Erection of Steel Roof Structure of GwangMyeong Velodrome

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ABSTRACT

GwangMyeong velodrome is the largest dome structure ever built in S. Korea. Since the roof structure of the velodrome was designed as support-free large space, the construction of the roof structure was the biggest issue during the entire construction process. This paper briefly introduces the lifting method of construction of the roof structure. Analytical results for the deflections and stresses of the roof structure are compared with measured data. Also explained are the monitoring methods for assuring safety requirements during construction of the roof structure.

KEYWORDS: Erection, Lifting, Jack- Down, Monitoring

INTRODUCTION

GwangMyeong velodrome(See Table 1 and Figure 1) is the largest dome structure ever built in South Korea. Since the roof structure of the velodrome was designed as a large support-free steel space truss which spans 180m in the longer direction and 132m in the shorter direction, erection of the roof structure was the biggest issue during the entire construction process. Conventional erection method using cranes had some unavoidable problems: Traveling tower crane could not be used since high-voltage lines were passing through within the working area of the tower crane. Storage area for PC members was unaffordable due to delayed dismantlement of the underground obstacles. Furthermore, the Compression Ring could not be installed by crawler crane neither within the construction site due to the existence of the inner supporting frame nor from outside of the site due to the limited arm length of the crane.

After considering several alternative construction methods, it was decided that part of the roof structure called Inner Roof weighing about 630 tons was first assembled on the ground and lifted to 50m above the ground. After the 1,645 ton remaining parts of the roof structure were assembled by cranes, the entire roof structure was jacked down to the final position. Analyses of the applied loads and the induced deformation were executed at every step of the erection process and the results were reflected on the design and manufacturing of the temporary structures. Real time monitoring of the deformations and strains was also carried out to ensure the structural safety during the erection process. In conclusion, the overall construction work above the ground was performed safely and successfully by adopting proper erection method for the large-space structure. The entire roof structure finally stood alone after removing the support towers that has been supporting the Inner Roof.

OUTLINE OF ERECTION

Outline of Roof Structure

Figure 2 shows the structural components and overall dimensions of the roof structure. Compression Ring (CR) and Inner Grid (IG) are called together as Inner Roof (IR) which are located at the center of the roof structure and resist to compression forces. Tension Ring (TR) forms the outer edge of the roof structure and resists to the deformation in the outward direction and circumferential tension forces. Flow Trusses (FT) connect TR and CR, and FTs are interwoven by Flow Shell (FS). There are also 60 Supporting Stubs (SS) which sit on Rubber Pads (RP) under TR and carry the weight of the roof structure to the concrete stand. RPs are free to deform in the direction of the FTs but are nearly restrained in the circumferential direction. They are also designed to absorb the deformations due to various loads and temperature variations. Roof panels are assumed to be installed after the erection of the roof structure is completed and, hence, the deformation due to the roof panels is designed to be absorbed by RPs.

Weight of Each Structural Component

The weight of each structural components were tabulated in Table 1 and 2.

ERECTION PROCEDURE

The IR is assembled on the ground. The CR is first set up on pedestals and then the IG is assembled inside the CR. The pedestals will be lifted up later together with the IR and bolted on top of Support Tower (ST). Six Jacking Towers (JT) are assembled along the perimeter of the CR. Since oil jacks for lifting 600 tons of IR are installed on top of each JT, the JTs should be built with strict inspection of member verticality and tightness of bolts. The tolerance of the verticality of tower is limited to ±20 mm and every bolt is inspected for its torque value(See Figure 3).

Assembled IR is elevated up to the designed height using the six JTs and the oil jacks. The verticality and stresses of steel members of the JTs and settlement of foundations of the JTs are inspected. Lifting speed equals roughly to 4 to 6 m/hr. Ten STs are installed under the IR to support it. Inspection for verticality is very important since the towers should be aligned with pedestals which were already lifted up with the IR. Construction time for the STs was greatly reduced by prefabricating the tower segments and simply stacking and assembling them using a crane at the site(See Figure 4).

The IR is set on top of the assembled STs. Supervision of the coordinates of the IR and the verticality of the JTs and the STs are strictly required for locating the IR at the expected position. The TR is installed on top of the concrete stand and the preassembled FTs are installed between the TR and the CR. Each FT is lifted up at four points using a 400 ton crane. Difficulties in installing the FTs were anticipated due to misalignments and fabrication errors in assembling the FTs, but margin of error was not so great as to influence the installation(See Figure 5).

