The earthquake responses of climbing-type tower cranes installed in high-rise buildings in consideration of various situations under construction

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Abstract

Determining measures to prevent accidents related to tower cranes during earthquakes is very important in construction sites. If someone falls off a tower crane, it would be a fatal blow to the construction project and may result in loss of lives, tremendous repair costs, and delay of the construction schedule. In many cases, because a tower crane is a temporary facility and structure due to its short-term use (e.g., less than 2 years), construction contractors follow the structural design criteria for the crane but do not undertake further consideration and countermeasures to prevent serious accidents during powerful earthquakes similar to those for permanent buildings due cost and effect consideration.

In this paper, the details of an actual example of a serious accident related to tower cranes caused by an earthquake in high-rise building construction is explained, which was experienced by one of the authors as the project director. In this accident, two tower cranes and counterweights of another tower crane fell from their installed location, which was at a height of more than 200 m from the ground, when a powerful earthquake occurred. In this disaster, 5 people were killed, 20 were injured, and there were serious damages to the buildings and neighborhood.

In addition, using simulation methods, earthquake responses of a tower crane considering the construction progress was studied. The amplification of the response of the tower crane due to co-oscillation between the building and the tower crane at a powerful earthquake was confirmed. Based on these results, the countermeasures to prevent such co-oscillation by changing the stiffness of the building frame and the tower crane mast. The tower crane mast unit connection details, which are the most critical structural portion, are proposed. The tower crane of Taipei 101 also failed at the connections of the mast units. The measures to minimize the tower crane failure during a powerful earthquake considering various operation patterns are also discussed. Finally, it is suggested that the plastic deformation ability of the tower crane structural member is very efficient in stabilizing the earthquake response beyond the elastic status of the structural steel members.

Keywords: tower crane; high-rise building; earthquake response

1. Introduction

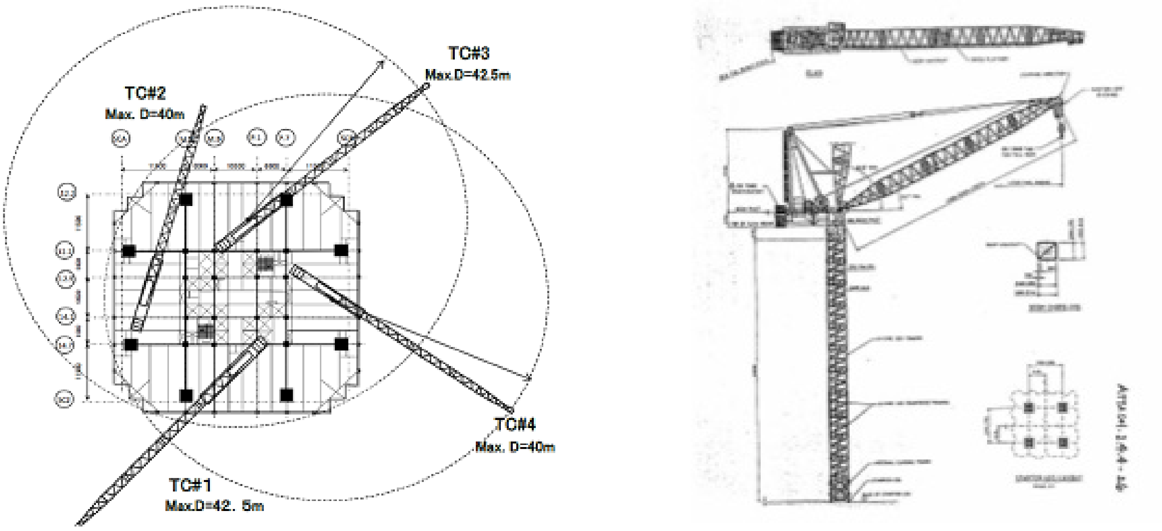
Determining measures to prevent accidents related to tower cranes during earthquake is very important in construction sites. If someone falls off a tower crane, it would be a fatal blow to the construction project and may result in loss of life, tremendous repair costs, and delay of the construction schedule. In many cases, because a tower crane is a temporary facility and structure due to its short-term use (e.g., less than 2 years), construction contractors follow the structural design criteria for the crane but do not take further consideration and countermeasures to prevent serious accidents during powerful earthquake similar to those for permanent buildings due to cost and effect consideration.

In this paper, the authors discuss on the earthquake response of climbing tower cranes in high-rise buildings and the measures to be taken for preventing serious accident at the time of a powerful earthquake based on more than 20 years of experience of one of the authors as a project engineer and a project director for high-rise building construction work.

