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OPTIMAL DESIGN ALGORITHM OF THE FOUNDATION OF TOWER CRANES

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ABSTRACT: As buildings nowadays become taller in height and larger in size the safety review of lifting plan takes larger portion in construction project management. However, the cost and safety in lifting plan have a contradictory effect on each other. Therefore, an optimization algorithm needs devising as a solution of the contradictory problem. In many cases at construction sites, selections and stability review of tower cranes are assigned to equipment suppliers or field managers, which cause the problems in safety and cost of the projects. To improve the part of the current situation, a study on the optimization algorithm for designing the foundation of tower cranes is conducted in this study, which can be utilized by equipment suppliers or field managers to check the stability of tower cranes easily and promptly without substantial knowledge.

Keywords: Tower Crane; Optimal Design; Foundation; Stability

1. INTRODUCTION

1.1 Background & Purpose

As buildings nowadays become taller in height, free-standing height of tower crane lifting construction materials is also rising. As tower crane is important lifting equipment in construction site and has high slenderness ratio, it requires through lifting plan and safety review upfront. However, according to statistics in Korea as of July, 2007, safety accidents relating to tower crane account for 32% of the total safety accidents that happen in construction sites, which seems to result from the fact that tower cranes installation is dictated by empirical and subjective judgment of field manager or installation regulations suggested by equipment suppliers in most construction sites without specific review of tower crane's lifting capacity in reference to structural performance and thorough stability examination. Furthermore, foundation design is also deemed to be excessive because of such conditions.

In terms of stability examination of tower crane, Ho, Jong-Kwan (2007) developed a system to support optimum tower crane selection and stability examination in reference to site conditions in lifting planning stage and Han, Kap-Kyu (2007) presented an approach to foundation using stability examination SW program after selection of tower crane configuration. However, conventional studies had limitations in that they focused on generic stability examination methods or approaches to acquiring data that would allow installation, operation and removal of tower crane within adequate scope.

This study aims to develop an algorithm to optimize the design of tower crane bases to ensure stability in tower crane installation and operation. Optimal design of base herein means a foundation design that can maintain stability of tower crane necessary for lifting operation from installation to removal at minimum costs. The study focuses on optimization of not only foundation attributes relating to stability of tower crane such as size and thickness but also design process itself and research deliverables will contribute to saving costs with optimal foundation design, examining and ensuring tower crane stability and improving operational efficiency in other aspects.

1.2 Scope & Method

Following is the sequence of study of optimal design algorithm that this study intends to achieve:

①Review preceding studies relating to review of tower crane stability;
②Examine tower crane stability examination items;
③Examine and analyze goals and requirements of optimal design algorithm;
④Analyze relationship between each review item using graphical solution.

In terms of research scope, as Fig. 1 illustrates, this study focuses on fixed trolley type tower crane used most extensively in construction sites of Korea and limits support configuration to direct foundation type. In addition, it is assumed that other supports such as lateral supports or pile foundations are not used, as site ground has sufficient bearing capacity to enable the use of shallow foundation.

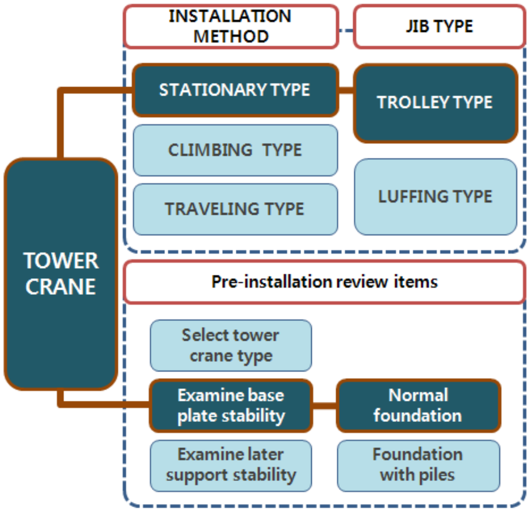


Fig. 1. Scope of Research

1.3 Literature Survey

Table 1. shows preceding studies on stability of tower crane. It is obvious that they dealt with analysis of disaster cases, generic foundation design and stability examination or reinforcement of support structure. In contrast, this research intends to ensure maximum stability of foundation [4] and optimum design of foundation at minimum costs.