The roof structure is completed as the FSs are installed between the FTs. Jack-Down (JD) of the IR is conducted until the entire roof structure stands alone(See Table 6). Adjustment of the 60 SSs are carried out one by one. Whole construction sequence for the roof structure is finished when the STs are dismantled after the JD. Roof deflections were measured during the JD procedure and values of the deflections are well in agreement with those of the analysis (See Table 8).

STRESS AND DEFORMATION ANALYSES AT EACH CONSTRUCTION STEP

Stress Analysis

The roof structure at each construction step is modeled by FEA software called LUSAS. Figure 7(a) shows the analysis model of the IR lifted at six points. Vertical members of the CR at support region are found to have the maximum stresses, of which values are 1.07 tf/cm^2 and 0.17 tf/cm^2 for axial and flexural stress, respectively.

Second model simulates the state of the IR when it is lifted and installed on top of the ten STs. The analysis model with the location of the ten STs is shown in Figure 7(b). The maximum stresses are developed in the lower horizontal members of the CR at support region. Axial stress is 1.41 tf/cm^2 and flexural stress is 0.73 tf/cm^2.

The entire roof structure including the TR, the FTs, and the FSs is modeled when the JD procedure is conducted. Figure 7(c) shows the analysis model as well as the ten STs and support reactions around TR. The lower horizontal members of the CR again show the maximum stresses, which equal 1.53 tf/cm^2 and 0.52 tf/cm^2 for axial and flexural stress, respectively.

Load and Deformation Analysis

Applied Load at IR Lifting

Predicted values of loads on the JTs at the time of the IR lifting are compared to the measured values. Figures in

Table **4** show the predicted and the measured values of loads on each JT and their total amounts. The loads include weights of auxiliary hardware, support frames, and saddles. The measured values are in good agreement with the predicted values within 2.3% of margin and the overall distribution of loads seems to be well balanced.

Deflection at IR Lifting

The deflections at IR Lifting were tabulated Table 5.

Horizontal Displacement of JTs at IR Lifting

The horizontal displacements of JTs at IR Lifting were tabulated in Table 6.

Applied Load at JD of roof structure

Most of the measured values of loads on the STs and their total amounts are slightly greater than the predicted(See Table 7). The JD was performed sequentially at two STs for effective utilization of equipments and the restraining actions from the remaining STs induced increase in measured loads. Simultaneous JD at all STs would have produced close simulation of the predicted loads.

Deflection at JD

There is little difference between predicted and measured deflections of the roof structure at each ST(See Table 8). The greatest difference occurred at ST #4 where the measured values exceed the predicted by 54 mm, which is equivalent to a ratio of 1/2375 of the longer roof span. Considering that the ordinary requirement for the deflection of building structure is 1/240 ~ 1/360, above value is the tenth of the code provisions and can be regarded as negligible. Deflections at center of the IR (Towers #1 and 4) are greater than the expected but deflections at ends of the IR (Tower #7, 8, 9, and 10) are smaller than the expected. Connections between the FTs and the FSs had to be reinforced since some eccentricities had developed due to construction errors in installing the FSs. Relatively small deflections at the ends of the IR can be ascribed to the increased stiffness of these connections, which are more densely distributed at the ends of the IR than at the center of the IR.

Radial displacement of Elastic Pad at Jack-Down

The measured values of the horizontal displacement of the Elastic Pads at Jack-Down were smaller than their predicted counterparts(See Table 9). It is assumed that connection reinforcement of FSs reduced the radial component of the displacement.

Installation of Sole Plate

Preliminary structural design was carried out without considering the possibility of the elastic pads being influenced by the roof dead load. Therefore, positions of elastic pads were relocated to adjust their displacement after the completion of the roof structure. Eccentricity was caused between column and the lower chord of the TR as shown in Figure 9(a). In original design, the eccentricity was intended to be absorbed by the column and the lower chord of the TR. However, this method was not realized due to the difficulty in making the different curvature of the upper part of each column. The Sole Plates were introduced instead to simultaneously resist to the stresses caused by the eccentricity and maintain the horizontal upper part of the columns (see Figure 9(b)). They also contribute to the punching capacity of the connection between column and the lower chord of the TR

MONITORING

Objective of Monitoring

The behavioral properties of the main structural members and foundations of the JTs are monitored and checked in real time for their structural safety at every construction stage.