2. Actual experiences during the collapse of tower cranes

For the Taipei 101 building, which was the tallest building in the world when it was built, four tower cranes had been installed to erect steel structures of the building tower. On March 31, 2002, the construction of Taipei 101 had reached a point of erecting steel frames for the 53rd floor to the 56th floor of the building, which is approximately 230 m above the ground level. During the main shock of the earthquake that day, among the four tower cranes, two collapsed and one was seriously damaged with the crane counterweight falling off the machine deck. The incident killed two crane operators, two steel workers, and one part-time student engineer. These four tower cranes were designed based on the New Zealand seismic standards. Tower cranes TC#1 and TC#3, located on the southern and northern sides of the building, respectively, were identical (Model M1250D) with a hoisting capacity of 22,000 kN-m. The collapsed tower cranes, TC#2 and TC#4, located on the east and west side of the building, respectively, were also identical (Model M440D) with a hoisting capacity of 6,500 kN-m, as shown in Fig.1 and Table 1.

When there was an earthquake at the Taipei 101 building construction site, TC#2 and TC#4 were waiting to hoist members and were not in operation. TC#1 was being used for erecting one of the small perimeter columns near the south-west corner of the building and TC#3 was also in stand-by for hoisting the next member. Due to the movement during the earthquake, TC#2 and TC#4 collapsed to the podium roof and the adjacent street, respectively. The long boom of collapsed TC#4 hit and broke the hoisting wire of TC#1, which was being used for erecting the column and was almost connected to the erected column with temporary bolts. This breaking of sling wire rope caused a sudden release of the hoisting weight of TC#1, which led to all the counter weights (15 pieces, 75 kN each) falling down from a height of 260 m to the ground and inside the south side of the building. This counterweight incident killed two people and caused substantial damage to the building. TC#3 had little damage and could be used for clearing and repairing the building; however, after close inspection of its damage, it was found that the bearing part between the mast and the crane machine deck was seriously damaged. The images of this disaster are shown in Fig. 2.



(1) Tower crane location

(2) Tower crane M1250D

Fig.1 - Location of the tower cranes used for the construction of Taipei 101 Building

Table 1 - Detail of the tower cranes used for the construction of Taipei 101 Building

	TC#1 & TC#3 (M1250D) Hoisting Capacity: 22,000KN-m	TC#2 & TC#4 (M440D) Hoisting Capacity: 6,500 KN-m
Machinery deck assembly	80.7 t	53.2 t
Boom assembly	14.7 t (45.8 m)	9.8 t (41.2 m)
Mast assembly	16.7 TON (48 m)	11.9t (48 m)
Counterweight	130.0 t (8.5t x 15pcs)	37.1 t (5.3t x 7pcs)

Fig. 2 - TC#4 fall off to the street

3. Structural design criteria for the climbing-type tower crane

3.1 Seismic Load to be considered for the design of the climbing type tower cranes

As for the structural design criteria for cranes in Japan, two types of crane standards exist for protection against earthquake; one is the Construction Code of cranes and the other is the Japan Crane Association standard. The Construction Code has legal force and specifies that all the cranes must be designed with a uniform value of lateral seismic factor of 0.2 in accordance with the JIS B 8821 standard. In case the combined design force includes short-term loads such as seismic or wind loads, the allowable stress of the permanent structural members and the connections is 1.33 times greater than the allowable stress under long-term loading for permanent structure and 1.5 times for temporary structures. It is considered that the application of this design criteria, in terms of being economical and safe, is reasonable and a common and standard practice prevalent in Japan, which is a country subject to frequent and intensive earthquakes. The Japan Crane Association standard specifies the seismic modification coefficient calculated by considering the structures where the crane is fixed; however, these criteria are for overhead traveling cranes and bridge-type cranes but not for jib cranes or tower cranes.

Structural behaviors of the collapsed tower crane (Type M440D) and the damaged (but not seriously damaged) tower cranes (Type M1250D) on the building frame erected up to the 56th floor are analyzed by relevant organizations through dynamic time-history analyses. Various analytical studies have been carried out to investigate the causes of the tower crane incident using simple models and detailed 3-D models including supporting building frames above ground level. Seismic vibration used for related analysis was recorded near the site. The calculated natural periods of the building and the two types of the tower cranes at the incident are as follows:

(1) Building: 2.2 second
(2) M440D: 2.7 second
(3) M1250D: 2.2 second

Three-dimensional analytical results of simplified Taipei 101 stick models incorporating the four tower cranes suggest that the peak horizontal acceleration of the tower crane is about 0.76 g at the 51st floor and 0.14 g at the ground floor under the effect of simultaneous application of two horizontal components of the earthquake wave recorded near the site. This shows that in case the tower crane is set at a higher floor of the building, the horizontal force of the tower crane will be amplified due to the co-oscillation between the building and the tower crane.

Both types of tower cranes should have collapsed according to this study. However, in reality, two M440D collapsed due to the failure of the tension bolt connections of mast blocks, which were designed and manufactured according the required standards, and there were no serious damages to one M1250.