Table 5. Literatures related to this paper

Researchers	Study Title	Description
Myeong-Gu Lee, Min-Lae Ro(2001.4)	Structural Analysis for the Collapse Accident of Tower Crane	Introduced cases of tower crane collapse, performed structural analysis as per cause of collapse and a total of 16 loading conditions and presented reinforcing approach by examining strength of each member with member force.
Lee, Byung-Koo, Seol, Jong-Hyup(2002)	Tower Crane Installation Planning & Approach to Reinforcing Structure	Explained crane installation planning & structural reinforcing approach with self-standing foundation and intermediate lateral support.
Ho, Jong-Kwan, Han, Kap-Kyu, Kim, Seon-Kook(2007)	Tower Crane Foundation Design and Stability Review Model	Proposed a tower crane stability simulation program to improve efficiency of stability examination after tower crane type selection.
Ho, Jong-Kwan, Kook, Dong-Hun, Kim, Seon-Kook	A System for the Selection of the Optimum Tower Cranes	Developed a system to optimize tower crane selection and stability examination as per site conditions in lifting planning stage.
Han, Kap-Kyu, Kim, Ah-Young, Kim, Seon-Kook (2007)	A Stability Examination of Tower Cranes Base through OptiCRANE-TC	Presented bases stability examination method using OptiCRANE TC following crane type selection.
Ho, Jong-Kwan (2006)	The Development of Tools Selecting Tower Crane and Reviewing the Safety	Surveyed tower crane operation status in Korea, identified needs for tower crane stability examination tool and presented development programs

[4] Maximum stability herein means tower crane performance that ensures adequate stability in tower crane installation/operation/removal and meets the minimization cost .requirement.

2. THEORETICAL CONSIDERATIONS

2.1 Generic Design Process

Fig. 2 summarizes generic tower crane foundation design process (Han, Kap-Kyu, et. al., 2008). Tower crane stability is examined in reference to data acquired by pre-installation review and site conditions or foundation conditions are modified in reflection of stability examination feedback prior to construction. However, such process is designed to deal with only generic items and limited in that it produces only foundation design at adequate level. In other words, concept of optimal design that Section 3 addresses is missing.

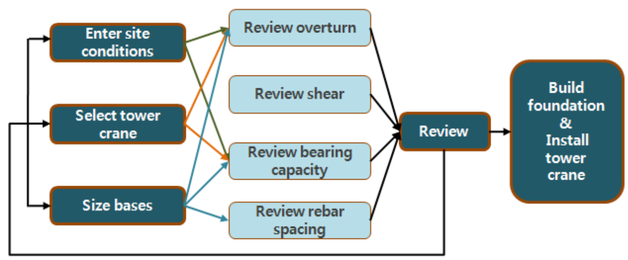


Fig. 2. Generic Design Process

2.2 Foundation of Tower Crane

Foundation of tower crane includes fixing anchor and concrete that holds it. As for foundation of fixed tower crane type targeted by this study, fixing anchor is held to the ground by concrete block and such basic installation approach is used usually for reinforced concrete apartment buildings and low-rise structures. As it was mentioned above in relation to the scope of this study, such foundation structure is applicable when sufficient bearing capacity is available and the strength of concrete block with fixing anchor must be $255 kg/cm^2$ or more.

2.3 Optimal Design Algorithm

Optimal design means foundation design that maintains lifting stability from installation of tower crane to removal at minimum costs. In other words, goals that optimal foundation design must fulfill include maximum stability and minimum cost.

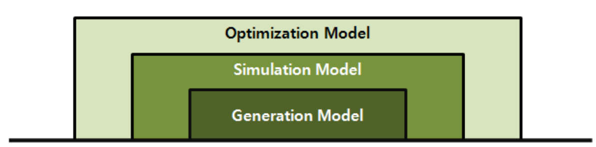
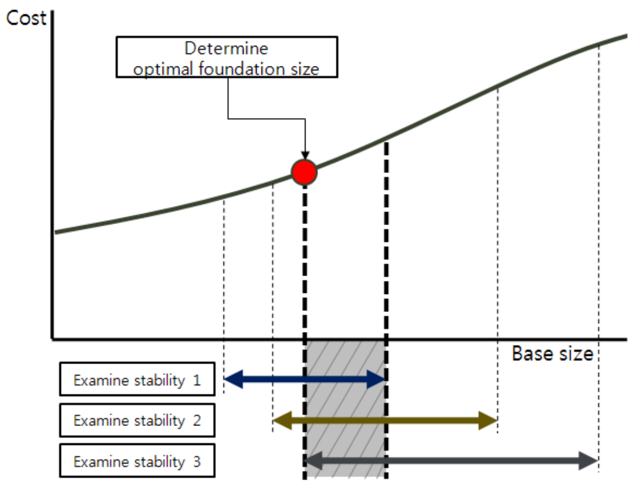


