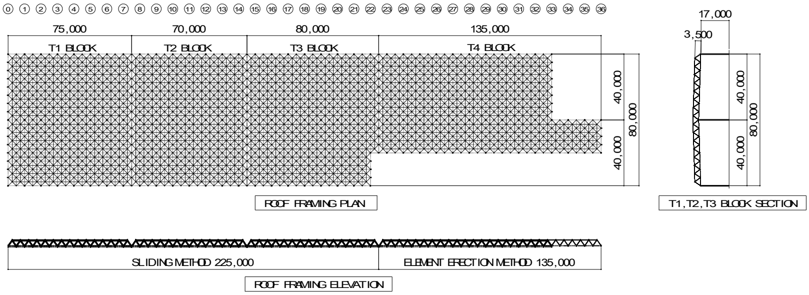

Figure 3: Slideing method, Fujikura Futtsu Factory (1991)

4.2. Sliding method with temporary cables

Indoor Swimming Pool of Mie Pref. Suzuka Sports Garden has a main pool and a sub pool. The two buildings for the pools have rectangular plans, that is, the one for the main pool has 55.5m span and 102.2m length, and the one for the sub pool has 40m span and 37m length. The both of the roofs are composed of a cylindrical part and a flat part. Tomoe Uni-truss was used for the two roof structures. The sliding method was adopted for their erections because the pool works could be carried out even under the erection of the roof, and therefore the construction period was shortened. The truss and secondary members were assembled on the stage and painter's work, roof finishing and electrical equipment work were also completed on the stage outside of the buildings. The roofs were pulled by wires in the ridge direction. During the erection and the slide, a number of temporary cables were used to control the deformation of the roofs, Figure 4 and Photo 7. The cables were made of carbon fiber and the rails settled for the slide were made of ultra high molecular weight polyethylene. The truss members and temporary materials, such as supports and cables, were designed, considering the both of the erection and the design loads. A number of members were sized up as the results of many studies, including computer analysis.

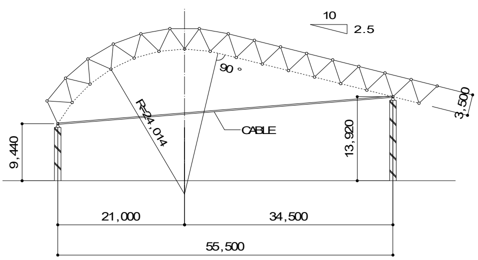

Figure 4: Sliding method with temporary cables, Suzuka Swimming Pool (1996)

Photo 7: Sliding method with temporary cables, Suzuka Swimming Pool (1996)

4.3. SWORD method

SWORD (Slide-Work Over a Railway and Down) method is the erection, that has been developed for erecting railroad buildings safely and efficiently. Generally speaking, the construction of a railroad building must be operated in the midnight so that the train traveling will not be affected. Nevertheless, such an operation involves a number of difficulties: restricted time schedule, risk of accident and so on. To avoid these in the method, the building concerned is erected on a stage adjoining to the railways in the daytime and is to be slid to the space over the railways in the midnight. The rigidity of the building is increased so that the building can travel on a number of pre-erected columns, therefore, temporary girders or launching girders are not required, Figure 5. During the slide operation, the level of the building is being controlled by the oil jacks settled vertically at the columns whilst it is being slid by the horizontal oil jacks settled behind the building. When the building is slid away, the stage will be available for erecting the next sequential building and the following slide operation can be continued. After the building reaches the designed position, its lowest girders and floors are suspended from the upper girders by other oil jacks, and then they are lifted down to the designed level.

Tachikawa Station was reformed by adopting the SWORD method, Photo 8. In this case, five sliding operations were carried out and the total sliding distance was more than 60m.

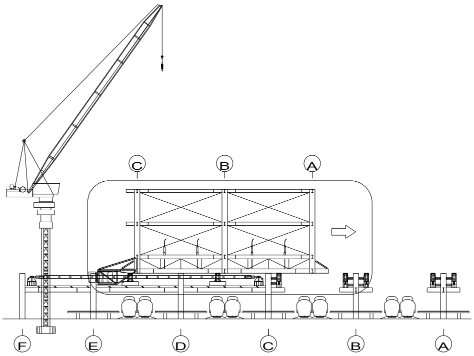

Figure 5: SWORD (Slide-Work Over a Railway and Down) method


Photo 8: SWORD method, Tachikawa Station Reform (2006)

5.Lift-up method

Lift-up method is the erection wherein a roof structure is assembled at lower level and is lifted up to designed level. The assembled structure is normally lifted up by a number of oil jacks or winches that are settled on columns or temporary supports to take the reactions. This method requires a large number of studies, including computer simulations of the process, as well as the sliding method. Also, the accuracy of the structure and the proper control of the lift-up method are necessary. Reinforcement of the structure may be required in some cases.