Outline of Monitoring

Monitoring items are selected considering the safety and economical efficiency of the construction. Also considered are structural behaviors of the target structure, general purpose of the monitoring system, and methods of monitoring and supervision. Principal monitoring items are explained as follows:

Stresses in Structural Members

Some representative sections of the structure are selected to monitor variations of member stresses. Since the behavior of the whole roof structure can be understood by checking the stresses in major structural members, safety provisions are ensured in constructing a large-space structure.

Settlement of Temporary Structures

Differential settlement of the foundations of the JTs should be prevented if the applied loads on the JTs at the time of the IR lifting are to be properly transferred to the ground without any structural damage to the entire structure. The settlement of the foundations of the JTs is monitored in real time at the time of the IR lifting.

Details of Sensors

Quantities of sensors and their detailed descriptions are presented in Table 10.

Configuration of Monitoring System

Strain gauges installed at the roof truss members and tilt meter installed at lifting towers are connected to real time data logger (CR-10X). The collected data are transferred through cables to the temporary monitoring room where the stress variations of members and settlement of tower foundations are automatically observed(See Figure 10 and Table 11).

CONCLUSION

Overall construction procedure from the Inner Roof assemblage to the Jack-Down of the roof structure was satisfactorily carried out as planned. In addition, measured values of loads and deformations were well in agreement with the predicted values.
The strains of roof truss members were monitored in real time from the IR lifting to the completion of the Jack-Down. Each strain value was less than two thirds of the yield strain, i.e., 1100$\mu\varepsilon$, and in accordance with the analytical value. It is, therefore, expected that

there has been no excessive stress in the roof members during the construction period and the entire roof structure is able to support itself after the Jack-Down procedure.

The measured values are in good agreement with the predicted values within 2.3% of margin in applied loads and 2.2% of margin in deflection at Inner Roof lifting.

Most of the measured values of loads on the Support Towers and their total amounts are slightly greater than the predicted. The Jack-Down was performed sequentially at two Support Towers for effective utilization of equipments and the restraining actions from the remaining Support Towers induced increase in measured loads. The measured values of the horizontal displacement of the elastic pads at Jack-Down were smaller than their predicted counterparts. It is assumed that connection reinforcement of Flow Shells reduced the radial component of the displacement.

The overall construction work above the ground was performed safely and successfully by adopting proper erection method for the large-space structure.

Following items were given due considerations when selecting and applying the lifting method.

1) Accurate calculation of level and quality inspection of Jacking Towers and Support Towers to minimize the errors of lifting.
2) Preventing of excessive stresses on some members due to eccentricity in Jack-Down process.
3) Organizing economic Jack-Down system.
4) Maximum stress ratios.
5) In-advance examination and reinforcing plan for the punching failure of the branching part of steel pipes during lifting or Jack-Down process.
6) Preparing and managing of site survey system for accurate assembly and installation of each member.
7) Measures for absorbing tolerances for installing, lifting, and Jack-Down.
8) Selecting efficient oil pressure system considering both economy and safety.

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REFERENCES

1. Construction report of GwangMyeong velodrome, Daewoo E&C. CO, Ltd, 2006
2. Architectural Institute of Japan, *"Dome Structures in Japan : Recent Advances in Structural Engineering"*, AIJ, 2004
3. Salmon, Charles G. and Johnson, John E.(1996). *" Steel Structures-design and behavior-4th"*. Harper Collins Publisher.
4. *John F. Abel, John W. Leonard, and Celina U. Penalba, "Spatial, Lattice and Tension Structures"*, ASCE, IASS'94, Vol. 1st, 1994

Table 1. Construction Outlines

Velodrome	10,863 seats on B1F ~ 5F
Structure of building	Reinforced concrete structure, precast concrete structure, and steel structure
Site area	197,013 m^2
Building area	39,338 m^2
Cumulative area	75,443 m^2
Maximum height	49.5 m
Construction companies	Consortium of Daewoo E&C, Samsung E&C, and Taeyoung Corp.