Fig. 3. Concept of Optimization

As Fig. 3 shows, generation model in conventional foundation design practices review each stability attribute once while simulation model in the foundation design process that this study presents modifies base size in multiple rounds of generation. Optimization model means using simulations to derive optimal design solution that is optimal base design.

Therefore, this study aims to conduct a research into optimal foundation design by optimizing stability and costs.

3. OPTIMAL FOUNDATION DESIGN



•Region in the shade satisfies all constraints: feasible region
•All coordinates in such region: feasible solution
•Among feasible solutions, a point that maximizes objective function value is optimal solution and (max. or min.) objective function value at such point is optimal value.

Fig.4. Concept of Optimal Foundation Design

This research focuses on determination of optimal base size that involves examination of two conditions, stability and cost. Correlation between stability and cost is analyzed to develop optimal foundation design and conceptualized as shown in Fig. 4 in the above. Fig. 4 shows the concept of optimal foundation design on the assumption that foundation size and cost have positive correlations, as concrete, formwork and rebar quantity increases in proportion to base size. Feasible scope can be identified by examining stability and scope of base size that satisfies each stability examination item can be obtained. Again, feasible region that satisfies all conditions by superimposing all scopes can be identified. All coordinates in the feasible region are deemed to represent a base size that enables stable installation, operation and removal of tower crane. However, if cost minimization is considered in optimal design and objective function is limited to cost minimization, a coordinate that maximizes objective function value is said to be ‘optimal solution’ or ‘optimal value’ and representative of optimal foundation design point where stability is maximized and cost is minimized.

$$Z_{min} = \sum\{(\text{concrete q'ty x unit price}) + (\text{formwork q'ty x unit price}) + (\text{rebar q'ty x unit price})\}$$

$$Z_{max} = \sum \text{Stability(overturn+bearing capacity+shear)}$$

3.1 Optimal Foundation Design Process

Fig. 5 shows optimal foundation design process.

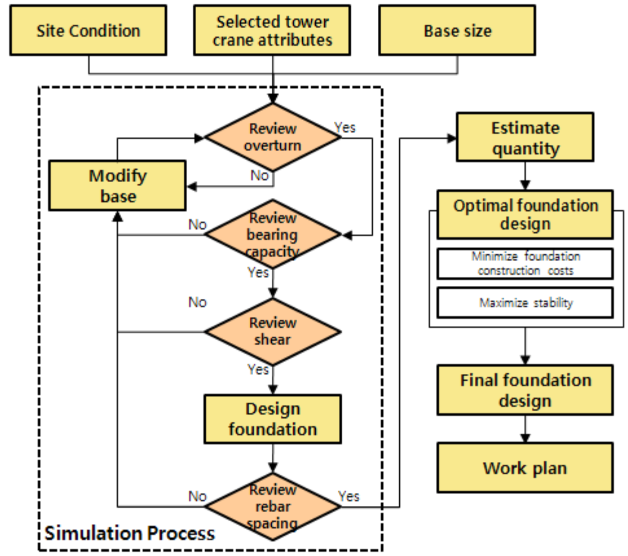


Fig. 5. Optimal Base Foundation Design Process

It shows adaptation of generic design process with addition of items necessary for optimal design. Stability is examined in reference to site conditions, selected tower crane attributes and initial base size and initial base size is modified in each step and rebar spacing is reviewed. Once base size is determined, concrete, formwork and rebar quantities are calculated and costs of not only materials but also equipment and labor are calculated. Then, both stability and costs are examined and foundation design is optimized by analyzing correlations between the two items.