Accordingly, detailed studies of dynamic responses of the tower crane installed on high-rise buildings under earthquake vibrations are recommended for the contractor to make a plan of the temporary site work with tower crane operation by considering the amplification due to the co-oscillation between the building and the tower crane.

3.2 Tower Crane Mast Connection Design

Another point to be discussed is the design criteria for the connections of the crane mast, between mast units, and the mast to the crane machine deck. Since the structural frame of the tower crane is a temporary structure, these frames should be reused several times. Therefore, the site connections of the mast units, which consist of the lattice frame with 4 H-shaped columns, horizontal members and bracings, should be designed such that the site assembling and disassembling of these mast units can be easily carried by considering the schedule and costs. Therefore, it seems to be the one of the reasons why the standards do not require the bolt connections to be stronger than the connected structural members, which means that the failure of the mast should not be at the bolt connections but at members such as the H-shaped columns. However, considering that the bolt connection failure as shown in Fig.3 is a typical failure pattern of the climbing-type tower cranes in the case of the Taipei 101 building and the buildings in the Kobe Earthquake in 1995, this criteria on the mast unit connections is recommended to be mandatorily applied to the crane design and also strong joints with easier assembling and disassembling should be designed.

Failure of the mast of the tower crane

End-plate bolt connection of the mast units

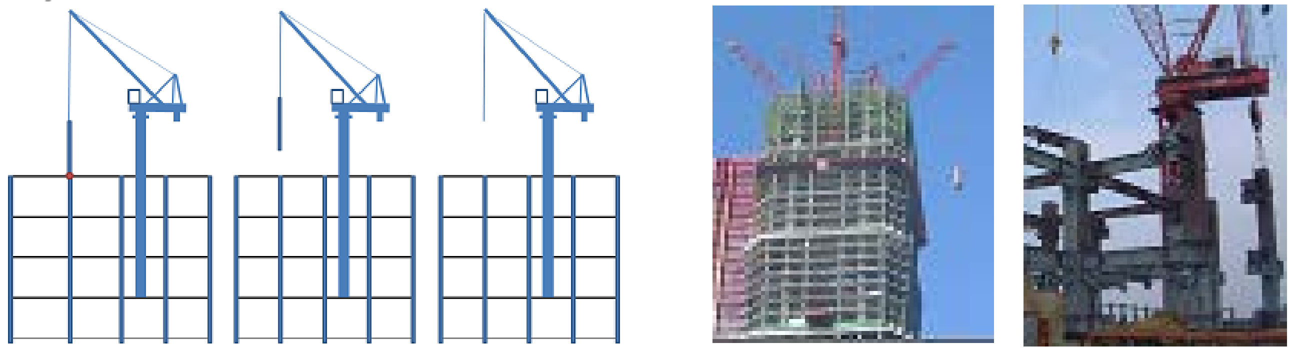
Fig. 3 - Failure of the bolt connections of the tower crane mast units

4. Operation of a tower crane

The classification of the operation processes of a tower crane used in high-rise buildings includes stand-by, lowering of the sling wire rope, hooking of material on the ground, hoisting material, fixing the material, and releasing the hook. Excluding the stand-by time, among the operation processes for each tower crane used in high-rise buildings, the most amount of time is spent on hoisting and fixing. At the time of the Taipei 101 incident, only one tower crane (Type M1250D) was in operation, which was being used for fixing a small perimeter column and the others were in stand-by, waiting for hoisting material instructions.

The M1250D in operation was seriously damaged with the falling down of all the counterweights as shown Fig. 5. The boom hit the sling wire rope hooked to the column being fixed to the building. The sling wire rope is not very strong because the column required to be hoisted is not very heavy, i.e., 20 kN, and it was already temporarily connected by erection bolts; therefore, the wire rope was easily broken and caused sudden release of the tension, which led to the fall of all the counterweights of TC#1. This sudden release of the sling wire rope should be avoided when a tower crane is hoisting materials to be fixed to the building during a powerful earthquake.

In the other case, when most amount of time is spent on hoisting, the large horizontal and vertical movements of the boom of the tower crane caused by intense earthquake results in large swing of the sling wire rope with material at the bottom. This large swing can cause serious damage to the building and people and should be avoided.



①Fixing materials ②Hoisting materials ③Stand-by Hoisting a column Fixing a column

Fig. 4 - Tower crane operation pattern

Counterweight

Fig. 5 - Fall of the counterweights of the tower crane

5. Recommendation for the action to be taken

5.1 Prevent co-oscillation between tower cranes and the building

The effects to the tower crane due to the co-oscillation between building and the tower crane have been studied for a typical office building with 14 stories (total floor area: 10,258 m^2, height: 633 m) in Japan, which has been published in the book named "Structural Design: The example of structural member sections". The structural frame is shown in Fig. 6 and the location of the tower crane (KCP-H1020) is shown in Fig. 6.