5.1. Lift-up method

Skylight roof of Ishikawa Pref. Administration Office was designed to have a high open ceiling space from the fifth floor to the roof level. The skylight roof was settled at the twentieth floor, of which level is 82.5m from the ground, measuring 28.8m by 17.2m. Tomoe Uni-truss was adopted for the roof and the lift-up method was chosen. The roof was assembled at the level of the fifth floor, which was 19.1m from the ground. After the roof finishing work was completed, the roof was lifted up by using wires and double-winches, which made it possible to lift up the roof in the distance of 65.5m in a day, Figure 6.

Fantasy Dome was designed as a leisure facility. The roof of the facility is virtually flat, measuring 76.05m by 92.95m, and has about 43m height from the ground. Diamond truss was adopted for this roof structure and Tomoe Uni-truss was used for the central part of the roof. This part was a skylight of about 928m^2, through which natural light came in. The lift-up method was adopted for the erection of the structure because it had a large area and was located at a high position. To raise the roof, six temporary supports were erected inside the roof, and two centre-haul jacks were installed at each support. The position of the each support had been determined by considering the deformation of the roof under the lift-up operation so that the roof could be connected to the side columns easily, Figure 7.

East Exhibition Hall of Tokyo Big Sight has six roofs, measuring 90m by 90m. Each roof has a number of keel trusses, and Tomoe Uni-truss was used for the roof to bridge them. The lift-up method was adopted for the erection of the roofs. To raise each roof, eight truss supports, which were composed of permanent structures and temporary supports, were firstly erected on the side of the roof. Also, oil jacks were installed; two for each column of the corner and four for the each center of the outside truss beam. The roof structure was assembled on the ground and its finishing work was sequentially completed. After these, the roof, weighted about 2000tf, was lifted up by the jacks, Photo 9.

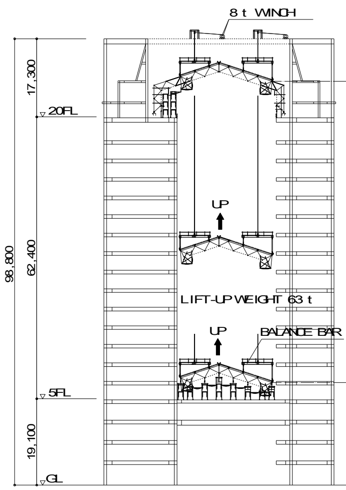

Figure 6: Lift-up method, Sky light of Ishikawa Pref. Administration Office (2002)

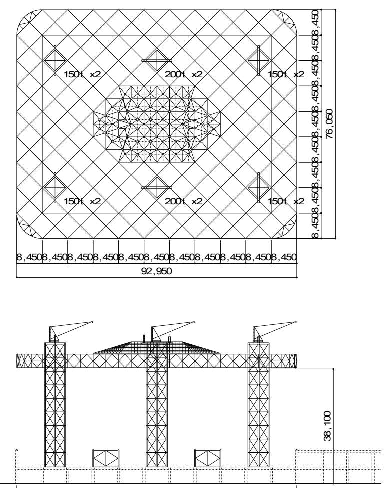

Figure 7: Lift-up method, Fantasy Dome (1990)

Koyagi Workshop Transfer Shed, which was constructed in Nagasaki Shipyard of Mitsubishi Heavy Industries Co., Ltd. consisted of two portal frames and a flat roof, measuring 106.1m in the span, 45m in the length and 48.3m in the height. Diamond Truss was adopted for the roof structure and the lift-up method was chosen for the erection. The two sidewalls and the roof were assembled on the ground. They were lifted up by the goliath crane that had been equipped in the dockyard of the site. This erection method can be categorized as the block method in a broad sense, Figure 8.

French Pavilions constructed for Osaka Expo. '70 consisted of four spherical domes of different sizes. Diamond Shell was adopted for the domes and the lift-up method was chosen. To raise a dome, a temporary tower was erected at the centre of the dome, being supported by anchor cables. Then, the dome was gradually lifted up by using winches and cables. During the operation, the lower elements were added sequentially, Figure 9.

Concourse of Tama-Plaza Station has a large rectangular roof with gentle curvature, measuring about 43m by 96m. This structure has a large sidewall suspended from the longer side of the roof. Tomoe Uni-truss was adopted for the roof and the lift-up method was chosen to minimize temporary supports and scaffold. The roof assembled by the element method were being hung by 16 wires, that is, eight hanging points were linked to the two side frames of the structure and eight hanging points were linked to the central columns. The roof was lifted up in the distance of about 12m and it spent two and half hours in the midnight, whilst general customers were kept away from the station. After the operation, the roof lifted up was connected to the upper frames, Figure 10.