In other words, conditions in this study of optimal tower crane design algorithm are summarized as follows:

① Design conditions : site conditions, selection of tower crane attributes, initial base size

② Stability review : overturn review, bearing capacity review, shear review, rebar spacing review

③ Optimal design goal : concrete cost, formwork cost, rebar cost

3.2 Design Conditions

3.2.1 Site Condition

Site conditions mean attributes of applicable project site and other conditions generically applicable to construction project. They include bearing capacity of applicable site found in ground survey, compressive strength of concrete, covering thickness and rebar strength, etc. Applicable safety factor is also one of the site conditions.

3.2.2 Selected Tower Crane Attributes

They mean tower crane attributes specified in manufacturer’s specification after suitable tower crane is selected in consideration of payload weight, structure height, construction scope, crane rental charge and other conditions. Such attributes include vertical force, horizontal force, moment and dead weight of tower crane and provides basic inputs to stability review.

3.2.3 Base Size

Although this study aims to optimize tower crane foundation design, base size in this step means a generic base size to be used basically. Generic base size for stability review is provided and modified in each step of stability review and cost review. Initial base size information includes lengths in X and Y axis respectively, base height and dead weight.

3.3 Stability Review

3.3.1 Overturn Review

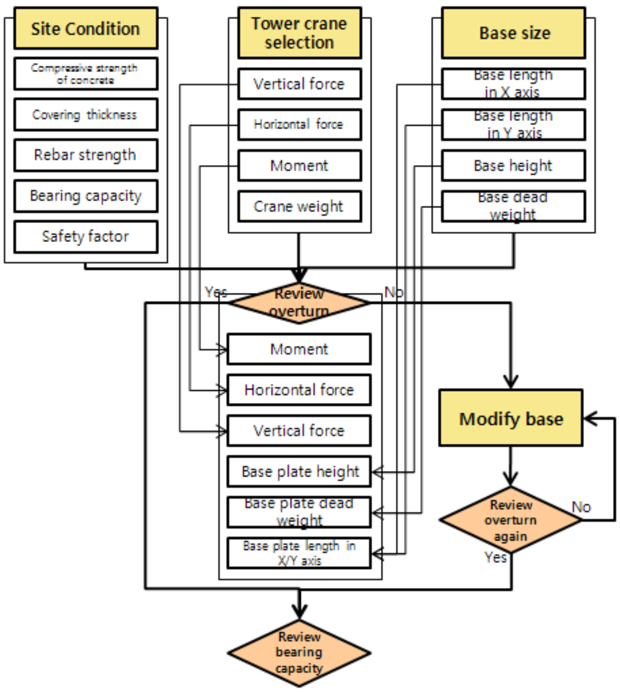


Fig. 6. Overturn Review Process

As for overturn stability calculation, Korean Industrial Standard (KS B ISO 12486) specifies that tower crane is stable when algebraic sum of stability moments is equal to or greater than the sum of overturn moments. As for overturn review, first, bearing capacity against vertical load must be secured and it must be reviewed whether overturn moment can be supported by foundation dead weight and anchor structure. Basic information necessary for overturn review, review process and relationship between calculation items are as described in Fig. 6.

Overturn review can be conducted on the basis of vertical force, horizontal force and moment acquired automatically upon selection of tower crane and base length in X/Y axis, height and dead weight available as parts of initial foundation configuration. Calculation formula for overturn is as described in Table 2 below.

3.3.2 Bearing Capacity Review

Basic information necessary for bearing capacity review, review process and relationship between calculation items are as described in Fig. 7.

Once overturn review is conducted, eccentricity acquired in overturn review, site conditions, base size and vertical force of tower crane are entered to initiate bearing capacity review.