For the construction of this building, the frame is divided into 6 tiers and the tower crane is self-climbing and fixed on the top floor of each tier. It is also assumed that all the construction work of the structural frame such as welding, bolt fastening, and floor concreting are completed for the floor till which the tower crane climb. The seismic response analysis was carried out at each stage of construction as shown in Fig. 7. In this analysis, a two-dimensional frame system and only one direction of seismic load, X1 to X6, are applied.

The lumped mass models of the 6 construction stages for seismic analysis are shown in Fig. 8 (1) and the structural characteristics of the model (system) are nonlinear as shown in Fig.8 (2), and the relevant values are listed in Table 2. El Centro NS (v_{max} =50 cm/second) is applied as the seismic load. The level of this seismic load is so large that some of the structural members of the buildings designed in accordance with the latest Japanese structural design code should have plastic deformation. This analysis was carried out using the "Dynamic PRO" computer software.

The results of the analysis are listed in Table 3. At stages 3 and 4, the response of the tower crane top is amplified due to the co-oscillation effect between the building and the tower crane under nonlinear structural system. The amplification is about two times compared with Stage 1, where the tower crane is fixed to the ground. In the case of the Taipei 101 incident, the tower crane response, which was obtained based on the analysis of linear structures, was amplified 6 times when the tower crane was on the 51st floor according to the study of the related organizations. It is confirmed that for a normal building such as a 14-story office building with nonlinear structural characteristics, there exists the amplification of response of the tower crane due to the effect of the co-oscillation between building and the tower crane at the attack of earthquake.

For countermeasures for preventing this co-oscillation effect, the following two measures are studied:

(1) changing the stiffness of the building structure to adjust the natural period of the building

(2) changing the stiffness of the tower crane mast to adjust the natural period of the tower crane

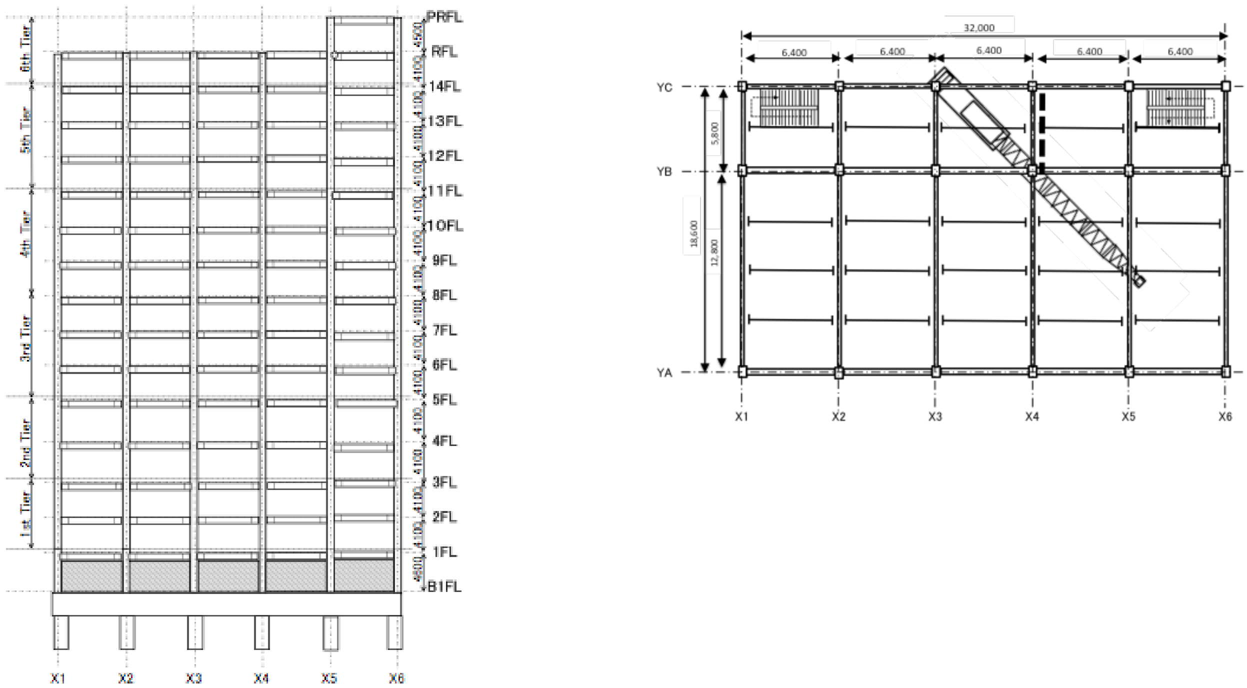


Fig. 6 - Elevation and floor plan of the S Office and the location of the tower crane

