Summary of this thesis

It is important to determine and apply the measures to prevent fatal tower crane accidents at construction sites during earthquakes because these accidents negatively and seriously impact construction projects, may result in losses of life and tremendous repair costs, and distort the construction schedule. In many cases, construction contractors follow the less stringent structural design criteria applying only to cranes because tower cranes are facilities and structures that are needed only for a short term (e.g., less than two years) and construction costs and time effectiveness are often emphasized over safety measures..

Chapter 1 presents the background and objectives of this thesis. The background briefly explains the seismic design criteria for tower cranes in Japan and details a serious tower crane accident caused by an earthquake. It occurred in 2002 during the construction of the Taipei 101 Building (101 stories); the accident was experienced by the author as the project director. In this tower crane accident, two cranes located at a height of more than 200 m from the ground fell down due to the site joint failure of tower crane mast, leading to the death of five people, injuring approximate 20 people, and seriously damaging the building itself and neighborhood.

The objectives of this thesis are highlighted as follows:

(1) To confirm the resonance effects of a tower crane seismic responses with the building, where the tower crane is installed, at construction sites of high-rise building, and propose countermeasures to prevent those effects and to minimize tower crane failures,

(2) To propose a new design method for end-plate-type tensile bolted joints that are commonly applied to the site joints of tower crane masts owing to their site workability. The method uses the calculation results obtained using a supercomputer by an application of static elastoplastic finite element analysis (LS-DYNA R 9.2.0 _ Rev. 119543, which was developed by Livermore Software Technology Company(LSTC)), to a tower-crane-mast structural models with extremely finely shaped solid elements, and

(3) To develop a modeling method for tower crane mast structures by creating a hybrid element model comprising solid, shell, and beam elements for seismic response non-linear FEM analysis (LS-DYNA) to enable structural engineers to grasp the precise dynamic ultimate behavior of mast site joints during earthquakes, and to promote better structural design.

Chapter 2 describes the earthquake responses of tower cranes at construction sites using simulation methods and discusses the amplification of the tower crane response due to resonance effects between the building and the tower crane during an earthquake. The analysis was performed using the "Dynamic PRO" computer software on a 14-story building designed according to the latest seismic design criteria. The lumped-mass models for six construction stages were prepared for seismic analysis using linear and non-linear structural models of the building. El Centro NS (v_{max} = 50 cm/s and v_{max}=32.25 cm/s) seismic loads were applied with a 3% damping ratio of the building and the tower crane structures. The seismic load (v_{max} = 50 cm/s) was large enough that some of the designed buildings' structural members should have experienced plastic deformation, and the seismic load (v_{max}=32.25 cm/s) was the level that the designed buildings' structural members were all within elastic range.

The results showed seriousness of the resonance effects caused by their close natural frequencies.Based on the corresponding results, the countermeasures such as changing the stiffness of the building frame and tower crane mast to prevent such resonance effects are proposed and discussed.

Chapter 3 proposes a new design method for end-plate-type tensile bolted joints that are commonly applied to the site joints of tower crane masts. End-plate-type tensile bolted joint possess good workability for the joining of vertical members, such as posts of a tower crane mast, during assembly and disassemble, and moreover, it is structurally capable of transmitting large loads efficiently. However, the problem is that the design of the joints is difficult and complicated because of the joint condition that the outer surface of the mast needs to be flat to enable climbing of the tower crane. Therefore, depending on the shapes of the post members of the mast, special joints such as large-diameter bolted (greater than 30 mm) and eccentric-bolted tension joints are applied to the site joints.

This new design method uses the calculation results obtained using a supercomputer through static elastoplastic finite element analysis (LS-DYNA) applied to structural models with extremely fine cubic-shaped solid elements with side lengths of 2.5 mm. To prove the effectiveness of this method, the conventional design method was also described. Using the design method proposed in this chapter, it is possible to realize not only more precise and reliable joint designs but also the design of various complicated joints in consideration of the construction conditions such as the pre-tension axial force on the bolts.

Chapter 4 proposes the modeling of a tower crane mast structure for seismic response non-linear FEM analysis. Consequently, the author created a new hybrid element model (HEM) composed of beam, shell, and solid elements that not only expressed the detailed ultimate behavior of the site joints of a tower crane mast, such as the stresses on individual solid elements of end plates and bolts, axial tension force of each bolt, and gap between the two end plates, etc. during an earthquake but also suppressed any increase in the total calculation time and revealed its behavior using LS-DYNA and a supercomputer. El Centro NS (v_{max} = 100 cm/s) was applied as a seismic load with 3% of the damping ratio of the structural model. The case study on the seismic responses of the joint models with diferent initial pretention forces of bolts was also done using this simulation analysis. This result suggested for end-plate-type tensile bolted joints that initial pretention axial force of bolts should be critical factor for designing of safer joints.

The simulations using the proposed structural model make it possible to provide effective and useful information for designing safe joints to prevent brittle disruptions of tower cranes during earthquakes while taking into consideration site workability (control of the bolt pre-tension axial force, etc.) and economy.

Finally, this thesis recommends a computer-simulation method, which can generally be less expensive and can take more parameters into account in the study than experiments with specimens that are common in studies on the mechanical behavior of joints in steel structures. Therefore, when an analytical model that allows more reproducibility and less computation time as this thesis proposed is devised, the computer simulation tool become very useful and effective for precise and reliable design of steel structure joints.