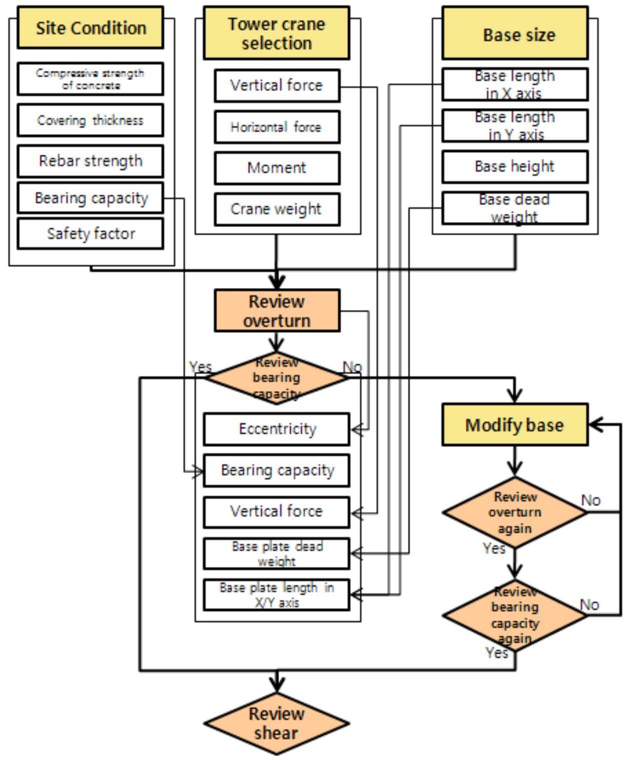


Fig. 7. Bearing Capacity Review Process

If base size needs to be modified, as it does not guarantee sufficient bearing capacity, review process goes back to overturn review prior to bearing capacity review to reiterate overturn and bearing capacity reviews. Once overturn and bearing capacity reviews are completed, shear review is initiated. Calculation formula for bearing capacity is as described in Table 2 below.

3.3.3 Shear Review

Basic information necessary for bearing capacity review, relationship between calculation items, review process and base size modification steps are as described in Fig. 8.

Shear review is initiated, as base size modified in overturn and bearing capacity reviews, compressive strength of concrete and rebar strength in site conditions are entered. Even a base size already proven to be stable in terms of possible overturn and bearing capacity must be modified again, unless it is proven to be stable in terms of shear. Base size modified to ensure shear stability needs to go through reiterative overturn, bearing capacity and shear review processes in the same manner as preceding steps. Calculation formula for shear capacity is as described in Table 2 below. Once, base size is proven to be stable in terms of overturn, bearing capacity and shear, foundation design process where rebar spacing is modified and foundation is designed based on base size modified above is initiated.

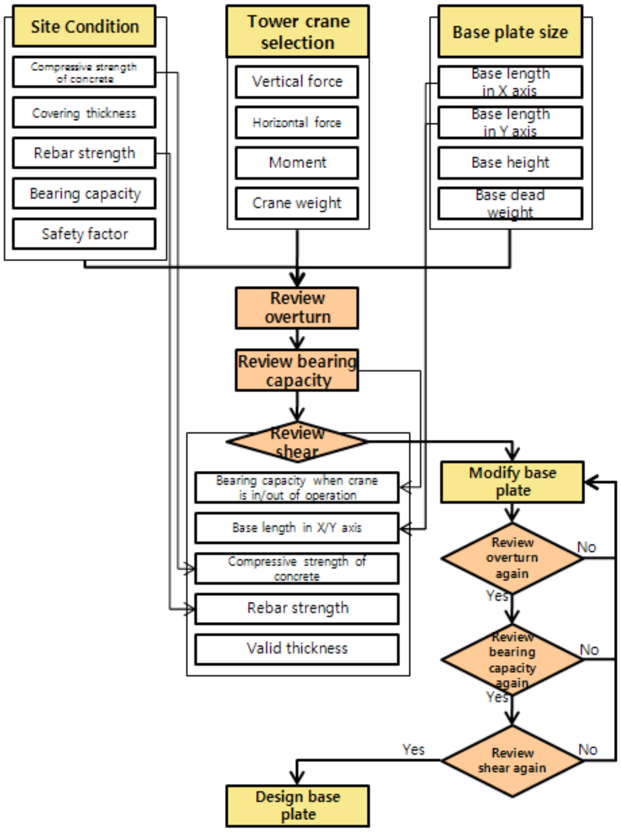


Fig. 8. Shear Review Process

Table 6. Stability Review Items & Calculation Formulas

Review Items		Calculation Formula
Overturn Review	1) In operation	Eccentricity e_s=(M +H×h)/(P+G) ≤ L_s/3
	2) Out of operation	Eccentricity e_s=(M +H×h)/(P+G) ≤ L_s/3
Bearing capacity Review	1) In operation	σ_b=2× (V+G)/(3×L_L×C) ≤ f_a
	2) Out of operation	σ_b=2× (V+G)/(3×L_L×C) ≤ f_a
Shear review	1) 1 Direction	V_u=1.7×σ_b×L_L×L' < ΦV_c=0.85×0.53×√fck×L_L×d
	2) 2 Directios	V_u=1.7×σ_b× (L_s×L_L-(ℓ+d)^2) < ΦVc=0.85×1.06×√fck×Bo×d