Table 2. Weight of each structural component at the time of IR lifting

Structural component	Weight (ton)
Compression Ring & Inner Grid	445
19% allowance for connections	85
Catwalk	48
Skylight	52
Total	630

Table 3. Weight of each structural component at the time of Jacking Down

Structural component	Weight (ton)
Compression Ring & Inner Grid	445
Tension Ring	475
Flow Trusses & Flow Shells	908
19% allowance for connections	347
Catwalk & Skylight	100
Total	2275

Table 4. Applied loads at lifting of IR

Tower No.	Applied loads on oil jacks (ton)		Remarks
	Predicted	Measured	
1	91	107	
2	141	132	
3	141	132	
4	91	107	
5	148	132	
6	148	132	
Total	760	742	

Table 5. Deflection at the ends of IR at the time of lifting

Tower No.	Deflection (mm)		Remarks
	Predicted	Measured	
7 & 8	41	-	
9 & 10	45	44	

Table 6. Horizontal displacement of JTs

Loads at oil jack (ton)	Predicted (mm)	Measured (mm)	Remarks
0	-45	-34	When prestressing back tie
91	40	25	Towers #1 & 4
141	86	55	Towers #2 & 3
147	92	45	Towers #5 & 6

Table 7. Applied loads at JD of roof structure

Tower No.	Applied loads on oil jacks (ton)		Remarks
	Predicted	Measured	
1	149	171	
2	114	57	
3	114	91	
4	149	195	
5	120	133	
6	120	108	
7	87	129	
8	87	160	
9	95	108	
10	95	112	

Table 8. Comparison of roof deflections at JD

Tower No.	Deflection (mm)		Margin (mm)	Tower No.	Deflection (mm)		Margin (mm)
	Predicted	Measured			Predicted	Measured	
1	179	214	+35	6	141	161	+20
2	136	132	-4	7	108	100	-8
3	136	154	+18	8	108	108	0
4	179	233	+54	9	113	83	-30
5	141	148	+7	10	113	93	-20

Table 9. Radial displacement at TR point due to gravity load (unit: mm)

Grid	Displacement		Grid	Displacement	
	Predicted	Measured		Predicted	Measured
0	54	26	30	54	32
2	51	25	32	50	28
4	45	19	34	44	26
6	35	18	36	34	19
8	21	8	38	22	12
10	13	4	40	15	9
12	9	2	42	13	5
14	8	2	44	12	3
16	8	4	46	12	2
18	11	1.5	48	14	3
20	17	4	50	18	8
22	27	9	52	27	16
24	41	16	54	39	26
26	49	18	56	47	28
28	53	26	58	52	36

Table 10. Details of measuring sensors

Name of sensors	Model	Quan-tity	Target measurement	Remarks
Strain gauge	WFLA	12 sets	Stress variations of IR	IR lifting
		3 sets	Stress variations at web, flange and back tie of JT #5	
		32 sets	Stress variations at top of roof	JD
Tilt meter	KB-5D	6 EA	Displacement of foundation of JTs	IR lifting & JD
Static data logger	CR-10X BASE	1 set	Logging and storing data from sensors	

Table 11. Monitoring intervals for each construction process

Construction process	Monitoring intervals
Before IR lifting after installing strain gauges	Every 1 hour
At the time of IR lifting	Every 15 seconds
At pauses during IR lifting for other works	Every 30 minutes
At the time of JD	Every 60 seconds