Photo 9: Lift-up method, East Exhibition Hall of Tokyo Big Sight (1994)

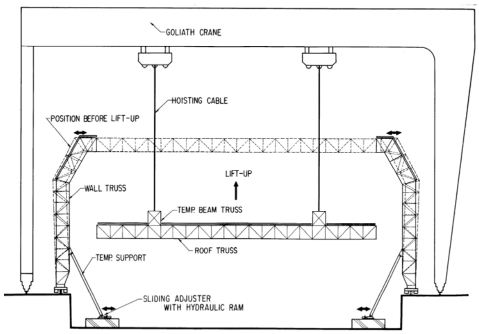

Figure 8: Lift-up method, Koyagi Workshop Transfer Shed (1972)

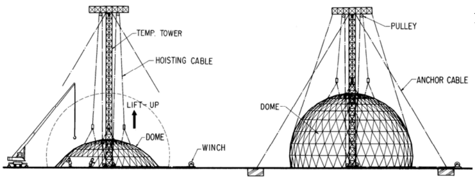

Figure 9: Lift-up method, French Pavilion For Osaka Expo. '70 (1970)

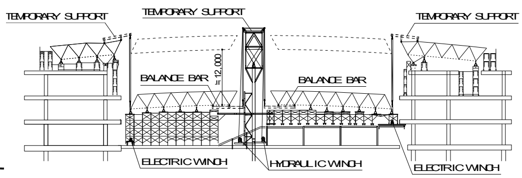

Figure 10: Lift-up method, Concourse of Tama-Plaza Station (2009)

5.2. Lift-up method with temporary wires

Air Nippon Airways, Osaka Overhaul Hangar has a mansard configuration roof, measuring 100m in the span, 80m in the ridge direction. Diamond Truss was adopted for the roof structure. The lift-up method was adopted for the erection because this structure located by runways, and then not only the height of structure but also those of cranes were strictly limited by the aviation code. The roof under the lift-up operation had not been stable, for this reason, temporary wires were set up between the both edges of the structure. These wires were pulled by winches, and then the deformation of roof could be controlled. To raise the roof, 22 temporary masts were installed at the top of the columns, and center-haul jacks were installed, Figure 11 and Photo 10. The lift-up method of the erection was operated after many studies, including computer analysis. The resultant sizes of the structural members were determined by considering the erection and the design loads.

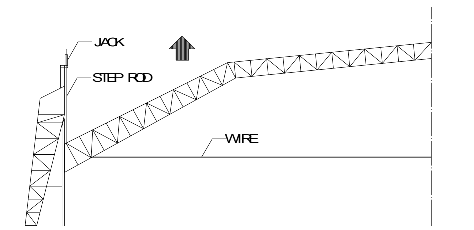

Figure 11: Lift-up method with temporary wires, ANA Osaka Overhaul Hangar (1987)

Photo 10: Lift-up method with temporary wires, ANA Osaka Overhaul Hangar (1987)

5.3. Lift-up method with temporary wires and a ring

Nagano Olympic Winter Games, Figure Skating Place (White Rink) is a shell structure, of which configuration is a dome of 92m by 104m. The maximum height of the dome is 39.5m, and the depth of the truss is 1.0m. The lift-up method was adopted for the structure in order to reduce temporary materials and shorten the construction period. Also, the quality of the roof and the safety of the site work were considered to be improved by the method. To operate the erection method, the roof was separated from the side structure, and a temporary tension ring was settled to avoid the outward deformation of the lifted roof. Before starting the lift-up operation, a number of wires were installed in a radical pattern between the tension ring and the perimeter of the roof. Tensile stresses were installed into the wires by using winches in order to control the deformation of the roof. The roof was lifted up by oil jacks, which were settled on 12 temporary supports located around the roof, Figure 12 and Photo 11. A large number of studies were carried out, such as computer analysis of the operation to investigate the structural behavior of the roof.

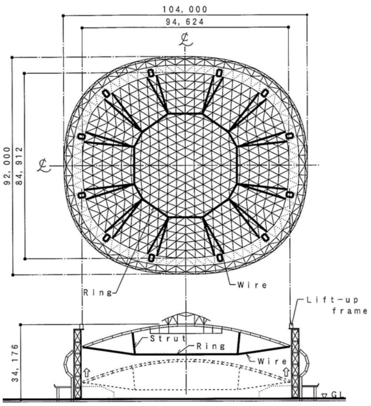

Figure 12: Lift-up method with temporary wires and a ring, White Rink (1995)

Photo 11: Lift-up method with temporary wires and a ring, White Rink (1995)

5.3. Jack-up turn method

Sukumo Viaduct crosses a steep valley. This viaduct is a four-span continuous steel twin-girder bridge with pre-stressed concrete slab, having the maximum span of 85m. The jack-up turn method was adopted for the erection. This method has been developed to erect the steel bridges over deep valleys wherein normal erection methods are difficult to operate. The jack-up turn method is the erection wherein the girders are erected upward along the pier of the bridge by using specific machines with jacks. After the jack-up operation, the mechanical hinges at the top of the pier became effective and the girders were rotated with controlling stresses of the wires settled at the both edges. The jack-up turn method was operated for three piers of the Sukumo viaduct wherein the maximum length of the girders was 113m and the weight of the girder was 430tf, Figure 13 and Photo 12. A large number of studies were carried out, including computer analysis. Also, experiments on the execution of the method were carried out, using a third scale mockup.