M:Moment H:Horizontal force h:Base height P:Vertical force G:Base dead weight
Ls:Base width V:Vertical force LL:Base length
C = Ls/2-es

3.4 Optimal Design Goal

3.4.1. Concrete Cost

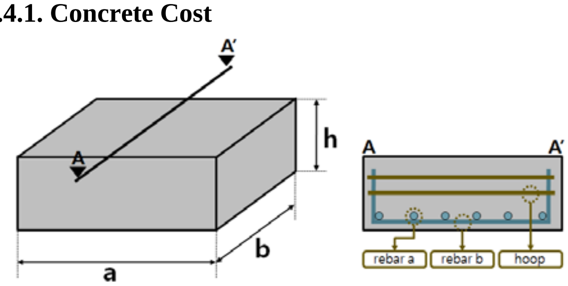


Fig. 9. Bases Size

Concrete quantity can be calculated by the following formula in reference to base size finalized in stability review and rebar spacing modification. Characters a,b and h used in the formula carry the meanings shown in Fig. 9. Concrete quantity(Q_{conc}) is calculated in the same manner as volume of generic rectangular box is calculated and multiplied by concrete unit price(UP_{conc}/ m³) that includes concrete cost, equipment cost and labor cost.

$$Cost_{conc} = Q_{conc} \times UP_{conc}$$
$$Q_{conc} = a \times b \times h\ (m^3)$$

3.4.2 Form Work Cost

As is the case with concrete quantity calculation, formwork cost ($Cost_{form}$) can be calculated on the basis of base size acquired in the preceding steps. It is calculated by calculated formwork quantity(Q_{form}) with unit price (UP_{form}/m²) that also includes formwork cost, equipment cost and labor cost in the same manner as generic formwork quantity calculation formula.

$$Cost_{form} = Q_{form} \times UP_{form}$$
$$Q_{form} = (a+b) \times 2 \times h\ (m^2)$$

3.4.3 Rebar Cost

Rebar quantity can be calculated after rebar spacing is reviewed in consideration of selected tower crane attributes and finalized base size. Rebar quantity is calculated by multiplying sum of side a rebar, side b rebar and rebar hoop with unit weight of each rebar and rebar cost is calculated by multiplying unit price per rebar diameter again. Rebar cost calculation formula is as follows.

$$Cost_{rebat} = Q_{rebar} \times UP_{rebar}$$
$$Q_{rebar} = \{(W_{rebar}a \times \sum L_{rebar}a)+(W_{rebar}b \times \sum L_{rebar}b)+(W_{rebar}hoop \times \sum L_{reba}hoop)\}/1{,}000\ (ton),$$ where,

$L_{rebar}a$: side a rebar cutting length (m)
$L_{rebar}b$: side b rebar cutting length (m)
$L_{rebar}hoop$: rebar hoop cutting length (m)
$W_{rebar}a$: unit weight of rebar a (kg/m)
$W_{rebar}b$: unit weight of rebar b (kg/m)
$W_{rebar}hoop$: unit weight of rebar hoop (kg/m)

Calculated cross section A_{rebar} is divided by converted cross section per rebar diameter Ra and number of necessary rebar strands is calculated by roundup [5] function.