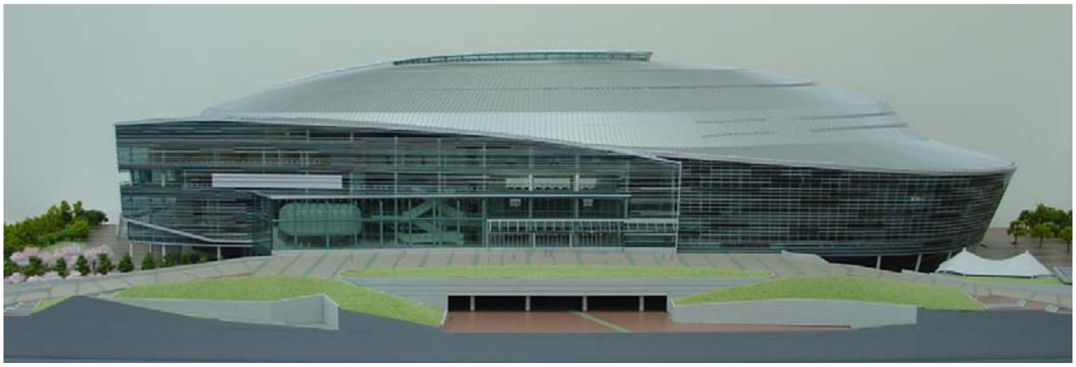


Figure 1. Front views of GwangMyeong velodrome

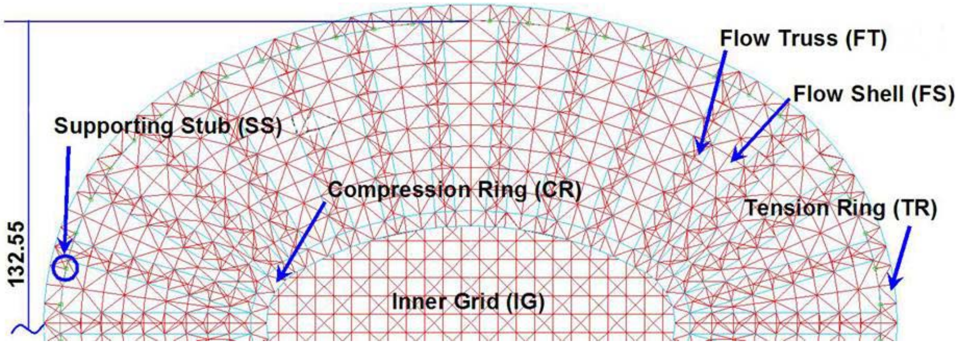


Figure 2. Structural components of roof structure

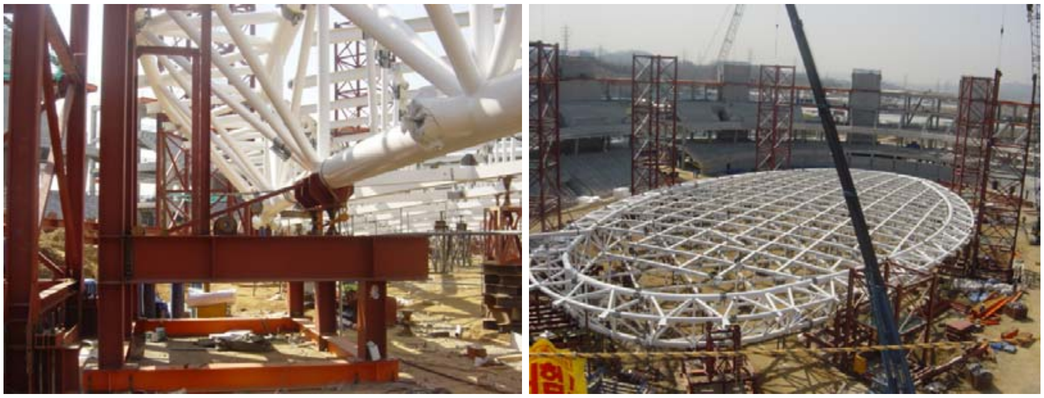


Figure 3. Assembly of IR and JT

Figure 4. IR lifted up and assembly of ST

Figure 5. Set up IR on top of ST and installing TR & FTs

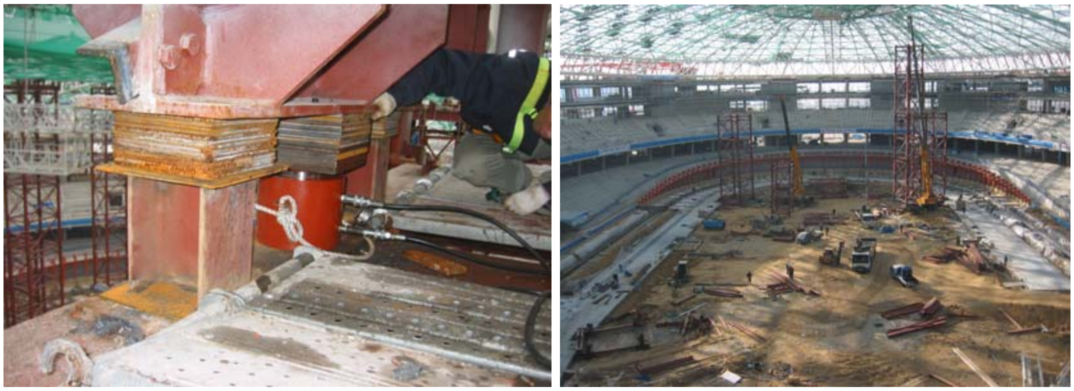
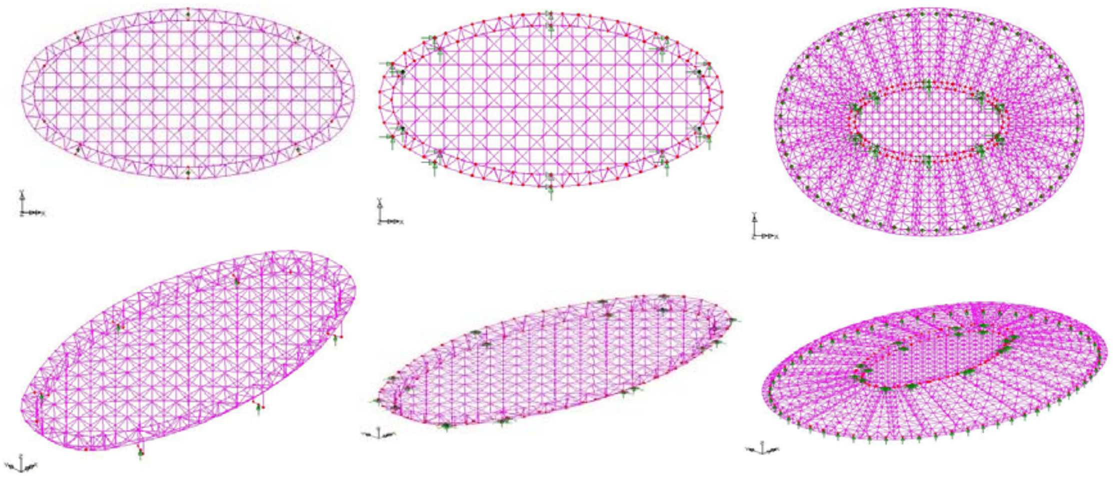


Figure 6. JD of roof structure and removal of STs