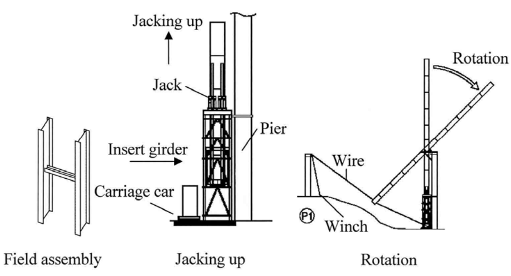

Figure 13: Jack-up turn method, Sukumo Viaduct (1999)

Photo 12: Jack-up turn method, Sukumo Viaduct (1999)

6.Jack-down

If a jack-down is inappropriately operated, it may damage the roof structure, temporary materials or its base structure. Even if any damages do not exist, residual stress or unexpected deformation, which is not expected in the designing period, may remain or happen. For this reason, sufficient studies are necessary for jack-down, especially when tension members are installed to the structure.

6.1. Jack-down with tie-beam

Okayama Dome, which is an all-weather multipurpose dome, has a plan of 114m by 95m, and its maximum height is 37.8m. Membrane is adopted for the roof and orthogonal two-way grid is used for the roof structure. A side of the dome is vertical and an arch keel truss supports the roof. During the erection, a number of temporary supports were used under the roof and a tie-beam was installed between the edges of the arch keel truss. Seven jack-downs were sequentially operated from the round side of the roof to the vertical one, as seen in Figure 15 and Photo 13. The jack-down of the arch keel truss and the tensioning of the tie-beam were alternately operated, not to let the keel truss deform large. The safety of the dome and the temporary materials was studied by computer simulation. The sizes of the structural members were determined by considering the erection and the design loads.

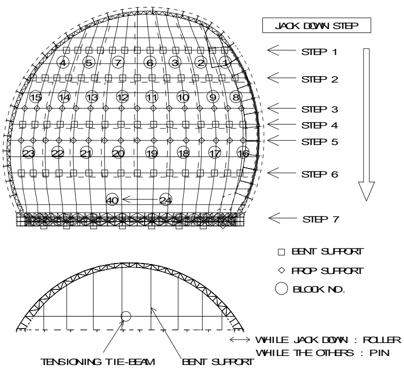

Figure 15: Jack-down with tie-beam, Okayama Dome (2002)

Photo 13: Jack-down with tie-beam, Okayama Dome (2002)

6.2. Jack-up and down method

Yamaguchi Kirara Sports Park Multipurpose Dome has a diameter of 157m. The system adopted for the dome is the tensegric structure, which is composed of Tomoe Uni-truss and high strength steel rods. A grid of the dome is about 4m by 4m and a block consisting of 4 by 4 grids was stabilized by tensioning the rods. This dome was supported by 38 base isolation bearings, each of which had a number of jacks to operate the jack-up and down method. The dome was firstly erected on temporary supports, and then the whole structure, which weighted 2146tf, was jacked up to stand itself. After this, the temporary supports were removed and then the structure was jacked down, Figure 16 and Photo 14.

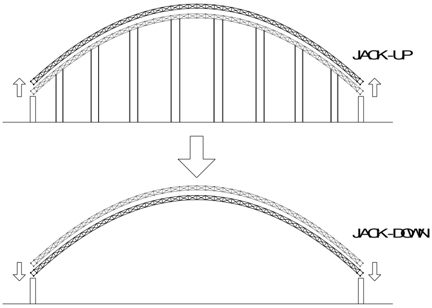

Figure 16: Jack-up and down method, Yamaguchi Dome (2000)

Photo 14: Jacks around a lead rubber bearing, Yamaguchi Dome (2000)

7. Remarks

Space structures have been structurally variegated and complicated. Also, tougher conditions are likely to be set in their designing and constructions these days, that is, restrictions of site, construction period, cost etc. Therefore, well-planed execution schemes, including computer simulations, are getting more important, and much collaboration between design engineers and site engineers is indispensable. A large number of new attempts for space structures will contribute to the progress of site engineering in the future.

Acknowledgement

Regarding the erections of the structures that TOMOE Corporation has been involved, we are grateful to have accomplished these structures. We would like to express our sincere gratitude to the owners, the architects, the supervisors, the contractors and the other people concerned.

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