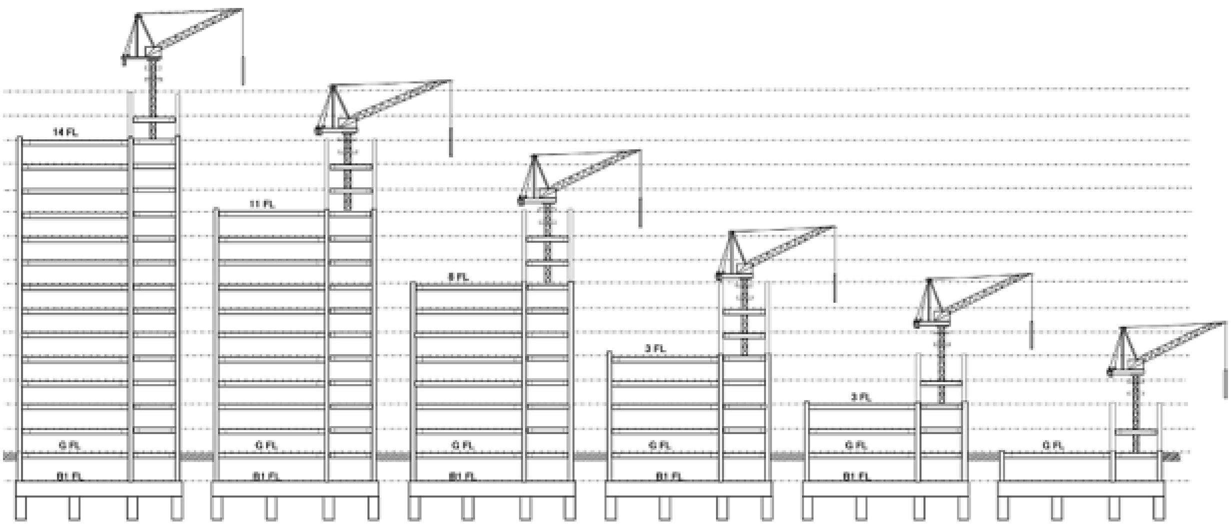
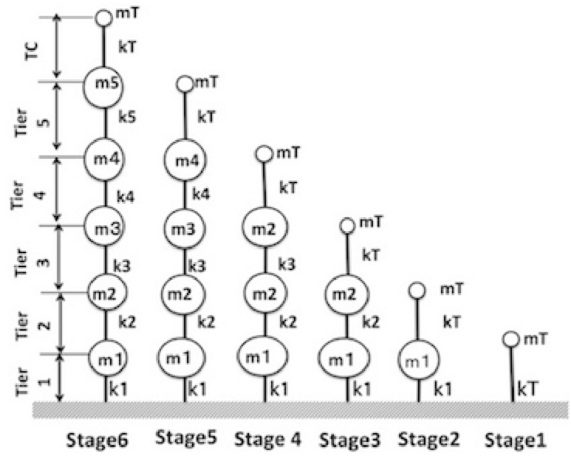
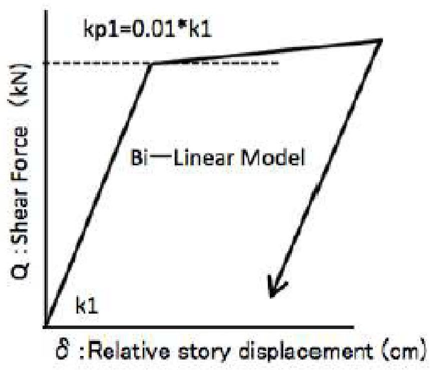


Fig. 7 - Tower crane locations in the 6 stages



(1) Lumped mass model



(2) Hysteresis restoring force characteristics

Fig. 8 - Lumped mass model of each stage of tower crane location

Table 2 Values of the lumped mass model of structural system of the building

Tier No	Height of each tier (cm)	Weight of lumped mass (kN)	Stiffness in elastic range (kN/cm)	Max. elastic capacity (kN)	Hysteresis restoring force characteristics
TC	2410	120	12.1	146	Bi-linear(see Fig.6)
5	1232	16017	1435	8841	Bi-linear(see Fig.6)
4	1230	16240	1781	10955	Bi-linear(see Fig.6)
3	1230	16415	2026	12462	Bi-linear(see Fig.6)
2	820	11030	3315	13592	Bi-linear(see Fig.6)
1	880	11122	4302	18930	Bi-linear(see Fig.6)

Table 3 - Natural period of the building and response of the tower crane in each stage

Stage	Natural period of the building (s)	Max. deflection of the tower crane (cm)	%
1	0.63	14.1	100
2	0.32	18.6	132
3	0.54	27,1	192
4	0.93	24.9	177
5	1.30	16..2	115
6	1.69	13.0	92

5.1.1 Case study considering the increase or decrease in the stiffness of the building frame

To countermeasure to the amplification of the tower crane response, the natural period of the building structure, on which the tower crane is fixed, is changed; this is done by increasing or decreasing the stiffness of the building frame such as by temporary installation of bracings and application of pin joints for the girder to column connections. The four cases shown in Table 4 are considered for analysis.