(a) (b) (c)

Figure 7. Analysis models at lifting of IR (a), at set up of IR on top of STs (b), and at JD of roof structure (c)

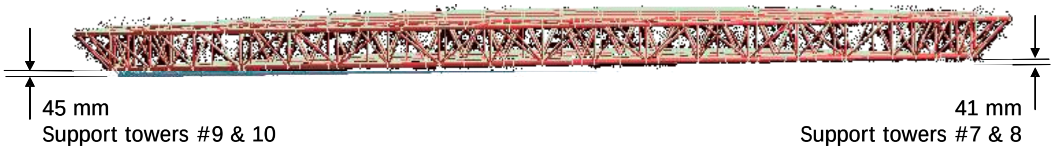
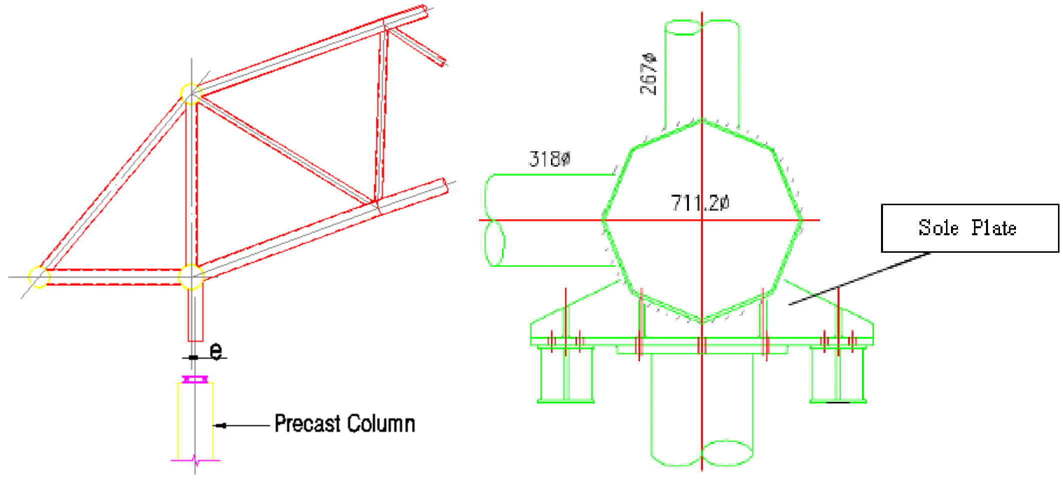


Figure 8. Predicted vertical movement of IR at the time of lifting



(a) Before

(b) After

Figure 9. Handling eccentricity between TR and column

Figure 10. Installation of strain gauges (left) and tilt meter (right)

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