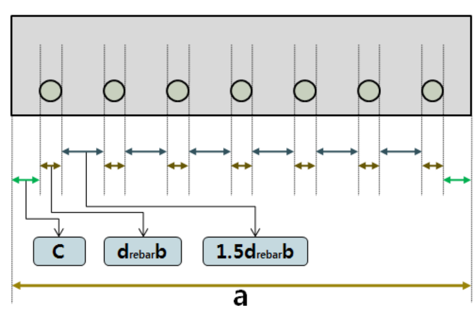


Fig. 10. Relationship between Long/Short Side Lengths & Rebar Spacing

Relationship between long/short side lengths and

[5] MS Excel, Roundup function

covering thickness C, rebar spacing and rebar diameter can be expressed as shown in Fig. 10. Covering thickness, rebar diameter and spacing must be equal to or smaller than the length of side a and the same also applies to side b.

$$a \geq (d_{rebar}b \times n) + 1.5d_{rebar}b(n-1) + 2C \rightarrow ok$$
$$b \geq (d_{rebar}a \times n) + 1.5d_{rebar}a(n-1) + 2C \rightarrow ok$$

In addition, rebar quantity can be calculated more accurately, if bending margin is considered. According to a study by Kim, Sun-Kuk et. al. (1991), bending margin means the phenomenon where high-tension steel bar is lengthened by 2.5 times its diameter when processed (See Fig. 11).

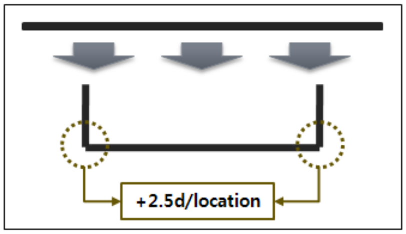


Fig. 11. Bending Margin

If rebar is cut without consideration of bending margin, about 1% rebar loss is incurred and rebar is not adequately covered by concrete, requiring additional labor, material and transportation costs. Therefore, bending margin warrants consideration in rebar work if rebar loss is to be reduced. In other words, rebar needs to be cut shorter than the rebar length in drawing by 2.5 times rebar diameter as many times as the number of bending locations in advance and bending margin is reflected on the algorithm herein to minimize potential rebar loss. Furthermore, additional rebar quantity calculation that each tower crane type may require, depending on its specific attributes is excluded from the scope of this research and only generic rebar quantity calculation is addressed herein.

Therefore, in case of tension rebar,

$$L_{rebar}a = (a-2C) + 40d_{rebar}a \times 2 - (2.5d_{rebar}a \times 2)$$
$$L_{rebar}b = (b-2C) + 40d_{rebar}b \times 2 - (2.5d_{rebar}b \times 2)$$
$$L_{reba}hoop = (a-2C) + (b-2C) \times 2 + 2 \times 10d_{hoop} - (2.5d_{hoop} \times 5)$$

and rebar quantity can be calculated by

$$Q_{rebar} = (W_{rebar}a \times \sum L_{rebar}a) + (W_{rebar}b \times \sum L_{reba}b) + (W_{rebar}hoop \times \sum L_{rebar}hoop)$$

as mentioned in the beginning of this section.

4. CONCLUSIONS

This study was intended to improve efficiency of foundation design upon recognition that stability of tower crane was not thoroughly examined, as installation of tower cranes is dictated by filed manager or installation specification presented by equipment supplier in most construction sites of Korea.

The research scope was limited to shallow foundation of fixed type tower crane and a foundation design process adapted from generic design process and added with elements of optimization was proposed. Following conclusions are derived from the study of optimal tower crane foundation design algorithm development, as this study aimed.

Firstly, items to be reviewed in relation to stability of tower crane foundation were analyzed. And optimal design process was proposed and correlations such items were identified. During the process, it was found that the stability review steps were not arranged in parallel but in series where a result from a certain step would affect the following step.

Secondly, concept of optimization was introduced into the generic foundation design process of tower crane to incorporate the concept of maximum stability at minimum costs.

Thirdly, a foundation design process was proposed to arrange base size modification processes and sequences in order, which is believed to provide references to subsequent studies and contribute to improving operational efficiency of field engineering staff as well.

Fourthly, additional rebar quantity deemed to be necessary, depending on tower crane features, is excluded from the research scope and only generically required rebar quantity calculation is addressed. However, rebar bending margin was factored into the algorithm to further improve accuracy of generic rebar quantity estimation.

This study marks the advanced step leading toward the development of tower crane foundation design algorithm and the results herein will provide references to further studies in support of tower crane foundation design algorithm model development. This study is deemed to have established the concept of optimal foundation design and analyzed the features and correlations of stability review processes as intended upfront.

※ This paper was performed with supporting of *Korea Science and Engineering Foundation* by financial resources of government (*Ministry of Education, Science and Technology*) in 2009
(NO. R11-2008-098-00000-0)

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