The results of the seismic analysis are shown in Table 3 and Fig. 5. From these results, it can be seen that the change in the stiffness of the building frame by temporary installation of bracings and application of pin joints is effective for reducing the amplification of the seismic response of the tower crane. However, it is also considered to be a problem as these measures may affect the construction cost and schedule. In addition, in case of the application of pin joints, the possibility of the failure of the building should be carefully studied.

Table 4 - Modification of the structural frame in construction (stage 3)

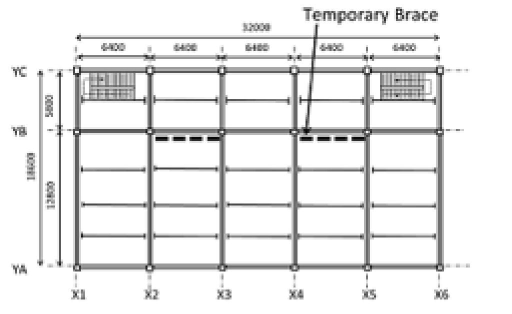
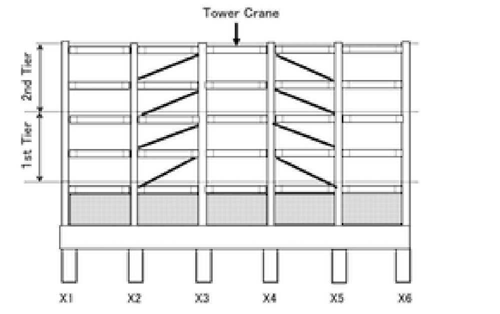
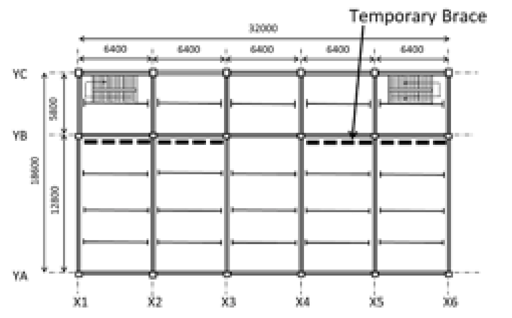
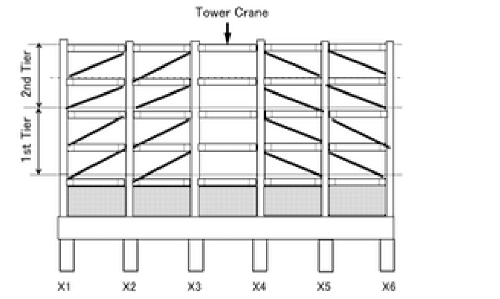
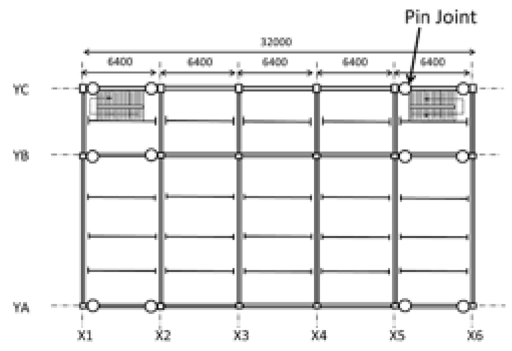
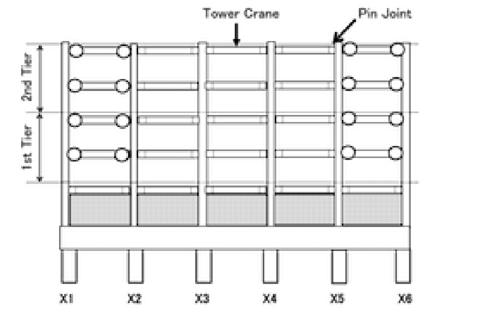
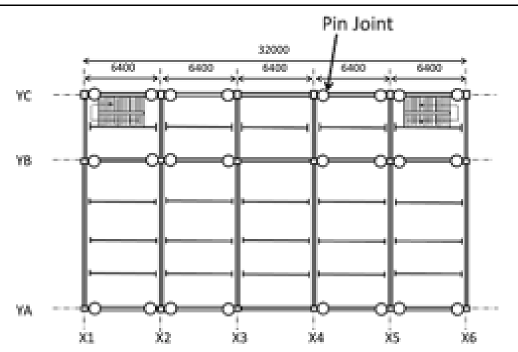
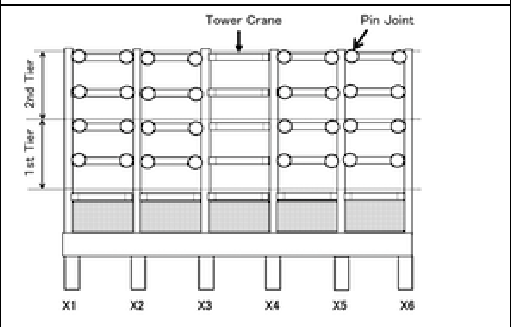
	Framing Floor Plan	Elevation of the building frame
Case 1		
Case 2		
Case 3		
Case 4		

Table 5 - Natural period of the building for each stage and maximum deflection of the tower crane top

	Natural period of the building in each case	Max. deflection of the tower crane top (cm)	%
Original	0.54	27.1	100
Case 1	0.45	20.9	77
Case 2	0.39	18.2	67
Case 3	0.70	23.1	85
Case 4	1.04	10.8	40

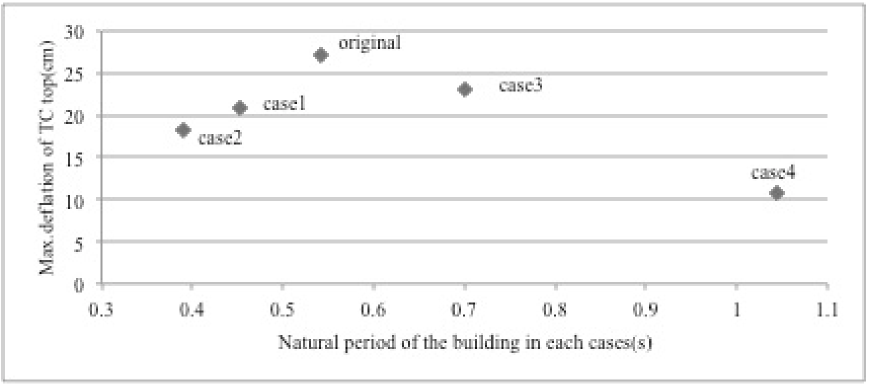
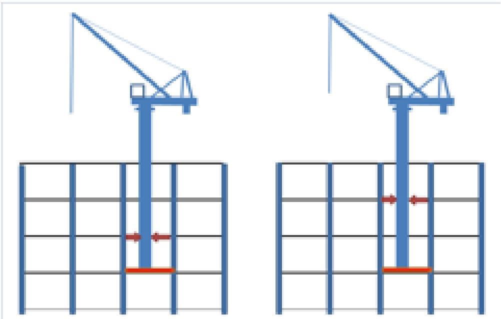


Fig. 9 - Natural period of the building in each case and maximum deflection of the tower crane top

5.1.2 Stiffness of the tower crane mast and the structural system of the temporary supporting frame

When the fixing system of a climbing crane consists of a pin joint on the base and roller joint on the mast, as shown in Fig. 10, the mast length of the tower crane can be adjusted by changing the roller joint of the mast and the building. If the extended mast length is shortened, the natural period of the tower crane is reduced, which will decrease the effect of the co-oscillation between the tower crane and the building.

In addition, the design of the temporary supporting frame by considering the stiffness and plastic deformation of the frame, e.g., by introducing damping devices, will help in reducing the magnitude of the earthquake response of the tower crane.



Temporary supporting frame for the tower frame

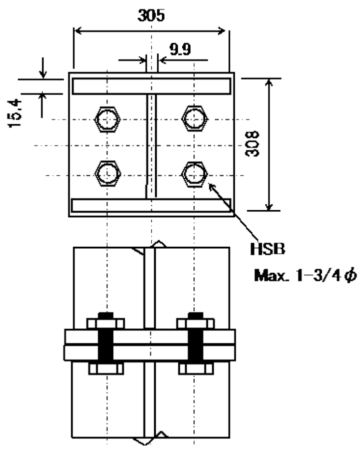
Adjustment of the length of the extended mast

Fig. 10 - Tower crane temporary support structure

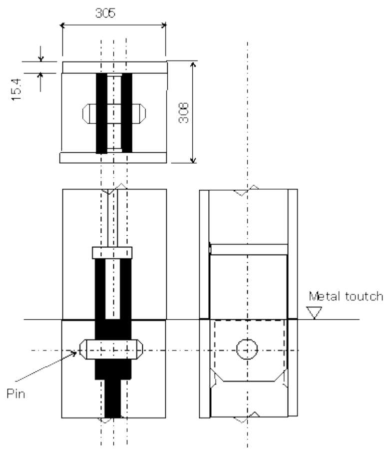
5.2 Improvement of the site connections of the structural members of the tower crane

The pin connection shown in Fig. 11 (2) is recommended. For the end plate-type bolt connections shown in Fig. 11 (1), the number of the high strength bolts (HSB) should be four because of the space required for bolt allocation and also because the size of the HSB (diameter) should be not more than 45 mm to ease tightening difficulty. Therefore, the strength of the connection is limited and it is difficult to satisfy the condition that the connection strength should be higher than that of the connected members. On the other hand, the pin connection, which was applied to M1250D type tower crane which was not collapsed, has more flexibility and is able to be designed to be stronger even though the fabrication of the connection is more expensive because it requires strict accuracy in manufacturing including machining of metal touch surfaces in the splice of the column members and bearing surface of pin holes.

Unless the mast is reused, the site welding with reinforced plates can be introduced for strong connections, which was used for the new replaced tower crane in Taipei 101. However, this measure is just for an emergency case and is not applicable for normal practices.



(1) Mast unit connection: End-plate connection



(2) Mast unit connection: Pin connection

Fig. 11 - Mast unit connection

5.3 Preventing falling of tower crane parts

Preventing falling of tower crane parts should be also considered for temporary work. The heaviest portions of a tower crane are the crane machine portion with the boom and the counterweight. For re-starting the construction of Taipei 101, the crane machine portion was connected to the building by using steel wire ropes and the counterweights were tied by wire rope one by one to prevent from falling off.

5.4 Operator education to take necessary measures during earthquakes

Operators should take necessary measures before the response of the tower crane becomes large during earthquakes. For example, at the time of fixing the hoisted material, the sling wire rope was tightened but not released for the sake of safety. If the tower crane operator had released the tightened sling wire rope during the earthquake, the counterweights may have been prevented from falling down. In another case, where the tower crane is hoisting material during an earthquake, the tower crane operator should try to lower the material to the ground as soon as possible right after the movement due to the earthquake begins to prevent large swing of the sling wire rope and thus to minimize the damage to the building and people. These measures should be documented in the operation manual and should be followed by operators during an earthquake. In addition, the alarm system linked with the seismometer should also be equipped for the operator’s necessary actions at earthquake attack.

5.5 Enhancement of plastic deformation ability

The design of allowable stress specifies the safety factor for each part of the tower crane structure but does not stipulate the aspect of failure mode. The danger of brittle fracture cannot be ignored if excessive force is applied. It is important that as a new and unprecedented concept design of tower crane structures in the case of failure will be done through the elastic-plastic design to secure the ductility of structures along with the appropriate assumption of the seismic input. Generally, it will be possible to prevent the structures from collapsing if they have high plastic deformation ability. High plastic deformation ability can be efficiently used for stabilizing the response beyond the elastic status of steel structures.

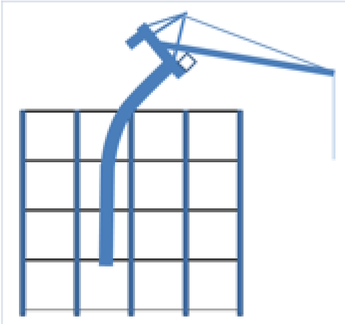


Fig. 12-Tower crane failure mode

It has been observed that codes or standards currently being applied to temporary structures including tower crane structures should be reconsidered and improved to secure proper structural safety of temporary work to save lives; there are many topics and issues to be researched and studied for this purpose.

6. Conclusion

For the design of temporary structures that include tower cranes, engineers are always under pressure to reduce the cost and follow the schedule for the construction. Particularly, planning measures to prevent serious human damage during powerful earthquake is difficult but important work. Some countermeasures based on the author's experiences were proposed in this paper; however, still many unknown issues exist. The author believes that further study in this area is still essential for saving human lives in the construction of high-rise building during powerful earthquakes.

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References

[1] C.H. Loh, K.C. Tsai, L.L. Chung, and C.H. Yeh (2003): Reconnaissance Report on the 31 March 202 Earthquake on the East Coast of Taiwan, *Earthquake Spectra, Volume 19 No.3*, Page 531-556

[2] S. Takanashi, H. Adachi, and M. Nakanishi (2007): Study on the seismic performance of the tower crane for construction, *Architectural Institute of Japan Technical Report Volume 13, No.26*, Page 415-420

[3] Y. Maeda and Y. Kitsunai (2000): *Specific research reports of the national institute of industrial safety*, NIIS-SRR-NO.20.

[4] JIS B 8821: *Calculation standards for steel structures of cranes.*

[5] Structural design: *The example of structural member sections (2007)* issued by The Japan Building Disaster Prevention Association